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Digital Camera Calibration For Mining Applications

by

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Abstract

This thesis examines the issues related to calibrating digital cameras and lenses, which is an essential prerequisite for the extraction of precise and reliable 3D metric information from 2D images. The techniques used to calibrate a Canon PowerShot A70 camera with 5.4 mm zoom lens and a professional single lens reflex camera Canon EOS 1Ds Mark II with 35 mm, 85 mm, 135 mm and 200 mm prime lenses are described. The test results have demonstrated that a high correlation exists among some interior and exterior orientation parameters. The correlations are dependent on the parameters being adjusted and the network configuration. Not all of the 11 interior orientation parameters are significant for modelling the camera and lens behaviour. The first two coefficients K_1, K_2 would be sufficient to describe the radial distortion effect for most digital cameras. Furthermore, the interior orientation parameters of a digital camera and lens from different calibration tests can change. This work has demonstrated that given a functional model that represents physical effects, a reasonably large number of 3D targets that are well distributed in three-dimensional space, and a highly convergent imaging network, all of the usual parameters can be estimated to reasonable values.

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Lists of Symbols and Abbreviations

B	Base line distance (m)
B_1, B_2	Affinity, non-orthogonality parameters
c	Circle of confusion
C	Principal distance (mm)
CCD	Charge-coupled device
CMOS	Complementary metal oxide semiconductor
D	Depth of field (m)
DLT	Direct linear transform
DTM	Digital terrain model
F	Focal length (mm)
fn	Lens f-number
K_n	Camera rotation about *Z* axis of image *n*
K_1, K_2, K_3, K_4	Radial distortion coefficients
LSE	Least square estimation
MTF	Modulation transfer function
O_n	Camera rotation about *X* axis of image *n*
ORI file	Orientation file
P	Focus distance
P(r)	Decentring distortion profile function
P_1, P_2	Decentring distortion coefficients
PF	The far point of acceptable focus
PN	The near point of acceptable focus
r	Radial distance (mm)
RMS	Root mean square
r_o	2/3 of the maximum of *r* (mm)
Rr	Radius of the smallest resolvable feature for a circular aperture
Sx, *Sy*, *Sz*	Degree of certainty of a set of observations in *x*, *y* and *z* direction (m)
x_0, y_0	Fiducial coordinates of the principal point
X_P,Y_P	Principal point offset
X_n, *Y_n*, *Z_n*	Camera position of image *n*
Δr	Radial lens distortion
δr	Radial displacement of an image point
ω	Camera rotation about *X* axis
Φ	Camera rotation about Y axis
κ	Camera rotation about Z axis

λ	Light wavelength (μm)
δr_x, δr_y	Radial lens distortion components in *x*-direction and *y*-direction
δx, δy	Decentring lens distortion components in *x*-direction and *y*-direction

1 Introduction

Photographs taken with calibrated digital cameras and processed with photogrammetry software can be used to generate accurate 3D digital terrain models of rock surfaces (Birch 2006). These models have many applications in the mining industry including mapping faults and other structures, determining feature coordinates and dip and dip direction, measuring as-built wall angles and bench widths, creating contour maps and cross-sections, and computing volumes (Tannant et al. 2006, Tannant & LeBreton 2007, Tannant et al. 2008). The accuracy of a digital terrain model is intrinsically related to the quality of the camera calibration.

There is no standard for camera calibration and various procedures are suggested in the literature. However, the relative merits of different procedures are poorly documented and there is a need for rigorous yet practical calibration methods that can be used by practitioners in the mining industry. Correlations are known to exist between camera calibration parameters. Such correlations may lead to instabilities in the least square estimation (LSE) process if the calibration network is geometrically weak. To identify systematic errors, two questions need to be addressed: (1) what is the appropriate calibration site configuration and control point distribution and (2) what parameters are needed to model camera distortion based on the combination of the network configuration and physical camera characteristics? Unlike metric cameras, interior orientation parameters of non-metric cameras from different calibration tests may change. The magnitude and influence of changes in interior orientation parameters on three-dimensional measurement needs to be evaluated.

This study examines the appropriate non-metric digital camera calibration procedure to maximize achievable accuracy. The thesis covers the techniques used for camera calibration as well as the field and laboratory calibration tests conducted to assess the stability of camera interior orientation parameters.

1.1 Research Objectives

The overall goal of this research is to develop practical procedures for calibration of cameras and lenses that would be used in mining applications. The research objectives are to:

- Assess internal orientation parameters needed to model non-metric digital camera calibration and evaluate variations by using different parameters
- Explore appropriate camera calibration test site configuration and control target distribution
- Investigate the stability of camera calibration parameters from different calibration tests for the same camera and lens.

Completion of these objectives would help to better understand the influence of imaging system quality, network configuration, control points distribution, and different calibration parameters on the calibration result and measurement accuracy.

1.2 Research Scope

This research involves examining appropriate and time-effective camera calibration procedures and evaluating the stability of the camera calibration parameters based on the results of various laboratory and outdoor calibration tests for Canon digital cameras and lenses. After an extensive literature review on camera calibration techniques used by the photogrammetry community and the computer vision field, four test ranges were purposely built in which a large number of surveyed control targets were well distributed in three-dimensional space. Images of the control targets within the test ranges were captured using a convergent geometry for the cameras. The 3DM CalibCam software package developed by Adam Technology (Birch 2006) was used to process the images and to derive the interior and exterior orientation parameters from the bundle adjustment.

1.3 Thesis Outline

Chapter 2 is a brief literature review on camera calibration approaches from both the photogrammetry and computer vision fields with their merits and limitations. With the objective of examining lessons learnt from past research and development, the focus of this review is upon camera calibration techniques that produce a timely and cost-effective solution to practical camera calibration that could be used for mining applications.

Chapter 3 presents the key considerations when choosing an imaging system for photogrammetric tasks. One prerequisite to reliable calibration is high quality images. The best practice of image capturing and network configuration is also discussed in this chapter.

Chapter 4 describes the process components in the 3DM CalibCam software package. The outcomes from a bundle adjustment report, which can be used to estimate the quality of calibration, is given. This chapter also describes the digital cameras and lenses employed in this study along with the test ranges purposely built for camera calibration tests. Observations during the calibration tests and challenges associated with calibrating long-range lenses in an outdoor environment are presented.

Chapter 5 presents the laboratory and outdoor calibration test results obtained from different calibration tests for both a lower-end Canon PowerShot A70 camera with 5.4 mm zoom lens and a professional single lens reflex (SLR) Canon EOS 1Ds Mark II camera with 35 mm, 85 mm, 135 mm and 200 mm prime lenses. The test results include principal distance, principal point offset, radial and decentring lens distortions, and the affinity and non-orthogonality parameters. The way in which the interior and exterior orientation parameters are correlated is explained. The calibration results determined at different calibration tests for the same camera and lens are also compared.

Finally, the conclusions and recommendations are presented in Chapter 6. Some suggestions for the future research are also included in this chapter.

2 Camera Calibration Review

2.1 Introduction

The fundamental photogrammetric problem is the determination of 1) interior orientation parameters, which describe the internal geometric and optical characteristics of a camera and lens system, and 2) exterior orientation parameters, which define the position and attitude of the perspective centre of the camera with respect to an object space coordinate system at the instant of exposure (McGlone 1989). The purpose of a camera calibration is to determine the interior orientation parameters. The process of evaluation of exterior orientation parameters is known as image resection. Bundle adjustment (Brown 1974) is one of the widely used procedures to solve simultaneously the interior and exterior orientation parameters of the cameras using least squares based on collinearity equations.

Camera calibration has always been an essential prerequisite for the extraction of precise and reliable 3D metric information from 2D images. The reasons why camera calibration is important can be summarized from both photogrammetry and computer vision points of view. First, only through advanced and complete calibration can a highly accurate system performance be expected. It has been reported that the resulting object space positional relative accuracies can surpass 1:1,000,000 in a modern photogrammetric system for industrial measurement (Fraser 1992). Second, camera calibration and orientation parameters favourably facilitate image analysis procedures in the sense that these parameters reduce the size of searching and solution space, and provide more reliable results.

Camera calibration in general consists of three aspects: geometric calibration, resolution determination and radiometric calibration. The main focus is the geometric calibration and the determination of optical resolution. Radiometric aspects are not considered. In computer vision, the determination of exterior orientation parameters is sometimes referred to camera calibration (such as Chen 1990 and Ito 1994, to name a few). For clarification, camera calibration in this thesis is the determination of the interior orientation parameters of the camera and lens system. These include the principal distance, the coordinates of the principal point, radial distortion coefficients, decentring distortion coefficients, affinity and non-orthogonality parameters. Grussenmeyer (2002) presents methods for the determination of the exterior orientation parameters.

Camera calibration has been addressed in photogrammetry research for a long time, starting in the second half of the 19th century, such that in the photogrammetric community it is considered a solved problem. This may be partly correct for metric cameras or professional cameras used in aerial photogrammetry. With the increased use of non-metric or amateur cameras today, all experience shows that camera calibration needs much effort in terms of error handling, network design and system quality control (Gruen 2001). It is worthy of mention that there is no standard for camera calibration. The role of a scientific society such as International Society for Photogrammetry and Remote Sensing (ISPRS) had been clarified as one of making recommendations for camera calibration procedures, but not defining a standard (Clarke 1998).

Today, there are a great number of camera calibration procedures and algorithms available in the photogrammetry and computer vision fields. A series of software packages for different application purposes exists in the market to solve the camera calibration task. In many respects, comprehensive comparison of calibration approaches from the two communities is difficult, since the focus of attention can be so different in each. Whereas a photogrammetric calibration might be designed to support a subsequent object space measurement demanding 1:20,000 accuracy, a calibration requirement for a structure involved in motion measurement application may need to position object points to an accuracy of only, say, 5% of the camera-to-object distance. As an end-user, choosing among the different procedures is not a simple task, especially when accuracy requirement and cost are considered.

This literature review aims to bring together ideas and approaches in camera calibration from both photogrammetry and computer vision. The focus of this review is camera calibration techniques that produce a timely and cost-effective solution for practical mining applications. Some references on camera calibration review are Salvi (2002), Fraser (2001), Clarke (1998), Fryer (1996).

2.2 Camera Calibration

Camera calibration can be divided into two phases: 1) Camera modelling with interior and exterior orientation parameters, and 2) estimation of these parameters with known control points as a calibrating pattern or just geometry properties without any control information.

2.2.1 Camera modelling

Camera modelling is to approximate the physical behaviour of light travelling from object space through the lens to the image sensor by using a set of mathematical equations. The modelling accuracy depends on how good the equations can approximate the real physical behaviour. Linear models and non-linear models exist. The simplest linear models are based on linear transformation between 3D object points and their corresponding 2D image points, such as the direct linear transform (DLT) (Abdel-Aziz & Karara 1971, Hall 1982, Toscani-Faugeras 1986). Linear models are simple and fast, but have low accuracy. In non-linear models, lens radial and decentring distortions are included. Camera interior and exterior orientation parameters are usually obtained through iteration with the constraint of minimizing a determined function. High accuracy can be achieved with non-linear models. However, these techniques require a good initial guess in order to guarantee mathematical convergence.

Combinations of linear and non-linear techniques are two-step techniques. These techniques use a linear optimization to compute an initial approximation for the parameters, after which the parameters are iteratively refined. In this way, the number of iterations is reduced considerably. Moreover, the convergence is nearly guaranteed due to the linear guess obtained in the first step. Some references on these techniques are Tsai (1987), Weng et al. (1992), Wei & Ma (1994), and Heikkilä & Silven (1997).

The main difference among these techniques is the lens distortion modelling, which may influence calibration results. Tsai (1987) considered only k_1 the first term of the radial distortion series, and concluded that the first term of this series is sufficient to model the radial distortion in most of the applications. While Zhang (2000) employed both k_1 and k_2 terms. Lavest et al. (1998) even added k_3 terms. Weng et al. (1992) introduced a thin prism distortion that could be merged into the decentring distortion. Most camera models assume zero skewness, i.e., the angle between x and y image axes is 90º, but Lavest (1998) and Zhang (2000) estimate skewness as a variable. However, the use of more complicated model does not improve the accuracy significantly (Salvi 2002).

2.2.2 Camera calibration methods

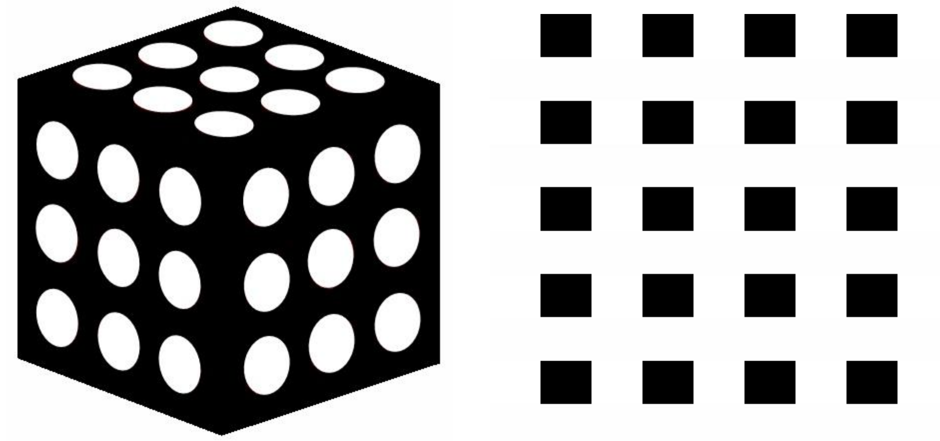
The methods used for the calibration of close range cameras started with an initial mimicking of those used for aerial cameras, in which optical calibration in the form of multi-collimators or a goniometer was involved. One advantage of this laboratory approach is that it can give a better insight into the physical behaviour of each calibration parameter. However, the disadvantages include the need for specialized equipment and facilities, and time-consuming alignment and measurement. These disadvantages limit application of this method for modern close range camera calibration. Since then, various methods have been developed to recover interior and exterior orientation parameters. These methods can be classified according to several different criteria. Here they are divided into two categories: 1) methods using known control points as a calibrating pattern, and 2) methods without any control points.

2.2.2.1 *Methods with known control points*

Stellar camera calibration: Stars whose positions are precisely known can be used as well-defined targets at infinity for camera calibration. Shmid (1974) described the calibration of the Orbigon lens. A disadvantage of this method is the requirement to identify each star and apply corrections for atmospheric refraction and diurnal aberration.

Test-range calibration: A widely used calibration technique is the test-range method. The test-range size depends on the lenses to be calibrated, from a small test-range with dimensions of 0.2 m by 0.2 m elaborately constructed in a laboratory (Faig 1973) to medium size test fields, such as a 3.5 m by 2.2 m test field built by Burnside (1992) and a 5 m square grid on a vertical concrete wall used by Short (1992). A 36 m long by 32 m high building wall was used as permanent test field for camera calibration (Wolf 1975). Within the test-range, a dense array of control targets, which are well-distributed across the entire camera field of view and in depth, were surveyed precisely by theodolite intersections or determined from precise measurements of images taken with metric cameras. The known three-dimensional coordinates of these targets were then used as input for calibration process. Rieke-Zapp et al. (2005) employed a steel frame with the dimension of 2 m long by 2 m wide by 1.5 m deep as indoor test range in which 173 circular target points and seven calibrated scale bars were well distributed in 3D space.

Small elaborate 3D objects or planar objects, such as a cubic object, checkerboard grid or planar pattern printed by a laser printer as illustrated Figure 2.1 are frequently used as a test range in computer vision (Heikkilä & Silven 1996, Zhang 2000). The white circle dots or the corners of black squares are used as control points in the calibration.



(a) Cubic object (b)Planar pattern

Figure 2.1 Examples of calibration test fields used in computer vision

One disadvantage of this calibration method is that it is almost impossible to use the same test-range for both long and short lenses. Specific patterns have to be set up for a given range of focal lengths. Various researchers have devised ‘space frames’ based on interlocking rods and struts that can be simply assembled and placed in the field of view.

The use of control targets in the form of circular or cross shapes is very common for an optical 3D measurement and camera calibration. Various studies indicate that the circular shape is more attractive compared to square or diamond shapes from the point of view of compactness and low maximum error of centroid location due to digitization (Bose & Amir 1990, Ahn et al. 1999). A circle is projected on the image plane as an ellipse if the object target plane and the camera image plane are not parallel to each other. The image coordinates of the centre of the ellipse are determined automatically by the image-processing algorithm, which are then used as the observations for the camera calibration. The accurate determination of the centre of the image ellipse is very important, because the overall measuring performance and the resulting accuracy levels of the 3D measurement are directly linked to the quality of this image point determination. In addition, the size of the control targets is also important. If the target is too small, automatic detection will be impossible. The use of a circular target of approximately 15 pixels radius was recommended by Bose & Amir (1990). Further size increase will not provide significant improvement in performance.

Various experimental studies with the test range calibration method (Fraser 1996, Fryer 1996, Gruen & Beyer 2001, El-Hakim et al. 2003) have shown that the control targets must be well distributed in three dimensions to facilitate the recovery of the principal distance and principal point offset. The combination of multiple images of the test range from several camera stations with a convergent geometric arrangement provide a robust and reliable solution.

2.2.2.2 *Methods without any control points*

Calibration can also be done with purely geometric properties (line coplanarity, parallelism or orthogonality) in the scene, such as line features (e.g. Chen & Tsai 1990 and Echigo 1990) or vanishing points or correspondence points, instead of known coordinates, although not all interior orientation parameters can be determined. These methods usually require measurement of certain variables.

Calibration using straight-line features: The concept of camera calibration using straight line features is not new. Brown developed the plumb line technique to derive radial and decentring distortion using straight lines. The principle behind this method is that all straight lines in object space would project as straight lines on the image plane in a distortion-free camera. Any departures from straightness in the image space are attributed to radial and decentring distortions. By measuring a number of points along each imaged line, a least squares solution can be performed to obtain the lens distortion coefficients. However, the principal distance and principal point offsets cannot be determined from this method.

With automated image processing techniques removing the need for tedious manual measurement of point coordinates along the imaged lines, this method has been employed in close-range camera calibration (Fryer & Brown 1986, Beyer

1987, Habib & Morgan 2003). With a Pulnix CCD camera and Fujinon 25 mm C-mount lens, accuracy results of the order of 1:50,000 had been reported using this technique (Fryer et al. 1994). The effectiveness of this method is largely dependent on the number and distribution of the straight-line images available. It is desirable to have the straight-line images in more than one direction by simply rotating the camera 90º.

Calibration using vanishing points: It is well known that any set of parallel lines that are not parallel to the image plane will converge to a vanishing point by perspective projection, as demonstrated in Figure 2.2. The vanishing point (or vanishing line) has been well used as important information for determining exterior orientation parameters (Chen et al. 1989, Chen & Jiang 1991).

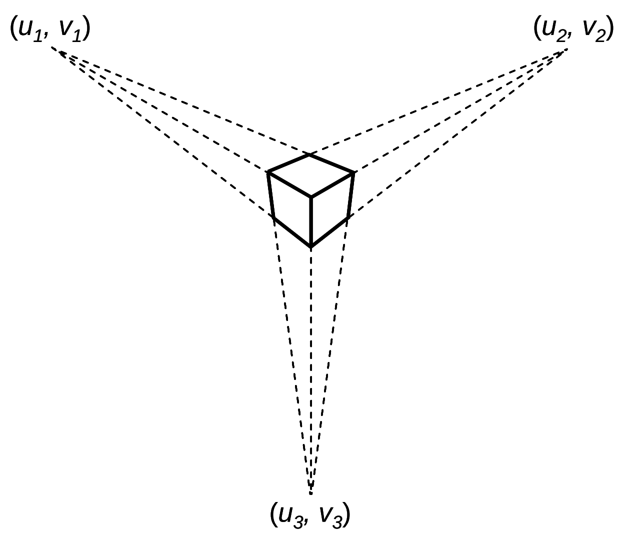


Figure 2.2 Vanishing points on image plane

It is shown in Caprile et al. (1990) that the focal length and principal point can be recovered from three vanishing points associated with three mutually perpendicular planes of a single image of a cube. In fact, the orthocentre of the triangle formed by these vanishing points represents the principal point (Figure 2.3). By using this principal point and two vanishing points, the focal length can be calculated. In Wang and Tsai (1991), a hexagon is employed as the calibration target to generate a vanishing line, and the exterior orientation parameters and focal length can be solved analytically. The accuracy of this method depends on the exact localization of vanishing points and on the error propagation in the estimate of rotation and translation. Due to image processing errors and camera distortion, the projected lines of parallel edges of the cube may not intersect at a point, as shown in Figure 2.4.

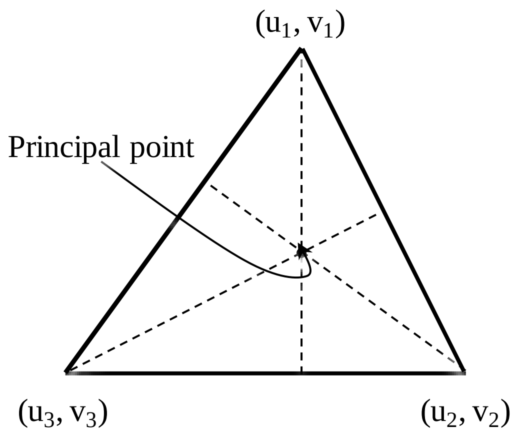


Figure 2.3 Vanishing points and principal point on image plane

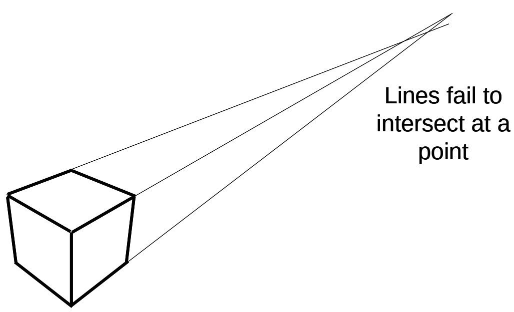


Figure 2.4 Mis-intersection of parallel edges of a cube

The main practical advantage of this technique over other approaches requiring iterative computation is its simplicity. By assuming some of the interior orientation parameters to be zero or known, the number of degrees of freedom of the calibration matrix is reduced. This also reduces the calibration complexity and enhances the efficiency. However, as discussed above, none of the lens distortions are incorporated in this approach. This technique may be adequate for applications in which the desired accuracy is not high, such as unmanned vehicle guidance, object recognition, and scene analysis.

Self-calibration using corresponding points: Brown (1989) discussed the criteria required for a successful self-calibration: 1) a single camera, of which the interior geometry must remain stable during the measurement process, 2) at least three images of the interested object, at least one image must have a roll angle that is significantly different from the others, 3) the photogrammetric network must be strong and exercise a high degree of convergence, and 4) a relatively large number of well distributed points should be used. Given these requirements, Brown commented "a satisfactory calibration of the camera can be accomplished as an integral part of the triangulation without the need for control of any kind".

Maybank & Faugeras (1992) described in detail the link between camera calibration and the epipolar transformation. The epipolar transformation is estimated from point correspondences among images taken from different points of view. No further information about the arrangement of camera stations or about the shapes of surfaces in the field of view is required. This ground-breaking paper showed that camera self calibration is theoretically and practically feasible without the aid of calibration pattern or control points. The method is applicable provided the mapping from space to the points of the image is projective linear. The problem of rotating camera and zooming lens has also been studied by Hartley (1997) and Agapito et al. (1999). With this method, usually only focal length is determined while lens distortion and other internal parameters are neglected or assumed known. Some minimal assumptions include zero skew (rectangular pixels), or square pixels, known pixel aspect ratio, and known principal point.

While this method is very flexible, it is not yet mature (Bougnoux 1998). Due to the difficulty in initialization (Fusiello 2000), the results tend to be unstable. As shown by Sturm (1997), this method can be problematic with certain critical configuration of camera stations, where the arrangement of the camera stations is not generally sufficient to allow for the recovery of calibration parameters and an ambiguity remains in the 3D reconstruction.

2.2.3 Lens distortion

One of objectives of camera calibration is to determine the geometric parameters of a lens-camera system. The reality of imperfectly constructed lenses means aberrations or deviations from the fundamental physical laws of optics must be considered, even though the deviations may be ignored for applications requiring only a low accuracy. Aberrations can be divided into two categories: 1) those that reduce image quality, and 2) those that alter the location of the image (Fryer 1996). Among various aberrations, lens distortions do not influence the image quality, but have significant impact on image geometry (Slama 1980). The detection and details of radial and decentring lens distortions concern photogrammerists, especially when inexpensive wide-angle lenses are used.

2.2.3.1 *Radial distortion*

As shown in Figure 2.5, if the image of an off-axis target is displaced radially either closer to (a") or farther from (a') the principal point, the variation Δr is interpreted as radial lens distortion (Fryer 1996). A common cause of distortion is the introduction of an aperture ring in a system of (thin) lenses (Jenkins & White 1976 and Hecht 1998).

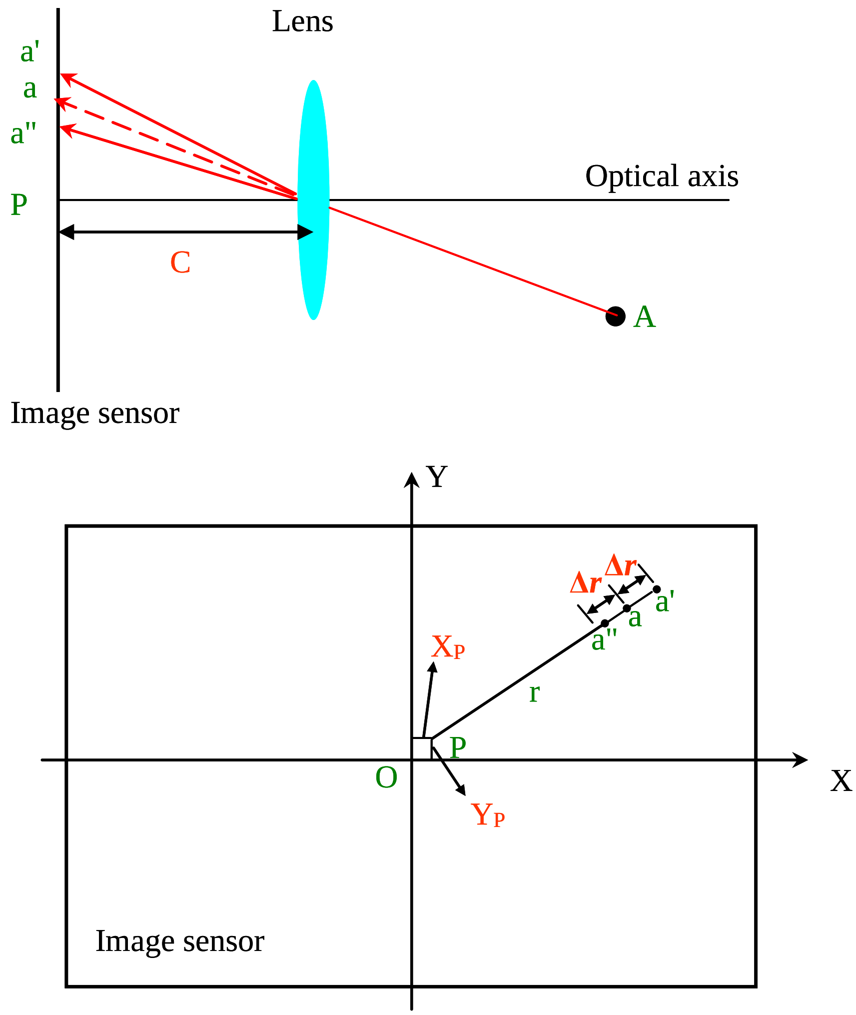


Figure 2.5 Geometry of radial distortion on the image plane

There are two major types of radial distortion (Slama 1980). When image points get displaced from their desired location to a position closer to the optical axis (negative displacement), barrel distortion occurs (Figure 2.6 (a)). Alternatively, image points can get displaced to a position further away from the optical axis (positive displacement), in this case pincushion distortion occurs (Figure 2.6 (b)).

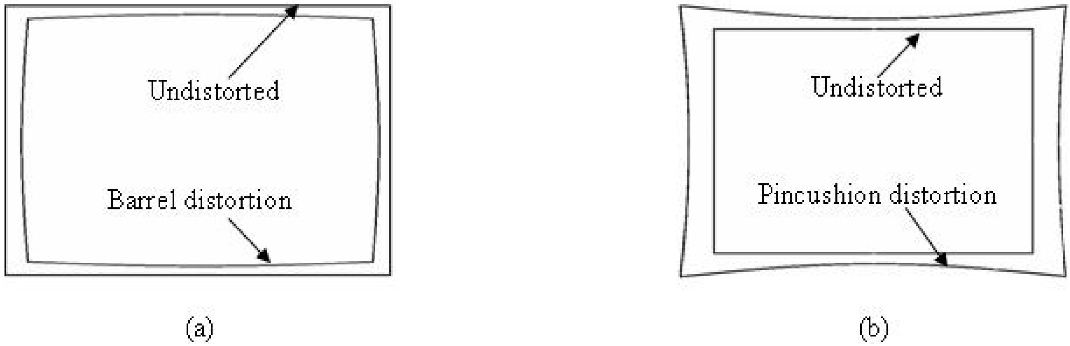


Figure 2.6 Barrel and pincushion distortion

A mixture of both types, sometimes referred to as 'moustache' distortion, is less common but not rare. It starts out as barrel distortion close to the image centre and gradually turns into pincushion distortion towards the image periphery. It is observed with certain retrofocus lenses, also more recently on large range zooms like the 18-200mm VR lens from Nikon.

Radial distortion is mapped relative to the principal point and is a function of the radial distance. It is usually expressed in Gaussian form as a polynomial function of the radial distance from the point of symmetry, which usually coincides with the principal point:

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + \ldots \qquad 2.1$$

where δr is the radial displacement of an image point, $r^2 = (x - x_0)^2 + (y - y_0)^2$, (x, y) are the fiducial co-ordinates of the image point, (x_0, y_0) are the fiducial co-ordinates of the principal point, and K_1, K_2, and K_3 are coefficients whose values depend upon the camera focal setting. The distortion δr is usually resolved into two components:

$$\begin{aligned} \delta r_x &= \delta r(x - x_0)/r \\ \delta r_y &= \delta r(y - y_0)/r \end{aligned} \qquad 2.2$$

Different software use different equations to calculate radial distortion that also influences the value of the principal distance. Adam Technology software and Australis software use the Gaussian lens distortion equation:

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + K_4 r^9 \tag{2.3}$$

Other programs such as DPAPro (Aicon 2009), PHIDIAS (Phocad 2006), Phoxy (Geodelta 2006) apply the balanced form for modeling the radial distortion:

$$\delta r = K_1 r(r^2 - r_0^2) + K_2 r(r^4 - r_0^4) + \cdots \tag{2.4}$$

The balanced form has a second zero distortion at a selected radial distance r_o, usually at approximately 2/3 of the maximum of r.

2.2.3.2 *Decentring distortion*

Decentring distortion is the displacement of a point in the image caused by misalignment of the components of the lens (Brown 1966, Fryer & Brown 1986), as shown in Figure 2.7. The displacement is described by two polynomials, one for the displacement in the direction of the x-fiducial axis and the other for displacement in the y-direction:

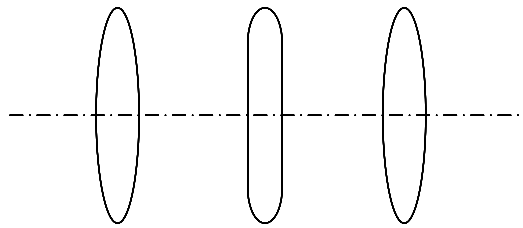
$$\begin{aligned} \delta x &= P_1[r^2 + 2(x - x_0)^2] + 2P_2(x - x_0)(y - y_0) \\ \delta y &= P_2[r^2 + 2(y - y_0)^2] + 2P_1(x - x_0)(y - y_0) \end{aligned} \tag{2.5}$$

where P_1 and P_2 are coefficients whose values depend on the camera focal setting. The other terms are the same as those above.

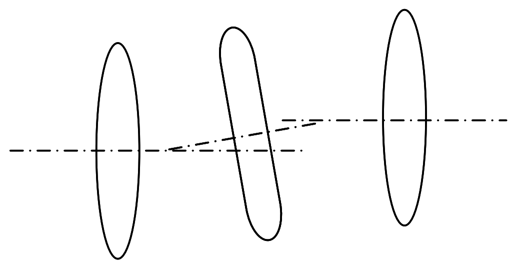
To make a graphical representation of decentring distortion, the profile function *P(r)* is employed such that

$$P(r) = (P_1^2 + P_2^2)^{1/2} r^2 \tag{2.6}$$

where the parameters P_1 and P_2 refer to values at infinity focus. It is worth pointing out that the $P(r)$ is not the square root of the sum of δx^2 and δy^2.



(a) Perfectly centered lens



(b) Decentered lens

Figure 2.7 scheme of lens element misalignment

2.3 Evaluation of Camera Calibration Results

A successful bundle adjustment does not guarantee camera calibration results are accurate and valid. It is well known that correlation or projective coupling exists between calibration parameters derived from bundle adjustment, which can lead to unstable calibration results under certain weak geometric configurations. Therefore, calibration result assessment must be performed to ensure that the results are not contaminated by bad measurement or assumptions. A first step is often a qualitative evaluation, in which graphical representation of the adjustment's output, such as image residuals, is examined in order to understand broad trends and to catch obviously bad inputs (Edward et al. 2001). Then statistical analysis is performed to evaluate the bundle adjustment results from three different aspects, the precision, the accuracy, and the reliability.

There are many factors that affect the accuracy of calibration results. Some of the major factors are 1) camera mathematical model used, 2) accuracy of control points, 3) pixel coordinate noise when image points are digitized (termed segmentation in computer vision), 4) geometric configuration of the set-up or photogrammetric network, which is mainly based on past experience, and 5) redundancy of the observation.

2.4 Summary

From the foregoing discussion, the following comments can be made.

- Various camera calibration methods have been developed, and various software packages are commercially available on the market. Depending on the desired accuracy, there are 1) linear models without modelling the lens distortion, and 2) non-linear models that accurately model the lens and are useful for applications where greater precision is required.
- The test-range method with known 3D control points as a calibrating pattern is still popular in both photogrammetry and computer vision community. To achieve high accuracy and reliable results, favourable image acquisition geometry is required.
- While self-calibration without any control points is very flexible, it can be problematic with certain critical camera station network configuration, where the arrangement of the camera stations is not generally sufficient to allow for the recovery of calibration parameters and an ambiguity remains in the 3D reconstruction.
- A successful bundle adjustment does not guarantee camera calibration results are accurate and valid. Calibration result assessment must be performed by qualitative evaluation and statistical analysis from three different aspects, the precision, the accuracy, and the reliability.

3 Imaging System and Image Capturing

3.1 Imaging System

The fundamental choice in any photogrammetric application is the image acquisition system, i.e., the camera and lenses. The major decision in camera selection is between film and digital cameras. It can be seen that a digital imaging system is preferred. However, the choice of a digital imaging system is complex since the technology incorporated in a digital camera is complex. New cameras are being released regularly and the price of cameras changes as the technology evolves. This section is not intended to be an exhaustive review of the digital cameras available to a prospective purchaser, nor can it be. The objective of preparing this section is to address some of the issues that must be considered when choosing a digital camera in the hope of making the decision 'easier'.

The consideration of an imaging system should take account 1) the specific tasks for which the camera is to be used and 2) the camera cost and stability of the interior orientation, and 3) the quality of the lens. A camera purchased for one task and used for a task with different technical requirements is likely to result in dissatisfaction on the part of the camera user and the end user of the images. The spatial, spectral, and radiometric resolution of the sensor chip as well as the dynamic range and the noise characteristics are important (Seiz et al. 2002).

3.1.1 Application task consideration

Different applications of close range photogrammetry demand different levels of measurement accuracy. Accuracy requirements dictate the selection of camera and lens system and calibration techniques. For example, industrial measurement of 1:100,000 or better demands the use of either large format metric film cameras or high-resolution, large image format digital cameras coupled with image measurement precision at levels approaching 1/50 of a pixel (Fraser & Edmundson 2000). In addition, to achieve high accuracy, a nonlinear calibration model should be used for the camera and lens calibration. In contrast, the requirements for medical measurements in terms of accuracy, precision and resolution are generally low. Applications in the mining industry such as geological mapping or volume measurements can be satisfactorily achieved with a measurement accuracy of about 1:10,000. However, measurement of small rock movements might require measurement accuracy in the order of 1:100,000. Therefore, the focus of a lot research in close range photogrammetry has been on how to deliver data effectively with measurement accuracy appropriate to the application requirements.

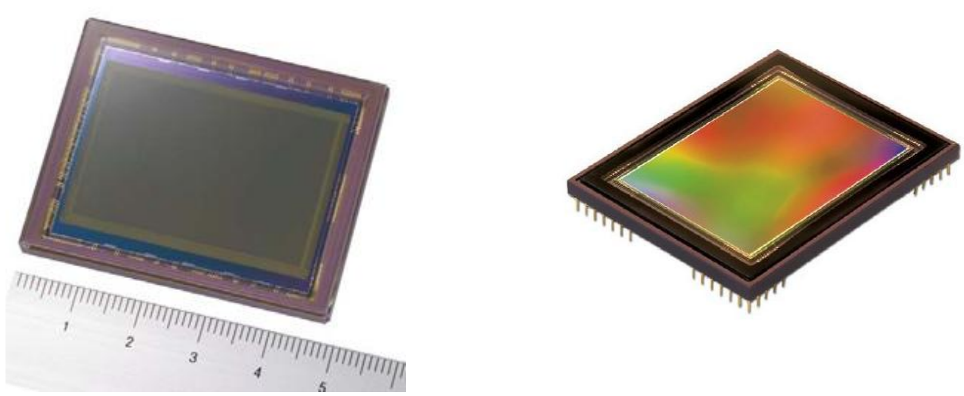
3.1.2 Metric or non-metric camera

Cameras used in photogrammetry are either metric or non-metric. A camera that has been designed and constructed to be used for photogrammetry is a metric camera. Traditionally such designs have included specific features to ensure close conformance to the perspective projection model. The lens is designed to ensure that the principal distance is constant for all incident rays for a given focal setting. For a metric cameras, the manufacturer provides a calibration certificate for each metric camera produced, which includes calibrated principal distance C corresponding to specific focal settings, and the co-ordinates (X_P, Y_P) of the principal point. Usually the principal distance value is quoted to the nearest 10 μm. Metric camera construction methods usually ensure that the principal point offset X_P, Y_P are no more than a few μm. Even though a metric camera is designed to produce imaging geometry that is a realization of the perspective centre projection, imperfections are inevitable so calibration is necessary. Moreover, calibrated values vary with camera usage, so regular re-calibration should be routine.

A metric camera often has a flat plate in front of the emulsion with reseau marks to help detect and correct for film deformation. The frame of the metric camera may also have fiducial marks in the corners or the midpoints of the side that can be used to locate the principal point (the optical centre of the image). Unlike metric cameras, non-metric cameras are typically of a consumer grade quality and do not have these markings or documented distortion characteristics. Non-metric cameras are inexpensive to buy, use and maintain. In addition, they are robust, mobile and require a minimum of accessories. In short, they are ideal for rapid, medium to low accuracy work. The availability of non-metric cameras may be appealing for low accuracy, low cost applications. However, in contrast with a metric camera, a non-metric camera lacks a stable inner orientation, fiducial reference system and standard method of calibration (Short 1992).

3.1.3 CCD or CMOS sensor

There are two main semiconductor technologies used in a digital imaging system: charge-coupled device (CCD) and complementary metal oxide semiconductor (CMOS). Both CCD and CMOS sensors (shown in Figure 3.1) are pixelated metal oxide semiconductors. They accumulate signal charge in each pixel proportional to the local illumination intensity, serving a spatial sampling function. When exposure is complete, a CCD transfers each pixel's charge packet sequentially to a common output structure, which converts the charge to a voltage, buffers it and sends it off-chip. In a CMOS imager, the charge-to-voltage conversion takes place in each pixel. This difference in readout techniques has significant implications for sensor architecture, capabilities and limitations.



(a) (b)

Figure 3.1 (a) Sony's 24.8 megapixels CMOS sensor (source: Sony) (b) Dalsa 33 megapixels full-frame CCD image sensor (source: Dalsa)

Eight attributes characterize image sensor performance:

- Responsivity: the amount of signal the sensor delivers per unit of input optical energy.
- Dynamic range: the ratio of a pixel's saturation level to its signal threshold.
- Uniformity: the consistency of response for different pixels under identical illumination conditions.
- Shuttering: the ability to start and stop exposure arbitrarily.
- Speed: an area in which CMOS arguably has the advantage over CCDs because all camera functions can be placed on the image sensor.
- Windowing: one unique capability of CMOS technology is the ability to read out a portion of the image sensor. This is an enabling capability for CMOS imagers in some applications, such as high-temporal precision object tracking in a sub region of an image. CCDs generally have limited abilities in this aspect.
- Antiblooming: the ability to gracefully drain localized overexposure without compromising the rest of the image in the sensor. CMOS generally has natural blooming immunity. CCDs, on the other hand, require specific engineering to achieve this capability.
- Biasing and clocking: CMOS imagers have a clear edge in this regard.

The sensor resolution or geometric resolution can be considered from two perspectives: 1) the image resolution and 2) the external or object resolution. The image resolution is related to the size and number of sensor pixels. This is a function of the physical size of the sensor array within the camera, which may be specified in terms of the horizontal and vertical pixels or may be specified as the total number of pixels. Until recently, the arrays of the sensor have been rectangular in arrangement. The external or object resolution depends on the dimension of an object being imaged by one sensor pixel. The focal length of the lens and the pixel size (spacing) determine the instantaneous angular field of view of each pixel (sometimes termed the geometric resolution). The instantaneous field of view is directly related to the size of a pixel in the object space by the range to the object being imaged.

3.1.4 Lens quality and signal to noise ratio

The resolution of a lens is a measure of the capability of the lens to resolve fine detail. It is commonly expressed in terms of line pairs per millimetre and specifies the highest number of line pairs that can be discerned on the focal plane. A more technical specification of resolution is embodied in the modulation transfer function (MTF) that is the optical analogue of the time domain frequency transfer function of an electronic system. It is a complex specification that is usually only provided by makers of more expensive lenses. In summary, the higher the value of the MTF at high spatial frequencies (analogous to line pairs per mm) the better the image quality is likely to be when all other parameters are equal. In terms of lens distortion, in general, the wider the field of view the greater the distortion and the more expensive the lens, the less the distortion (usually).

All electric systems such as digital cameras experience noise. Noise may corrupt images and other signals. Low signal to noise ratios cause poor quality images and will introduce unacceptable artefacts into the image. Therefore signal to noise ratios should be the maximum possible. Signal to noise ratios are dependent on the sensitivity of the sensor, which is in many cases determined by the size of the sensor. Extremely small image pixels on the sensor will have higher noise than large pixels. For example, a sensor with 6 μm by 6 μm pixels will have approximately twice the noise compared to a sensor with 12 μm by 12 μm pixels. ‘Noise’ may also be caused by ‘leakage’ of energy between adjacent sensors and lag in the sensor. Many digital cameras provide facilities to adjust the speed rating of the sensor, the equivalent ISO rating. If noise is evident in a digital image, the noise may be reduced by taking the photograph with a lower ISO setting. This will reduce the noise in many cases but will require a longer exposure time and thus, possibly, the use of a tripod if the available light is not adequate.

Lens quality and sensor resolution combine to determine the overall ‘quality’ of the image. A large number of very small pixels combined with a poor lens will result in an image where the quality may not as good as that achieved with a smaller number of larger pixels and a better quality lens.

Once the image acquisition system has been selected, attention must be given to various photographic matters, such as adequate stereoscopic overlap, appropriate camera-to-object distance and suitable base-to-object distance ratio (all of which influence the achievable accuracy and precision), which depend on object size, the precision of measurement required, and constraints on the camera and/or the object position.

3.2 Network Configuration

The calibration network configuration defines the imaging geometry (imaging locations and orientations), and determines the quality of the calibration. In order to optimise the accuracy and reliability of 3D point measurement, particular attention must be given to the design of the network configuration. Unfortunately, in many applications, the network design phase is not considered or is impossible to apply in the actual object setting, leading to less than ideal imaging geometry. Therefore, it is important to undertake the network configuration design based on the constraints of the test field.

One of the network configuration for camera calibration recommended by Adam Technology is to set up the camera stations in a triangular shape, as illustrated in Figure 3.2. There are three stations on the base of the triangle (Station 4, 5, and 6). The next two stations are set in the middle of the triangle (Station 2 and 3) and last station is set on the last corner of the triangle (Station 1). At least two images are taken at each camera station with every second image of each station rotated 90° when images are taken.

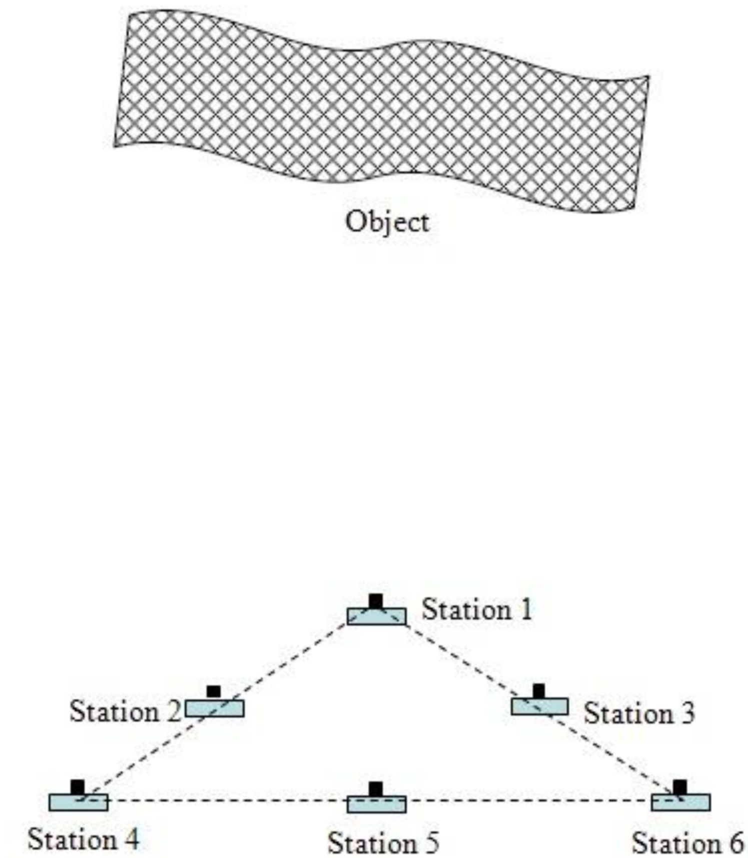


Figure 3.2 Plan view of camera calibration network configuration

The network configuration adopted in the *Australis* photogrammetric software package (Photometrix 2004) consists of six camera stations at different elevations, two camera stations aimed at the centre of the object interested, and two at both left-hand side and right-hand side. A minimum of six convergent images with four images rotated 90° (3 clockwise and 1 anti-clockwise) are absolutely necessary for camera calibration. This imaging network arrangement is particularly useful to allow the recovery of the correct focal length if a flat test field is employed for camera calibration.

There are some general rules to follow in terms of network configuration. Different studies in close range photogrammetry (including Clarke et al. 1998; Fraser 2001; Gruen & Beyer 2001; El-Hakim et al. 2003) confirm that 1) calibration should be done with convergent images rather than images with parallel optical axes, 2) the depth accuracy of a network increases with an increase of the ratio of the distance between camera stations (base line B) to the average object distance (depth D), but the image-matching will be compromised with an increase of B:D ratio due to the fact that left camera is viewing a different part of an object compared to that of the right camera, 3) imaging geometry should be arranged to allow as many control points as possible to appear in the images taken, and 4) at least two or three images should be rotated by 90 degrees to allow the recovery of the principal point, that is, to break any projective coupling between the principal point offset and the camera station orientation, and to provide a different variation of scale within the image.

3.3 Control Target Network

Although it is possible to complete a bundle adjustment without any control targets, it is still recommended to have visible control as this allows the bundle adjustment to accurately determine focal lengths. The minimum number of control targets depends on how many interior and exterior orientation unknowns need to be determined and what calibration model is used. For example, at least three control targets or camera stations are required in 3DM CalibCam to determine the 11 unknown interior parameters. Having more control targets is strongly recommended as this allows the bundle adjustment to compensate and recover from errors. A well distributed network of control targets in 3D space is favourable. Any control targets must be stable and clearly visible and facing directly to the camera without obstruction.

3.4 Camera Settings

To obtain high accuracy and reliability, photographs must be of the highest quality. The following are some main considerations in practice for good photography.

3.4.1 Lens and lens aperture

Real lenses do not focus all rays perfectly even under the best of conditions. As shown in Figure 3.3, nonparaxial rays that proceed from a given object point do not all intersect at precisely the same point after they are refracted by a lens. Instead, the rays converge within a circle of minimum radius, called the circle of least confusion. Note that decreasing the size of the lens aperture cuts off the larger-angle rays, thus decreasing spherical aberration.

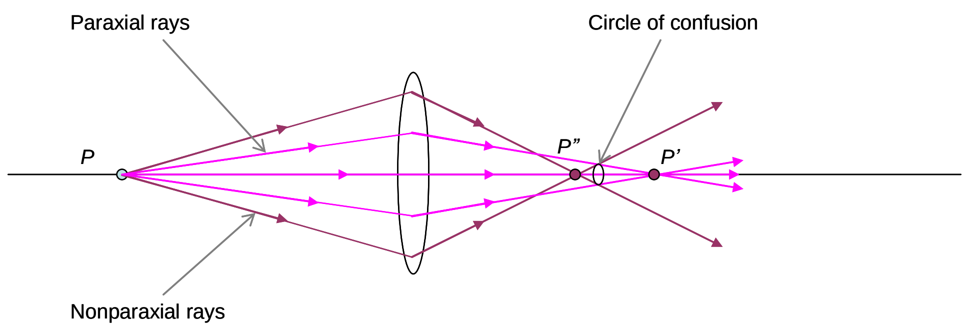


Figure 3.3 Circle of confusion due to spherical aberration for a lens

The smaller the circle of confusion, the sharper the image is. Also the smaller the circle of confusion, the better accuracy is. However, the smallest size for the image circle of confusion is limited by other factors, such as pixel size of the image sensor and lens diffraction. Diffraction limits the resolution of pictures. Imagine when light from a point source passes through a small circular aperture, it does not produce a bright dot as an image, but rather a diffuse circular disc known as an Airy's disc surrounded by much fainter concentric circular rings, as shown in Figure 3.4.

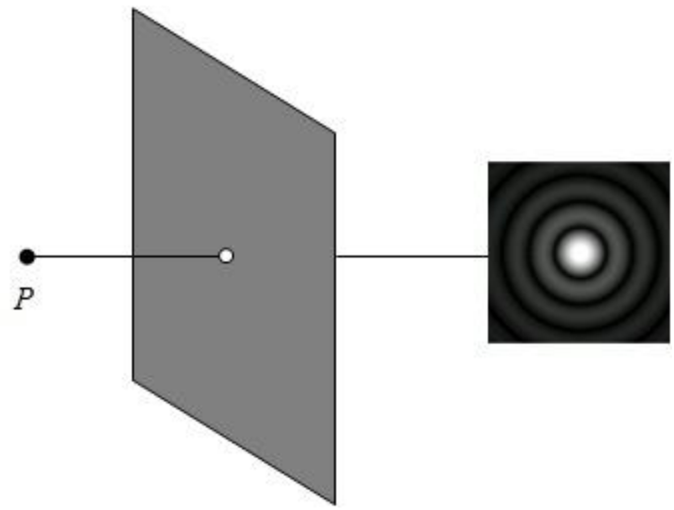


Figure 3.4 Airy's disc

Based on the Airy disc formula, the radius of the smallest resolvable feature for a circular aperture is given by

$$R_r \approx 1.22 * \lambda * fn \qquad 3.1$$

where λ = light wavelength (e.g. 0.55 μm) and *fn* = lens *f*-number (e.g. f/8)

For example, with $\lambda = 0.55$ μm and $f/8$, the radius of the smallest resolvable feature is about 5.4 μm (close to a typical pixel size). In other words, the diameter of the smallest resolvable feature is about 2 pixels. For digital sensors, the circle of confusion cannot be smaller than the physical size of two pixels (image element). For Canon EOS 1Ds Mark II, the circle of confusion should not be smaller than 14.21 μm, say 15 μm. Similar effects occur with film emulsions since the grain size determines the size of an individual image element. The typical "graininess" of film varies from 4 to 18 μm.

With an average wavelength of visible light of about 0.55 μm, diffractions under different nominal f/stops are listed in Table 3.1.

Table 3.1 Diffraction under different nominal f/stops with $\lambda = 0.55$ µm

Nominal f/stop	Diffraction (µm)
2.0	2.7
2.8	3.8
4.0	5.4
5.6	7.6
8.0	10.7
11.0	15.2
16.0	21.5
22.0	30.4

To ensure that diffraction is not greater than the desired circle of confusion (say 15 µm), the f/stop should not go down to f/11.0 as shown in Figure 3.5.

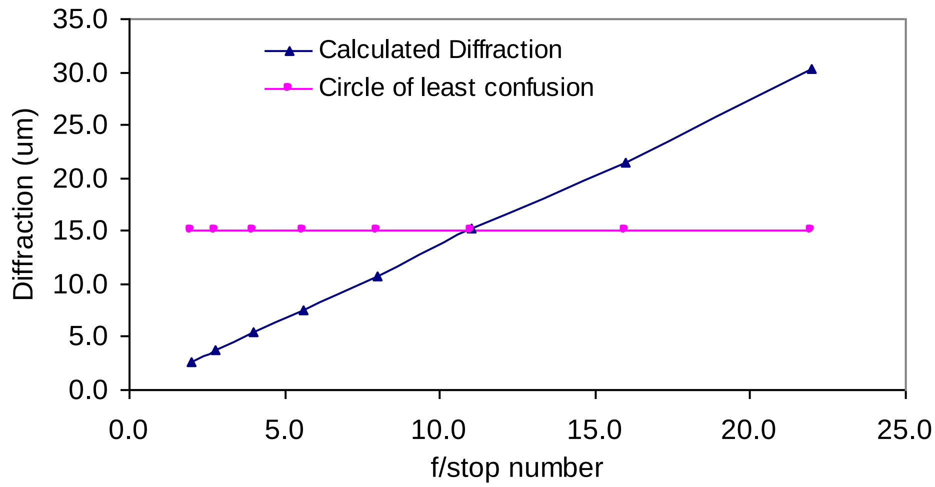


Figure 3.5 Diffraction under different nominal f/stop number

To summarize the above discussion, at larger apertures (e.g. f/2), the image will lose sharpness due to lens aberrations, while at smaller apertures (e.g. f/16), the image will lose sharpness due to diffraction. In most practical cases, an aperture setting of f/8 will result in the sharpest images with almost all lenses.

3.4.2 Focus

For field applications, the camera lens usually needs to be focused at infinity. Unfortunately it is not possible to simply rotate the focal ring all the way to the stop and leave it there because lenses are designed to work in a wide range of atmospheric conditions. The maximum setting is actually slightly “beyond” infinity in normal conditions, making the image slightly blurred. The best way to focus at infinity is to point the camera at something very far away (e.g. clouds, distant mountains, etc.) and then use the auto-focus function. Then, turn the auto-focus off. Ensure that the manual focus is not touched when subsequent photos are taken.

3.4.3 Depth of field

Generally, depth of field is not a problem for aerial photogrammetry due to the large object distances involved, but it must be considered for close-range photogrammetry. For any given focus setting, there exist near and far points, P_N and P_F, where the amount of blur reaches unacceptable amounts. The range of distance between the near and far points is referred to as the depth of field for that focus setting, as shown in Figure 3.6.

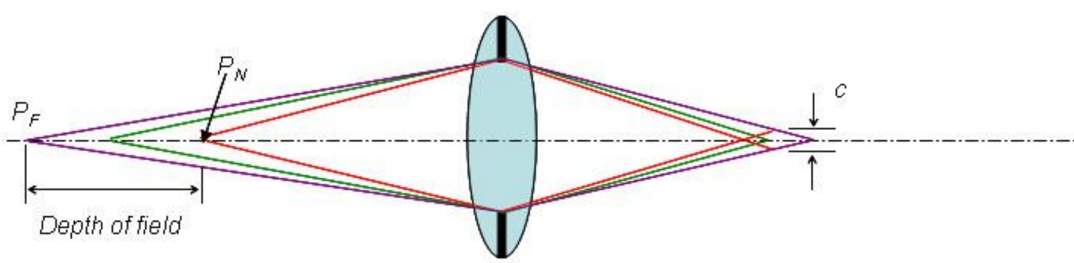


Figure 3.6 Depth of field

The depth of field is a function of the lens focus setting, the lens aperture, and the amount of blur acceptable or circle of confusion. The near and far points of acceptable focus, P_N and P_F, can be calculated for a given focus distance P, circle of confusion c, aperture fn, and focal length F using:

$$P_N = \frac{P}{1+(P-F)*c*\frac{fn}{F^2}}$$
$$P_F = \frac{P}{1-(P-F)*c*\frac{fn}{F^2}} \qquad 3.2$$

By setting the denominator of the equation for P_F to zero, so that P_F goes to infinity, and then solving for P, we obtain the hyperfocal distance P_H.

$$P_H = \frac{F^2}{c*fn} + F \qquad 3.3$$

Given a circle of confusion of 15 μm, and setting P_F to infinity, the minimum distances between camera and object of interest for different Canon EF lenses are listed in Table 3.2. For example, a camera with an 85 mm lens should be set up at least 60.3 m away from the object of interest, in order to get sharp image while setting the lens focus at infinity.

Table 3.2 Depth of field for Canon EF lenses with circle of confusion 15 μm

Focal Length f (mm)	Distance P (m)	Hyperfocal Distance P_H (m)	Near Point in Focus P_N (m)	Far Point in Focus P_F (m)
24	4.8	4.8	2.4	Infinity
35	10.2	10.2	5.1	
85	60.3	60.2	30.2	
135	152.1	151.9	76.0	
200	333.6	333.3	166.8	

By following the above recommended camera settings, good quality images with good texture and less noise can be achieved. This helps the image matching process and helps produces a high accuracy camera calibration.

Last but not least, always remember to turn off the auto-rotate function when taking images. Nowadays cameras come with an auto-rotate function that lets the user enjoy photos in the right orientation. 3DM CalibCam software requires the images to be in exactly the same orientation as they were when the image sensor ‘saw’ them. The software assumes the images are already in the correct orientation when they are loaded into the software. The problem with auto-rotation is that the calibration applies to images as seen by the image sensor. Once the image has been rotated, the relationship between calibration and image is broken.

3.5 Summary

The general procedure essential for a successful camera calibration is shown in Figure 3.7. This flow chart shows a progression from planning the calibration to practical image capturing to final calibration result.

Some key considerations for camera calibration are: 1) the quality of imaging system (image sensor resolution and lens quality) influences the accuracy of camera calibration and computed object coordinates, 2) high quality photographs are an essential requirement for reliable and accurate camera calibration and object measurement, 3) a calibration is reliable only when the network configuration is favourable, with highly convergent images and a large number of spatially well distributed control targets, and 4) at least two or three images should be rotated by 90° to allow the recovery of the principal point.

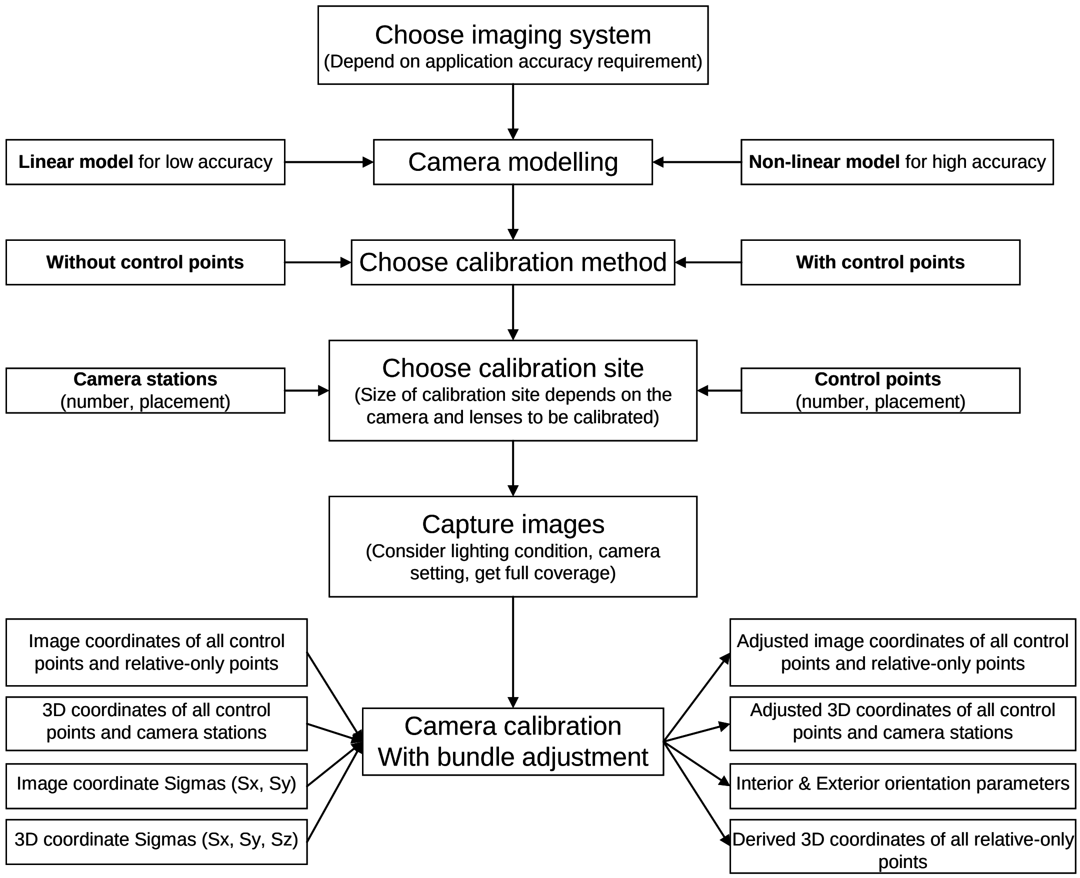


Figure 3.7 Generic workflow for camera calibration

4 3DM CalibCam and Camera Calibration Test

The first part of this chapter presents the basic functionalities of 3DM CalibCam, the software package used for camera calibration. The review covers process components, the input from the user, and output from the software. The second part describes the camera and lens systems employed in this research, and the test ranges where camera calibration work was conducted.

4.1 Camera Calibration Software - 3DM Calibcam

While camera and computer technology have undergone dramatic change, the mathematical models for photogrammetry have essentially remained the same. There are many PC-based photogrammetric software packages available on the market, such as Australis (Photometrix, 2008), Photomodeler (EOS Systems, 2009), ShapeCapture (ShapeQuest, 2008), to name a few. Underlying the different algorithms employed in different software packages are the two basic functional models: the colinearity and coplanarity models. For the end-user, the important thing is the application accuracy requirement and economical consideration. Using a three-dimensional test field, Peipe & Tecklenburg (2006) performed a comparison of camera interior parameters (principal distance, principal point position and lens distortion) determined by different camera calibration software packages. Their results showed a sufficient coincidence of the principal distance and position of principal point, and small discrepancies with lens distortion.

In this research, the software package 3DM Calibcam from Adam Technology is employed to facilitate camera calibration. 3DM CalibCam is a camera calibration and block adjustment package designed to be used with both close range and aerial images, ideally suited for terrestrial applications. Some of the 3DM CalibCam software functions include determining: 1) the 11 unknown interior orientation parameters, 2) exterior orientations which include camera position (X, Y, Z) and camera orientation (ω, φ, κ) parameters for each camera station, and 3) basic surveying to derive 3D coordinates of unknown points. More details on the interior orientation parameters are described in Appendix A. Two terminologies used in 3DM CalibCam are described as follows. A control point or target is a point with known 3D coordinates that is used for camera calibration. A relative point or common point is a point with unknown 3D coordinates that is observed on two or more images. Both control points and relative points contribute as observations to solve the bundle adjustment equations.

Camera calibration with 3DM CalibCam software is a two-step procedure, as illustrated in Figure 4.1. First, an image resection is performed to derive the initial approximation of all the interior and exterior orientation parameters. These estimated values can then be refined by a full least squares bundle adjustment. Even if the image resection works, the bundle adjustment may fail. Typically the resection will have much higher residuals than the bundle adjustment. Details on image coordinate system and the image coordinate correction in 3DM CalibCam are presented in Appendix A.

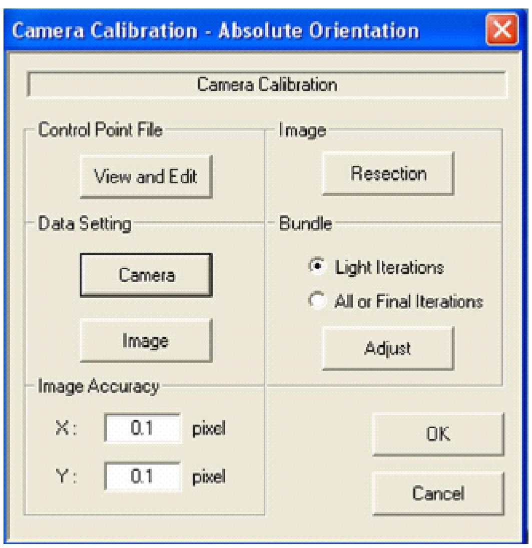


Figure 4.1 Control network camera calibration

4.1.1 Process components in 3DM CalibCam

The various components of a camera calibration conducted using 3DM CalibCam are best illustrated through reference to the three main elements: a Manager View, an Image View and a 3D View, as indicated in Figure 4.2 - Figure 4.4.

4.1.1.1 Manager View

The Manager View embodies project management aspects as well as the essential elements of the camera calibration process, namely the camera(s) employed, the imagery used, and any object space information such as scale constraints or control point coordinates in 3D space.

Shown in Figure 4.2 are a number of elements in the Manager View when a new project is created. The left pane shows the camera database, the list of images that have been specified under the camera icon, any scale setting and control point files. The right pane will show the currently selected image in the image list.

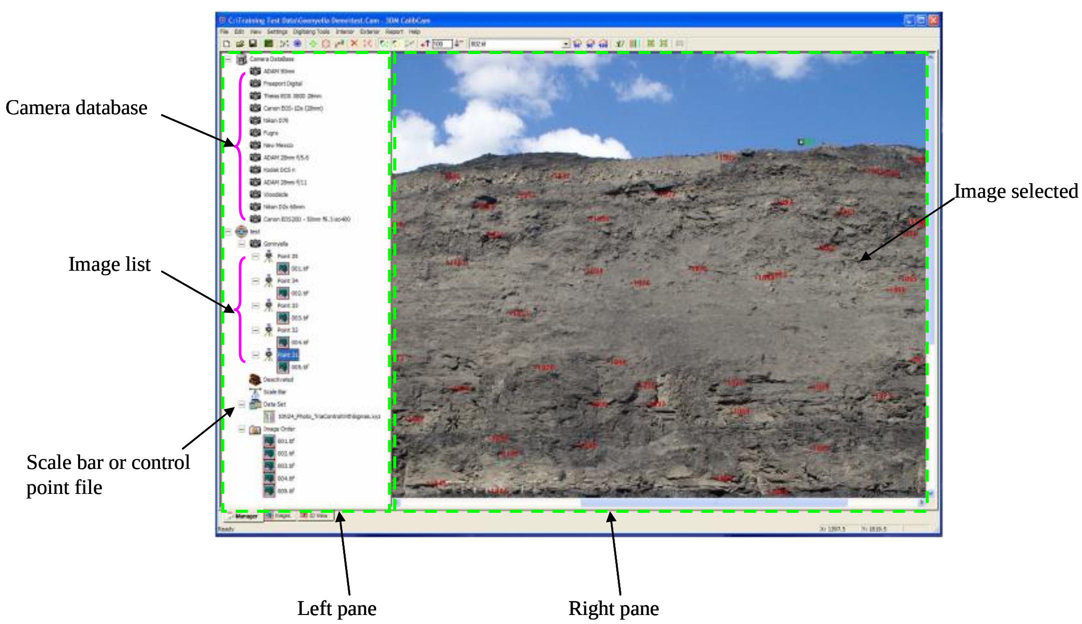


Figure 4.2 Manager View in 3DM CalibCam

4.1.1.2 Image View

As an example, Figure 4.3 shows a pair of images side-by-side in the Image View and allows a range of operations (such as view residuals, match existing features) to be performed. Image View is also a good place to carry out trouble shooting, for example, to check the digitized target for its positional accuracy in pairs of images. The left and right images can be selected via the two combo boxes in the toolbar. If both images are the same when the matching tools are used, the system will generate a warning.

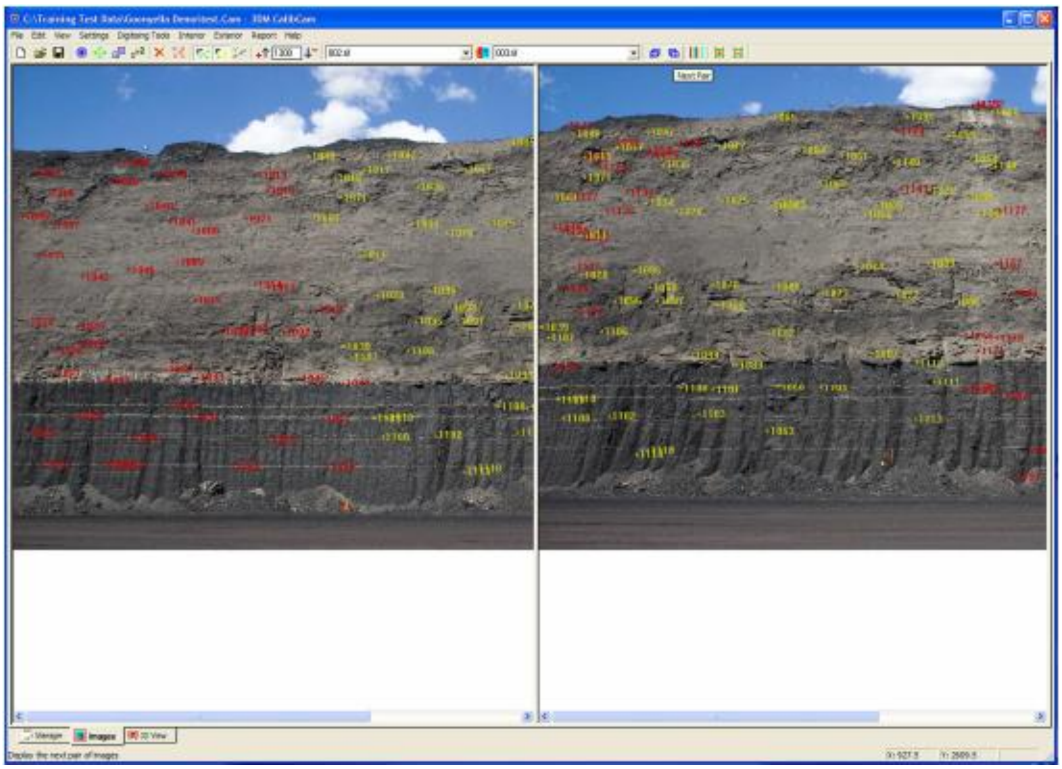


Figure 4.3 Image View in 3DM CalibCam

4.1.1.3 3D View

The two previous views were strictly two-dimensional. Both views showed the data from each individual camera’s viewpoint. The 3D View shows the data in full 3D, allowing the viewpoint to be rotated arbitrarily and the data to be inspected from any angle. This comprises straightforward graphics displays of the network geometry for visual interpretation.

To prevent distortions an orthogonal projection is used. This means that objects do not appear smaller the further away they are from the camera like they do in a perspective projection. The advantage of this is that the perceived distance between points in the scene does not depend on the distance of those points from the viewer.

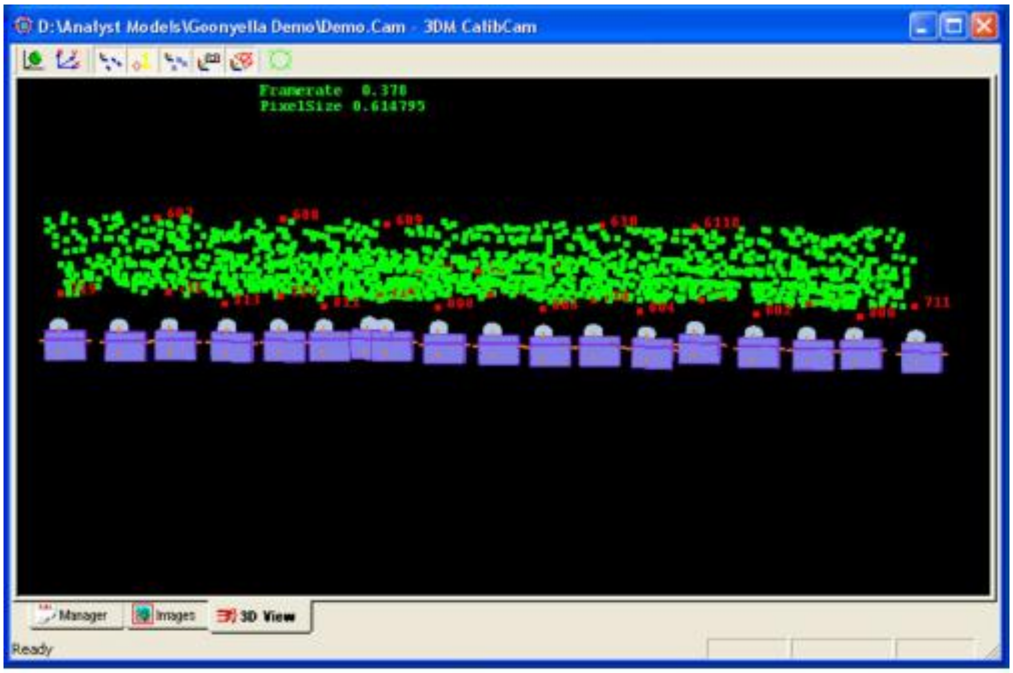


Figure 4.4 3D View in 3DM CalibCam

4.1.2 Image file format

3DM Calibcam can accommodate the image formats of BMP, PNG, TIFF, TGA and JPEG. Lossless compression file formats, such as BMP and TIFF, may improve the software's ability to automatically extract data. The disadvantage of lossless compress file formats is that more store space is needed for big projects. Higher compression ratio formats like JPEG introduce artefacts into the image, and can hinder the image matching performance as well as introduce spurious matches. 3DM Calibcam is presently designed to operate only with 8-bit imagery. Higher quality digital SLR cameras should capture and store images in a lossless RAW format. The RAW images must then be converted into 8-bit formats compatible with 3DM software.

After processing, each original image will have an *.ori ("orientation") file saved with it. This file contains information about the calibration and digitized points for that image. All the information will be loaded automatically when the corresponding image is loaded into another new project. After successful camera calibration, a "*.cal" file containing the camera calibration information can be created for further use with the same camera and lens settings.

4.1.3 Control target and centroiding methods

Control targets with known locations are required to register the data in a real-world coordinate system. In order to achieve this accuracy, the target should be at least six pixels wide in the image, and the background should extend another five pixels beyond the circle. The entire target should occupy a total of at least 16 pixels edge to edge. Figure 4.5 shows an optimal target design.

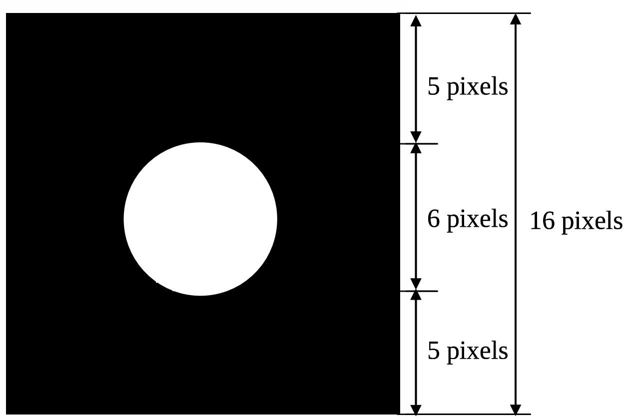
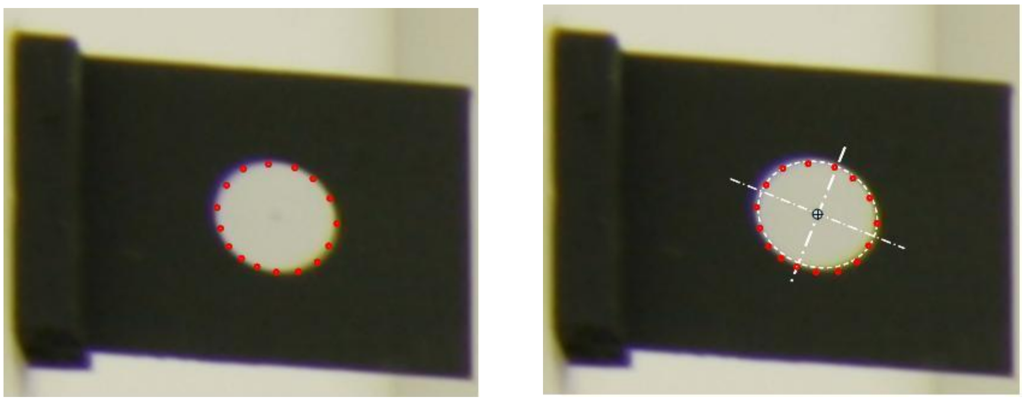


Figure 4.5 Optimal target design (modified from Adam Technology 2006)

As mentioned in previous chapter, the accurate determination of the centre of control target is very important, because the overall measuring performance and the resulting accuracy levels of the 3D measurement are directly linked to the quality of this image point determination. 3DM CalibCam uses a centroiding algorithm to accurately locate the centre of a target to within 1/10th of a pixel (ADAM Technology 2004). As shown in Figure 4.6, there are four methods for detecting the centre of a control target in 3DM CalibCam, named edge fitting, unweighted, weighted and square weighted respectively. These four methods use different algorithms to determine the centre of the control target.

Figure 4.6 Centroiding methods in 3DM CalibCam

In the edge fitting method, the target periphery points are extracted first (Figure 4.7 (a)), and an ellipse fitting is then applied to these periphery points. The target centre can be calculated from the ellipse function (Figure 4.7 (b)). In other three methods, the centre of the target is based on the calculation of the centre of gravity of the target pixels. The target pixels are determined by thresholding and binarization which separate the background from the target. The main difference among these three methods is whether the pixel position is weighted with the corresponding grey value of the pixel or not and the weight applied to the grey value of the pixel. A problem of the unweighted method is the selection of appropriate threshold which becomes crucial if the boundary of the target and the background is not well-defined. In that case, small variations of the threshold can change the detecting result significantly. With the weighted and square weighted methods, the results are not so sensitive to incorrect thresholding as the small weight of the uncertain edge pixels do not influence the results too much. With different methods, different centre locations could be determined for the same control target.



(a) Extract the target periphery (b) Calculated centre from ellipse function

Figure 4.7 Centroiding algorithm, edge fitting method

4.1.4 Input from user

The essential elements of the photogrammetric measurement process include the camera(s) employed, the imagery to be measured, and the optional provision of object space information such as scale constraints, control point coordinates.

4.1.4.1 Camera sensor information

At the outset in 3DM CalibCam, the following information regarding sensor and pixel size must be input (as shown in Figure 4.8): the number of horizontal and vertical sensor pixels, the horizontal and vertical pixel size (in millimetres), and the nominal focal length (in millimetres). This information can be found in the camera and lens manuals. Other parameters can be set to be zero for now. The selection of the parameters to be employed in camera calibration can be made by the user by setting the unwanted parameter to zero, or an appropriate default set can be readily imported.

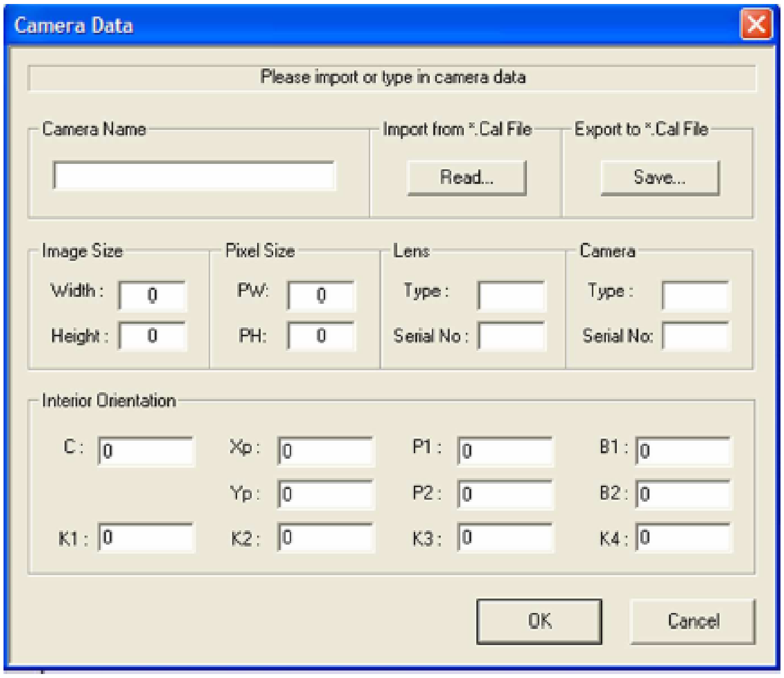


Figure 4.8 Camera detail dialog

4.1.4.2 Image accuracy

The second item the user can specific is the image accuracy. By default, the image accuracy in both x and y direction are set to 0.1 pixel. The user can change them to fit the real situation after a free-network bundle adjustment.

The expected accuracy in the image in pixels will vary depending on the observation method chosen. For targets larger than six pixels across, measured using 3DM CalibCam's centroiding algorithm, the accuracy can be as high as 0.1 pixels. For points generated by least squares matching, the accuracy should be around 0.3 pixels. For human observation, the accuracy may be closer to 0.5–1.0 pixels.

4.1.5 Output from 3DM CalibCam

4.1.5.1 Bundle adjustment successful

All successful bundle adjustments can produce an HTML report as illustrated in Figure 4.9. The report will vary depending on the type of bundle adjustment performed but the information reported will be of the following where relevant: 1) project information, 2) bundle adjustment type, 3) image residuals, control point residuals and final camera orientations results, 4) final calibration data for each camera in the project and associated accuracies, and 5) parameter relationships.

It is crucial to check the camera calibration result in the HTML report. The parameters the user should check are described below.

- Posteriori Variance Factor. The posterior variance factor is a reference variance or standard deviation of a measurement of unit weight. This value is relative to the estimated image point digitized error. For a good camera calibration, the posterior variance factor should be close to 1. If this value is below 1, it shows the result is too pessimistic. If the posterior variance factor is above 1, that means the estimate point accuracy is too high or some relative only points has been mismatched.
- Number of Degrees of Freedom. This parameter is a measure of redundancy. The least square adjustment uses redundant data to improve the result and to calculate deviation.
- Image Residuals. The image residual also contributes to the camera calibration result. The purpose of listing each image RMS error is for checking wrong points. If one image’s RMS error is quite large, there must be some problems with that image. It is recommended that the total RMS error of each image is between 0.1 and 0.2 pixels.
- Control Point Residuals. If control points are used in the bundle adjustment, correct control point accuracy must be provided. A straight line links the control point, camera location, and image point. After bundle adjustment, the software gives residuals for control and image points. If control point accuracy is set too high, the residual of the 3D control point will be smaller and the residual of the 2D image point will be larger. The control point accuracy is provided by the surveyor based on the surveying instrument employed, while the image point accuracy is estimated by the user. In order to estimate the image point accuracy correctly, the user

should always run the bundle adjustment with a free network first, and adjust Posteriori Variance Factor to 1 by changing image point accuracy.

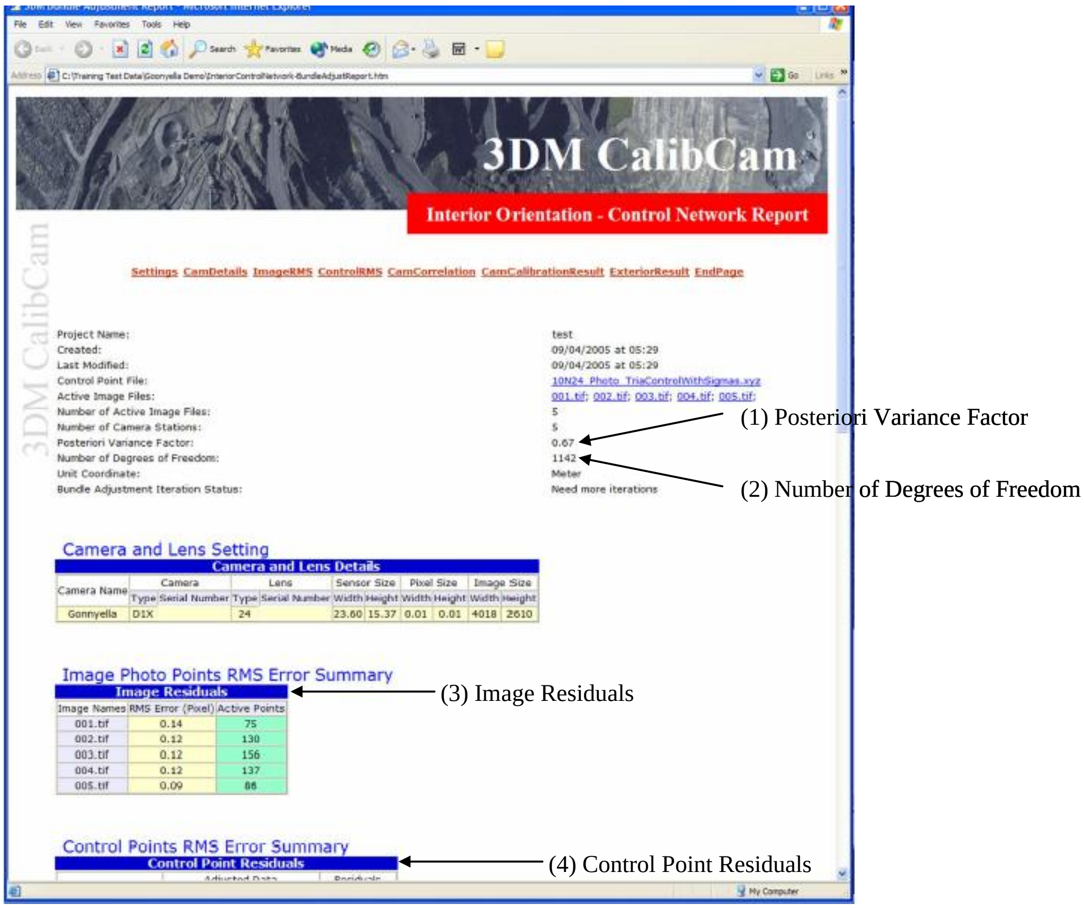


Figure 4.9 Bundle adjustment report

After successfully completing a bundle adjustment, the user should check the calibration project for blunders by visually viewing the residual vectors that are produced from the bundle adjustment. By pressing the ‘view residuals button’ on the toolbar, residual values are displayed automatically once the bundle adjustment has successfully finished. Generally, a scaling factor of 100 is sufficient to determine if the residuals look reasonable or not. Large residuals can result from a digitizing error or incorrect values set in either the control point file or the calibration data settings.

4.1.5.2 Resection or bundle adjustment failed

Although performing a calibration in 3DM CalibCam is fairly straightforward, things can go wrong. The most common problem with camera calibration occurs when the resection or bundle adjustment fails. It is important that users not only be aware of the problems, but also know how to fix the problems once they have occurred and, ideally how to avoid them in the first place. Possible causes include bad observations (such as mismatched relative points, incorrectly labelled control points or camera stations), poor configuration (all known locations coplanar), and insufficient data.

The resection or bundle adjustment often fails due to bad observations. There are two types of observational errors that users will encounter: 1) bad control point or camera station coordinates used for an absolute orientation; 2) incorrectly identified control points or relative-only points digitized manually by the user or generated automatically by the software itself. To address the first type of observational errors requires redundancy. If there are only three known locations, then the software cannot determine whether they are wrong or not. However, if there are more than three known locations, the software can detect bad control data using robust and sophisticated mechanisms. The most common cause of the second observational error is when two different points have been incorrectly identified with the same ID, or when a control point has been mislabelled. The solution is to double-check the data. Bad points are relatively easy to detect due to their large residuals. The user should check the residuals of each individual point to ensure that none of them are anomalous. An unusually large residual suggests a problem with that point that warrants further investigation.

Remove all bad points and run the resection or bundle adjustment again until the bundle adjustment is successful with sufficiently small residuals.

4.1.6 General camera calibration workflow in 3DM CalibCam

Regardless of the type of project 3DM CalibCam will be used for, the following steps are required: 1) load images, any scale constraints or 3D control data, 2) digitize control points, 3) digitize relative-only points, 4) perform a bundle adjustment, and 5) check data. The flow chart shown in Figure 4.10 covers the general procedure involved in performing these steps to a successful camera calibration.

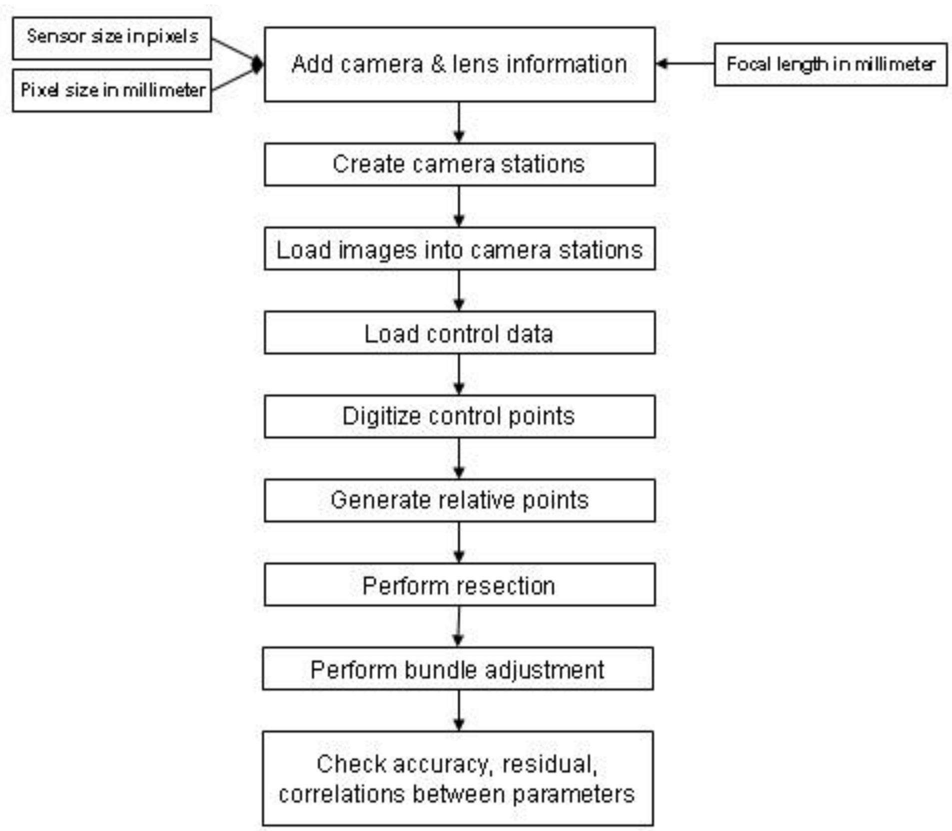


Figure 4.10 General workflow of camera calibration in 3DM CalibCam

4.2 Digital Cameras and Lenses

The following cameras and lenses are calibrated in this study: 1) lower-end zoom camera Canon PowerShot A70; 2) Canon EOS 1Ds Mark II camera, and lenses 35 mm, 85 mm, 135 mm and 200 mm.

4.2.1 Camera and lens specification

The Canon PowerShot A70 camera is a 3.2 megapixel consumer-grade camera (Canon 2003). This camera has an aperture range F2.8 - F4.8, and 3 x optical zoom lens, with a focal range of 5.4-16.2 mm. Only the fully zoom-in setting (5.4 mm nominal focal length) is used in this study.

Featuring a full-frame 36mm×24mm 16.7 Megapixel CMOS sensor, the Canon EOS 1Ds Mark II is a high-performance digital AF single lens reflex (SLR) camera (Canon 2005). It produces images with outstanding colour rendition and dynamic range. It has sufficient resolution (4992×3328) to produce files that convert to 50 MB uncompressed TIFF at 8 bit colour depth. The camera is compatible with all Canon EF lenses except the EF-S lens. In this research, Canon EF 35mm f/1.4L USM lens, EF 85mm f/1.2L USM lens, EF 135 mm f/2.0L USM lens, and EF 200 mm f/2.8L II USM lens are used.

To ensure the camera and lenses are calibrated with focus set to infinity, which they are intended to be used at, the camera and lens is pointed at something very far away (such as clouds in the sky) and the auto-focus is used to position the focal ring to proper place. The auto-focus function is then turned off and care is made to ensure the focal ring is not disturbed.

Some relevant camera and lens specifications are summarized in Table 4.1 and Table 4.2 respectively.

Table 4.1 Cameras specification summary

Camera	Sensor type	Sensor size W x H (mm)	Max resolution	Effective pixel (MPixels)	Pixel size W x H (mm/pixel)
Canon A70	CCD	5.27 x 3.96	2048 x 1536	3.1	0.00257 x 0.00258
Canon EOS 1Ds Mark II	CMOS	36 x 24	4992 x 3328	16.7	0.00721 x 0.00721

Table 4.2 Summary of lens specification

Lens	Maximum aperture	Diagonal angle of view (°)	Lens construction
Canon EF 35 mm	1.4	63	11 elements in 9 groups
Canon EF 85 mm	1.2	28.5	8 elements in 7 groups
Canon EF 135 mm	2.0	18	10 elements in 8 groups
Canon EF 200 mm	2.8	12	9 elements in 7 groups

4.3 Camera Calibration Sites

4.3.1 Test range considerations

The wide range of application tasks has encouraged the use of long focal length lenses as well as very short ones (such as 3.5mm fish-eye) to obtain a large inspection field. The fact one must realize when choosing a test range for camera calibration is that it is almost impossible to use the same calibration pattern set-up for both long range and short range applications. Specific patterns have to be set-up for a narrow range of focal length lenses.

For small scale applications, a rigid calibration frame to which control points are fixed can be used. For large scale applications, the typical rigid-frame approach does not work.

The calibration test range must be large enough include the full field of view of the lens. If it is too small, there is a danger of extrapolation and, as a result, inaccurate coordinate computation. The calibration test range should include as many control points as possible and these should be spread uniformly throughout the whole area. This will increase the redundancy of the system and improve the accuracy of the calibration.

4.3.2 Test ranges

Since it is impossible to use the same test-range for both long and short focal length lenses, several test sites were chosen and built to calibrate different lenses.

4.3.2.1 *First test range*

The first test range was built with desks in a classroom at the University of Alberta. It measured about 3.1 m in X direction and 2.1 m in Y direction with a depth of 1.4 m in Z direction. 54 paper-targets were distributed in 3 parallel planes (one wall, two desk planes), and dispersed across the imaged area, forming a relatively well-distributed target network as shown in Figure 4.11. The white circle in the centre of the target is 20 mm in diameter, and square dark background is 52 mm. In order to check the centroiding algorithm used in 3DM Calibcam, a small crosshair in the centre of the circle is drawn. Unfortunately, the crosshair was not identified in the captured images due to low image resolution.

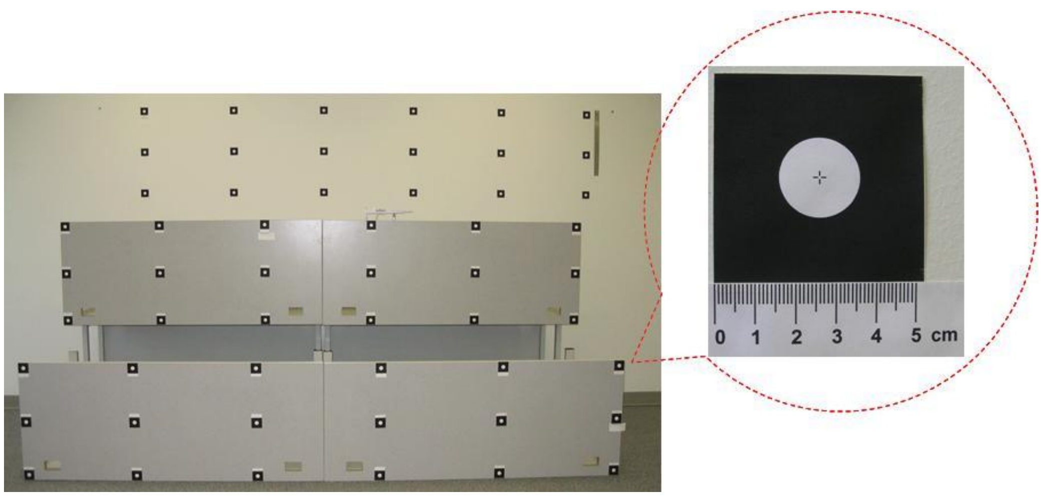


Figure 4.11 First test range targets network configuration

An arbitrary right-hand coordinate system and original point are defined in Figure 4.12. 54 control targets are divided into 9 lines. Each line has 6 targets with centres arranged to have same elevation. A soft tube filled with water (level) and steel tape were used to determine the control target centre coordinates. The three-dimensional coordinates of targets are provided in Appendix B. The estimated standard deviation of each control point is ±0.010 m in X, Y and Z direction. Due to the space constraint, this test range was employed to calibrate Canon PowerShot A70 and its 5.4 mm lens. The lens was always used at the fully zoom-in position during the calibration test. In this test, camera calibration images were captured under convergent mode with close to 100% overlap between images. Cameras were located 3.3 m and 5 m away from the closest point on the test field. The camera base was approximately aligned along the X axis of the co-ordinate system. Figure 4.12 illustrated the layout of the targets and camera stations.

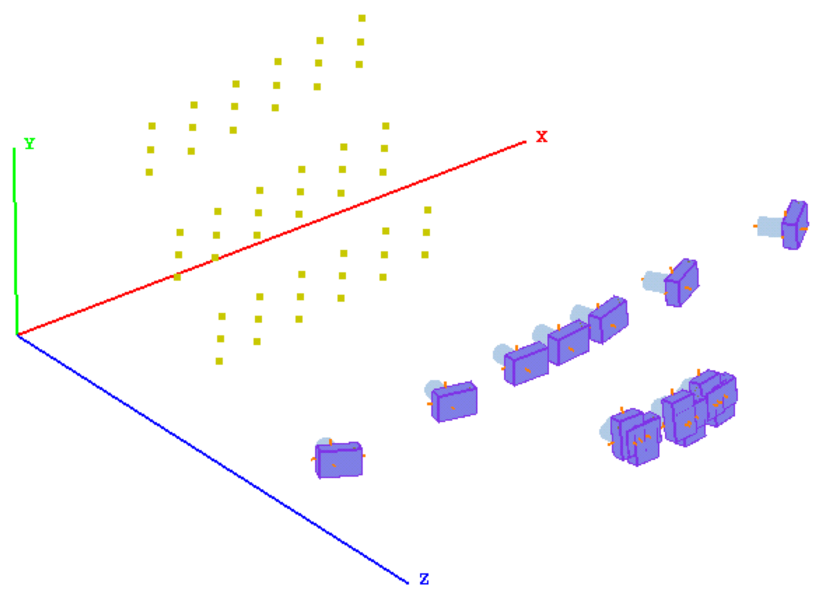


Figure 4.12 Targets and camera stations layout at the first test range

4.3.2.2 *Second test range*

The second test range was set up in a large lab in the Markin / CNRL Natural Resources Engineering Facility at the University of Alberta. Figure 4.13 is a photograph showing the general layout of the test range. The space available for the test field was by no means ideal but the only recourse was to make the best use of the available space. The test range consists of three rectangular arrays of targets set out in three roughly vertical planes separated by a distance of 2.0 m respectively. The arrangement of targets is made up of the following three components.

A rectangular array of 20 targets covering an area approximately 6.0 m long and 4.0 m high consisting of targets fixed with adhesive to the concrete wall of the room.

A rectangular array of 16 targets covering an area approximately 3.0 m long by 3.6 m high. These targets are glued on an open vertical wood frame fixed at a distance of 2.0 m in front of the back wall.

Another rectangular array of 22 targets glued on a vertical wood frame 4.9 m long by 3.6 m high placed 2.0 m away from the first wood frame. In addition, 12 targets were fixed on two fishing lines hanging by weight. One fishing line was placed at the centre of the test range. The other was at the right-hand side of the test range. It was possible to take photographs 20.0 m away from the nearest target, but the base distance was limited to 3.0 m. This test range was used for calibrating the 35 mm and 85 mm Canon lenses.

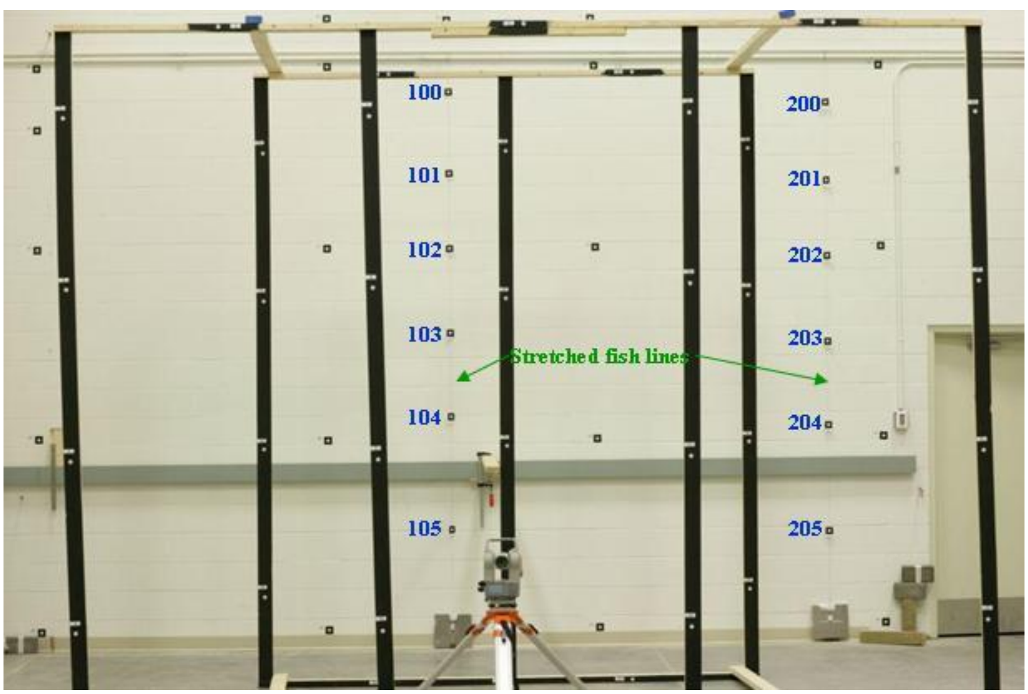


Figure 4.13 Second test range in the basement of NREF

To meet 3DM CalibCam target design requirement and considering surveying requirements, white targets in circular shape with a contrasting black background were made with 3M reflective sheet. The circle was in 20 mm diameter. To help survey the centre of the target accurately, a small crosshair was drawn in the centre of the circle. For targets on the concrete wall, the entire target was 52 mm. For targets glued on the wood columns, columns were painted black to provide contrasting background.

A local coordinate system was established for the test site with the X-axis perpendicular to the wall face, the Y-axis running from left to right along the wall, and the Z-axis vertical as shown in Figure 4.14. A Sokkia Powerset 2010 total station was used to survey the 59 circular targets as control points. The surveyed three-dimensional coordinates of targets are provided in Appendix B. The estimated standard deviation of each control point is ±0.003 m in X, Y and Z direction. The three dimensional coordinates of the 59 control points were loaded into 3DM Calibcam to do the bundle adjustment.

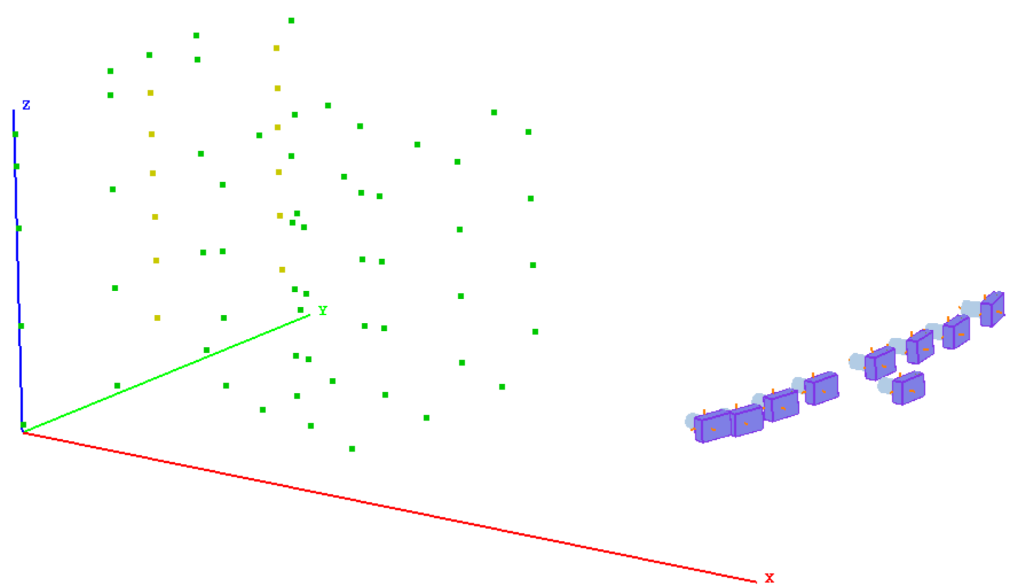


Figure 4.14 Targets and camera stations layout at the second test range

To achieve high accuracy for the control points coordinates, the total station was set up at three different locations that were positioned to allow line of sight to the majority of the targets. From each location, every control point was surveyed with the Sokkia PowerSet 2010, as shown in Figure 4.15. The total station has 2 seconds of arc angular precision with a distance measurement accuracy of ±(4+3ppm×D) mm to reflective targets under fine measurement mode (Sokkia 1998). Using the slope distance, horizontal angle and vertical angle, 3D coordinates of control points are calculated. Control point coordinates from three stations are averaged to determine the final control point coordinate.

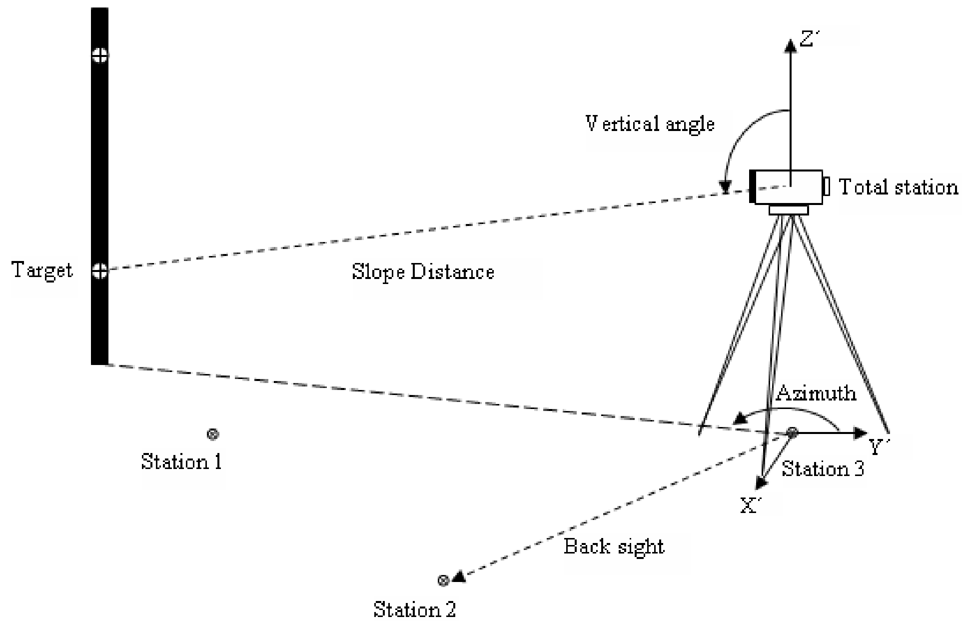


Figure 4.15 Scheme of control point surveying

4.3.2.3 *Third test range*

A lot of effort was required to find a suitable calibration site for long lenses (such as 135 mm and 200 mm lens). The top level of the Windsor parking lot was chosen to be the third test range as it allows taking photographs at a distance of 100 m away from the side wall of the parking lot, and 120 m away from the Chemical Engineering building. This test site is by no means ideal with the constraints of space and uniform background texture, which created difficulties for image-matching. The original plan was to glue a dozen of circular retro-reflective targets on the office window, so that a three-dimensional control network could be created. Eventually only 3 targets were glued on the office windows due to the lack of permission from the individual who occupy the offices. There are 27 control targets on this test range, 17 control targets epoxy-resin anchored on the side wall and lighting stands, 6 placed on the ground, and 1 glued on the foreground post, as shown in Figure 4.16.

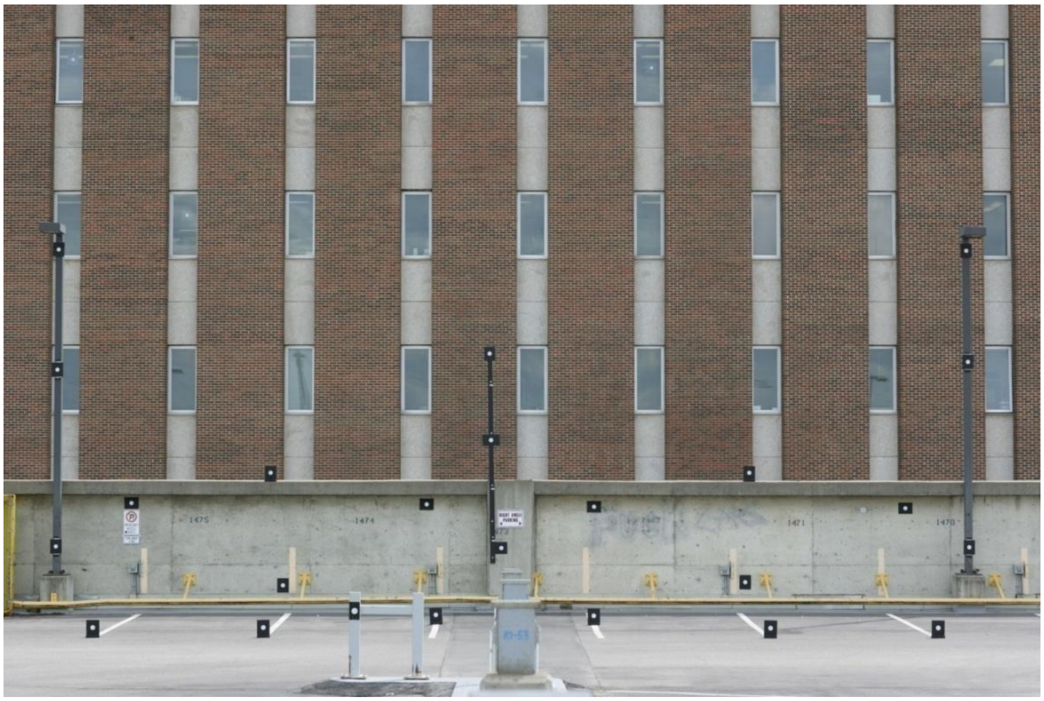


Figure 4.16 Third test range at the Windsor parking lot

Before taking any images, the camera and lens was pointed to the clouds in the sky which are far away, and the auto-focus function was used to make sure the camera was focused at infinity. Then the auto-focus function was turned off and the focal ring was left at that specific position. However, it was noticed that the position of focus ring was not stable enough and drifted during the calibration test.

All control points were surveyed with a Sokkia PowerSet 2010 total station. The surveyed three-dimensional coordinates of targets are given in Appendix B. During the surveying process, it was observed that the levelled total station became unlevelled after 5 minutes mainly because of the temperature influence. It was a challenge to survey these targets to sub-centimetre accuracy. The estimated standard deviation of each control point is ±0.020 m in X, Y and Z direction. Also, it was noticed that the images taken with 135 mm and 200 mm lenses were blurry. One possible reason is that the object distances (70 m for 135 mm lens, 110 m for 200 mm lens) are too small to get a sharp image by focusing the lens at infinity. The other reason is that the images were affected by the heat wave from the concrete floor heated by the sunshine.

One lesson learned from this test range is that auto-matching function does not work properly due to the similar pattern and texture that was present in the repeating pattern of bricks in the building wall. The user had to manually digitize relative-points to get the bundle adjustment started.

Canon EOS 1Ds Mark II camera and the Canon EF 35 mm, 85 mm, 135 mm, 200 mm lenses were calibrated with this test range.

4.3.2.4 *Fourth test range*

The fourth test range was built in the lab in the Markin / CNRL Natural Resources Engineering Facility at the University of Alberta, as shown in Figure 4.17. Fifty-two control targets were distributed in a three-dimensional space of 8.6 m long by 5.1 m high by 6.8 m deep. Among them, 8 targets were placed on the floor, 16 mounted on the walls, 28 glued on the 2’’× 4’’ wood columns. The local coordinate system and typical camera stations arrangement is shown in Figure 4.18. All control targets were surveyed with the Sokkia PowerSet 2010 total station from three different locations that were positioned to allow line of sight to the majority of the targets. The estimated standard deviation of each control point is ±0.003 m in X, Y and Z direction. The surveyed three-dimensional coordinates of targets are provided in Appendix B.

The Canon EOS 1Ds Mark II camera with 35 mm, 85 mm lenses and the Canon PowerShot A70 zoom camera were calibrated with this test range. Table 4.3 summarizes the test ranges employed for camera calibration in this research.

Figure 4.17 Fourth test range at the basement of NREF

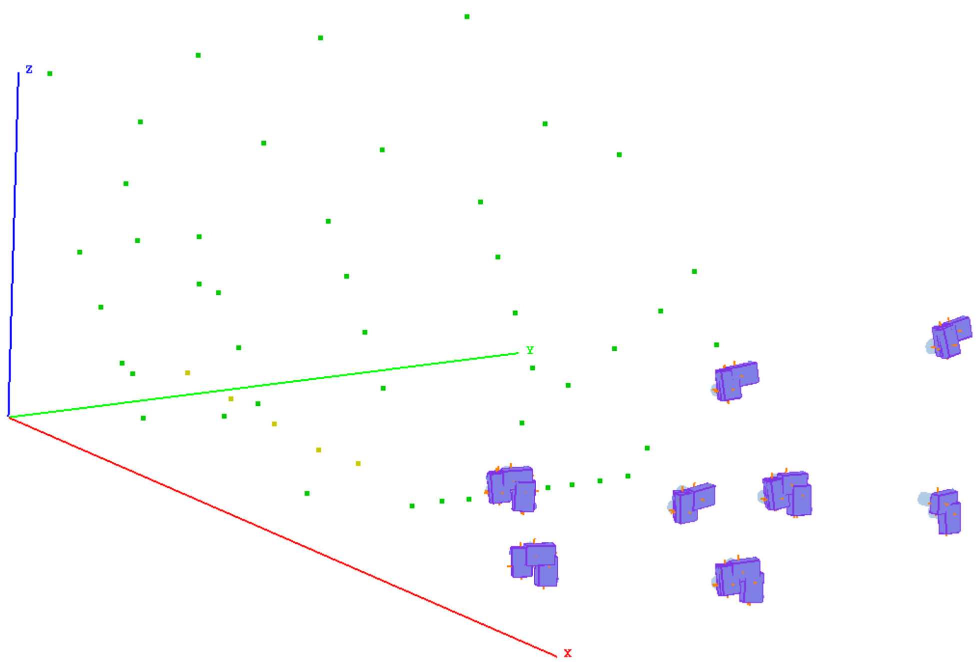


Figure 4.18 Control targets and typical camera station arrangement

Table 4.3 Summary of the test ranges employed in this research.

Test range #	Test range dimension			Control targets in 3D space	Camera & lens calibrated
	X (m)	Y (m)	Z (m)		
1	3.1	2.1	1.4	54	Canon PowerShot A70 with 5.4mm lens
2	4.0	6.0	4.0	59	Canon EOS 1Ds Mark II 35 mm & 85 mm lens Canon PowerShot A70 with 5.4mm lens
3	19.5	33.0	30.0	27	Canon EOS 1Ds Mark II 35 mm, 85 mm, 135 mm & 200 mm lens
4	6.8	8.6	5.1	52	Canon EOS 1Ds Mark II 35 mm & 85 mm lens Canon PowerShot A70 with 5.4mm lens

Table 4.4 lists some relevant information on all of the camera calibration tests used in this research. Image accuracy setting is set to be 0.1 pixel for indoor calibration (test range #1, 2 and 4) and 0.3 pixels for outdoor calibration (test range #3).

Table 4.4 Camera calibration test summary

Camera	Lens nominal (mm)	Date of calibration	Test range #	Average object distance (m)	Maximum base line (m)	Number of camera stations	Number of images used for calibration	Roll camera (Y/N)
Canon PowerShot A70	5.4	2004-12-11	1	5.6	6.5	16	16	Y
		2005-04-10	2	9.0	4.3	7	7	N
		2005-09-11	4	9.5	7.4	6	12	Y
Canon EOS 1Ds Mark II	35	2005-03-13	2	11.0	5.9	9	9	N
		2005-06-17	3	25.0	8.0	5	30	Y
		2005-09-13	4	10.4	7.4	30	30	Y
		2005-09-16	4	10.0	7.1	29	29	Y
	85	2005-03-13	2	15.0	7.5	7	7	N
		2005-06-17	3	47.0	19.0	7	26	Y
		2005-09-13	4	16.4	2.3	34	34	Y
		2005-09-16	4	16.1	2.2	25	25	Y
	135	2005-06-17	3	75.5	29.2	5	18	Y
	200	2005-06-17	3	109.5	25.9	5	12	Y

4.3.3 Summary

By describing the components and input requirements of the 3DM CalibCam software, the focus is to gain an understanding of how the software functions, and the output from the software, which have direct impact on the quality of the calibration results. The relevant bundle adjustment output used to judge the quality of a calibration include the posterior variance factor, number of degrees of freedom, and image and control point residuals. For a good camera calibration, the posterior variance factor should be close to 1. It is recommended the total RMS error of each image is between 0.1 and 0.2 pixels and the control point residuals should be within the survey error specified by the user.

The test ranges used to calibrate a Canon PowerShot A70 camera with zoom lens and a professional SLR Canon EOS 1Ds Mark II with various prime lenses are reported in this chapter. It is almost impossible to use the same calibration pattern in the experimental set-up for both long range and short range applications. Specific calibration patterns have to be set-up for a given range of focal length lenses. Also lessons learned from outdoor calibration and the difficulties encountered when calibrating long range lenses are presented.

5 Camera Calibration Test Results

5.1 Bundle Adjustment Report

With the 11 unknown interior orientation parameters, detailed in Appendix A, and 6 unknown exterior orientation parameters (camera position X, Y, Z and camera rotation ω, φ, κ) for each camera station, the bundle adjustments for all of the camera calibration tests listed in Table 4.4 were successful, although not without difficulty for the long 135 mm and 200 mm lenses. As mentioned previously, the difficulty results from the blurry images and the similar pattern and texture of the building wall at the background, which makes the automatic image-matching malfunction.

The bundle adjustment reports from the camera calibration tests with all of the 11 unknown interior orientation parameters are given in Appendix C. Summarized in Table 5.1 are some of the relevant calibration results which can be used to judge the calibration quality.

From Table 5.1, the following observations can be obtained: 1) all of the posterior variance factors are less than 1.0, 2) the image residual for most tests is less than 0.2 pixels with the exception of the outdoor calibrations, and 3) the control point residuals are within the survey error specified by the user.

Table 5.1Camera calibration results from bundle adjustment - 11 interior orientation parameters

Camera	Lens nominal (mm)	Date of calibration	Test range #	Posterior variance factor	Number of redundancy	Maximum total image residual RMS (pixel)	Maximum control point residual RMS (m)
Canon PowerShot A70	5.4	2004-12-11	1	0.64	1607	0.09	0.010
		2005-04-10	2	0.70	693	0.10	0.003
		2005-09-11	4	0.84	821	0.16	0.003
Canon EOS 1Ds Mark II	35	2005-03-13	2	0.37	971	0.08	0.003
		2005-06-17	3	0.50	2057	0.41	0.010
		2005-09-13	4	0.55	2167	0.11	0.003
		2005-09-16	4	0.86	2081	0.29	0.004
	85	2005-03-13	2	0.33	617	0.05	0.003
		2005-06-17	3	0.95	1939	0.42	0.010
		2005-09-13	4	0.42	1609	0.09	0.003
		2005-09-16	4	0.79	953	0.23	0.004
	135	2005-06-17	3	0.86	1117	0.62	0.010
	200	2005-06-17	3	0.93	691	0.93	0.020

5.2 Correlation Between Parameters

5.2.1 Introduction

The basic principal of photogrammetry is to calculate 3D points through measuring image coordinates. The relation between the image coordinates and their corresponding object points is built by using the interior and exterior orientation of cameras. However, the parameters of interior and exterior orientation are not independent. Correlations are known to exist among the interior and exterior orientation parameters. It is quite possible to have two different sets of parameters, but the transformations between the image coordinates and their corresponding object points are the same at given points.

The magnitude of the correlation coefficient describes the inter-relationship between parameters. High correlation coefficients imply high correlations between the relevant parameters. The correlation value ranges from 1.0 to –1.0. If the value is above 0.9, then both parameters are highly correlated.

5.2.2 Correlation among camera calibration parameters

In the 3DM CalibCam software, correlations among camera calibration parameters and their standard deviations estimated by observation redundancy are obtained directly from the covariance matrix resulting from the bundle adjustment report.

The interior and exterior orientation parameters that were highly correlated (correlation coefficient above ±0.9) are summarized in Table 5.2. Parameters highly correlated with exterior orientation parameters are marked with shaded background in Table 5.2.

Table 5.2 High correlation between parameters

Camera	Lens nominal (mm)	Date of calibration	Test range #	Parameter 1	Parameter 2	Correlation coefficient
Canon PowerShot A70	5.4	2004-12-11	1	K_1	K_2	-0.96
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-04-10	2	X_p Y_P	K_5^* O_5^*	1.00 -0.98
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
				P_1	X_P	-0.98
		2005-09-11	4	X_P	P_1	-0.96
				K_1	K_2	-0.98
				K_2	K_3	-0.99
				K_3	K_4	-0.99

Camera	Lens nominal (mm)	Date of calibration	Test range #	Parameter 1	Parameter 2	Correlation coefficient
Canon EOS 1Ds Mark II	35	2005-03-13	2	X_P	P_1	-0.95
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-06-17	3	X_P	P_1	-0.97
				K_1	K_2	-0.96
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-09-13	4	X_P	P_1	-0.95
				Y_P	P_2	-0.93
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-09-16	4	X_P	P_1	-0.95
				Y_P	P_2	-0.93
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
	85	2005-03-13	2	X_p	K_6*	0.97
				Y_P	O_4*	-0.91
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
				P_1	X_P	-0.95
		2005-06-17	3	C	Y_1*	-0.94
				X_P	P_1	-0.97
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-09-13	4	X_P	P_1	-0.97
				Y_P	P_2	-0.92
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
		2005-09-16	4	X_P	P_1	-0.96
				Y_P	P_2	-0.92
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
	135	2005-06-17	3	C	Y_3*	-0.95
				X_P	P_1	-0.97
				K_1	K_2	-0.97
				K_2	K_3	-0.99
				K_3	K_4	-0.99
	200	2005-06-17	3	C	Y_3*	-0.97
				X_P	P_1	-0.96
				Y_P	P_2	-0.91
				K_1	K_2	-0.98
				K_2	K_3	-0.99
				K_3	K_4	-0.99

* Note: *K*_5 – camera rotation about Z axis of image 5; *O*_5 – camera rotation about X axis of image 5; *K*_6 - camera rotation about Z axis of image 6; *O*_4 – camera rotation about X axis of image 4; *Y*_1 – camera position of image 1; *Y*_3 – camera position of image 3.

From Table 5.2, the following can be observed.

- The radial distortion parameters K_1, K_2, K_3, K_4 are always highly correlated with each other, no matter what the network configuration is.
- There is often high correlation between principal point offset X_P, Y_P and decentring distortion parameters P_1, P_2. The only exception is Canon PowerShot A70 with test range #1.
- When calibrating the Canon PowerShot A70 and Canon EOS 1Ds Mark II with 85 mm lens using test range #2, the exterior orientation rotation angles (*K*_5, *O*_5, *K*_6, *O*_4) are linked to the principal point offset X_P, $Y_{P.}$
- When calibrating the Canon EOS 1Ds Mark II 85 mm, 135 mm and 200 mm lenses using test range #3, the principal distance C is related to the Y coordinate of the camera position.

From the above observations, one could conclude that the correlations obtained from a bundle adjustment are dependent on the network configuration. As illustrated in Table 5.2, the projective coupling between the principal point offset and the camera station orientations can be broken by rotating images 90 degrees. Without these rotated images, it is very likely that high correlation will exist between the principal point offset and exterior orientation rotation angles. The high correlation between the radial lens distortion parameters originates from the mathematical model used to approximate the physical behaviour of light travelling from object space through the lens to the image sensor.

One of the concerns with high correlation between parameters is that such correlations may lead to instabilities in the bundle adjustment process if the network is geometrically weak. If a pair of parameters having a correlation coefficient greater than 0.9 is found, one parameter should be removed from the functional model, because they cannot be determined properly. Then the bundle adjustment process is repeated. If a parameter is highly correlated with the exterior orientation parameters of an image, that specific image should also be removed from the bundle adjustment process.

The bundle adjustment for each test was run again with highly correlated parameters set to zero. All of the bundle adjustments were successful. The bundle adjustment reports of camera calibration tests with highly correlated parameters set to zero are given in Appendix D. Table 5.3 lists the interior orientation parameters which are set to zero for each calibration test and some relevant calibration results, such as posterior variance factor, image residual and control point residual. Compared to the values in Table 5.1, the posterior variance factor and maximum total image residual RMS have slightly increased. The control point residuals are still within the survey error specified by the user.

Table 5.3 Camera calibration results from bundle adjustment with highly correlated parameters set to zero

Camera	Lens nominal (mm)	Date of calibration	Test range #	Parameters set to zero	Posterior variance factor	Maximum total image residual RMS (pixel)	Maximum control point residual RMS (m)
Canon PowerShot A70	5.4	2004-12-11	1	K_3, K_4	0.65	0.09	0.005
		2005-04-10	2	P_1, K_3, K_4	0.72	0.11	0.003
		2005-09-11	4	P_1, K_3, K_4	0.90	0.16	0.003
Canon EOS 1Ds Mark II	35	2005-03-13	2	P_1, K_3, K_4	0.38	0.08	0.003
		2005-06-17	3	P_1, K_3, K_4	0.53	0.42	0.010
		2005-09-13	4	P_1, K_3, K_4	0.80	0.15	0.003
		2005-09-16	4	P_1, K_3, K_4	1.00	0.29	0.004
	85	2005-03-13	2	P_1, K_3, K_4	0.32	0.05	0.003
		2005-06-17	3	P_1, K_3, K_4	0.95	0.42	0.010
		2005-09-13	4	P_1, K_3, K_4	0.46	0.10	0.003
		2005-09-16	4	P_1, K_3, K_4	0.81	0.23	0.004
	135	2005-06-17	3	P_1, P_2, K_3, K_4	0.86	0.63	0.004
	200	2005-06-17	3	X_p, K_2, K_3, K_4	0.94	0.92	0.010

For comparison purposes before and after highly correlated parameter are set to zero, the value of one parameter and its standard deviation are presented in Table 5.4.

Table 5.4 Summary of parameters set to zero and remaining parameters

Camera & lens	Date of calibration	Parameters set to zero	Remaining relevant parameters	Remaining relevant parameter value & its standard deviation	
				Before	After
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	K_3, K_4	K_1	6.05e-03 ± 5.34e-05	6.05e-03 ± 1.54e-05
			K_2	-2.35e-04 ± 2.25e-05	-2.18e-04 ± 1.42e-06
	2005-04-10	P_1, K_3, K_4	X_p	6.54e-02 ± 3.14e-03	8.10e-02 ± 6.68e-04
			K_1	5.86e-03 ± 1.49e-04	6.05e-03 ± 3.24e-05
			K_2	-1.84e-04 ± 5.61e-05	-2.20e-04 ± 3.05e-06
	2005-09-11	P_1, K_3, K_4	X_p	4.41e-02 ± 1.33e-03	5.65e-02 ± 4.18e-04
			K_1	5.73e-03 ± 8.34e-05	5.90e-03 ± 1.55e-05
			K_2	-1.55e-04 ± 3.28e-05	-2.11e-04 ± 1.51e-06
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	P_1, K_3, K_4	X_p	1.15e-01 ± 5.89e-03	8.03e-02 ± 1.92e-03
			K_1	8.81e-05 ± 1.19e-06	8.81e-05 ± 2.64e-07
			K_2	-9.13e-08 ± 1.77e-08	-1.02e-07 ± 9.67e-10
	2005-06-17	P_1, K_3, K_4	X_p	1.34e-01 ± 1.90e-03	1.07e-01 ± 5.16e-04
			K_1	8.93e-05 ± 7.51e-07	8.80e-05 ± 1.95e-07
			K_2	-1.11e-07 ± 6.50e-09	-9.97e-08 ± 3.87e-10
	2005-09-13	P_1, K_3, K_4	X_p	1.40e-01 ± 8.19e-04	1.04e-01 ± 3.82e-04
			K_1	8.82e-05 ± 2.66e-07	8.70e-05 ± 8.55e-08
			K_2	-1.01e-07 ± 2.42e-09	-9.59e-08 ± 1.87e-10
	2005-09-16	P_1, K_3, K_4	X_p	1.11e-01 ± 1.36e-03	7.53e-02 ± 4.87e-04
			K_1	8.92e-05 ± 4.65e-07	8.77e-05 ± 1.20e-07
			K_2	-1.13e-07 ± 4.48e-09	-9.90e-08 ± 2.89e-10
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	P_1, K_3, K_4	X_p	9.83e-02 ± 1.92e-02	1.16e-01 ± 5.76e-03
			K_1	9.76e-06 ± 4.30e-07	1.08e-05 ± 9.44e-08

			K_2	1.34e-08 ± 3.42e-09	7.53e-09 ± 1.90e-10
	2005-06-17	P_1, K_3, K_4	X_p	1.84e-01 ± 5.64e-02	1.10e-01 ± 1.29e-02
			K_1	4.75e-06 ± 4.56e-06	1.08e-05 ± 9.98e-07
			K_2	5.05e-08 ± 3.98e-08	5.40e-09 ± 2.35e-09
	2005-09-13	P_1, K_3, K_4	X_p	1.60e-01 ± 4.14e-03	1.32e-01 ± 1.15e-03
			K_1	7.96e-06 ± 2.41e-07	1.05e-05 ± 5.62e-08
			K_2	2.50e-08 ± 1.99e-09	8.49e-09 ± 1.22e-10
	2005-09-16	P_1, K_3, K_4	X_p	1.83e-01 ± 1.07e-02	1.61e-01 ± 3.10e-03
			K_1	8.42e-06 ± 6.46e-07	1.01e-05 ± 1.21e-07
			K_2	1.69e-08 ± 5.93e-09	7.94e-09 ± 2.72e-10
Canon EOS 1Ds Mark II with 135 mm lens	2005-06-17	P_1, P_2, K_3, K_4	X_p	2.78e-01 ± 6.25e-02	2.15e-01 ± 1.49e-02
			K_1	-1.15e-05 ± 2.12e-06	-1.49e-05 ± 4.67e-07
			K_2	-1.58e-08 ± 1.88e-08	9.74e-09 ± 1.07e-09
Canon EOS 1Ds Mark II with 200 mm lens	2005-06-17	X_p, K_2, K_3, K_4	P_1	1.70e-05 ± 3.26e-06	1.90e-06 ± 8.75e-07
			K_1	-3.18e-05 ± 6.92e-06	-2.39e-05 ± 4.45e-07

It can be seen from Table 5.4 that before correlated parameters are set to zero, the standard deviation of the parameter is about the same order of magnitude as that of the parameter itself (marked with shaded background in Table 5.4). After correlated parameters are set to zero, the standard deviation becomes smaller. From statistics point of view, the accuracy of that parameter is improved even though the true value of that parameter is unknown. It appears that the interior orientation parameters can be better determined by setting some highly correlated parameters to zero.

However, it is observed from Appendix D that for the calibration of Canon PowerShot A70 on 2005-04-10 at test range #2, the principal point offset X_P, Y_P, which is originally correlated to exterior orientation of image #5 (*K*_5, *O*_5), are now highly correlated to exterior orientation of image #6 (*K*_6, *O*_6) after P_1 is set to zero. For the calibration of Canon EOS 1Ds Mark II with 135 mm lens, the principal distance *C*, which is originally correlated to exterior orientation of image #3 (*Y*_3), are now not highly correlated to other parameters. Apparently the correlations obtained from the bundle adjustment are also dependent on the parameters being adjusted.

A series of sensitivity tests were conducted to understand the influence of fixing some highly correlated parameters to zero on one of the most important interior orientation parameters - the principal distance. The principal distances and its standard deviations under the different combinations of parameters set to zero are present in Table 5.5 for each calibration test.

Table 5.5 Summary of principal distances and its standard deviations under various combinations of parameters set to zero

Camera & lens	Date of calibration	Parameters fixed to zero									
		No parameters set to zero	K_4	P_1, K_4	K_3, K_4	P_1, K_3, K_4	P_1, P_2, K_4	P_1, P_2, K_3, K_4	X_p, Y_p, K_3, K_4	X_p, K_2, K_3, K_4	P_1, P_2, K_2, K_3, K_4
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	5.52 ± 0.001	5.52 ± 0.001	-	5.52 ± 0.001	-	-	-	-	-	-
	2005-04-10	5.50 ± 0.001	5.50 ± 0.001	5.50 ± 0.001	-	5.50 ± 0.001	-	5.50 ± 0.001	-	-	5.51 ± 0.003
	2005-09-11	5.58 ± 0.001	-	-	5.58 ± 0.001	5.58 ± 0.001	-	5.59 ± 0.001	-	-	-
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	34.30 ± 0.005	-	-	-	34.29 ± 0.005	-	-	-	-	-
	2005-06-17	34.29 ± 0.006	34.29 ± 0.006	34.29 ± 0.006	-	34.29 ± 0.006	-	-	-	-	-
	2005-09-13	34.37 ± 0.001	34.37 ± 0.001	34.37 ± 0.002	-	34.37 ± 0.002	-	34.37 ± 0.002	-	-	-
	2005-09-16	34.29 ± 0.006	34.29 ± 0.006	34.29 ± 0.006	-	34.29 ± 0.006	-	-	-	-	-
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	83.25 ± 0.014	83.25 ± 0.014	83.25 ± 0.014	-	-	83.25 ± 0.014	83.25 ± 0.014	-	-	83.27 ± 0.027
	2005-06-17	83.02 ± 0.086	83.03 ± 0.086	83.03 ± 0.086	-	83.05 ± 0.085	-	-	-	-	-
	2005-09-13	83.28 ± 0.007	83.28 ± 0.007	83.27 ± 0.007	-	83.29 ± 0.008	-	83.29 ± 0.008	-	-	-
	2005-09-16	83.06 ± 0.015	83.05 ± 0.015	83.05 ± 0.015	-	83.06 ± 0.015	-	83.05 ± 0.015	-	-	-
Canon EOS 1Ds Mark II with 135 mm lens	2005-06-17	133.21 ± 0.110	-	-	-	-	-	133.21 ± 0.148	133.27 ± 0.152	-	-
Canon EOS 1Ds Mark II with 200 mm lens	2005-06-17	198.08 ± 1.180	-	-	-	-	-	-	-	197.92 ± 1.170	-

The comparisons of principal distance and its standard deviation under different parameter combinations indicate that fixing radial distortion parameters K_3, K_4 to zero will not have a large impact on the principal distance. However, fixing K_1, K_2, K_3 to zero will cause principal distance shift beyond the range of $C \pm \delta C$, as demonstrated in Table 5.5 for Canon PowerShot A70 with 5.4 mm zoom lens and for Canon EOS 1Ds Mark II with 85 mm lens.

To get a sense of the difference of radial distortion between using all four radial distortion coefficients K_1, K_2, K_3, K_4 (denoted as C-1) and just using two coefficients K_1, K_2 (denoted as C-2), a comparison is made for Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2004-12-11, Canon EOS Mark II with 35 mm and 85 mm lenses calibration on 2005-09-16, and Canon EOS Mark II with 135 mm lens calibration on 2005-06-17, as shown in Table 5.6.

Table 5.6 Radial distortion comparison between using K_1 to K_4 and K_1, K_2

Radial distance (mm)	Canon PowerShot A70			Canon EOS 1Ds Mark II								
	5.4 mm zoom lens			35 mm lens			85 mm lens			135 mm lens		
	C-1 (μm)	C-2 (μm)	Δ (μm)	C-1 (μm)	C-2 (μm)	Δ (μm)	C-1 (μm)	C-2 (μm)	Δ (μm)	C-1 (μm)	C-2 (μm)	Δ (μm)
1.6	22.4	22.5	0.1	0.4	0.4	0	0.03	0.04	0.01	-0.05	-0.06	0.01
3.2	123.3	125.1	1.8	2.9	2.8	0.1	0.3	0.3	0	-0.4	-0.5	0.1
5.0	-	-	-	10.8	10.6	0.2	1.1	1.3	0.2	-1.5	-1.8	0.3
10.0	-	-	-	78.3	77.8	0.5	10.0	10.9	0.9	-12.4	-13.9	1.5
15.0	-	-	-	221.5	220.8	0.7	39.0	40.1	1.1	-40.9	-42.9	2.0
20.0	-	-	-	385.6	384.8	0.8	103.6	106.2	2.6	-84.4	-88.1	3.7
21.5	-	-	-	415.3	416.8	1.5	130.9	136.8	5.9	-99.8	-103.4	3.6

The maximum difference in Table 5.6 is about 6 μm, and this occurred around the edge of the image sensor. It appears that not all of the four radial distortion coefficients are significant. For the Canon 5.4 mm zoom lens, and the Canon EF 35 mm, 85 mm, and 135 mm lenses, the first two coefficients K_1, K_2 would be sufficient to describe the radial distortion effect.

It is also observed that fixing highly correlated parameters to zero has influence on the exterior orientation parameters. As an example, presented in Table 5.7 and

Table 5.8 are the change of camera locations and camera rotations for the calibration test of Canon EOS 1Ds Mark II with 85 mm lens on 2005-03-13 at test range #2.

Table 5.7 Camera location change – calibration test of Canon EOS 1Ds Mark II with 85 mm lens on 2005-03-13

Image name	No parameters fixed to zero			P_1, P_2, K_2, K_3, K_4 fixed to zero			Camera location difference		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	Δ X (m)	Δ Y (m)	Δ Z (m)
Center	16.287	2.784	0.803	16.285	2.785	0.803	-0.002	0.001	0.000
Left05	14.974	-0.237	0.801	14.972	-0.235	0.802	-0.002	0.002	0.001
Left14	14.961	2.092	0.797	14.959	2.092	0.797	-0.002	0.000	0.000
Left33	14.973	0.859	0.799	14.971	0.860	0.799	-0.002	0.001	0.000
Right05	15.016	6.250	0.805	15.014	6.249	0.805	-0.002	-0.001	0.000
Right14	14.994	3.908	0.804	14.992	3.907	0.804	-0.002	-0.001	0.000
Right33	15.007	5.144	0.806	15.005	5.143	0.806	-0.002	-0.001	0.000

Table 5.8 Camera rotation change – calibration test of Canon EOS 1Ds Mark II with 85 mm lens on 2005-03-13

Image name	No parameters fixed to zero			P_1, P_2, K_2, K_3, K_4 fixed to zero			Camera rotation difference		
	ω (°)	φ (°)	κ (°)	ω (°)	φ (°)	κ (°)	Δ ω (°)	Δ φ (°)	Δ κ (°)
Center	110.79	-88.44	-21.33	111.83	-88.46	-22.38	1.04	-0.02	-1.05
Left05	91.16	-73.54	-1.41	91.22	-73.57	-1.47	0.06	-0.03	-0.06
Left14	97.91	-86.54	-8.25	98.30	-86.57	-8.64	0.39	-0.03	-0.39
Left33	93.28	-82.15	-3.94	93.43	-82.18	-4.09	0.15	-0.03	-0.15
Right05	-94.32	-77.52	-175.62	-94.41	-77.49	-175.54	-0.09	0.03	0.08
Right14	-96.36	-85.58	-173.71	-96.58	-85.55	-173.50	-0.22	0.03	0.21
Right33	-94.66	-79.85	-175.29	-94.76	-79.83	-175.19	-0.10	0.02	0.10

It can be seen from Table 5.7 and Table 5.8 that although the change of the camera location is within the survey error specified by the user, some of the camera rotation angle changes are as high as 1°. This indicates that the software can compensate for the impact of fixing some highly correlated parameter to zero by changing the camera positions (locations and rotation angles). So the next logical step is to survey camera locations or perspective centre of the imaging system. However, it is very difficult to find the exact location of the perspective center, if not impossible, because the physical behaviour of light travelling from object space through the lens to the image sensor is very complicated.

5.3 Calibration Results

After setting some highly correlated parameters to zero, the remaining interior orientation parameters of each camera and lens determined from each calibration test are summarized in Table 5.9.

Table 5.9 Summary of interior orientation parameters from each test

Camera & lens	Date of calibration	Interior orientation parameters								
		C (mm)	X_p (mm)	Y_P (mm)	P_1	P_2	B_1	B_2	K_1	K_2
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	5.52	3.79e-02	-2.06e-02	1.28e-04	3.20e-04	1.92e-03	1.67e-04	6.05e-03	-2.18e-04
	2005-04-10	5.50	8.10e-02	-2.54e-02	-	2.82e-04	1.83e-03	2.16e-04	6.05e-03	-2.20e-04
	2005-09-11	5.59	5.65e-02	-2.04e-02	-	3.14e-04	1.93e-03	4.51e-04	5.90e-03	-2.11e-04
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	34.30	8.03e-02	-1.55e-01	-	5.17e-06	-2.63e-04	7.20e-05	8.81e-05	-1.02e-07
	2005-06-17	34.29	1.07e-01	-1.77e-01	-	4.07e-07	-7.55e-05	6.72e-06	8.80e-05	-9.97e-08
	2005-09-13	34.37	1.04e-01	-1.57e-01	-	2.48e-06	-1.13e-05	-4.35e-05	8.70e-05	-9.59e-08
	2005-09-16	34.29	7.53e-02	-1.64e-01	-	2.70e-06	-2.65e-05	-4.95e-05	8.77e-05	-9.90e-08
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	83.25	1.17e-01	-6.19e-02	-	9.87e-07	-1.54e-04	3.47e-05	1.08e-05	7.53e-09
	2005-06-17	83.05	1.10e-01	-1.67e-01	-	1.07e-06	-6.39e-05	-6.69e-05	1.08e-05	5.40e-09
	2005-09-13	83.29	1.32e-01	-1.22e-01	-	1.37e-06	-3.09e-05	-6.05e-06	1.05e-05	8.49e-09
	2005-09-16	83.06	1.61e-01	-1.03e-01	-	1.43e-06	-2.01e-05	4.11e-06	1.01e-05	7.94e-09
Canon EOS 1Ds Mark II with 135 mm lens	2005-06-17	133.21	2.15e-01	-1.84e-01	-	-	-9.63e-05	-1.07e-04	-1.49e-05	9.72e-09
Canon EOS 1Ds Mark II with 200 mm lens	2005-06-17	197.92	-	5.64e-01	1.90e-06	-1.57e-06	-1.43e-04	-1.11e-04	-2.39e-05	-

5.3.1 Principal distance *C*

It can be seen from Table 5.9 that the principal distances for all of the prime lenses are smaller than the nominal values. For the Canon PowerShot A70 with zoom lens at fully zoom-in position, the determined principal distances from the calibration tests are higher than the nominal 5.4 mm.

For comparison purposes, presented in Table 5.10 are principal distances and their standard deviations determined from different calibration tests for the Canon

PowerShot A70 with 5.4 mm zoom lens and Canon EOS 1Ds Mark II with 35 mm and 85 mm lenses.

Table 5.10 Principal distances and standard deviations determined from different calibration tests

Camera	Lens (mm)	Date of calibration					
		2004-12-11	2005-03-13	2005-04-10	2005-06-17	2005-09-13	2005-09-16
Canon PowerShot A70	5.4	5.52 ± 0.001	-	5.50 ± 0.001	-	5.59 ± 0.001	-
Canon EOS 1Ds Mark II	35	-	34.30 ± 0.005	-	34.29 ± 0.006	34.37 ± 0.002	34.29 ± 0.002
	85	-	83.25 ± 0.014	-	83.05 ± 0.085	83.29 ± 0.008	83.06 ± 0.015

The results shown in Table 5.10 indicate that principal distance of each lens is changed slightly from different calibration tests. Ideally, the principal distance should be kept as constant as possible to achieve highest accuracy. However, this is very difficult practically, if not impossible, for non-metric camera and lens. As mentioned in section 4.2.1, to ensure the camera and lenses are calibrated at infinity which they are intended to be used at, the technique employed in this study is to point the camera and lens at something very far away (such as clouds in the sky) and use the auto-focus to position the focal ring to the proper place. The focal ring is left undisturbed and the auto-focus function is turned off. Using this technique, it is very difficult, practically, to ensure the focal ring is at the exactly same location for each calibration test. It is very likely the position of focal ring is not stable and drifted during each calibration test. This would cause the principal distance change. The only real solution if the highest accuracy is required is to physically fix the focal length of the camera (such as by drilling a screw into the lens) to prevent it from changing once it has been calibrated, which is the traditional approach in photogrammetry and also used with the cameras mounted on laser scanners.

5.3.2 Principal point location

Figure 5.1 shows the determined positions of the principal points for the Canon PowerShot A70 with 5.4 mm zoom lens and the Canon EOS 1Ds Mark II with 35 mm and 85 mm lenses. The position of principal point changes from different calibration tests. The maximum change is less than 0.2 mm. If the image sensor is divided into four quadrants, then the principal points are all located in the third quadrant.

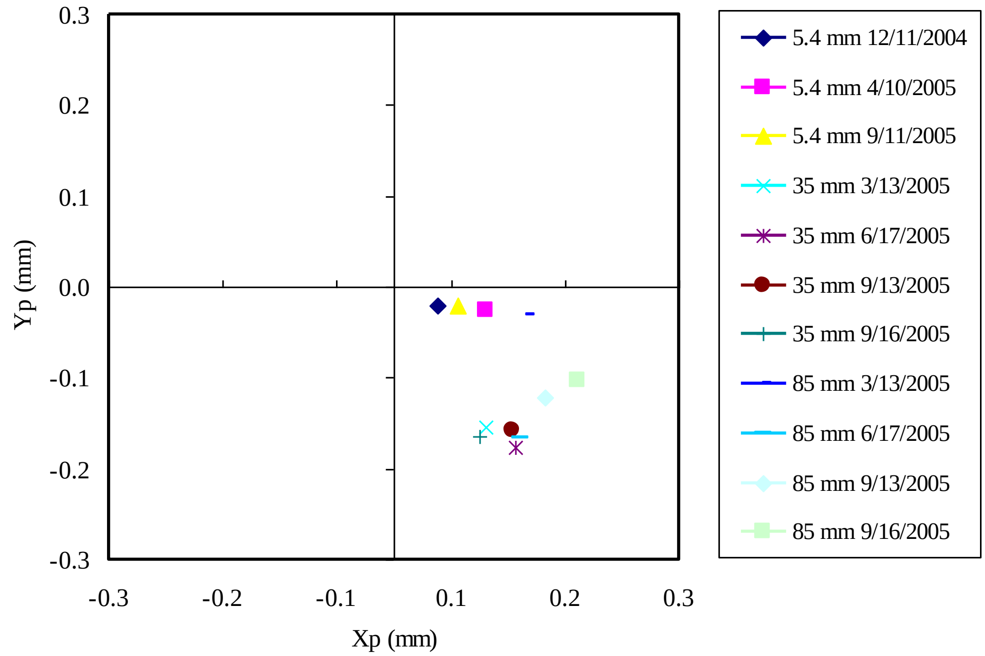


Figure 5.1 Determined principal point locations from different tests

5.3.3 Radial distortion

Figure 5.2 is an example of radial distortion for various Canon lenses. Radial distortion for the Canon EF 35 mm lens may be as large as 400 µm towards the edge of the image or outer part of the lens. Inspection of Figure 5.2 reveals that for different Canon lenses, long lenses generally have smaller radial distortion than short lenses at the same radial distance. However, this does not hold true for the 200 mm lens which has higher radial distortion than the 135 mm lens at the same radial distance. This may be due to the fact that longer focal length lenses are physically bigger and hence more difficult to make.

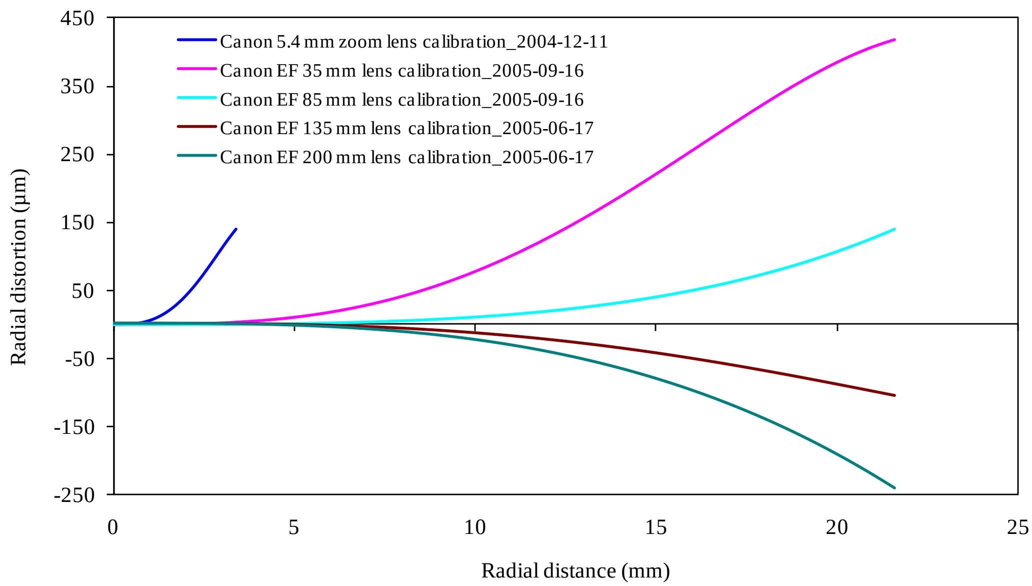
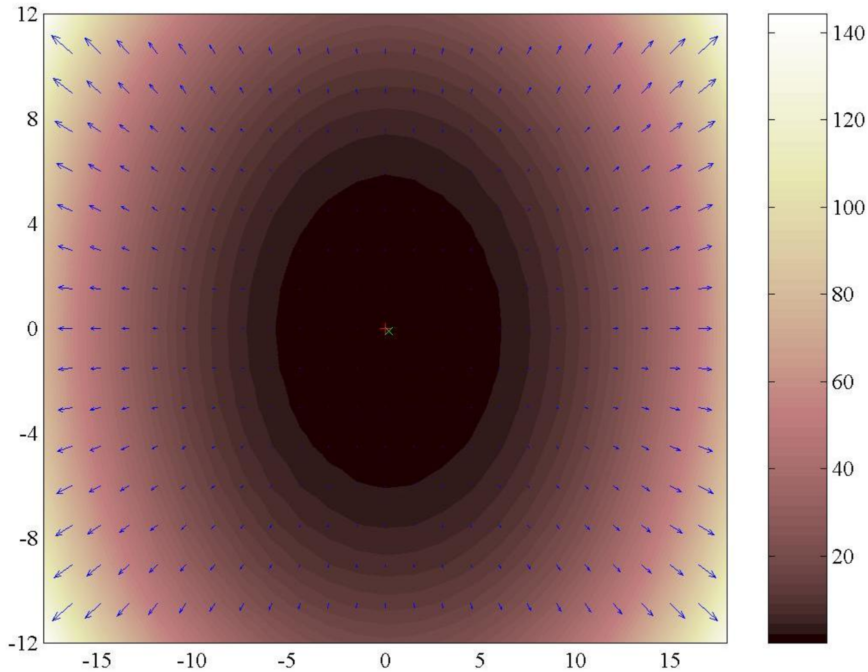
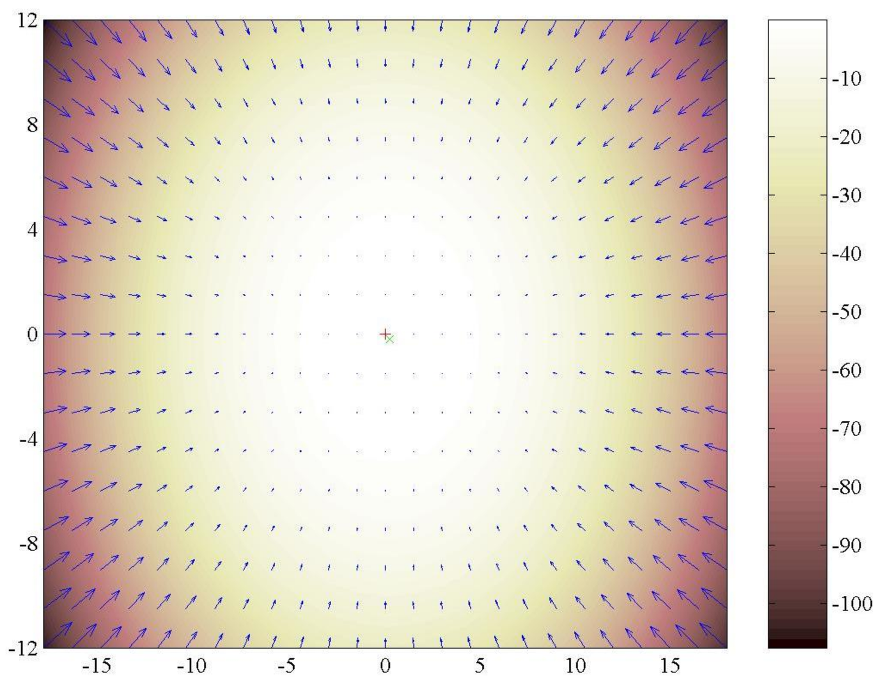


Figure 5.2 Gaussian radial distortion for various Canon lenses

Using the radial distortion coefficients in Table 5.9, the two components in x and y directions can be computed with Equation 2.2 at discrete positions of the whole image format. Illustrated in Figure 5.3 are radial distortion vector maps for the Canon EOS 1Ds Mark II with 85 mm and 135 mm lenses calibrated on 2005-09-16 and 2005-06-17 respectively. Similar graphs could be produced for other camera and lenses calibrated at different tests. The red '+' symbol indicates the physical centre of the image plane whereas the green 'x' symbol denotes the estimated principal point. The arrows denote magnitude and orientation of the gradient of radial distortion. The intensity of the images is proportional to the amount of compensation necessary to find the correct location of any given pixel. It can be seen from Figure 5.3 that the radial distortion effect is largest at the edge of the image format and negligible near the center. It should also be noted that, near the four corners, the corrective displacement is of the order of 20 pixels and 15 pixels for the 85 mm lens and 135 mm lens respectively. The arrows are pointing away from the image centre for the 85 mm lens, while the arrows are pointing to the image centre for the 135 mm lens.



(a) Canon EOS 1Ds Mark II with 85 mm lens 2005-09-16 calibration



(b) Canon EOS 1Ds Mark II with 135 mm lens 2005-06-17 calibration

Figure 5.3 Radial distortion vector map in µm

Examining Table 5.9, Figure 5.2 and Figure 5.3 reveals that the radial distortion coefficient K_1 has the dominant influence on the radial lens distortion. If K_1 is a positive value, a barrel distortion occurs. If K_1 is negative, a pincushion distortion happens.

Shown in Table 5.11 are radial distortions at various radial distances for the same lenses calibrated at different calibration tests. The results indicate that the radial distortion obtained from different calibrations is quite stable.

Table 5.11 Radial distortions in μm at various radial distances determined from different calibration tests

Camera & lens	Date of calibration	Radial distance (mm)					
		1.6	3.2	5.0	10.0	15.0	20.0
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	22.5	125.1	-	-	-	-
	2005-04-10	22.5	124.4	-	-	-	-
	2005-09-11	22.0	122.5	-	-	-	-
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	0.4	2.9	10.7	77.9	219.9	378.4
	2005-06-17	0.4	2.9	10.7	78.0	221.3	385.0
	2005-09-13	0.4	2.8	10.6	77.4	220.8	389.1
	2005-09-16	0.4	2.8	10.7	77.8	220.8	384.8
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	0.0	0.4	1.4	11.6	42.2	110.5
	2005-06-17	0.0	0.4	1.4	11.3	40.6	103.7
	2005-09-13	0.0	0.3	1.3	11.3	41.9	111.2
	2005-09-16	0.0	0.3	1.3	10.9	40.1	106.2

5.3.4 Decentring distortion

Using the decentring distortion coefficients in Table 5.9, an example of graphical representation of decentring distortion calculated with the profile function Equation 2.6 is shown in Figure 5.4. The decentring distortions found here are up to two orders of magnitude smaller than radial distortions shown in Figure 5.2.

The comparison of the two reveals that the radial distortion accounts for most of the lens distortion.

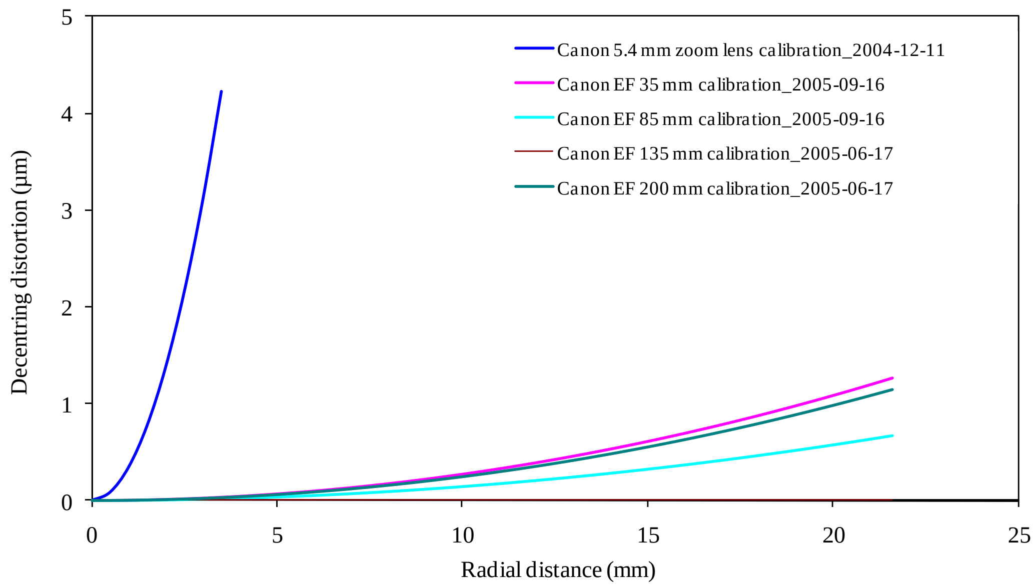
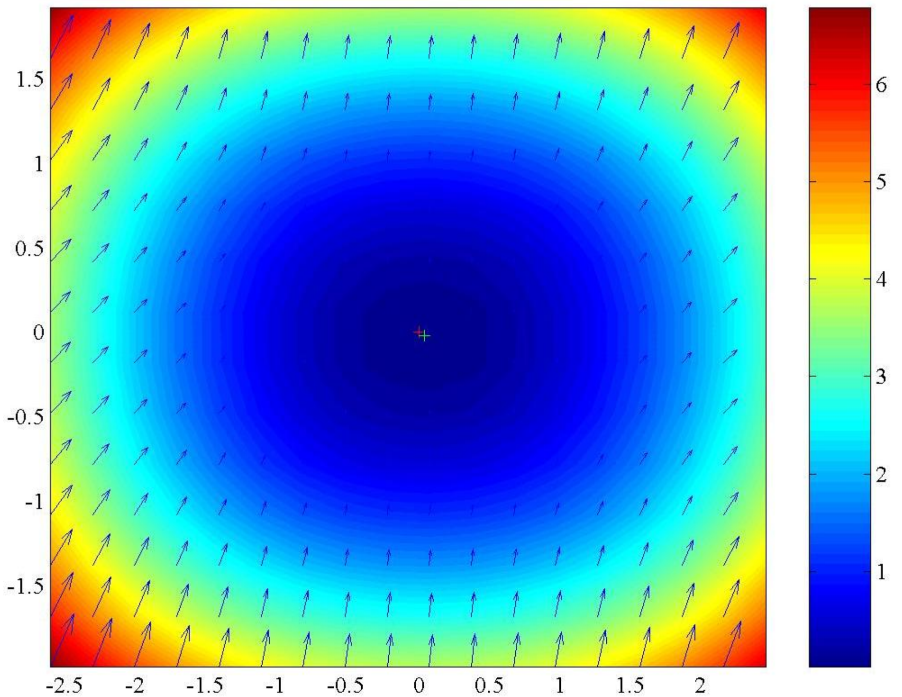


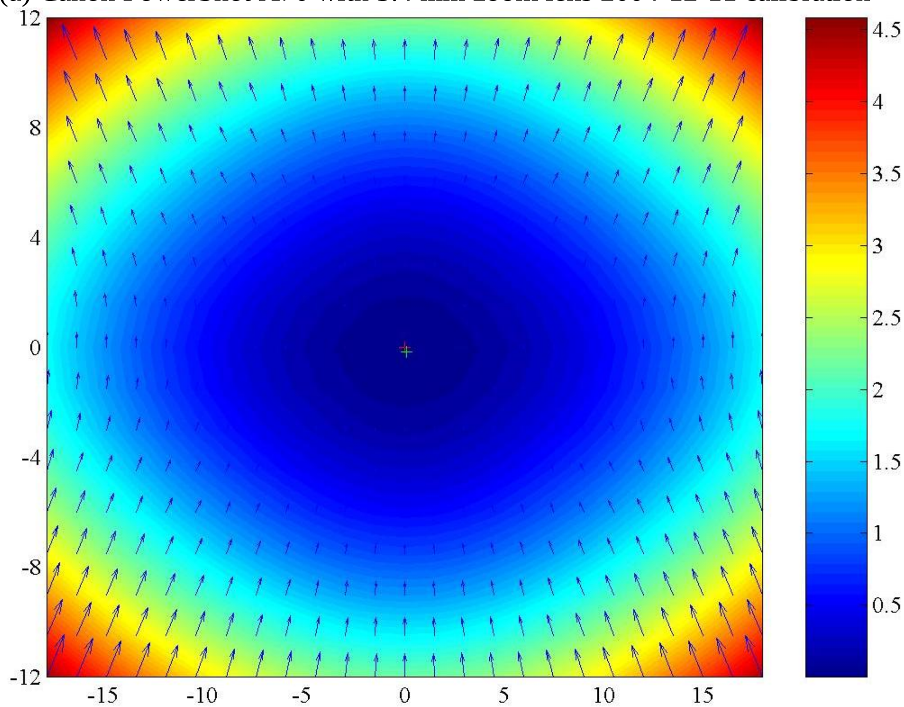
Figure 5.4 Decentring distortion calculated with profile function for various lenses calibrated at different tests

Using the decentring distortion coefficients and principal point offsets in Table 5.9, the two components in x and y directions can be computed with Equation 2.5 at discrete positions of the whole image format. Illustrated in Figure 5.5 are decentring distortion vector maps for the Canon PowerShot A70 with 5.4 mm zoom lens calibrated on 2004-12-11, and the Canon EOS 1Ds Mark II with 35 mm lens calibrated on 2005-09-16. Similar graphs could be produced for other camera and lenses calibrated at different tests. The red '+' symbol indicates the physical centre of the image plane whereas the green 'x' symbol denotes the estimated principal point. The arrows denote magnitude and orientation of the gradient of decentring distortion. The intensity of the images is proportional to the amount of compensation necessary to find the correct location of any given pixel. It can be seen from Figure 5.5 that the decentring distortion effect is largest at the edge of the image format and negligible near the center. It should also be noted that, near the four corners, the corrective displacement is only about 3 pixels and

1 pixel for the Canon PowerShot A70 with 5.4 mm zoom lens and the Canon EOS 1Ds Mark II with 35 mm lens.



(a) Canon PowerShot A70 with 5.4 mm zoom lens 2004-12-11 calibration



(b) Canon EOS 1Ds Mark II with 35 mm lens 2005-09-16 calibration

Figure 5.5 Decentring distortion vector map in µm

5.3.5 Lens distortion parameter check

It is known that the unknown real behaviour of the camera system depends on the suitability of the mathematical model used in the camera calibration. An appropriate mathematical model guarantees that the image measurements and the derived object measurements in 3D space are free of systematic error, or at least that the error is negligible. Lens radial and decentring distortion parameters have been determined by the mathematical models described in the previous sections. A question arises concerning how good the lens distortion parameters are. An independent check of lens distortion parameters using plumb-line principle is presented in this section.

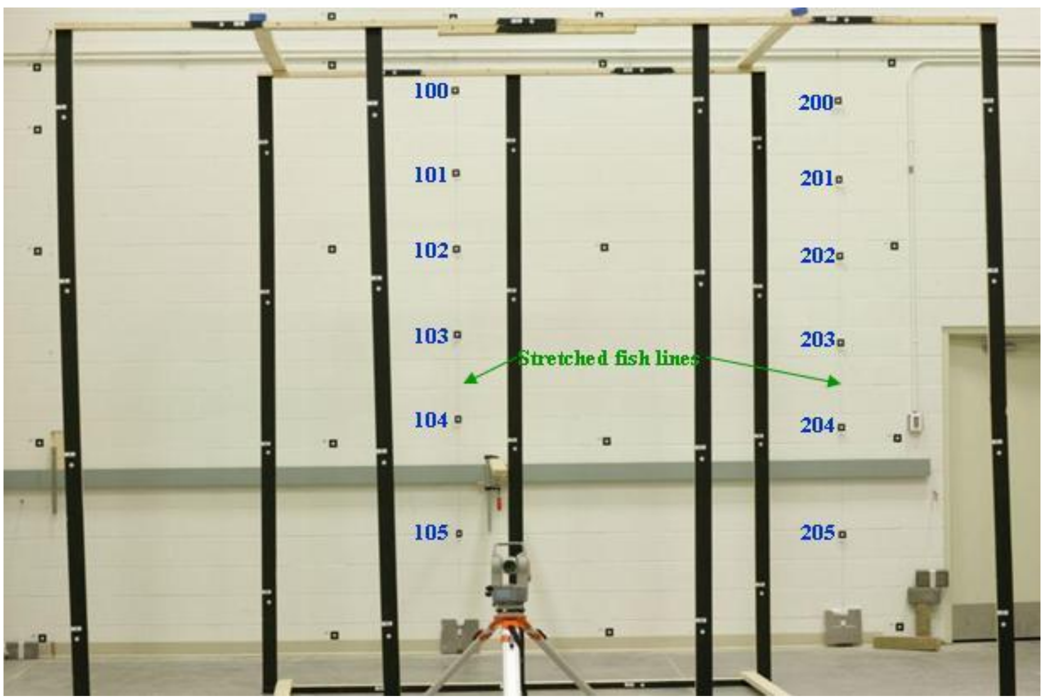


Figure 5.6 Straight-line features at the test range #2

As shown in Figure 5.6, two straight-line features were generated from fishing string stretched by a weight at one end in the second test range described in previous chapter. One fishing line was located in the centre of the image, while the other at the right edge of the image. There were 6 circular targets attached on each fishing line in a way that the fishing string runs through the centre of each target. Theoretically, 6 targets on each fishing string should be located on same line after correction of lens radial and decentring distortions.

Images were captured with the Canon PowerShot A70 camera with zoom lens, and the Canon EOS 1Ds Mark II 35 mm and 85 mm lenses. The 3D coordinates of these 12 targets were obtained from each camera calibration bundle adjustment. In other words, the 3D coordinates of those targets were the by-product of camera calibration. Based on the 3D coordinates of these 6 targets, a best-fit straight line can be found, and the co-linearity of the 6 targets can be examined. Table 5.12 lists the comparison of measured coordinates and corresponding coordinates on the best-fit line.

Table 5.12 Comparison of measured coordinates and best-fit coordinates

Camera & lens	Target #	Measured coordinates			Best-fit coordinates			Distance between measured coordinates and best-fit coordinates (m)
		X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	
Canon EOS 1Ds Mark II 35 mm lens	100	-0.085	2.742	2.773	-0.085	2.742	2.773	1.0000E-04
	101	-0.082	2.742	2.206	-0.082	2.742	2.206	3.1623E-04
	102	-0.080	2.742	1.683	-0.080	2.742	1.683	5.0000E-04
	103	-0.077	2.741	1.097	-0.077	2.741	1.097	4.4721E-04
	104	-0.074	2.741	0.516	-0.074	2.741	0.516	2.0000E-04
	105	-0.070	2.741	-0.266	-0.070	2.741	-0.266	2.8284E-04
	200	-0.068	5.368	2.687	-0.069	5.369	2.687	1.0630E-03
	201	-0.070	5.368	2.141	-0.070	5.368	2.141	1.0000E-04
	202	-0.072	5.367	1.614	-0.071	5.367	1.614	8.9443E-04
	203	-0.073	5.367	1.017	-0.073	5.367	1.017	5.0000E-04
	204	-0.074	5.366	0.435	-0.074	5.366	0.435	1.0000E-04
	205	-0.075	5.365	-0.304	-0.076	5.365	-0.304	6.0000E-04
Canon EOS 1Ds Mark II 85 mm lens	100	-0.085	2.742	2.773	-0.085	2.742	2.773	3.1623E-04
	101	-0.082	2.742	2.206	-0.082	2.742	2.206	3.1623E-04
	102	-0.079	2.741	1.683	-0.079	2.742	1.683	5.3852E-04
	103	-0.076	2.741	1.097	-0.076	2.741	1.097	3.6056E-04
	104	-0.073	2.741	0.517	-0.073	2.741	0.517	4.0000E-04
	105	-0.070	2.741	-0.265	-0.070	2.741	-0.265	5.8310E-04
	200	-0.069	5.369	2.687	-0.069	5.369	2.687	0.0000E+00
	201	-0.070	5.368	2.141	-0.070	5.368	2.141	3.1623E-04
	202	-0.071	5.368	1.614	-0.071	5.368	1.614	5.0000E-04
	203	-0.073	5.367	1.017	-0.073	5.367	1.017	5.3852E-04
	204	-0.074	5.366	0.435	-0.074	5.366	0.435	2.2361E-04
	205	-0.075	5.365	-0.304	-0.075	5.365	-0.304	3.1623E-04
Canon PowerShot A70 zoom lens	100	-0.085	2.742	2.774	-0.086	2.742	2.774	1.0050E-03
	101	-0.081	2.742	2.206	-0.083	2.742	2.206	1.7263E-03
	102	-0.082	2.741	1.684	-0.080	2.742	1.684	2.4515E-03
	103	-0.076	2.741	1.098	-0.076	2.741	1.098	2.2361E-04
	104	-0.076	2.741	0.517	-0.073	2.741	0.517	3.4000E-03
	105	-0.065	2.741	-0.265	-0.068	2.741	-0.265	3.0150E-03
	200	-0.067	5.368	2.687	-0.067	5.369	2.687	6.4031E-04
	201	-0.068	5.368	2.141	-0.069	5.368	2.141	1.4142E-03
	202	-0.071	5.368	1.614	-0.071	5.368	1.614	3.1623E-04
	203	-0.077	5.369	1.017	-0.073	5.368	1.017	3.9000E-03
	204	-0.076	5.367	0.435	-0.076	5.367	0.435	5.3852E-04
	205	-0.076	5.366	-0.303	-0.078	5.367	-0.303	2.2136E-03

Table 5.12 gives an idea of how good the correction of lens distortion is. For the Canon EOS 1Ds Mark II camera with 35 mm and 85 mm lenses, the distances between the measured coordinates and best-fit coordinates are in the sub-millimeter range, while the distances are around sub-centimeter for the Canon Powershop A70 with 5.4 mm zoom lens. The results show that the practical reality may be something which is not perfectly modelled by any combination of radial and decentring distortion parameters. Another possible source of error in this case can be the error of digitizing the centre of targets. The result also indicates that the camera and lens quality can influence the accuracy of the computed object coordinates.

5.3.6 Affinity and non-orthogonality parameters

As mentioned in Appendix A, the affinity and non-orthogonality coefficients *B1* and *B2* are used to compensate for any difference in pixel width and height in 3DM CalibCam. Using the coefficients *B1*, *B2* and principal point offsets in Table 5.9, the maximum differences calculated with Equation A.7 for all of the calibration tests in this study are presented in Table 5.13. For the Canon PowerShot A70 with 5.4 mm zoom lens, the maximum difference in pixel width and height is 6.1 μm, which is less than 3 pixels and this occurred at the lower-left corner of the sensor. For the Canon EOS 1Ds Mark II with 35 mm, 85 mm, 135 mm and 200 mm lenses, the maximum compensation in pixel width is 5.6 μm, less than 1 pixel of the image sensor.

Table 5.13 Maximum compensation in pixel width for all calibration tests

Camera & lens	Date of calibration	Maximum compensation in pixel width (μm)	Location of the maximum compensation	
			X (mm)	Y (mm)
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	5.5	-2.64	-1.98
	2005-04-10	5.4	-2.64	-1.98
	2005-09-11	6.1	-2.64	-1.98
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	5.6	-18.00	12.00
	2005-06-17	1.4	-18.00	12.00
	2005-09-13	0.7	18.00	12.00
	2005-09-16	1.1	18.00	12.00
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	3.2	-18.00	12.00
	2005-06-17	2.0	18.00	12.00
	2005-09-13	0.6	-18.00	-12.00
	2005-09-16	0.4	-18.00	-12.00
Canon EOS 1Ds Mark II with 135 mm lens	2005-06-17	3.0	-18.00	-12.00
Canon EOS 1Ds Mark II with 200 mm lens	2005-06-17	4.0	-18.00	-12.00

Vector maps of the compensation made by *B1* and *B2* are shown in Figure 5.7 and Figure 5.8 for the Canon PowerShot A70 with 5.4 mm zoom lens calibrated on 2005-09-11 and the Canon EOS 1Ds Mark II with 35 mm lens calibrated on 2005-03-11. Again, the red '+' symbol indicates the physical centre of the image plane whereas the green 'x' symbol denotes the estimated principal point. The arrows denote magnitude and orientation of the gradient of decentring distortion. The intensity of the images is proportional to the amount of compensation necessary to find the correct location of any given pixel. Similar graphs could be made for other calibration tests.

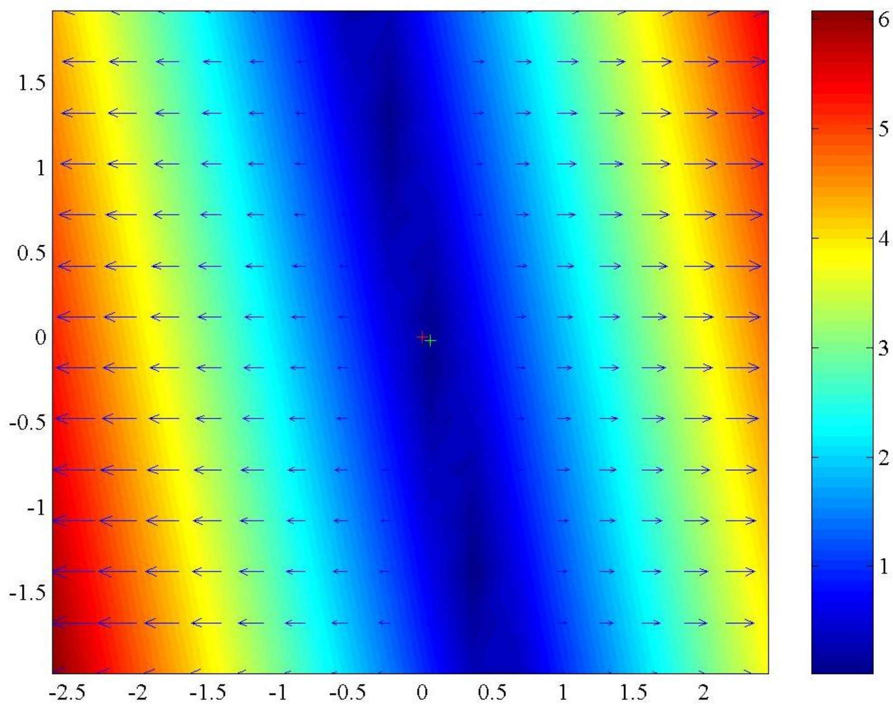


Figure 5.7 Compensation vector map made by *B1* and *B2* for Canon PowerShot A70 with 5.4 mm zoom lens calibrated on 2005-09-11

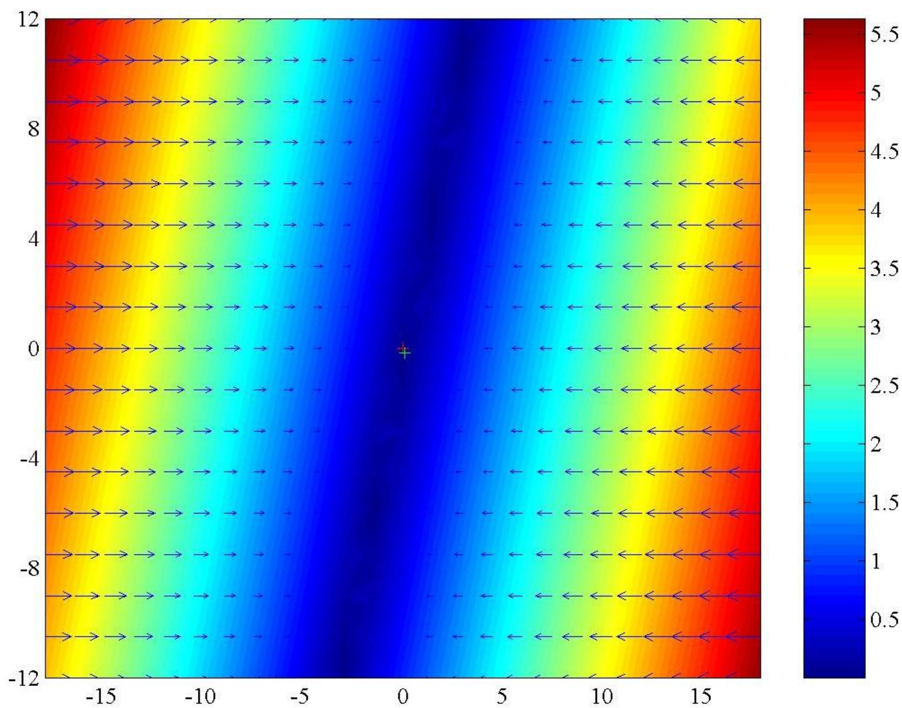


Figure 5.8 Compensation vector map made by *B1* and *B2* for Canon EOS 1Ds Mark II with 35 mm lens calibrated on 2005-03-13

It can be seen from Figure 5.7 and Figure 5.8 that the largest compensation always occurs at the two side-edge of the sensor. It is interesting to note that the arrows are pointing to different directions on each side of the sensor edge. In Figure 5.7, the arrows point towards the side-edge of the sensor, while the arrows point away the side-edge of the sensor in Figure 5.8.

5.4 Camera Calibration Comparison

5.4.1 Introduction

The previous sections have been dedicated to exploring and gaining an understanding of the relationships between camera calibration parameters, and the behaviour of calibration parameters from different calibration tests. A series of sets of calibration parameters for the same camera and lens have been estimated from various tests. A pertinent question to ask at this point is whether these sets of calibration parameters are compatible or if the camera and lens is stable enough to meet photogrammetric measurement requirements.

Two sets of calibration parameters can be compared in the 3DM CalibCam software by dragging and dropping one on top of the other. The overall difference, which is the root-mean-square (RMS) of the discrepancy of corrections at each pixel over the entire image format between the two camera calibrations, is displayed. It is claimed in the 3DM CalibCam 2.2 User’s Manual – First Draft that if the difference between two calibrations is within 0.1 pixels over the whole image area, the two calibrations can be considered stable.

As an example, the calibrations of the Canon EOS 1Ds Mark II with 35 and 85 mm lenses on September 16, 2005 and the Canon PowerShot A70 with 5.4 mm zoom lens on September 11, 2005 are compared with calibrations at other times. The RMS results in pixels are presented in Table 5.14.

Table 5.14 RMS in pixels comparing September 2005 calibration with other calibrations

Camera & lens	Date of calibration	RMS (pixel)	
		2005-09-11	2005-09-16
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	0.82	-
	2005-04-10	0.64	-
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	-	0.29
	2005-06-17	-	0.12
	2005-09-13	-	0.12
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	-	0.31
	2005-06-17	-	0.09
	2005-09-13	-	0.23

Based on the criteria of 0.1 pixels, the results in Table 5.14 indicate that the different calibrations for the same camera and lens are not stable. Does this mean these calibrations are not compatible?

5.4.2 Comparison with all images and all control points

To answer this question, a series of bundle adjustment are repeated with the same images, same image point accuracy setting (Sx=0.1 pixel, Sy=0.1 pixel) and same control points on September 16, 2005 for Canon EOS 1Ds Mark II with 35 mm and 85 mm lenses, and on September 11, 2005 for Canon PowerShot A70 with 5.4 mm zoom lens, but with interior orientation parameters determined from different calibration tests held fixed, which means the parameters values are not allowed to change during the bundle adjustment. All of the bundle adjustment tests were successful. The RMSs of image residual and control point residual are shown in Table 5.15.

Table 5.15 RMS of image sigma and control point residual

Camera & lens	Date of calibration	Image Sigma (pixel)	Control point residual			
			S_X (m)	S_Y (m)	S_Z (m)	Overall (m)
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	3.55	0.008	0.007	0.004	0.011
	2005-04-10	4.90	0.011	0.009	0.006	0.015
	2005-09-11	0.90	0.003	0.003	0.003	0.003
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	2.42	0.001	0.001	0.001	0.002
	2005-06-17	1.67	0.001	0.001	0.001	0.002
	2005-09-13	1.90	0.002	0.002	0.001	0.003
	2005-09-16	1.00	0.001	0.001	0.001	0.002
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	1.22	0.002	0.002	0.001	0.003
	2005-06-17	1.09	0.002	0.001	0.001	0.002
	2005-09-13	1.20	0.003	0.002	0.001	0.003
	2005-09-16	0.81	0.001	0.001	0.001	0.002

With the interior orientation parameters held fixed, the image sigmas increase as expected. For the Canon PowerShot A70 with 5.4 mm lens, the control point residuals are higher than the survey error (±0.003 m), especially in the depth direction (S_x). However, the overall control point residuals for the Canon EOS 1Ds Mark II with 35 mm and 85 mm lenses are still within the survey error.

Since the true values of exterior orientation parameters (camera perspective centre location and orientation) are unknown, the calculated exterior orientation parameters from the bundle adjustment on September 16, and September 11, 2005 are considered as base-line. The exterior orientation parameters from the bundle adjustment tests using other calibrations from different tests are then compared to the base-line. The RMSs of the differences are listed in Table 5.16.

Table 5.16 RMS of the difference of exterior orientation parameters between September calibration and calibration determined at other times

Camera & lens	Date of calibration	RMS of the difference of exterior orientation					
		Camera location (m)			Camera rotation (°)		
		ΔX	ΔY	ΔZ	ω	φ	κ
Canon PowerShot A70 with 5.4 mm lens	2004-12-11	0.103	0.033	0.014	0.882	0.103	0.877
	2005-04-10	0.136	0.044	0.018	2.658	0.171	2.638
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	0.002	0.001	0.002	0.111	0.012	0.110
	2005-06-17	0.002	0.001	0.001	0.199	0.028	0.196
	2005-09-13	0.023	0.007	0.004	0.304	0.040	0.301
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	0.030	0.003	0.008	0.708	0.066	0.708
	2005-06-17	0.005	0.003	0.002	0.295	0.034	0.293
	2005-09-13	0.036	0.002	0.007	0.271	0.037	0.272

The results in Table 5.16 show that the software algorithm is making the bundle adjustment work by sacrificing the exterior orientation. With the constraints in control point specified by the user, and the interior orientation parameters held fixed, the only parameters the software can manoeuvre are the exterior orientation. By changing the exterior orientation, the image ray bundles which connect the object space point, the perspective centre and the projected image point can be maintained to satisfy the bundle adjustment in the whole network.

Examining the residuals in Table 5.15 and the changes of exterior orientation in Table 5.16 indicates that although the bundle adjustment is successful using the pre-determined interior orientation parameters, there is risk of uncorrected errors occurring due to the differences between the operational condition in which the parameters are being used and the calibration condition in which the parameters are derived from. The potential errors may not be acceptable for applications requiring high accuracy.

5.4.3 Comparison with two images and six control points

The reality in many photogrammetric applications is that only two images are used to create down-stream products (digital terrain model, etc.) and limited control points are available due to field constraints. To quantify the impact of different calibration results from different calibration tests on the down-stream products under application situations, two images and six control points distributed in 3D space were used. A series of bundle adjustments were performed in CalibCam with the interior orientation parameters determined from different calibration tests held fixed. The 3D coordinates of relative points as by-product of the bundle adjustments were then compared with the baseline.

For the Canon Powershot A70 camera with 5.4 mm zoom lens, the calculated coordinate using interior orientation parameters from calibration test on April 10, 2005 is selected as the baseline for comparison. As shown in Figure 5.9, the six control points in red were chosen to run bundle adjustment and the coordinates of relative points in green were calculated.

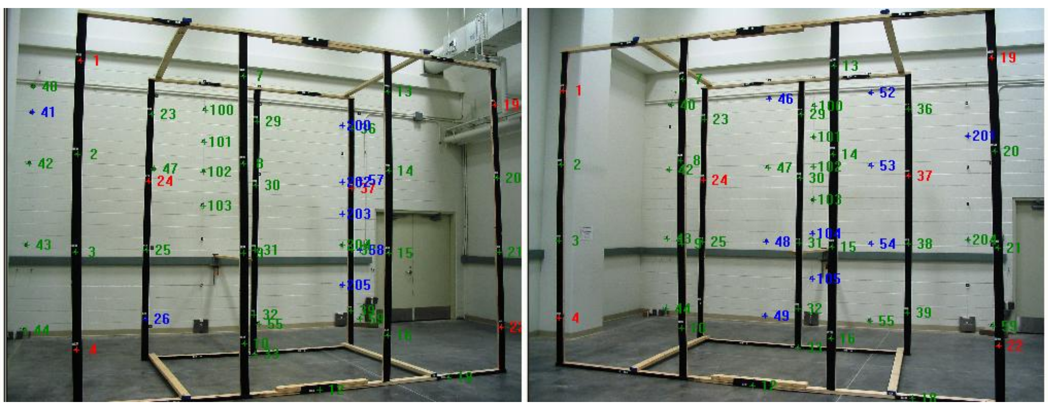


Figure 5.9 Left and right views of the control points and relative points at the test range #2 for Canon Powershot A70 with 5.4 mm zoom lens

For the Canon EOS 1Ds Mark II camera with 35 mm and 85 mm lenses, the baseline is the calculated coordinates using interior orientation parameters obtained from the calibration test on March 13, 2005. Figure 5.10 illustrated the distribution of control points (in red) and relative points (in blue) for the Canon EOS 1Ds Mark II with 35 mm.

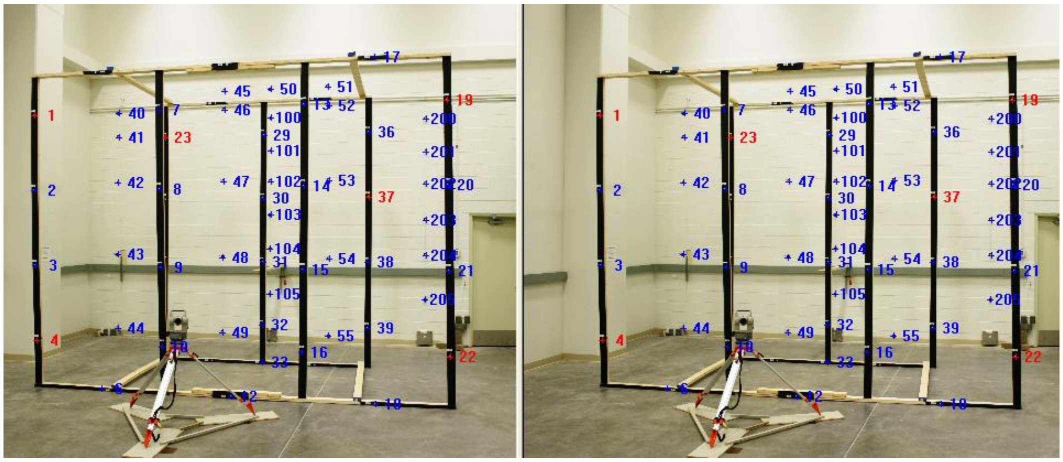


Figure 5.10 Left and right views of the control points and relative points at the test range #2 for Canon EOS 1Ds Mark II with 35 mm lens

The comparison of calculated coordinates and baseline coordinates for relative points are given in Appendix E. The root mean square (RMS) calculated from the coordinate difference of all the relative points compared to baseline are listed in Table 5.17.

Table 5.17 Summary of the root mean square of coordinate difference using calibration from different tests

Camera & lens	Calibration date as baseline	Calibration date for comparison	Coordinate RMS			
			S_X (m)	S_Y (m)	S_Z (m)	Overall (m)
Canon Powershot A70 with 5.4 mm zoom lens	2005-04-10	2004-12-11	0.007	0.003	0.002	0.008
		2005-09-11	0.031	0.014	0.009	0.036
Canon EOS 1Ds Mark II with 35 mm lens	2005-03-13	2005-06-17	0.002	0.001	0.001	0.002
		2005-09-13	0.003	0.001	0.001	0.004
		2005-09-16	0.002	0.001	0.001	0.002
Canon EOS 1Ds Mark II with 85 mm lens	2005-03-13	2005-06-17	0.003	0.002	0.001	0.004
		2005-09-13	0.001	0.001	0.001	0.001
		2005-09-16	0.003	0.002	0.001	0.003

The result in Table 5.17 shows that under the application configurations (two images and limited control points), the overall difference between the baseline and calculated coordinates is about one to four centimetres for the Canon Powershot A70 with 5.4 mm zoom lens. For the Canon EOS 1Ds Mark II with 35 mm and 85 mm prime lenses, the difference is less than one centimetre. In view of the fact that the survey control point accuracy is no better than a centimetre for most mining applications with moderate accuracy requirement, it is safe to conclude that the calibration results from different tests for the same professional camera and prime lens are compatible.

5.5 Summary

The calibration test results on Canon digital cameras with a zoom lens and prime lenses are presented and discussed in this chapter. For all of the tests, the image residual for most tests is less than 0.2 pixels with the exception of the outdoor calibrations, which indicates the image accuracy specified by the user is adequate for the whole image format of each image and all images included, and there is no mis-matched image points. The control point residuals are within the survey error specified by the user. This implies that the combination of control point distribution and imaging geometry has no obvious weakness. From a bundle adjustment point of view, the rays linking points in 3D space and image space through perspective centres have been established properly. The posterior variance factors are less than 1.0, but not significantly less than 1.0. This means the image accuracy or/and control-point accuracy have been slightly underestimated.

Correlations are known to exist among the interior and exterior orientation parameters. Investigation of the relationships between the parameters has shown the following.

- The correlations obtained from bundle adjustment are dependent on the network configuration and are also dependent on the parameters being adjusted.
- The radial distortion parameters K_1, K_2, K_3, K_4 are always highly correlated, no matter what the network configuration is. The high correlation between the radial lens distortion parameters originates from

the inclusion of higher order polynomial terms in the mathematical model used to represent physical radial distortions.

- There are often high correlations between the principal point offset X_P, Y_P and the decentring distortion parameters P_1, P_2.
- Without rotating the camera when taking images, it is very likely that high correlation exists between the principal point offset X_P, Y_P and exterior orientation rotation angles.

One of the concerns with high correlation between parameters is that such correlations may lead to instabilities in the bundle adjustment process if the network is geometrically weak. If the correlation coefficient between a pair of parameters is higher than 0.9, one parameter should be removed from the functional model. Then the bundle adjustment process is repeated. The following observations have been noted in this chapter.

- From a statistical point of view, the interior orientation parameters can be better determined by setting some of the highly correlated parameters to zero.
- Not all of the four radial distortion coefficients are significant. For the Canon 5.4 mm zoom lens, Canon EF 35 mm, 85 mm, and 135 mm lenses, the first two coefficients, K1 and K2, would be sufficient to describe the radial distortion effect.
- Fixing highly correlated parameters to zero has influence on the exterior orientation parameters.

It was found that the principal distance would change for different calibrations performed over a period of time for the Canon PowerShot A70 with 5.4 mm zoom lens and for the Canon EOS 1Ds Mark II with 35 mm and 85 mm lenses. A possible solution to achieve more stable calibrations is to physically fix the focal length of the camera by drilling a screw into the lens to prevent the focus from changing once it has set to infinity.

The results in Table 5.15 and Table 5.16 show that when pre-determined interior orientation parameters are used and held fixed to perform a bundle adjustment, there can be errors introduced because the field geometric and imaging conditions will differ from the calibration setup in which the calibration parameters were derived. These errors may not be acceptable for applications requiring high accuracy. However, for most mining applications with moderate accuracy requirement, the calibration results from different calibration tests for the same professional camera and prime lens are exchangeable as demonstrated in Table 5.17.

6 Conclusions and Recommendations

6.1 Conclusions

The camera calibrations carried out over a one-year period have demonstrated that the accuracy of the camera calibration parameters derived from bundle adjustment is a function of the quality of the observables in image space (image coordinates) and in 3D object space (control target coordinates), and the quality of the imaging network configuration including such aspects as the locations of camera stations and control targets, imaging geometry. The recommended practices to obtain a good calibration result are summarized below.

Image capturing

- Ensure that the optical characteristics of the camera and lens remain constant during the image capturing process
- Always remember to turn off the auto-rotate function when taking images. Once the image has been rotated, the relationship between calibration and image is broken
- Follow the image capturing recommendations by Adam Technology to obtain good quality images.

Imaging geometry

- Calibration should be done with convergent images rather than images with parallel optical axes.

The ratio of baseline to object distance

- The ratio of baseline to object distance was maintained in the range of 0.5 to 1 for the majority of camera calibration tests in this research.
- Although increasing B/O ratio will improve the accuracy in the depth direction, this may also cause problems for image-matching when the B/O ratio is more than 1.0.

Number of control targets

- The calibration tests carried out at test range #1, 2 and 4 have demonstrated that around 50 control targets well distributed in 3D space works well, given a strong imaging network.
- From a cost and efficiency point of view, the number of control targets could be reduced down to say 30 by utilizing more relative points and more camera stations without sacrificing object measurement accuracy.

Control target placement

- Control targets should be evenly distributed in 3D space and across the entire image format.
- Do not put all targets in a cluster or close to each other as this will lead to a very weak solution for the calibration parameters and a risk of extrapolation error.

Number of camera stations and multiple exposures at each station

- At least 6 camera stations should be employed, with at least two images per station, one image rotated 90°.
- The use of additional camera stations and multiple exposures at each camera station can be expected to not only improve precision, but also to significantly enhance the network's reliability.
- It is worth pointing out that if successive exposures cannot be assumed to be taken from precisely the same position, the images should not be grouped into the same camera station in CalibCam. Instead, an additional camera station or a set of exterior orientation parameters is introduced into the network for the bundle adjustment.

Camera station placement

- Camera stations should be arranged in such that as many as possible control targets can be "seen" from each camera station. Sufficient imaging rays linking control targets and corresponding image points increases the redundancy in a spatial intersection, and also alters the intersection geometry. This redundancy can help to detect surveying blunders and mis-matching errors.

- From an error control point of view, systematic error components that change from exposure to exposure can be averaged out in a sense. The camera stations should not be placed along the same line or plane or at the same elevation.

The process of designing and laying out an imaging network configuration is an art. Quantifying the quality of the network employed for camera calibration is a complex task. The recommendations described above are some guidelines drawn from the lessons learned from the calibration tests in this work. In reality, a calibration site that is appropriate for camera lenses and focus settings that might be used at a mining site can impose restraints on the selection of an ideal imaging geometry. Thus, the adoption of a less than optimal imaging geometry is frequently necessary in practice. This limitation should be kept in mind when examining the results.

Where ground truth of the camera calibration parameters is not available and there is no easy means to verify their accuracies, the successful bundle adjustment report from the CalibCam software must be relied on as an overall quality control measure. A successful bundle adjustment does not guarantee camera calibration results are accurate and valid. The image residuals and control point residuals must be carefully evaluated to ensure that a weak image network configuration has not compromised the accuracy of the results.

The calibration results in this study have shown that high correlation can exist among the interior and exterior orientation parameters. The correlations obtained from bundle adjustment are dependent on the network configuration and also dependent on the parameters being adjusted. It has been illustrated that the interior orientation parameters can be better determined by removing some of the highly correlated parameters (correlation coefficient higher than 0.9) from the functional model.

For the Canon PowerShot A70 with 5.4 mm zoom lens and Canon EOS 1Ds Mark II with 35 mm, 85 mm, 135 mm and 200 mm prime lens, the principal point offset are within a 0.3 mm range in both X and Y directions. Compared to metric cameras and lenses made specifically for photogrammetric purposes where the difference between the fiducial centre and the determined principal point is within few µms, the principal point offset determined in this study is large. This may be due to the fact that for many digital cameras the position of the sensor with respect to the lens is not considered important as it makes little difference to the visual quality of the image.

Compared to the professional SLR Canon EOS 1Ds Mark II camera with prime lenses, the accuracy attainable for the lower-end Canon PowerShot A70 camera with 5.4 mm zoom lens is of necessity lower, but this research has indicated that the lower-end digital camera with zoom lens can still be useful in low accuracy requirement applications.

For the professional SLR Canon EOS 1Ds Mark II camera with 35 mm and 85 mm prime lenses, three-dimensional coordinates comparison result shows that interior orientation parameter sets determined from different calibration tests are compatible for most mining applications with moderate accuracy demand. However, it is worth mentioning that when pre-determined interior orientation parameters are used and held fixed to perform a bundle adjustment in other photogrammetric applications, there is risk of uncorrected errors due to differences between the operational conditions in which the parameters are being used and the calibration condition in which the parameters are derived. This risk may not be acceptable for applications requiring high accuracy. For applications demanding high accuracy, site-specific camera calibration should be employed by determining the camera calibration parameters and performing the actual measurement of the object of interest simultaneously.

6.2 Future Research

The 135 mm and 200 mm long-range lenses need to be calibrated at a test site with sufficient control targets well distributed in 3D space and with several hundred metres object distance to ensure good quality images are captured. In addition, the influence from the surrounding environment on the independent survey accuracy of the control targets and on the image acquisition should be minimized in order to maximize the achievable calibration accuracy. The test site that was used in this study was not ideal for this purpose.

It is recommended that the focal length of the camera should be physically fixed to avoid focal ring drifting. This could facilitate evaluating geometric stability of the imaging system.

Given the fact that there is a direct link between the accuracy of surveyed control targets and the calibration result derived using this survey data, and considering the realistically achievable surveying accuracy in practice, it is most desirable to take advantage of known geometric constraints between points, lines, and planes on three-dimensional objects to improve the accuracy of estimates in the camera calibration process. Therefore, future research could examine the straight plumb-line method to derive the radial and decentring lens distortion coefficients. Then hold these lens distortion parameters fixed to recover the principal point offset and the other parameters from the test-range method using a scale bar with high length accuracy, rather than surveyed 3D control points. It is hoped that the principal point offset would be retrieved with more confidence.

One application of digital photogrammetry in the mining industry is to generate digital terrain models. Accuracy assessment of digital terrain model data is essentially an intricate process. Further research could investigate the impact of camera calibration accuracy on the quality of digital terrain models since the camera calibration has a direct influence on the construction of a digital terrain model from a discrete distribution of points that have been sampled on the terrain.

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Appendix A: Adam Technology Image Coordinate System

Pixel and image coordinate systems used in Adam Technology software are illustrated in Figure A - 1. The origin of pixel coordinate system is located at the bottom-left corner of the sensor, with the positive X-axis directed towards right and positive Y-axis upwards. The origin of image coordinate system is the centre of sensor with the same direction designation as the pixel coordinate system.

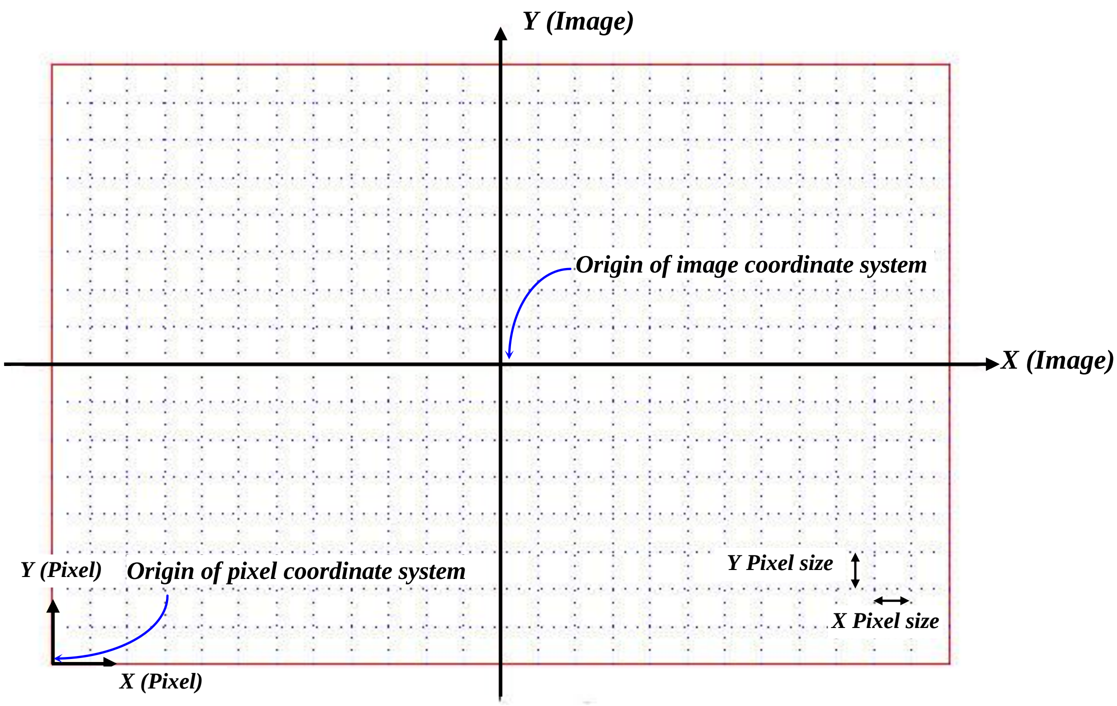

Figure A - 1 Adam Technology pixel and image coordinate systems

The location of any artificial target or natural feature digitized either manually or by centroid algorithm is measured to 1/10 pixel accuracy in the pixel coordinate system, expressed as $XPixel$ and $YPixel$ respectively. With total number of pixels and pixel size in both X and Y directions known from camera manufacture specification, the measured pixel coordinates are then converted to the image coordinate system as follows. The centre of the sensor in pixel coordinate system is:

$$CenterX = \frac{Total\ Number\ of\ \ Pixel\ in\ X\ \ direction}{2}$$
$$CenterY = \frac{Total\ Number\ of\ \ Pixel\ in\ Y\ direction}{2} \qquad \text{A. 1}$$

Then, the measured image coordinates are

$$X_{Image} = (\ XPixel - CenterX\ ) \times XPixelSize$$
$$Y_{Image} = (\ YPixel - CenterY\ ) \times YPixelSize \qquad \text{A. 2}$$

In reality, the transformation from object space to image space with a camera and lens is distorted. In Adam Technology software, the following calibration parameters are used to model distortion:

Principal distance: C

Principal point offset: X_P, Y_P

Radial distortion coefficients: K_1, K_2, K_3, K_4

Decentring distortion coefficients: P_1, P_2

Affinity, non-orthogonality parameters: B_1, B_2

The radial distortion is expressed as a polynomial function of the radial distance from the principal point:

$$\delta r = K_1 r^3 + K_2 r^5 + K_3 r^7 + K_4 r^9 \qquad \text{A. 3}$$

$$r^2 = (\ X_{Image} - X_P\ )^2 + (Y_{Image} - Y_P\ )^2 \qquad \text{A. 4}$$

The radial distortion δr can be resolved into two components:

$$\delta r_x = \delta r (X_{\mathrm{Im}age} - X_P) / r$$
$$\delta r_y = \delta r (Y_{\mathrm{Im}age} - Y_P) / r \qquad \text{A. 5}$$

The decentring distortion is described by two polynomials, one for the displacement in the direction of the x-fiducial axis and the other for displacement in the y-direction:

$$\delta x = P_1[r^2 + 2(X_{\mathrm{Im}age} - X_P)^2] + 2P_2(X_{\mathrm{Im}age} - X_P)(Y_{\mathrm{Im}age} - Y_P)$$
$$\delta y = P_2[r^2 + 2(Y_{\mathrm{Im}age} - Y_P)^2] + 2P_1(X_{\mathrm{Im}age} - X_P)(Y_{\mathrm{Im}age} - Y_P) \qquad \text{A. 6}$$

The affinity and non-orthogonality coefficients B_1 and B_2 are used to compensate for any difference in pixel width (x direction) compared to the pixel height (y direction), which is calculated:

$$\delta x_B = B_1 \cdot (X_{\mathrm{Im}age} - X_P) + B_2 \cdot (Y_{\mathrm{Im}age} - Y_P) \qquad \text{A. 7}$$

The corrected image coordinate can be calculated from the measured image coordinates by using the following formula:

$$X_{corrected} = (X_{\mathrm{Im}age} - X_P) + \delta r_x + \delta x + \delta x_B$$
$$Y_{corrected} = (Y_{\mathrm{Im}age} - Y_P) + \delta r_y + \delta y \qquad \text{A. 8}$$

Appendix B: Control Point Coordinates

Control points coordinates for test range #1

Pt No	*Control point coordinates*			*Standard deviations of the control point*		
	X (m)	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
1	0.026	0.305	0.000	0.010	0.010	0.010
2	0.026	0.913	0.000	0.010	0.010	0.010
3	0.026	1.521	0.000	0.010	0.010	0.010
4	0.026	2.129	0.000	0.010	0.010	0.010
5	0.026	2.737	0.000	0.010	0.010	0.010
6	0.026	3.345	0.000	0.010	0.010	0.010
7	0.305	0.305	0.000	0.010	0.010	0.010
8	0.305	0.913	0.000	0.010	0.010	0.010
9	0.305	1.521	0.000	0.010	0.010	0.010
10	0.305	2.129	0.000	0.010	0.010	0.010
11	0.305	2.737	0.000	0.010	0.010	0.010
12	0.305	3.345	0.000	0.010	0.010	0.010
13	0.584	0.305	0.000	0.010	0.010	0.010
14	0.584	0.913	0.000	0.010	0.010	0.010
15	0.584	1.521	0.000	0.010	0.010	0.010
16	0.584	2.129	0.000	0.010	0.010	0.010
17	0.584	2.737	0.000	0.010	0.010	0.010
18	0.584	3.345	0.000	0.010	0.010	0.010
19	0.814	0.029	0.737	0.010	0.010	0.010
20	0.814	0.582	0.737	0.010	0.010	0.010
21	0.814	1.190	0.737	0.010	0.010	0.010
22	0.814	1.798	0.737	0.010	0.010	0.010
23	0.814	2.406	0.737	0.010	0.010	0.010
24	0.814	3.011	0.737	0.010	0.010	0.010
25	1.090	0.029	0.737	0.010	0.010	0.010
26	1.090	0.582	0.737	0.010	0.010	0.010
27	1.090	1.190	0.737	0.010	0.010	0.010
28	1.090	1.798	0.737	0.010	0.010	0.010
29	1.090	2.406	0.737	0.010	0.010	0.010
30	1.090	3.011	0.737	0.010	0.010	0.010
31	1.366	0.029	0.737	0.010	0.010	0.010
32	1.366	0.582	0.737	0.010	0.010	0.010
33	1.366	1.190	0.737	0.010	0.010	0.010
34	1.366	1.798	0.737	0.010	0.010	0.010
35	1.366	2.406	0.737	0.010	0.010	0.010
36	1.366	3.011	0.737	0.010	0.010	0.010
37	1.519	0.029	1.379	0.010	0.010	0.010
38	1.519	0.582	1.379	0.010	0.010	0.010
39	1.519	1.190	1.379	0.010	0.010	0.010
40	1.519	1.798	1.379	0.010	0.010	0.010
41	1.519	2.406	1.379	0.010	0.010	0.010
42	1.519	3.011	1.379	0.010	0.010	0.010
43	1.795	0.029	1.379	0.010	0.010	0.010
44	1.795	0.582	1.379	0.010	0.010	0.010
45	1.795	1.190	1.379	0.010	0.010	0.010
46	1.795	1.798	1.379	0.010	0.010	0.010
47	1.795	2.406	1.379	0.010	0.010	0.010
48	1.795	3.011	1.379	0.010	0.010	0.010
49	2.071	0.029	1.379	0.010	0.010	0.010

50	2.071	0.582	1.379	0.010	0.010	0.010
51	2.071	1.190	1.379	0.010	0.010	0.010
52	2.071	1.798	1.379	0.010	0.010	0.010
53	2.071	2.406	1.379	0.010	0.010	0.010
54	2.071	3.011	1.379	0.010	0.010	0.010

Control points coordinates for test range #2

Pt No	*Control point coordinates*			*Standard deviations of the control point*		
	X (m)	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
1	3.944	0.736	2.167	0.003	0.003	0.003
2	3.942	0.747	1.268	0.003	0.003	0.003
3	3.939	0.763	0.369	0.003	0.003	0.003
4	3.930	0.779	-0.530	0.003	0.003	0.003
5	3.968	1.554	2.638	0.003	0.003	0.003
6	3.933	1.631	-1.065	0.003	0.003	0.003
7	3.931	2.336	2.165	0.003	0.003	0.003
8	3.930	2.349	1.266	0.003	0.003	0.003
9	3.919	2.369	0.366	0.003	0.003	0.003
10	3.905	2.384	-0.534	0.003	0.003	0.003
11	3.946	3.150	2.645	0.003	0.003	0.003
12	3.916	3.206	-1.061	0.003	0.003	0.003
13	3.914	4.018	2.177	0.003	0.003	0.003
14	3.911	4.014	1.276	0.003	0.003	0.003
15	3.905	4.011	0.367	0.003	0.003	0.003
16	3.896	4.006	-0.532	0.003	0.003	0.003
17	3.928	4.786	2.648	0.003	0.003	0.003
18	3.914	4.808	-1.052	0.003	0.003	0.003
19	3.883	5.545	2.180	0.003	0.003	0.003
20	3.883	5.553	1.281	0.003	0.003	0.003
21	3.886	5.569	0.380	0.003	0.003	0.003
22	3.887	5.584	-0.519	0.003	0.003	0.003
23	1.929	1.617	2.164	0.003	0.003	0.003
24	1.909	1.614	1.265	0.003	0.003	0.003
25	1.897	1.608	0.363	0.003	0.003	0.003
26	1.903	1.604	-0.537	0.003	0.003	0.003
27	1.954	2.386	2.638	0.003	0.003	0.003
28	1.922	2.346	-1.061	0.003	0.003	0.003
29	1.915	3.093	2.169	0.003	0.003	0.003
30	1.917	3.086	1.270	0.003	0.003	0.003
31	1.912	3.085	0.371	0.003	0.003	0.003
32	1.901	3.084	-0.529	0.003	0.003	0.003
33	1.916	3.087	-1.063	0.003	0.003	0.003
34	1.937	3.867	2.646	0.003	0.003	0.003
35	1.913	3.837	-1.061	0.003	0.003	0.003
36	1.900	4.576	2.179	0.003	0.003	0.003
37	1.891	4.568	1.280	0.003	0.003	0.003
38	1.886	4.567	0.382	0.003	0.003	0.003
39	1.887	4.563	-0.520	0.003	0.003	0.003
40	-0.074	-0.114	2.958	0.003	0.003	0.003
41	-0.076	-0.111	2.528	0.003	0.003	0.003
42	-0.076	-0.114	1.695	0.003	0.003	0.003
43	-0.077	-0.112	0.382	0.003	0.003	0.003
44	-0.077	-0.107	-0.955	0.003	0.003	0.003
45	-0.082	1.902	3.289	0.003	0.003	0.003

46	-0.082	1.902	2.955	0.003	0.003	0.003
47	-0.084	1.893	1.690	0.003	0.003	0.003
48	-0.086	1.889	0.359	0.003	0.003	0.003
49	-0.085	1.885	-0.955	0.003	0.003	0.003
50	-0.085	2.733	3.275	0.003	0.003	0.003
51	-0.089	3.735	3.285	0.003	0.003	0.003
52	-0.091	3.754	2.952	0.003	0.003	0.003
53	-0.092	3.753	1.687	0.003	0.003	0.003
54	-0.092	3.755	0.355	0.003	0.003	0.003
55	-0.091	3.762	-0.956	0.003	0.003	0.003
56	-0.100	5.751	2.952	0.003	0.003	0.003
57	-0.101	5.752	1.683	0.003	0.003	0.003
58	-0.101	5.758	0.356	0.003	0.003	0.003
59	-0.099	5.762	-0.948	0.003	0.003	0.003

Control points coordinates for test range #3

Pt No	*Control point coordinates*			*Standard deviations of the control point*		
	X (m)	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
1	98.47	119.267	100.955	0.010	0.010	0.010
2	98.476	119.279	104.031	0.010	0.010	0.010
3	98.483	119.307	106.136	0.010	0.010	0.010
4	99.814	119.362	101.704	0.010	0.010	0.010
5	102.339	118.462	100.265	0.010	0.010	0.010
6	104.725	117.635	101.687	0.010	0.010	0.010
7	107.511	116.665	101.646	0.010	0.010	0.010
8	110.016	115.758	100.319	0.010	0.010	0.010
9	112.697	114.812	101.617	0.010	0.010	0.010
10	113.506	113.991	100.942	0.010	0.010	0.010
11	113.512	113.999	104.178	0.010	0.010	0.010
12	113.515	114.023	106.133	0.010	0.010	0.010
14	105.579	142.295	109.294	0.010	0.010	0.010
15	117.69	138.021	113.405	0.010	0.010	0.010
16	98.237	114.065	99.878	0.010	0.010	0.010
17	100.705	113.201	99.886	0.010	0.010	0.010
18	103.913	114.566	99.941	0.010	0.010	0.010
19	106.34	113.713	99.925	0.010	0.010	0.010
20	108.051	110.668	99.871	0.010	0.010	0.010
21	110.492	109.813	99.865	0.010	0.010	0.010
22	113.711	111.171	99.898	0.010	0.010	0.010
23	109.986	115.511	102.242	0.010	0.010	0.010
24	102.07	118.307	102.242	0.010	0.010	0.010
25	105.668	116.89	102.813	0.010	0.010	0.010
26	105.645	116.903	104.325	0.010	0.010	0.010

Control points coordinates for test range #4 on 2005-09-13

Pt No	*Control point coordinates*			*Standard deviations of the control point*		
	X (m)	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
1	5.781	-0.566	-0.146	0.003	0.003	0.003
2	4.947	-0.533	1.628	0.003	0.003	0.003
3	4.274	-0.272	0.156	0.003	0.003	0.003
4	2.634	-0.179	3.456	0.003	0.003	0.003
5	2.634	-0.165	1.680	0.003	0.003	0.003
6	2.634	-0.178	-0.290	0.003	0.003	0.003
7	5.546	1.035	-1.529	0.003	0.003	0.003
8	-0.068	-0.056	3.530	0.003	0.003	0.003
9	0.241	0.355	0.891	0.003	0.003	0.003
10	0.814	0.383	0.199	0.003	0.003	0.003
11	1.394	0.413	-0.489	0.003	0.003	0.003
12	1.971	0.442	-1.178	0.003	0.003	0.003
13	4.241	0.485	-0.327	0.003	0.003	0.003
14	-0.080	1.309	1.727	0.003	0.003	0.003
15	4.215	1.245	-0.812	0.003	0.003	0.003
16	4.208	2.004	-1.293	0.003	0.003	0.003
17	6.783	2.056	-1.534	0.003	0.003	0.003
18	-0.078	2.472	3.510	0.003	0.003	0.003
19	0.230	2.382	0.891	0.003	0.003	0.003
20	0.807	2.381	0.202	0.003	0.003	0.003
21	1.384	2.385	-0.489	0.003	0.003	0.003
22	1.961	2.384	-1.180	0.003	0.003	0.003
23	4.367	2.599	-1.533	0.003	0.003	0.003
24	6.725	2.597	-1.545	0.003	0.003	0.003
25	-0.091	3.633	2.078	0.003	0.003	0.003
26	6.774	3.010	-1.540	0.003	0.003	0.003
27	-0.072	4.534	3.541	0.003	0.003	0.003
28	0.226	4.577	0.886	0.003	0.003	0.003
29	0.805	4.550	0.197	0.003	0.003	0.003
30	1.392	4.524	-0.495	0.003	0.003	0.003
31	1.976	4.495	-1.179	0.003	0.003	0.003
32	6.706	3.499	-1.544	0.003	0.003	0.003
33	6.747	3.993	-1.533	0.003	0.003	0.003
34	6.690	4.399	-1.543	0.003	0.003	0.003
35	6.729	4.797	-1.530	0.003	0.003	0.003
36	-0.100	5.661	1.751	0.003	0.003	0.003
37	4.215	5.471	-1.281	0.003	0.003	0.003
38	6.680	5.298	-1.545	0.003	0.003	0.003
39	6.707	5.746	-1.518	0.003	0.003	0.003
40	-0.075	7.010	3.589	0.003	0.003	0.003
41	0.205	7.161	0.882	0.003	0.003	0.003
42	0.784	7.117	0.195	0.003	0.003	0.003
43	1.370	7.080	-0.486	0.003	0.003	0.003
44	1.961	7.041	-1.164	0.003	0.003	0.003
45	4.217	6.240	-0.812	0.003	0.003	0.003
46	1.189	7.601	2.221	0.003	0.003	0.003
47	4.215	7.008	-0.342	0.003	0.003	0.003
48	5.494	6.821	-1.509	0.003	0.003	0.003
49	3.247	7.605	2.245	0.003	0.003	0.003
50	4.213	7.777	0.124	0.003	0.003	0.003
51	4.701	8.037	0.809	0.003	0.003	0.003
52	5.278	8.079	-0.152	0.003	0.003	0.003

Control points coordinates for test range #4 on 2005-09-16

Pt No	*Control point coordinates*			*Standard deviations of the control point*		
	X (m)	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
1	5.783	-0.567	-0.145	0.003	0.003	0.003
2	4.948	-0.534	1.627	0.003	0.003	0.003
3	4.275	-0.269	0.111	0.003	0.003	0.003
4	2.634	-0.180	3.456	0.003	0.003	0.003
5	2.636	-0.166	1.680	0.003	0.003	0.003
6	2.637	-0.178	-0.290	0.003	0.003	0.003
7	5.547	1.034	-1.529	0.003	0.003	0.003
8	-0.064	-0.057	3.529	0.003	0.003	0.003
9	0.241	0.353	0.889	0.003	0.003	0.003
10	0.814	0.381	0.199	0.003	0.003	0.003
11	1.393	0.411	-0.489	0.003	0.003	0.003
12	1.973	0.441	-1.178	0.003	0.003	0.003
13	4.241	0.495	-0.360	0.003	0.003	0.003
14	-0.079	1.308	1.728	0.003	0.003	0.003
15	4.215	1.264	-0.832	0.003	0.003	0.003
16	4.210	2.032	-1.299	0.003	0.003	0.003
17	6.782	2.054	-1.534	0.003	0.003	0.003
18	-0.076	2.470	3.509	0.003	0.003	0.003
19	0.230	2.381	0.891	0.003	0.003	0.003
20	0.809	2.379	0.202	0.003	0.003	0.003
21	1.384	2.383	-0.489	0.003	0.003	0.003
22	1.962	2.383	-1.180	0.003	0.003	0.003
23	4.376	2.617	-1.533	0.003	0.003	0.003
24	6.725	2.598	-1.544	0.003	0.003	0.003
25	-0.091	3.631	2.079	0.003	0.003	0.003
26	6.774	3.011	-1.540	0.003	0.003	0.003
27	-0.071	4.532	3.541	0.003	0.003	0.003
28	0.225	4.575	0.885	0.003	0.003	0.003
29	0.804	4.548	0.198	0.003	0.003	0.003
30	1.393	4.521	-0.496	0.003	0.003	0.003
31	1.976	4.494	-1.179	0.003	0.003	0.003
32	6.706	3.500	-1.545	0.003	0.003	0.003
33	6.747	3.993	-1.533	0.003	0.003	0.003
34	6.692	4.399	-1.542	0.003	0.003	0.003
35	6.729	4.797	-1.530	0.003	0.003	0.003
36	-0.099	5.658	1.750	0.003	0.003	0.003
37	4.215	5.470	-1.280	0.003	0.003	0.003
38	6.683	5.298	-1.544	0.003	0.003	0.003
39	6.707	5.745	-1.517	0.003	0.003	0.003
40	-0.075	7.008	3.590	0.003	0.003	0.003
41	0.205	7.161	0.881	0.003	0.003	0.003
42	0.783	7.116	0.195	0.003	0.003	0.003
43	1.369	7.078	-0.487	0.003	0.003	0.003
44	1.959	7.040	-1.165	0.003	0.003	0.003
45	4.216	6.239	-0.812	0.003	0.003	0.003
46	1.189	7.599	2.221	0.003	0.003	0.003
47	4.215	7.007	-0.343	0.003	0.003	0.003
48	5.494	6.821	-1.509	0.003	0.003	0.003
49	3.247	7.603	2.246	0.003	0.003	0.003
50	4.213	7.776	0.124	0.003	0.003	0.003
51	4.702	8.036	0.809	0.003	0.003	0.003
52	5.278	8.077	-0.152	0.003	0.003	0.003

Appendix C: Bundle Adjustment Reports Using 11 Unknown Interior Orientation Parameters

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2004-12-11

Project Name:	Canon PowerShot A70 calibration_2004-12-11
Created:	14/03/2007 at 14:06
Last Modified:	14/03/2007 at 14:06
Control Point File:	ControlPoints-Excel.xyz
Number of Active Image Files:	16
Posteriori Variance Factor:	0.64
Number of Degrees of Freedom:	1607
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon PowerShot A70 interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.03	0.25	0.25	-0.23	0.21	-0.20	0.04	-0.14	0.20	0.01	0.70	Z_3
Xp		1.00	-0.01	0.02	-0.02	0.02	-0.02	-0.87	0.01	0.02	0.21	-0.87	P1
Yp			1.00	-0.08	0.03	-0.01	0.01	0.02	-0.87	-0.23	0.02	-0.87	P2
K1				1.00	-0.96	0.91	-0.86	-0.02	0.09	0.07	0.03	-0.96	K2
K2					1.00	-0.99	0.96	0.01	-0.02	-0.03	-0.04	-0.99	K3
K3						1.00	-0.99	-0.01	0.01	0.02	0.05	-0.99	K4
K4							1.00	0.01	0.00	-0.02	-0.05	-0.99	K3
P1								1.00	-0.02	-0.06	0.05	-0.87	Xp
P2									1.00	0.10	0.00	-0.87	Yp
B1										1.00	0.00	-0.23	Yp
B2											1.00	0.21	Xp

Canon PowerShot A70 - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.52		8.27e-04	0.19
Xp	3.80e-02	14.77	5.74e-04	0.22
Yp	-2.04e-02	-7.94	5.80e-04	0.23
K1	6.05e-03	84.15	5.34e-05	0.74
K2	-2.35e-04	-35.55	2.25e-05	3.40
K3	5.44e-06	8.93	3.73e-06	6.13
K4	-4.21e-07	-7.52	2.08e-07	3.72
P1	1.28e-04	1.75	6.93e-06	0.09
P2	3.20e-04	3.61	7.09e-06	0.08
B1	1.91e-03	1.96	2.00e-05	0.02
B2	1.70e-04	0.13	2.00e-05	0.02

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2005-04-10

Project Name:	Canon PowerShot A70 calibration_2005-04-10
Project Last Modified:	15/03/2007 at 14:18
Bundle Adjustment Created:	19/06/2008 at 12:42
Control Point File:	Dummy01.txt
Number of Active Image Files:	7
Posteriori Variance Factor:	0.70
Number of Degrees of Freedom:	693
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon PowerShot A70 interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.02	0.02	0.65	-0.59	0.53	-0.49	-0.02	-0.01	0.38	-0.02	0.65	K1
Xp		1.00	-0.10	0.04	-0.05	0.06	-0.06	-0.98	0.12	-0.05	0.01	1.00	K_5
Yp			1.00	-0.01	0.01	-0.01	0.01	0.11	-0.55	0.02	-0.02	-0.98	O_5
K1				1.00	-0.97	0.92	-0.87	-0.05	0.02	-0.03	0.02	-0.97	K2
K2					1.00	-0.99	0.96	0.06	-0.02	0.00	-0.02	-0.99	K3
K3						1.00	-0.99	-0.06	0.02	0.00	0.02	-0.99	K4
K4							1.00	0.06	-0.02	-0.01	-0.02	-0.99	K3
P1								1.00	-0.11	0.05	-0.02	-0.98	Xp
P2									1.00	0.00	0.03	0.56	O_2
B1										1.00	-0.01	0.51	Pz33
B2											1.00	-0.56	Py33

Canon PowerShot A70 - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.50		1.13e-003	0.26
Xp	6.54e-002	25.42	3.14e-003	1.22
Yp	-2.44e-002	-9.50	1.61e-003	0.63
K1	5.86e-003	81.54	1.49e-004	2.08
K2	-1.84e-004	-27.79	5.61e-005	8.48
K3	-2.82e-007	-0.46	8.49e-006	13.93
K4	-2.30e-007	-4.11	4.42e-007	7.87
P1	1.26e-004	1.73	3.77e-005	0.52
P2	2.76e-004	3.12	1.37e-005	0.16
B1	1.87e-003	1.92	9.26e-005	0.09
B2	1.85e-004	0.14	9.14e-005	0.07

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2005-09-11

Project Name:	Canon PowerShot A70 calibration_2005-09-11
Project Last Modified:	20/06/2008 at 11:32
Bundle Adjustment Created:	20/06/2008 at 11:36
Control Point File:	ControlCoordinates.txt
Number of Active Image Files:	12
Posteriori Variance Factor:	0.84
Number of Degrees of Freedom:	821
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon PowerShot A70 interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.05	0.13	0.56	-0.53	0.50	-0.47	-0.06	-0.14	0.09	0.04	0.57	X_4
Xp		1.00	0.02	0.03	-0.04	0.04	-0.05	-0.96	-0.03	-0.01	0.50	-0.96	P1
Yp			1.00	0.02	-0.04	0.05	-0.06	-0.03	-0.89	-0.21	0.04	-0.89	P2
K1				1.00	-0.98	0.94	-0.90	-0.03	-0.02	-0.03	0.02	-0.98	K2
K2					1.00	-0.99	0.97	0.03	0.04	0.02	-0.02	-0.99	K3
K3						1.00	-0.99	-0.04	-0.05	-0.03	0.02	-0.99	K4
K4							1.00	0.04	0.06	0.03	-0.02	-0.99	K3
P1								1.00	0.03	0.02	-0.52	-0.96	Xp
P2									1.00	0.36	0.00	-0.89	Yp
B1										1.00	0.01	0.36	P2
B2											1.00	-0.52	P1

Canon PowerShot A70 - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.58		6.73e-004	0.15
Xp	4.41e-002	17.15	1.33e-003	0.52
Yp	-2.03e-002	-7.90	9.64e-004	0.37
K1	5.73e-003	79.71	8.34e-005	1.16
K2	-1.55e-004	-23.49	3.28e-005	4.96
K3	-6.26e-006	-10.29	4.98e-006	8.18
K4	2.24e-007	3.99	2.54e-007	4.54
P1	9.27e-005	1.27	1.49e-005	0.20
P2	3.13e-004	3.54	1.05e-005	0.12
B1	1.93e-003	1.97	3.50e-005	0.04
B2	2.70e-004	0.21	3.55e-005	0.03

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-03-13

Project Name:	Canon EOS 1Ds Mark II with 35 mm lens calibration_2005-03-13
Project Last Modified:	26/06/2008 at 13:52
Bundle Adjustment Created:	04/07/2008 at 08:45
Control Point File:	Dummy02.txt
Number of Active Image Files:	9
Posteriori Variance Factor:	0.37
Number of Degrees of Freedom:	971
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.15	-0.06	0.16	-0.15	0.13	-0.11	0.19	-0.05	0.81	-0.08	0.81	B1
Xp		1.00	0.03	-0.01	0.02	-0.03	0.03	-0.95	0.06	-0.20	0.09	-0.95	P1
Yp			1.00	-0.03	0.03	-0.02	0.02	-0.00	-0.64	-0.10	0.21	-0.90	O_8
K1				1.00	-0.97	0.93	-0.88	0.04	-0.00	-0.03	-0.05	-0.97	K2
K2					1.00	-0.99	0.96	-0.05	-0.00	0.02	0.05	-0.99	K3
K3						1.00	-0.99	0.05	0.00	-0.03	-0.06	-0.99	K4
K4							1.00	-0.05	-0.00	0.03	0.06	-0.99	K3
P1								1.00	-0.07	0.24	-0.01	-0.95	Xp
P2									1.00	0.01	-0.05	-0.64	Yp
B1										1.00	-0.15	0.81	C
B2											1.00	-0.42	Py33

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.30		4.76e-003	0.42
Xp	1.15e-001	15.90	5.89e-003	0.82
Yp	-1.56e-001	-21.64	4.74e-003	0.66
K1	8.81e-005	123.64	1.19e-006	1.66
K2	-9.13e-008	-59.91	1.77e-008	11.60
K3	-1.08e-010	-33.04	1.05e-010	32.19
K4	2.83e-013	40.69	2.13e-013	30.66
P1	-8.98e-006	-1.93	1.83e-006	0.39
P2	5.43e-006	0.89	6.84e-007	0.11
B1	-4.09e-004	-1.02	1.07e-004	0.27
B2	8.50e-005	0.14	7.18e-005	0.12

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-06-17

Project Name:	Windsor parking lot-Canon EOS 1Ds Mark II 35mm
Project Last Modified:	19/06/2008 at 14:21
Bundle Adjustment Created:	24/06/2008 at 10:30
Number of Control Points:	25
Number of Active Image Files:	30
Posteriori Variance Factor:	0.50
Number of Degrees of Freedom:	2057
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.01	0.07	0.06	-0.16	0.14	-0.13	0.00	-0.05	0.26	-0.02	-0.45	Y_26
Xp		1.00	0.01	-0.00	0.00	-0.00	0.00	-0.97	-0.02	0.01	0.03	-0.97	P1
Yp			1.00	-0.00	-0.00	0.01	-0.01	-0.01	-0.89	-0.00	0.00	-0.89	P2
K1				1.00	-0.96	0.91	-0.86	-0.00	0.01	-0.02	-0.04	-0.96	K2
K2					1.00	-0.99	0.96	0.00	-0.01	-0.06	0.04	-0.99	K3
K3						1.00	-0.99	-0.01	0.01	0.07	-0.04	-0.99	K4
K4							1.00	0.01	-0.01	-0.08	0.05	-0.99	K3
P1								1.00	0.01	-0.01	-0.03	-0.97	Xp
P2									1.00	-0.00	-0.00	-0.89	Yp
B1										1.00	0.00	0.26	C
B2											1.00	0.05	K4

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.29		5.92e-003	0.52
Xp	1.34e-001	18.55	1.90e-003	0.26
Yp	-1.77e-001	-24.56	1.56e-003	0.22
K1	8.93e-005	125.34	7.51e-007	1.05
K2	-1.11e-007	-72.62	6.50e-009	4.27
K3	3.49e-011	10.71	2.21e-011	6.79
K4	-3.68e-014	-5.29	2.55e-014	3.67
P1	-7.22e-006	-1.55	5.81e-007	0.12
P2	3.15e-007	0.05	4.51e-007	0.07
B1	-7.40e-005	-0.18	1.17e-005	0.03
B2	1.04e-005	0.02	1.19e-005	0.02

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-09-13

Project Name:	Canon EOS 1Ds Mark II 35mm calibration_2005-09-13
Project Last Modified:	24/06/2008 at 15:15
Bundle Adjustment Created:	24/06/2008 at 15:21
Control Point File:	ControlPoints-Sep-16_without bad points.txt
Number of Active Image Files:	30
Posteriori Variance Factor:	0.55
Number of Degrees of Freedom:	2167
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.00	0.06	0.16	-0.19	0.17	-0.15	-0.01	-0.06	0.19	-0.03	0.44	X_25
Xp		1.00	-0.01	-0.02	0.02	-0.02	0.01	-0.95	0.02	-0.04	0.16	-0.95	P1
Yp			1.00	0.03	-0.03	0.04	-0.04	0.01	-0.93	-0.26	0.01	-0.93	P2
K1				1.00	-0.97	0.93	-0.88	0.02	-0.00	-0.07	-0.01	-0.97	K2
K2					1.00	-0.99	0.96	-0.01	0.01	0.02	0.01	-0.99	K3
K3						1.00	-0.99	0.01	-0.01	-0.02	-0.02	-0.99	K4
K4							1.00	-0.00	0.02	0.03	0.02	-0.99	K3
P1								1.00	-0.02	0.02	-0.16	-0.95	Xp
P2									1.00	0.28	0.00	-0.93	Yp
B1										1.00	-0.00	0.28	P2
B2											1.00	-0.16	P1

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.37		1.08e-003	0.09
Xp	1.40e-001	19.36	8.19e-004	0.11
Yp	-1.59e-001	-21.99	8.31e-004	0.12
K1	8.82e-005	123.80	2.66e-007	0.37
K2	-1.01e-007	-66.46	2.42e-009	1.59
K3	-2.64e-012	-0.81	8.40e-012	2.58
K4	2.42e-014	3.47	9.70e-015	1.39
P1	-9.51e-006	-2.04	2.43e-007	0.05
P2	2.67e-006	0.44	2.36e-007	0.04
B1	-1.32e-005	-0.03	5.13e-006	0.01
B2	-1.03e-005	-0.02	4.54e-006	0.01

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-09-16

Project Name:	Canon EOS 1Ds Mark II 35mm calibration_2005-09-16
Project Last Modified:	24/06/2008 at 11:14
Bundle Adjustment Created:	24/06/2000 at 13:25
Control Point File:	[ControlPoints-Sep-16_without bad points.txt]()
Number of Active Image Files:	29
Number of Inactive Image Files:	1
Posteriori Variance Factor:	0.86
Number of Degrees of Freedom:	2081
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.03	0.08	0.27	-0.28	0.25	-0.23	0.04	-0.07	0.08	0.02	0.40	X_1
Xp		1.00	0.02	0.01	-0.01	0.02	-0.02	-0.95	-0.01	0.05	0.22	-0.95	P1
Yp			1.00	0.00	-0.00	0.00	-0.00	-0.02	-0.93	-0.27	0.16	-0.93	P2
K1				1.00	-0.97	0.92	-0.87	0.00	0.01	-0.02	0.02	-0.97	K2
K2					1.00	-0.99	0.95	0.00	-0.01	-0.01	-0.01	-0.99	K3
K3						1.00	-0.99	-0.00	0.01	0.02	0.01	-0.99	K4
K4							1.00	0.01	-0.00	-0.01	-0.01	-0.99	K3
P1								1.00	0.02	-0.06	-0.23	-0.95	Xp
P2									1.00	0.30	-0.16	-0.93	Yp
B1										1.00	-0.02	0.30	P2
B2											1.00	-0.23	P1

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.29		1.56e-003	0.14
Xp	1.11e-001	15.40	1.36e-003	0.19
Yp	-1.63e-001	-22.60	1.34e-003	0.19
K1	8.92e-005	125.14	4.65e-007	0.65
K2	-1.13e-007	-74.21	4.48e-009	2.94
K3	5.02e-011	15.43	1.68e-011	5.15
K4	-5.98e-014	-8.59	2.11e-014	3.03
P1	-9.50e-006	-2.04	4.12e-007	0.09
P2	2.60e-006	0.43	3.95e-007	0.07
B1	-1.25e-005	-0.03	7.61e-006	0.02
B2	-7.78e-006	-0.01	7.02e-006	0.01

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-03-13

Project Name:	Canon EOS 1Ds Mark II 85mm calibration_2005-03-13
Bundle Adjustment Created:	05/06/2008 at 09:52
Control Point File:	Dummy02.txt
Number of Active Image Files:	7
Posteriori Variance Factor:	0.33
Number of Degrees of Freedom:	617
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.12	0.12	0.07	-0.08	0.08	-0.08	0.16	-0.06	0.79	-0.03	0.79	B1
Xp		1.00	0.03	0.05	-0.02	-0.01	0.03	-0.95	0.00	-0.04	0.07	0.97	K_6
Yp			1.00	0.01	-0.01	0.01	-0.02	-0.03	-0.66	0.10	0.21	-0.91	O_4
K1				1.00	-0.97	0.91	-0.86	-0.06	-0.02	-0.02	-0.00	-0.97	K2
K2					1.00	-0.99	0.96	0.03	0.02	0.01	-0.02	-0.99	K3
K3						1.00	-0.99	-0.00	-0.02	-0.01	0.03	-0.99	K4
K4							1.00	-0.02	0.02	0.01	-0.04	-0.99	K3
P1								1.00	0.01	0.06	-0.07	-0.95	Xp
P2									1.00	-0.01	-0.02	-0.66	Yp
B1										1.00	-0.06	0.79	C
B2											1.00	-0.53	Py35

Canon EOS 1Ds Mark II - interior orientation results

Camera Name	Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
			(Pixel)		(Pixel)
Camera	C	83.25		1.42e-002	0.51
	Xp	9.83e-002	13.64	1.92e-002	2.66
	Yp	-6.12e-002	-8.49	1.29e-002	1.79
	K1	9.79e-006	13.75	4.30e-007	0.60
	K2	1.34e-008	8.79	3.42e-009	2.24
	K3	-1.17e-011	-3.60	1.09e-011	3.36
	K4	6.41e-015	0.92	1.21e-014	1.73
	P1	5.33e-007	0.11	9.74e-007	0.21
	P2	1.00e-006	0.16	4.04e-007	0.07
	B1	-1.51e-004	-0.38	1.26e-004	0.31
	B2	5.47e-005	0.09	9.67e-005	0.16

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-06-17

Project Name:	Canon EOS 1Ds Mark II 85mm calibration_2005-06-17
Project Last Modified:	19/06/2008 at 14:33
Bundle Adjustment Created:	19/06/2008 at 15:50
Number of Control Points:	25
Number of Active Image Files:	26
Posteriori Variance Factor:	0.95
Number of Degrees of Freedom:	1939
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.01	0.03	0.12	-0.12	0.10	-0.08	-0.01	-0.03	0.00	-0.02	-0.94	Y_1
Xp		1.00	0.04	-0.01	0.02	-0.02	0.02	-0.97	-0.03	-0.05	0.01	-0.97	P1
Yp			1.00	0.00	-0.00	0.00	-0.00	-0.03	-0.88	-0.01	-0.02	-0.88	P2
K1				1.00	-0.97	0.92	-0.87	0.03	0.02	0.01	-0.01	-0.97	K2
K2					1.00	-0.99	0.95	-0.03	-0.02	-0.01	0.01	-0.99	K3
K3						1.00	-0.99	0.04	0.02	0.01	0.00	-0.99	K4
K4							1.00	-0.04	-0.02	-0.00	-0.01	-0.99	K3
P1								1.00	0.03	0.05	-0.01	-0.97	Xp
P2									1.00	0.01	0.04	-0.88	Yp
B1										1.00	-0.01	-0.07	P_18
B2											1.00	0.13	O_11

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.02		8.61e-002	3.11
Xp	1.84e-001	25.52	5.64e-002	7.83
Yp	-1.66e-001	-22.97	3.88e-002	5.37
K1	4.75e-006	6.66	4.56e-006	6.40
K2	5.05e-008	33.13	3.98e-008	26.14
K3	-1.23e-010	-37.78	1.38e-010	42.27
K4	1.08e-013	15.46	1.62e-013	23.25
P1	-3.08e-006	-0.66	3.04e-006	0.65
P2	1.05e-006	0.17	2.17e-006	0.36
B1	-7.07e-005	-0.18	5.23e-005	0.13
B2	-6.16e-005	-0.10	5.19e-005	0.09

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-09-13

Project Name:	Canon EOS 1Ds Mark II 85mm calibration_2005-09-13
Project Last Modified:	23/06/2008 at 14:13
Bundle Adjustment Created:	23/06/2008 at 16:36
Control Point File:	ControlPoints-Sep-16_Without bad points.txt
Number of Active Image Files:	34
Posteriori Variance Factor:	0.42
Number of Degrees of Freedom:	1609
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.08	-0.09	0.09	-0.12	0.11	-0.10	-0.05	0.10	0.10	-0.04	0.77	X_5
Xp		1.00	0.05	-0.02	0.03	-0.03	0.03	-0.97	-0.05	-0.01	0.28	-0.97	P1
Yp			1.00	-0.00	0.01	-0.01	0.01	-0.06	-0.92	-0.13	0.14	-0.92	P2
K1				1.00	-0.97	0.93	-0.88	0.03	0.00	0.03	-0.09	-0.97	K2
K2					1.00	-0.99	0.96	-0.04	-0.01	-0.04	0.08	-0.99	K3
K3						1.00	-0.99	0.04	0.01	0.04	-0.06	-0.99	K4
K4							1.00	-0.03	-0.00	-0.03	0.05	-0.99	K3
P1								1.00	0.05	-0.00	-0.28	-0.97	Xp
P2									1.00	0.19	-0.12	-0.92	Yp
B1										1.00	-0.03	0.19	P2
B2											1.00	-0.28	P1

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.27		6.86e-003	0.25
Xp	1.60e-001	22.15	4.14e-003	0.57
Yp	-1.19e-001	-16.54	3.21e-003	0.45
K1	7.96e-006	11.17	2.41e-007	0.34
K2	2.50e-008	16.41	1.99e-009	1.31
K3	-3.75e-011	-11.50	6.46e-012	1.98
K4	2.46e-014	3.53	7.15e-015	1.03
P1	-1.18e-006	-0.25	2.21e-007	0.05
P2	1.27e-006	0.21	1.78e-007	0.03
B1	-3.44e-005	-0.09	2.98e-006	0.01
B2	5.67e-006	0.01	2.93e-006	0.00

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-09-16

Project Name:	Canon EOS 1Ds Mark II 85mm calibration_2005-09-16
Project Last Modified:	24/06/2008 at 21:43
Bundle Adjustment Created:	24/06/2008 at 21:47
Control Point File:	ControlPoints-Sep-16_Without bad points.txt
Number of Active Image Files:	25
Posteriori Variance Factor:	0.79
Number of Degrees of Freedom:	953
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.13	-0.18	0.10	-0.13	0.12	-0.12	-0.05	0.18	0.11	0.04	0.85	X_9
Xp		1.00	-0.07	0.01	-0.02	0.03	-0.04	-0.96	0.06	-0.12	0.35	-0.96	P1
Yp			1.00	0.00	0.01	-0.01	0.01	0.06	-0.92	-0.14	-0.11	-0.92	P2
K1				1.00	-0.97	0.93	-0.89	-0.01	0.02	0.06	0.02	-0.97	K2
K2					1.00	-0.99	0.96	0.02	-0.03	-0.06	-0.05	-0.99	K3
K3						1.00	-0.99	-0.03	0.03	0.04	0.07	-0.99	K4
K4							1.00	0.04	-0.02	-0.02	-0.08	-0.99	K3
P1								1.00	-0.04	0.17	-0.34	-0.96	Xp
P2									1.00	0.22	0.15	-0.92	Yp
B1										1.00	-0.02	0.22	P2
B2											1.00	0.35	Xp

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.05		1.48e-002	0.53
Xp	1.83e-001	25.42	1.07e-002	1.49
Yp	-1.04e-001	-14.37	8.66e-003	1.20
K1	8.42e-006	11.82	6.46e-007	0.91
K2	1.69e-008	11.12	5.93e-009	3.89
K3	-1.16e-011	-3.57	2.11e-011	6.48
K4	-5.85e-015	-0.84	2.53e-014	3.63
P1	-9.39e-007	-0.20	5.70e-007	0.12
P2	1.35e-006	0.22	4.70e-007	0.08
B1	-3.00e-005	-0.07	7.93e-006	0.02
B2	1.57e-005	0.03	7.66e-006	0.01

Canon EOS 1Ds Mark II with 135 mm lens calibration on 2005-06-17

Project Name:	Canon EOS 1Ds Mark II 135mm calibration_2005-06-17
Project Last Modified:	13/04/2006 at 16:11
Bundle Adjustment Created:	16/02/2008 at 15:12
Control Point File:	ControlPointCoordinate.txt
Number of Active Image Files:	18
Posteriori Variance Factor:	0.86
Number of Degrees of Freedom:	1117
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	0.02	0.04	0.07	-0.08	0.06	-0.05	-0.02	-0.02	0.01	0.00	-0.95	Y_3
Xp		1.00	-0.03	-0.01	0.02	-0.02	0.03	-0.97	0.03	-0.05	0.04	-0.97	P1
Yp			1.00	-0.01	0.00	-0.00	0.00	0.03	-0.90	-0.02	-0.04	-0.90	P2
K1				1.00	-0.97	0.92	-0.87	0.01	0.02	0.08	-0.04	-0.97	K2
K2					1.00	-0.99	0.96	-0.02	-0.02	-0.07	0.04	-0.99	K3
K3						1.00	-0.99	0.03	0.01	0.05	-0.05	-0.99	K4
K4							1.00	-0.03	-0.01	-0.04	0.05	-0.99	K3
P1								1.00	-0.03	0.06	-0.05	-0.97	Xp
P2									1.00	0.04	0.07	-0.90	Yp
B1										1.00	-0.00	0.08	K1
B2											1.00	0.07	P2

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	133.21		1.10e-001	2.48
Xp	2.78e-001	38.52	6.25e-002	8.67
Yp	-3.96e-001	-54.96	4.49e-002	6.23
K1	-1.15e-005	-16.12	2.12e-006	2.98
K2	-1.58e-008	-10.37	1.88e-008	12.34
K3	7.38e-011	22.65	6.64e-011	20.40
K4	-7.10e-014	-10.20	7.99e-014	11.48
P1	-1.96e-006	-0.42	1.32e-006	0.28
P2	7.57e-006	1.25	9.92e-007	0.16
B1	-8.59e-005	-0.21	2.23e-005	0.06
B2	-9.69e-005	-0.16	2.16e-005	0.04

Canon EOS 1Ds Mark II with 200 mm lens calibration on 2005-06-17

Project Name:	Canon EOS 1Ds Mark II 200mm calibration_2005-06-17
Project Last Modified:	13/02/2008 at 10:03
Bundle Adjustment Created:	13/02/2008 at 10:50
Control Point File:	ControlPointCoordinate-3.txt
Number of Active Image Files:	12
Posteriori Variance Factor:	0.93
Number of Degrees of Freedom:	691
Unit Coordinate:	Meter
Bundle Adjustment Iteration Status:	No iteration required

Canon EOS 1Ds Mark II - interior parameter correlation matrix

Camera Parameter	C	Xp	Yp	K1	K2	K3	K4	P1	P2	B1	B2	Max	
C	1.00	-0.00	0.07	-0.04	0.05	-0.06	0.07	0.02	-0.09	0.05	-0.01	-0.97	Y_3
Xp		1.00	-0.01	-0.02	0.02	-0.02	0.02	-0.96	0.01	-0.00	-0.05	-0.96	P1
Yp			1.00	-0.03	0.04	-0.04	0.04	0.01	-0.91	0.05	0.03	-0.91	P2
K1				1.00	-0.98	0.94	-0.90	0.01	-0.00	0.01	0.01	-0.98	K2
K2					1.00	-0.99	0.97	-0.00	0.00	0.01	-0.01	-0.99	K3
K3						1.00	-0.99	-0.00	-0.00	-0.03	0.01	-0.99	K4
K4							1.00	-0.00	-0.00	0.04	-0.01	-0.99	K3
P1								1.00	-0.01	-0.00	0.06	-0.96	Xp
P2									1.00	-0.08	-0.03	-0.91	Yp
B1										1.00	-0.01	-0.08	P2
B2											1.00	0.06	P1

Canon EOS 1Ds Mark II - interior orientation results

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	198.08		1.18e+000	17.85
Xp	-4.48e-001	-62.18	3.33e-001	46.13
Yp	5.64e-001	78.16	2.67e-001	37.04
K1	-3.18e-005	-44.59	6.92e-006	9.71
K2	8.48e-008	55.67	6.97e-008	45.76
K3	-3.59e-010	-110.34	2.80e-010	85.95
K4	5.14e-013	73.85	3.82e-013	54.92
P1	1.70e-005	3.65	3.26e-006	0.70
P2	-2.00e-005	-3.30	2.70e-006	0.45
B1	-1.29e-004	-0.32	5.07e-005	0.13
B2	-6.23e-005	-0.10	4.96e-005	0.08

Appendix D: Bundle Adjustment Reports Using Highly Correlated Parameters Set to Zero

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2004-12-11

Camera Parameter	C	Xp	Yp	K1	K2	P1	P2	B1	B2	Max	
C	1.00	-0.03	0.26	0.11	-0.16	0.05	-0.15	0.20	0.00	0.72	Z_3
Xp		1.00	-0.01	0.02	-0.01	-0.87	0.01	0.02	0.21	-0.87	P1
Yp			1.00	-0.16	0.11	0.02	-0.87	-0.22	0.02	-0.87	P2
K1				1.00	-0.90	-0.02	0.26	0.13	-0.01	-0.90	K2
K2					1.00	0.01	-0.15	-0.09	-0.01	-0.90	K1
P1						1.00	-0.02	-0.06	0.05	-0.87	Xp
P2							1.00	0.10	0.00	-0.87	Yp
B1								1.00	0.00	-0.22	Yp
B2									1.00	0.21	Xp

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.52		8.11e-04	0.19
Xp	3.79e-02	14.75	5.78e-04	0.22
Yp	-2.06e-02	-8.00	5.83e-04	0.23
K1	6.05e-03	84.20	1.54e-05	0.21
K2	-2.18e-04	-33.00	1.42e-06	0.22
P1	1.28e-04	1.75	6.98e-06	0.10
P2	3.20e-04	3.61	7.14e-06	0.08
B1	1.92e-03	1.96	2.02e-05	0.02
B2	1.67e-04	0.13	2.01e-05	0.02

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2005-04-10

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.02	0.03	0.28	-0.27	-0.03	0.49	-0.03	0.78	X_0
Xp		1.00	0.05	-0.02	0.13	0.06	-0.02	-0.01	0.91	K_6
Yp			1.00	-0.03	0.03	-0.55	0.02	-0.01	-0.98	O_6
K1				1.00	-0.95	-0.00	-0.10	0.02	-0.95	K2
K2					1.00	0.02	0.06	-0.01	-0.95	K1
P2						1.00	0.01	0.03	0.56	O_2
B1							1.00	-0.01	0.51	Pz33
B2								1.00	-0.57	Py33

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.50		9.01e-04	0.21
Xp	8.10e-02	31.46	6.68e-004	0.26
Yp	-2.54e-002	-9.87	1.66e-003	0.64
K1	6.05e-003	84.15	3.24e-005	0.45
K2	-2.20e-004	-33.26	3.05e-006	0.46
P2	2.82e-004	3.18	1.41e-005	0.16

B1	1.83e-003	1.88	9.56e-005	0.10
B2	2.16e-004	0.17	9.44e-005	0.07

Canon PowerShot A70 with 5.4 mm zoom lens calibration on 2005-09-11

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	-0.02	0.13	0.25	-0.29	-0.16	0.11	0.01	0.65	X_4
Xp		1.00	-0.05	0.04	-0.01	-0.02	0.06	0.00	0.53	K_7
Yp			1.00	-0.07	0.02	-0.89	-0.21	0.02	-0.89	P2
K1				1.00	-0.94	0.02	-0.08	-0.00	-0.94	K2
K2					1.00	0.00	0.04	-0.01	-0.94	K1
P2						1.00	0.35	0.02	-0.89	Yp
B1							1.00	0.03	0.35	P2
B2								1.00	0.16	P_9

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	5.59		6.09e-004	0.14
Xp	5.65e-002	21.96	4.18e-004	0.16
Yp	-2.04e-002	-7.92	1.03e-003	0.40
K1	5.90e-003	82.14	1.55e-005	0.22
K2	-2.11e-004	-31.87	1.51e-006	0.23
P2	3.14e-004	3.55	1.13e-005	0.13
B1	1.93e-003	1.98	3.76e-005	0.04
B2	4.51e-004	0.35	3.26e-005	0.03

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-03-13

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.11	-0.06	0.05	-0.11	-0.04	0.82	-0.07	0.82	B1
Xp		1.00	0.09	-0.08	0.07	-0.00	0.08	0.25	0.67	K_0
Yp			1.00	0.00	-0.00	-0.64	-0.10	0.21	-0.90	O_8
K1				1.00	-0.95	-0.03	-0.04	-0.02	-0.95	K2
K2					1.00	0.03	0.01	0.01	-0.95	K1
P2						1.00	0.02	-0.06	-0.64	Yp
B1							1.00	-0.15	0.82	C
B2								1.00	-0.42	Py33

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.30		4.72e-003	0.41
Xp	8.03e-002	11.13	1.92e-003	0.27
Yp	-1.55e-001	-21.55	4.85e-003	0.67
K1	8.81e-005	123.69	2.64e-007	0.37
K2	-1.02e-007	-67.07	9.67e-010	0.63
P2	5.17e-006	0.85	6.98e-007	0.11
B1	-2.63e-004	-0.66	1.06e-004	0.26
B2	7.20e-004	0.12	7.33e-005	0.12

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-06-17

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	-0.01	0.07	-0.40	-0.07	-0.05	0.26	-0.01	-0.45	Y_26
Xp		1.00	-0.00	0.01	-0.02	-0.01	0.00	-0.00	0.02	K_7
Yp			1.00	-0.02	-0.00	-0.89	-0.00	0.00	-0.89	P2
K1				1.00	-0.84	0.03	-0.30	-0.01	-0.84	K2
K2					1.00	-0.00	0.16	0.02	-0.84	K1
P2						1.00	-0.00	-0.00	-0.89	Yp
B1							1.00	0.00	-0.30	K1
B2								1.00	0.02	K2

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.29		6.12e-003	0.54
Xp	1.07e-001	14.85	5.16e-004	0.07
Yp	-1.77e-001	-24.59	1.63e-003	0.23
K1	8.80e-005	123.55	1.95e-007	0.27
K2	-9.97e-008	-65.42	3.87e-010	0.25
P2	4.07e-007	0.07	4.72e-007	0.08
B1	-7.55e-005	-0.19	1.22e-005	0.03
B2	6.72e-006	0.01	1.24e-005	0.02

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-09-13

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	-0.03	0.06	-0.16	-0.10	-0.06	0.19	-0.03	0.45	X_25
Xp		1.00	-0.01	-0.00	0.06	0.00	-0.05	0.00	0.12	K_27
Yp			1.00	0.02	-0.02	-0.93	-0.26	0.02	-0.93	P2
K1				1.00	-0.89	0.01	-0.27	0.02	-0.89	K2
K2					1.00	-0.02	0.12	0.01	-0.89	K1
P2						1.00	0.27	-0.00	-0.93	Yp
B1							1.00	0.00	0.27	P2
B2								1.00	-0.05	O_23

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.37		1.53e-003	0.13
Xp	1.04e-001	14.36	3.82e-004	0.05
Yp	-1.57e-001	-21.84	1.21e-003	0.17
K1	8.70e-005	122.08	8.55e-008	0.12
K2	-9.59e-008	-62.97	1.87e-010	0.12
P2	2.48e-006	0.41	3.44e-007	0.06
B1	-1.13e-005	-0.03	7.45e-006	0.02
B2	-4.35e-005	-0.07	6.52e-006	0.01

Canon EOS 1Ds Mark II with 35 mm lens calibration on 2005-09-16

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.01	0.09	-0.08	-0.10	-0.08	0.08	0.03	0.41	X_1
Xp		1.00	-0.02	-0.04	0.01	0.01	-0.02	0.01	0.12	K_5
Yp			1.00	0.03	-0.04	-0.93	-0.27	0.16	-0.93	P2
K1				1.00	-0.92	-0.02	-0.22	-0.01	-0.92	K2
K2					1.00	0.03	0.13	0.03	-0.92	K1
P2						1.00	0.30	-0.16	-0.93	Yp
B1							1.00	-0.04	0.30	P2
B2								1.00	-0.16	P2

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	34.29		1.73e-003	0.15
Xp	7.53e-002	10.45	4.87e-004	0.07
Yp	-1.64e-001	-22.70	1.56e-003	0.22
K1	8.77e-005	123.13	1.20e-007	0.17
K2	-9.90e-008	-65.02	2.89e-010	0.19
P2	2.70e-006	0.44	4.61e-007	0.08
B1	-2.65e-005	-0.07	8.87e-006	0.02
B2	-4.95e-005	-0.08	7.97e-006	0.01

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-03-13

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.10	0.13	-0.01	-0.04	-0.06	0.80	-0.03	0.80	B1
Xp		1.00	0.01	-0.24	0.18	0.03	0.05	0.02	0.77	K_1
Yp			1.00	-0.01	0.00	-0.66	0.10	0.20	-0.91	O_4
K1				1.00	-0.94	-0.01	-0.01	-0.05	-0.94	K2
K2					1.00	0.01	0.00	0.04	-0.94	K3
P2						1.00	-0.01	-0.02	-0.66	Yp
B1							1.00	-0.06	0.80	C
B2								1.00	-0.53	Py35

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.25		1.41e-002	0.51
Xp	1.17e-001	16.21	5.71e-003	0.79
Yp	-6.19e-002	-8.59	1.30e-002	1.81
K1	1.08e-005	15.17	9.35e-008	0.13
K2	7.53e-009	4.94	1.88e-010	0.12
P2	9.87e-007	0.16	4.07e-007	0.07
B1	-1.54e-004	-0.38	1.26e-004	0.32
B2	3.47e-005	0.06	9.71e-005	0.16

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-06-17

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.00	0.03	-0.02	-0.09	-0.03	0.00	-0.02	-0.95	Y_1
Xp		1.00	0.01	0.04	-0.00	-0.02	-0.01	-0.01	-0.51	K_16
Yp			1.00	-0.00	0.00	-0.88	-0.01	-0.02	-0.88	P2
K1				1.00	-0.94	0.03	-0.06	0.01	-0.94	K2
K2					1.00	-0.02	0.01	-0.01	-0.94	K1
P2						1.00	0.01	0.03	-0.88	Yp
B1							1.00	-0.01	0.06	Z_18
B2								1.00	0.12	O_11

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.05		8.53e-002	3.08
Xp	1.10e-001	15.21	1.29e-002	1.79
Yp	-1.67e-001	-23.18	3.88e-002	5.37
K1	1.08e-005	15.20	9.98e-007	1.40
K2	5.40e-009	3.55	2.35e-009	1.54
P2	1.07e-006	0.18	2.17e-006	0.36
B1	-6.39e-005	-0.16	5.23e-005	0.13
B2	-6.69e-005	-0.11	5.19e-005	0.09

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-09-13

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.09	-0.09	-0.19	-0.01	0.11	0.10	-0.04	0.77	X_5
Xp		1.00	0.00	-0.06	0.03	-0.02	-0.07	0.03	0.22	K_31
Yp			1.00	0.08	-0.05	-0.92	-0.13	0.14	-0.92	P2
K1				1.00	-0.93	-0.04	-0.13	-0.04	-0.93	K2
K2					1.00	0.02	0.08	0.07	-0.93	K1
P2						1.00	0.19	-0.12	-0.92	Yp
B1							1.00	-0.03	0.19	P2
B2								1.00	0.14	Yp

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.29		7.53e-003	0.27
Xp	1.32e-001	18.25	1.15e-003	0.16
Yp	-1.22e-001	-16.87	3.56e-003	0.49
K1	1.05e-005	14.75	5.62e-008	0.08
K2	8.49e-009	5.57	1.22e-010	0.08
P2	1.37e-006	0.23	1.97e-007	0.03
B1	-3.09e-005	-0.08	3.30e-006	0.01
B2	-6.05e-006	-0.01	3.10e-006	0.01

Canon EOS 1Ds Mark II with 85 mm lens calibration on 2005-09-16

Camera Parameter	C	Xp	Yp	K1	K2	P2	B1	B2	Max	
C	1.00	0.29	-0.17	-0.14	-0.01	0.18	0.11	0.02	0.85	X_9
Xp		1.00	-0.05	-0.02	-0.02	0.05	0.12	0.07	0.39	K_23
Yp			1.00	0.04	0.03	-0.92	-0.15	-0.10	-0.92	P2
K1				1.00	-0.95	-0.06	-0.11	-0.01	-0.95	K2
K2					1.00	0.01	0.04	0.02	-0.95	K1
P2						1.00	0.23	0.14	-0.92	Yp
B1							1.00	0.05	0.23	P2
B2								1.00	0.14	P2

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	83.06		1.50e-002	0.54
Xp	1.61e-001	22.30	3.10e-003	0.43
Yp	-1.03e-001	-14.29	8.85e-003	1.23
K1	1.01e-005	14.19	1.21e-007	0.17
K2	7.94e-009	5.21	2.72e-010	0.18
P2	1.43e-006	0.24	4.80e-007	0.08
B1	-2.01e-005	-0.05	7.92e-006	0.02
B2	4.11e-006	0.01	7.29e-006	0.01

Canon EOS 1Ds Mark II with 135 mm lens calibration on 2005-06-17

Camera Parameter	C	Xp	Yp	K1	K2	B1	B2	Max	
C	1.00	0.01	0.05	-0.11	-0.03	0.07	0.00	-0.81	Y_11
Xp		1.00	0.02	0.05	-0.03	0.04	0.01	-0.11	K_0
Yp			1.00	-0.06	0.06	0.02	0.04	-0.14	O_10
K1				1.00	-0.95	-0.01	-0.02	-0.95	K2
K2					1.00	-0.01	0.01	-0.95	K1
B1						1.00	-0.00	-0.09	Y_16
B2							1.00	0.04	Yp

Camera Parameter	Final Value		$\delta_{\text{Final Value}}$	
		(Pixel)		(Pixel)
C	133.21		1.48e-001	3.33
Xp	2.15e-001	29.87	1.49e-002	2.07
Yp	-1.84e-001	-25.56	2.02e-002	2.80
K1	-1.49e-005	-20.89	4.68e-007	0.66
K2	9.72e-009	6.38	1.08e-009	0.71
B1	-9.63e-005	-0.24	2.26e-005	0.06
B2	-1.07e-004	-0.18	2.17e-005	0.04

Canon EOS 1Ds Mark II with 200 mm lens calibration on 2005-06-17

Camera Parameter	C	K1	P1	P2	B1	B2	Max	
C	1.00	-0.34	0.03	-0.03	0.03	-0.01	-0.97	Y_3
K1		1.00	0.09	0.07	-0.07	0.03	0.35	Y_2
P1			1.00	-0.00	-0.01	0.00	0.09	K1
P2				1.00	-0.04	0.03	0.07	K1
B1					1.00	-0.00	-0.07	K1
B2						1.00	0.04	Py3

Camera Parameter	Final Value		$\delta_{Final\ Value}$	
		(Pixel)		(Pixel)
C	197.92		1.17e+000	17.72
K1	-2.39e-005	-33.51	4.45e-007	0.62
P1	1.90e-006	0.41	8.75e-007	0.19
P2	-1.57e-006	-0.26	1.06e-006	0.17
B1	-1.43e-004	-0.36	5.01e-005	0.13
B2	-1.11e-004	-0.18	4.94e-005	0.08

Appendix E: Comparison of Calculated and surveyed Coordinates

Coordinates comparison using calibration file from 2004-12-11 test for the Canon Powershot A70 camera with 5.4 mm zoom lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
2	3.941	0.745	1.270	3.942	0.747	1.269	0.001	0.002	-0.001
3	3.937	0.760	0.369	3.938	0.762	0.370	0.001	0.002	0.001
7	3.930	2.336	2.167	3.932	2.336	2.165	0.002	0.000	-0.002
8	3.929	2.349	1.267	3.931	2.349	1.266	0.002	0.000	-0.001
9	3.917	2.368	0.367	3.920	2.368	0.367	0.003	0.000	0.000
10	3.903	2.384	-0.534	3.906	2.383	-0.533	0.003	-0.001	0.001
12	3.915	3.207	-1.060	3.917	3.205	-1.060	0.002	-0.002	0.000
13	3.912	4.020	2.177	3.915	4.018	2.177	0.003	-0.002	0.000
14	3.908	4.015	1.277	3.910	4.014	1.277	0.002	-0.001	0.000
15	3.901	4.012	0.368	3.903	4.011	0.368	0.002	-0.001	0.000
16	3.892	4.008	-0.531	3.895	4.007	-0.532	0.003	-0.001	-0.001
18	3.911	4.811	-1.050	3.914	4.809	-1.052	0.003	-0.002	-0.002
20	3.879	5.553	1.281	3.882	5.552	1.281	0.003	-0.001	0.000
21	3.881	5.570	0.382	3.884	5.569	0.381	0.003	-0.001	-0.001
23	1.932	1.621	2.162	1.930	1.618	2.163	-0.002	-0.003	0.001
25	1.897	1.611	0.363	1.895	1.608	0.363	-0.002	-0.003	0.000
29	1.920	3.096	2.167	1.916	3.094	2.169	-0.004	-0.002	0.002
30	1.920	3.088	1.269	1.916	3.087	1.270	-0.004	-0.001	0.001
31	1.915	3.088	0.371	1.911	3.086	0.370	-0.004	-0.002	-0.001
32	1.904	3.087	-0.528	1.900	3.085	-0.530	-0.004	-0.002	-0.002
33	1.921	3.089	-1.061	1.917	3.086	-1.064	-0.004	-0.003	-0.003
36	1.906	4.576	2.174	1.901	4.576	2.178	-0.005	0.000	0.004
38	1.890	4.567	0.382	1.885	4.567	0.381	-0.005	0.000	-0.001
39	1.892	4.564	-0.518	1.886	4.564	-0.521	-0.006	0.000	-0.003
40	-0.066	-0.108	2.953	-0.073	-0.114	2.956	-0.007	-0.006	0.003
42	-0.065	-0.106	1.691	-0.072	-0.113	1.694	-0.007	-0.007	0.003
43	-0.065	-0.104	0.382	-0.073	-0.111	0.383	-0.008	-0.007	0.001
44	-0.066	-0.101	-0.955	-0.073	-0.108	-0.956	-0.007	-0.007	-0.001
47	-0.068	1.898	1.685	-0.083	1.892	1.689	-0.015	-0.006	0.004
55	-0.067	3.762	-0.951	-0.087	3.761	-0.957	-0.020	-0.001	-0.006
59	-0.072	5.752	-0.941	-0.098	5.760	-0.949	-0.026	0.008	-0.008

Coordinates comparison using calibration file from 2005-09-11 test for the Canon Powershot A70 camera with 5.4 mm zoom lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
2	3.935	0.739	1.272	3.942	0.747	1.269	0.007	0.008	-0.003
3	3.931	0.754	0.370	3.938	0.762	0.370	0.007	0.008	0.000
7	3.925	2.335	2.170	3.932	2.336	2.165	0.007	0.001	-0.005
8	3.924	2.348	1.269	3.931	2.349	1.266	0.007	0.001	-0.003
9	3.913	2.367	0.367	3.920	2.368	0.367	0.007	0.001	0.000
10	3.899	2.382	-0.534	3.906	2.383	-0.533	0.007	0.001	0.001
12	3.910	3.206	-1.062	3.917	3.205	-1.060	0.007	-0.001	0.002
13	3.907	4.022	2.180	3.915	4.018	2.177	0.008	-0.004	-0.003
14	3.902	4.018	1.279	3.910	4.014	1.277	0.008	-0.004	-0.002
15	3.896	4.015	0.369	3.903	4.011	0.368	0.007	-0.004	-0.001
16	3.887	4.011	-0.532	3.895	4.007	-0.532	0.008	-0.004	0.000
18	3.906	4.814	-1.052	3.914	4.809	-1.052	0.008	-0.005	0.000
20	3.873	5.559	1.283	3.882	5.552	1.281	0.009	-0.007	-0.002
21	3.875	5.576	0.383	3.884	5.569	0.381	0.009	-0.007	-0.002
23	1.945	1.626	2.156	1.930	1.618	2.163	-0.015	-0.008	0.007
25	1.910	1.616	0.364	1.895	1.608	0.363	-0.015	-0.008	-0.001
29	1.933	3.096	2.161	1.916	3.094	2.169	-0.017	-0.002	0.008
30	1.933	3.089	1.267	1.916	3.087	1.270	-0.017	-0.002	0.003
31	1.927	3.088	0.372	1.911	3.086	0.370	-0.016	-0.002	-0.002
32	1.917	3.087	-0.523	1.900	3.085	-0.530	-0.017	-0.002	-0.007
33	1.933	3.089	-1.054	1.917	3.086	-1.064	-0.016	-0.003	-0.010
36	1.920	4.571	2.168	1.901	4.576	2.178	-0.019	0.005	0.010
38	1.904	4.563	0.383	1.885	4.567	0.381	-0.019	0.004	-0.002
39	1.905	4.559	-0.513	1.886	4.564	-0.521	-0.019	0.005	-0.008
40	-0.012	-0.078	2.928	-0.073	-0.114	2.956	-0.061	-0.036	0.028
42	-0.011	-0.078	1.680	-0.072	-0.113	1.694	-0.061	-0.035	0.014
43	-0.012	-0.076	0.384	-0.073	-0.111	0.383	-0.061	-0.035	-0.001
44	-0.013	-0.074	-0.940	-0.073	-0.108	-0.956	-0.060	-0.034	-0.016
47	-0.016	1.908	1.675	-0.083	1.892	1.689	-0.067	-0.016	0.014
55	-0.016	3.756	-0.937	-0.087	3.761	-0.957	-0.071	0.005	-0.020
59	-0.018	5.727	-0.927	-0.098	5.760	-0.949	-0.080	0.033	-0.022

Coordinates comparison using calibration file from 2005-06-17 test for the Canon EOS 1Ds Mark II with 35 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
2	*3.940*	*0.748*	*1.269*	*3.940*	*0.747*	*1.269*	*0.000*	*-0.001*	*0.000*
3	*3.937*	*0.763*	*0.370*	*3.937*	*0.762*	*0.369*	*0.000*	*-0.001*	*-0.001*
6	*3.934*	*1.630*	*-1.064*	*3.934*	*1.630*	*-1.064*	*0.000*	*0.000*	*0.000*
7	*3.932*	*2.336*	*2.165*	*3.932*	*2.336*	*2.166*	*0.000*	*0.000*	*0.001*
8	*3.930*	*2.349*	*1.266*	*3.930*	*2.349*	*1.266*	*0.000*	*0.000*	*0.000*
9	*3.919*	*2.368*	*0.367*	*3.919*	*2.368*	*0.366*	*0.000*	*0.000*	*-0.001*
10	*3.905*	*2.383*	*-0.533*	*3.905*	*2.383*	*-0.533*	*0.000*	*0.000*	*0.000*
12	*3.918*	*3.204*	*-1.060*	*3.917*	*3.205*	*-1.060*	*-0.001*	*0.001*	*0.000*
13	*3.915*	*4.018*	*2.177*	*3.914*	*4.018*	*2.177*	*-0.001*	*0.000*	*0.000*
14	*3.910*	*4.013*	*1.277*	*3.910*	*4.014*	*1.277*	*0.000*	*0.001*	*0.000*
15	*3.903*	*4.010*	*0.368*	*3.903*	*4.010*	*0.368*	*0.000*	*0.000*	*0.000*
16	*3.896*	*4.006*	*-0.531*	*3.895*	*4.006*	*-0.531*	*-0.001*	*0.000*	*0.000*
17	*3.929*	*4.786*	*2.649*	*3.929*	*4.787*	*2.649*	*0.000*	*0.001*	*0.000*
18	*3.915*	*4.808*	*-1.052*	*3.915*	*4.808*	*-1.052*	*0.000*	*0.000*	*0.000*
20	*3.882*	*5.552*	*1.281*	*3.882*	*5.553*	*1.281*	*0.000*	*0.001*	*0.000*
21	*3.885*	*5.568*	*0.381*	*3.885*	*5.568*	*0.381*	*0.000*	*0.000*	*0.000*
29	*1.915*	*3.093*	*2.169*	*1.916*	*3.093*	*2.169*	*0.001*	*0.000*	*0.000*
30	*1.914*	*3.086*	*1.270*	*1.915*	*3.086*	*1.269*	*0.001*	*0.000*	*-0.001*
31	*1.910*	*3.085*	*0.370*	*1.911*	*3.085*	*0.369*	*0.001*	*0.000*	*-0.001*
32	*1.899*	*3.083*	*-0.530*	*1.900*	*3.084*	*-0.531*	*0.001*	*0.001*	*-0.001*
33	*1.915*	*3.086*	*-1.064*	*1.916*	*3.086*	*-1.064*	*0.001*	*0.000*	*0.000*
36	*1.899*	*4.575*	*2.178*	*1.900*	*4.575*	*2.178*	*0.001*	*0.000*	*0.000*
38	*1.883*	*4.566*	*0.381*	*1.884*	*4.566*	*0.381*	*0.001*	*0.000*	*0.000*
39	*1.884*	*4.564*	*-0.521*	*1.886*	*4.564*	*-0.522*	*0.002*	*0.000*	*-0.001*
40	*-0.080*	*-0.115*	*2.956*	*-0.078*	*-0.114*	*2.955*	*0.002*	*0.001*	*-0.001*
41	*-0.081*	*-0.112*	*2.526*	*-0.079*	*-0.111*	*2.525*	*0.002*	*0.001*	*-0.001*
42	*-0.080*	*-0.115*	*1.693*	*-0.078*	*-0.114*	*1.692*	*0.002*	*0.001*	*-0.001*
43	*-0.081*	*-0.114*	*0.380*	*-0.078*	*-0.112*	*0.379*	*0.003*	*0.002*	*-0.001*
44	*-0.080*	*-0.109*	*-0.958*	*-0.077*	*-0.107*	*-0.959*	*0.003*	*0.002*	*-0.001*
45	*-0.087*	*1.901*	*3.288*	*-0.085*	*1.902*	*3.287*	*0.002*	*0.001*	*-0.001*
46	*-0.088*	*1.901*	*2.953*	*-0.085*	*1.902*	*2.952*	*0.003*	*0.001*	*-0.001*
47	*-0.088*	*1.891*	*1.688*	*-0.085*	*1.892*	*1.687*	*0.003*	*0.001*	*-0.001*
48	*-0.089*	*1.887*	*0.357*	*-0.086*	*1.888*	*0.356*	*0.003*	*0.001*	*-0.001*
49	*-0.089*	*1.883*	*-0.957*	*-0.085*	*1.884*	*-0.958*	*0.004*	*0.001*	*-0.001*
50	*-0.091*	*2.732*	*3.273*	*-0.088*	*2.733*	*3.272*	*0.003*	*0.001*	*-0.001*
51	*-0.096*	*3.733*	*3.283*	*-0.093*	*3.733*	*3.282*	*0.003*	*0.000*	*-0.001*
52	*-0.097*	*3.753*	*2.951*	*-0.094*	*3.754*	*2.949*	*0.003*	*0.001*	*-0.002*
53	*-0.098*	*3.752*	*1.685*	*-0.094*	*3.752*	*1.684*	*0.004*	*0.000*	*-0.001*
54	*-0.096*	*3.754*	*0.354*	*-0.092*	*3.755*	*0.353*	*0.004*	*0.001*	*-0.001*
55	*-0.095*	*3.761*	*-0.959*	*-0.091*	*3.761*	*-0.959*	*0.004*	*0.000*	*0.000*

Coordinates comparison using calibration file from 2005-09-13 test for the Canon EOS 1Ds Mark II with 35 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
2	3.939	0.747	1.269	3.940	0.747	1.269	0.001	0.000	0.000
3	3.936	0.762	0.370	3.937	0.762	0.369	0.001	0.000	-0.001
6	3.933	1.630	-1.064	3.934	1.630	-1.064	0.001	0.000	0.000
7	3.931	2.336	2.166	3.932	2.336	2.166	0.001	0.000	0.000
8	3.929	2.349	1.267	3.930	2.349	1.266	0.001	0.000	-0.001
9	3.918	2.368	0.367	3.919	2.368	0.366	0.001	0.000	-0.001
10	3.905	2.383	-0.533	3.905	2.383	-0.533	0.000	0.000	0.000
12	3.917	3.205	-1.060	3.917	3.205	-1.060	0.000	0.000	0.000
13	3.914	4.018	2.177	3.914	4.018	2.177	0.000	0.000	0.000
14	3.909	4.014	1.277	3.910	4.014	1.277	0.001	0.000	0.000
15	3.902	4.011	0.368	3.903	4.010	0.368	0.001	-0.001	0.000
16	3.895	4.006	-0.531	3.895	4.006	-0.531	0.000	0.000	0.000
17	3.928	4.787	2.649	3.929	4.787	2.649	0.001	0.000	0.000
18	3.914	4.809	-1.052	3.915	4.808	-1.052	0.001	-0.001	0.000
20	3.881	5.553	1.281	3.882	5.553	1.281	0.001	0.000	0.000
21	3.884	5.569	0.381	3.885	5.568	0.381	0.001	-0.001	0.000
29	1.917	3.093	2.168	1.916	3.093	2.169	-0.001	0.000	0.001
30	1.916	3.086	1.269	1.915	3.086	1.269	-0.001	0.000	0.000
31	1.912	3.085	0.370	1.911	3.085	0.369	-0.001	0.000	-0.001
32	1.901	3.084	-0.530	1.900	3.084	-0.531	-0.001	0.000	-0.001
33	1.917	3.086	-1.062	1.916	3.086	-1.064	-0.001	0.000	-0.002
36	1.901	4.575	2.177	1.900	4.575	2.178	-0.001	0.000	0.001
38	1.885	4.566	0.381	1.884	4.566	0.381	-0.001	0.000	0.000
39	1.887	4.563	-0.521	1.886	4.564	-0.522	-0.001	0.001	-0.001
40	-0.072	-0.111	2.952	-0.078	-0.114	2.955	-0.006	-0.003	0.003
41	-0.073	-0.109	2.523	-0.079	-0.111	2.525	-0.006	-0.002	0.002
42	-0.072	-0.111	1.691	-0.078	-0.114	1.692	-0.006	-0.003	0.001
43	-0.072	-0.109	0.380	-0.078	-0.112	0.379	-0.006	-0.003	-0.001
44	-0.071	-0.105	-0.956	-0.077	-0.107	-0.959	-0.006	-0.002	-0.003
45	-0.079	1.903	3.283	-0.085	1.902	3.287	-0.006	-0.001	0.004
46	-0.080	1.902	2.949	-0.085	1.902	2.952	-0.005	0.000	0.003
47	-0.080	1.893	1.686	-0.085	1.892	1.687	-0.005	-0.001	0.001
48	-0.080	1.889	0.357	-0.086	1.888	0.356	-0.006	-0.001	-0.001
49	-0.080	1.885	-0.955	-0.085	1.884	-0.958	-0.005	-0.001	-0.003
50	-0.083	2.732	3.269	-0.088	2.733	3.272	-0.005	0.001	0.003
51	-0.088	3.732	3.279	-0.093	3.733	3.282	-0.005	0.001	0.003
52	-0.089	3.752	2.947	-0.094	3.754	2.949	-0.005	0.002	0.002
53	-0.089	3.751	1.683	-0.094	3.752	1.684	-0.005	0.001	0.001
54	-0.087	3.754	0.354	-0.092	3.755	0.353	-0.005	0.001	-0.001
55	-0.086	3.760	-0.957	-0.091	3.761	-0.959	-0.005	0.001	-0.002

Coordinates comparison using calibration file from 2005-09-16 test for the Canon EOS 1Ds Mark II with 35 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
2	3.941	0.747	1.269	3.940	0.747	1.269	-0.001	0.000	0.000
3	3.937	0.762	0.369	3.937	0.762	0.369	0.000	0.000	0.000
6	3.934	1.630	-1.064	3.934	1.630	-1.064	0.000	0.000	0.000
7	3.932	2.336	2.165	3.932	2.336	2.166	0.000	0.000	0.001
8	3.930	2.349	1.266	3.930	2.349	1.266	0.000	0.000	0.000
9	3.919	2.368	0.367	3.919	2.368	0.366	0.000	0.000	-0.001
10	3.905	2.383	-0.533	3.905	2.383	-0.533	0.000	0.000	0.000
12	3.917	3.205	-1.059	3.917	3.205	-1.060	0.000	0.000	-0.001
13	3.915	4.018	2.177	3.914	4.018	2.177	-0.001	0.000	0.000
14	3.910	4.014	1.277	3.910	4.014	1.277	0.000	0.000	0.000
15	3.903	4.010	0.368	3.903	4.010	0.368	0.000	0.000	0.000
16	3.895	4.006	-0.531	3.895	4.006	-0.531	0.000	0.000	0.000
17	3.929	4.787	2.649	3.929	4.787	2.649	0.000	0.000	0.000
18	3.915	4.808	-1.051	3.915	4.808	-1.052	0.000	0.000	-0.001
20	3.882	5.552	1.281	3.882	5.553	1.281	0.000	0.001	0.000
21	3.885	5.568	0.381	3.885	5.568	0.381	0.000	0.000	0.000
29	1.916	3.093	2.169	1.916	3.093	2.169	0.000	0.000	0.000
30	1.915	3.086	1.269	1.915	3.086	1.269	0.000	0.000	0.000
31	1.910	3.085	0.370	1.911	3.085	0.369	0.001	0.000	-0.001
32	1.899	3.084	-0.530	1.900	3.084	-0.531	0.001	0.000	-0.001
33	1.915	3.086	-1.063	1.916	3.086	-1.064	0.001	0.000	-0.001
36	1.899	4.576	2.178	1.900	4.575	2.178	0.001	-0.001	0.000
38	1.883	4.567	0.381	1.884	4.566	0.381	0.001	-0.001	0.000
39	1.885	4.564	-0.521	1.886	4.564	-0.522	0.001	0.000	-0.001
40	-0.080	-0.115	2.956	-0.078	-0.114	2.955	0.002	0.001	-0.001
41	-0.082	-0.112	2.526	-0.079	-0.111	2.525	0.003	0.001	-0.001
42	-0.081	-0.115	1.693	-0.078	-0.114	1.692	0.003	0.001	-0.001
43	-0.081	-0.113	0.379	-0.078	-0.112	0.379	0.003	0.001	0.000
44	-0.080	-0.109	-0.959	-0.077	-0.107	-0.959	0.003	0.002	0.000
45	-0.087	1.902	3.287	-0.085	1.902	3.287	0.002	0.000	0.000
46	-0.087	1.901	2.953	-0.085	1.902	2.952	0.002	0.001	-0.001
47	-0.088	1.892	1.688	-0.085	1.892	1.687	0.003	0.000	-0.001
48	-0.088	1.888	0.357	-0.086	1.888	0.356	0.002	0.000	-0.001
49	-0.088	1.884	-0.957	-0.085	1.884	-0.958	0.003	0.000	-0.001
50	-0.090	2.733	3.273	-0.088	2.733	3.272	0.002	0.000	-0.001
51	-0.095	3.734	3.282	-0.093	3.733	3.282	0.002	-0.001	0.000
52	-0.096	3.754	2.950	-0.094	3.754	2.949	0.002	0.000	-0.001
53	-0.096	3.752	1.685	-0.094	3.752	1.684	0.002	0.000	-0.001
54	-0.095	3.755	0.354	-0.092	3.755	0.353	0.003	0.000	-0.001
55	-0.094	3.762	-0.959	-0.091	3.761	-0.959	0.003	-0.001	0.000

Coordinates comparison using calibration file from 2005-06-17 test for the Canon EOS 1Ds Mark II with 85 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
7	3.939	2.337	2.163	3.935	2.338	2.165	-0.004	0.001	0.002
8	3.936	2.349	1.265	3.931	2.350	1.266	-0.005	0.001	0.001
9	3.924	2.368	0.366	3.919	2.369	0.366	-0.005	0.001	0.000
10	3.909	2.383	-0.533	3.904	2.384	-0.534	-0.005	0.001	-0.001
13	3.922	4.017	2.174	3.916	4.020	2.176	-0.006	0.003	0.002
14	3.916	4.012	1.275	3.910	4.015	1.276	-0.006	0.003	0.001
15	3.908	4.009	0.367	3.903	4.012	0.367	-0.005	0.003	0.000
16	3.899	4.005	-0.531	3.894	4.007	-0.532	-0.005	0.002	-0.001
19	3.891	5.542	2.177	3.886	5.547	2.179	-0.005	0.005	0.002
20	3.888	5.549	1.279	3.883	5.554	1.280	-0.005	0.005	0.001
21	3.89	5.565	0.380	3.885	5.570	0.380	-0.005	0.005	0.000
22	3.891	5.58	-0.518	3.886	5.585	-0.519	-0.005	0.005	-0.001
29	1.921	3.093	2.169	1.919	3.094	2.170	-0.002	0.001	0.001
30	1.919	3.086	1.270	1.917	3.087	1.270	-0.002	0.001	0.000
32	1.901	3.084	-0.530	1.899	3.085	-0.530	-0.002	0.001	0.000
36	1.905	4.575	2.178	1.902	4.577	2.178	-0.003	0.002	0.000
38	1.887	4.566	0.381	1.885	4.567	0.382	-0.002	0.001	0.001
39	1.888	4.563	-0.521	1.885	4.564	-0.521	-0.003	0.001	0.000
53	-0.095	3.752	1.687	-0.092	3.753	1.687	0.003	0.001	0.000
54	-0.095	3.755	0.356	-0.091	3.755	0.356	0.004	0.000	0.000
55	-0.095	3.762	-0.957	-0.091	3.762	-0.956	0.004	0.000	0.001
57	-0.102	5.751	1.683	-0.100	5.751	1.682	0.002	0.000	-0.001
58	-0.103	5.758	0.355	-0.100	5.758	0.355	0.003	0.000	0.000

Coordinates comparison using calibration file from 2005-09-13 test for the Canon EOS 1Ds Mark II with 85 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
7	*3.934*	*2.338*	*2.165*	*3.935*	*2.338*	*2.165*	*0.001*	*0.000*	*0.000*
8	*3.930*	*2.350*	*1.266*	*3.931*	*2.350*	*1.266*	*0.001*	*0.000*	*0.000*
9	*3.919*	*2.369*	*0.366*	*3.919*	*2.369*	*0.366*	*0.000*	*0.000*	*0.000*
10	*3.904*	*2.384*	*-0.534*	*3.904*	*2.384*	*-0.534*	*0.000*	*0.000*	*0.000*
13	*3.916*	*4.020*	*2.176*	*3.916*	*4.020*	*2.176*	*0.000*	*0.000*	*0.000*
14	*3.910*	*4.015*	*1.276*	*3.910*	*4.015*	*1.276*	*0.000*	*0.000*	*0.000*
15	*3.902*	*4.012*	*0.367*	*3.903*	*4.012*	*0.367*	*0.001*	*0.000*	*0.000*
16	*3.894*	*4.008*	*-0.532*	*3.894*	*4.007*	*-0.532*	*0.000*	*-0.001*	*0.000*
19	*3.885*	*5.548*	*2.179*	*3.886*	*5.547*	*2.179*	*0.001*	*-0.001*	*0.000*
20	*3.882*	*5.555*	*1.280*	*3.883*	*5.554*	*1.280*	*0.001*	*-0.001*	*0.000*
21	*3.884*	*5.570*	*0.380*	*3.885*	*5.570*	*0.380*	*0.001*	*0.000*	*0.000*
22	*3.886*	*5.586*	*-0.519*	*3.886*	*5.585*	*-0.519*	*0.000*	*-0.001*	*0.000*
29	*1.919*	*3.094*	*2.170*	*1.919*	*3.094*	*2.170*	*0.000*	*0.000*	*0.000*
30	*1.917*	*3.087*	*1.270*	*1.917*	*3.087*	*1.270*	*0.000*	*0.000*	*0.000*
32	*1.899*	*3.085*	*-0.530*	*1.899*	*3.085*	*-0.530*	*0.000*	*0.000*	*0.000*
36	*1.902*	*4.577*	*2.178*	*1.902*	*4.577*	*2.178*	*0.000*	*0.000*	*0.000*
38	*1.884*	*4.568*	*0.382*	*1.885*	*4.567*	*0.382*	*0.001*	*-0.001*	*0.000*
39	*1.885*	*4.565*	*-0.521*	*1.885*	*4.564*	*-0.521*	*0.000*	*-0.001*	*0.000*
53	*-0.091*	*3.753*	*1.687*	*-0.092*	*3.753*	*1.687*	*-0.001*	*0.000*	*0.000*
54	*-0.090*	*3.755*	*0.356*	*-0.091*	*3.755*	*0.356*	*-0.001*	*0.000*	*0.000*
55	*-0.091*	*3.762*	*-0.956*	*-0.091*	*3.762*	*-0.956*	*0.000*	*0.000*	*0.000*
57	*-0.100*	*5.751*	*1.682*	*-0.100*	*5.751*	*1.682*	*0.000*	*0.000*	*0.000*
58	*-0.100*	*5.758*	*0.355*	*-0.100*	*5.758*	*0.355*	*0.000*	*0.000*	*0.000*

Coordinates comparison using calibration file from 2005-09-16 test for the Canon EOS 1Ds Mark II with 85 mm lens

Pt No	*Calculated coordinates*			*Baseline coordinates*			*Coordinate difference*		
	X (m)	*Y (m)*	*Z (m)*	*X (m)*	*Y (m)*	*Z (m)*	*ΔX (m)*	*ΔY (m)*	*ΔZ (m)*
7	3.939	2.336	2.162	3.935	2.338	2.165	-0.004	0.002	0.003
8	3.935	2.349	1.265	3.931	2.350	1.266	-0.004	0.001	0.001
9	3.923	2.368	0.366	3.919	2.369	0.366	-0.004	0.001	0.000
10	3.908	2.383	-0.533	3.904	2.384	-0.534	-0.004	0.001	-0.001
13	3.921	4.017	2.174	3.916	4.020	2.176	-0.005	0.003	0.002
14	3.915	4.012	1.275	3.910	4.015	1.276	-0.005	0.003	0.001
15	3.908	4.009	0.367	3.903	4.012	0.367	-0.005	0.003	0.000
16	3.899	4.004	-0.531	3.894	4.007	-0.532	-0.005	0.003	-0.001
19	3.891	5.542	2.177	3.886	5.547	2.179	-0.005	0.005	0.002
20	3.888	5.549	1.279	3.883	5.554	1.280	-0.005	0.005	0.001
21	3.890	5.565	0.380	3.885	5.570	0.380	-0.005	0.005	0.000
22	3.891	5.580	-0.518	3.886	5.585	-0.519	-0.005	0.005	-0.001
29	1.921	3.093	2.169	1.919	3.094	2.170	-0.002	0.001	0.001
30	1.919	3.086	1.270	1.917	3.087	1.270	-0.002	0.001	0.000
32	1.901	3.084	-0.529	1.899	3.085	-0.530	-0.002	0.001	-0.001
36	1.905	4.575	2.178	1.902	4.577	2.178	-0.003	0.002	0.000
38	1.887	4.566	0.381	1.885	4.567	0.382	-0.002	0.001	0.001
39	1.888	4.563	-0.521	1.885	4.564	-0.521	-0.003	0.001	0.000
53	-0.094	3.752	1.687	-0.092	3.753	1.687	0.002	0.001	0.000
54	-0.094	3.755	0.356	-0.091	3.755	0.356	0.003	0.000	0.000
55	-0.094	3.761	-0.956	-0.091	3.762	-0.956	0.003	0.001	0.000
57	-0.102	5.751	1.683	-0.100	5.751	1.682	0.002	0.000	-0.001
58	-0.102	5.758	0.355	-0.100	5.758	0.355	0.002	0.000	0.000