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Accuracy optimisation and error detection in automatically generated digital elevation models derived using digital photogrammetry

A Doctoral thesis

by

Michael Gooch BEng

Submitted in partial fulfilment of the requirements for the award of PhD Degree of Loughborough University

September 1999

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Users of current Digital Photogrammetric Systems (DPS) can now rapidly generate dense Digital Elevation Models (DEMs) with a minimal amount of training. This procedure is controlled through a set of strategy parameters embedded in the software. Previous research into the effect of these parameters on the resulting DEMs produced mixed results, with some researchers finding that significant changes to the DEM can be made through manipulation of the parameters whilst others suggested that they have little effect.

This thesis builds upon this early work to develop two systems that provide assistance for novice users. The first technique optimises the parameters with respect to DEM accuracy and takes the form of an expert system and compares the output from the DEM with a knowledge base to prescribe an improved set of parameters. The results suggest that the system works and can produce improvements in the accuracy of a DEM. It was found that in certain circumstances, changes to the parameters can have a significant effect on the resulting DEM, but this change does not occur across the entire DEM.

The second aspect of the thesis details the development of a completely new approach that automatically detects low accuracy areas of the DEM and presents this information graphically. This is an important development since, as documented in the current literature, few quality control procedures are offered to users. The user can use this information to assist in the manual checking and editing of the final DEM, thus speeding up the workflow and improving the accuracy of the output. The results of tests (using the ERDAS Imagine OrthoMAX software) on a wide variety of imagery are presented and show that the technique reliably detects areas of a DEM with high errors. More significantly, the technique has also been tested on two other DPSs (Zeiss Phodis TS and VirtuoZo) and it was found that it worked well for the Zeiss system but could not be applied to the VirtuoZo software. This demonstrates that the research is not limited to the users of one software package and is of interest to the wider photogrammetric community.

**Key Words**

Digital Photogrammetry, accuracy, data quality, DEM, strategy parameters, error detection.
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Chapter 1 A brief introduction to photogrammetry.

"Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena" (Slama, 1980). It is the process of obtaining three dimensional information through measurement of photographic images. The word photogrammetry is made up from three Greek words; photos meaning "light," gramma meaning "something drawn or written," and metros meaning "to measure."

Photogrammetry can be traced back to the work of Albrecht Dürer (1471 - 1528) and his laws of perspective. With the advent of flight and the camera in the 18th and 19th centuries, aerial photography was soon being used for military reconnaissance and mapping (Slama, 1980).

Since the turn of the century, photogrammetry has been used for precise engineering and mapping works. The achievable accuracy was made possible with the realisation that three dimensional data could be obtained from stereopairs - pairs of overlapping photographs (Wolf, 1983). The basic principle relies on the fact that a point on the ground, the centre of the camera and the image of the point in the photograph lies (in theory) on a straight line. This is called the principle of collinearity (section 2.5), and can be represented by two equations. If two photographs of the same point are taken from slightly different locations, two such lines can be defined - one for each photograph with the intersection of the lines occurring at the point on the ground. The ground coordinates (defined by three unknowns $X$, $Y$, $Z$) for any point appearing in both images can be obtained by simultaneously solving the four equations (2 collinearity equations for each photograph).
There are in effect three eras in photogrammetry (Fryer, 1996). The first two eras used expensive, high precision optical and mechanical instruments that required a large amount of experience to be operated with any degree of accuracy and efficiency. Many of the later machines, known as analytical plotters are still used today. Since the late 1980's however, a new era of photogrammetry has dawned, that of digital or softcopy photogrammetry.

With digital photogrammetry, the images are stored in a digital format such that they can be manipulated by a computer. The result of this is that the entire photogrammetric workflow can now be completed within the digital domain, eliminating the need for the sophisticated machinery previously required. Many of the tasks such as interior orientation, relative orientation and the generation of digital elevation models (DEMs) and orthophotos have been successfully automated (Dowman, 1996b) but there is scope for tasks such as mosaicing and feature extraction to be added to this list (Walker and Petrie, 1996).

This move towards a black box technology brings both benefits and problems to the industry. When combined with the use of standard off-the-shelf PC hardware at ever reducing costs, the user base expands. What was once seen as a specialized technique is now a realistic option for an ever greater number of people, from geologists, geographers and geomorphologists (Butler et al, 1998, Pyle et al, 1997) to glaciologists (Baltsavias et al., 1996), medical users (Newton and Mitchell, 1996) and industrial metrology practitioners (Fraser, 1993a).

Digital photogrammetry has matured to a level now whereby new users can generate 7000 coordinate points in ten minutes, a task that would take an experienced operator between 6 and 8 hours on an analytical plotter (Smith and Smith, 1996). However, novice users are unlikely to be aware of all of the issues involved in the accurate representation of objects appearing in the imagery and there are few quality control procedures embedded in current software. It is unlikely that they will be aware of the steps that need to be taken to ensure that the data are reliable, or the choices that are needed to reliably recreate the object space. As these systems evolve and the level of automation increases, the technical gap between the user and the technology grows.
When this happens, the product is likely to be a compromise, not fully utilizing the opportunities, benefits and capabilities afforded by the technique (Gooch et al., 1999a).

At present, there are few ways of assessing the quality of the output. The main way remains to overlay the DEM on a stereo-model of the object and manually check the entire DEM, a potentially lengthy process that negates many of the advantages of automation and requires a degree of experience to complete economically. The other way is to compare the output from the software with external data, collected by an independent source of a higher order of accuracy. This data is assumed to be "true" and allows the user to quantify errors in the DEM. However, this external data is rarely available, can be costly to acquire and there are no easy ways of comparing the two data sources. As Heipke (1999) states, the current digital photogrammetric software has "only little knowledge about when they work correctly and when they fail." Similarly, Cooper (1998) suggests that the development of "automated indication[s] of quality lag far behind" the field of 3D terrain analysis.

One of the concerns with automated DEM extraction software is the degree of control over the DEM generation algorithm exercised by a set of strategy parameters (Smith and Smith, 1996). These parameters control the search and acceptance criteria for the individual points in the DEM and alterations to the parameter settings can have a significant effect on the resulting DEM (Gooch et al., 1999a). Changes to the parameters have no effect on the orientation parameters, they merely change the way in which the algorithm searches for and accepts the individual points in the DEM. Previous research (Smith, 1997) has shown that changes to these parameters can improve the accuracy of the resulting DEM, whilst other research has suggested that they have little effect (Butler et al., 1998). An explanation for this conflict of results will be provided. This thesis is focused on the manipulation of these strategy parameters in order to optimise the accuracy of the derived DEMs and identify areas of the DEMs with large errors.
1.1 The aims of this research

This work builds upon the research of Smith (1997) who tested the effect of varying the strategy parameters on two sets of aerial imagery. The work presented in this thesis (Chapter 5) is more rigorous, through more exhaustive testing upon a more diverse range of imagery and examines if the conclusions from Smith (1997) can be applied to other data sets. The work also aims to clarify the apparent discrepancy in the literature (Smith, 1997; Butler et al., 1998) with respect to the effect on altering the strategy parameters on the accuracy of the DEM.

There are three clear aims to this research;

1. Identify reasons for the inconsistencies in the current literature (Butler et al., 1998, Smith, 1997).
2. Develop a technique for prescribing strategy parameter settings for different sets of imagery.
3. Develop a technique for identifying low accuracy areas of automatically generated DEMs

The first section of this thesis (Chapter 5) is focused on the optimisation of the strategy parameters with respect to the accuracy of the resulting DEM. Two optimisation methods (one manual and one automated technique) are described in the work and results of extensive testing on a range of different sets of imagery are presented. The development of a parameter optimization process is important for many users. Digital photogrammetric processes are being applied to more and more high accuracy work, projects in which all sources of error need to be accounted for and where appropriate minimised. At present, the user is required to define suitable parameter settings, a potentially problematic process as the technique is used for an increasing number of applications. A reliable, robust system would continue the trend towards full automation and take away the need for parameter definition by the user.
The originality of the research that has been undertaken is explained in the second section of the thesis (Chapters 6 and 7). This work was developed on the basis of the work carried out on the strategy parameter manipulation. An algorithm that automatically defines low accuracy areas of a DEM based upon the results from manipulating the strategy parameters has been developed. This technique is validated by extensive testing of the technique on a wide variety of data sets. The software presents the information in an easy to understand graphical format and the results demonstrate that the approach is valid for different scales of imagery and image contents. More significantly, the results presented in this section also suggest that the technique can be used on different DPS. Such a system is vital for the current digital photogrammetric systems as they move towards a black box technology. The lack of quality control procedures (Heipke, 1999; Cooper 1998) means that novice users have no real means of assessing the quality of their output and this software provides one answer to the problem.

1.2 Structure of the thesis

Chapter 2 deals with the basic concepts behind the photogrammetric workflow. Data capture methods are described, along with an introduction to the theory of errors. It is vital for the user to have an understanding of these basic principles if the output from the photogrammetric workflow is to be as accurate as possible. Chapter 3 examines digital photogrammetric techniques in more detail, with attention to the software used in this thesis. The subject of DEM generation is also outlined along with an examination of the factors affecting DEM accuracy. Details of the strategy parameters are also provided along with results from similar research projects. Chapter 4 details the imagery used in the testing procedure and provides examples of orthophotographs derived from each of the data sets. A methodology for the initial tests carried out in the study is provided along with details of the custom software developed for use in the project.
The results of the optimisation of the strategy parameters with respect DEM accuracy are presented in Chapter 5. The chapter is split into three main sections, the first of which provides the results of the tests carried out using the conclusions from previous research projects (Smith, 1997). The second part provides the results from the manual manipulation process completed as part of this research project before a new technique for prescribing parameter settings based upon a comparison with a knowledge base is detailed and tested in the third section. The details of an error detection algorithm developed in this project are presented in Chapter 6. This is a completely new technique that makes use of changes to the strategy parameters to identify low accuracy areas of a DEM and presents the information in a graphical format. The results of testing of the technique on a wide variety of data sets and two other photogrammetric systems are detailed in Chapter 7. Conclusions of the work are included in Chapter 8 along with recommendations for further work.
Chapter 2 The principles of photogrammetry.

The purpose of this chapter is to introduce the reader to the basic concepts and principles of photogrammetry. Different types of photogrammetry will be discussed along with image acquisition methods and the theory of errors.

Photogrammetry relies on the principle that a line joining a point on the ground, the centre of the camera and the point on the image is a straight line in 3D space (i.e. the collinearity condition – Section 2.5). If the position and orientation of the camera and the image co-ordinates are known then this line can be defined. The only unknown that remains is the exact location along the line of the point on the ground. If one or more images is taken of the same point from different locations, their spatial intersection will occur at the true location of the point on the ground (see Figure 2-1).

Once the positions and rotations of the two exposure stations have been determined, the co-ordinates of any point in the overlap between the two images can be calculated simply by measuring the location of the point in the two images. This is the primary aim of the photogrammetric process, to obtain spatial information about the objects in the image, enabling output such as maps, contours, Digital Elevation Models (DEM)s and orthophotographs to be produced.

Photogrammetry can be classified in a number of ways, either by the type of imagery or the technology used to process data. Technology evolves with time and, as mentioned in chapter 1, it is possible to identify three eras in which significant developments occurred in photogrammetry; analogue, analytical or digital. The type of imagery can be defined as close-range/terrestrial, aerial or satellite and either vertical or oblique (Wolf, 1983). The term aerial photogrammetry may be applied when the imagery has been captured from an airborne platform whereas close-range applies to imagery captured from ground based camera systems.
2.1 Analogue Photogrammetry

Up until the 1950s and 60s, production photogrammetry exclusively used a class of instruments known as analogue plotters (Burnside, 1996; Slama, 1980; Walker, 1995; Wolf, 1983). First used in 1901, analogue instruments recreate the light rays (either by optical projection or through precise opto-mechanical linkages) to generate a 3 dimensional model (stereomodel) of the ground (Petrie, 1977) using the two photographs (also called diapositives) acquired at the time of exposure (Slama, 1980). This enables height contours and co-ordinates to be traced from the model onto a map sheet.
2.2 Analytical Photogrammetry

With the development of the digital computer in the 1950s came a new class of instrument, the *analytical* plotter (Petrie, 1992; Smith, 1996; Slama, 1980; Walker, 1995; Barker et al., 1997). By using the collinearity equations in their direct form, it is possible to trace object points to determine the photo-coordinates of the left and right hand photographs. By knowing the exterior orientation parameters, the measuring mark is moved to that location on each image. This computation is repeated in a 'real time' loop at 60Hz and effectively enables the images to be measured in a simple 2D photo coordinate system. Originally designed by U. V. Helava and announced in 1957, the analytical plotting instrument is still used and manufactured today and has allowed for increased production of digital maps, Digital Elevation Models (DEMs) and topographic maps (ERDAS, 1997). However, when compared to modern techniques, such machines are specialized devices produced for a focused market. As a consequence they are expensive to purchase and have high running costs. Analytical instruments can be complicated pieces of machinery that require a high degree of user experience before reliable and accurate results can be obtained. Whilst sales of analytical systems remain buoyant, their development has largely ceased and between 1992 and 1996, only one new design of analytical plotter was released (Petrie, 1992).
2.3 Digital Photogrammetry

Since the middle of the 1980s, a new branch of photogrammetry has appeared, that of *softcopy* (Boniface, 1992; Schenk, 1996) or *digital* photogrammetry (Fryer, 1996). Both terms can be applied to the technology although digital photogrammetry is now more widely used. Digital photogrammetry is very similar to analytical photogrammetry in that it uses computers to mathematically determine the coordinates but the imagery is stored in the computer in a digital form. The significant difference between the two is that in digital photogrammetry, a digital representation of the image is used and all of the processing is carried out on a workstation or PC. However, when combined with the computing power of modern workstations and sophisticated software, it offers an increased level of automation (Al-Garni, 1995;
Ackermann, 1996a; Torlegard, 1996), greater operational abilities, speed and concepts over analytical systems, and through the use of standard off-the-shelf parts, reduced construction and operating costs.

The primary advantage offered by digital photogrammetry is the potential to automate many of the tasks in the photogrammetric workflow. Automation is sought after (Dowman, 1996a; Liang and Heipke, 1996; Heipke, 1995) because it offers much greater speed (the computer is well suited to repetitive mathematical operations and is much quicker than the human brain) and eliminates inherent human variability (Garbrecht and Starks, 1995; Ley, 1988). Constant research and development means that full automation is becoming more feasible (Kersten and O'Sullivan, 1996). These advantages combined with its ability to offer "total system" packages in which all operations are carried out on the one machine, means that digital photogrammetry is rapidly overtaking analytical instrumentation (Ackermann, 1996a). It contains no high precision, expensive components and few of the optical components required for the other systems. High specification Digital Photogrammetric Systems (DPS) (Heipke, 1995; Usery, 1996) still cost more (Dowman, 1996a) than an analytical machine (Methley, 1994) but the nature of the electronics industry and the increasing use of standard components (Schenk, 1996; Kolbl, 1996b) means that this will not be the case for much longer (Boniface, 1992).

Certain tasks (scanning, some parts of the interior orientation process, DEM and ortho-photo generation) have already been successfully automated and are operational within the digital environment (Hartfield, 1998). Others (e.g. full aerial triangulation) are in the process of being automated, but will take more time and research before they are operational (Ackermann, 1996c; Dowman, 1996(c); Walker, 1997). As automation progresses, so does the availability of digital photogrammetry to the untrained photogrammetrist. Many of the digital systems operate in a window type environment on platforms familiar to the computer literate and use interface tools such as Wizards and linear workflow to guide the user through the process (Shears, 1999). As manufacturers make the systems more user friendly, there is a distinct danger of it becoming a "black box" technology, with the user not being fully aware of the
consequence of actions. As Smith and Smith (1996) point out, it can become dangerous to use the technology in such situations.

Figure 2-3 A DSW200 Digital Scanning Workstation (Walker 1996)

However, increased availability and widening applications of the technology (Cooper and Robson, 1990; Fraser, 1993; Shortis et al., 1994; Simmons, 1996; Stanbridge, 1996; Tait and Uren, 1996) promotes research (Gruen, 1994), reliance and dependence. Before industrial acceptance can occur, the technology must be reliable, efficient, cost effective and above all accurate (Logan, 1996). Only in this way can the user have confidence in the quality of the output from the system.
2.4 Data Collection Methods

The purpose of this section of the chapter is to give the reader an insight into data collection methods and some of the issues that affect the quality of derived data. Both cameras and scanners will be discussed, as scanning plays a vital part of the data collection process.

With a DPS, the images are represented in a digital form, with the analogue photograph or image represented by elements or rows of *pixels* (picture elements) (Graham, 1998) which have finite size, a distinct value and can be manipulated and stored by a computer (Figure 2-4). Each pixel has a grey level value (colour imagery can be used), its level (the greyness is measured on a scale of 1 to 256) representing the light intensity of the ground at that point (Dowman, 1996a). The advantages of using the images in this form include (from Shortis et al., 1994):

- the images can be displayed on the screen
- the images are stable and need no calibration
- enhancement methods can be applied if required
- automation can be applied
- operations can be carried out in real time

The digital data can be collected in one of two ways, either directly using a *digital camera* (Heijden, 1994; King et al., 1994) or using a *scanner* to convert analogue photographs taken from film cameras into a digital format (Colomer and Colomina, 1994). Both methods work by measuring the intensity of light falling on each element of the sensor - the sensor market being dominated by Charge Couple Devices (CCD). The output from the sensor can then be input directly into the DPS for reconstruction.
2.4.1 Film Cameras

A camera that has been designed specifically for the use in photogrammetry is called a *metric* camera (Cooper and Robson, 1996). Such cameras are designed to fulfill the condition of collinearity (Chandler, 1999) which requires that the internal geometry (the spatial relationship between the lens and the focal plane) of the camera is known.

Imperfections in the camera can be modelled and allowances made for in the image processing stages. Therefore, manufacturers supply metric cameras with calibration certificates (Cooper and Robson, 1996).

Metric film cameras exist in a variety of forms, the most common of which is the *frame camera* where the entire frame is exposed simultaneously through a lens which is fixed relative to the camera body (Slama, 1980). Applications using aerial photography have traditionally dominated photogrammetry and much work has been carried out into the development of cameras specifically for the task of obtaining the imagery from an airplane (Wolf, 1983). Most aerial frame cameras have a 23cm x
23cm format size and a wide angle lens with a nominal focal length of 152mm, although other sizes are available (Wolf, 1983). The exposed film can be thought of as a nearly infinite number of focal-plane detectors because each element on the ground will cause a corresponding reaction on the silver halide grains of the emulsion of the film with no overlap. Hence, film cameras produce the finest resolution of all the data capture devices and offer the distinct advantage that the entire frame is exposed at one instant making the frame one homogenous unit (Light, 1996). Other camera types include (Wolf, 1983; Slama, 1980):

- **panoramic** cameras which produce a wide coverage image from horizon to horizon
- **multilens** cameras which work on the same principle as single lens cameras except that they have two or more lenses and expose two or more images simultaneously
- **strip** cameras which, as the name suggests, produces a continuous strip image, formed by moving the film past a stationary slit in the focal plane.

The main feature of all metric cameras is that the spatial relationship between the lens, the focal plane and the fiducial marks can be assumed to be stable and can be determined by calibration (Section 2.6.2) (Clarke and Fryer, 1998).

A measure of quality for aerial film cameras is the area weighted average resolution (AWAR) which is measured in line pairs per millimetre (lp/mm). A line pair is “the width of one black bar and one white space as contained on resolution targets” (Light, 1996). The theoretical relationship between the AWAR and CCD pixel size would suggest that two pixels are equal to one line-pair, but in practice two pixels can often fail to resolve one black line and an adjacent white line (a line-pair). The Kell factor is used to describe the relationship between pixels and resolution which states that (Dowman, 1996a)

\[
\text{Resolution (lp m}^{-1}\text{)} = \text{pixel size} \times 2\sqrt{2} \text{ m at object scale.}
\]
Metric film cameras are extremely expensive so many users have looked to non- or semi-metric cameras as an alternative (Stojic et al., 1998; Butler et al., 1998). These are cameras which provide an appropriate format size but tend to have an unstable internal geometry that could have serious implications upon the accuracies of data generated by the photogrammetric process (Dallas, 1996) if overlooked or ignored.

2.4.2 Scanners

Scanners are an essential part of digital photogrammetry (Baltsavias, 1998) and are used to convert analogue film images into a digital representation at an appropriate resolution (Kolbl and Bach, 1996). The scanning of film images plays a vital part in the photogrammetric work-flow, since it can be one of the first tasks to be carried out in the post-processing phase and any errors made are compounded through the rest of the process. The professional scanners used for photogrammetric purposes can be categorized in one of four ways (Petrie, 1992; Baltsavias, 1996):

- drum scanners
- 2D flatbed scanners
- 1D scanning linear array
- CCD areal array

In addition to these types of scanners, research has been carried out to assess the potential of desk-top scanners in photogrammetry. Baltsavias (1996) provides comprehensive results from tests on five desk-top scanners. They offer distinct cost advantages over the professional machines (Shortis et al., 1994; Walker, 1997) but typically with lower resolution and accuracy (Shortis et al., 1994). Baltsavias (1996) suggests that the accuracy of these type of machines is not likely to improve enough to meet the demands of the photogrammetric community since the vendors prefer to concentrate on bigger markets such as desk top publishing. Jacobsen (1996) states that only scanners designed specifically for photogrammetric tasks have an appropriate accuracy (Colomer and Colomina, 1994). Baltsavias (1998) suggests a useful set of
criteria for selecting suitable film scanners and compares 5 machines currently available.

Kolbl and Bach (1996) suggest the following as a list of criteria for defining scanner quality:

- Geometry - select a precision which is comparable to that which can be achieved during triangulation
- Image resolution - determined by the quality of the film and the camera
- Image noise - defined by the granularity of the film
- Dynamic range - should correspond to the contrast of the photographs
- Colour reproduction - important as colour imagery is used more frequently
- Data compression - effectively reduces the file sizes produced

Care should be taken when choosing the scanner, as there are considerable differences in the image quality between scanners (Kolbl, 1996c) and few if any will meet all of the users requirements (Baltsavias, 1996). A standard aerial photogrammetric camera has a 23cm x 23cm format and the AWAR normal range for this type of photography is between 20 and 40 lp/mm. To maintain the resolution of the imagery, the required pixel size for scanning is between 12.5μm to 25μm. A 23cm x 23cm image scanned at 25μm results in an 81Mb file size. With two images in use, the resulting image and memory handling requirements of the workstation are large (Walker and Petrie, 1996).

Image compression is one solution (Kern and Carswell, 1994; Lammi and Sarjakoski, 1995; Novak and Shahin, 1996; Smith and Smith, 1996) but raises separate concerns over accuracy (Reeves et al., 1998) and this will be discussed in more detail in section 3.6.5. The choice of pixel size will always be a compromise between accuracy (Aspinall et al., 1994) and economy until data storage no longer becomes an issue within computing.

Automation is sought in scanning as well as image processing (Miller et al., 1996; Baltsavias et al., 1998) and some scanners now have the ability to scan sequential film
negatives on a roll directly (Walker and Petrie, 1996). However, as Walker (1997) states, "the technical challenges of accurate film advance, totally autonomous interior orientation and the digital equivalent of electronic dodging and compensation for "hot spots" are considerable".

2.4.3 Digital Cameras

Digital cameras are being used increasingly in photogrammetry because they eliminate the need for scanning methods and do not suffer from many of the error sources associated with film based photography such as film shrinkage. Instead, the entire data capture process is completed in one stage.

A digital camera works in the same way as a frame camera (Dowman, 1996a) with a lens and shutter, but instead of a light sensitive emulsion, (CCD) sensors (Heijden, 1994; Robson and Shortis, 1998) are used to measure the intensity of light falling on them from the object. They offer several distinct advantages over film-based cameras when used for photogrammetry. The image geometry is stable because the CCD array does not suffer from physical distortions associated with film warping, they offer better radiometric image quality (a greater dynamic range), the ability to process data in real time (King et al., 1994), small size, no maintenance and insensitivity to magnetic fields (Shortis, 1988). However, they also have several disadvantages, namely data transfer and storage rates (King et al., 1994) and are prone to several unique problems such as blooming, dynamic range, and smear (Heijden, 1994). Shortis et al. (1998) suggest potential problems with movement of the CCD array (in the Kodak DCS series of cameras) with different camera orientations. An example of a digital camera can be seen in Figure 2-5.

A digital version (of comparable quality to a frame camera) of the aerial camera is yet to be developed (King et al., 1994; Mills et al., 1996; Walker and Petrie, 1996). As Walker (1998) states "the performance and format of aerial film cameras are the result
of 75 years of continuous development and they are daunting to beat.” It is anticipated that airborne digital cameras will offer performance comparable with film cameras in the future but when is open to debate (Shortis, 1988). As well as the benefits listed earlier, they have the added advantage of the ability to offer multispectral performance superior to film systems. Digital cameras are gaining widespread acceptance in other fields, particularly in close-range vision metrology and architectural recording (Shortis et al., 1998).
2.5 The Functional Basis of Photogrammetry

In this section, the basic theory of photogrammetry will be discussed in more detail. It is important for users of both analytical and digital techniques to have an understanding of these principles.

2.5.1 Co-ordinate Systems

It is common practice to use 2 different co-ordinate systems in photogrammetry. Points which lie on the ground or surface being photographed are said to exist in object space, whilst points in the image (including the internal geometry of the camera) are said to lie in image space. The principle of photogrammetry relies on a small amount of a priori knowledge of the ground being modelled. This knowledge takes the form of ground control points (GCP) (Davison, 1994; Liang and Heipke, 1996; Vanommeslaeghe, 1996) and are points visible on the photograph whose position are accurately known. Three GCPs are required as a minimum for a stereopair (more are normally used (Chandler, 1999) and they are defined by their own arbitrary Cartesian co-ordinate system, said to be located in object space or the primary co-ordinate system - see section 2.6. (Cooper and Robson, 1996).

When control information is not available for an image in a block, tie points can be used (ERDAS, 1997). These are points that are clearly visible on both images in the overlap. Also expressed in terms of the primary co-ordinate system are the coordinates of the perspective centre (O) of the secondary co-ordinate system \((X_0, Y_0, Z_0)\) (i.e. the centre of the camera), as illustrated in figure 2-6.

The secondary Cartesian coordinate system \((x, y, z)\) is called the image co-ordinate system. The position of any point on the photograph can be defined by a set of three co-ordinates in the image co-ordinate system. The x and y axes of the system are parallel to the plane of projection (the image/photograph) and the z axis coincides with the principal axis of the camera. This is the line perpendicular to the focal plane that passes through the perspective centre of the camera and intersects the focal plane.
the centre of the image (the principal point, \( p \)). Note that the principal point may not necessarily occur at the centre of the image and may have an offset that should be modelled in the interior orientation process. The distance \( Op \) is called the principal distance (or focal length) and is denoted by the letter \( c \). Hence, a point \( A \) can be presented by its position in the object \((X_A, Y_A, Z_A)\) with image coordinates of \((x_a, y_a, z_a)\).

Figure 2-6 Image and Object Coordinate Space
The axes for the image co-ordinates are defined (on metric cameras) by *fiducial marks* (Figure 2-7). These are marks are usually located in the four corners, in the middle of the four sides or in all eight positions of the photograph and are rigidly connected to the camera lens through the camera body so that they appear on the negative. Their intersection occurs at the *centre of collimation* (Wolf, 1983). Precise camera construction is undertaken to ensure that the centre of collimation is as near to the principal point as possible.
2.5.2 The Collinearity Condition

A straight line can be defined which joins the image of a point on the photograph, passes through the perspective centre of the camera and joins the location of the point on the ground. In matrix form, this relationship can be written as:

\[
\begin{bmatrix}
X_A \\
Y_A \\
Z_A
\end{bmatrix} = \begin{bmatrix}
X_O \\
Y_O \\
Z_O
\end{bmatrix} - \mu \begin{bmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{bmatrix} \begin{bmatrix}
x_a \\
y_a \\
z_a
\end{bmatrix}
\]

Equation 2-1

Where \( \mu \) is a scalar quantity greater than zero and the elements \( r_{ij} \) represent the 9 elements of a rotation matrix. The rotation matrix describes the attitude or rotation of the camera axis at the time of exposure (Slama, 1980, Cooper, 1986). A clockwise rotation around the camera's x axis is denoted by \( \omega \), a clockwise rotation around the y axis by \( \phi \) and a clockwise rotation around the z axis by \( \kappa \) - see Figure 2-8. The elements of the rotation matrix can be determined through knowledge of the three rotation angles where:

\[
\begin{align*}
    r_{11} &= \cos \phi \cos \kappa \\
    r_{12} &= \sin \omega \sin \phi \cos \kappa + \cos \omega \sin \kappa \\
    r_{13} &= -\cos \omega \sin \phi \cos \kappa + \sin \omega \sin \kappa \\
    r_{21} &= -\cos \phi \sin \kappa \\
    r_{22} &= -\sin \omega \sin \phi \sin \kappa + \cos \omega \cos \kappa \\
    r_{23} &= \cos \omega \sin \phi \cos \kappa + \sin \omega \cos \kappa \\
    r_{31} &= \sin \phi \\
    r_{32} &= -\sin \omega \cos \phi \\
    r_{33} &= \cos \omega \cos \phi
\end{align*}
\]
The camera coordinates \((X_0, Y_0, Z_0)\) and the three rotations \((\omega, \phi, \kappa)\) are called the *elements of exterior orientation*. The perspective transformation equations can be rearranged to eliminate the scalar quantity, thus forming the *collinearity equations*:

\[
\begin{align*}
x &= -c \frac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)} \\
y &= -c \frac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}
\end{align*}
\]

Equation 2-2

These 2 equations form the basis of analytical and digital photogrammetry.

It can be seen that if the co-ordinates of the GCPs in image \((x, y)\) and object space \((X, Y, Z)\) are known, the only unknowns are the elements of exterior orientation. Thus, if sufficient GCPs are visible on an image, these elements can be calculated. Once these parameters have been determined, the unknown object space co-ordinates \((X, Y, Z)\) of unknown points (that appear in the overlap of two adjacent images) can be calculated (3 unknowns, 4 equations) using either a space intersection or more typically a process called the bundle adjustment (Section 2.5.4) (Cooper, 1987; Granshaw, 1980).
The exterior orientation relative to the photo co-ordinate system of another can be achieved using a process called *relative orientation* (Cooper and Robson, 1996), effectively recreating the relative position and orientation of the cameras at the time of the photography.

### 2.5.3 Space Resection

The six unknown parameters of exterior orientation can be estimated using the equations of collinearity in a process called *space resection* (Wolf, 1983). A minimum of three ground control points are needed to evaluate all six of the parameters (since the image and object coordinates are known from measurements of the GCPs and the image coordinates).

### 2.5.4 Bundle Adjustment

The relationship between the elements that are measured and the elements that are evaluated is called a *functional model* (Cooper and Cross, 1988). To establish the position of the camera relative to the Earth’s surface at the time of exposure, a process called bundle adjustment is undertaken, (Granshaw, 1980; Grun, 1982) a process which makes use of *the principle of least squares* and redundant observations to provide the best estimates for parameters (Chandler, 1999). A least squares approach is used to derive the best estimates for the exterior and interior orientation parameters, camera calibration data and object co-ordinates through a process of minimising measurement residuals. The use of many measurements (it can handle large *blocks* or *strips* of photographs) results in high degrees of freedom and reliability and a determinable precision (Chandler, 1999). However, the drawback is that the large number of estimable parameters means that computational requirements are much larger than the functionally simpler space resection/intersection.
Least squares (Cooper and Cross, 1988; Wolf, 1983; Thapa and Bossler, 1992) forms a vital role within the bundle adjustment process. It is a method for adjusting survey measurements that contain random errors. It estimates optimum or "best estimates" for parameters based upon the ideal of minimizing the residuals (Stojic, 1997). In the case of photogrammetry, the parameters used are the ground co-ordinates, the position and orientation of the images and possibly the inner orientation parameters as well. These parameters are related to the photo measurements through the functional model comprised of the collinearity condition. This is the process used by most analytical and digital systems.

If a non-metric camera is being used for which the camera calibration certificate is not available, the user may consider a procedure called self-calibration to obtain the elements of interior orientation. This is done by measuring the photo co-ordinates of at least 40 photo-control and pass points appearing on a minimum of 4 images and then using a self-calibrating bundle adjustment (SCBA) (Granshaw, 1980; Chandler and Cooper, 1989; Chandler, 1999). Much work has been carried out on the calibration of digital cameras (Shortis et al., 1998; Robson and Shortis, 1998; Mills et al., 1996) which have brought their own unique problems into the field of camera calibration (such as a lack of fiducial marks and the potential movement of the CCD array with different camera orientations).

2.5.5 Systematic Errors

The collinearity equations provide the functional model used in photogrammetry but systematic errors will occur if they are applied to a system without compensation for camera deformities, since they assume that the light passes in a straight line through the camera. Evaluation of these deformities is called the process of Interior Orientation and this is the first step in the triangulation process. Interior orientation is carried out with the aim of finding three elements; the calibrated focal length, the location of the principal point and the parameters of lens distortion (Wiley and Wong, 1995). If these values are known accurately (from a camera calibration certificate)
and input correctly into the software, the internal geometry can be recreated and accurate data obtained (Chandler, 1999).

2.5.6 Output from Photogrammetric Systems.

Once the exterior orientation parameters have been obtained for both camera locations, the coordinates in object space of any unknown point can be evaluated using a process called intersection. This is the reverse of resection and uses the four equations derived using two sets of collinearity equations for the two photographs, to obtain the three unknown co-ordinates \((X_A, Y_A, Z_A)\) of the point. The process of determining \(X\), \(Y\) and \(Z\) co-ordinates of individual points based upon photographic measurements is called spatial intersection.

This is one of the processes that has been successfully automated with the advent of digital photogrammetry. In effect, the process of intersection is computed for many thousands of points in a regular grid to form a DEM. The use of high-powered PCs and workstations means that the process can be completed very quickly. Once the DEM has been generated, the coordinates can then later be used to generate other products such as orthophotographs.

2.6 Accuracy and Error

Of primary importance to this work is the detection of errors and the measurement of accuracy. All measurements contain errors (Schofield, 1993). It therefore follows that even though the true value of the measurement exists, it can never be found (Uren, 1995). If the true value can never be found, then neither can the true error. This means that the position of a point can only be known to exist within certain error bounds. In many cases, the magnitude of errors remains unknown (Giles and Franklin, 1996).
2.6.1 Types of Errors

There are three types of error associated with surveying measurements. Systematic errors can be constant or variable throughout an operation and can be modelled or assigned a numerical value. A good example in photogrammetry is that of camera calibration. Here, imperfections in the lens and camera are measured and allowances made for in the interior orientation process. Whilst it is unlikely that systematic errors will ever be eliminated (Cooper and Cross, 1988), attempts should be made to estimate their value and significance.

A second class of errors exist and are defined as blunders. Blunders are caused by the operator and are usually recognized by their high residuals. Typical examples of blunders are the misidentification of photo-control, the incorrect input of co-ordinates or the identification of the wrong fiducial mark on an image. Blunders can only be avoided through experience and care at all stages of the photogrammetric workflow. No allowance is made for blunders in the stochastic model. Blunders usually cause the largest errors. They can only be minimized by taking care and through experience, although they can often be detected by their large residuals.

Random errors are the errors that remain once the systematic errors and blunders have been eliminated. They remain beyond the control of the user and are present in all readings. They are assumed to follow the normal or Gaussian distribution, which predicts that:

- small errors will occur more frequently than large errors
- very large errors are extremely unlikely
- positive and negative errors occur with equal frequency
- the probability of a certain error occurring in a set of observations can be calculated
The effect of the random errors are described using a stochastic model (Cooper and Cross, 1988; Thapa and Bossler, 1992).

2.6.2 Quantification of Accuracy

Of primary concern in this thesis is the maximization of DEM accuracy. Accuracy can be defined as the "closeness of a measurement to the true value". We therefore need to be able to quantify accuracy. Since the true value is not known, then this involves the minimization of errors and the comparison of derived data with other estimates of the ground elevation (of a higher order of accuracy) known as check data.

Once check point data has been obtained, the differences between the DEM and the check data can be found. The United States Geological Survey (USGS) suggest that a minimum of 28 well distributed check points should be used as a minimum in the determination of DEM accuracy calculations (USGS, 1996). Similarly, Li (1991) suggests that between 20 and 30 check points should be used. They should also have an accuracy "well within the DEM accuracy criteria" i.e. be of a higher order of accuracy. The USGS state that r.m.s.e should be used to describe DEM vertical accuracy (USGS 1996).

The normal way of analyzing this data is to use the root mean square error (rmse) (Li, 1988; Uren, 1995):

\[
rmse = \sqrt{\frac{\sum (DH_i)^2}{N}}
\]

Equation 2-3

where

DH = check point residuals
N = number of check points

Li also suggests some other methods for measuring DEM accuracy, including the range of errors (R) where
\[ R = DH_{\text{MAX}} - DH_{\text{MIN}} \]

Equation 2-4

where \( DH_{\text{MAX}} \) = maximum elevation difference between DEM and check point data
\( DH_{\text{MIN}} \) = minimum elevation difference between DEM and check point data

Another possibility is to use the mathematical expectation (\( \mu \)) where

\[ \mu = \frac{DH_1}{N} \]

Equation 2-5

and the standard deviation (SD(DH)) of the elevation differences where

\[ SD(DH) = \sqrt{\frac{1}{N} \sum (DH_i - \mu)^2} \]

Equation 2-6

Makarovic (1972) uses the notion of fidelity to measure the amount of information transferred from the data source to the reconstructed data. This makes the assumption that a seemingly random surface can be represented as a series of periodic surfaces.

2.7 Summary

This chapter has introduced the reader to the concepts behind photogrammetry. A brief description of previous technology was given before the subject of digital photogrammetry was introduced. The capture of the digital imagery was discussed along with the process of estimating the elements of exterior orientation of an image. Finally, the basic theory of errors was described along with the measurement and definition of accuracy.

In the next chapter, details of digital photogrammetric techniques will be provided, along with a discussion of DEMs and issues pertaining to their accuracy.
In the next chapter, details of digital photogrammetric techniques will be provided, along with a discussion of DEMs and issues pertaining to their accuracy.
Chapter 3 Digital photogrammetry

The purpose of Chapter 3 is to develop the concepts of digital photogrammetry introduced in Chapter 2 and to introduce the reader to issues affecting the accuracy of DEMs. Basic hardware and software issues will be discussed before the subject of automated DEM extraction and their strategy parameters is examined in detail. The status of previous research in the field of parameter optimisation will also be presented.

3.1 Hardware Requirements

The advent of the digital era of photogrammetry has brought about a host of new technologies for the photogrammetrist, one of the most important of which is undoubtedly the host computer. Whereas once the wide variety of tasks in the photogrammetric workflow had to be carried out on a variety of machines by a number of specialised operators, this can now be achieved using either a PC or workstation by one relatively inexperienced user (Armenakis, 1998). The basic design of a Digital Photogrammetric System (DPS) can be seen in Figure 3-1.

The requirements for a DPS will vary according to applications but the basic prerequisites are (Dowman, 1996a):

- A high resolution display
- Flexible, fast access memory for image roaming
- Interface capabilities for cameras and scanners
- Interface capabilities for an output device (printer, plotter, CD writer etc.)
- Three dimensional measurement
- Sub-pixel accuracy
Others that can be added to this list are networking and archiving abilities (Walker and Petrie, 1996) along with high capacity disks, graphics accelerators and 3D measurement devices (Heipke, 1995). Networking capabilities are a vital part of any modern DPW, since it enables the storage and retrieval of data from external sources, reducing the dependence on the computer's internal hard drive to store data and easing the transfer of data from one source to another.

Figure 3-1 DPS hardware configuration (from Dowman 1996a)
3.1.1 Display

All digital photogrammetric systems must have at least one monitor, but some have two or more to enable comfortable 3D viewing. With the increasing use of 24 bit colour imagery, high quality monitors with a high resolution (1280 x 1024 pixels) are mandatory (Walker and Petrie, 1996).

Stereo viewing is seen by most users as an essential part of the DPS (Heipke, 1995) but as Walker and Petrie (1996) state "only three operations are inherently stereoscopic: (i) measurement of ground control points ... (ii) editing of automatically generated DTMs and (iii) feature extraction. They argue that the last two of these, however, will become increasingly automated. Thus stereoscopic viewing will be needed on a decreasing proportion of the DPWs [Digital Photogrammetric Workstations] at each site." Stereo viewing is possible through the use of the following systems (Heipke 1995);

- Spatial separation of the two images using two monitors equipped with optics
- Radiometric separation (anaglyph or polarisation systems)
- Temporal separation (alternate display of the two images)

The last of these three systems is now the most popular (Dowman, 1996a).

3.1.2 Host Computer

Digital photogrammetric systems have been based around workstations since their inception in the late 1980s. Two brands of workstation are most commonly used - Sun and Silicon Graphics under their UNIX derivative platforms (Petrie, 1997; Smith, 1997). This is rapidly changing with the availability of high-powered Pentium PCs. As Dowman et al. (1992) state, a "tendency can be observed to employ commercial off-the-shelf products in a modular approach" with "standard computer architectures, especially RISC
architectures... becoming more and more popular.” The fast development of the PC market is likely to increase this trend away from specialised workstations.

The move towards PCs also means that more software runs under the familiar Windows operating systems instead of the UNIX platforms associated with workstations (Walker and Petrie, 1996). The use of standard off-the-shelf components and PC’s brings prices down and the use of Windows based software increases the functionality of the DPS, since the machine can be used for many other tasks. As Smith and Smith (1996) state “the success of digital systems will only be fulfilled if it can be seen that the financial outlay will be recompensed…”

An illustration of the rapid development of the PC market can be seen in Walker and Petrie’s 1996 overview of DPWs. At that time, 64MB of RAM was recommended for new DPSs. This is now the standard (1999) for home PCs costing less than £1000. The latest DPWs (1999) such as the Intergraph ImageStation ZIV are equipped with dual P111 Xeon 450MHz processors, 256MB of RAM, a 9.1GB system disk drive and two 18.2 GB data drives (http://www.intergraph.com).

3.1.3 Control Devices

Movement of the images is facilitated in most cases by the computer’s mouse and keyboard. However, some manufacturers now offer specialised control devices to assist users who were trained originally on analogue or analytical systems. These older systems which, as illustrated in Figure 2.2, are controlled by foot disks and hand wheels which have been refined over many years to facilitate maximum accuracy, precision and user comfort (Walker and Petrie, 1996). By offering such devices, manufacturers attempt to make the transition to digital systems easier.
3.2 Software

The software packages used to operate DPWs are complex and the result of many years of development. Kolbl (1996b) points out the need for reliable, not sophisticated systems to be developed, particularly for automated DEM generation. Automation only makes sense if it accelerates the overall process; if the software is unreliable, then more time will be required to check and edit the DEM (Kolbl 1996a).

The tendency is for manufacturers to produce more user-friendly software to aid integration with other CAD and GIS applications (Kolbl 1996b). Most of the packages operate in a windows type environment with pull down menus with, as Smith and Smith (1996) point out, a potential for getting lost in the menus. This can only be avoided through experience and effective training.

The basic software requirements for a DPS are (Petrie 1997):

- aerial triangulation
- map compilation
- orthophoto production
- DEM generation

These requirements will be discussed in greater detail in the following sections.

3.2.1 Aerial Triangulation

While progress has been made in the automation of the aerial triangulation process (such as automatic interior orientation and tie point generation), one of the main tasks in the process, the identification of ground control points remains a user led task. Despite this, Ackermann (1996c) states that "automated digital aerial triangulation is faster, less expensive, and more accurate than conventional analytical triangulation." The latest
photogrammetric software suites from Carl Zeiss (PHODIS) and LH Systems (SOCET SET) both offer automatic interior orientation and tie point transfer and semi automatic identification of control points (www.czi.com, www.lhsystemsgroup.com)

As stated in Chapter 2, many of the software packages operate in a Windows type environment with Wizards and linear workflows to guide the user through the operations. This can only serve to assist new users of the technology and will help to make digital photogrammetry available to a wider user community.

3.2.2 Orthophoto Generation

An orthophoto or orthophotograph (Aspinall et al 1994; Hohle 1996; Romeu 1996) is “a photograph showing images of objects in their true orthographic positions” and is therefore “geometrically equivalent to conventional line and symbol planimetric maps” (Wolf, 1983). An orthophoto has the distinct advantage over the map in that it maintains the feature characteristics of the original image, providing a distinct benefit in the fields of photo-interpretation and Geographical Information Systems (GIS) (Smith, 1997).

An example of an un-corrected photograph can be seen in Figure 3-2. In this image, the sides of the tall buildings can be clearly seen. In an orthophotograph, this would not be the case and only the tops of the buildings would be visible, as in a traditional map. The process of generating orthophotographs requires elevation information for the objects in the imagery, so the generation of accurate DEMs is required for this purpose.
Virtually every DPW system has the ability to generate orthophotographs (Petrie, 1997). Only one or two manufacturers offer “true orthophotographs” where areas which have been occluded by tall buildings and trees have also been corrected (Walker, 1997). A greater challenge than the generation of orthophotographs is the mosaicing of the images together, since it requires both radiometric and geometric balancing of the two images (Walker, 1997).
3.2.3 Digital Elevation Models

The terms DEM and DTM (Digital Terrain Model) are often used interchangeably although with a strict usage of the terminology, a difference can be distinguished. Robinson (1994) suggests that the term DEM refers to “computer based model elevation values” such as those used in this work whilst DTM refers to “a more general model of landscape that includes other parameters such as slope and aspect.” For this reason, the term DEM will be used in this thesis.

Petrie and Kennie (1987) describe surface modelling as “a general term used to describe the process of representing a physical or artificially created surface by means of mathematical expression. Terrain [or elevation] modelling is one particular category of surface modelling which deals with the specific problems of representing the surface of the earth. Ayeni (1982 from Robinson, 1994) provides another definition with “the numerical and mathematical representation of a terrain by making use of adequate elevation and planimetric measurements, compatible in number and distribution with that terrain, so that the elevation of any other point of known planimetric co-ordinates can be automatically interpolated with specified accuracy for any given application.” This definition has several key phrases: “adequate ... number and distribution...” of points being particularly significant.

If the number and distribution of the points is not sufficient, then the data that can be extracted from the model will be of little value. Four points can accurately and economically describe a flat surface such that any other point on the surface can be accurately interpolated from the information. However, if four points are used to describe anything more complicated than a laminar surface when linear interpolation is used, any derived data will contain potentially significant errors. A greater number and appropriate distribution of points is therefore needed in such a situation. The use of automated stereo matching procedures enables the user to specify a much denser grid of points, reducing the size of errors that will be caused by interpolation.
The data for DEMs can be based on one of two methods of collection. The data can be collected and arranged in a regular square, triangular, or rectangular grid or the data can be based on an irregular pattern of points with the nodes joined to form triangles of random shape, size and orientation (Petrie and Kennie, 1987), with the advantage that features such as breaklines can be identified and therefore modelled with increased accuracy.

Gridded DEMs are the easiest to capture, especially since the development of the analytical stereoplotter which automatically “drove” the user to the next grid point allowing for manual elevation measurement. Most DPWs generate DEMs in a regular square or rectangular grid pattern (regular hexagonal or triangular grids have also been used). Regular grids have one major disadvantage and that is that the distribution of the points bears no resemblance to the surface of the ground i.e. the sampling interval over rough and complex terrain is identical to that over smooth, laminar areas. In these smoother areas, fewer points could model the surface just as accurately and save on disk space and computing power during the generation process. In the more complex areas, an increased density of points is needed to accurately the surface. The issue of sampling interval will be discussed in Section 3.6.3.

It is possible to avoid this problem with the use of progressive sampling. This is achieved by first generating a coarse grid of the area and then analysing the distribution of the point elevations. In areas with a greater distribution of elevations, the sampling interval is decreased and the model re-generated. This is normally carried out three times (Petrie and Kennie, 1987). Alternatively, a combination of the regular grid and random sampling can be used (composite sampling) which combines the advantages of both techniques, so that the speed advantages of regular sampling are combined with the improved accuracy of random techniques.
Triangulation based terrain modelling is being increasingly used since every point forms a vertex of one of the triangles. In this way, every elevation value collected is honoured and no interpolation is required. This is important, since any interpolation at a point is likely to have a detrimental affect on the accuracy of the DEM. As Giles and Franklin (1996) state "the user of a DEM should be aware that the digital value at a point may have little correlation with the landscape that is being modelled." The use of an irregular network also facilitates easy inclusion of breaklines which makes the subsequent surface more accurate than a regular grid DEM. Robinson (1994) points out that, as with progressive sampling, the sampling interval can be decreased in areas with monotonous terrain. There are two main methods for implementing triangular based terrain modelling: a) the
Delauney triangulation method; and b) the radial sweep algorithm (Petrie and Kennie, 1990) although the Delauney approach is more popular.

3.3 DEM Generation

Photogrammetric DEM generation is now fully automated and is regarded as being one of the primary advantages of digital photogrammetry (Smith and Smith, 1996; Heipke 1995). It offers significant speed advantages (up to 1,000,000 points per hour) over analytical systems. What can take between 6 to 8 hours for an experienced user on an analytical system can now be done in 10 minutes on a digital system (Smith and Smith, 1996). It should be remembered however that time needs to be spent after the DEM has been generated to check and edit the data. This is especially true in areas where the software is subject to blunders (section 2.7.1) (Heipke 1995).

3.3.1 Image Matching

One of the critical processes involved in DEM generation is image matching (Gasior, 1996; Heipke, 1996b; Li et al., 1996; Mitchell, 1991; Toth and Krupnik, 1994). This is the process of finding conjugate points on the two images. Image matching "automatically establishes the correspondence between primitives extracted from two or more digital images depicting at least partly the same scene" (Heipke, 1996a). Once the conjugate points have been found, the collinearity equations and least squares can be used to obtain MPV best estimates for the co-ordinates in the object space.
Two methods are used to implement image matching; *area based* techniques and *feature based* techniques. Area based systems find either the degree of correlation between patches in the left and right images (Duperet 1996) using some mathematical function or use a least squares approach to find the match.

The usual cross-correlation approach is to select an area in the left window and find the degree of correlation with a number of nearly corresponding patches in the right image (Dowman, 1996a). The area with the highest correlation coefficient (between 0 and 1 where 1 is a perfect match) is deemed to be the match.
The algorithm employed in the ERDAS Imagine OrthoMAX software compares the (orthorectified) search and template windows using the normalized cross-correlation coefficient ($\Omega$) (ERDAS, 1994). This is computed using the following formulae:

$$\Omega = \frac{(s' \ast t')}{\sqrt{((s' \ast s') \ast (t' \ast t'))}} \quad \text{Equation 3-1}$$

where $s'$ and $t'$ are the normalized intensities of search and template pixels (average value subtracted from actual value).

Least squares matching offers the potential of greater precision (0.1 pixels) than cross correlation techniques (1 pixels) but requires a more accurate a priori approximation (accurate to within 2 pixels) (ERDAS, 1997b). One of the main advantages of least squares matching is the ability to include corrections for radiometric and geometric differences between the two images.

Feature based matching matches features such as lines or shapes in the two images. This approach is most successful when the imagery contains numerous discontinuities and edges whereas area based systems work well on continuous surfaces with a random variation of pixel values (i.e. good image texture). Area based systems are the most widely used, although some software packages use both (Dowman 1996a).

Although the process of image matching is understood, well documented and has been successfully translated into various computer algorithms, its application to imagery in a production environment is not always successful or is at least subject to partial success. The process of image matching is an ill-posed problem since it is subject to occlusion and variation in the image content between adjacent images (Heipke, 1996a). These differences in the overlap area cause variation in the results when factors such as grid spacing, strategy parameters and triangulation results are altered.
3.4 The OrthoMAX Software

The software used in this study is the ERDAS Imagine OrthoMAX version 8.3 software developed by Autometric. The OrthoMAX part of the Imagine suite encompasses the Block tool (which establishes the exterior orientation (EO) parameters for each frame using the bundle adjustment method), stereoscopic viewing of the imagery, automated DEM generation with stereo editing facilities, TIN extraction, orthorectification and mensuration of the imagery (both in stereo and monoscopically).

3.4.1 The Block Tool

The Block Tool within the OrthoMAX environment is used for the entering of camera data, ground control data, the measurement of film and control data and imagery, and for the triangulation of the imagery to derive the EO parameters (ERDAS, 1994). The basic process follows the following steps:

The first stage of the process, the entering of the ground control data, allows for the definition of the control points in the desired object co-ordinate system. Various datums can be adopted including ellipsoid co-ordinates, those relating to national mapping projections, or simply rectangular cartesian values. Included in this process is the definition of the type of control provided (horizontal, vertical or both) and the entering of the stochastic properties for each control point.

The input of the camera calibration data involves entering the calibrated positions of the fiducial marks, the radial lens distortion values, the calibrated focal length of the lens and the principal point offset. The user can import frames and their associated stochastical properties (precision estimates of their estimated exterior orientation parameters).
The process of interior orientation involves the task of measuring the pixel co-ordinates of the calibrated fiducial marks in the digital image. The software then estimates the six elements of an affine transformation necessary to relate the pixel and photoco-ordinate systems. In practice, this is done by manually measuring the pixel co-ordinates of the first two fiducial marks and then refining the estimated positions for the remaining points.

Figure 3-6 Block Process flow (adapted from ERDAS 1994)
The next stage in the block adjustment process is the measurement of the photo-control points on the images and the generation of tie points. With the OrthoMAX software, the identification of potential tie points is a manual process.

The bundle adjustment employed by OrthoMAX is implemented using a least squares approach using the condition of collinearity. This solution is non-linear and requires an iterative approach. Initial estimates for all estimable parameters are required and these are derived by a simple pre-processing step optionally carried out by the software. If the triangulation is successful, a results file is generated which contains estimates of the positions in the object space of the frames, the control points and the tie points with their estimated precisions and residuals for all measurements. Any measurement with a high residual error can then be either edited or removed from the calculation and the process re-run.

Once the bundle adjustment (called triangulation in the OrthoMAX software) has been successfully completed, the software computes a set of rational functions. These are rational polynomials that are often called rubber sheeting and they are used to emulate the projective geometry at the time of exposure. They are computed using the condition of collinearity and the results of the interior and exterior orientation (ERDAS, 1994). Rubber sheeting models are popular as they require no knowledge of the sensor geometry and are easy to implement and solve. The polynomials take the form (McGlone, 1994):

\[
F(u, v, w) = a_0 + a_1u + a_2v + a_3w + a_4uv + a_5uw + a_6vw + a_7u^2 + \\
a_8u^2 + a_9w^2 + a_{10}uvw + a_{11}u^2 + a_{12}v^2u + a_{13}w^2u + \\
a_{14}u^2v + a_{15}v^3 + a_{16}w^2v + a_{17}u^2w + a_{18}v^2w + a_{19}w^3
\]

Equation 3-2

The image co-ordinates are calculated as quotients of the polynomials.
3.4.2 The OrthoMAX DEM Extraction Algorithm

The Vision International DEM Extraction algorithm used by ERDAS in the OrthoMAX software works on an iterative object / space matching technique (Wang et al., 1993) using the normalized cross correlation algorithm. The system works by correlating conjugate pairs of image points (Section 3.3.7) on the left and right images. The search space is minimised by using prior height estimates of the ground surface.

The first step in the process is to establish a uniform grid on the ground representing the locations of the desired height estimates. The user defines the X and Y grid spacing (a minimum value is suggested by the software) and the extremities of the area (either manually by the co-ordinates of the upper left and lower right corners or visually from an overview of the imagery).

If not previously generated, the algorithm then creates Reduced Resolution Data Sets (RRDS) layers. These form a hierarchical pyramid structure of resampled images that are used in the estimation process (see Figure 3-7). Their use minimizes erroneous results and cuts computation times (Weisensee and Wrobel, 1991) by performing the image matching procedure on successively finer resolutions. The algorithm starts with a coarse re-sampled image and finishes with the original image, using the elevations obtained as a priori knowledge for the subsequent RRDS. In the case of the first RRDS, the average elevation of all the control points is used. The number of RRDSs is defined by the user through the Start RRDS and End RRDS strategy parameters (Section 3.5.8)
With a knowledge of the X, Y and the approximate Z values of each point, the algorithm can obtain approximate image co-ordinates for each point on the grid. This is done using a set of rational functions, the parameters of which are determined using the condition of collinearity and the estimated exterior orientation parameters. Orthocorrelation of the two conjugate points is then carried out by centering the template and search windows over the estimated image co-ordinates. Orthorectification is performed on both windows to remove rotational and relief displacements from the search patches (ERDAS, 1994) before correlation of the two windows is performed. If the point correlation falls below a user-defined value (the Minimum Threshold strategy parameter and the Noise Threshold strategy parameter - section 3.5.1) the search window is moved in the x direction along the epipolar line (Wolf, 1983; Cooper and Robson, 1996). Movement is only allowed in the y direction (perpendicular to the epipolar line) if specified by the user (with the Y-parallax strategy parameter - section 3.5.2). The epipolar line is the vector that defines the line through the image point and the centre of the camera. The point on the ground must lie somewhere along this line. The images are resampled using the triangulated imagery so that the search is constrained to the epipolar line, reducing computational requirements.

Providing that the Minimum Threshold and Noise Threshold specifications have been exceeded, the image co-ordinates are projected back to the ground surface using the rational functions. This enables the quality of the intersection to be assessed. Checks on
each point include the variation in the elevation of each point (from the estimate used as a priori knowledge in the computation from the previous RRDS and the result from the cross-correlation computation).

Other tests that are carried out on each point include precision and uniqueness tests. The precision of each point is estimated and assigned a classification of good, fair, poor or interpolated based upon a comparison with a user-definable assessment criterion (the Minimum Precision strategy parameter - Section 3.5.3). The precision is a function of the correlation coefficient of the point, the number of pixels in the template and the correlation coefficients of the points surrounding it. The results from this test are written to the results (.log file) and also to an image file (.stat.img file) that illustrates the spatial relationship between the different classes. The uniqueness of the point is estimated by examination of the error ellipse of the point. An elongated ellipse is an indication that the correlation is not reliable in one particular direction (perpendicular to the edge). The algorithm searches for elongated ellipses, where the ratio of the axes is greater than a user-defined value (the Edge Factor strategy parameter - Section 3.5.7). If this occurs, the status of the point is set to null.

The precise location of the peak correlation is then found. This is done using quadratic interpolation, thus enabling sub-pixel accuracy to be achieved. The elevation is once again determined using the condition of collinearity. In effect, a graph of the correlation coefficients along the epipolar line is plotted to find the uniqueness of the match (see Figure 3-8). If the graph has a peaked, narrow distribution, the match is deemed to be unique with less chance for false fixes. If however, the graph shows a wide, flat distribution, this would suggest that there are a greater number of potential matches and the status of the point is set to null.
The status of each point is then assigned a status (either good, fair or poor - the distribution of which is defined by the Minimum Precision parameter) based upon its precision. Points with a precision less than poor are set to null.

Post processing of each point is finally carried out. The elevation of each point is compared with an estimated elevation based upon the elevation of the points surrounding the candidate match. If the difference is greater than the standard deviation of the elevations surrounding the point multiplied by a user-definable value (the Rejection Factor strategy parameter - Section 3.5.5), then the status is set to null. If the status of a point is, at this stage, null, then the size of the template window (the initial and final value of which is defined by the Minimum and Maximum Template Size strategy parameters - Section 3.5.3) is increased and the search process repeated. If after the largest template has been used, the status of the point is still null, then the elevation of the point is interpolated. The method of interpolation used is either bilinear or nearest neighbour. Bilinear interpolation estimates the elevation using four of the surrounding successfully correlated
points, whereas nearest neighbour, as the name suggests, assigns an elevation derived from the nearest adjacent point that has been successfully correlated.

The procedure is repeated for all points within the grid and then the entire process is repeated for the next RRDS using the elevation as a priori. The elevation estimates obtained from the final RRDS (using the original imagery) are used to produce the final DEM.

3.5 DEM Strategy Parameters

In the description of the OrthoMAX DEM extraction algorithm (Section 3.4.2) it is apparent that a whole series of parameters play a critical role in the procedure. Indeed, the DEM extraction algorithm is controlled by this set of strategy parameters. This approach is offered in other DPS (Phodis from Carl Zeiss, VirtuoZo, etc.) although the exact details of the parameters differ. The ERDAS Imagine OrthoMAX digital photogrammetric system has 14 DTM strategy parameters whilst the Match-T package has 28 parameters (Smith et al., 1996). The parameters control the internal operation of the area-based image matching algorithm, including defining the search characteristics, sizes of the search and template windows, acceptance criterion and quality control of points (Gooch et al., 1997). In OrthoMAX, the user specifies these parameters when defining the DEM. Each parameter is provided with a default value with the option for the user to alter all, some or none of the parameters. This differs from other packages. The DPW DPS from Helava provides the user with just 3 strategy parameters (Gasior, 1996) - flat, rolling and steep, with the operator dividing the image into area types depending upon terrain characteristics. This is similar to the approach offered in the Phodis TS software, which allows the user to select the terrain type (flat, undulating or mountainous) and the level of smoothing (low, medium, high)).
DEM parameterization may vary for each photogrammetric application so any set of parameters will inevitably involve a compromise (Gooch et al, 1999a). Zhang and Miller (1997) state that the parameters are functions of terrain type, signal power, flying height, x and y parallax, and image noise level. In theory, a correct set of parameters will provide an accurate DEM with successfully correlated points included and unsuccessful points rejected from the DEM processing. An incorrect set may result in filtering successful points and the inclusion of badly correlated points or simply a failure to find a correlated point.

If the correct set of parameters is a function of image content, it follows that the correct set of parameters for one area of an image will not necessarily be the correct set for another (Liang and Heipke, 1997). Zhang and Miller (1997) describe a system that utilizes an inference engine to generate the correct set of parameters based on a set of facts and rules. These rules are based upon the terrain type, signal power, flying height, and x and y parallax.

A full list of the ERDAS Imagine OrthoMAX system parameters and their default values are given in Table 3.1 and Section 3.5.1 describes the role of each parameter in detail.
3.5.1 Minimum and Noise Threshold

The threshold values (Minimum and Noise) define the minimum acceptable correlation coefficients (0 to 1.0) between a window of pixels in the left and right images. A correlation coefficient below the threshold values forces the algorithm to reject the point and use an estimated value based on the elevations of the surrounding points instead. The Minimum Threshold is the minimum acceptable correlation coefficient used to accept a point, whilst the Noise Threshold is the minimum acceptable correlation coefficient used to consider a point.

Setting a high threshold value means that the algorithm becomes more “selective” and only accepts points with a high correlation coefficient. Hence, the probability of obtaining a large percentage of interpolated points increases as more points are rejected and a smoothing effect may occur. If a relatively low value is specified, the algorithm will accept points with a lower correlation coefficient and may result in a higher number of

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Table 3.1 Default Strategy Parameters (adapted from ERDAS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Threshold</td>
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</tr>
<tr>
<td>Noise Threshold</td>
<td>0.4</td>
</tr>
<tr>
<td>Maximum Parallax (x)</td>
<td>5 pixels</td>
</tr>
<tr>
<td>Minimum Template Size</td>
<td>7 pixels</td>
</tr>
<tr>
<td>Maximum Template Size</td>
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</tr>
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<td>Skip Factor</td>
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</tr>
<tr>
<td>Edge Factor</td>
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</tr>
<tr>
<td>End RRDS</td>
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</tr>
<tr>
<td>Y-Parallax Allowance</td>
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</tr>
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<td>Bilinear</td>
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<td>Post Processing</td>
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</tr>
</tbody>
</table>
potentially false fixes. A false fix is the name given to an incorrect match in the image matching process. The optimum value should ideally accept all of the correct correlations and reject the false matches.

3.5.2 Maximum and y-Parallax Allowance

The Maximum Parallax and Y Parallax Allowance parameters facilitate movement of the search window in the right image in the x and y directions respectively (the units are in pixels). A Maximum Parallax specification of 5 pixels infers a maximum shift of 10 pixels (along the epipolar line) as the movement is not restricted to the positive direction. The Y Parallax Allowance is designed to allow successful DEM generation even when the bundle adjustment (triangulation) suggests that perfect collinearity has not been achieved. A y-parallax setting is appropriate for photogrammetric projects containing residual y-parallax, perhaps arising from small systematic error sources associated with non-metric imagery. Both parallax allowances enable a greater area to be searched, thus increasing the chances of finding the correct match. An inevitable consequence of the search relaxation is an increase in processing time and, more significantly, an increased chance of finding false fixes (incorrect matches), since more pixels are being included in the search.

3.5.3 Minimum and Maximum Template Size

The Minimum and Maximum Template Size parameters establish the dimensions (in pixels) of the square template window (a value of 5 indicates a 5x5 pixel window) on the left image (Hodgson 1994). The image matching approach begins with the minimum template size and increments to a larger size if a successful correlation is not found. Larger window sizes are usually needed if the grey level variation is low but this has the
effect of generalising the terrain and potentially lowers the accuracy (peaks lowered and 
troughs raised). Again, raising the value increases the chances of "success" but increases 
both the processing time and the possibility of finding false fixes. The choice of window 
size should reflect the land cover type, the grey level variation and relief displacement. 
Low grey level variation and high relief displacement require a larger template size.

3.5.4 Minimum Precision

Once a pair of correlated points has passed the threshold tests, the corresponding 
precision of the match in pixel space is estimated. The minimum allowable precision is 
defined by the user with the Minimum Precision parameter. Points failing the test are 
assigned a null status and the elevation of the point is subsequently interpolated using 
surrounding elevation values. Reducing this value makes the procedure more selective 
and, as a consequence, more matches are rejected.

Once a point has been successfully correlated, it is assigned a classification (either good, 
fair or poor) based upon the estimated precision. The bounds of the categories are defined 
by the Minimum Precision parameter. For example, if the Minimum Precision parameter is 
set to 1.0 pixels, the upper bounds for good and fair will be 0.33 and 0.67 pixels 
respectively.

3.5.5 Rejection Factor

The Rejection Factor is considered to be a smoothing filter that removes local maxima and 
minima in the DEM. For each point in the DEM, an elevation is derived using the 
estimated heights within a local neighbourhood. This predicted elevation is compared with 
the estimated value and if the difference is greater than the Rejection Factor multiplied by

56
the standard deviation of the surrounding elevations, then the point is rejected and the predicted elevation used. A lower specification will force the algorithm to reject more points, thereby creating a smoothing effect. A larger value will accommodate greater terrain variation but may allow spurious elevations to be included in the final model.

3.5.6 Skip Factor

In common with other systems, the DEM extraction algorithm employed by OrthoMAX uses a hierarchical Reduced Resolution Data Set (RRDS) approach (Section 3.4.2). The Skip Factor allows the collection rate to be increased by collecting grid points no closer than the specified value in all but the last RRDS. The last RRDS usually uses the original image unless otherwise specified.

3.5.7 Edge Factor

The Edge Factor is used to minimise the number of false fixes in the final DEM caused by false correlations arising from linear features. Linear features cause problems to automated systems because, if the imagery includes the side of a tall building, there are an infinite number of points along a vertical line up the side of the building with the same planimetric position. The error ellipse of each correlation is therefore computed using the estimated precision of each correlated pair of image points. An elongated ellipsoid suggests that the correlation may not be reliable. The Edge Factor describes the ratio between the major and minor axis of the error ellipse. If the ratio is higher than the factor, then the point is rejected and an interpolated elevation used. Lowering the value will make the software more selective.
3.5.8 Start and End RRDS

The Start and End RRDS values dictate the image resolutions used in the hierarchical image matching process. To optimise accuracy, a value of 0 (the original image) is recommended for the End RRDS since detail and image content can be distinguished at the original resolution, although Smith (1997) suggests that in rural areas, the End RRDS parameter should be set to 1. A larger Start RRDS value may be required for rugged terrain and can be a more appropriate way of coping with rugged terrain than raising the Maximum Parallax parameter.

This raises the issue of the interaction between the parameters, which can be complex to predict and model. For example, increasing the template size and lowering the minimum threshold are both ways of dealing with a low image content. However, changing both of these parameters at the same time is not necessarily desirable and care should be taken in adopting this course of action without testing beforehand.

3.5.9 Resampling

This parameter defines if bilinear or nearest neighbour resampling is used in the orthorectification of the image patches. ERDAS (1994) suggest that “this parameter produces little difference in results.”

3.5.10 Post Processing

This parameter, as the name suggests, controls the post processing of the DEM data. With it switched on, the algorithm performs blunder editing after each RRDS, and it is recommended that it is always used.
3.6 Factors Affecting DEM Accuracy

There are many factors that are recognised as having an affect on DEM accuracy (Garbrecht and Starks, 1995; Sasowsky et al, 1992; Torlegard, 1996) and there are many papers written on the subject. Unfortunately, there are some inconsistencies between them along with a number of factors which authors agree on. The following section summarises the current status of the existing literature.

3.6.1 Terrain type

Terrain has for a long time been recognised as having a significant affect on DEM accuracy (Li, 1992, 1993a, 1993b; Robinson, 1994; Acharya and Chaturvedi, 1997; Torre and Ruiz, 1996) all confirm this in their papers. Ley (1988) reported that accuracy worsened by a factor of two with severe terrain as opposed to gentle terrain. This is because over steep terrain where the elevation range is greater, parallax or relief displacement is increased. As a result of relief displacement, a greater search area is required to find conjugate points. If the search window or the Maximum Parallax allowance is not large enough to find the correct match, then the point will be interpolated resulting in a rectilinear slope profile that probably does not exist. Bolstad and Stowe (1994) found that the most accurate results were achieved over gentle undulating terrain.

In areas with sudden elevation changes such as rural environments with tall buildings occlusion can be a problem to automated techniques. This is the phenomenon of tall buildings or shadows (Armenakis, 1998) shielding a point on the ground from view in one of the two images. The software is therefore trying to match a point on one image with a point that will not appear on the second. Ackermann (1996b) suggests that multiple image
matching is the only way around this problem, as interactive editing of the DEM may not always be successful in such areas.

Interpolation is necessary where a DEM (or the data derived from it) is required to have a different spatial structure from that presented by the source data (Robinson, 1994). Day and Miller (1988) suggest that the method of interpolation used will prove to be a significant source of error in the DEM. Any system of interpolation will result in errors since it is by definition an estimation of a value based on surrounding information. If the DEM spacing is large, then it can be expected that interpolated data will be subject to large errors. It is impossible to produce a perfect method of interpolation for every application so care should always be taken to minimise the level of interpolation used. This is not always possible depending on the software and imagery used. In the OrthoMAX software, the easiest way to manipulate the level of interpolation is through the use of strategy parameters or by reducing the grid spacing. Interpolation can be beneficial to DEM accuracy, especially if the terrain is flat or planar. However, in areas of sudden elevation change, it can be the source of potentially significant errors.

Bolstad and Stowe (1994) found that, when using SPOT imagery, the most accurate results were achieved over gentle undulating terrain whilst Sasowsky et al (1992) reports that the most accurate areas of DEMs generated from SPOT imagery are over areas with a slope of less than 5%. However, it should be remembered that SPOT imagery has a different interior orientation. The images are collected by scanning the terrain in lines perpendicular to the direction of travel, the second dimension being provided by the movement of the sensor. Therefore, for each line scanned, there is a unique perspective centre. Hence, the problems associated with occlusion and sudden elevation changes tend to occur perpendicular to the line of flight only.

Image content is recognised as having a significant affect on DEM accuracy (Neill, 1994 and Toth, 1994). The findings from these papers are that good image content and texture are required for accurate results. The software may not be sensitive enough to find
conjugate points in areas with low image texture. If the image content is high, the algorithm will be able to identify the correct match with ease. Torre and Ruiz (1996) reinforce this by reporting accuracy problems with linear man made features, ravines and ridges, valleys and slopes surrounded by trees and other poor textured areas. Man made features cause problems because they tend to be constructed from uniform materials. On objects such as long straight roads, there are many “acceptable” (incorrect) matches surrounding the conjugate points.

Neill (1994) contradicts this statement slightly however by reporting that measurements should be made on hard surfaces. The reason for this statement is that over natural surfaces such as woodland and fields, the point that the software determines the elevation for lies on the top of the vegetation, since the true ground is not visible on the imagery. One way of dealing with this is to assume a constant offset in the measurements but this requires the assumption that all the vegetation is the same height.

Relating to the quality of the imagery is the flying height/orientation and scanning resolution of the imagery, factors that can seriously affect the accuracy of DPS output (Acharya and Chaturvedi, 1997). Butler et al., (1998) suggest that DEM quality is also subject to different lighting conditions.

It is common practice to quote accuracy statistics as a function of flying height. Fryer et al. (1994), suggest that a precision of 1/10,000 of the flying height can be achieved (i.e. a flying height of 1,500m results in a vertical precision of ±0.15m). The results from other studies are presented in the paper and suggest a figure of 1/10,000 is achievable when an analytical plotter is used. This can be improved upon with the use of cameras fitted with Forward Motion Compensation.
3.6.2 The Software

As the level of automation in digital photogrammetry increases, users become more dependent on the software packages used. There are a number of different algorithms available on the market, each with their own inherent benefits and drawbacks. The choice of software is therefore likely to affect the resulting output.

The study by Neill (1994) used a range of analytical plotters and assessed their relative accuracy. This was done by giving the same tests to a set of ten companies using five different plotters between them. One of the most significant findings was that "the companies using the same photography and the same analytical plotter show a similar range of differences and there were no outstanding results, for example, a test result which showed one company achieving half the [error] of any other." This result suggests that the choice of equipment and software used for the DEM generation can have a profound affect on the accuracy of the product. These tests were carried out before the widespread acceptance of automated DEM generation methods and so no digital systems were used in this test. It is possible that the increased levels of automation offered by a DPS will further enhance this finding, since the level of human intervention (and corresponding variability) would be reduced.

This conclusion is reinforced by Ley (1988) who compared an analytical, semi automated and a fully automated digital system for generating DEMs. He confirmed that as the level of automation increases, the reliance on user experience reduces, a fact stated as one of the major advantages of DPWs. He also suggested that the increase in the level of automation does not decrease the accuracy of the DEM, even if an experienced user operates the analytical system.

Mikhail (1993) noted that differences between operators is a major factor in some results. Li (1992, 1993b) and Robinson (1994) both confirm that the method used to generate a
DEM will affect the resulting accuracy although the imagery used is another important factor.

Smith (1997) performed some extensive testing on both the ERDAS Imagine OrthoMAX software and the Intergraph ImageStation. He reports that “OrthoMAX generally produces more accurate results ... but appears to produce less precise results ... than the ImageStation. He reported that both software packages were well suited to smooth textured surfaces but differences occurred when modelling erratic elevation changes. However, Smith and Waldram (1996) reported that choosing “the appropriate simple terrain parameters in the ImageStation does consistently improve the quality of the results” and the "ERDAS system appears to be less predictable when changing the variable parameters..." suggesting again that correct parameter specification is important.

3.6.3 Imagery and Grid Size

Robinson (1994) reports that DEM accuracy ultimately depends on the quality and resolution of the source data. The user needs to find the balance between the density of sampling and the volume of data produced. A larger pixel size is recognized as having a detrimental affect on accuracy (Novak and Shahin, 1996; Ackermann, 1996b; Kern and Carswell, 1994; Acharya and Chaturvedi, 1997) since it generalizes the terrain. The user needs to find the balance between the density of sampling and the volume of data produced, remembering that higher resolutions increase processing time exponentially and computer handling requirements become difficult, effectively raising the cost of production. Acharya and Chaturvedi (1997) suggest that degrading the scanning resolution from 15 microns to 25 microns “substantially affects the accuracy of the DTM
generated using automated techniques." Ideally, the sampling interval should be sufficient to enable accurate reconstitution of the terrain (Blais et al., 1986, Ayeni 1982).

Obviously, one of the major controlling factors of DEM accuracy is the scale of the photography used - the achievable r.m.s.e from a set of 1:70 scale close range imagery is going to be significantly better than a set of 1:13000 scale aerial imagery! Neill (1994) demonstrates this well and achieves the following results from a set of comprehensive tests on three sets of imagery:

<table>
<thead>
<tr>
<th>Scale</th>
<th>r.m.s.e (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:3,000</td>
<td>35</td>
</tr>
<tr>
<td>1:2,500</td>
<td>30</td>
</tr>
<tr>
<td>1:2,000</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 3.2 Accuracy results (from Neill, 1994)

Torlegard et al. (1996) describe a set of tests in which a set of check points are derived from a set of larger scale imagery than the test imagery, using the same technology to collect the points. The assumption here is that the points from the larger scale imagery will be of a higher order of accuracy and can therefore be accepted as truth. However, the danger with this approach is that both sets of data are subject to similar systematic error sources arising from both the machinery and the users, resulting in the check data not being truly "independent". The authors of the paper recognise this problem when, after repeated measurements of the check points by different users, they note "considerable differences between elevation values for certain check points."
Krupnik and Veidman (1998) used this approach also, but found that a small grid size results in a more accurate DEM (Acharya and Chaturvedi, 1997) since it reduces the number of breaklines needed (Ackermann, 1996b). If the grid spacing is too large, there is a danger of missing important information such as the tops of peaks or the bottom of ravines (Torre and Ruiz 1996). Robinson (1994) suggests that, on man-made features, the grid spacing can be increased without reducing accuracy because of the more uniform nature of the object.

The size of the grid spacing also has an influence on the post-processing of the data. For example, the Rejection Factor test in the ERDAS Imagine OrthoMAX software compares the estimated elevation of a point with those of the surrounding points. Depending on the nature of the terrain, a large grid size can indeed result in the neighbouring points having a large elevation range resulting in some of the points being filtered during post-processing.

3.6.4 DEM Strategy Parameters

In this section, the results and conclusions from studies into the effect of strategy parameters on DEMs will be presented. Smith et al. (1996) states that the parameter lists (for OrthoMAX and Match-T) are long and question their usage. They state that “the parameters are written in a technical language and, even if the basic image matching technique is understood, it does not always help in determining the use of all the parameters as many are obviously software dependant." Provided in the paper is an example of the magnitude of change to a DEM if just one parameter is modified, which highlights the need for the correct choice of parameters. Gasior (1996) and Baltsavias et
al. (1996) give details of the parameters used by the Leica/Helava DPW software. Here, the user is presented with just three options, based on the terrain (flat, hilly or steep), emphasizing the importance placed on image content. Neither paper makes any estimation as to the impact of parameters on DEM accuracy.

The approach selected by Leica/Helava is similar to that adopted by the VirtuoZo software developed by Wuhan Technical University of Surveying and Mapping in China (Baltsavias et al., 1996). Again the user is offered a selection of parameters (five in this case) depending upon image content. Baltsavias et al. (1996) found that changing the parameter from rugged to smooth had absolutely no effect on the DEM at all (using 1:10,000 scale imagery). Neither Baltsavias et al. nor Gasior (1996) provide any methods for determining the optimum strategy for a project.

Loodts (1996) criticises the use of "uncontrollable magic strategies" in automatic DTM algorithms but again, no details are given as to how to specify the parameters and no consideration is given to their impact.

Zhang and Miller (1997) state that "the set of parameters are functions of many imaging characteristics including terrain type, signal power, flying height, x and y parallax, and image noise level. It is unrealistic to assume that users can or will always select a set of correct parameters." They describe a new system called Adaptive Automatic Terrain Extraction (AATE) for Leica/Helava's DPW software. It is based upon an inference engine that asks the user a set of questions and specifies a set of parameters based upon the answers. The system is able to select the best images for the project and change the parameters for different areas of the project, depending on the terrain and image content. They report that with this system, DEM accuracy can be increased by between 15 and 35% on average. However, details of the algorithm (understandably!) or how the approach can be implemented in other packages are not supplied with the paper.
Butler et al., (1998) describe a series of tests carried out on the strategy parameters of the ERDAS Imagine OrthoMAX software on a set of close range imagery. The factors were optimized with respect to the precision estimates of the match, the aim being to maximise the number of points falling into the "good" category and minimize the level of interpolation.

The tests were carried out on three sub-areas of the imagery to identify the optimum set of parameters that could then be applied to the full area.

The following observations were made in the study;

- Increasing the maximum and minimum template sizes increased the number of points classified as "good".
- Variation of the Minimum Threshold and Noise Threshold parameters had little effect on the number of "good" points.
- Increasing the Rejection Factor parameter, the Edge Factor parameter and Nearest Neighbour parameter improved the matching results.
- The use of an optimized parameter set facilitated in improvement in the number of "good" points.
- Strategy parameter optimization "has not been accompanied by an overall improvement in DEM accuracy".
- An automatic system for detecting and correcting false fixes is required.
- An improvement in the number of "good" points in not necessarily accompanied by an improvement in the accuracy of the DEM - possibly due to the position of the check points.
- The results are site specific.

The most important conclusion in the paper by Butler et al. (1998) is probably that an automatic system for detecting false fixes is required and the number of "good" points in not necessarily accompanied by an improvement in the accuracy of the DEM. The classification of the points (good, fair, poor) is misleading since it implies that some of the
points are "better" than others, when in reality, as the authors point out, this is not always the case. This reinforces the need for alternative internal quality systems and procedures within DPWs that can reliable isolate the accurate points from the inaccurate points.

The work by Butler et al. (1998) raises some of the issues surrounding the use of check points for accuracy assessment. The authors note problems with the check data, in particular "uncertainties in the positioning of check points" (points along a steel band levelled with an engineer's automatic level and staff) and "the number, density and quality of profile-aligned check points may not have been sufficient to pick up the smaller variations in DEM values which occurred as a result of altering collection parameters..." If the assumption is made that this value can be used for close-range imagery (the quoted figure of 1/10,000 is for aerial imagery) and applied to the authors camera height of 2.2m, an estimated of precision of 0.22mm could be achieved. To obtain check point data of a higher order to enable effective accuracy assessments to be made is clearly difficult and expensive at this scale of imagery. This would be the case for any close-range application and highlights the need for alternative methods of quality assessment.

The work by Smith (1997) strongly relates to the work discussed in this thesis, since he assesses the impact of a number of factors on automated DEM generation. One of the factors that he assesses is the strategy parameters used in the generation of the DEMs and he assesses their impact using two software packages; ERDAS Imagine OrthoMAX and Intergraph ImageStation.

In the work, Smith tests the strategies on two sets of imagery;

- 1:3,000 scale black and white imagery of an urban environment (residential and industrial).
- 1:10,000 scale rural colour imagery with isolated buildings and trees
He further divides each set of imagery up into detailed land-cover types (e.g. golf course, residential, allotment, factory etc.). He then assesses the impact of parameter variation on each of these sub-areas. As a result of the testing, the following conclusions are made for the Intergraph ImageStation:

- from the limited testing of software, there was little variation in the DEMs when the Terrain Type strategies (Flat, Hilly, Mountainous) were varied.
- the software had difficulties accurately modelling erratic surfaces, inconsistent slopes, cluttered features and highly textured images (the software uses feature based matching instead of area based matching strategies).

From the testing of the ERDAS Imagine software, the following conclusions were made:

- increase the template size and do not raise the Maximum Parallax specification above 7 pixels for urban imagery:
- residential and areas with high rise flats cause problems
- rural and areas with large elevation changes such as factories are well suited to the software
- individual optimal parameter settings were influenced by other parameter changes (two optimal parameter settings could not necessarily be combined)
- reduce the Maximum Parallax setting, increase the range of the Minimum and Maximum template sizes, increase the Skip Factor and set the End RRDS value to 1 in rural areas
- reduce the grid spacing in all areas
- trees and buildings can cause problems if the grid spacing is large enough to identify them as outliers
- the software works well in regular, non-complex areas
- there was "tremendous variability in the DEMs, both between different parameter setups and within each DEM"
• manual measurement is “still important” in urban areas in order to reduce interpolation and occlusion errors.

Overall, Smith reports that “both systems are particularly suited to the smooth, textured surfaces of [rural areas]”.

The conclusions of Smith (1997) are, as demonstrated in the preceding paragraph, very specific. The quality of the DEMs produced was found to be highly variable, even within different areas of a stereopair. It therefore appears to be contradictory to recommend specific parameter changes for various land-cover types after testing just two stereopairs, with no attempt to verify the conclusions on any independent data sets. The testing of these conclusions will form part of this study (Chapter 5).

Smith suggests that in urban areas, the parameters that were found to have the most effect should be focused upon, instead of trying to optimize them all together. These parameters were;

• Ground Spacing
• Rejection Factor
• Maximum Parallax
• Minimum and Maximum Template Size

Table 3.3 and Table 3.4 give details of results of Smith's tests (Smith, 1997) for the different sub-areas with variation of the Minimum Precision (MP) and Minimum and Maximum Template Size parameters.

The results in Table 3.3 illustrate the extreme variability within different areas of a stereopair. Whilst the accuracy results for the whole model are good, the results from the woodland area produce a worse result, and explain the degradation of the potential of the system, as illustrated by the open moorland results. The results also show that alteration of the Maximum Parallax from the default of 5 pixels to 3 (MP3 column) and 10 (MP10
column) and Minimum and Maximum Template Size parameters (from their defaults of 7 and 9 pixels to 7 and 15 pixels respectively (Min Max Temp column) can, in certain areas, have a significant effect on the results, whilst in other areas, the change is less noticeable.

The results from the urban imagery (Table 3.1) illustrate the influence of landcover type to a greater extent with variations in the Maximum Parallax parameter to 10(MP10 column) and 15 (MP15 column) pixels and the Minimum and Maximum Template sizes from the default values to 5 and 20 pixels (Min/max temp column). When the whole model is generated, the mean error was -0.551m, but looking at the allotment area in isolation, a figure of -0.09m is recorded. The worst results were recorded for the flats area (mean error = 0.576m with default parameters), although why this should be much different from the factory area is not clear (both contain large buildings with regular, large elevation changes).
<table>
<thead>
<tr>
<th></th>
<th>Default</th>
<th>MP 3</th>
<th>MP 10</th>
<th>Min/Max Temp 7/15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Whole Model</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>0.084</td>
<td>0.079</td>
<td>0.118</td>
<td>0.096</td>
</tr>
<tr>
<td>SD (m)</td>
<td>2.625</td>
<td>2.573</td>
<td>2.555</td>
<td>2.562</td>
</tr>
<tr>
<td><strong>Open Moorland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>-0.061</td>
<td>-0.022</td>
<td>0.006</td>
<td>0.019</td>
</tr>
<tr>
<td>SD (m)</td>
<td>1.785</td>
<td>1.668</td>
<td>1.657</td>
<td>1.643</td>
</tr>
<tr>
<td><strong>Woodland</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>1.553</td>
<td>0.939</td>
<td>1.283</td>
<td>1.205</td>
</tr>
<tr>
<td>SD (m)</td>
<td>3.302</td>
<td>2.987</td>
<td>3.362</td>
<td>3.081</td>
</tr>
<tr>
<td><strong>Residential</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>0.146</td>
<td>-0.186</td>
<td>-0.474</td>
<td>0.036</td>
</tr>
<tr>
<td>SD (m)</td>
<td>2.657</td>
<td>2.811</td>
<td>2.957</td>
<td>2.639</td>
</tr>
<tr>
<td><strong>Golf Course</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>0.202</td>
<td>0.225</td>
<td>0.248</td>
<td>0.124</td>
</tr>
<tr>
<td>SD (m)</td>
<td>2.102</td>
<td>2.071</td>
<td>2.028</td>
<td>2.14</td>
</tr>
<tr>
<td><strong>Sewerage Plant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean (m)</td>
<td>0.147</td>
<td>0.09</td>
<td>0.218</td>
<td>0.172</td>
</tr>
<tr>
<td>SD (m)</td>
<td>0.921</td>
<td>0.954</td>
<td>0.914</td>
<td>0.899</td>
</tr>
</tbody>
</table>

Table 3.3 Rural Results (from Smith, 1997)
There is no reason to mistrust the results recorded in Smith (1997). The tests carried out were comprehensive and the conclusions are therefore justified for those two sets of imagery. It is not clear if the conclusions are meant to be applied to other data sets, although the wording of the conclusions suggests that the author is under the impression that they can.

Smith's work also ignores the widening use of digital photogrammetry in close range applications where the traditional land-cover classifications such as “rural” or “residential”
are inappropriate. Applications of the technology to areas such as machine tooling utilize images that are completely different in image content to those encountered in aerial mapping type applications. Therefore, Smith's conclusions are of marginal value to the wider body of potential users.

3.6.5 Image Compression

Image compression systems (Novak and Shahin, 1996) are used to reduce file sizes and file reduction of between 25 and 33% can be achieved without any visual loss of image quality (Kern and Carswell, 1994). The basic idea behind the system is that redundancy in the image is removed (Lammi and Sarjakoski, 1995). The result of this is that file backup, transfer and restore times are drastically reduced. Ackermann (1996b) suggests that methods such as the JPEG (Reeves et al., 1998) algorithm (the industry standard) with a linear compression factor up to at least 5 have no deteriorating affect on DEM accuracy. However, this conclusion can only be applied to the global accuracy measures and not local, high contrast areas of the DEM. Novak and Shahin (1996) suggest that large compression ratios "may distort the images considerably and are not recommended for aerial [digital] photogrammetry" and that compression alone will not solve the problem of image storage.

However, as stated in chapter 2, the computer industry is developing at a rapid rate. As the technology evolves, computer storage capabilities increase and the need for image compression reduces.
3.6.6 Other Factors

Other more minor factors that were raised in the literature were:

1) A sufficient density of ground control, good photographic conditions and properly calibrated FMC cameras (Neill 1994);
2) Good approximations of the conjugate [pixel] locations (Toth and Krupnik, 1994). This can be achieved by systems such as RRDS used by OrthoMAX;
3) Errors in the camera model (Day and Muller 1988); however this can be minimized with the use of computer designed lenses and proper camera calibration;
4) The size of the search window used (Robinson 1994). A small window might miss the correct match in areas of poor contrast or large parallax.

3.7 Conclusion

The previous section has shown that there are many factors that will affect the accuracy of a DEM, and to assess and optimise them all would be a considerable undertaking and beyond the scope of just one project. What the section has attempted to do is to outline some of the issues to which users should be aware. Without allowances and an understanding of such effects, the accuracy of any derived data is likely to be reduced.

From the literature review, it became apparent that there were contrasting views expressed as to the influence of the strategy parameters on DEMs. Smith (1997) suggested that alterations to the parameters can have a significant effect on a DEM whilst Baltsavias et al. (1996) suggested that they have little effect. The reasons for this partial success will be outlined in this thesis.
The literature review also highlighted calls from several authors (Heipke, 1999; Cooper, 1998; Smith, 1997) for more quality control procedures within DPS. The current method for quality control remains stereo editing (not always available) and the comparison of the model with check point data (not always available at the required level of accuracy).

The next chapter will provide details of the testing strategy for the work in this thesis including samples of the imagery used.
Chapter 4  Imagery used and initial testing procedure

Chapters 2 and 3 have introduced the concepts involved in the digital photogrammetric system used in this study and presented the results of related work in the field. Chapter 4 introduces the imagery used in this study and details of the initial tests presented in Chapter 5. The early work was designed to continue the work of Smith (1997) who tested the effects of changing the strategy parameters on two sets of data.

A similar strategy to that used by Smith (1997) was adopted for testing, with the exception that more data sets were included in the study. A significant limitation on this work was funding, such that all of the data sets were either already available in Loughborough University or were kindly donated by external bodies. Similarly, access to the Zeiss Phodis and VirtuoZo systems was kindly provided by Photarc Surveys Ltd and Bath Spa University respectively. The techniques and systems described in this thesis could have been tested on more data sets and photogrammetric systems, but time and cost constraints meant that limits had to be imposed.

It was decided to optimise the parameters with respect to the accuracy of the DEM, since this would not be subjective and would facilitate data reproducibility. From evaluation of other work in the literature, it became apparent that this is common practice and is often the standard by which DEMs are measured (USGS, 1996). Although the DPS (ERDAS Imagine OrthoMAX) used in the study had a stereo viewing capability, it was not practicable to attempt to present the subjective results of such a study.

A prerequisite of the work presented in this thesis was to test the effect of variations to the strategy parameters on as many types and scales of imagery as possible. Details of the data sets used are presented in this chapter and it was a specific intention to ensure
that the tests covered a wide variety of imagery types. Both close-range and aerial imagery were used, some captured using a metric camera, and others with a semi-metric digital camera.

The photogrammetric workflow is long and complex, and there are many variables in the process. As detailed in Chapter 3, the accuracy of a DEM is dependent on many of these. Whilst the literature has shown that variation of many of these factors can produce large changes to the accuracy of a DEM, it was decided that the examination of all of these factors was clearly impracticable. For this reason, only the strategy parameters were varied in the testing procedure. It was also felt that the system should be tested as it would be used in a production environment. In such situations, the user is not likely to experiment with different scanning resolutions or interior orientation parameters. It is likely that they are going to set up the block of imagery and proceed to the production phase, if results are acceptable. Provided that the results of the bundle adjustment fell within the recommendations set by the manufacturers, the block was accepted and not changed.

Also included for reference in this chapter are the details of and some of the issues surrounding the checkpoint data, the recording of data and the measurement and evaluation of accuracy statistics. All of the testing (with the exception of the Zeiss Phodis and VirtuoZo tests) and processing of the data was carried out within the ERDAS Imagine (version 8.3) and OrthoMAX (version 8.3) environments. The software was mounted on a Sun Sparc Ultra-1 workstation equipped with 128Mb RAM.
4.1 Imagery

Of primary importance to this study was the use of a wide variety of imagery. It was important that the testing procedure should include both close-range terrestrial and aerial imagery with as many land cover types as possible. All of the data was collected with either a metric or semi-metric camera, and was accompanied with suitable check point data.

A detailed description of the data sets used in the study will now be presented.

<table>
<thead>
<tr>
<th>Scale</th>
<th>f</th>
<th>H</th>
<th>Pixel Size</th>
<th>Land cover type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:6,000</td>
<td>152.794mm</td>
<td>1,000m</td>
<td>25</td>
<td>Rural &amp; urban</td>
</tr>
<tr>
<td>1:13,000</td>
<td>154.006mm</td>
<td>2,000m</td>
<td>30</td>
<td>fields &amp; residential</td>
</tr>
<tr>
<td>1:45,000</td>
<td>28.362mm</td>
<td>1,246m</td>
<td>9.2</td>
<td>Dry river bed</td>
</tr>
<tr>
<td>1:70</td>
<td>28.675mm</td>
<td>4.2m</td>
<td>9.2</td>
<td>Man-made flume (drained)</td>
</tr>
<tr>
<td>1:25,000</td>
<td>153mm</td>
<td>4,600m</td>
<td>30</td>
<td>Snow covered mountain</td>
</tr>
<tr>
<td>1:17,000</td>
<td>152.400mm</td>
<td>2,500m</td>
<td>20</td>
<td>University campus</td>
</tr>
</tbody>
</table>

Table 4.1 Summary of Imagery Used
4.1.1 1:6,000 scale imagery

The imagery was captured using a Zeiss RMKA camera (f=152.794mm) equipped with Forward Motion Compensation (FMC) and supplied courtesy of ERDAS. The average flying height was 1000m and the scanning resolution was 25μm. An example of the imagery can be seen in Figure 4-1. The imagery contains a variety of landcover types including residential, urban, forested, agricultural and floodplain areas covering a section of the City of London in Ontario, Canada. The photo control and the check point data for this set of imagery were digitized from a set of 1:2,000 scale topographic maps using a Calcomp 9500 digitizing tablet (Stojic et al., 1997).

Figure 4-1 Example of orthophotograph derived from the 1:6,000 scale imagery
From an initial examination of the imagery, it was anticipated that the tall buildings and forested areas would cause the most problems to the automated DEM software. The large number of roads (monotonous texture) could perhaps also produce large errors. The large rural, open field areas would appear to be well suited for automated DEM generation methods.

4.1.2 1:13,000 scale imagery.

The 1:13,000 scale data set (supplied courtesy of OEEPE - European Organization for Experimental Photogrammetric Research) was captured using a Zeiss RMK-TOP camera with a wide angle lens with full GPS support (f=154.006 mm) at an average flying height of 2,000m. The imagery was scanned at a pixel size of 30μm. This data set was of prime importance since it was accompanied with comprehensive check point data derived using analytical photogrammetry and GPS, allowing a thorough analysis of the DEM accuracy.

The imagery covers a wide area, the majority of which is made up from farmland surrounded by woodland. A river (bordered by trees) runs across the overlap and separates the farmland from a large residential area. At the north end of the imagery, there is a steep slope covered with what appears to be a vineyard. The imagery (and the analytical check point grid) were orientated to the north.

Examination of the imagery (Figure 4-2) would suggest that, with the exception of the residential and forested areas, the imagery is well suited to automated DEM generation techniques. The fields appear to have good image texture and are small in size (separated by hedgerows that are beneficial to image matching). There are no large man-made features (such as the car parks in the 1:6,000 scale imagery described earlier) and no large sudden elevation changes.
4.1.3 1:45,000 scale imagery.

The imagery (collected as part of the MEDALUS III Project IV funded by EU contract ENV4-CT95-0118 by J. Shannon) was captured using a Kodak DCS420 digital camera equipped with a f=28mm lens). The CCD array in this camera has an approximate pixel
size of 9.2\(\mu\)m (0.4 metres in the object space). With this particular camera, no fiducial marks were available so the corners of the images were used to define the image coordinate system. The average flying height of the imagery was 1,246 metres with the ground level ranging between 600 and 620 metres ASL (Stojic and Shannon, 1998). An example of the imagery used is shown in Figure 4-3.

Figure 4-3 Example of orthophotograph derived from the 1:45,000 scale imagery
It can be seen from Figure 4-3 that the 1:45,000 scale imagery would appear to be well suited to automated DEM generation techniques. There are no sudden elevation changes in the terrain (the darker areas signify small bushes approximately 1m high and there are no buildings in the area) and there is plenty of image texture and no monotonous man-made features.

4.1.4 1:70 scale imagery

The 1:70 scale imagery used in the testing captured a man-made flume bed at the Flow-channel Facility, Hydraulics Research Wallingford (Chandler et al., under review). The imagery was captured using a Kodak DCS460 digital camera located 4.2m above the flume, the calibration for which was obtained from a SCBA. Check point data for the imagery was generated using a physical profiling tool.

The bed of the flume (no water was running down it at the time of data capture) was made up of fine sand, with plenty of image texture. The banks of the bed were flat and constructed of concrete and proved to be problematic with regard to the generation of DEMs. However, the checkpoint profiles only covered the main channel and not the banks (or only a small portion of the banks) so it was not possible to assess the accuracy of the DEMs in these areas. However, the main channel had an image content well suited to automated DEM generation methods (good image content and no sudden elevation changes). Other problem areas in the imagery are likely to be the steep concrete banks, which are high relative to the elevation range of the sand in the flume. A good example of this is provided in Chapter 6.
Figure 4-4 Example of orthophotograph derived from the 1:70 scale imagery.
4.1.5 1:25,000 scale imagery

The 1:25,000 scale data set (Figure 4-5) was kindly supplied by the British Antarctic Survey (BAS) and is a quite unique data set because of its image content. It contains most of the areas and problems encountered by BAS when compiling maps of Antarctica such as large, featureless snow beds and steep rock slopes. The photography was acquired using a metric camera with a lens having a 153mm focal length at a flying height between 4,600 m and 1,225m. The substantial topographic relief in the study area reduces the photo-scale on the plateau surface, which has an average elevation of about 700 m, to about 1:25,000 (Fox, pers. comm.).

The photo control for the imagery was captured using differential GPS. The points were well distributed and situated on easily identifiable, natural features. The check point data was derived by an experienced operator using an AP190 analytical plotter, with the points located in areas well suited to the analytical technique. This is the methodology currently used for generating DEMs of Antarctic regions so it was felt appropriate to compare the digital technique with this approach.
4.1.6 1:17,000 scale imagery

The 1:17,000 scale data set covers sections of the university campus at Loughborough and covers a wide variety of land cover types from residential areas to the large buildings and open playing fields of the campus. The photo control and the check point information were collected using differential GPS as part of an undergraduate project. The check point information covered one of the playing fields on the campus. An example of an orthophotograph derived from the imagery can be seen in Figure 4-6.
4.2 Checkpoint Data

As stated earlier, of prime importance to this study was the ability to measure the accuracy of each DEM. To do this, check point data was required for each data set. A number of different methods were used to collect these data and will be detailed in the following sections.
4.2.1 Digitisation of Check Points from Other Vector Information

The 1:6000 imagery used check point data which was digitized from a set of 1:2,000 scale topographic maps using a Calcomp 9500 digitising tablet (Stojic et al., 1998). These maps contained contour lines at a 1m interval, and reference benchmark points and spot heights surveyed to an accuracy of ±0.01m. Repeating the measurements between 8 and 14 times validated the precision of the control points (digitised from the same set of maps). The results showed that the average X and Y standard deviation values for the 13 control points were ±0.10 and 0.11 metres respectively.

4.2.2 The Use of Check Point Data Derived from Analytical Instrumentation

Two sets of check point data were supplied with the 1:13,000 scale data set. The first, primary set was derived by an experienced operator using an analytical plotter. The use of analytical check point data can be seen as the most important source of check information, since up until the advent of the DPS, the analytical instrument was the benchmark and was used to provide the most accurate elevation data derived photogrammetrically. If digital photogrammetry is going to prove successful, it must provide more accurate data and offer increased functionality over the analytical range of instruments.

The counter argument for the use of check data derived from analytical systems is the danger of circularity. Analytical systems use the same functional model as most DPS so there is a possibility that systematic errors in the analytical data could be reproduced in the data derived from the DPS. This would mean that accuracy measures are relative rather than absolute.

An advantage of using an analytical plotter to obtain check point data is that the user of the analytical plotter has the option to ignore areas prone to large residual errors or can
include specific features such as breaklines or the edges of buildings. Another advantage is that the user will measure the same surface as the DPS, which may not be the case with independent measures. For instance, in rural areas, the analytical user and the DPS will measure the top of any crops in a field. However, independent surveying methods such as GPS or total station are likely to measure the true ground level. Depending on the height of the crops in the field, this could be a significant difference and one that should be taken into consideration where comparisons are made.

4.2.3 Independent Check Point Data

The "best" source of checkpoint data is that which is derived from an independent (i.e. non-photogrammetric) source of a higher degree of accuracy. In this way, systematic errors derived from the photogrammetric workflow are avoided. For aerial imagery, systems such as total station or GPS (as used for the 1:13,000, 1:45,000 and 1:17,000 scale data sets) would be suitable. These are established technologies with proven levels of accuracy (Twigg, 1998).

There are however, some disadvantages to the use of these technologies. The prime problem is, as stated previously, they measure the ground level instead of the surface level. Whilst this may not sound significant, it may result in systematic errors in rural areas. Another disadvantage of such techniques is the time required to capture the information. Whilst a GPS survey is quicker than a total station survey and only requires one operator, it is still a time consuming activity and will increase the cost of the control survey significantly.

The check data for the 1:70 scale imagery was captured using a bed-profiling tool (Chandler et al., under review) which consists of a probe that can move up and down. The instrumentation is controlled by a PC. The probe is mounted on a carriage that moves horizontally along a support beam. The probe (which is controlled by a computer) is
moved incrementally along the beam and then lowered on to the surface being measured. The claimed vertical resolution of the system is ±0.5mm. This is a good source of independent check point data with a high order of accuracy.

4.3 Data Collection

Each data set was set up within the OrthoMAX software according to the instructions provided by ERDAS (ERDAS, 1994). It was decided at an early stage of the project that other factors in the photogrammetric workflow (such as the interior orientation or the bundle adjustment) should be kept constant throughout the testing, the only variable being the strategy parameters used in the automated generation of the DEMs.

For each block of images, the camera calibration and check point information were entered into the Block tool. Once the Interior Orientation had been completed, the bundle adjustment process was executed. The success of the bundle adjustment was judged on the basis of the control point residuals (<1 pixel in the image space) and the "a posteriori variance of unit weight" factor in the output file. This factor is a measure of the conformance of the adjustment with respect to the estimated parameters and measurement precisions and should be unity. A value greater than 1 suggests that the solution is "over-constrained" and the residual errors exceed their a priori precisions. A value less than 1 indicates that the adjustment is "under-constrained" and the residual errors were lower than the assigned standard deviations. Once a block had been accepted and deemed acceptable, it was not changed. A summary of the results of the bundle adjustment for each data set can be seen in Table 4.2
<table>
<thead>
<tr>
<th>Imagery scale</th>
<th>Object residuals (m)</th>
<th>Image residuals (pixels)</th>
<th>Variance factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>1:13,000</td>
<td>0.031</td>
<td>0.022</td>
<td>0.043</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±0.05</td>
<td>±0.05</td>
<td>±0.05</td>
</tr>
<tr>
<td>1:70</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±0.001</td>
<td>±0.001</td>
<td>±0.001</td>
</tr>
<tr>
<td>1:25,000</td>
<td>1.845</td>
<td>1.815</td>
<td>1.889</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±10</td>
<td>±10</td>
<td>±10</td>
</tr>
<tr>
<td>1:45,000</td>
<td>0.036</td>
<td>0.057</td>
<td>0.019</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±0.03</td>
<td>±0.03</td>
<td>±0.04</td>
</tr>
<tr>
<td>1:6,000</td>
<td>0.458</td>
<td>0.215</td>
<td>0.117</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±0.5</td>
<td>±0.5</td>
<td>±0.15</td>
</tr>
<tr>
<td>1:17,000</td>
<td>1.061</td>
<td>1.959</td>
<td>0.118</td>
</tr>
<tr>
<td>Precision est.</td>
<td>±1</td>
<td>±1</td>
<td>±0.2</td>
</tr>
</tbody>
</table>

Table 4.2 Bundle adjustment results

Different areas within the overlapping regions of each set of imagery were then selected for the DEM generation process. The choice of areas was based upon two criteria:

- The land-cover type and image content in the area. Where possible, as many different types of land-cover as possible were selected from each set of imagery, to identify if

- The number of check points in the area. It was decided to attempt to get at least 28 checkpoints in each area as a minimum in accordance with the recommendations of the USGS (1996). This was not a problem with some of the data sets (such as the 1:13,000 scale or the 1:70 scale imagery) for which there was an abundance of check point data but with other areas (1:6,000 scale, 1:45,000 scale) this proved to be the limiting factor.

For the 1:13,000 scale imagery, a larger number of areas were used in the optimization process. This enabled the use of more than one grid spacing (between 1 and 5m). For the other sets of imagery, the grid size was not altered as the number of areas suitable for testing was limited. The 1:13,000 scale imagery was also supplied with a set of GPS checkpoint data, enabling a comparison of the two check point systems used. The choice of grid spacing was subjective and kept constant for each area used in the study.

The strategy parameters were varied for each area used in the testing. A DEM was generated for each area using the default strategy parameters to serve as a benchmark DEM before the parameters were varied. Each parameter variation was kept within bounds suggested by ERDAS (1994). Each parameter was varied systematically before different parameter combinations were used.

Each time that a DEM is generated by OrthoMAX, a results file.log is created. This file contains a wide variety of information about the process, each RRDS used and the resulting DEM including:

- The level of interpolation and the percentage of good, fair and poor points in the DEM
- An elevation summary of the DEM
- Reasons why points were interpolated as a percentage of the entire DEM
- Estimates for precision of the DEM in both pixel and object space.
A full version of a typical .log file is shown in Appendix 1. For each DEM generated in the testing, a large part of the .log file was recorded and a list of the results recorded can be seen in Table 4.3. These results were taken from the final RRDS since they pertain to the final DEM.

The purpose of collecting all of this data in addition to the accuracy results was to identify if trends in the data could be identified.

No stereo editing was carried out on any of the DEMs. Whilst this process could make a significant difference to the accuracy of the DEM, it is a process that relies on user experience and expertise. It was decided to measure the accuracy of the DEMs as generated by the software, enabling the data to be recreated and making the results of use to users without the stereo editing facility.
<table>
<thead>
<tr>
<th>Collection percentages by status</th>
<th>Classification of each point on the DEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>Interpolated</td>
<td></td>
</tr>
<tr>
<td>Off-image</td>
<td></td>
</tr>
<tr>
<td>Collection terrain statistics</td>
<td>Elevation summary of DEM prior to post-processing</td>
</tr>
<tr>
<td>Min,max elevation</td>
<td></td>
</tr>
<tr>
<td>Average elevation</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma magnitude of y-parallax</td>
<td></td>
</tr>
<tr>
<td>Postprocessing statistics</td>
<td>Results from post-processing</td>
</tr>
<tr>
<td>Percent of points filtered by rejection criteria</td>
<td></td>
</tr>
<tr>
<td>Interpolation passes</td>
<td></td>
</tr>
<tr>
<td>Post-processed terrain statistics</td>
<td>Elevation summary of DEM after post-processing</td>
</tr>
<tr>
<td>Min,max elevation</td>
<td></td>
</tr>
<tr>
<td>Average elevation</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>Automatic collection statistics</td>
<td>Summary of automatic point collection results</td>
</tr>
<tr>
<td>Templating resizing success</td>
<td>% of points collected for each size of template</td>
</tr>
<tr>
<td>Template size, percent</td>
<td></td>
</tr>
<tr>
<td>Template size, percent</td>
<td></td>
</tr>
<tr>
<td>Percent points adopted</td>
<td>% of points retained from previous RRDS</td>
</tr>
<tr>
<td>Successful move percent</td>
<td>% of successful points which required movement of the search window due to excessive parallax</td>
</tr>
<tr>
<td>Failure analysis (percent)</td>
<td>Reasons points were interpolated (% of points interpolated)</td>
</tr>
<tr>
<td>Off-image</td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td></td>
</tr>
<tr>
<td>Precision</td>
<td></td>
</tr>
<tr>
<td>Curvature</td>
<td></td>
</tr>
<tr>
<td>Peak threshold</td>
<td></td>
</tr>
<tr>
<td>Parallax changes (pixels)</td>
<td>Summary of height parallax</td>
</tr>
<tr>
<td>Min,max parallax</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma parallax</td>
<td></td>
</tr>
<tr>
<td>Parallax changes (ground)</td>
<td></td>
</tr>
<tr>
<td>Min,max parallax</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma parallax</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma SNR</td>
<td>Estimation of the Signal to Noise Ratio of the DEM</td>
</tr>
<tr>
<td>Est precisions (pixels)</td>
<td>Estimated precisions of successfully correlated points</td>
</tr>
<tr>
<td>Min,max precision</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma precision</td>
<td></td>
</tr>
<tr>
<td>Est precisions (ground)</td>
<td></td>
</tr>
<tr>
<td>Min,max precision</td>
<td></td>
</tr>
<tr>
<td>Ave, sigma precision</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Results recorded in final RRDS.
4.4 Examination of the Phodis and VirtuoZo software.

Also tested during this research project were the Phodis TS DPS from Carl Zeiss Inc and the VirtuoZo DPs. The Phodis program uses the TopoSURF algorithm, which in turn uses digital images in a correlation procedure to generate a large number of elevation points, from which a grid-type DEM is then derived (www.czi.com). The Phodis TS software has two user definable strategy parameters, the Terrain Type parameter (flat, hilly or mountainous) and the Smoothing Factor (low, medium or high). The output from Phodis is an ASCII file containing the Cartesian co-ordinates of each point in the grid followed by an estimate of the accuracy of each point (Gooch and Chandler, 1999b).

The VirtuoZo DEM generation algorithm uses a different matching technique. The matching process utilised is an area and feature based, bridge mode technique using dynamic programming and least squares matching algorithms (www.sds.co.uk). The user has one strategy parameter to define which defines the terrain type through one of 5 settings. The DEM output from VirtuoZo is an ASCII file of the co-ordinates.

As part of the experimentation process, the strategy parameters used in the Phodis TS software from Zeiss and the VirtuoZo DPS were examined. A similar approach to that adopted for the OrthoMAX software was utilised. Once the block had been accepted, the strategy parameters used were varied systematically and the DEMs recorded. The ASCII output was imported into the Imagine environment for processing. The DEMs were saved as .img files thus enabling post-processing for accuracy assessment (see Section 4-5).
4.5 The ERDAS Imagine Model Maker Tool and the Measurement of DEM Accuracy

The Model Maker is a tool within the ERDAS Imagine suite of software that allows for the creation of graphical models (ERDAS, 1997b). The software uses the Spatial Modeler Language enabling the editing, running and archiving of the models.

A graphical model is a set of instructions for performing geoprocessing operations (ERDAS, 1997b). For example, two DEMs can be subtracted from one another such that elevations at planimetrically identical locations are differenced and the results written to an output raster file. Complex mathematical functions can be also used in such a model. The inputs for a graphical model can come from a number of sources, including raster files, vector files, matrices or scalar quantities, and the outputs can be written to raster files, vector files and tables.

It was decided to develop a macro within the Imagine environment for the assessment of DEM accuracy. There is no facility within the OrthoMAX software to automatically measure DEM accuracy so the macro had to be written using the spatial modeller language.

The main advantages of using a macro within the Imagine environment is that the raster output of the DEM generation process can be used without change and the check point data can be used in a vector format. The DEM is saved as a .img file that can be used as input for a macro. The check point information was saved in a vector file for comparison with the DEM file. The spatial modeller allows for a number of outputs including numerical values and raster files showing the magnitude of individual residuals. This is useful when examining the spatial distribution of the errors.
Chapter 5  Accuracy optimisation by strategy parameter manipulation

In this chapter, the issue of improving DEM accuracy by manipulating the strategy parameters will be discussed. Previous research (Smith, 1997) suggested that improvements in the accuracy of the DEM can be achieved through this method.

The first part of this chapter examines the possibility (in the context of other literature on the subject and tests) that Smith's (1997) conclusions can be applied to other data sets. Two methods that have been developed for prescribing new and optimised parameter settings are then described. A manual system and a novel automated system are described and test results are presented.

5.1 Testing the conclusions of Smith (1997)

As stated in Chapter 3, Smith (1997) performed extensive testing on the strategy parameters used in the ERDAS Imagine OrthoMAX software. One weakness of the study was that tests were carried out on just two sets of imagery; one rural, and the other urban. Optimum strategy parameter settings were defined based upon trial and error manipulation and it is not clear from the conclusions (Smith, 1997) if these optimal parameter settings are recommended for application to other data sets. A decision was made to test whether optimum parameter settings are universally applicable by using three sets of the imagery introduced in Section 4.1.

From the testing on the "rural imagery", Smith (1997) suggested that the following changes should be made to the strategy parameters:
- Reduce the Minimum Threshold.
- Reduce the Maximum Parallax to 3 pixels.
- Increase the range of the Minimum and Maximum Template sizes.
- Increase the Rejection Factor to 3.
- Increase the Skip Factor to 8.

From the testing on the "urban imagery", Smith (1997) recommends the following changes to the strategy parameters:

- Reduce the Minimum Threshold.
- Reduce the Minimum Precision parameter to 0.3 pixels.
- Increase the Skip Factor to 6 or 8.
- Increase the y-Parallax Allowance to 2 pixels.

It was not clear from the conclusions in Smith (1997) whether these changes to the strategy parameters should be applied individually or whether they should all be changed together or altered in specific combinations. The recommendations were tested by changing every possible combination of the conclusions listed above (see Table 5.1 and Table 5.2).

The imagery selected for this part of the testing was:

- 1:6,000 scale imagery (Section 4.1.1)
- 1:13,000 scale imagery (Section 4.1.2)
- 1:70 scale imagery (Section 4.1.3)

For each set of imagery, two areas were selected for testing. For the two sets of aerial imagery, one rural and one urban area were selected, whilst two random areas of the 1:70 scale imagery were selected. The appropriate parameter changes were then applied to each area. All areas included more than 28 check points, as recommended by USGS (1996). For the two areas of the 1:70 scale imagery used in the test, it was not clear
whether these regions should be classified as rural areas or urban areas. For these two areas, every possible parameter change recommended by Smith (1997) was applied.

The testing strategy for the urban areas can be seen in Table 5.1. (Note that blank spaces indicate that default settings were used)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Minimum Threshold</th>
<th>Template Sizes</th>
<th>Skip Factor</th>
<th>y-Parallax Allowance</th>
</tr>
</thead>
<tbody>
<tr>
<td>d1</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d2</td>
<td></td>
<td>9,11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d3</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d4</td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>d5</td>
<td>0.5</td>
<td>9,11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d6</td>
<td>0.5</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>d7</td>
<td>0.5</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d8</td>
<td></td>
<td>9,11</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>d9</td>
<td></td>
<td>9,11</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d10</td>
<td></td>
<td></td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>d11</td>
<td>0.5</td>
<td>9,11</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d12</td>
<td>0.5</td>
<td>9,11</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d13</td>
<td></td>
<td>9,11</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>d14</td>
<td>0.5</td>
<td></td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>d15</td>
<td>0.5</td>
<td>9,11</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.1 Testing strategy for the urban imagery.

The testing strategy for the urban areas can be seen in Table 5.2.
<table>
<thead>
<tr>
<th>Test Number</th>
<th>Minimum Threshold</th>
<th>Max. Parallax</th>
<th>Template Sizes</th>
<th>Rejection Factor</th>
<th>Skip Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>d16</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d17</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d18</td>
<td></td>
<td></td>
<td>9,11</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>d19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>d21</td>
<td>0.5</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d22</td>
<td>0.5</td>
<td></td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d23</td>
<td>0.5</td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>d24</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>d25</td>
<td></td>
<td>3</td>
<td>7,15</td>
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</tr>
<tr>
<td>d26</td>
<td></td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
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<tr>
<td>d27</td>
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<td>3</td>
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</tr>
<tr>
<td>d28</td>
<td></td>
<td></td>
<td>7,15</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>d29</td>
<td></td>
<td></td>
<td>7,15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>d30</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>d31</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d32</td>
<td>0.5</td>
<td>3</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>d33</td>
<td>0.5</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d34</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d35</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d36</td>
<td>0.5</td>
<td>3</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>d37</td>
<td></td>
<td>3</td>
<td>7,15</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>d38</td>
<td></td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d39</td>
<td></td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d40</td>
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<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d41</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d42</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d43</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d44</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d45</td>
<td></td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d46</td>
<td>0.5</td>
<td>3</td>
<td>7,15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 Testing strategy for the rural imagery

5.1.1 Results

Of primary importance to this thesis is the impact of parameter modification upon DEM accuracies, so for each DEM generated, the r.m.s.e. value was determined. The accuracy results for the testing of the 1:13,000 scale urban area are summarised in Figure 5-1.
It can be seen from Figure 5-1 that the variation of the strategy parameters for the 1:13,000 scale urban area provided highly variable accuracy results. Whilst improvements in the accuracy (approximately 20%) from the value achieved using the default strategy parameters were achieved (tests d4, d6, d8, d10 and d14), it is clear from the graph that some of the recommended parameter changes also had a significantly detrimental effect on the accuracy of the DEM. The largest impact upon accuracy was achieved for test d7 in which the r.m.s.e value was worsened by 30% when the Minimum Threshold parameter was reduced to 0.5 and the y-Parallax allowance was increased to 2 pixels. One link between the parameter changes that resulted in a reduction in the r.m.s.e value is that they all required an increase in the Skip Factor to 6. However, improvements in accuracy were not achieved every time the Skip Factor was increased.
The tests on the urban area of the 1:6,000 scale imagery proved to be even more variable than the 1:13,000 scale imagery. It is clear from the graph that there is a significant error source (signified by a r.m.s.e approximately 30 - 40m) although what the cause of this is cannot be defined from a simple measure such as r.m.s.e. It is likely in such circumstances that the large value of r.m.s.e. can be attributed to a few large check point residuals rather than a systematic error across the entire DEM. Table 4.2 shows that the bundle adjustment for this data set was successful.

A closer examination of the individual check point residual errors confirms this fact. Of the 43 points that fall within area 2 of the 1:6,000 imagery, 31 points have errors within the range of -1m to +1m, whilst 34 are in the range -4m to +4m. Nine of the 43 points have residual errors greater than 10m whilst two points have errors of 252m and 254m. If these nine points which can be classified as blunders are removed from the r.m.s.e calculations, the r.m.s.e is reduced from ±54.9m to ±0.7m.

As with the 1:13,000 scale imagery, increasing the Skip Factor to 6 occasionally improved the accuracy of the DEM (tests d4, d8, d10, d13) whilst, when combined with other parameters, it had little effect (d6, d11, d14, d15). A reduction in the Minimum
Threshold parameter can have a significantly detrimental effect (d1 and d12) as can increasing the y-Parallax allowance.

Figure 5-3 shows the accuracy results for the 1:13,000 scale rural imagery. The figure clearly shows that no significant reduction in the accuracy of the DEM generated with the default strategy parameters was achieved, yet some of the parameter changes resulted in a degradation in the accuracy (d16, d23, d28, d34, d37, d41). When the impact of these parameter changes are studied, it becomes apparent that there is no consistency between the changes. For example, the Minimum Threshold parameter was reduced for test d16 whilst the Maximum Parallax was reduced and the template range and Rejection Factor parameters were increased in test d37. Both combinations resulted in a significant change in the r.m.s.e. value.
The converse of this observation can be seen in Figure 5-4 where significant improvements in the accuracy of the DEM were achieved for the rural area of the 1:6,000 scale imagery. This is most noticeable for tests d27 (reduction in the Maximum Parallax and an increase in the Skip Factor) and test d39 (reduction in the Maximum Parallax and an increase in the Skip Factor and the Rejection Factor). This would suggest that changing the Skip Factor and the Maximum Parallax allowance together should be recommended. However, when it is combined with changes to the Minimum Threshold (d33) or the Minimum Threshold and the Minimum and Maximum Template sizes (d42), it can be seen that the r.m.s.e. value is changed very little. When all of the recommended parameter changes are combined (d46) the r.m.s.e. value has a similar magnitude to that of the DEM generated using the default strategy parameters.

As with the urban area of the 1:6,000 scale imagery, the very large r.m.s.e. value suggests that there is something seriously wrong with the DEM. Once again however, this is due to a small group of very large check point residuals and not due to a poor bundle adjustment, a topic that will be discussed further in Chapter 7.
5.1.2 Matching Success.

The level of image matching (and thus the level of interpolation) gives an indication of the suitability of the imagery to automated techniques. The higher the level of interpolation, the greater the risk of high residuals since the estimates of individual points are, by definition, an assumption based upon the elevations of successfully correlated surrounding points. Whilst interpolation can be appropriate on flat terrain (since it tends to a laminar surface) it can seriously degrade the accuracy of the model in areas with sudden elevation changes where ridges are lowered and troughs raised.

Figure 5-5 Interpolation percentages for the urban areas.

Figure 5-5 shows the level of interpolation for both urban areas used in the testing of the 1:6,000 scale and the 1:13,000 scale imagery. It shows that the level of interpolation in these two DEMs is high, with more than 50% of the points being interpolated when the
default strategy parameters are used. Whilst improvements in this figure are achieved (to 35%), the level remains high for all of the strategy parameter combinations used. The main reason for this high figure will be the large number of sudden elevation changes, which are symptomatic of urban areas.

The greatest reduction in interpolation was produced by tests d1, d7 and d14. In all three of these parameter combinations, the Minimum Threshold parameter had been reduced. In Section 3.5.1, it was stated that this is the parameter that controls the acceptance criteria (i.e. the minimum correlation coefficient) for the matching process. The lower the specification, the less selective the algorithm becomes. In urban areas, occlusion caused by buildings is going to result in much lower correlation coefficients, so any strategy that reduces the need for high correlation's is going to result in a higher number of successful matches, at the increased risk of false matches.

An interesting phenomena noted in these and other tests (Gooch and Chandler, 1999) is that changes to the strategy parameters has a similar effect on the internal results (i.e. those produced by the software, not externally calculated such as accuracy statistics) for different areas and sets of imagery. This is the case even when the imagery is of very different scales and image content, as with the imagery in this set of tests. This pattern is evident in Figure 5-5, which shows a consistent trend in the level of interpolation for the two areas.

The graph also shows that the default strategy parameters produced, relative to the other parameter combinations used in these tests, a high level of interpolation that was only exceeded by small amounts three times (tests d2, d4, and d8). This would suggest that the default parameters are not well suited to automated techniques in urban areas.
Figure 5-6 shows the level of interpolation for the two rural areas used in the study. Of immediate notice is the similarity of the two lines and the fact that for the 1:13,000 scale imagery, the level of interpolation for the DEM generated using the default strategy parameters is lower (30%) than for the urban area. This was to be expected since, as stated in Section 3.6.1, rural areas are well suited to automated techniques since there are few sudden elevation changes and plenty of image texture. It is not immediately clear as to why the interpolation percentages for the urban and rural areas of the 1:6,000 scale imagery are of similar magnitude.

Figure 5-6 also shows that, for the 1:13,000 scale imagery, considerable improvement in the level of interpolation was possible with a reduction in the Minimum Threshold parameter (tests d16, d22, d31, d34 and d41). These particular parameter changes also produced the greatest reduction in the level of interpolation in the 1:6,000 scale imagery.

Conversely, certain parameter changes also resulted in a significant increase in the level of interpolation when compared with the DEM generated with the default specifications (tests d20, d27, d30 and d39). Interestingly, for all of the parameter combinations used, the Skip Factor had been increased to 8.
s clear from Figure 5-6 is that in rural areas, greater reductions in the level of
lation are possible by manipulation of the strategy parameters than for urban areas.
ests that the level of interpolation in rural areas can be reduced to around 10%,
in urban areas the lowest bounds are likely to be around 35%. This phenomenon
examined later in this thesis.

Testing of Conclusions from Smith (1997) on 1:70 scale imagery

ision was made to test the conclusions of Smith (1997) on a set of close-range
ry. The reasons for this are that it was not made clear in Smith (1997) if the
ions were robust enough to be applied to a data set with a different scale and a
different image content, thus suggesting the generality of the approach.

areas of the 1:70 scale data set were selected for testing. Due to the nature of the
et, these two areas were similar in both terrain type and elevation range. For each of
eas used, every parameter combination recommended by Smith (1997) (tests d1 to
s defined in Table 5.1 and Table 5.2) was applied and the DEM generated.
Figure 5-7 shows the accuracy results for the two areas used in the tests. It shows that in area 1, changing the strategy parameters had no effect on the r.m.s.e. value. The default parameter set resulted in a DEM with the same accuracy as all the other parameter combinations.

Area 2 provided some very different results. Figure 5-7 shows that the default strategy parameters resulted in a DEM with an r.m.s.e value of approximately ±1.8m, a clearly unacceptable value at this scale of imagery. Table 4.2 shows that the bundle adjustment for this block of imagery was successful. However, every parameter combination used in the tests (with the exception of test d4) resulted in an improved accuracy. These improvements in the r.m.s.e can be attributed once again to a small number of check points. This particular result will be discussed in more detail in section 6.1. The results were extremely variable however, with the optimum settings resulting in an accuracy similar to that achieved in area 1.

When the parameter changes that resulted in the most accurate DEMs are examined in detail, it can be seen that there is no obvious link between them. For example, tests d17, d18 and d20 all produced accurate DEMs, yet for d17 Maximum Parallax parameter was
reduced to 3 pixels, for d18 the Minimum and Maximum Template sizes were increased to 9 and 11 respectively and for d20 the Skip Factor was increased to 8. Similarly, there is no obvious link between the three parameter changes which resulted in the largest r.m.s.e (tests d3, d21 and d34).

5.1.4 Conclusions for Testing of Previous Research

These simple tests carried out on three different data sets established a number of important facts. There can be no doubt from the exhaustive testing carried out in Smith (1997) that the changes to the strategy parameters recommended in the work are appropriate for the imagery used in those tests. However, when those conclusions are applied to other data sets, it has been shown that the success of the technique is highly variable, especially when the success is measured by simple global measures such as the r.m.s.e.

It also became apparent that the relationship between the r.m.s.e. and the parameter changes is unclear. A successful parameter combination used for one area certainly does not necessarily work for another area. If one particular parameter modification has appeared in all of the successful changes, there is no guarantee that it will not result in a degraded r.m.s.e when combined with another parameter change.

As stated earlier, it was not clear from Smith (1997) whether the conclusions made should or could be applied to other data sets. These tests have established that to do so results in mixed success, with no way of predicting which changes are going to be successful in terms of simple global measures of accuracy.
5.2 Manual Manipulation of the Strategy Parameters.

A large amount of time was spent during the work for this thesis on the manual manipulation of the strategy parameters. The reasons for this were to identify trends in an attempt to identify optimum strategy parameter settings and to improve on the conclusions of Smith (1997). A trial and error approach was adopted since it was found that individual optimum values for parameters rarely combine positively with respect to accuracy.

Complete lists of the parameter settings used for this section of the testing along with both accuracy results and data from the .log file for each set of imagery are presented in appendix 2.

5.2.1 1:6,000 scale imagery

For each area used in the study, a standard set of parameter changes was applied before the manual manipulation process was started. The use of standard parameter changes on all of the areas used in the study allowed for the different areas and sets of imagery to be compared directly. The standard parameter changes are listed in Table 5.3. For each test, all other parameters are kept at their default value (listed in Table 3.1).
Once these initial parameter changes had been applied to each area, the lengthy process of manual manipulation was carried out.

The first set of imagery to be tested was the 1:6,000 scale data set (Section 4.1.1). Three areas of the imagery were studied in detail. Area 1 covered a mainly urban area consisting of large buildings and contained 24 check points at a grid spacing of 0.83m. Area 2 covered a mainly rural area with forested areas, fields and an occasional car park and contained 43 check points with a grid spacing of 3m. Area 3 covered an urban area with large buildings and contained 43 check points with a grid spacing of 5m. All three of the areas were located on a single stereopair and identical EO parameters were used for all tests.

### Table 5.3 Initial parameter changes applied to each area used in the study.

<table>
<thead>
<tr>
<th>Test</th>
<th>Parameter change</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Default values</td>
</tr>
<tr>
<td>b</td>
<td>Minimum threshold = 0.8</td>
</tr>
<tr>
<td>c</td>
<td>Minimum threshold = 0.4</td>
</tr>
<tr>
<td>d</td>
<td>Noise threshold = 0.7</td>
</tr>
<tr>
<td>e</td>
<td>Noise threshold = 0.2</td>
</tr>
<tr>
<td>f</td>
<td>Maximum parallax = 8 pixels</td>
</tr>
<tr>
<td>g</td>
<td>Maximum parallax = 3 pixels</td>
</tr>
<tr>
<td>h</td>
<td>Template size (pixels): Minimum = 9 Maximum = 11</td>
</tr>
<tr>
<td>i</td>
<td>Template size (pixels): Minimum = 5 Maximum = 7</td>
</tr>
<tr>
<td>j</td>
<td>Minimum Precision = 0.8 pixels</td>
</tr>
<tr>
<td>k</td>
<td>Minimum Precision = 0.3 pixels</td>
</tr>
<tr>
<td>l</td>
<td>Rejection factor = 2.5</td>
</tr>
<tr>
<td>m</td>
<td>Rejection factor = 1.0</td>
</tr>
<tr>
<td>n</td>
<td>End RRDS = 1</td>
</tr>
<tr>
<td>o</td>
<td>Y-Parallax allowance = 2 pixels</td>
</tr>
</tbody>
</table>
The r.m.s.e results for the initial tests on area 1 are summarised graphically in Figure 5-8. It can be seen that improvements on the default r.m.s.e. value are small whilst one of the tests (test b - minimum threshold = 0.8) has a large detrimental effect on the DEM. The general trend for the tests is for the accuracy of the DEM to be slightly degraded from that of the DEM generated with the default strategy parameters.

![Graph](image)  
Figure 5-8 Accuracy results from the initial tests on area 1 of the 1:6,000 scale imagery.

This result is in contrast to that encountered with area 2, as shown in Figure 5-9. It can be seen from the graph that there is a significant source of error within the area used resulting in a very large r.m.s.e. value (circa ±45m). The usual explanation for such large residuals is errors in the orientation process, yet the results for area 1 suggest that this is not the case and that the stereopair had been orientated correctly. Figure 5-9 shows that, unlike area 1, the default strategy parameter specification results in a poor r.m.s.e. value compared to the other parameter specifications and four of the parameter changes result in large improvements in the r.m.s.e (circa 10m or 20%). Of note is that, unlike area 1, changing the Minimum Threshold parameter to 0.8 produces a DEM with the lowest r.m.s.e of all the DEMs.
Figure 5-9 Accuracy results from the initial tests on area 2 of the 1:6,000 scale imagery

Figure 5-10 illustrates the accuracy results for the third area taken from the 1:6,000 scale imagery and shows that the initial parameter changes applied to all three areas resulted in a very different result than for the other two areas. It can be seen that, when compared to the other DEMs of the same area generated with different parameters, the default parameter specification produced a DEM of an average accuracy although there is still a significant source of error illustrated by the large r.m.s.e (circa ±40m). Figure 5-10 shows that in area 3, large positive and negative changes in the r.m.s.e. value were possible through manipulation of the parameters. Of particular significance appears to be the Maximum Parallax setting (tests f and g), the reduction of which resulting in a DEM with the lowest r.m.s.e. value.
Figures 5-10 Accuracy results from the initial tests on area 3 of the 1:6,000 scale imagery.

Whilst the initial tests provided some interesting results, it was decided to extend the testing strategy to include a trial and error parameter manipulation system. This made it possible to identify if other, more successful parameter combinations could be identified from the data sets.

Interestingly, the trends noted in Figure 5-8, Figure 5-9 and Figure 5-10 were mirrored in the results from the manual parameter manipulation process of each area. It can be seen in Figure 5-11 that for area 1, improvements in the r.m.s.e of the DEM generated with the default strategy parameters were minimal and only occurred in two occasions. However, as with the initial parameter changes, significantly larger r.m.s.e results were noted in several occasions (test 18 - Minimum threshold = 0.7 and Maximum Parallax = 7 pixels and test 24 - Minimum threshold = 0.7 and Maximum Parallax = 7 pixels and Minimum and Maximum Template Sizes increased to 11 and 13 pixels respectively). The general trend in the data clearly shows that changes to the strategy parameters result in a worsening of the r.m.s.e. value.
Figure 5-11 Accuracy results from the process of manual manipulation for area 1 of the 1:6,000 scale imagery.

Similar to Figure 5-9, Figure 5-12 shows that for area 2 of the 1:6,000 scale imagery, significant improvements in the r.m.s.e were possible by a process of manual manipulation of the strategy parameters. In all but one of the areas (t26 - Minimum Threshold = 0.5, Maximum Template = 15 pixels, Rejection Factor = 3 and Skip Factor = 8), improvements in the r.m.s.e occurred. Two sets of parameters resulted in a very large reduction in the r.m.s.e (t32 - Noise Threshold = 0.6, Maximum Parallax = 7 pixels, Minimum and Maximum Template sizes = 11 and 13 and y-parallax allowance = 2 pixels and t33 - Maximum Parallax = 7 pixels, Minimum and Maximum Template sizes = 11 and 13, Minimum Precision = 0.3 pixels and y-parallax allowance = 2 pixels). Many other parameter combinations resulted in improvements in the r.m.s.e value of around 40% of the r.m.s.e value of the default DEM.
Figure 5-12 Accuracy results from the process of manual manipulation for area 2 of the 1:6,000 scale imagery.

Figure 5-13 mirrors the results illustrated in Figure 5-10 with both positive and negative changes to the r.m.s.e. value occurring in area 3 of the 1:6,000 scale imagery. The largest improvement in the r.m.s.e. value was achieved in test t35 (Minimum Threshold = 0.7, Start RRDS = 5 and y-Parallax allowance = 2 pixels) although test t3 (Skip factor = 6) also resulted in a significant reduction in the r.m.s.e. value. Many of the parameter changes resulted in little or no change in the r.m.s.e. value, signified by the flat sections of the graph.
5.2.2 1:13,000 scale imagery.

The manual optimisation process was also applied to the 1:13,000 scale imagery (section 4.1.2). Ten areas of the imagery were selected for the testing, some of which were rural areas, some of which covered the residential section of the imagery and a couple of the areas contained both rural and residential areas. A range of grid spacings (between 1 and 5m were used in the study). For brevity, the results from just three of the areas are presented in this thesis. They are typical of all areas studied.

Area 2 of the 1:13,000 scale imagery covers a section of the residential area and a small rural area, separated by a river. Along the banks of the river are some tall trees. The accuracy results from the initial tests can be seen in Figure 5-14. It can be seen that, with the exception of test c (Minimum threshold reduced to 0.4), alterations of the strategy parameters have had little effect on the accuracy of the DEM, with little or no
improvement on the accuracy of the DEM generated with the default parameters (test a). The range of r.m.s.e. values measures is also comparatively small, with most of them falling within the range of ±2.0m to 2.5m.

Figure 5-14 Accuracy results from the initial tests on area 2 of the 1:13,000 scale imagery.

When the manual optimisation process was applied to area 2 of the imagery, the success mirrored that of the initial tests. It can be seen from Figure 5-15 that few if any of the tests improve on the accuracy of the DEM generated with the default strategy parameters. As with the initial tests, most of the r.m.s.e. values fall within the range of ±2.0m to 2.5m with just one test (test t2 - Maximum Parallax reduced to 3 pixels and the End RRDS raised to 1) having an r.m.s.e. result larger than the others (±3.08m).
Area 3 of the 1:13,000 scale imagery covered a rural area consisting mainly of flat open fields and a small wooded area. There are a few individual trees in the area and few visible hedgerows. It can be seen from Figure 5-16 that the default parameters work well in this area producing a DEM with a r.m.s.e. value of ±1.5m. It can be seen that with the exception of two of the parameter changes (test c - Minimum Threshold parameter reduced to 0.4 and test i - Minimum and Maximum Template Sizes reduced to 5 and 7 pixels respectively), the initial parameter changes have little or no effect on the accuracy of the DEM. Also of note is that the accuracy of the DEM generated with the default strategy is higher than for the default DEM of area 2 (which contained a large residential area).
As with area 2 of the 1:13,000 scale imagery, the manual optimisation of the strategy parameters (Figure 5-17) produced results similar to those of the initial tests. Although some of the tests produce a slightly worse r.m.s.e. value than that of the default DEM, most of them are of similar magnitude. Of immediate note is the presence of a number of DEMs with a significantly degraded r.m.s.e. value (between 10 and 12m c.f. 1.5m for the default DEM). For test t2, the Minimum Threshold was reduced to 0.5, the Noise Threshold reduced to 0.3 and the y-Parallax allowance increased to 2 pixels. The parameters for test t4 were as for t2 with the exception of the y-Parallax, which was set to 1 pixel. For test t27, the Minimum Threshold was set to 0.5, the Noise Threshold was 0.34 and the y-parallax was changed to 1 pixel. The link between these three DEMs is obvious, yet when these parameter changes are combined with others, the result is very different. In all of the tests from t5 to t13, the Minimum Threshold parameter was reduced to 0.5, the Noise Threshold was reduced to 0.3 and the y-Parallax allowance was increased to 2 pixels, yet some of the other parameters were changed at the same time. In all of these tests, the r.m.s.e. value was degraded compared to the DEM derived with the default parameters.

Figure 5-16 Accuracy results from the initial tests on area 3 of the 1:13,000 scale imagery.
Area 7 of the 1:13,000 scale imagery provided a very different set of results. In this area, the land cover type was mainly rural with a few trees and buildings and a steep slope covered with vegetation. In this area, the initial parameter changes had both positive and negative effects on the r.m.s.e. value. Figure 5-18 shows that test b (Minimum Threshold increased to 0.8) had a significant detrimental effect on the DEM accuracy whilst test c (Minimum Threshold reduced to 0.4) had a beneficial effect on the DEM. It can be seen that most of the parameter changes improved the accuracy of the DEM (compared with the accuracy of the DEM generated with the default strategy parameters).
Figure 5-18 Accuracy results from the initial tests on area 7 of the 1:13,000 scale imagery.

The manual parameter optimisation process provided some similarly variable results, as illustrated in Figure 5-19. It can be seen that, as with the initial tests, some parameter changes improved the accuracy of the DEM whilst others had a detrimental effect. Test 0 produced the least accurate DEM. For this DEM, the Minimum Threshold parameter was reduced to 0.5, the Noise Threshold was reduced to 0.3, The Maximum Parallax was reduced to 3 pixels, the Minimum and Maximum Template sizes were increased to 11 and 13 pixels respectively and the y-Parallax allowance was increased to 2 pixels. Test 06 produced the most accurate DEM (Minimum Threshold = 0.7, Maximum Parallax = 7 pixels, the Minimum and Maximum Template sizes increased to 9 and 11 pixels respectively, the Start RRDS value set to 5 and the y-Parallax allowance increased to 2 pixels. The general trend in these data suggests that most changes to the strategy parameters have had a beneficial effect on the accuracy of the DEM.
Figure 5-19 Accuracy results from the manual manipulation process on area 7 of the 1:13,000 scale imagery.

5.2.3 1:70 scale imagery

It will be remembered that the 1:70 scale imagery (Section 4.1.4) covers a simulated riverbed (drained) with good image texture. A total of four areas of the imagery were selected for testing, all of which covered sections of the main channel since this was where the check point data was located.

Tests on the first three areas produced some very interesting results. In all three areas, the r.m.s.e result for each area could not be changed by manipulating the strategy parameters. The r.m.s.e. value of area 1 was between ±4 and 5mm as illustrated in Figure 5-20; for area 2, it was around ±30mm; and for area 3, it was approximately ±43mm. All of these values remained constant for all of the parameter combinations tested.
Figure 5-20 Accuracy results from the manual manipulation process on area 1 of the 1:70 scale imagery

The tests on area 4 of the 1:70 scale imagery provided some very different results to the other three areas of the imagery. As can be seen in Figure 5-21, the initial parameter changes resulted in some highly variable accuracy results. It can be seen that some of the tests (tests b, g, and h in particular) produced some very significant improvements in the r.m.s.e. value. Conversely, tests f, j, m, n and o produced little or no improvement to the r.m.s.e. value obtained using the default parameters.
Figure 5-21 Accuracy results from the initial tests on area 4 of the 1:70 scale imagery.

When the manual manipulation process was carried out on area 4 of the 1:70 scale imagery, it was found that without exception, every parameter change resulted in an improvement in the r.m.s.e. value compared with that achieved with the default settings. Whilst some of the changes resulted in small changes, many resulted in considerable improvements (21 of the parameter changes resulted in an r.m.s.e. value lower than $\pm 0.1m$ (the r.m.s.e. value of the default DEM was $\pm 1.831m$).
5.2.4 Summary

This section has shown that variation of the strategy parameters can have a highly variable effect on the accuracy of the DEM. In some of the areas, changes to the parameters had a very beneficial effect on the r.m.s.e. value, whilst in others it had little or no effect. There also proved to be no obvious links between land cover type and the recommended parameter changes from Smith (1997) for the data sets examined in this study.

It was decided to identify whether the land cover could be classified by some means other than a visual comparison. One idea was to examine the internal results from the DEM generation software and use these results to guide the selection of the strategy parameters. This approach was examined and it will be discussed in the next section.
5.2.5 Correlation Between Accuracy Results and .log Results.

For every area used in the manual manipulation process, an attempt was made to identify accuracy trends that may be apparent from examination of the internal results recorded in the .log file. As stated in Section 4.3, a large amount of data pertaining to the final RRDS was recorded for each DEM generated, facilitating an easy comparison of the data.

A number of the results in the .log file were identified as having a potential link with the DEM accuracy. They were as follows:

- % of points classified as "Good" according to the estimated precision
- % of points interpolated in the DEM
- estimated average Signal to Noise Ratio (SNR) result
- The reasons why points were interpolated (failure analysis)

The purpose behind this analysis was to try and identify a method that could be used to optimise parameters that did not require use of check points to assess accuracy. Optimisation can only be attempted if there is a measure against which the object can be optimised. In most cases, check point data is unavailable, so there is a need for an alternative method for the assessment of accuracy (other than through the use of stereo viewing which is subjective).

To illustrate this process, area 4 of the 1:70 scale imagery will be examined in more detail. The internal results from the .log file for this area is typical of all of the areas used in the study and whilst the exact graphs may differ, the conclusions are valid for all of the areas studied.

Figure 5-23 shows the collection percentages for the area (percentage of points classified as either "good" or "interpolated" by the software). The tests listed along the X-axis are identical to that shown in Figure 5-22 which shows the r.m.s.e. results for the same tests.
It can be seen that there is no correlation between the graphs. Both lines on the graph demonstrate an apparently random distribution similar to the r.m.s.e results but with no link between the peaks and troughs on the graphs. Trends can be identified in portions of the graph (for instance the percentage of points classified as "good" in tests t44 to t50 shows a similar distribution to the r.m.s.e results for the same tests); however the trends are not consistent.

![Graph showing percentage of points classified as "Good" or "interpolated" by the software in area 4 of the 1:70 scale imagery.](image)

Figure 5-23 Percentage of points classified as "Good" or "interpolated" by the software in area 4 of the 1:70 scale imagery.

A similar result was recorded for the SNR results, as illustrated in Figure 5-24. ERDAS (1992) states that the average SNR result in the .log file "approximate[s] the actual SNR of the imagery." A higher SNR generally means fewer false fixes and a higher SNR signifies a greater correlation coefficient for a match (ERDAS, 1992).

From comparison of Figure 5-24 and Figure 5-22, it can be seen however that an increase in the average SNR of a whole DEM is not necessarily accompanied by a reduction in the
r.m.s.e. value. The values for this area (around 4.5) signify a high average correlation coefficient for the imagery (the typical range is 1.5 to 3.0). The trends in the graph however do not match those of Figure 5-22.

![Graph showing average SNR results for area 4 of the 1:70 scale imagery.](image)

**Figure 5-24** Average SNR results for area 4 of the 1:70 scale imagery.

Figure 5-25 illustrates the failure analysis for area 4 of the 1:70 scale imagery. The failure analysis is the record of the reasons why points were rejected in the area-matching algorithm, resulting in interpolation of the point. It is a percentage of the level of interpolation, not the whole DEM and the percentages will therefore always add up to 100%.

It can be seen that the failure analysis exhibits a similarly random pattern when compared to the accuracy results, but, as with the other potential indicators, the trends in the data are not coincident.

It could be argued that the level points failing the curvature test (defines the uniqueness of the match) in tests t1 to t43 broadly match the r.m.s.e results shown in Figure 5-22, but in tests t44 to t50 the similarity ends. It could also be argued that the threshold Failure
result also matches the r.m.s.e results but the level of consistency is low and not matched in other areas used in the study.

Figure 5-25 Failure analysis for area 4 of the 1:70 scale imagery.

5.2.6 Conclusions to Manual Optimisation Process.

The manual optimisation process that was carried out on the three sets of imagery (1:6,000 scale, 1:13,000 scale, 1:70 scale) were of prime importance to this thesis. For the users of many DPSs, manual optimisation is the only optimisation process available and this work has shown that this approach is clearly problematic.

Of immediate concern is the time taken to carry out the tests for each area used in the study. In some of the areas used, over 50 different parameter combinations were applied, sometimes with little or no success. As illustrated in the previous sections, success was only partial. In some areas, significant improvements in the r.m.s.e. value (greater than in current literature such as Smith (1997); Zhang and Miller (1997)) were possible, an excellent example being area 4 of the 1:70 scale imagery. In areas such as this, the
approach was of benefit. However, in other areas, manipulation of the parameters resulted in only partial success or worse, a degradation of the r.m.s.e. value, with no improvements in the accuracy possible (c.f. the accuracy of the default DEM).

A number of important points can be made:

1. The user is never entirely sure that the maximum possible accuracy of the DEM has been achieved. In DPS packages such as OrthoMAX with a large number of parameters, the number of possible parameter combinations is large and to attempt every combination is impracticable.

2. For the process to be successful, check point data must be available. It has been shown that no link between the results in the .log file and the check point residuals could be made. Without check data, a manual manipulation process with respect to accuracy is impossible and therefore not an option for many applications. However, the use of check points to define accuracy is not without danger, since a few check points with very large check point residuals can distort the resulting measures, not fully representing what is happening in the rest of the DEM.

As can be seen in the results presented previously, the optimisation process was unpredictable. Two supposedly optimal parameter settings did not always combine in a positive manner with respect to the r.m.s.e. value, a finding also noted in Smith (1997). The internal results in the .log files were more predictable however, with parameter changes having very similar effects on both different areas of a stereopair and different sets of imagery (Gooch and Chandler, 1998), suggesting that it may be appropriate to classify the areas according to these measures. This will be discussed in Section 5.4.
5.3 The Effect of Grid Point Interpolation Errors on DEM accuracy

One criticism which could be made about this work (and other similar papers) is that the location of the check point data does not coincide exactly with the DEM nodes. As stated in Section 4.5, DEM elevations are compared with the available check points during accuracy quantification using the spatial modeller tool. The elevation of the DEM at the location of the check point is derived using bilinear interpolation. Ideally, the check points and the grid points would be coincident to avoid this potential source of error. However, this is not always possible, particularly when the method used to collect the check point information is a non grid based technique such as GPS or the profiling tool used with the 1:70 scale imagery.

To assess the effect of this potential interpolation error upon the accuracy results, some simple tests were carried out using the 1:13,000 scale imagery. Two forms of check point data were available for the rural area of the imagery used in the testing.

In the first area selected (denoted "coincident") the location of the grid points were collected at a grid spacing of 5m and aligned such that they coincided exactly with the check point data collected with an analytical plotter. The analytical check point data formed a regular grid with a 25m spacing whilst the automatically generated DEM was given a 5m grid spacing. A second DEM was then generated (denoted "offset") which covered the same area but with the grid offset by 2.5m in both the x and y directions to "coincident" (see Figure 5-26). Theoretically, both areas were modelling the same section of terrain with the only differences being due to the effects of the interpolation used in the assessment of the DEM accuracy. Each area covered an identical number of check points.
Also within the area used in this part of the study were check points collected by a GPS survey. A total of 93 check points were covered by the two DEMs (compared with 275 check points collected with the analytical plotter), enabling a comparison between the two methods of check point data collection.

5.3.1 Results

The results of the initial tests (the parameter changes for which can be seen in Table 5.3) are shown in Figure 5-27. It can be seen that in the majority of the tests, neither the method of collection of the check data or the orientation of the grid with respect to the
location of the check points have much effect on the derived measure of accuracy. The
check data collected using the analytical plotter for "coincident" is denoted as "coincident
(analytical)" in the key. Similarly the GPS check data is denoted " coincident (gps)" and
the analytically derived check point data for "offset" is denoted "offset (analytical)". However, in two of the areas (test c and test i), the location of the check points appears to
be critical. In both areas though, it is the grid which is offset from the check point grid
that proves to be the most accurate. It was anticipated that if any differences did exist, it
would be the DEM with the offset grid that would be the least accurate.

![Figure 5-27 Accuracy results for "coincident" and "offset" using both the check point
data collected with an analytical plotter and data collected with a GPS system.]

If the two DEMs ("coincident" test c and "offset" test c) are subtracted from one another
it is possible to identify where the greatest differences occur. Figure 5-28 illustrates this
difference (values around 0 have a grey colour whilst large differences are shown as
black) and it can be seen that the significant difference between the two measures is
attributable to one section of "coincident". The rest of the image suggests that the two DEMs have similar height estimates. There is no obvious reason why "coincident" should have failed in that one section and "offset" was apparently successful (the r.m.s.e result shown in Figure 5-1 is consistent with the other results).

![Figure 5-28 Difference image between "coincident" test c and "offset" test c.](image)

This pattern was also evident in other parameter combinations that were applied to the two areas. In Figure 5-29, the tests noted along the x-axis denote parameter changes that were applied to both areas. As with the results from the initial tests, it can be seen that in most cases, the orientation of the grid and the choice of check points has little affect on the resulting measure of accuracy. Once again however, some parameter combinations do cause significant differences. As with the initial tests, these differences can be attributed to small failed areas in one of the DEMs and not to a systematic error source covering the whole DEM.
There is a slight trend in the data that suggests that the use of the GPS check points results in slightly larger values of r.m.s.e. This can be explained by the fact that the two systems (photogrammetry and GPS) measure slightly different surfaces in rural areas. Whilst photogrammetry measures the tops of crops (since that is all that is visible on the imagery), a GPS system will measure the elevation of the soil surface. Most GPS receivers are carried on poles which, when held upright, will rest on the ground. Thus, when the length of the pole is subtracted from the elevation of the receiver, the resulting height estimate is that of the ground. This can be modelled by making an allowance for the crop height in this calculation but this will assume that all of the crops are of a constant height.
5.3.2 Discussion

The previous section has shown that the orientation of the photogrammetrically derived DEM with respect to the location of the check points does not have a significant affect on the resulting measure of accuracy for the undulating terrain surfaces tested here. Differences and significant errors have been shown to be due to failed areas of the DEM. The results have shown that interpolation on the DEM has had little effect on DEM accuracy. In residential areas, it is possible that offsetting the DEM would have a more significant effect due to the sudden elevation changes. However, it is likely that any check point data used in such areas will be located away from sudden elevation changes (unless it is the effect of such changes which are being modelled), therefore reducing this effect. One method for minimising this effect would be to reduce the grid spacing to a minimum.

5.4 Automated Parameter Prescription

As is clear from Section 5.2, a manual optimisation process is highly unpredictable and prone to highly variable results when optimising global measures of success such as the r.m.s.e. value. This suggests that there is a distinct need for an automated system for the specification of an ideal set of strategy parameters for a particular DEM. An automated system has several distinct advantages over manual processes:

- it removes human variability to provide more consistent and robust results. The decision and responsibility is taken away from the user.
- It should be able to cope with all sets of imagery, both close-range and aerial with any landcover types.
• It is quicker and more cost effective than the lengthy process outlined in the previous section.

The system that was therefore developed which fulfils these criteria was based around the idea of an expert system (Allwood, 1989). An expert system is a computer program that provides advice in a selected specialist field through the use of a "knowledge base." The knowledge base is a set of facts about the field that are known to be true.

The hypothesis behind the Parameter Interpolation Program that was developed is that a DEM can be defined by the results of the .log file and that these results form a unique description of the data set. It was decided to identify whether an automated system could be developed that would take into account more data from the .log file, therefore increasing the reliability of the knowledge base. Instead of the DEM being defined by the usual attributes such as land-cover type or image-scale (or guesswork!), the large amount and variety of output data from the software (the information in the .log file) is used. It is this information from the final RRDS (since this pertains to the actual DEM) which forms the knowledge base in the expert system.

Also associated with each set of data in the knowledge base is an optimised parameter list. These optimised parameter settings would be obtained from the manual optimisation process detailed in Section 5-3. The system would compare the sample .log file with those in the knowledge base and would then be able to prescribe a new set of parameters for the sample area based upon the results of the comparison. Provided the knowledge is valid, then the new set of parameters should provide a more accurate DEM.

Such an expert system was developed using the Microsoft Excel spreadsheet environment. This allows for the knowledge base to be entered and manipulated with ease and facilitates easy input of the test data. A DEM (or DEMs) of the test area is generated and the .log file collected. The relevant information is entered into the spreadsheet, which then automatically compares each value entered with the
corresponding values in the knowledge base. The comparison is based upon a weighted average criteria as detailed below:

\[ A_u = \frac{\sum (a_{esn} \times w_{esn})}{\sum w_{esn}} \]  \hspace{1cm} \text{Equation 5-1}

and

\[ w_{esn} = \left( \frac{r_{esn}}{\sum r_{esn}} \right)^1 \]  \hspace{1cm} \text{Equation 5-2}

Where:

- \( A_u \) = recommended parameter setting for test area
- \( a_{esn} \) = optimum parameter setting for data set \( n \) in the knowledge base
- \( w_{esn} \) = weight of optimum parameter setting for data set \( n \)
- \( r_{esn} \) = absolute difference between the value of a particular result in the .log file of the test area and the corresponding value of data set \( n \) in the knowledge base.

Where if \( r_{esn} = 0 \), then \( w_{esn} = 1000 \).

In this way, values that have an exact match are assigned a higher weighting.

In all, five versions of the knowledge base were developed and tested on a variety of data sets. In the first version, fifteen areas of the 1:6,000 scale imagery were used to define the knowledge base. The process used the results from all of the 15 initial tests (as defined in Table 5.3 - Section 5.2.1) in the comparison so the computational requirements were high. It was felt that this solution was impracticable so it was refined such that only the results from the DEMs generated with the default parameters were used.

When testing this version of the spreadsheet approach on different data sets it was found that the parameter settings prescribed by the software did not vary by much. This suggested that too many comparisons were being made and the resulting output was an
average of them all so it was decided to use a smaller but more robust knowledge base. Several versions of the knowledge base were tested before a final design was defined.

In the final version of the spreadsheet, the same approach to the initial interpolation technique was used but the knowledge base was refined to include DEMs from a wide range of imagery with a range of parallax changes (in pixel space). This is an estimate of the parallax within the image space made by the software. The OrthoMAX software records this measure and the results presented in the .log file. For brevity, this version will be focused upon since this version produced the most successful results.

5.4.1 Results.

The accuracy results for the test areas used in the study are presented in Table 5.4 (for reference, the r.m.s.e. value of the DEMs generated using the default strategy parameters are also included). The results suggest that the success of this approach is again highly variable (against global measures such as the r.m.s.e. value). In some of the areas used, the improvement in the r.m.s.e. value (compared with that of the default DEMs) is considerable (area 4 of the 1:70 scale imagery and area 1 of the 1:30,000 imagery) whilst in others the effect is the opposite. Changing the strategy parameters to those suggested by the spreadsheet comparison has resulted in very significant degradation of the DEM accuracy (areas 2 and 5 of the 1:13,000 scale imagery and area 1 of the 1:1:45,000 scale) imagery. This would suggest that the approach is a high-risk strategy, especially if (as would be the case in many production type environments) check point data was not available to monitor the accuracy of the DEM.
Area/imagery | Default r.m.s.e (m) | r.m.s.e (m) defined using parameters derived from spreadsheet
--- | --- | ---
1:13,000 scale | 2 | ±2.076 | ±17.36
5 | ±1.266 | ±21.143
6 | ±2.542 | ±2.579
7 | ±3.59 | ±2.702
9 | ±1.03 | ±1.878
10 | ±1.224 | ±1.278
1:1:45,000 scale | 1 | ±1.491 | ±8.689
2 | ±273.811 | ±233.304
1:70 scale | 3 | ±0.042 | ±0.042
4 | ±1.831 | ±0.016
1:30,000 | 1 | ±22.525 | ±17.703
1:17,000 | 1 | ±2.094 | ±2.13

Table 5.4 Accuracy of DEMs generated using the parameters specified by the spreadsheet approach compared with the DEMs generated using the default strategy parameters.

5.4.2 Discussion

Based upon these results, it would be fair to suggest that this approach is not robust enough to be considered for use in a production environment, especially if there is no check point data to verify its success. However, close inspection of the results and tests
revealed that the approach is indeed valid. In addition, the results revealed interesting and valuable issues of distinct relevance to this thesis.

Global measures of accuracy such as the r.m.s.e. value compare derived elevations with ground truth data to provide quantitative measures of accuracy. Ideally, at least 28 check points distributed around the entire DEM should be used in the accuracy analysis (USGS, 1996). However, if more than 28 check points are available, then the question is should they all be used in the evaluation of the accuracy? Common sense would suggest that as many check points as possible should be used in any analysis. Li (1991) suggests that this is one method for increasing the reliability of accuracy measures.

If the number of check points is low, the inclusion of a few check points with large residuals can lead to correspondingly high r.m.s.e figures. Whilst it provides an indication of the fact that there are problematic areas in the DEM, these large r.m.s.e values do not reflect the fact that, for the majority of the check points the residuals may be perfectly acceptable. If 28 check points situated in areas well suited to automated generation techniques are used (without prior knowledge of their residuals) the user would conclude that the DEM is accurate and within tolerance. If a couple of the check points were situated in areas not suited to the technique the conclusions would be very different. When the OrthoMAX software fails or has difficulty in finding conjugate points the elevation estimates generated are often nonsensical values (such as large negative values). These large discrepancies cause significant changes to the r.m.s.e estimates.

To illustrate this, a number of areas were re-analysed with the check points with the highest residual errors (residual errors that are significantly higher than the other values) removed from the r.m.s.e calculations. This approach enables attention to be focused on areas of the DEMs which appear to be well suited to automated generation techniques. Whilst it is acknowledged that it is very "un-scientific" to selectively filter out poor results it does allow a new insight into the nature of the DEM generation process.
Table 5.5 illustrates these phenomena. Columns two and three provide the two r.m.s.e results (one of the DEM generated with the default strategy parameters and one of the DEM generated with the parameters prescribed by the spreadsheet) which were calculated using all of the check points available. Columns 5 and 6 give the same results with the check points with the largest residuals removed from the calculations (the same check points are removed from both DEMs).

<table>
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<th>default rmse</th>
<th>optimised rmse</th>
<th>no. check pts</th>
<th>default filtered</th>
<th>optimised filtered</th>
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<td>±1.3</td>
<td>±21.1</td>
<td>762</td>
<td>±1.0</td>
<td>±0.9</td>
<td>518</td>
</tr>
<tr>
<td>6</td>
<td>±2.5</td>
<td>±2.6</td>
<td>45</td>
<td>±1.7</td>
<td>±1.3</td>
<td>34</td>
</tr>
<tr>
<td>7</td>
<td>±3.6</td>
<td>±2.7</td>
<td>120</td>
<td>±2.4</td>
<td>±1.3</td>
<td>114</td>
</tr>
</tbody>
</table>

| 1:1:45,000 scale |              |                |               |                  |                    |               |
| 1                | ±1.5         | ±8.7           | 15            | ±1.6             | ±2.9               | 12            |
| 2                | ±273.8       | ±233.3         | 17            | ±3.6             | ±3.2               | 5             |

| 1:30,000 |              |                |               |                  |                    |               |
| 1        | ±22.5        | ±17.7          | 2714          | ±9.4             | ±2.7               | 1335          |

| 1:17,000 |              |                |               |                  |                    |               |
| 1        | ±2.1         | ±2.1           | 116           | ±1.7             | ±1.6               | 96            |

Table 5.5 Results of DEMs generated using optimised parameters with the check points with the largest residuals filtered from the r.m.s.e calculations.

For example, in area 5 of the 1:13,000 scale imagery, a total of 244 check points were removed from the calculations. Thirteen of these points had residual errors ranging from 5m to 17m and as a result of removing them from the calculations, the r.m.s.e. value of the optimised DEM is reduced from ±21.1m to 0.9m.
What is clear from the table is that the analysis of these revised r.m.s.e results produces very different conclusions. It can be seen that in all but one of the areas, the parameters recommended by the spreadsheet resulted in a lower r.m.s.e. value for these successfully correlated points than for the corresponding points with the default parameters. Considerable improvements in the r.m.s.e. value were achieved in areas 2, 6 and 7 of the 1:13,000 scale imagery and area 1 of the 1:30,000 imagery. It can also be seen that in all but the two areas from the 1:1:45,000 scale imagery the number of check points retained remains above the required 28 and by a considerable margin.

These results suggest that such an approach is indeed valuable and can improve the accuracy of certain sections of a DEM but not necessarily across the entire DEM. What is not clear is why certain areas fail or how to identify them, other than by stereo editing and checking of the entire model. The technique can only be of benefit if these low accuracy areas can be defined, such that the user need only check and edit these areas. This problem will be discussed in greater detail in Chapter 6. The phenomena has been tested on a number of independent data sets and has exhibited a degree of success.

5.5 Summary

The results presented in this chapter are highly significant because they are based upon that analysis of many datasets. Recommendations from past research suggested that the parameters can be prescribed by land-cover type. The results presented in this thesis suggest that such an approach is highly variable and prone to large errors. In some areas, improvements in the r.m.s.e. value were achieved, but in other areas this was not possible. It is appropriate to conclude that this approach is of little use in a production environment, especially when the processing time is taken into account. The lack of certainty in the technique means that a number of parameter combinations has to be attempted, resulting in an obvious increase in processing time and storage requirements.
This lack of certainty also means that every DEM needs to be checked using stereo editing, again negating the obvious speed advantages offered by system automation.

The success of manual manipulation of the strategy parameters to lowering the r.m.s.e. values proved to be highly variable, with some areas showing a clear improvement in accuracy, whilst others showed little or no change. Also noted was the fact that the process was extremely lengthy and unpredictable. Of particular significance is the fact that two independently beneficial parameter changes do not always combine in a positive manner with respect to accuracy.

A system was then described that uses a knowledge base of optimum parameter settings to prescribe new parameters for an area based upon comparison with the results from the .log file of a test DEM. The results have suggested that in the diverse independent data sets used (at 1:1:45,000, 1:70, 1:30,000, 1:17,000 scales), the system works well in those parts of the DEM well suited to automated techniques (open flat and rolling areas with good image texture) and clear improvements in the r.m.s.e. value were identified in these areas. A difficulty arises when all check points are used in the analysis. In these situations, the results are not conclusive, with the r.m.s.e values being distorted by a small number of extremely large residuals.

This fact explains the variable results encountered in the manual manipulation tests described earlier in the chapter. In areas which exhibited large improvements in the accuracy it can be shown that these improvements can be attributed to a reduction of the residual errors at a small number of check points and not across the entire DEM. In the other parts of the model it can be seen that the elevations vary by only small amounts between successive parameter changes.

This has raised the question of the suitability of global measures of accuracy. Is it appropriate to use such measures if a small number of check points can distort the measured accuracy of what, on the whole, may be an accurate DEM? Conversely, by placing check points in areas well suited to automated techniques, the resulting measure
uracy will be good and not represent the accuracy of the DEM in other areas. It be very easy for an experienced user to select check points in "good" areas, ignoring check points with the highest residuals. However, whilst the numerical is of accuracy is used in the specification of DEMs, this problem will persist. Li has examined the effects of varying check point distributions and density on cacy measures and found that, for some data sets, varying the distribution can effect curacy results. He suggests that one method for improving the reliability of the re is to use a larger sample size.

as that exhibited little or no improvement in the r.m.s.e. value, it can be shown that check points were situated in areas well suited to automated techniques. This suggests f the area is suitable and a clear pair of matching points can be identified in the two is then the software will successfully identify them. This is a logical conclusion, if a clear match is present, alteration of the strategy parameters is not going to e their location in the image and their subsequent estimated elevation.

reas with low grey level variations or large elevation ranges, the software has ulty in finding conjugate points. Altering the parameter specifications result in a letely different search area, making it increasingly that a different pair of points will und that fulfil the acceptance criteria. It is therefore suggested that changes to the gy parameters only significantly affect areas that are ill suited to automated DEM ation techniques and which are therefore prone to large residual errors. However, s of little use unless these low accuracy areas can be identified. Without this ability, user must still check and edit the entire DEM, a lengthy process that requiresience and negates the benefits brought about by such an expert system. A tool that tates such an identification process would enable the user to focus on the low acy areas of the DEM, thus reducing the overall production time and increasing the of automation in the workflow. This problem will be discussed in detail in Chapter
Chapter 6 The detection of errors by manipulation of strategy parameters

In the previous section, it was shown that changes to strategy parameters affect only some of the points in a DEM and not the entire model. It was also proposed that the points affected by changes to the parameters usually had larger check point residual errors and that high accuracy points are less susceptible to parameter changes. This is an important finding from this work and forms the basis for the developments presented in the following two chapters.

In a production environment, it therefore becomes critical to identify regions that are likely to be of low accuracy. The user would then be able to concentrate on manually checking and editing these low accuracy areas knowing that the remainder of the DEM will be as accurate as possible.

In this chapter, a system will be introduced that automatically detects these low accuracy areas and presents the information to the user in a graphical format for manual editing of the DEM. The design of the system and the testing of some of the parameters within the algorithm will be described in this section.

6.1 Introduction

To illustrate the finding that changes to the parameters only affect certain points and to introduce the next set of tests, the results from one area will be focused upon. The area studied was area 4 of the 1:70 scale imagery, the results for which were presented in Section 5.1.3. In the tests presented earlier in this thesis, changes to the strategy parameters induced large improvements in the r.m.s.e values of the DEM (when compared with the DEM generated with the default strategy parameters). In other areas within the same 1:70 scale imagery it was found that changes to the strategy
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parameters had little or no effect on the r.m.s.e. value of the DEM. This contradictory result demanded further investigation.

When the residual errors at the check point for area 4 were examined individually, it was found that 8 points at the end of the profile had comparatively large residuals and it was these check points that were subject to large changes when the parameters were modified. The remaining 112 checkpoints in the profile exhibited little or no change to their residuals, which was the case for the other DEMs generated for the area.

An easy way to quantify this phenomenon involved calculating the r.m.s.e. value with and without these checkpoints included in the calculations. Figure 6-1 illustrates the accuracy results for the initial tests carried out on area 4. It can be seen that, with all of the checkpoints included in the r.m.s.e calculations (the red squares on the graph), the resulting measure is subject to large variations. However, when 8 (out of a total of 120 points) of the check points with the largest residuals area are removed from the r.m.s.e calculation, the result is subject to little variation. Of significance is that the resulting values are similar in magnitude to those achieved in the other three areas used in the study, where points with large residuals are not apparent.

![Figure 6-1 Accuracy results for area 4 of the 1:70 scale imagery, with and without the checkpoints with the largest residuals included in the calculations.](image)
This result indicates that manipulation of the strategy parameters only affects the area around these eight check points. When the location of these check points is examined, it can be seen that they lie in an area that is clearly subject to failure. Figure 6-2 shows the location of the check profile overlaid on an orthophoto (generated using the default DEM) of the area. The profile is shown as a white line. It can be seen that the profile crosses the main streambed and finishes in an area that appears as a series of "wrinkles" or smudges on the orthophoto. These "wrinkles" suggest that the elevation data is unreliable in this area (Pyle et al., 1997) and is probably due to a lack of image texture (the area covers a section of the floodplain which had puddles of water laying on it). The eight check points that were removed from the accuracy calculations were all located in this area. All of the other points were located outside of this area in sections of the orthophoto which appear "normal".

Figure 6-2 Orthophoto of test area showing the location of the check profile.
The question remains as to how such areas can be identified. One possible way, as illustrated in Figure 6-2 is to generate an orthophoto of the area and identify the "wrinkles" in the output, a method suggested by Pyle et al (1997). In Figure 6-2, the wrinkles appear more as smudges but are clearly visible in the bottom of the orthophotograph. However, whilst this method works well in large areas that have significant residuals, this approach will not identify smaller regions or areas with smaller but still unacceptable checkpoint residuals.

One possible method suggested by the finding that changes to the strategy parameters only affects low accuracy areas, would involve generating two DEMs of the same area but using different strategy parameter settings for each model. According to the results presented previously, the areas affected most by the parameter variation will show clear changes in the height estimates. If these two DEMs are then subtracted from each other such that the two elevation estimates for each point are differenced and then plotted, the largest differences should coincide with points with the highest check point residuals. Areas that are not affected by the changes will have a value insignificantly different from zero.

Examples of such a plot can be seen in Figures 6.3a and 6.3b. In these illustrations, two different DEMs (of area 4 of the 1:70 scale imagery) were subtracted from one another and differences insignificantly different from zero were assigned a white colour. Larger differences are shown as the grey areas. It can be seen that the two DEMs used in Figure 6.3a were DEMs created in tests (Section 5.2.3) c and o whilst f and m were used for plot 6.3b.

Of immediate note is the similarity between the two plots. With the exception of the small area on the left-hand side of plot 6.3a, the shape of the areas exhibiting the large differences is very similar. The four DEMs used in these two examples were picked at random but similar results can be achieved for any of the combinations. Of note also is the similarity between the areas highlighted in these two plots and the area highlighted by the "wrinkles" in Figure 6.2. This suggests that the choice of strategy parameter settings for the two DEMs is not of prime importance and that any two different DEMs of the same area will produce a similar DEM of difference.
6.2 The Failure Warning Model

The phenomena that differencing DEMs derived from slightly modified parameters identifies problematic areas was regarded as extremely significant and could be of value in production photogrammetry. A piece of software was therefore developed which can automatically define these areas and present them in a useable form for users. The system is based around the idea presented in the previous section and is designed purely to identify the areas that are susceptible to changes in the strategy parameters and which appear likely to include high check point residuals. The software does not automatically correct or change the elevation estimates in these areas; their location is just highlighted to enable the user to identify and edit, perhaps using a stereo editing tool.
Previous attempts at quality control procedures (including the system detailed in the previous chapter) based upon manipulation of strategy parameters, have evolved around the idea of changing the parameters to produce more accurate DEMs (Zhang and Miller; 1997). This is the technique used by some of the software manufacturers such as Zeiss and VirtuoZo where parameters are defined according to land-cover type and the level of smoothing required. However, the application of such an approach is based upon the assumption (or at least the idea) that manipulating the parameters will result in an accurate DEM - provided that the correct set of parameters are selected. If the assumption is correct, the incorrect selection of parameters will result in a DEM of lower accuracy than is potentially possible.

As a result of the detailed testing completed for this work and the results outlined in Chapter 5, it has become clear that such an assumption is not always valid. In many areas, manipulation of the strategy parameters will produce more accurate DEMs but there are areas of the imagery where this is not the case. Such areas are ill-suited for DPS and may be for a number of reasons:

- Occlusion caused by sudden elevation changes, particularly in residential or forested areas;
- A lack of image texture, particularly in man-made objects produced using homogenous materials;
- Areas with large elevation ranges that are prone to filtering during the post-processing stage.

In these areas, no amount of manipulation of the strategy parameters will result in an accurate DEM. The areas provide an ill-posed solution. The software may produce an elevation estimate in such areas but these will be prone to large errors.

Instead of correcting such areas, the system outlined in Section 6.1 is designed to identify these areas. The user is then able to manually correct the elevation estimates in the post-processing stage (using the stereo-editing facilities in the software). In this way, the user can decide upon a suitable value for the elevations based upon experience and common sense, e.g. if the surface is flat and textureless (and therefore
prone to errors in an automatically generated DEM) the user can manually edit the DEM or even use field survey methods.

It is very easy to identify the areas that have failed by significant amounts. These areas often exhibit (in the OrthoMAX software) very large negative or positive elevation estimates which result in big spikes or dips in the final DEM. The key to the success of such a system is the ability to identify areas with smaller but still significant check point residual errors. These are the areas that are the hardest (particularly for inexperienced users) to identify when editing the final DEM.

By isolating areas that are not susceptible to changes in the strategy parameters, the assumption is made that the accuracy of the points that are classified as acceptable are as high as the software can achieve with the current configuration. No amount of manipulation of the strategy parameters will significantly alter the accuracy of the points in these areas. It therefore follows that if the accuracy of the points in these areas is not acceptable, improvements should be made elsewhere in the photogrammetric workflow i.e. by reducing the grid spacing, improving the quality of the orientation process or possibly by using field survey methods.

The lack of standards for DEMs created by photogrammetry means that there is no clear way of defining an unacceptable error. Specifications are usually designed on a case by case basis. The definitions of what is unacceptable and acceptable is therefore subjective.

6.2.1 Inputs Required for the Failure Warning Model.

In total, five inputs are required for the Failure Warning Model in its full OrthoMAX configuration. The first two inputs required are two DEMs of the area. The first DEM is generated using the default strategy parameters and the second using a set of parameters which is likely to induce some sort of changes in the areas susceptible to parameter manipulation.
Each time that a DEM is generated, a second image (with a \textit{.stat.img} file extension) is produced in the OrthoMAX package. This second image contains the details of the internal precision estimates (good, fair, poor and interpolated) made by the software for each point on the DEM. Each point is assigned a value according to its classification. Points that have been interpolated are given a value of 2 in the image whilst poor, fair and good points are assigned values of 4, 5 and 6 respectively. The two \textit{.stat.img} files for the two DEMs provide valuable information and are also required as inputs for the Failure Warning Model.

The final input required for the Failure Warning Model is an orthophoto of the area (this can be generated from the default DEM). This is required as a backdrop image for the output. The areas that are isolated by the Failure Warning Model are highlighted on the orthophoto. This allows for a hard copy output to be printed, making identification of the areas easier, particularly for novice users.

6.2.2 Output from the Failure Warning Model

The output from the Failure Warning Model is overlaid on an orthophoto of the area. The algorithm searches for two potential error sources. The first classification is points that are susceptible to changes in the strategy parameters and are therefore prone to large check point residuals. These areas are assigned a white classification in the output orthophotograph.

The second potential source of errors that are identified by the Failure Warning Model are the points that have been interpolated over areas with sudden elevation changes. All interpolation will involve some error since it is by definition an estimation of a value based upon the values surrounding it. This is an appropriate strategy for planar surfaces but is a particularly "risky" strategy in areas with erratic surfaces since the surrounding points may bear little in common with the point of interest. A simple illustration of this can be seen in Figure 6-4, which represents a cross section through a flat surface and a building. It can be seen that the point on the left hand side of the building, if not successfully correlated, will have an interpolated value above the
actual surface. This is an inevitable consequence of using automated techniques in areas with sudden elevation changes. Whilst the errors at these locations may not be huge (it depends on the size of the elevation change) they may still be significant. These areas are assigned a black value in the output orthophotograph.

Figure 6-4 The effect of interpolating in areas with sudden elevation changes.

An example of the output from the Failure Warning Model can be seen in Figure 6-5. It can be seen that there is a large part of the orthophoto that is still visible after the execution of the Failure Warning Model. These are the points that the model suggests will have the highest possible accuracy using the current information.

The areas that are denoted by the white areas on the image are the points that are susceptible to changes in the strategy parameters and are therefore likely to have large check point residuals. It can be seen that the two largest highlighted areas cover a number of trees (an area prone to failure) and a steep slope in the north-east corner of the area. There are also a large number of points that have been identified as having been interpolated on areas with a sudden elevation changes. These are shown as black areas in the image and it can be seen that these highlighted areas can be seen around the edges of the trees and buildings.
6.2.3 The Algorithm Used in the Failure Warning Model

The details of the algorithm used by the Failure Warning Model are comparatively easy to understand. The two main error classification processes are computed by two separate functions with the information overlaid on to the orthophoto after each stage. A flow chart of the algorithm is provided in Figure 6-6.

The first stage of the algorithm examines the classification of each individual point and the slope of the region around the point. The algorithm compares the two .stat.img files and identifies points that have been interpolated on both DEMs. Once these points have been identified, the algorithm examines the slope in the area around the point (the size of the area can be defined and the affect of altering this parameter will be examined in Section 6.2.3.1.1). Areas with an average slope greater than a user definable value (this value can also be varied and this will be examined in Section 6.2.3.1.2) are then highlighted on the orthophotograph of the area. They are assigned a black colour since the imagery is typically grey scale imagery with 256 levels. The
resulting pure black areas (pixel value of 0) can be easily identified. The orthophoto with this first classification is stored as a temporary file for use as an input later in the work flow.

The next stage of the algorithm involves identifying the areas that are susceptible to changes in the strategy parameters. The first step in the process requires the two DEMs of the area to be subtracted from one another to produce a difference image (as

![Flowchart]

Figure 6-6. A flow chart detailing the Failure Warning Model
in Figures 6.3a and 6.3b). This difference image is stored as a temporary raster file for processing in the next stage of the algorithm.

The value of each point in the difference image is examined individually. If the value of the point is greater than the standard deviation of all of the points in the model multiplied by a user definable parameter (the variation of this parameter will be examined in Section 6.2.3.1.3) the point is "tagged" and assigned a pixel value of 256 / white in the output raster image. All other points are ignored such that when this new raster image is overlaid on the modified orthophoto produced earlier, only the white areas are added.

The final output is therefore in the form of a grey scale orthophoto with additional white and black areas. These are the areas to which it is suggested that the user should pay attention to during the post-processing operations. The areas of the original orthophoto that are visible are likely to be accurate. As stated earlier, if the accuracy of these areas is not acceptable, it is advised that the improvements should be made elsewhere in the workflow (i.e. reduce the scanning resolution, decrease the grid-interval etc.).

6.2.3.1 Variation of the Parameters within the Failure Warning Model.

Embedded within the algorithm for the Failure Warning Model are three parameters that alter the way the algorithm works. Variation of these parameters affects the acceptance criteria for the points failing the quality control tests in the algorithm. Some simple tests were carried out to examine the effect of varying these parameters. Also examined were the strategy parameter settings used for the second input DEM.

Each of the parameters was varied individually and the results analysed. The model was altered to enable the resulting output image to be combined with the check point information and then exported. This facilitated the analysis of each individual check point and its associated classification from the Failure Warning Model.
6.2.3.1.1 Variation of the size of the Focul Area parameter.

The Focul Area parameter is used in the identification of the points that have been interpolated on areas with a sudden elevation changes. The expression used in the model to search for the points as is follows:

\[
\text{EITHER } 0 \text{ IF } (((\text{<default DEM> } \& \text{ <second DEM> } ==2) \& ((\text{DEGREE SLOPE (<default DEM>, 15, 15)}) > 1))) \text{ OR <orthophotograph> OTHERWISE Equation 6-1}
\]

The Focul Area parameter refers to the two values (15,15) that control the size of the window in which the slope is computed. The larger the values entered, the larger the size of the window. It therefore follows that increasing the size of the window has the effect of generalising the terrain since a greater area is used in the computation of the slope. Reducing the parameter makes it more likely to find regions with a slope greater than the specified value.

Three arbitrary areas were selected for the testing of this (and the other two parameters). The areas selected were:

- 1:13,000 scale imagery, area 6
- 1:13,000 scale imagery, area 7
- 1:6,000 scale imagery, area 3.

For each of the areas selected, the Focul Area parameter was varied whilst all other parameters were kept at a constant value. The strategy parameter settings selected for the second DEM was as follows:

- Minimum threshold = 0.7
- Maximum Parallax = 7 pixels
- Start RRDS = 5
- y Parallax Allowance = 2 pixels

These parameters were selected since it was found during the manual manipulation of the strategy parameters that this particular combination consistently altered the
elevation estimates in the regions susceptible to the changes. The orthophoto of each area was generated using the default DEM.

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<tr>
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<th>classification</th>
<th>Focal Area setting (pixels)</th>
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<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>+3.730</td>
</tr>
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<td>1:13,000</td>
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<tr>
<td></td>
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Table 6.1 Accuracy results (metres) for areas from the Failure Warning Model with different Focal Area settings.

Table 6.1 shows the results for the tests on the three areas. The optimum parameter setting should provide a clear distinction between the three areas, the points classified as acceptable/OK have a better accuracy than the points classified as 0 (black) or 256 (white) i.e. a small r.m.s.e value in the OK row and a larger r.m.s.e value in the 0 and 256 rows.

It can be seen from Table 6.1 that all but two of the parameter specifications used worked successfully with a clear distinction between the accuracy of the points classified as acceptable (r.m.s.e value OK) and the points highlighted as potentially problematic (r.m.s.e value 0, r.m.s.e value 256).

The table shows that the smaller Focal Area specifications (5 and 10 pixels) are subject to varied results with a failure to isolate the more accurate points in one of the sets of imagery. However, it should be noted that changing the Focal Area parameter
had little or no effect on the areas that are prone to changes in the strategy parameters, a result signified by the no change result for the r.m.s.e. value of the points classified as 256 in Table 6.1.

The larger settings for the Focal Area (15, 20 and 50) all worked well with better results being produced by the highest setting. However, the problem with the higher setting is that it has the effect of generalising the terrain and thus highlights fewer points. Whilst this may be useful in some areas, it is proposed that it is better to include more points and allow the user decide which points are acceptable in the stereo-editing phase. This way, the user gets more potentially inaccurate points to filter but at least gets the option to decide.

One option to solve this choice would be to give the user the option of selecting a setting for the parameter. However, this of course results in even more parameters for the user to define, negating somewhat the trend towards full automation of the photogrammetric workflow. It is therefore suggested that a setting of 15 pixels is used (this will be the value used in the testing of the model) but it has been shown that larger values work equally well.

6.2.3.1.2 Variation of the Size of the Degree Slope Parameter.

The Degree Slope parameter is used in Equation 6.1 to identify points that have been interpolated in areas with a sudden elevation change. The Degree Slope parameter provides the threshold for establishing the slope of the area with the Focal Area (Section 6.2.3.1.1). The mean slope of the region (in degrees) is calculated and if it is less than the Degree Slope specification then the status is set to null (the point is classified as OK). Therefore, increasing the value makes the algorithm more selective and less likely to highlight a point.

The testing strategy for this parameter was similar to that adopted for the Focal Area parameter in that the same two DEMs were used as the input for the Failure Warning Model and the Degree Slope parameter was varied whilst the other parameters in the
Failure Warning Model were kept constant. The DEMs were exported in an ASCII format to enable individual check points to be analysed in more detail rather than examining global measures of accuracy.

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<th>classification</th>
<th>Degree Slope setting (degrees)</th>
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<td>±1.994</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±3.730</td>
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<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±20.600</td>
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<td>1:6,000 scale - 3</td>
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<td>±1.127</td>
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<td>r.m.s.e OK</td>
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</tr>
<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±128.985</td>
</tr>
</tbody>
</table>

Table 6.2 Accuracy results (metres) for areas from the Failure Warning Model with different Degree Slope settings.

The results showing the variation of the Degree Slope parameter can be seen in Table 6.2 and yield a number of immediate points. Firstly, it can be seen from the results for the two areas of the 1:13,000 scale imagery used in the testing that all of the settings used in the testing worked well, with a clear distinction between the three classifications and the points classified as acceptable/OK having the better accuracy. The results for the third area of the 1:6,000 scale imagery are not as convincing. Although there is a clear distinction between the points classified as white/256 and the other points, the distinction between the other two classifications is not as well defined. In four of the five Degree Slope settings, the points classified as acceptable/OK had a worse accuracy than the points classified as black/0. Clearly, this result is not acceptable and the only parameter setting for which the Failure Warning Model did work was 5 degrees.
Secondly, it can be seen that, as with variation of the Focul Area parameter, variation of the Degree Slope parameter had little or no effect on the points classified as white/256 (points susceptible to changes in the strategy parameters). In all three of the areas, the number of check points falling in these areas was small (5/45, 3/120 and 3/43 respectively) but it is encouraging that for all three of the areas, the accuracy of the points with this classification is much worse than other areas.

With regard to selecting an optimal parameter setting for the Degree Slope, the obvious choice would be to select the highest value tested (5 degrees) as this setting resulted in the best distinction between the points classified as black/0 and OK in all three areas. However, as with the Focul Area parameter, selecting a relatively high value makes the algorithm very selective and can seriously reduce the number of points with the black/0 classification. For the check point locations used in this study, a high value worked well. However, it was felt that whilst a smaller setting does result in more work for the user in the post-processing phase, it does again give the user a choice and the chance to identify more potentially inaccurate areas. For this reason, a value of 1 is suggested as being most suitable. A value of two does produce slightly better accuracy results but reduces the number of points highlighted by the algorithm.

6.2.3.1.3 Variation of the Size of the Global Standard Deviation Parameter.

The Global Standard Deviation parameter is used in the second part of the Failure Warning Model algorithm. This is the section that identifies the points in the DEM that are susceptible to changes in the strategy parameters and are subsequently assigned a white/256 classification.

The first step in the process is to subtract the two input DEMs to produce a difference DEM. All of the points in this difference DEM are squared and then square rooted to produce absolute values. This absolute difference DEM is then used as an input in the following expression:
It is the value of the parameter "A" that can be varied in the expression. The algorithm searches for points in the absolute difference image with a value greater than the standard deviation of all the points in the image multiplied by this value "A". Therefore, increasing the value of "A" makes the algorithm more selective as the range of acceptable values is increased. The output from this process should (in theory) be an image with a majority of points having a null status and the spikes or points with the largest values in the absolute difference image being highlighted as white. This image is then superimposed on the orthophoto output from the previous section of the Failure Warning Model to produce the final output for the algorithm.

<table>
<thead>
<tr>
<th>Area</th>
<th>classification</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:13,000 scale - 6</td>
<td>r.m.s.e 0</td>
<td>±3.598</td>
<td>±3.401</td>
<td>±3.357</td>
<td>±3.357</td>
<td>±3.464</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e OK</td>
<td>±2.055</td>
<td>±2.049</td>
<td>±2.020</td>
<td>±2.263</td>
<td>±2.248</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±3.242</td>
<td>±3.730</td>
<td>±2.952</td>
<td>±3.331</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>classification</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:13,000 scale - 7</td>
<td>r.m.s.e 0</td>
<td>±1.920</td>
<td>±2.063</td>
<td>±2.131</td>
<td>±2.131</td>
<td>±2.131</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e OK</td>
<td>±1.219</td>
<td>±1.596</td>
<td>±1.596</td>
<td>±1.596</td>
<td>±1.596</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±13.221</td>
<td>±20.600</td>
<td>±25.124</td>
<td>±25.124</td>
<td>±25.124</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>classification</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:6,000 scale - 3</td>
<td>r.m.s.e 0</td>
<td>±1.645</td>
<td>±1.645</td>
<td>±1.645</td>
<td>±1.645</td>
<td>±1.645</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e OK</td>
<td>±2.070</td>
<td>±2.070</td>
<td>±34.056</td>
<td>±34.056</td>
<td>±36.782</td>
</tr>
<tr>
<td></td>
<td>r.m.s.e 256</td>
<td>±128.985</td>
<td>±128.985</td>
<td>±68.784</td>
<td>±68.784</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3 Accuracy results (metres) for areas from the Failure Warning Model with different Global Standard Deviation settings.

The results from Table 6.3 show that variation of the Global Standard Deviation parameter produce very similar results to those presented in Table 6.1 and Table 6.2. It can be seen that for the two areas from the 1:13,000 scale data set used in the study,
variation of the parameter resulted in consistently good results with, in all cases, the points classified as OK having a better accuracy than the other two classifications.

However, for area 3 of the 1:6,000 scale imagery the tests were not as successful. It can be seen that, in four of the five tests, the points assigned a white/256 classification had a much worse accuracy than the other two classifications as expected. However, for all five settings tested, the points classified as OK had a worse accuracy than the points classified as black/0, although this was only slightly more for values of 0.5 and 1.

The results in Table 6.3 would suggest that a larger value for the Global Standard Deviation would be better since it generally (with the exception of area 7 of the 1:13,000 scale imagery) produces worse accuracy results for the points classified as 0/black. However it can be seen that raising the value decreases the points classified as white/256 and reduces the accuracy of the points classified as OK. From the analysis of the results in table 6.3, a value of "1" provides a balance between maximising the accuracy of the points classified as OK and reducing the accuracy of the other two classifications. By keeping this parameter to a minimum, the chance of eliminating all of the points classified as white/256 is also reduced.

6.2.3.1.4 Variation of the Strategy Parameters Used for the Second Input DEM

The Failure Warning Model requires two input DEMs, one generated with the default strategy parameters, the second generated with a different set of parameter settings. The main requirement for the parameter settings for this second DEM is for them to consistently result in a different elevation estimate in the areas ill-suited to the DEM generation algorithm for all data sets. The results of tests on the effects of using different parameter settings for this second DEM are presented.

Smith (1997) suggested that it would be possible to specify parameter changes based upon land cover type but the testing outlined in Section 5.1 showed that this is not possible. An optimal setting for one area may not necessarily result in an
improvement in DEM accuracy for a similar area. This makes the problem of defining a suitable set of strategy parameters for the second DEM difficult.

It was also stated in Section 5.2 that changes to the strategy parameters had a varied effect on the resulting DEMs, making it impossible to predict changes to the accuracy. The results also showed that optimum settings for one could be very different to those for another area. One of the design requirements for the Failure Warning Model is that it should work on every data set, independent of the image content or scale of imagery. Ideally, the parameter settings for the second DEM should remain the same for all types and scales of imagery. A requirement for different settings would negate the automation benefits brought about by the technique.

The settings for the strategy parameters for the second DEM should therefore be large enough to cause changes in the low accuracy areas. However, they should not cause change in the areas well suited to automated DEM generation techniques. For instance, setting the Minimum Threshold to a very high value such as 0.95 (the default is 0.6) would result in many successfully correlated points failing the correlation test and being assigned a null status instead. This is clearly unacceptable, since the Failure Warning Model may incorrectly classify it as a problematic area (since the two DEMs would be different in these areas).

Figure 6-7 and Figure 6-8 show two difference DEMs for the same area (the area is shown in Figure 6-5). In the two images, values around zero have a grey colour whilst the white areas show larger changes. The parameter settings for the two DEMs used in the comparisons are very different. However, it can be seen from the two images that both parameter changes result in broadly similar results, with the largest differences occurring in the forested areas and little change occurring in the open fields. Importantly, the trends in the two images are very similar. This result was typical of all of the areas and parameter combinations examined.
Figure 6-7 Difference Image between default DEM and DEM with the following changes; Minimum Threshold = 0.7, Maximum Parallax = 7 pixels, End RRDS = 5, Y-Parallax allowance = 2 pixels

This result suggests that the choice of parameter setting is not crucial for the second DEM, as long as the modifications force change in the low accuracy areas. The parameter modifications used for the DEM of difference in Figure 6-7 were found to
meet this requirement in all of the areas studied, so an arbitrary decision was made to use these settings in the testing of the Failure Warning Model. These changes are listed in Section 6.2.3.2. It was desirable to use just one parameter setting for all of the areas studied, enabling a thorough comparison of the performance of the technique in the different sets of imagery.

6.2.3.2 Conclusions Regarding Variations in the Failure Warning Model Parameters.

From the testing of the three adjustable parameters used in the Failure Warning Model, a number of conclusions can be made. Firstly, for the areas from the 1:13,000 scale imagery, all settings used worked well and provided a clear distinction between the accuracy of the three different classifications. In all cases, the points classified as OK had a better accuracy than the points with one of the other two classifications. This is one of the primary aims of the system.

However, the tests were not as successful for the third area used in the testing. In this area, it was found that points classified as white/256 consistently had a worse accuracy than the other two areas but there was less of a distinction between the other two classifications.

Based upon these simple tests, it is proposed that the following parameter settings should be used in the Failure Warning Model:

- Focal Area = 15 x 15 pixels
- Degree Slope = 1 degree
- Global Standard Deviation = 1

A decision was made to use the following parameter settings for the second input DEM for the Failure Warning Model:
Minimum Threshold = 0.7
Maximum Parallax = 7 pixels
End RRDS = 5
Y-Parallax = 2 pixels

6.3 Discussion and Conclusions

This chapter has introduced the concept of the Failure Warning Model, a graphical model that classifies points on a DEM into one of three classes. Points that are assigned a black/0 status are points that have been interpolated within areas of sudden elevation change. Points that are susceptible to changes in the strategy parameters (and are thus prone to large errors) are assigned a white/256 status. These classifications are overlaid onto an orthophotograph of the area. Points that are deemed acceptable are assigned a null status and as a result, the original orthophoto is visible in these areas.

Algorithmic details of the Failure Warning Model are provided in this chapter along with the test results which assess the criticality of variable parameters embedded within the model.

A number of other methodologies for quality control procedures of DEMs have been presented over recent years in the photogrammetric literature. Hannah (1981) suggested one approach that focused on a set of constraints on both the allowable slope and the allowable change in slope in local areas. An important point made in the paper is that "terrain is rarely uniform in roughness, so uniform application of a global technique can produce over-smoothing in rough areas while failing to correct errors in relatively flat areas. Local techniques, on the other hand, have the potential for coping with different terrain types within a model." The tests presented in this thesis have proved that the global parameters in the OrthoMAX software (and the Phodis software from Zeiss presented in Chapter 7) only influence small portions of the DEM. From their descriptions in the user manuals, their suggestions for parameter settings can never be applied with confidence to an entire DEM.
However, the approach suggested by Hannah (1981) is not appropriate for all data sets. It relies on the assumption that sudden elevation changes in a DEM are indicative of potentially large errors. This may be the case in areas of open flat land such as the open fields in the 1:13,000 scale data set or the flume section of the 1:70 scale imagery used in these tests but it cannot be applied to residential, urban or forested areas. In these areas, sudden elevation changes are a key feature of the terrain.

The algorithm presented by Hannah (1981) contains an error correction facility based upon the slope classification system. Points that fail these tests are interpolated from surrounding elevation data. The application of such a technique to an urban environment would result in significant interpolation, the lowering of rooftops and the raising of street levels. The paper presents results from a set of tests on a rural area but no tests on urban imagery. In essence, this approach is similar to that adopted by the Rejection Factor strategy parameter used in the OrthoMAX software.

An alternative approach is that suggested by Li et al. (1996). This technique uses matching of orthophotographs of the area to identify residual parallax. Since orthophotographs should contain no relief displacement, the presence of any parallax in the two images may indicate an elevation error. An iterative approach is described which automatically corrects the DEM based upon this technique and allowable parallax and is usually convergent after two or three iterations.

The results of several tests on the technique are presented in Li et al. (1996) and suggest that the approach is valid. However, problems existed in areas with steep slopes (greater than 45 degrees) and no comparisons with external check data were carried out to quantitatively measure the success of the system. No tests were carried out on aerial urban imagery, one of the types of imagery which are prone to large errors and the authors admit that "this method has the problem with DTM covering large terrain variations". The presence of such areas meant that some facility was needed to report for interactive editing.

The iterative nature of the technique means that computational requirements and time are lengthy, with no guarantee that interactive editing will not be required after the
process has finished. If such editing is required, can the user have complete confidence in the technique and not check the entire DEM or areas prone to failure? Krupnik (1998) suggests that problems with such a technique will persist in areas with repetitive or homogenous texture since most matching techniques fail in such areas. If the matching technique fails when generating the DEM in the first place, what chance has it got when trying to match the orthophotographs or equally, what chance does the user have using manual photogrammetric measurement?

Instead, Krupnik (1998) proposes an a priori technique for the detection of erroneous areas. The system identifies areas that are difficult or impossible for matching and suggests different strategies for overcoming the difficulties. The basic design of the system proposed by Krupnik is detailed in Table 6.4.

<table>
<thead>
<tr>
<th>Observed phenomenon</th>
<th>Suggested approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areas with homogenous gray values, or repetitive elongated patterns</td>
<td>A-priori texture analysis, with filters appropriate for each phenomenon; Definition of the perimeter of the area by segmenting the filtered image; Matching the perimeters (or points close to them) and interpolating points within the areas.</td>
</tr>
<tr>
<td>Areas with shaded creeks and valleys.</td>
<td>Identifying shadows by gray-value classification; Marking the areas as &quot;don't match&quot;; Completing missing points from other sources.</td>
</tr>
<tr>
<td>Area along a road that lies along an epipolar line.</td>
<td>Identifying ribbon-type features that lie along an epipolar line; Performing matching in this area by a different technique.</td>
</tr>
</tbody>
</table>

Table 6.4 Determined phenomena and suggestions for solutions (from Krupnik 1998)

Unfortunately, no results for the system were presented in the paper. The technique assumes that different techniques (laser altimetry and radar interferometry are suggested in the paper) are available to obtain elevation estimates in the areas where the photogrammetry cannot. However, it is not clear how problems such as occlusion are to be dealt with. It is not clear either how the system will identify ribbon type
structures or the shadows, particularly in areas that are naturally dark such as many types of natural rock or in urban environments. One point made in the discussion is that other quality analysis techniques are rather expensive but no estimation is made as to the potential cost of a multi-sensor approach suggested in the paper or the increase in processing time required to analyse the imagery prior to processing. An attempt has been made to contact Dr Krupnik to discuss his proposed system but at the time of writing no response has been received.

The approach offered by the Failure Warning Model differs significantly from this technology. Instead of attempting to correct and allow for problematic areas in a DEM, the areas are identified for interactive editing by the user. Until a perfect photogrammetric solution is produced, interactive editing and checking of the output will always be required. This will be the case with the three approaches outlined in this section. This view reflects that of Autometric, the developers of OrthoMAX who suggest that it is an "inevitable fact that errors and blunders will occur in the automatic collection process, as they do in all ... measurement processes" (Grafton, 1999). The Failure Warning Model therefore offers the user assistance in this editing and checking process, instead of trying to replace it.

Whilst there is a distinct overlap between some of the technologies, for example the Failure Warning Model and the technique described by Hannah (1981), there is also the potential for integration of the systems. The technique described by Li et al. (1996) could easily be integrated with the Failure Warning Model such that an attempt is made to improve on the quality of the DEM as well as reporting on potentially erroneous areas for interactive editing by the user. Although full automation is often stated as the aim of current photogrammetric research, it would be dangerous to use it as a black box technology, to accept without questioning the results from the system.

The next chapter will demonstrate the validity of the Failure Warning Model on detailed accuracy tests carried out on the varied data sets used in the study. In addition, it will be shown that the approach is not limited to just the OrthoMAX software but is applicable to other digital photogrammetric systems.
Chapter 7 Testing the Failure Warning Model

In the previous chapter, the design and implementation of the Failure Warning Model was described. The system takes two DEMs (each generated with slightly different strategy parameter settings) and an orthophotograph of the area and assigns one of three classifications to each point, which identifies areas with unreliable height estimates.

In this chapter, the efficacy of the Failure Warning Model will be demonstrated, and the results of testing the approach on a range of different imagery will be presented. For each data set used, both a quantitative and qualitative analysis of the output will be performed. Check point data was available for all of the data sets used in this set of experiments, enabling a thorough quantitative analysis of the success of the Failure Warning Model to be made. These tests will demonstrate the success of the system by proving that the areas classified as acceptable by the system have a better accuracy, compared with those highlighted for future editing. Also included in this section of the work are the results from tests carried out using other digital photogrammetric systems, to identify if the Failure Warning Model approach is generic and could be applied successfully to other systems.

Ideally, a system such as the Failure Warning Model should clearly identify low accuracy areas of a DEM. There should be a clear distinction between the accuracy of the points classified as acceptable by the system and those highlighted for possible editing. The system should be easy to use and offer a clear benefit to the user.
7.1 Testing of the Failure Warning Model using the 1:13,000 scale data set.

The Failure Warning Model was tested on eight areas of the 1:13,000 scale imagery (Section 4.1.2). The imagery covers mainly flat farmland with some small forested areas and one residential area. Initial tests presented in Section 5.1.1 suggested that the imagery was well suited to area based matching techniques. The eight areas had a range of different grid spacings and covered a variety of landcover types. For each area, the input DEMs for the Failure Warning Model were the DEM generated using default strategy parameters and a DEM generated with the following specification changes:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default setting</th>
<th>Modified setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum threshold</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Maximum parallax</td>
<td>5 pixels</td>
<td>7 pixels</td>
</tr>
<tr>
<td>y - Parallax Allowance</td>
<td>0 pixels</td>
<td>2 pixels</td>
</tr>
</tbody>
</table>

Table 7.1 Parameter settings for Failure Warning Model input DEMs

The settings adopted for other variable parameters used by the Failure Warning Model are detailed in Section 6.2.3.1

7.1.1 1:13,000 scale imagery - Results

A brief summary of the results can be seen in Table 7.2. The table illustrates the results for eight sub areas, with results divided into four rows. The first three rows of data detail measures of accuracy for the three area classifications derived using the Failure Warning Model. The fourth row provides the r.m.s.e. value for the entire DEM derived using merely the default strategy parameters, the result that the user would need to assess without access to the Failure Warning Model.
Table 7.2 Accuracy results from tests of Failure Warning Model on 1:13,000 scale imagery.

<table>
<thead>
<tr>
<th>FWM Category</th>
<th>Area / r.m.s.e. value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/black</td>
<td>3.91 2.76 1.898 0.39 1.00 2.89 1.94 1.99</td>
</tr>
<tr>
<td>OK</td>
<td>1.88 1.25 1.044 0.48 1.48 1.59 1.59 1.25</td>
</tr>
<tr>
<td>256/white</td>
<td>6.26 5.58 2.001 2.95 4.76 3.68 26.78 6.27</td>
</tr>
<tr>
<td>Default overall DEM</td>
<td>3.466 2.076 1.538 0.855 1.266 2.542 3.59 1.961</td>
</tr>
</tbody>
</table>

Table 7.2 clearly suggests that the Failure Warning Model has worked as intended for all eight areas examined within this data set. In all but two of the areas (areas 4 and 5), there is a clear distinction between the accuracy of the three areas, with the points classified as acceptable/OK having the best accuracy.

Although in areas 4 and 5 of the imagery, the accuracy of points classified as OK is slightly worse than those classified as black (interpolated on areas with a sudden elevation change), there is still a clear difference in the accuracy of points classified as white (point susceptible to changes in the parameters) by the model. For area 4, the accuracy of the points falling into this category is 2.95m compared to 0.48m for the points classified as acceptable and 0.855m for the overall DEM. For area 5, the accuracy of the points falling into white category is 4.76m compared to 1.48m for the points classified as acceptable and 1.266m for the overall DEM. Analysis of the results suggests that the white classification consistently contains the points with the highest check point residuals so it is important for the software to work consistently for these areas.

Table 7.2 suggests that the Failure Warning Model has worked particularly well in some of the areas, most notably areas 1, 2, 7 and 8. In these areas, the accuracy of the points classified as acceptable is considerably better than those highlighted for editing, with the accuracy of the points classified as white being significantly worse than both the
acceptable and overall results. This is of particular note in area 7. The accuracy of the points classified as white in this area is 26.78m compared with 1.59m for the points classified as acceptable and 3.59m for the overall DEM. This is a clear indication that the software has successfully identified the points with the largest check point residuals.

7.1.2 1:13,000 scale imagery - Qualitative Analysis.

In this section of the work, the results from one of the areas used in the testing of the Failure Warning Model will be examined in more detail. The output from the Failure Warning Model for area 7 can be seen in Figure 7.1. A visual inspection of the data suggests that the output from the model has highlighted successfully areas that are typically problematic for automated matching techniques.

It can be seen from Figure 7-1 that the Failure Warning Model has indicated large areas adjacent to the river running across the middle of the image. Trees that can cause problems due to occlusion predominate in this area. Also highlighted is a large section of land in the north east corner, in an area of steep slopes. Although the image texture is good in this area, the steepness of the slope presents problems for the algorithm during the post-processing phase.
Figure 7-1 Failure Warning Model output for area 7

There are small areas around the edges of some of the buildings in the north west corner of the image that have been interpolated and subsequently highlighted by the Failure Warning Model. Also of note is that the Failure Warning Model has successfully identified that the algorithm has successfully correlated the flat open fields on the south side of the river. Again, image texture is good in this section of the imagery so it is an area well suited to automated matching techniques.

7.1.3 1:13,000 Scale Imagery- Quantitative Analysis

Analysis of individual check point residuals again reinforces the success of the system. A detailed distribution of the check point residuals for area 7 can be seen in Table 7.3. It can be seen that the points classified as acceptable by the Failure Warning Model have a
residual of less than 1m, 15 fall in the range 1 to 5m and three have residual errors between 5 and 10m (5.0m, 5.7m, 9.0m). The location of these three check points can be seen in figure 7.1. The point with the highest residual error lies adjacent to an area classified as 0/black, whilst the other two points lie in an area prone to higher check point residuals (the gap between adjacent buildings, the elevations of which cause the road level to be raised during post-processing). The only way to minimise the errors in areas such as this is to reduce the grid spacing, thus forcing more points to fall in-between the gaps between the buildings.

<table>
<thead>
<tr>
<th>Residual Range (m)</th>
<th>BLACK /0</th>
<th>OK</th>
<th>WHITE /256</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>14</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>1-5</td>
<td>6</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>5-10</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>10-20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-30</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>&gt;30</td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.3 Distribution of check point residuals in Failure Warning Model classification

Table 7.3 shows that the points classified as white /256 have particularly large check point residuals. The algorithm has successfully identified the check points with the largest residuals.

7.2 Testing of the Failure Warning Model Using the 1:45,000 Scale Data Set.

The second data set to be tested was the 1:45,000 scale data set. The data set covers a dry, sandy river bed with occasional small bushes and trees. Two areas were used in the study (since there was little terrain variation in the four images). For each DEM a different stereopair was used. The strategy used for the testing was described in Section 7.1.
7.2.1 1:45,000 Scale Imagery - Results.

A summary of the results of the testing of the Failure Warning Model on the 1:45,000 scale imagery (Section 4.1.3) can be seen in Table 7.4.

<table>
<thead>
<tr>
<th>FWM Category</th>
<th>Area / r.m.s.e. value (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>O/black</td>
<td>+2.369</td>
</tr>
<tr>
<td>OK</td>
<td>+1.304</td>
</tr>
<tr>
<td>256/white</td>
<td></td>
</tr>
<tr>
<td>Default overall DEM</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4 Results from testing the Failure Warning Model on 1:45,000 scale imagery

It can be seen from the bottom row of the results table that the matching algorithm worked with varying degrees of success in the two DEMs (or at least at the location of the check points in the two DEMs). From the accuracy results alone, the terrain extraction algorithm appears to have worked well in the first area (r.m.s.e. value = ±1.49m) but experienced some difficulties in the second area (r.m.s.e. value = ±273.81m). This extremely large r.m.s.e. value is a clear indication that there is a serious problem with sections of this second area (all four images form part of the same block).

DEM’s of the two areas used in the study (generated using the default strategy parameters) are shown in Figure 7-2. It can immediately be seen from the two DEMs that problems exist with the matching algorithm in both areas (indicated by the black or dark grey pixels). Unfortunately, the check points in area 1 only lie in the regions in which the image matching has worked well, and thus the r.m.s.e. value for the whole DEM do not reflect problems with these other areas. The area that has failed in area 2 is of immediate note in the DEM. In situations such as this, it would be easy for even a novice user to identify the inaccurate areas. However, the Failure Warning Model should still be able to reliably identify such regions.
The numerical analysis of the output from the Failure Warning Model can be seen in Table 7.4 also. It shows that the algorithm again worked well in both areas, with a clear distinction between the accuracy of the three classifications. Encouragingly, the points classified as acceptable again have the highest accuracy.

For area 1, the Failure Warning Model found that none of the check points lay in areas susceptible to changes to the strategy parameters, hence the lack of an entry in the 256/white row.

For area 2 however, there still appears to be a problem with the points classified as acceptable since they have a high r.m.s.e. value of ±195.30m. This is clearly an unacceptable result and will be examined in more detail later in Section 7.2.3.
7.2.2 1:45,000 Scale Imagery - Qualitative Analysis

The graphical output from the Failure Warning Model for area 1 is presented in Figure 7-3. Comparison with Figure 7-2 shows that there is a broad agreement between the two figures with the areas highlighted as 256/white in the output corresponding with the failed areas of the DEM. Similarly, the points that appear to reflect the nature of the surface on the DEM are classified as OK by the Failure Warning Model. Similarly for area 2 of the 1:45,000 scale imagery, there is broad agreement between the DEM and the output from the Failure Warning Model shown in Figure 7.4. The algorithm has correctly identified the large failed section on the right hand side of the DEM (caused by the DEM covering the edge of the overlap area) and even picked out the small areas in the top left hand corner.

7.2.3 1:45,000 Scale Imagery - Quantitative Analysis

A more detailed examination of the results from the tests on area 2 of the 1:45,000 scale imagery show that 13 check points were classified as OK by the Failure Warning Model. Of these, all but two have check point residuals of less than 6m, with eight of the points having residual errors less than 1m. A full list of the check points and their residual errors can be seen in Table 7.5. The two check points with larger residuals are 598800, 4159532 (residual = 347.0m) and 598820, 4159408m (residual = 612.7m). Examination of figure 7.4 shows that these two points are on the edge of the area classified as 256/white by the Failure Warning Model whilst the other points are within the area classified as OK. All of the check points classified as white by the Failure Warning Model had extremely large errors. Also, the accuracy of most of the points classified as OK are within the level (1/10,000 of flying height) suggested as being achievable by Fryer et al., (1994).
Figure 7-3 Output from Failure Warning Model for area 1 of the 1:45,000 scale imagery
Figure 7-4 Failure Warning Model output from area 2 of the 1:45,000 scale imagery
<table>
<thead>
<tr>
<th>X (m)</th>
<th>Y (m)</th>
<th>residual (m)</th>
<th>FWM classification</th>
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<tr>
<td>598816 4159558</td>
<td>606.0436</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>598744 4159606</td>
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<tr>
<td>598752 4159602</td>
<td>5.205148</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598748 4159590</td>
<td>4.622556</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598724 4159560</td>
<td>0.465193</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598860 4159544</td>
<td>0.890113</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598800 4159532</td>
<td>346.9842</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598584 4159514</td>
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<td></td>
</tr>
<tr>
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<td>0.5872</td>
<td>OK</td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>598622 4159424</td>
<td>0.078276</td>
<td>OK</td>
<td></td>
</tr>
<tr>
<td>598662 4159412</td>
<td>0.147431</td>
<td>OK</td>
<td></td>
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<td>598820 4159408</td>
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<td>459.2666</td>
<td>256</td>
<td></td>
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<td>598756 4159414</td>
<td>364.5451</td>
<td>256</td>
<td></td>
</tr>
<tr>
<td>598732 4159406</td>
<td>259.9663</td>
<td>256</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.5 Check point residual errors for Failure Warning Model for area 2 of the 1:45,000 scale imagery

7.3 Testing of the Failure Warning Model using the 1:6,000 scale data set.

The 1:6,000 scale data set (Section 4.1.1) covered a wide variety of land cover types including residential, university campus, forested and rural areas. Testing of the Failure Warning Model was carried out on two of the three areas used in the analysis of the 1:6,000 scale imagery carried out in Section 5.1.
7.3.1 1:6,000 Scale Imagery - Results

A summary of the results from the testing using the 1:6,000 scale imagery can be seen in Table 7.6. It can be seen from examination of the overall accuracy results for the two areas that significant errors exist in both default DEMs resulting in the large r.m.s.e values (±54.901m and ±40.618m).

<table>
<thead>
<tr>
<th>FWM Category</th>
<th>Area / r.m.s.e (m)</th>
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<th></th>
</tr>
</thead>
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<tr>
<td></td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>0/black</td>
<td>±13.56</td>
<td>±1.65</td>
<td></td>
</tr>
<tr>
<td>OK</td>
<td>±4.30</td>
<td>±2.07</td>
<td></td>
</tr>
<tr>
<td>256/white</td>
<td>±205.53</td>
<td>±128.98</td>
<td></td>
</tr>
<tr>
<td>Default overall DEM</td>
<td>±54.901</td>
<td>±40.618</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.6 Results from the testing of the Failure Warning Model on the 1:6,000 scale data set

With the application of the Failure Warning Model to these two areas, it can be seen that the classification system has worked well. The r.m.s.e. value of the points classified as OK have been reduced to ±4.30m and ±2.07m respectively. The algorithm also appears to have isolated the points with the largest check point residuals, especially for the points classified as white / 256. The check points falling in these two regions have a r.m.s.e. values of ±205.53m and ±128.98m respectively.

7.3.2 1:6,000 Scale Imagery - Qualitative Analysis.

Examination of the DEMs of the two areas support the success of the Failure Warning Model. The DEM for area 2 of the imagery (Figure 7-5) shows that there is a region at the top of the DEM in which the area matching algorithm has clearly failed (as indicated
by the black area). This is caused by the DEM covering the edge of the overlap area. However, the algorithm has appeared to correlate successfully around the buildings and there are no other obvious problematic areas. The Failure Warning Model result for the area can be seen in Figure 7-7.

![Figure 7-5 Default DEM of area 2 (1:6,000 scale data set)](image)

A similar result can be seen for area 3 of the 1:6,000 scale data set (illustrated in Figure 7-6). As with the default DEM for area 2, there is a region of the DEM in which the algorithm has clearly failed, again due to the DEM covering the edge of the overlap area. However the large buildings of the campus are clearly visible on the DEM, suggesting that in these areas the DEM generation algorithm has worked well. The output for the area illustrating the locations of the buildings can be seen in Figure 7-8.
The output from the Failure Warning Model reflects the results presented above. Figure 7-7 illustrates this output and it can be seen that the algorithm has correctly identified the failed area at the top of the DEM. It has also isolated areas around the edges of some of the taller buildings and the forested areas, again areas in which one would expect the algorithm to have difficulty in finding conjugate points.
Three of the points with large check point residuals that were not identified by the Failure Warning Model were 477096, 4761787 (residual = 14.1m), 477057, 4761712 (residual = 16.0m) and 477465, 4761205 (residual = 11.6m). Examination of the figure above shows that the first two points are located in a forested area, areas which are prone to large check residuals. The results from the Failure Warning Model and Figure 7-5 suggest that the automated DEM generation algorithm works reliably in this area with no sudden peaks or troughs in the surface. This result suggests that the check data and the automated DEM surface are not coincident and different surfaces have been defined.
hence the high check point residual. Figure 7-7 shows that the third check point with a high residual lies adjacent to a small area highlighted by the Failure Warning Model.

Similarly for area 3 (illustrated in Figure 7-8), the Failure Warning Model has clearly identified the poor area of the DEM and also highlighted the edges of some of the larger buildings. Other than those areas, the Failure Warning Model suggests that the remaining areas have been successfully correlated with a high degree of accuracy.

Figure 7-8 Failure Warning Model output for area 3 of the 1:6,000 scale imagery

7.4 Testing of the Failure Warning Model on the 1:25,000 Scale Imagery.

The next data set to be used in the testing of the Failure Warning Model was the 1:25,000 scale imagery (Section 4.1.5). This data set was provided by British Antarctic Survey and covered a mountain in Antarctica. It is interesting in that it is probably a "worse case scenario" for digital area matching techniques in that it contains large areas with a very
monotonous texture and a large elevation range. An orthophoto of the area used in the study can be seen in Figure 7-9. The large snow banks contain very white, clean snow and are therefore ill suited for either analytical or digital photogrammetric techniques. Glacial regions tend to have snow containing plenty of rock debris resulting in plenty of image texture making them well suited to area based matching techniques. It can also be seen however that there are large areas in the data set covered by rocks and other debris to form screes. Image texture is prevalent in these areas and they would appear to be areas well suited to automatic matching techniques, at least from first inspection.

![Orthophoto of area from the 1:25,000 scale data set used in the testing](image)

Figure 7-9 Orthophoto of area from the 1:25,000 scale data set used in the testing

7.4.1 1:25,000-Scale Imagery -Results.

The output from the Failure Warning Model for the 1:25,000 scale data set is somewhat confusing at first sight. It does not help that the areas highlighted as white / 256 appear as a very similar pixel value to the snow; however, this can be changed when viewed on
screen. The output is illustrated in Figure 7-10 and it can be seen that the algorithm has highlighted large areas of the major snowfields, reinforcing the need for good image texture. The areas identified as being susceptible to changes in the strategy parameters are assigned a green colour, whilst the areas that have been interpolated on areas with a sudden elevation change are coloured red.

It can also be seen from the output of the Failure Warning Model that the terrain extraction algorithm has worked well in some of the large scree area, particularly in the top right hand corner of the image. It can also be seen however that the algorithm has had difficulty in some of the scree areas, particularly those at the top of the image.
A quantitative analysis of the results can be seen in Table 7.7 and it suggests that once again the Failure Warning Model has worked well. The r.m.s.e. value for the whole DEM generated using the default strategy parameters was 22.5m, indicating that some areas of the DEM contain significant errors. However, application of the Failure Warning Model has resulted in isolation of a significant portion of the points with the highest accuracy, as shown by the much better accuracy of the points classified as OK. The r.m.s.e. value of the points highlighted for editing is higher than that of the whole DEM, providing further indication that the correct set of points have been identified.

<table>
<thead>
<tr>
<th>FWM Category</th>
<th>r.m.s.e (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/black</td>
<td>+26.7</td>
</tr>
<tr>
<td>OK</td>
<td>+6.2</td>
</tr>
<tr>
<td>256/white</td>
<td>+34.1</td>
</tr>
<tr>
<td>Default overall DEM</td>
<td>+22.5</td>
</tr>
</tbody>
</table>

Table 7.7 Failure Warning Model Results for 1:25,000 scale data set

The distribution of the check point residual errors can be seen in Figure 7-11. The graph illustrates the number of points within each of the ranges falling within each of the Failure Warning Model classifications. The results show that for the points classified as OK by the model, the majority of check point residual errors fall in the range 0 to 5m with a significant number in the range 5 to 10m. However, there were still 107 points that had check point residuals greater than 10m (maximum 37.7m) that were classified as being OK by the model.

The distribution of the points classified as OK by the Failure Warning Model is as expected, with a graph approximating a normal distribution. This is important because it
suggests that the Failure Warning Model is working correctly. If we assume that the Failure Warning Model has identified all of the gross errors (or blunders) from the data and highlighted them for editing and that the systematic errors have been removed through proper calibration of the photography etc., the only errors that will remain are the random errors. The theory of errors (Section 2.6) states that these errors should have a normal distribution. Figure 7.11 shows that this is the case, providing further evidence of the success of the technique.

Figure 7-11 1:13,000 scale data set - check point distribution

The distribution of the two highlighted groups from the Failure Warning Model is not ideal as there is a significant number of points falling within the smallest group. Ideally, the Failure Warning Model should classify all of the points in this range as OK.
Encouragingly, it can be seen that the majority of points with high check point residuals have been highlighted by the model, and it has successfully found the check points with the highest residuals (140.0m in the points classified as 0 and 133.5m in the points classified as 256).

7.5 Testing of the Failure Warning Model on the 1:17,000 scale data set.

The 1:17,000 scale data set covering a university campus was also used in the testing of the Failure Warning Model. The area of the data set used covered a section of playing fields with a small residential area on the east side.

7.5.1 1:17,000 Scale Imagery- Results

An orthophotograph of the area used in the testing can be seen in Figure 7-12. It can be seen that the majority of the area consists of an open, flat field. This region provides the location for most of the check points. From first inspection, this imagery would appear to be well suited to automated techniques in that there appears to be good image texture and few sudden elevation changes either from buildings or trees.

The output from the Failure Warning Model for this section of the 1:17,000 scale data set can be seen in Figure 7-12. It shows that the output is particularly "messy" and of little practical use. However, it does convey a number of things. Primarily, it suggests that the stereo matching algorithm employed by OrthoMAX is having difficulty finding conjugate points in this area, probably due to a lack of image texture. However, it also suggests that this is a localised problem within small pockets of the image, since there are areas of the image that are being successfully and reliably correlated.
Another point of interest from the output is that the algorithm suggests that significant problems may exist in the small residential area on the right hand side of the area. It shows that changes to the strategy parameters are having an effect on the points within these areas, reinforcing much of the current literature on area based matching techniques (Smith, 1997).

A numerical analysis of the output from the Failure Warning Model can be seen in Table 7.8. It can be seen that the points classified as 0/black have a significantly larger r.m.s.e. value than the other two classifications, but check points identified as white/256 are in fact accurate.
Of note is that fact that of the points classified as 0/black by the algorithm, the highest check point residual error is 9.9m whilst for the other two classifications, the largest was 3.4m for both regions. This large check point residual error (9.9m) was the only value greater than 3.4m, suggesting that the algorithm has worked well and successfully identified the area of poorest accuracy.

Figure 7-13 Failure Warning Model output for area 1 of the 1:17,000 scale data set

<table>
<thead>
<tr>
<th>FWM Category</th>
<th>r.m.s.e (m)</th>
</tr>
</thead>
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<tr>
<td>OK</td>
<td>+1.907</td>
</tr>
<tr>
<td>256/white</td>
<td>+1.900</td>
</tr>
<tr>
<td>Default overall DEM</td>
<td>+2.094</td>
</tr>
</tbody>
</table>

Table 7.8 Numerical analysis of tests on 1:17,000 scale imagery
7.6 Testing of the Failure Warning Model on the 1:70 scale data set.

The final version of the Failure Warning Model was tested on the 1:70 scale data set - imagery of a simulated river bed flume captured using a Kodak DCS460 digital camera. Area 4 of the imagery will be focused upon since it provided the most interesting results in the initial analysis of the data. The output from the algorithm for area 4 can be seen in Figure 7-14, along with a DEM of the area generated using the default strategy parameters. Figure 6.2 illustrates the region of the default DEM in which the stereo matching algorithm had difficulty and it can be seen that there is good correlation between the two images.

The Failure Warning Model output suggests that the DEM generation algorithm has worked successfully in the main channel area. As with some of the results presented earlier in this chapter, the failure in this area of the imagery is obvious, and even the most novice of users could identify it with ease. However, it is also clear from Figure 7-14 that the Failure Warning Model has worked successfully and not mis-classified the areas.

Unfortunately, because of the way that the information was collected, it was not possible to perform a quantitative analysis for this data set. However, a visual comparison of the DEM and output from the Failure Warning Model demonstrates clearly the success of the technique.
7.7 The wider applicability of the Failure Warning Model

All of the development work and testing for the Failure Warning Model has been completed within the ERDAS Imagine environment. Whilst this is of clear benefit to users of this software it is of little use to users of other digital photogrammetric systems. Thus, it was judged to be important to assess whether the principles underlying the Failure Warning Model could be applied to other software packages. If so, it would suggest that the technique (and as a consequence this thesis) is of use to the wider photogrammetric community.

It was therefore decided to identify if the principles of the Failure Warning Model could be applied to other software packages. Two packages were identified for testing, the
Phodis TS software from Zeiss and the VirtuoZo DPW. Access to these two packages was kindly provided by Clive Boardman at Photarc Surveys Ltd and Alexander Koh at Bath Spa University. These two packages were particularly suitable for the testing as DEMs generated could be output in an ASCII format, allowing for processing within the Imagine software. Ideally, the Failure Warning Model would have been tested on other software packages but limitations on time and, more importantly, access to software meant that this was not possible.

7.7.1 Application of the Failure Warning Model Principle to the Zeiss Phodis Software

The automatic (feature based matching) DEM generation software by Zeiss (Phodis TS) is controlled by two strategy parameters. When defining a new DEM, the user has the opportunity to select one of the three options for either of the parameters or accept the default settings.

The two parameters are;

- **Terrain Type** – flat/undulating/mountainous
- **Smoothing** – low/medium/high

The default values are mountainous terrain type and low smoothing. In addition, an adaptive matching technique is also offered, a system designed to adapt the grid spacing in areas with sudden elevation changes.
7.7.1.1 Methodology

A set of tests were carried out on the Zeiss Phodis TS software to identify primarily if the principle of the Failure Warning Model could be applied to the Phodis software. The Phodis TS software also classifies each point on a scale of 1 to 7 based upon the estimated accuracy of the point, 1 being the most accurate. A secondary aim of the study was to compare this point classification system with the Failure Warning Model.

The testing was carried out on three areas of a set of 1:13000 scale imagery. Check point data was available for all three areas again facilitating a numerical analysis of the success of the tests. As with the tests on the OrthoMAX software, the technique should result in a clear distinction between the accuracy of the points highlighted for editing and those marked as acceptable.

Area 1 – rural area with forest along western edge and small forest in the north east corner. Grid spacing = 5m. Number of checkpoints in area = 762.

Area 2 – Residential and flood plain coverage. The river is flanked with trees and there is a slope with a steep gradient in the north east corner of the area. Grid spacing = 5m. Number of check points in area = 261.
Figure 7-15 Orthophotograph of area 1
Figure 7-16 Orthophotograph of area 2
Area 3 – Residential and rural area. Grid spacing = 10m. Number of check points in area = 957.

The DEMs were generated using the Phodis software and imported into the ERDAS Imagine software for processing. A macro was written within the ERDAS Imagine Spatial Modeller environment to enable the DEMs created in Phodis to be compared with the check point data.
7.7.1.2 Zeiss Phodis software - results.

As can be seen in Figure 7-15, area 1 covers an area consisting mainly of flat fields with a couple of large wooded areas and an occasional building. It would appear from previous results that this imagery (with the exception of the wooded areas) would be well suited to automated techniques. Examination of the results in Table 7.9 supports this with a r.m.s.e of a DEM generated with the default parameters (mountainous terrain type and low smoothing) of 1.6m. The most accurate result was achieved using a Terrain Type setting of Mountainous and Medium Smoothing (r.m.s.e 1.5m) whilst the worst results were achieved using the Terrain Type set to flat. This may be due to the presence of the wooded areas although the check data was located mainly in the field areas and away from the trees. The results suggest that for this area, a low smoothing setting provided the most accurate results, followed by medium and then high.

Figure 7-16 shows that area 2 consists of open fields, a river, a large number of trees, a steep slope (NE corner) and a large residential area. It would appear from a visual inspection of the imagery that parts of this area are ill suited to image matching techniques, especially the residential and steep slope areas. Paradoxically, Table 7.9 suggests that of the three areas used in the testing, this area is the most successful with the lowest average r.m.s.e. value.
### Table 7.9 RMSE results for Phodis test areas

<table>
<thead>
<tr>
<th>Area: 1</th>
<th>DEM ID</th>
<th>RMSE (m)</th>
<th>Terrain Type</th>
<th>Smoothing</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Mountainous</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>+1.6</td>
<td>Flat</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>+1.5</td>
<td>Undulating</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>+1.5</td>
<td>Mountainous</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>+1.6</td>
<td>Mountainous</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>+1.7</td>
<td>Undulating</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>f</td>
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<td>Undulating</td>
<td>High</td>
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</tr>
<tr>
<td>g</td>
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<td>Flat</td>
<td>Medium</td>
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<tr>
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<td>Flat</td>
<td>Low</td>
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</tr>
<tr>
<td>b</td>
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<td>Undulating</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>+1.5</td>
<td>Mountainous</td>
<td>Medium</td>
<td></td>
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<tr>
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<td>Medium</td>
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</tr>
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<td>f</td>
<td>+1.5</td>
<td>Undulating</td>
<td>High</td>
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</tr>
<tr>
<td>g</td>
<td>+1.6</td>
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<td>Medium</td>
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</tr>
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<td>h</td>
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<td>High</td>
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</tr>
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<td>i</td>
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</tr>
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<tr>
<td>a</td>
<td>+2.7</td>
<td>Flat</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>+2.1</td>
<td>Undulating</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>+2.1</td>
<td>Mountainous</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>+2.3</td>
<td>Mountainous</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>+2.7</td>
<td>Undulating</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>+2.9</td>
<td>Undulating</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>+2.8</td>
<td>Flat</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>+3.0</td>
<td>Flat</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>+1.9</td>
<td>Mountainous</td>
<td>Low</td>
<td>Adaptive Matching</td>
</tr>
</tbody>
</table>

Adaptive Matching
Table 7.9 shows that the lowest r.m.s.e results are achieved with a Mountainous Terrain Type and High Smoothing, followed by Undulating Terrain Type and High Smoothing. The choice of these two terrain type settings is logical but the High Smoothing Factor setting would be (in theory) more suitable for an undulating terrain. The presence in the object space of a significant number of houses and trees would suggest that a low smoothing setting would be required to prevent the roof tops being lowered and the street elevations from being raised in the final DEM by interpolation. The worst r.m.s.e results are achieved with a Flat Terrain Type and High Smoothing. The range of r.m.s.e results (±0.3m) is slightly greater than area 1 (±0.3m) but less than area 3 (±0.9m), suggesting that the choice of parameters is less important for areas 1 and 2 than with area 3.

The r.m.s.e. value for area 3 suggest that of the three areas, this is the least suitable for the production of an accurate DEM with a default r.m.s.e. value of ±1.929m. The orthophoto of the area (Figure 7-17) shows that the area consists of large residential and forested areas. Of note also is the increase of the grid spacing from 5m in areas 1 and 2 to 10m in area 3, a factor which could decrease the accuracy of the DEM, particularly in the residential area. A grid spacing as large as this is likely to classify more points as outliers during post-processing. This is reinforced by examination of the parameters, with the worst result coming from a Terrain Type of Flat and a High Smoothing factor (r.m.s.e. value = ±3.048m), a set of parameters that results in high levels of interpolation.

As with the ERDAS Imagine OrthoMAX DPS, changes to the strategy parameters only affect certain points on the DEM (Gooch and Chandler, 1999). This can be illustrated by subtracting one DEM from another to see where the greatest differences occur. Points that are not affected by alterations to the strategy parameters will have a difference that is insignificantly different from zero. Figure 7-18 and Figure 7-19 show two difference images created for area 2. In the figures, points with a value around 0m (i.e. not affected by changes to the strategy parameters) are coloured grey whilst those most affected are coloured white. Whilst the two difference images are not identical, there is a strong correlation between the areas highlighted. Comparison with the orthophotograph of the
area (Figure 7-16) indicates that the areas susceptible to changes are the forested areas adjacent to the river and the residential area.

Figure 7-18 Difference between DEMs a and b for area 2.

Figure 7-19 Difference between DEMs c and d for area 2
This result supports much of the literature available on DEM accuracy that suggests that automated DEM generation software is prone to failure in areas with monotonous texture and areas containing sudden elevation changes (Krupnik, 1998).

7.7.1.3 Testing of the Failure Warning Model on the Phodis Data.

For the output data from the Phodis software to be used in the Failure Warning Model, the model had to be altered slightly. The Phodis software provides no information about the location of the interpolated points in a DEM. The section of the model that identified the points that have been interpolated on areas with a sudden elevation change was therefore removed, leaving just the module that identifies the areas that are susceptible to changes in the strategy parameters. This was not considered a problem since results presented earlier in this chapter suggest that this is the most important part of the model as it tends to highlight the areas with the largest check point residuals.

The results of the tests can be seen in Table 7.10. For each area, several parameter combinations were used as inputs. For each test of the Failure Warning Model, the two input DEMs were the default DEM (mountainous terrain type and low smoothing) and the DEM listed in column 2 of Table 7.10. The output from the model was then analysed quantitatively by comparing checkpoints in each category (i.e. the r.m.s.e. value of all the points classified as OK versus the points highlighted by the model).

The results of the tests can be seen in Table 7.10. The results show that the Failure Warning Model works extremely well using the Phodis data. It can be seen that in all of the areas with all of the parameter combinations used, the points highlighted as being potentially problematic (assigned a white/256 value in the orthophoto) by the Failure Warning Model have a significantly larger r.m.s.e. value than the points classified as acceptable. This implies that the unreliable points are being correctly identified by the Failure Warning Model implemented to work using the Phodis output data. It can be seen
that, in all three of the areas, all of the parameter combinations used resulted in the accuracy of the results classified as acceptable being between 1.0m and 1.5m. However, using an undulating terrain type setting and a high smoothing factor setting for the second DEM in area 1 resulted in an accuracy of ±0.7m for the acceptable areas and ±6.7m for the points highlighted for editing. Encouragingly, the accuracy of the points classified as acceptable in the three areas is similar, suggesting that the DEM generation software is working consistently in these areas and the Failure Warning Model is consistently finding the successfully correlated areas.

7.7.1.4 *The Phodis TS Point Accuracy Classification System.

Attached to the co-ordinates of each point in the ASCII output file is an accuracy classification based upon a scale of 1 to 7, 1 being the most accurate. This data was recorded and incorporated into Imagine for post processing and enabled the r.m.s.e. value for each of the classifications to be obtained.

The results presented in Table 7.11 suggest that the classifications of 1 and 2 work well with the points classified as 1 having a lower r.m.s.e. value than those classified as 2 in all but 5 of the test DEMs. This result is most apparent in area 3, where it can be seen that the points having a classification of 2 have a much larger r.m.s.e. value (6.2m) than the points classified as 1. Points classified as 7 had a larger r.m.s.e. value than those classified as 1 in all but 6 of the areas (there were no points with a classification of 7 in area 1) but was lower than those classified as 2. Why this is the case is not clear and further testing would need to be undertaken to establish why this happened.
<table>
<thead>
<tr>
<th>Area</th>
<th>Parameters of 2nd input DEM</th>
<th>r.m.s.e (m)</th>
<th>r.m.s.e (m)</th>
</tr>
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<tr>
<td>1</td>
<td></td>
<td>256</td>
<td>OK</td>
</tr>
<tr>
<td>a</td>
<td>+6.311</td>
<td>±1.204</td>
<td></td>
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<tr>
<td>b</td>
<td>+6.428</td>
<td>±0.987</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>+6.050</td>
<td>±1.028</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>+5.990</td>
<td>±0.946</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>+5.387</td>
<td>±1.120</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>+6.881</td>
<td>±0.743</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>+5.973</td>
<td>±1.193</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>+5.852</td>
<td>±1.193</td>
<td></td>
</tr>
<tr>
<td>average</td>
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<td>±1.080</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>default</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>+4.874</td>
<td>±1.176</td>
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<td>b</td>
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<td></td>
</tr>
<tr>
<td>c</td>
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<td></td>
</tr>
<tr>
<td>d</td>
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<tr>
<td>f</td>
<td>+5.261</td>
<td>±1.101</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>+4.374</td>
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<td>I</td>
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<td>±1.412</td>
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<td>±1.206</td>
<td></td>
</tr>
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<td>3</td>
<td>default</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>+6.493</td>
<td>±1.400</td>
<td></td>
</tr>
<tr>
<td>b</td>
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<td>c</td>
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<td>d</td>
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<td>e</td>
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<td>±1.552</td>
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</tr>
<tr>
<td>g</td>
<td>+5.814</td>
<td>±1.449</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>+5.335</td>
<td>±1.488</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>+2.348</td>
<td>±1.908</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>+5.385</td>
<td>±1.549</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.10 Results of FWM applied to Phodis DEM output data
Comparing the Phodis accuracy classification system and the Failure Warning Model, it has been shown is that the average r.m.s.e for points classified as acceptable by the Failure Warning Model is lower than those identified as 1 by Phodis.

These tests on the Phodis software have resulted in a number of important conclusions. Most importantly, the results have shown that the Failure Warning Model approach has worked reliably on a different digital photogrammetric system with a high degree of success. The technique consistently highlighted areas with large check point residuals. Secondly, The results showed that the Failure Warning Model was more successful at highlighting areas with large check point residuals than the system currently employed in the Phodis software.

7.7.2 Testing of the Failure Warning Model on the VirtuoZo DPS.

The image matching technique used by the VirtuoZo system is an "area, feature and bridge mode based global image matching procedure using probability relaxation and neural network techniques" (Zhang et al., 1996). VirtuoZo permits the selection of one of 5 matching strategies, 1 is used for flat terrain whilst 5 is aimed at rugged terrain.

Baltsavias et al. (1996) carried out some basic tests on the VirtuoZo software and and changed this matching strategy parameter from 3 to 5 and reported that "the results were completely identical." This appeared to be an unusual outcome so it was decided to repeat the tests on a different data set, testing all five of the parameters with a variety of grid spacings to identify if this is always the case.
<table>
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</tr>
</thead>
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<td>2</td>
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<tr>
<td>default</td>
<td>+1.477</td>
<td>+1.865</td>
</tr>
<tr>
<td>a</td>
<td>+0.922</td>
<td>+3.955</td>
</tr>
<tr>
<td>b</td>
<td>+1.588</td>
<td>+1.380</td>
</tr>
<tr>
<td>c</td>
<td>+1.291</td>
<td>+2.369</td>
</tr>
<tr>
<td>d</td>
<td>+0.862</td>
<td>+2.940</td>
</tr>
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<td>e</td>
<td>+1.366</td>
<td>+2.595</td>
</tr>
<tr>
<td>f</td>
<td>+1.002</td>
<td>+6.047</td>
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<td>g</td>
<td>+0.793</td>
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</tr>
<tr>
<td>h</td>
<td>+0.656</td>
<td>+3.595</td>
</tr>
<tr>
<td>average</td>
<td>1.106</td>
<td>3.224</td>
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<th>7</th>
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<td>default</td>
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<td>+1.316</td>
<td>+1.275</td>
</tr>
<tr>
<td>a</td>
<td>+1.430</td>
<td>+2.935</td>
<td>+1.322</td>
</tr>
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<td>b</td>
<td>+1.860</td>
<td>+0.967</td>
<td>+1.307</td>
</tr>
<tr>
<td>c</td>
<td>+1.324</td>
<td>+2.410</td>
<td>+1.170</td>
</tr>
<tr>
<td>d</td>
<td>+1.159</td>
<td>+2.444</td>
<td>+1.536</td>
</tr>
<tr>
<td>e</td>
<td>+1.524</td>
<td>+1.608</td>
<td>+1.354</td>
</tr>
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<td>f</td>
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<td>+1.142</td>
<td>+1.700</td>
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<tr>
<td>g</td>
<td>+0.993</td>
<td>+3.513</td>
<td>+2.401</td>
</tr>
<tr>
<td>h</td>
<td>+0.993</td>
<td>+3.513</td>
<td>+2.401</td>
</tr>
<tr>
<td>i</td>
<td>+1.654</td>
<td>+1.414</td>
<td>+1.281</td>
</tr>
<tr>
<td>average</td>
<td>1.401</td>
<td>2.126</td>
<td>1.574</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>default</td>
<td>+1.514</td>
<td>+4.408</td>
<td>+2.007</td>
</tr>
<tr>
<td>a</td>
<td>+1.558</td>
<td>+7.228</td>
<td>+1.434</td>
</tr>
<tr>
<td>b</td>
<td>+1.592</td>
<td>+5.461</td>
<td>+1.882</td>
</tr>
<tr>
<td>c</td>
<td>+1.506</td>
<td>+4.510</td>
<td>+2.031</td>
</tr>
<tr>
<td>d</td>
<td>+1.533</td>
<td>+6.207</td>
<td>+2.060</td>
</tr>
<tr>
<td>e</td>
<td>+1.679</td>
<td>+6.445</td>
<td>+1.808</td>
</tr>
<tr>
<td>f</td>
<td>+1.694</td>
<td>+8.184</td>
<td>+1.880</td>
</tr>
<tr>
<td>g</td>
<td>+1.596</td>
<td>+7.871</td>
<td>+1.640</td>
</tr>
<tr>
<td>h</td>
<td>+1.421</td>
<td>+7.775</td>
<td>+3.060</td>
</tr>
<tr>
<td>i</td>
<td>+1.526</td>
<td>+4.393</td>
<td>+2.005</td>
</tr>
<tr>
<td>average</td>
<td>1.562</td>
<td>6.248</td>
<td>1.987</td>
</tr>
</tbody>
</table>

Table 7.11 Phodis accuracy classification result
The results of these tests suggest that results are not affected by parameter changes. The Failure Warning Model technique relies on the fact that changing these strategies induces some effect in the resulting DEM. Unfortunately, VirtuoZo's insensitivity to the parameter makes the system impracticable. DEMs of the 1:13,000 scale data set were generated with 5m, 10m and 15m grid spacings and it was found that changing the parameters had no effect on the DEMs at all. Conversation with SDS (the suppliers of Virtuozo in the UK) suggested that this is likely to be the case for any data set. As a result of this, the Failure Warning Model cannot be applied to the VirtuoZo software.

7.8 Comparison of Failure Warning Model with OrthoMAX Internal Quality Assessment.

Some tests were carried out to examine how well the internal quality data produced by the OrthoMAX software correlated with the check point information. The software automatically assigns a classification of "Good", "Fair" and "Poor" based upon a precision test so it was decided to identify if this information could be used as an accuracy estimate. If there is a correlation, the system would be an easy to use alternative to the Failure Warning Model.

The precision of each point passing the correlation process in the OrthoMAX algorithm is estimated and compared with the Minimum Precision strategy parameter. Points failing this test are assigned a null status and the elevation is interpolated from the surrounding elevation information. Points that pass the test are assigned a collection status of either Good Fair or Poor depending upon the precision of the match and the bucket sizes (defined by the Minimum Precision parameter).

Although ERDAS admit that "high success (large percentages of Good, Fair, Poor, along with corresponding small percentages for interpolated... does not always translate to good
results" (ERDAS, 1992), the results do provide the user with a form of quality assessment. The information is presented in a visual format allowing the user to examine the spatial distribution of the data. An example of one of these files can be seen in Figure 7-20 ("Interpolated" points are shown as black, "Poor" as dark grey, "Fair" as light grey and "Good" as white areas).

Figure 7-20 OrthoMAX quality assessment output (1:13,000 scale data set - area 4)

Ideally, points assigned a Poor status would have a check point residual error value greater than the points classified as Fair etc. a macro was written that enabled this information to be collated within the Imagine environment.
For brevity, the results of tests on just one of the data sets (the 1:13,000 scale imagery) are presented. This data set was selected since it was well suited to the area based matching technique of the OrthoMAX algorithm. The results for the tests are presented in Table 7.12.

<table>
<thead>
<tr>
<th>Interpolated</th>
<th>Area 1</th>
<th>Area 2</th>
<th>Area 3</th>
<th>Area 4</th>
<th>Area 5</th>
<th>Area 6</th>
<th>Area 7</th>
<th>Area 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>2.885</td>
<td>2.768</td>
<td>1.751</td>
<td>1.443</td>
<td>0.489</td>
<td>0.933</td>
<td>1.627</td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td>3.901</td>
<td>1.920</td>
<td>2.373</td>
<td>0.794</td>
<td>1.722</td>
<td>2.056</td>
<td>4.049</td>
<td>2.777</td>
</tr>
<tr>
<td>Good</td>
<td>0.692</td>
<td>0.790</td>
<td>0.348</td>
<td>0.501</td>
<td>0.415</td>
<td>1.387</td>
<td>0.623</td>
<td>0.719</td>
</tr>
</tbody>
</table>

Table 7.12 Accuracy results for OrthoMAX classification system

The results show that there is no reliable link between the points classified as "Fair" or "Poor" and the accuracy of the points in the respective areas. Ideally, the points classified as "Poor" should have the worst accuracy but it can be seen that this is not always the case. In all but one of the areas presented, the accuracy of the points classified as "Good" are more accurate than the other groupings but the distinction is less clear for the other classifications. Also, it can be seen that in areas 2 and 4, the distinction between the "Good", "Fair" and "Poor" points are as expected. However, in 5 of the areas, the distinction is not ideal. For instance, in area 1, the accuracy of the points classified as "Fair" is worse than the points classified as "Poor". The results also suggest that the accuracy of the points classified as Interpolated is generally worse than the other classifications. However, the point needs to be made that interpolated points are not always inaccurate. The flat, planar regions, interpolation can be beneficial to DEM accuracy. It only decreases accuracy in areas with sudden elevation changes.

Comparison with the Failure Warning Model results for the same DEMs (Table 7.2) suggest that the system employed by OrthoMAX is not as robust as the technique developed in this thesis. Although the internalOrthoMAX system produces a better
accuracy result for the acceptable points, it has not identified points with high values of check point residual error. In all of the areas presented in Table 7.12, the accuracy of the points highlighted for editing by the Failure Warning Model is worse than those highlighted as "Interpolated" or "Poor" by the OrthoMAX software.

Another point that should be made is the distribution of these OrthoMAX collection percentages. Table 7.13 illustrates the distributions for the eight areas of the 1:13,000 scale imagery and it can be seen that in this data set, the level of interpolation was very high. The previous discussion suggest that in many of these areas, interpolated points are of the poorest accuracy, so the user is still required to check and edit between a third and half of the entire DEM. Even this approach will not guarantee that the points identified will have high check point residuals.

<table>
<thead>
<tr>
<th></th>
<th>Area 5</th>
<th>Area 6</th>
<th>Area 7</th>
<th>Area 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolated</td>
<td>33%</td>
<td>53%</td>
<td>43%</td>
<td>42%</td>
</tr>
<tr>
<td>Poor</td>
<td>11%</td>
<td>2%</td>
<td>7%</td>
<td>12%</td>
</tr>
<tr>
<td>Fair</td>
<td>29%</td>
<td>27%</td>
<td>22%</td>
<td>21%</td>
</tr>
<tr>
<td>Good</td>
<td>27%</td>
<td>18%</td>
<td>26%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Table 7.13 Distribution of Collection Percentages for 1:13,000 scale data set

These results suggest that the Failure Warning Model is more robust than the OrthoMAX technique (the OrthoMAX technique did not work in all of the areas tested) and is better at finding the points with the poorest accuracy. The output orthophoto generated by the Failure Warning Model is also more useable whereas the system employed by ERDAS requires a more sophisticated viewer system linked to the DEM output.
7.9 Conclusions

In this chapter, some of the results of extensive testing of the Failure Warning Model have been presented. The system was tested on a wide variety of imagery including the 1:30,000, 1:6,000, 1:45,000, 1:17,000, 1:25,000 and 1:70 scale data sets.

The results have shown that the system worked well for all data sets used in the testing. The system regularly identified the points with the highest check point residual errors and correctly isolated the areas with the highest accuracy. The Failure Warning Model has also been compared with the OrthoMAX internal quality assessment and it proves to be more successful at identifying points with large check point residual errors. When the system has failed to identify check points with large check point residual errors, it has in most cases identified poor accuracy areas adjacent to the point.

In areas with minimal image content such as the 1:17,000 scale and the 1:25,000 scale data sets, the technique has a tendency to highlight many of the points. Whilst on first inspection, this output may be of minimal value, it does at least identify the fact that the software is having difficulty in finding conjugate points, indicating a need for a different strategy either in terms of parameters, grid spacing or scan resolution or even perhaps a different survey method such as total station or GPS.

A criticism of the technique could be that it is only applicable when using the ERDAS OrthoMAX software. Further tests have demonstrated that the principles underlying the technique may be applied to other digital photogrammetric systems. The model worked extremely well on the Zeiss Phodis TS software and indeed outperformed its current accuracy classification system. However, the insensitivity to changes in the strategy parameters for the ViruoZo DPS meant that the system could not be applied. Further experimentation would be needed before applying the technique to other software packages.
The system provides a simple graphical output to assist the user in identifying areas with low accuracy and the process takes only a few seconds to execute. However, obviously more time and processing power is required since two DEMs and an orthophotograph of the area is required. In productivity terms, an experienced user with good stereo vision abilities may not find the technique as useful or beneficial as an inexperienced user. However, for a novice user (of which there are many as software and hardware prices reduce and greater numbers of potential applications are found), the system would greatly speed up productivity and reliability.

The design of the Failure Warning Model means that it could easily be incorporated into an existing DPS. The reliance of direct products of the DPS means that the integration could be seamless, the only noticeable difference for the user being the slight increase in processing time. The nature of the Failure Warning Model also makes it easy to implement into other DPSs.
Chapter 8 Conclusions

This thesis is based upon the accuracy optimization and the detection of erroneous areas in automatically generated DEMs by manipulation of the strategy parameters used in the image matching algorithms. The results of extensive tests on these parameters have been presented along with the development of several techniques for proving the technique. The systems developed have been compared and the status of current research and commercial systems has been presented also.


The manual optimisation process (Section 5.2) provided some very interesting conclusions. Of immediate significance was the time required to carry out the required processing, rendering the approach clearly impracticable in a production environment. For some of the imagery used in the testing program, over 50 DEMs were generated in an attempt to improve the global measures of accuracy such as the r.m.s.e. value. Such a lengthy procedure clearly negates the primary advantage of the move towards full automation in digital photogrammetry, that of speed. The extreme variability of the process also makes the technique difficult to implement with certainty, especially for novice users with little knowledge of the algorithm or the strategy parameter descriptions. In many cases, two independently beneficial parameter changes did not combine beneficially with respect to accuracy, mirroring one of the findings of Smith (1997).

Smith (1997) had carried out extensive testing of the OrthoMAX strategy parameters on two sets of aerial imagery so it was decided to repeat his experiments to identify if the conclusions could be applied to other scales and types of imagery. The results (Section 5.1) showed that the parameter changes recommended by Smith (1997) had
varied success on global measures of accuracy such as r.m.s.e. The tests proved that to define the strategy parameters based upon land-cover type can be unsatisfactory, especially if success is being measured by a global measure. The development of an expert system (the Parameter Interpolation Program - Section 5.4) for prescribing strategy parameter settings based upon comparisons with a knowledge base suggested that improvements in areas of DEMs well suited to matching techniques can be made. However, improvements will not occur across the entire DEM and are focused mainly in the areas well suited to automated DEM generation techniques. The magnitude of these improvements are small for reasons outlined below and the more critical problem remains as to how these improved areas will be detected and isolated. Such a technique still relies on a thorough stereo editing procedure to check the quality of the output.

Above all, the tests showed that unless stereo vision capabilities are available (it is not provided as a standard feature on all photogrammetric systems), check point data are vital if strategy parameters are to be assessed with respect to accuracy. An attempt was made to correlate accuracies with the results from the internal .log file produced by the OrthoMAX software, perhaps facilitating an alternative and much simpler optimisation strategy without the need for external check data. It was shown that such a comparison could not be made, although the internal results were much more predictable than external measures. Tests were also made to examine the accuracy of the points classified as "Good", "Fair" and Poor" by the OrthoMAX algorithm (Section 7.9) and they showed that there was no guarantee that the points classified as "Poor" would have a worse accuracy than the points classified as "Fair".

The most important finding from the manual manipulation tests was the fact that changes to the strategy parameters only affect certain points on the DEM and not the entire DEM (Section 5.5.1). Previous research, most notably Smith (1997) only examined the effects of changing the parameters on global measures of accuracy such as the r.m.s.e. value and ignored what was happening to individual points. This research has established that changes to the parameters has most effect in areas that tend to have large check point errors, areas where the software is having difficulty in reliably estimating the elevation of the object. In areas where the software has worked
well, where check point residual errors are small, changes to the parameters have an insignificant effect. This is an important finding that can be easily explained. In successful areas, there tends to be sufficient image texture and no sudden elevation changes. A clear pair of conjugate points exists for the software to identify, therefore changes to the strategy parameters are not going to change the position of the conjugate points in the image space. So the "correct" pair of points will always be identified despite variations in strategy parameters. In the areas ill-suited to the automated DEM generation technique, clearly identifiable conjugate points will not exist, so changes to the parameters are likely to result in a different pair of points being identified and a subsequent change in the elevation estimate of the object. This is due to the change in the search and acceptance criteria.

This finding is important for a number of reasons. Firstly, it explains the variable success in the manual manipulation process. It will be remembered that in some of the areas, changes to the strategy parameters brought about significant improvements in the r.m.s.e. value, whilst for others, little or no change was reported. It is proposed that this is because in the areas with a significant change in the r.m.s.e. value, at least one of the check points used to define the accuracy was in an area ill-suited to automated DEM generation techniques, either due to low image content, occlusion or large elevation changes. In such areas, changes to the strategy parameters can significantly change the search area and acceptance criterion for the algorithm so the software accepts a different pair of conjugate points. It is these areas that require a large amount of testing to find suitable parameter settings. This thesis has shown that this can be an uncertain process with the user never entirely sure that the "correct" set of conjugate points have been identified. In areas that exhibited little or no change to the r.m.s.e. value, it is suggested that all of the check points lay in areas well suited to automated DEM generation techniques so the changes to the parameters have little effect on the resulting accuracy estimates.

Secondly, this finding has highlighted the problems associated with using global measures of accuracy such as the r.m.s.e. value. Single measures of accuracy can never reflect what is happening spatially across an entire DEM and its use can therefore lead to unrealistic conclusions. Whilst it can identify DEMs with significant
problems if one or more of the check points fall in one of the problematic areas, it is of little use if all of the check points lie in areas well suited to automated techniques. In these areas, the r.m.s.e measure will only reflect the accuracy of these successfully correlated regions.

These tests have showed that the software works well in areas well suited to area based automated correlation techniques. A scenario could easily exist where all of the check points lie in these areas, yet there remain problematic, inaccurate areas in the DEM. When this occurs, any global measure of accuracy is likely to suggest that the DEM generation algorithm has worked well, signified by a "good" accuracy result, not reflecting the problems that may exist within the low accuracy areas. An experienced user may perhaps be able to identify low accuracy areas during stereo editing, but a novice user could quite easily miss them. This will be particularly prevalent in areas with small numbers of check points.

Users of such measures must understand these implications. In a production environment, both the client and the data agency must agree on suitable check point locations and quantities prior to the data generation. A failure to do so may result in inaccurate data being accepted or data being rejected that is not necessarily "beyond repair". This notion is supported by Gwaspari (1996) on the subject of specifications who states that "communication between provider and client is the most essential factor in achieving a successful specification." Li (1991) suggests that "only if the sample size [of the check point data] is increased... can the reliability of the final estimates be improved."

Thirdly, the result has highlighted the need for a thorough stereo checking process to be carried out. It is not enough to rely on check point information only, for reasons presented in the previous paragraphs. Check point information can only be relied on if at least one check point falls in all areas ill suited to the automated techniques that have been employed, and there can be no guarantee that this will be the case. The user always needs to check the entire DEM for spurious results. The results have showed that no amount of manipulation of the strategy parameters can reliably model these areas, so stereo editing will always be required.
It is now being accepted that blunders will occur in such areas. Petrie (1997) states that "failure cases must occur to at least some extent during all automatic DEM and ortho-imaging operations. In areas containing few well-defined features, and exhibiting a lack of contrast and little texture, more severe difficulties can occur. In general, the software used for automated DEM generation works best at medium scales and in areas for which images with good texture are available. At larger scales, difficulties arise from the occluded/dead areas and height discontinuities arising from the presence of high buildings and forests in the areas being mapped. Thus the key to the successful implementation of the whole process is the provision by the software package of the interactive editing facilities needed to correct the inevitable errors in the DEM data." This view is also shared by Heipke (1995) and Autometric, the developers of OrthoMAX, who suggest that it is an "inevitable fact that errors and blunders will occur in the automatic collection process, as they do in all ... measurement processes" (Grafton, 1999).

8.2 The Parameter Interpolation Program

This finding would explain the partial success of the Parameter Interpolation Program. This was a simple expert system that prescribes new strategy parameter settings based upon comparison of the internal results from the DEM generation process with a knowledge base. The results presented from the testing of the system on a range of different data sets showed that when global measures of accuracy such as the r.m.s.e. value were used as an indicator of success, the system worked only on some of the areas. However, when attention was focused upon the areas of the DEM that were well suited to area based automated matching techniques (good image texture, no sudden elevation changes) the system was much more robust and consistently improved the accuracy of these areas.
8.2.1 The Need for Area Classification Systems

The need for area classification systems was another significant finding from this research since it suggests that it is appropriate to recommend parameter changes based upon comparison with some sort of knowledge base only in areas well suited to automated DEM generation techniques. In the other areas, the technique is not suitable. Previous research on the topic (Smith, 1997) suggested that the entire DEM should be used for the comparison with the knowledge base but this thesis has demonstrated that this cannot be the case. In areas well suited to automated techniques, it is debatable as to whether such improvements will warrant the time required to manipulate the parameters, especially if the user cannot be sure of the magnitude of the improvements without check point information. One comment made during a presentation of this work (Gooch and Chandler, 1998) was that larger improvements in the accuracy can be made by improving the bundle adjustment, decreasing the grid spacing or reducing the scanning resolution. The technique can only be used when the ill-suited areas are filtered out from the process and their elevation estimates made separately, either by stereo viewing and manually editing the data or by using a different data collection method such as airborne laser scanning, GPS or ground survey.

The need to filter out ill-suited areas creates a new problem - how can these low accuracy areas be identified? Any parameter manipulation system requires that these areas are identified and their elevation estimates estimated by some other means. At present, stereo viewing remains the only option for users (for many users this is not even a possibility, as stereo viewing is not offered as a standard feature on some digital photogrammetric systems). To an experienced user, this would not be too much of a problem, any blunders in a DEM would be immediately obvious, but to novice users of the technology the task may be daunting. The need to carry out such a task negates many of the benefits of automation and using the Parameter Interpolation Program in the first place as the user would still have to check the entire DEM, reinforcing the need for some sort of quality assessment procedure for DEMs. This is
a view supported by Cooper (1998) who suggests that the development of automated techniques for assessing data quality "lags far behind" automated terrain modelling.

8.3 The Failure Warning Model

The second part of this thesis has addressed the issue of data quality assessment and a completely new technique called the Failure Warning Model (Chapter 6) has been presented that automatically defines such low accuracy areas. This is a completely new approach to identifying low accuracy areas of DEMs, making full use of the actual DEM output from the DPS and is unlike the approaches suggested by Hannah (1981) and Krupnik (1998). The technique was developed within the Spatial Modeler tool of ERDAS Imagine and tested primarily on the ERDAS OrthoMAX digital photogrammetric software.

The output from the Failure Warning Model is presented in an easy to understand graphical format, in the format of a classified monochrome orthophotograph so that any user with access to a printer can obtain a hardcopy version. However, the data can also be viewed on a display screen which would allow colour to be added, easing the identification of failed areas. Full details of the Failure Warning Model can be found in Chapter 6 whilst the results of the tests on a wide range of data sets are presented in Chapter 7.

It can be seen from the results (Chapter 7) that the Failure Warning Model works extremely well on all of the data sets used in the study. The imagery used covered a wide range of photo-scales, image content and data capture devices and it has been shown that the technique worked successfully in all of the scenarios tested. It performs an *a posteriori* analysis of the data generated as opposed to a potentially risky *a priori* analysis of the imagery (as suggested by Krupnik, 1998). This research has shown that it can be very difficult to predict regions in which the DEM generation algorithm will fail, thus rendering *a priori* techniques difficult to implement.
The system was also compared with the limited internal quality assessment made by the OrthoMAX software (Section 7.9) and demonstrated that the Failure Warning Model is significantly better at identifying areas with a low accuracy than the OrthoMAX system. The OrthoMAX internal assessment procedure does successfully identify areas with a good accuracy (denoted "good" in the .stat file) however the points classified as "good" by the software typically form just between 0 and 20% of the DEM, requiring the user to check the remainder. This necessity again negates the advantages brought about by using automated DEM extraction techniques.

The software was also tested on the Zeiss Phodis TS and Virtuozo digital photogrammetric software packages. It was found that the model worked extremely well on the Phodis system and was better at identifying the low accuracy areas of the DEM than the system employed in the Phodis software. The Failure Warning Model required some minor modifications before implementation, but afterwards successfully highlighted the low accuracy areas of the DEM. Unfortunately, it was found that the technique could not be applied to the VirtuoZo software since the DEM generation technique employed in the software was insensitive to variations in the strategy parameters, a prerequisite of the Failure Warning Model. These two results suggest that the approach can be suitable for other systems, but further testing would be required prior to implementation.

The design of the Failure Warning Model is such that it could easily be incorporated into existing photogrammetric software. To maximise efficiency the two input DEMs would be generated by repeating the final RRDS for a DEM, using different strategy parameter settings each time. A simple coarse orthophotograph could also be generated automatically. All of the inputs could therefore be generated automatically without significantly increasing the processing time, facilitating full automation of the process. Coarse orthophotographs of the area suitable for the approach can be generated in a matter of seconds with current hardware configurations.

As Heipke (1999) states; "Care has to be taken, that each automatic step is followed by interactive control, since most of the employed algorithms have only little knowledge about when they work correctly and when they fail." The Failure Warning
Model provides one answer to such calls in current literature for more quality control procedures within modern digital photogrammetric systems (Cooper, 1998). The technique provides an easy to use system with a very simple, visual output - one that can be easily understood by novice users. It requires no stereo viewing capabilities to operate (the quality information currently employed in the OrthoMAX software is overlaid on the stereo-model during stereo editing) and has been tested successfully on a very wide variety of data sets. A quantitative assessment was made of each test and proved that the Failure Warning Model reliably highlights areas with a low accuracy.

8.4 Future Work.

This work has demonstrated one new approach for detecting potentially erroneous areas in automatically generated DEMs. However, the literature review of the subject revealed a number of other techniques and there is a definite need for a performance analysis of these varied systems. Techniques such as Information Loss systems (Huang, in press) could also be incorporated into such technologies. This is a technique for assessing the decrease in DEM accuracy as the grid spacing is increased. The widening user base and acceptance of digital photogrammetry make research in this area of quality assessment vital.

This work has demonstrated that testing of conclusions derived from one digital photogrammetric system need to be tested on other systems before implementation. There are significant algorithmic differences between the packages and future testing should, if possible, make allowances for this. Any testing of error detection systems needs to be implemented on as many different systems as possible.

The dangers of using global measures of accuracy such as the r.m.s.e. value have been outlined, signifying the need for a clear set of guidelines for defining and measuring accuracy. The use of standard test fields with prescribed check point locations could be one solution (as described in Al-Rousan, 1998). The growing development and availability of the internet would make the distribution and
availability of such data technically possible. It is a possible scenario whereby bodies such as OEEPE could maintain and develop such sites, keeping up to date, accurate information available and located in one, central location. OEEPE is carrying out research into suitable methods for defining and measuring DEM accuracy (Cooper, 1998). This is of particular importance for individual projects, many of which will not be accompanied with check point information.

It would be easy for bodies such as OEEPE to make techniques such as the Failure Warning Model available via their web-sites. This would facilitate a thorough testing of the technique by the wider photogrammetric community on a much larger range of data sets including close-range, aerial and satellite imagery.
References


Bibliography


*http://www.odyssey.maine.edu/gisweb/spatdb/acsm/ac94009.html.*


Appendix 1  Example .log file
DEM ID: /dtm/campus_la

NOTE: Linear units are Meter unless noted

User-defined parameters:
X,Y ground spacing: 2.000,2.000 (m)
Minimum threshold: 0.600 (SNR = 1.225)
Noise threshold: 0.400 (SNR = 0.816)
Maximum x-parallax: 5
Minimum template size: 7
Maximum template size: 9
Minimum precision: 0.50
Rejection factor: 1.5
Skip factor: 2
Edge factor: 2.50
Start RRDS: 5
End RRDS: 0
Y-parallax allowance: 0
Resampling (last RRDS): Bilinear
Post-processing: Yes
Band used in correlation: 1

Set, derived, or computed parameters:
Pre-set template resizing:
Initial RRDSs: Yes
Final RRDS: Yes
Coordinate conversions: Yes
Pre-set min curvature: 0.15
Derived thresholds (pixels):
GOOD maximum: 0.17
FAIR maximum: 0.33
POOR maximum: 0.50
Pre-set Z step sizes:
Initial RRDSs: 1.000
Final RRDS: 0.500
Initial height estimate: 62.199

Details for RRDS 5:
Raw pixel spacing: 0.359
Actual pixel spacing: 2.2
Actual grd X,Y spacing: 46412608.026, 76504888.969
Columns, rows, total: 20, 23, 460
Z step size (pixels): 1.0
Z step size (linear units): 20.908
Z range (linear units): 209.077

Details for RRDS 4:
Raw pixel spacing: 0.718
Actual pixel spacing: 2.2
Actual grd X,Y spacing: 23206304.013, 38252444.484
Columns, rows, total: 38, 43, 1634
Z step size (pixels): 1.0
Z step size (linear units): 10.454
Z range (linear units): 104.538

Details for RRDS 3:
Raw pixel spacing: 1.437
Actual pixel spacing: 2.9
Actual grid X,Y spacing: 15470869.342, 25501629.656
Columns, rows, total: 57, 64, 3648
Z step size (pixels): 1.0
Z step size (linear units): 5.227
Z range (linear units): 52.269

Details for RRDS 2:
Raw pixel spacing: 2.873
Z step size (pixels): 1.0
Z step size (linear units): 2.613
Z range (linear units): 26.135

Details for RRDS 1:
Raw pixel spacing: 5.746
Z step size (pixels): 1.0
Z step size (linear units): 1.307
Z range (linear units): 13.067

Details for RRDS 0:
Raw pixel spacing: 11.492
Z step size (pixels): 0.5
Z step size (linear units): 0.327
Z range (linear units): 3.267

Results for RRDS 5:
-------------------
Left image is memory-mapped
Right image is memory-mapped
Collection percentages by status:
   Good: 82.2
   Fair: 0.2
   Poor: 0.0
   Interpolated: 17.6
   Off-image: 0.0
Collection terrain statistics:
   Min, max elevation: -66.347, 150.256
   Average elevation: 59.734
   Standard deviation: 12.550
Postprocessing statistics:
   Percent of points filtered by rejection criteria: 20.1
   Interpolation passes: 1
Post-processed terrain statistics:
   Min, max elevation: 45.027, 80.128
   Average elevation: 60.425
   Standard deviation: 5.792
Automatic collection statistics:
   Templating resizing success:
      Template size, percent: 7, 85.5
      Template size, percent: 9, 14.5
   Percent points adopted: 0.0
   Successful move percent: 0.7
   Failure analysis (percent):
      Off-image: 0.0
      Edge: 27.2
      Precision: 0.0
      Curvature: 29.6
Peak threshold: 43.2
Parallax changes (pixels):
Min, max parallax: -5.3, 4.4
Ave, sigma parallax: 0.3, 0.5
Parallax changes (ground):
Min, max parallax: -110.083, 91.353
Ave, sigma parallax: 5.8, 10.2
Ave, sigma SNR: 2.201, 0.853
Est precisions (pixels)
Min, max precision: 0.20, 0.03
Ave, sigma precision: 0.07, 0.02
Est precisions (ground)
Min, max precision: 4.148, 0.632
Ave, sigma precision: 1.529, 0.441

Results for RRDS 4:
------------------------
Interpolating from previous RRDS
Left image is memory-mapped
Right image is memory-mapped
Collection percentages by status:
Good: 83.1
Fair: 0.4
Poor: 0.0
Interpolated: 16.5
Off-image: 0.0
Collection terrain statistics:
Min, max elevation: -7.609, 152.333
Average elevation: 60.566
Standard deviation: 6.950
Postprocessing statistics:
Percent of points filtered by rejection criteria: 16.6
Interpolation passes: 2
Post-processed terrain statistics:
Min, max elevation: 47.211, 85.311
Average elevation: 60.199
Standard deviation: 4.121
Automatic collection statistics:
Templating resizing success:
Template size, percent: 7, 88.6
Template size, percent: 9, 11.4
Percent points adopted: 0.0
Successful move percent: 0.6
Failure analysis (percent):
Off-image: 0.0
Edge: 33.0
Precision: 0.0
Curvature: 15.2
Peak threshold: 51.9
Parallax changes (pixels):
Min, max parallax: -5.6, 8.7
Ave, sigma parallax: 0.4, 0.6
Parallax changes (ground):
Min, max parallax: -58.353, 90.489
Ave, sigma parallax: 4.3, 5.9
Ave, sigma SNR: 2.349, 1.143
### Results for RRDS 3:

Interpolating from previous RRDS
Left image is memory-mapped
Right image is memory-mapped

Collection percentages by status:
- Good: 88.3
- Fair: 0.2
- Poor: 0.0
- Interpolated: 11.5
- Off-image: 0.0

Collection terrain statistics:
- Min, max elevation: 15.042, 105.356
- Average elevation: 60.285
- Standard deviation: 4.560

Postprocessing statistics:
- Percent of points filtered by rejection criteria: 14.8
- Interpolation passes: 2

Post-processed terrain statistics:
- Min, max elevation: 49.674, 78.081
- Average elevation: 60.240
- Standard deviation: 3.303

Automatic collection statistics:
- Templating resizing success:
  - Template size, percent: 7, 87.4
  - Template size, percent: 9, 12.6
- Percent points adopted: 0.0
- Successful move percent: 1.1
- Failure analysis (percent):
  - Off-image: 0.0
  - Edge: 27.3
  - Precision: 0.0
  - Curvature: 25.4
  - Peak threshold: 47.3

Parallax changes (pixels):
- Min, max parallax: -8.3, 8.7
- Ave, sigma parallax: 0.5, 0.6

Parallax changes (ground):
- Min, max parallax: -43.469, 45.411
- Ave, sigma parallax: 2.4, 3.3
- Ave, sigma SNR: 2.330, 1.044

Est precisions (pixels)
- Min, max precision: 0.31, 0.02
- Ave, sigma precision: 0.07, 0.02

Est precisions (ground)
- Min, max precision: 3.210, 0.173
- Ave, sigma precision: 0.750, 0.225

Points/second this RRDS: 272.3

Points/second this RRDS: 304.0
Results for RRDS 2:
-----------------------------------
Interpolating from previous RRDS
Left image is memory-mapped
Right image is memory-mapped
Collection percentages by status:
  Good: 79.3
  Fair: 0.3
  Poor: 0.0
  Interpolated: 20.4
  Off-image: 0.0
Collection terrain statistics:
  Min, max elevation: 30.090, 88.161
  Average elevation: 60.465
  Standard deviation: 3.659
Postprocessing statistics:
  Percent of points filtered by rejection criteria: 17.1
  Interpolation passes: 3
Post-processed terrain statistics:
  Min, max elevation: 54.918, 78.863
  Average elevation: 60.461
  Standard deviation: 3.286
Automatic collection statistics:
  Templating resizing success:
    Template size, percent: 7, 84.3
    Template size, percent: 9, 15.7
  Percent points adopted: 0.0
  Successful move percent: 0.6
  Failure analysis (percent):
    Off-image: 0.0
    Edge: 13.0
    Precision: 0.0
    Curvature: 25.5
    Peak threshold: 61.5
Parallax changes (pixels):
  Min, max parallax: -9.2, 9.1
  Ave, sigma parallax: 0.5, 0.6
Parallax changes (ground):
  Min, max parallax: -24.117, 23.670
  Ave, sigma parallax: 1.3, 1.7
  Ave, sigma SNR: 2.094, 0.914
Est precisions (pixels)
  Min, max precision: 0.42, 0.02
  Ave, sigma precision: 0.08, 0.02
Est precisions (ground)
  Min, max precision: 1.108, 0.045
  Ave, sigma precision: 0.219, 0.056
Points/second this RRDS: 284.2

Results for RRDS 1:
----------------------
Left image is NOT memory-mapped
Right image is NOT memory-mapped
Collection percentages by status:
  Good: 56.1
  Fair: 0.8
  Poor: 24.1
Interpolated: 19.0
Off-image: 0.0

Collection terrain statistics:
Min, max elevation: 43.208, 78.955
Average elevation: 61.088
Standard deviation: 3.859

Postprocessing statistics:
Percent of points filtered by rejection criteria: 19.6
Interpolation passes: 2

Post-processed terrain statistics:
Min, max elevation: 55.155, 78.189
Average elevation: 60.612
Standard deviation: 3.340

Automatic collection statistics:

Templating resizing success:
Template size, percent: 7, 80.1
Template size, percent: 9, 19.9

Percent points adopted: 24.0
Successful move percent: 2.3

Failure analysis (percent):
Off-image: 0.0
Edge: 4.9
Precision: 0.0
Curvature: 20.3
Peak threshold: 74.7

Parallax changes (pixels):
Min, max parallax: -10.0, 10.0
Ave, sigma parallax: 0.8, 1.1

Parallax changes (ground):
Min, max parallax: -13.067, 13.067
Ave, sigma parallax: 1.1, 1.5
Ave, sigma SNR: 2.021, 0.955

Est precisions (pixels)
Min, max precision: 0.48, 0.02
Ave, sigma precision: 0.10, 0.03

Est precisions (ground)
Min, max precision: 0.633, 0.025
Ave, sigma precision: 0.125, 0.037

Points/second this RRDS: 243.6

Results for RRDS 0:
--------------

Left image is NOT memory-mapped
Right image is NOT memory-mapped

Collection percentages by status:
Good: 4.9
Fair: 36.3
Poor: 22.0
Interpolated: 36.7
Off-image: 0.0

Collection terrain statistics:
Min, max elevation: 52.680, 78.427
Average elevation: 60.609
Standard deviation: 3.486

Postprocessing statistics:
Percent of points filtered by rejection criteria: 23.8
Interpolation passes: 3
Post-processed terrain statistics:
Min, max elevation: 55.306, 78.427
Average elevation: 60.927
Standard deviation: 3.454

Automatic collection statistics:
Templating resizing success:
Template size, percent: 7, 80.9
Template size, percent: 9, 19.1
Percent points adopted: 18.8
Successful move percent: 9.8

Failure analysis (percent):
Off-image: 0.0
Edge: 2.1
Precision: 0.2
Curvature: 31.0
Peak threshold: 66.7

Parallax changes (pixels):
Min, max parallax: -10.0, 10.0
Ave, sigma parallax: 2.3, 2.2

Parallax changes (ground):
Min, max parallax: -3.267, 3.267
Ave, sigma parallax: 0.8, 0.7
Ave, sigma SNR: 1.967, 0.947

Est precisions (pixels)
Min, max precision: 0.50, 0.03
Ave, sigma precision: 0.23, 0.06

Est precisions (ground)
Min, max precision: 0.163, 0.009
Ave, sigma precision: 0.077, 0.021

Points/second this RRDS: 38.2

Timing summary:
Total elapsed time (min): 8.03
Rate of collection (pps): 28.30
Appendix 2 Parameter manipulation results

Appendix 2 provides results from each of the data sets used in this study. For each area, the results of the initial tests (tests a to o detailed in table 5.3) and the manual parameter manipulation tests (section 5.2) are provided. The test numbers for the manual manipulation experiments listed on the top row of each table are prefixed by the letter t. Note that not all of the areas used in the study are presented, but the results presented are typical of the results recorded.

The parameter changes for each of the manual manipulation tests are also included. Note that only the strategy parameters with values different to the default values (listed in table 3.1) are recorded. All other parameters are set at their default values. The imagery and area number is recorded in the bottom left hand corner of each table.
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<th>Parameter Lists</th>
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| Skip Factor       | 2.492 |
| Edge Factor       |       |

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### Parameter Lists

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