OMC Camera Calibration Software Guide

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1. Introduction

Cameras can be used for a wide variety of tasks. In many cases it is important to know the precise relationship between what a camera sees and what is in the object space. This document serves two purposes, to explain the process of camera calibration and to act as a guide for the OMC camera calibration software.

Why is camera calibration necessary? Lenses cause distortion, the discrepancy between a perfect camera and a real camera is due to many factors. Long focal length lenses can exhibit relatively small levels of distortion while short focal length lenses generally distort images more. It is possible to calibrate most lenses such that the error across the field of view is less than 1/20 of a pixel and sometimes as small as 1/80 of a pixel.

This theory used in the OMC software has been developed by photogrammetrists over the past 50 years or more. Academics and Industrialists have gradually pushed what can be achieved by cameras systems to levels where the relative precision of measurements made with cameras can approach 1 part in a million and are typically 1 part in 100,000. Even small electronic cameras can achieve results of the order of 1 part in 30,000. Photogrammetrists have worked on lenses for space, remote sensing, aerial surveying, civil engineering surveying, industrial measurement, medical measurement, and microscopic measurements. However, the research and developments are often not accessible to those in other disciplines. The OMC camera calibration software allows the user to obtain the results from the photogrammetry field and make better measurements from cameras.

Features:

- Single camera camera calibration
- Multiple camera camera calibration
- Image point distortion correction
- Estimation of relative orientation of cameras
- Coded targets for automatic identification of targets
- Simple operation with a few button presses
- Calibration results report
- Incorporation of scale
- Software can use more than 40 images and hundreds of target points

2. The physical model used in camera calibration

In this section the physical model used in camera calibration is defined. First the geometry of an ideal camera is described followed by the mathematical modelling of imperfect lenses. The purpose of camera calibration is to allow the user to correct images or image information so the imperfect camera can be treated as a perfect one. This extent to which this can be achieved or is needed will depend on the application.

2.1. Defining the geometry of an ideal camera

With the possible exception of astronomy, experts in the area of photogrammetry have made the greatest geometric use of lenses over the past hundred years. They have required lenses to perform aerial and satellite mapping of vast areas of the world as well as performing measurements with a precision of up to 1 part in a million of the object space. As a result the models for camera calibration can be relied upon to represent the best that is likely to be achieved with a lens for all but the most exotic applications.

This section provides a description of the geometric parameters of lenses and their mathematical models. It is useful to define the terms when dealing with camera-lens systems. Interior orientation and Exterior orientation are terms employed to describe the internal and external geometric configurations of a camera and lens system, others use the terms intrinsic and extrinsic parameters.

Principal point

The location of an image on the image plane formed by the direct axial ray passing through the centre of the lens system is known as the principal point. The focal plane should be perpendicular to the optical axis, but a parameter to correct for any misalignment is usually necessary. This is particularly necessary for the electronic sensor camera where the requirements for geometric alignment of the lens with the sensor array are minimal. The principal point can also be thought of as the foot of the perpendicular from the nominal centre of the lens system (more exactly the rear node of the lens) to the plane of focus. It represents the point that would be the ideal origin for a coordinate system on the image plane.

When images are being used for 3-D measurement purposes it is normal to convert from pixel related co-ordinates to image co-ordinates in millimetres. To achieve this the following equation is used

$$x_i = (x_{sensor} - x_{centre})s_x \qquad (2.1)$$
$$y_i = -(y_{sensor} - y_{centre})s_y$$

where

x_i, y_i are the new co-ordinates of the image in mm,
x_{sensor}, y_{sensor} are the co-ordinates of the image as given by the camera/frame-grabber in pixels,
x_{centre}, y_{centre} is the notional centre of the image in pixels, and
s_x, s_y are the pixel sizes in mm

The principal point should ideally be at the centre of the image. The centre of the image format may be found by dividing the number of x and y axis pixels in the image by two or by (intersecting the diagonal fiducial marks if they are present in a film camera). Any differences in the x and y directions between the centre of the image plane and the base of this perpendicular are known as offsets of the principal point and conventionally expressed as x_{pp}, y_{pp} or sometimes as x_o, y_o. The principal distance, c, and the offsets of the principal point (Figure 2.1) are key elements in the set of parameters defining camera calibration. The principal point location was not included in equation 2.1 because it is included as an unknown parameter in a calibration procedure. For applications where the principal point is required ***a priori*** then x_{sensor} and y_{sensor} can be substituted by x_{pp}, and y_{pp}.

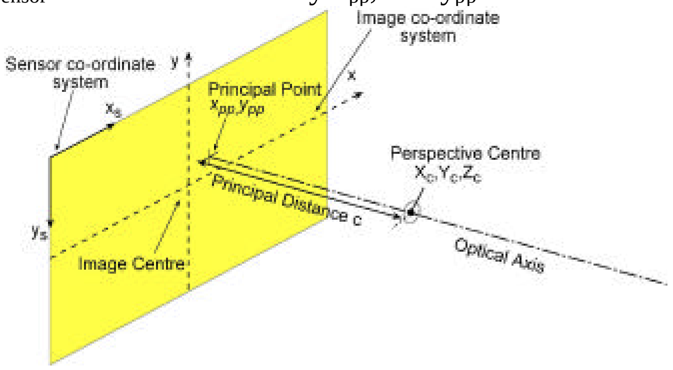


Figure 2.1. The definition of the principal distance, principal point, and image centre

To correctly "centre" the image co-ordinates, the offsets (x_{pp}, y_{pp}) from the principal point to the notional image centre or fiducial origin must be added to image co-ordinates. These offsets may not always be known initially, so they may be estimated, often at zero, and solved for in the calibration procedure with all other unknowns. The magnitude of the offsets (x_{pp},y_{pp}) are usually under one millimetre for a film based camera, and less than twenty of pixels for a digital or video camera.

The relationship between the principal point and the image centre will usually remain stable for long periods of time for medium precision purposes. In some cases cameras used for 3-D measurement are only checked every six months or so. However, the relationship cannot be guaranteed when the lens is adjusted or moved in any way. This is especially true with zoom lenses that are particularly prone to principal point shifts as the focal distance is changed. In these situations the unknowns for these values should be included in the photogrammetric solution for each occasion the focus has been altered. Recently, cases of unstable principal point location in Kodak DCS digital cameras have been encountered. This is because these cameras have been made for studio photographic purposes where the principal point location is not an issue. However, when multiple images are taken with the camera in various orientations the sensor has been shown to move with respect to the camera body.

Principal distance

The perpendicular distance from the perspective centre of the lens system to the image plane is termed the principal distance and usually denoted by 'c' (Figure 2.1). In aerial mapping, where the camera lens is fixed at infinity focus, the terms focal length and principal distance are often used synonymously. In other applications the lenses are usually of variable focus the principal distance will not equal the focal length and will often need to be determined. In some industrial applications, the lens will be focused in each image collection phase, so the principal distance will vary from one image to the next. It is good practice not to confuse the focal length of the lens 'f' with 'c'.

The values for the principal distance and the offsets of the principal point can be determined in a laboratory if required. However, other methods (discussed later) provide a direct means of determining their values so an exact value of the principal distance does not have to be known ***a priori***. The method of least squares can be applied to solve the unknown parameters to model the relationship between the image and object co-ordinates given reasonably close initial approximation. Similarly for the values of the offsets to the principal point as noted in section 2.2.

Camera position and orientation

The position and orientation of a camera require definition for the calibration methods described later. Figure 2.2 illustrates the common photogrammetric definition where the camera position is described by X_c,Y_c,Z_c and the orientation by ω,ϕ,κ is defined with reference to a world co-ordinate system. The rotation parameters ω,ϕ,κ are calculated with respect to the world co-ordinate system in the order they are written in (this is important as other orders will produce different results). The image co-ordinate system co-ordinates x_i, y_i are aligned parallel to the camera X and Y co-ordinate axes respectively.

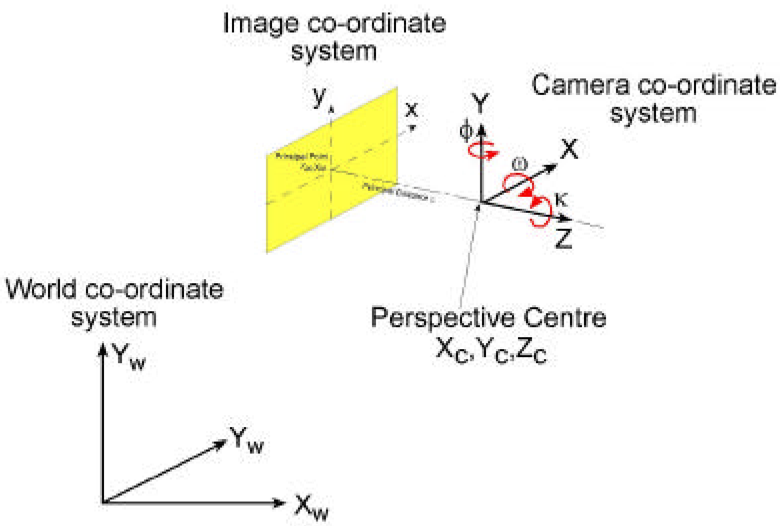


Figure 2.2. Definition of the exterior orientation parameters for a camera

The parameters of inner orientation discussed so far are supplemented by further parameters that are described later.

Collinearity equations

The mathematical model used in camera calibration has evolved over a fifty years along with the ability to solve large, redundant sets of equations and the gradual increase in image resolution. The collinearity equations are a set of equations that describe the geometry of a ray of light from an object point (subscripted by 'p') through the perspective centre of the lens (usually referred to as the location of the camera and subscripted by 'c') to the image plane (subscripted by 'i'). These equations use the exterior orientation parameters to describe the direction of the principal ray through the lens with respect to the world co-ordinate system X_w, Y_w, Z_w. In addition the interior parameters are used to define the image location corresponding to the object point that it is (in an ideal situation) collinear with.

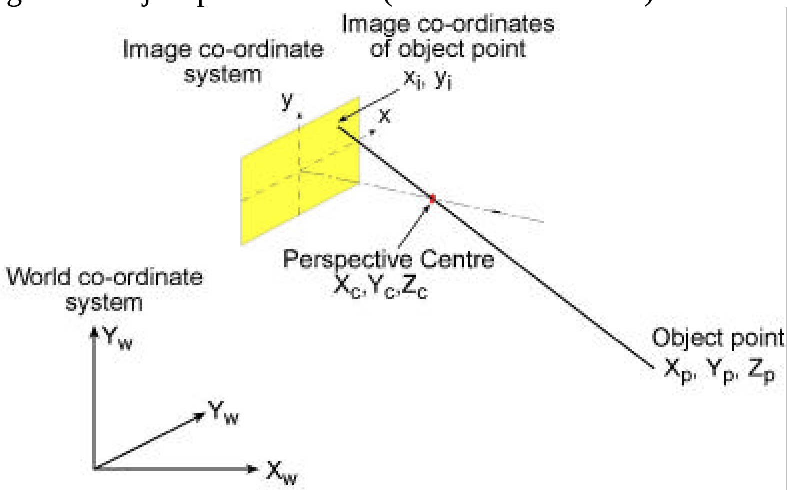


Figure 2.3. The central configuration described by the collinearity equations

The collinearity equations may be expressed as:

$$x_i = x_{pp} - c_x \cdot \frac{m_{11}(X_p - X_c) + m_{12}(Y_p - Y_c) + m_{13}(Z_p - Z_c)}{m_{31}(X_p - X_c) + m_{32}(Y_p - Y_c) + m_{33}(Z_p - Z_c)}$$

$$y_i = y_{pp} - c_y \cdot \frac{m_{21}(X_p - X_c) + m_{22}(Y_p - Y_c) + m_{23}(Z_p - Z_c)}{m_{31}(X_p - X_c) + m_{32}(Y_p - Y_c) + m_{33}(Z_p - Z_c)} \qquad (2.2)$$

where x_i, y_i are the image co-ordinates of an object point X_p, Y_p, Z_p and X_c, Y_c, Z_c is the location of a camera in object space. The m_{ij} (i =1,3; j=1,3) terms are the elements of a rotation matrix, M, and contain trigonometric functions of the angles ω, ϕ and κ. The principal distance, c, may be represented by two components, one in each of the x and y axis directions but it is usual to replace c_x and c_y with a common value 'c' for most photogrammetric applications.

Given sufficient image observations and diversity of viewpoints it is possible to use the collinearity equations to solve for the unknown 3-D co-ordinates of the object points. The process of camera calibration makes use of the fact that a useful by-product is that not only can the parameters relating to the object co-ordinates be estimated but also all of the other parameters such as camera exterior and interior parameters.

The collinearity equations are non-linear and so it is necessary to linearise them by use of a Taylor's Theorem expansion for solution by iterative least squares techniques. Reasonable approximations to all unknowns are needed before a convergent solution can be guaranteed.

At this point in this discussion a perfect "pin hole" camera model has been defined - no account has been taken of the distortions present in all real lenses. In the next section a mathematical model is defined that completes the picture.

2.2. Defining the geometry of an imperfect camera

Camera calibration is the process of estimating the parameters that best describe what happens to a bundle of rays coming from the object when they pass through the lens and onto the image plane. The geometric configuration of the passage of a bundle of light rays through the lens to the image plane can be described mathematically by a set of parameters. The parameters relating to radial and decentering distortion, the location of the principal point, the focal length (more correctly known as the principal distance) and the interrelationship of these parameters with translation and rotation of the camera itself are described. It should be noted that camera calibration refers here to the determination of the parameters that enable undistorted images to be created. The computer vision community often refers to the process of estimating the external orientation of the camera as camera calibration. This section does deal with the external parameters because these are necessary for some methods of determining the interior parameters. It is recommended that the term ‘camera calibration’ is used to refer to the process of estimating parameters belonging to a camera and perhaps the term ‘system calibration’ might be appropriate for a collection of cameras that may make up a measurement system.

Aberrations, or deviations from theoretically exact models, can be grouped into two categories: those that reduce image quality and those that alter the location of the image. Image quality aberrations may have an influence on geometric location but are not considered further here. Radial and decentering distortions comprise the primary aberrations that affect image geometry and measurement and modeling of these distortions is crucial to good results.

The equations for radial and decentering distortions are derived from the Seidel aberrations, named after the 19th century German mathematician who developed the relevant equations. These aberrations may be expressed in terms of polynomial curves. Only the lower order terms in the series are relevant for most lenses.

Radial lens distortion

If the image of an off-axis target is displaced radially either closer to or for further from the principal point then it has been radially distorted. The terms barrel or pin-cushion are used, respectively, to describe the image shape of a rectangle which has been radially distorted closer to or farther from the principal point.

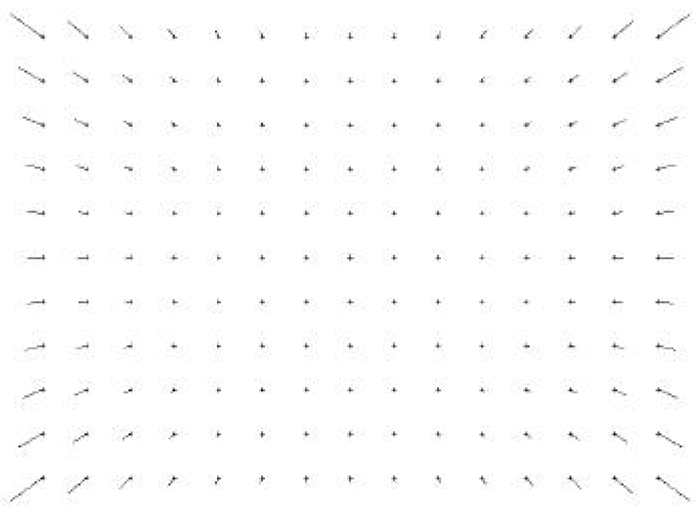


Figure 2.4 Radial lens distortion vectors for pin-cushion distortion – the grid represents the corrected image and the ends of the vectors the observed positions. In a map for barrel distortion the vectors would be pointing from the grid towards the principal point

Gaussian radial distortion describes the magnitude of radial distortion when the nominal principal distance is used as a basis for calculations. Figure 2.5 illustrates that the magnitude of these distortions generally increases with radial distance and may change with focus. Lens distortion graphs typically show the distortion in micrometres against the radial distance in millimetres, although it is reasonable to replace the horizontal scale in millimetres by a distance in pixels for some tasks.

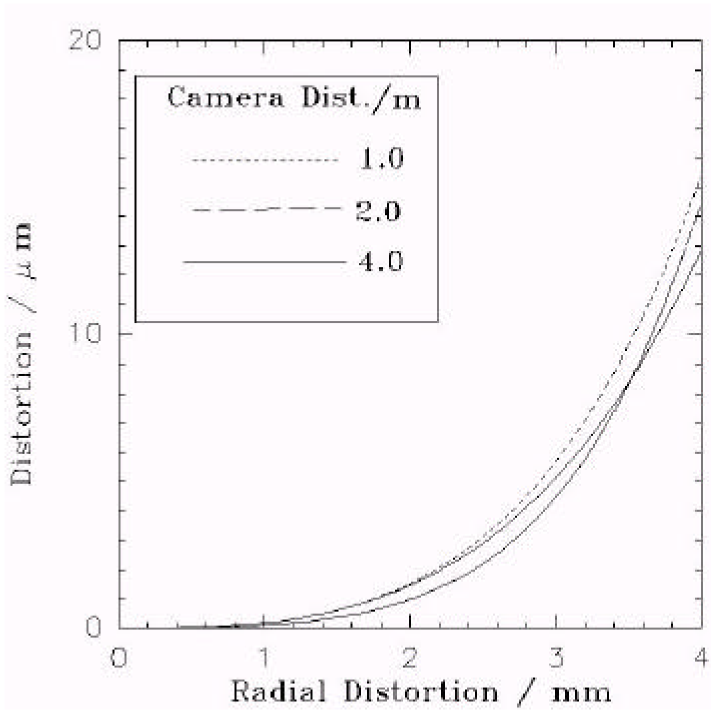


Figure 2.5 Radial distortion calibration curves for three object distances

Balanced radial distortion is the term used where the Gaussian curve has been mathematically transformed by shifting the principal distance by an amount Δc which has usually been chosen such that the mean value of the transformed distortion curve out to a certain radial distance is zero. Gaussian radial distortion can be expressed as a series of odd powered terms,

$R_{xy} = K_1r^3 + K_2r^5 + K_3r^7 + \ldots$ (2.3)

where K_1, K_1, K_3 are the coefficients of radial distortion corresponding to infinity focus, R_{xy} is in micrometres, and

$r^2 = (x - x_{pp})^2 + (y - y_{pp})^2$ (2.4)

where r is the radial distance to the point which has co-ordinates (x, y) and x_{pp},and y_{pp} are the offsets of the principal point from an indicated (or assumed) centre of the image. All values are usually expressed in millimetres. The number of terms required to model a given lens will vary depending on the lens geometry. Long focal length lenses will often require fewer terms compared to short focal length, wide angle lenses. The significance of each terms should be tested for the highest accuracy work. As a rule of thumb the first term will model most of the distortion while the second and third terms will be useful to refine the solution, further terms are not often required.

Decentering Distortion

All elements in a lens system ideally should be aligned, at the time of manufacture, to be collinear to the optical axis of the entire lens system. Any displacement or rotation of a lens element from a perfect alignment with the optical axis will cause the geometric displacement of images known as decentering distortion. Decentering refers to the "off-centering" of the lens elements (figure 2.6).

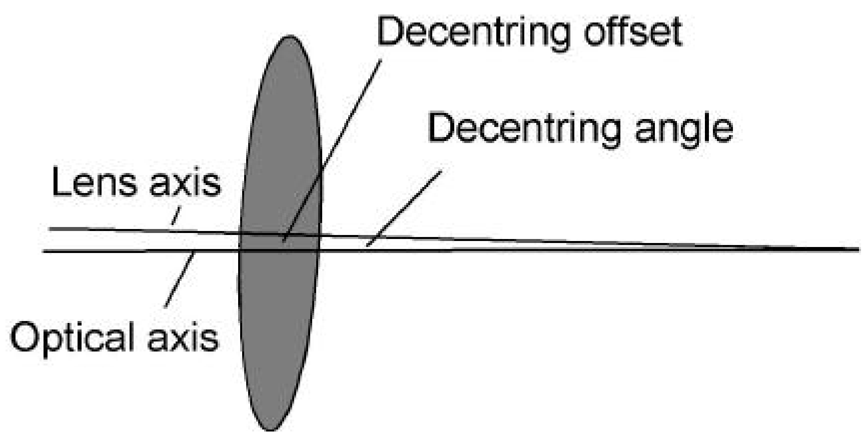


Figure 2.6. Decentering of a lens element

Decentering distortion was initially thought to be identical with the effect caused by placing a thin prism in front of the lens system. This model is a reasonable approximation but has been improved further. The typical decentering angle expected for ordinary lenses is approximately 1/diameter of the lens in minutes. The lens itself may not be perfectly made and can have a difference in thickness between opposite sides creating a residual wedge effect (Smith, 1990). It is usual for the lens decentering parameters to provide an improvement of between 1/7 and 1/10 of the magnitude of radial lens distortion. The decentering distortion effect contains both radial and tangential components (figure 2.7).

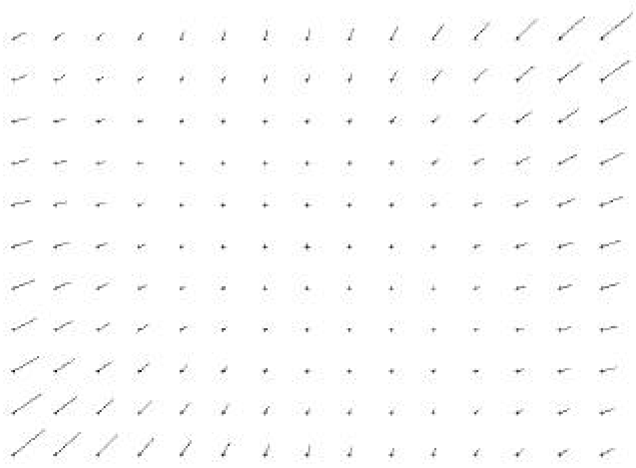


Figure 2.7. Tangential distortion error vectors

The commonly accepted mathematical model for decentering distortion includes a term that allows for variation within the depth of field and for different focus settings. In practice these refinements to the basic quadratic formula (equations 2.11, 2.12) are seldom used, apart from extremely close range situations as variation within the field are generally very small. A graphical representation of decentering distortion can be made in a manner analogous to radial distortion (see Figure 2.8).

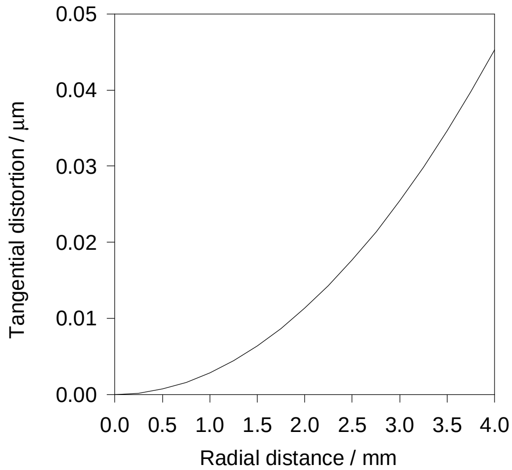


Figure 2.8. Tangential distortion plot P(r)

The function that is graphed is called the "profile function" and is represented by P(r),

$$P(r) = \left(P_1^2 + P_2^2\right)^{1/2} r^2 \qquad (2.11)$$

where the parameters P_1 and P_2 refer to values at infinity focus. The effect of decentering distortion can be represented to sufficient accuracy in a truncated polynomial form as

$$T_x = P_1(r^2 + 2(x - x_{pp})^2) + 2P_2(x - x_{pp})(y - y_{pp})$$
$$T_y = P_2(r^2 + 2(y - y_{pp})^2) + 2P_1(x - x_{pp})(y - y_{pp}) \qquad (2.12)$$

where T_x, T_y are the components of the decentering distortion at an image point x, y; r is the radial distance as described in equation (2.4).

2.3 A complete model for camera calibration

A complete mathematical model that enables close to perfect correction for most cameras can be formed by combining the previously described parameters. Experience has shown that a few additional parameters are required to model any difference in scale between the x and y direction (see A in 2.14) and non-perpendicularity in the image plane (see B in 2.14). The pixel co-ordinates are first converted to mm using the following equation

X_{image} = (x_location_pixels - no_xpixels/2)*x_pixel_size;
Y_{image} = -(y_location_pixels - no_ypixels/2)*y_pixel_size;

	Parameters	Equations
Radial	R_{xy}	$K_1r^3 + K_2r^5 + K_3r^7 + \ldots$
Tangential	T_x T_y	$P_1(r^2 + 2(x - x_{pp})^2) + 2P_2(x - x_{pp})(y - y_{pp})$ $P_2(r^2 + 2(y - y_{pp})^2) + 2P_1(x - x_{pp})(y - y_{pp})$
Scale difference	A_x	$A(x - x_{pp})$
Non-orthogonality	B_x	$B(y - y_{pp})$
View sensor from side	C_x	$C(x – x_{pp})\ (y - y_{pp})$
Radius	r	$\mathrm{Sqrt}\ ((x – x_{pp})^2 + (y - y_{pp})^2)$
Corrected x position	$x_{corrected}$	$X_{image} - x_{pp} + R_{xy} + T_x + A_x + B_x + C_x$
Corrected y position	$y_{corrected}$	$Y_{image} - y_{pp} + R_{xy} + T_y$

Table 2.1. Complete set of equations for distortion correction

The following pseudo "C" code illustrates how the correction is applied to each target co-ordinate assuming that they have first been converted to mm using the pixel size together with an offset from pixel co-ordinates to the centre of the image.

```
Example
// conversion of pixels to mm
x[n] = (X[n] - 768/2)*0.0083
y[n]= -(Y[n] - 576/2)*0.0083
// correction of image co-ordinates
for (n=0; n< no_targets; n++)
       {
       rr = (x[n] - x0) * (x[n] - x0) +
            (y[n] - y0) * (y[n] - y0);
       xd =   (x[n] - x0) * (rr * k1 + rr * rr * k2 + rr * rr * rr * k3)+
              p1 * ( rr + 2 * (x[n] - x0) * (x[n] - x0 )) +
              2 * p2*(x[n] - x0) * (y[n] - y0) +
             A*(x[n] - x0) +
             B * (y[n] - y0) +
             C * (x[n] – x0) * (y[n] - y0);
       yd =   (y[n] - y0) * (rr * k1 + rr * rr *  k2 + rr * rr * rr * k3) +
             p2 * (rr + 2*(y[n] - y0) * (y[n] - y0)) +
             2 * p1 * (x[n] - x0) * (y[n] - y0);
        pimg->x[n] = x[n] - x0 + xd;
        pimg->y[n] = y[n] - y0 + yd;
       }
```

2.4 Selection of the appropriate model for a given measurement task

The selection of an appropriate model for lens distortion will depend on the application. If a wide-angle lens (of short focal length) is used then distortion is likely to be greater than for a normal lens. If the quantity of distortion is unknown a straight line can be imaged at the edge of the image and the deviation of the line from straight can be measured using any simple graphics program. Remember that this distortion only indicates the difference in distortion between the middle of the line and the edges and not the level of gross distortion that will always be greater in magnitude.

Table 2.2.gives is an aid to determine which lens distortion modeling parameters is necessary to achieve a given level of image modeling and hence correction. It is only approximate as the requirements change considerable depending on the focal length and design of the lens but at least the progression of the general scheme is indicated. The current OMC software does not allow the user to arbitrarily select the parameters and most calibrations obtain the highest accuracy results as standard. However, the end user can select which of the parameters is used for subsequent image correction to account for the level of accuracy required for a given task and this table enables this choice to be made.

Level of accuracy required across whole image (pixels)	Model parameters required	Comment
0.5 - 2	Modify c to average distortion	Gross lens distortion removed
0.2 - 0.5	c, K_1	Next level of distortion removed
0.15 - 0.3	c, x_{pp}, y_{pp}, K_1	Improvement due to principal point location
0.08 - 0.15	c, x_{pp}, y_{pp}, K_1, P_1, P_2	Decentring distortion added
0.04 - 0.08	c, x_{pp}, y_{pp}, K_1, K_2, K_3, P_1, P_2	Higher order lens distortion terms
0.01 - 0.04	c, x_{pp}, y_{pp}, K_1, K_2, K_3, P_1, P_2, A,B,C	Sensor orientation parameters required

Table 2.2. Approximate indication of which lens parameters to use

Occasionally estimating parameters that are redundant can cause the problem usually referred to as “over-parameterisation” which can lead to unrealistic precision estimates compared to the accuracy of calibration actually achieved. It is also likely that with long focal length lenses the self-calibration algorithm will encounter problems if the principal point and principal distance are not fixed.

2.5 Summary

Knowledge of the geometry of the bundle of light rays that pass through a lens is essential for the accurate application of high accuracy techniques. The model described by the formulae in this chapter is capable of correcting the geometric location of an image to within a few tenths of a micrometre.

3. Calibration parameter estimation issues

3.1. Introduction

There are a number of methods that can be used for parameter estimation. Some involve the direct estimation of distortion using theodolites or goniometers. Other methods are indirect such as the so-called “plumb line” method based upon distortion of straight lines. Another indirect method is known as “self-calibration” using multiple convergent images and “bundle adjustment” software. The bundle adjustment is a least squares method of solving a set of non-linear equations relating to the “bundle” of rays from an object that appear in each image. The parameters that are estimated in the solution are the 3-D co-ordinates of the object points but also the internal parameters for the camera.

3.2. Providing appropriate input information

For the calibration procedure to work the user provides suitable images of a stable object. If the images do not contain appropriate information the algorithm may not be able to converge to a solution or if it does to weak or erroneous values. For instance, images taken from the same or broadly similar viewpoints will cause the algorithm to fail to converge. If the angle between the images is relatively small a solution may be obtained by the estimated values of some parameters are likely to be poor. For optimum results, the angle of convergence of the images is recommended to be between 40 and 60 degrees.

If all of the images are taken with the camera oriented in the same way correlation between the principal point location and the exterior orientation can lead to a poor estimation of the principal point location. If images are taken with a 90 degree roll about the camera axis the correlation problem is reduced and a better calibration is possible. It may appear to the end user that this is a tedious procedure to remember to do but the reason behind it is clear even if it is conceptually difficult to grasp.

Another related aspect is coverage of the image format. If the calibration features do not extend to the full range of the image format then, although the calibration model will extend to the full image size any use of the parameters at these locations will be an extrapolation with unknown validity.

The shape of the object being measured is an issue that must be considered. For images taken with relatively short focal length lenses (where the focal length does not exceed the image format size by more than two times for instance) a flat calibration artifact is convenient to make and measure.

The feature location method used to identify the same point in more than one image must not itself introduce geometric errors, especially systematic ones. It may be that the objective of calibration is to improve a relatively low accuracy process but the camera calibration process would preferably not influence this process at all. As a result it is always a good idea to perform the camera calibration aspect as well as possible without excessive effort. The OMC software uses small round features and wherever possible it is recommended that these are used. Care should also be taken to ensure that the image quality and brightness of these features is optimised as much as possible.

3.3. What is not required

The self-calibration technique does not require any object-space information for the technique to work as a means of camera calibration. Put another way - the photogrammetric method cannot determine the scale of the object but this is not necessary to perform the calibration of the camera.

3.4. Redundancy issues

If a satisfactory physical camera configuration is for the moment assumed the number of unknowns will be: 3 for each object point n, 6 for the position and orientation of m camera, 11 to model the camera. The number of observations will be: 2 for each object
int n for each camera station m. To achieve redundancy 2nm > 3n+6m+11. A typical calibration will involve four locations with two rotations about the camera axis at each location. Hence m = 8. In this case 2n > 3n + 48 + 11 i.e. n > 59/5 = 6 targets.

To give an example that explains the concept of self-calibration, consider the following scenario. 50 targets, whose exact locations are unknown, are imaged from 8 camera stations, the location and orientation of which are also unknown. There are 3 unknowns per target point (X, Y, Z) and 6 per camera station, making a subtotal of 50 x 3 + 8 x 6 = 198 unknowns. There are up to another 11 unknown parameters describing the principal distance, offsets of the principal point, radial and decentering distortion and the effects of shear in the sensor array and non-perpendicularity of that array to the principal axis to be determined. This brings the total number of unknowns to 198 + 11 = 209. Each observation of an imaged target produces 2 values (x and y), so that the total possible number of observations will be 8 images x 50 x 2 = 800 observations. As each observation relates to an observation equation in a combined solution, a considerable redundancy of 800 - 209 = 591 exists for this solution.

Where no mechanical manufacture or processing issues needs to be considered the number of targets used for calibration should be at least more than 100 but between 200 and 500 are preferred. No significant benefit is likely for target numbers above this number. A minimum of 4 pairs of images are recommended with and without a roll.

3.5 Conclusions

Successful calibration is dependent upon collecting appropriate image information. If certain rules are followed then the procedure is simple and effective. The next section discusses how OMC software is operated.

4. Operation of OMC software

4.1. Introduction

To calibrate a camera it is necessary to obey the following five basic rules:

- Enough targets. Minimum of 100 - preferably 500
- Enough images. A minimum of 8 images, four with a 90 degree roll. If possible 16 images with variations in depth and camera pointing angle
- Convergent viewpoints. Between 35 to 60 degrees to the calibration artifact normal
- Image coverage. All of the image format should be covered
- The distance of the camera from the calibration artifact should be approximately the same as that when the camera is being used

The calibration procedure does require some care in setting up and execution when not familiar with the process. When a camera has been calibrated before and the equipment is set up the process need not take longer than half an hour. Most of the above rules can be broken, the calibration process will appear to work but the results obtained are likely to be deficient. In some cases this may not be important, in others serious problems may occur.

4.2. Camera location requirements

A calibration artifact is required with easily recognised target features that can be located to high accuracy in the images. The OMC software works with both retro-reflective targets that require special lighting or with white targets on a black background. A number of schemes have been developed to make the process as easy as possible. One scheme uses a large easily reproduced geometric pattern that is printed onto a sheet of paper and a number of these stuck to planar material such as plywood. Another scheme uses a smaller geometric feature that is printed onto a sheet of paper and used in a similar way.

A coded feature somewhere near to the middle of the test field is normally required for initial camera orientation purposes. The only definite requirement for the test field is that any paper is attached properly to whatever surface is used and that the surface being used is not able to deform during the camera calibration process. This may easily be achieved using a wall, a section of floor or a reasonably rigid board. The various positions that the camera is required to image the calibration object for image collection are illustrated in figure 4.1.

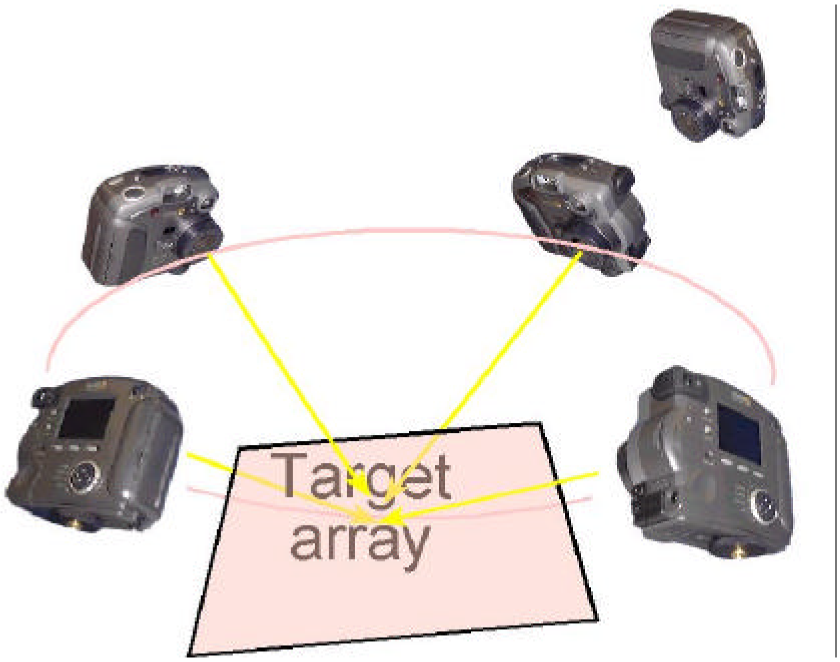


Figure 4.1. Basic configuration for image collection

Several aspects should be noted:

- The cameras all have similar object to camera distances
- The angles between the circles when looking straight down to the surface of the target array are approximately equal (about 90 degrees)
- The angle made between the normal to the target array and the camera optical axis is about 45 degrees
- One of the cameras is illustrated with the appropriate 90 degrees roll

This configuration is simple to visualise and remember. However, the calibration only takes place over a small camera to object range. If the images are moved closer or further away from the object this will provide image data from a greater range of 3-D positions which will improve the calibration volume (figure 4.2).

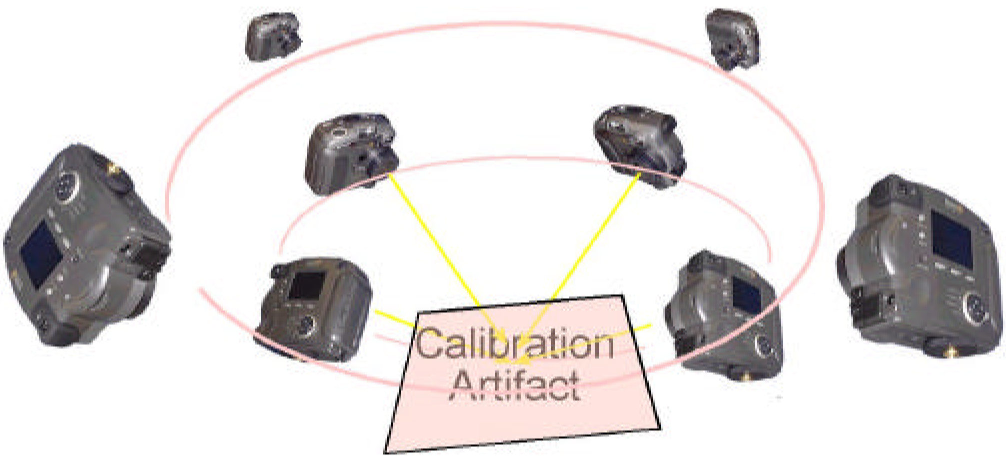


Figure 4.2. Camera configuration with added depth

The figure does not illustrate the required 90 degree rolls of the camera at each location but equal numbers of roll per camera station.

4.3 Operation of the software

4.3.1. Loading a project file

To calibrate a camera it is assumed that the user has used other software to estimate the 2-D location of targets in the images collected as described in the previous section. To make the process of loading varying different project with differing cameras and focal length lenses a project file concept is used. The dialog box selection for selecting a project is illustrated in figure 4.3.

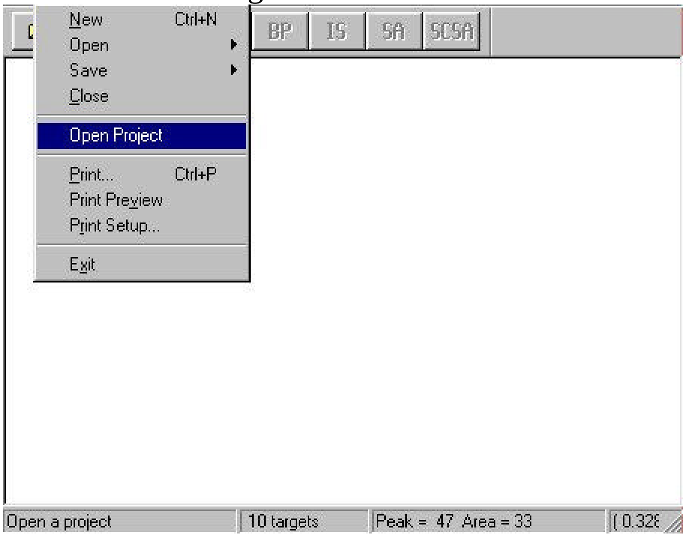


Figure 4.3 Selecting the project input option

The project extension is usually .PRO and the format for the plain text file is illustrated in the following figure

```
752 580
0.0084 0.0082
50
collected_image_data.i2d
measured_points.t3d
```

Figure 4.4. Project file contents

The first line represents the number of pixels in the image with the x direction first followed by the y. The second line is the pixel size in microns, the third line is the focal length lens being used in mm. The final two lines are the image data collected by the image processing software and the 3-D data to be used to determine the camera's initial orientation estimate.

4.3.2. Loading files individually

As an alternative to loading a single project file it is possible to load each file individually. This option is illustrated in figure 4.5.

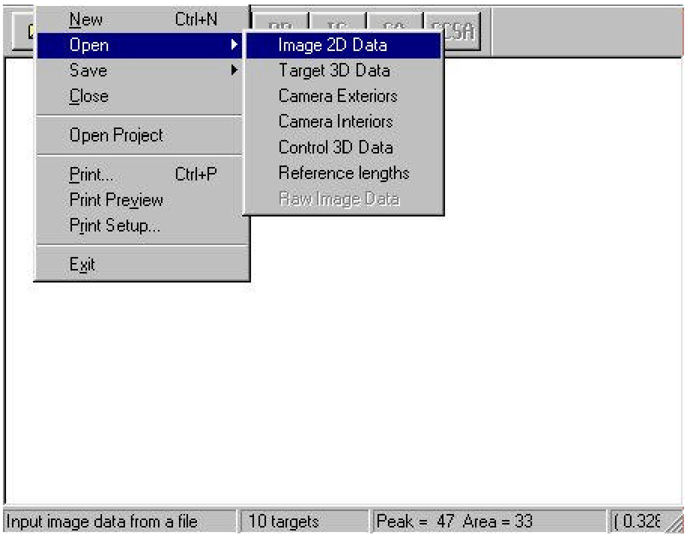


Figure 4.5. Loading files individually

In this option the user can input 2-D image data, 3-D target data, camera interior and exterior parameters, control points for resection and reference lengths used for verification purposes.

4.3.3. Viewing the target image locations

In all of the OMC software the original image is rarely seen. The user can see the target locations or coded targets on the computer screen. The primary view allows the user to scroll down multiple images by using the scroll bars on the right hand side of the screen. The target representation process is illustrated in figure 4.6.

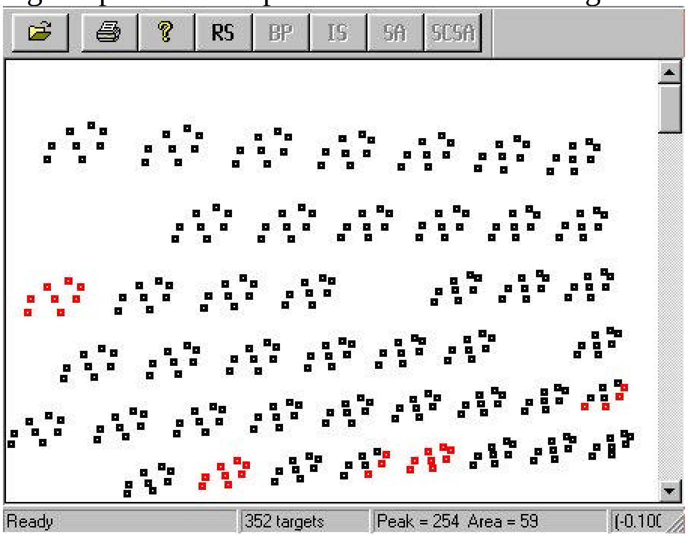


Figure 4.6. Target view in scrolling mode

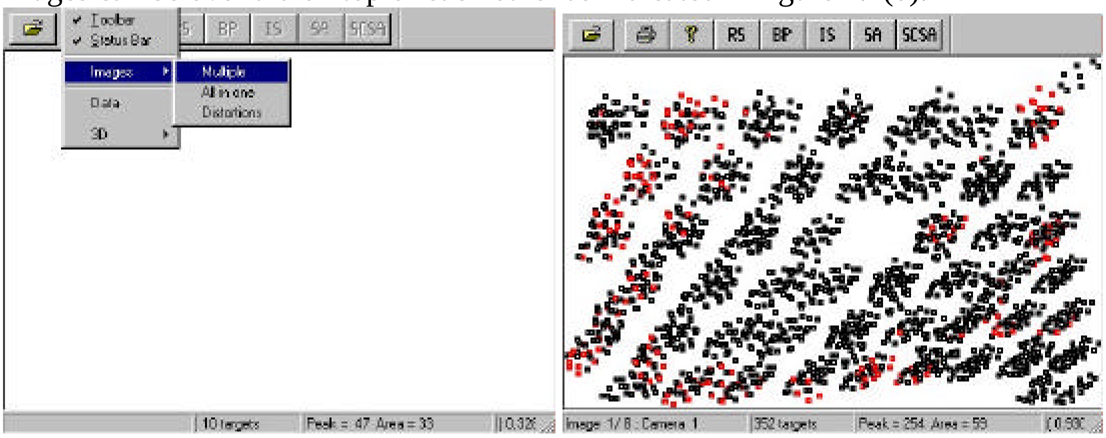
A current deficiency of the software is a requirement to scroll in whole image sections otherwise the cursor/target identification functions does not work correctly.

The number of targets is given in the information status bar at the bottom indicating the number of targets as well as the average peak and intensity values. The position of the targets in the image along with the current ID label is just out of the view on the right hand side.

If a coded target group has been partially identified the target locations will be visible in red instead of black and the ID for all of the targets in the group will be “-1”. Under most circumstances the loss of a coded target identity in one image is not significant, however if the target is being used for resection purposes this problem must be dealt with. The correct ID can usually be found by viewing the neighboring coded targets. To change the target ID select the ***Image*** pull down menu and the ***Find Control Targets - Manual*** option. The user can then enter a number into the dialog box and should then click the cursor on top of the target that requires changing. Moving the cursor away and back again should indicate whether the change has been successful. Subsequent selection of targets will increment the current number and label accordingly.

4.3.4. Viewing overlaid multiple images

By selecting the all in one option as illustrated in figure 4.7(a) all of the collected images can be overlaid on top of each other as indicated in figure 4.7(b).



(a) **(b)**

Figure 4.7 Viewing multiple overlaid image data

Targets that are in red are not correctly identified in each image or are rejected in the calibration process.

4.3.5. Determining the camera initial orientation estimates (RS)

Pressing the RS button will prompt the user for information concerning whether 2-D information is being used to determine the approximate camera locations or 3-D. This step is necessary for the later steps where these estimates will be used as starting values. For focal lengths that are relatively long it is recommended or may be proved necessary to use the 3-D option. For shorter focal length lenses a flat calibration artifact can be used. The information required in either case is a reasonable estimate of the 3-D co-ordinates of four or more points for the flat object and six or more for the 3-D object. The format for this data is illustrated in figure 4.8 that is the text from a typical input file.

1110	-7.9	-7.9	0	0	0	0
1270	7.9	-7.9	0	0	0	0
1130	7.9	7.9	0	0	0	0
970	-7.9	7.9	0	0	0	0

Figure 4.8. Input file for initial camera orientation estimation

The syntax is: X, Y, Z, 0, 0, 0. The final three zeros are retained for legacy reasons with old code. In the example given the co-ordinate system origin is in the middle with all of the points given a zero Z.

Following the resection process the 6 DOF estimates for the camera locations can be viewed using the View - Data pull down window selection that is explained later. If the process fails this is generally due to incorrect labeling, missing targets, or the wrong focal length. In some cases, with long focal length lenses failures may also occur. The first image that failure occurs in will be notified to the user.

4.3.6. Back projection (BP)

After the resection process has succeeded the BP or BP and IS buttons will become active. If coded targets or self-identifying targets are used and the ID is known the user should select the targets corresponded option in the Process - Systems Settings pull down menu which will make the IS option active. If no identities are known for the targets then two options are available. The user can create a file of approximate 3-D locations for the object being measured and these data will be used to project the object points into the images and check to see if any points are close in the image. If they are they are given the same identity in each image. To avoid problems with some targets being to close together it is possible to change the BP matching tolerance in the Systems Settings Menu.

4.3.7. Intersection (IS)

When the IS button becomes active either because targets are already identified or after the BP process, pressing it will perform an initial 3-D estimation step based on the estimates of the camera initial orientation parameters.

4.3.8. Separated Adjustment (SA)

This step refines the rough estimates to arrive at the best orientation and 3-D co-ordinates possible without performing any estimation of the camera distortion parameters. The dialog box for this process is illustrated in figure 4.9

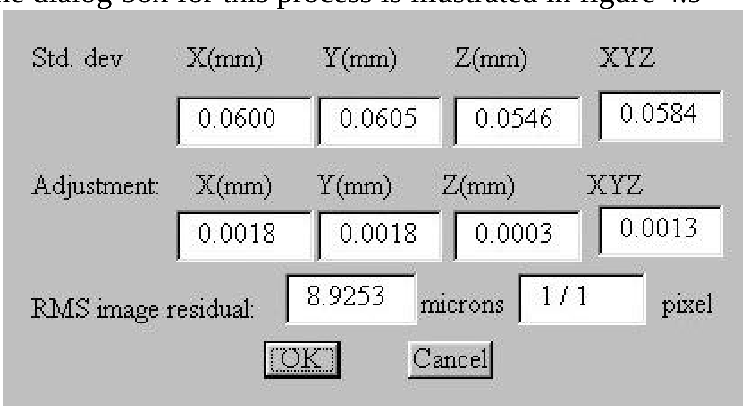


Figure 4.9 Separated adjustment results

In this example the subpixel error across the whole image plane had a rms value of just over one pixel. In the situation where the cameras are already calibrated - for instance with a stereo system, reading in the camera's parameters and correcting the images will result in an optimum measurement performance. When the cameras have not been calibrated the final step is to perform a full self-calibration.

4.3.9. Self Calibrating Separated Adjustment (SCSA)

The SCSA button will perform the final self-calibration step. The output at the end of the process is illustrated in figure 4.10.

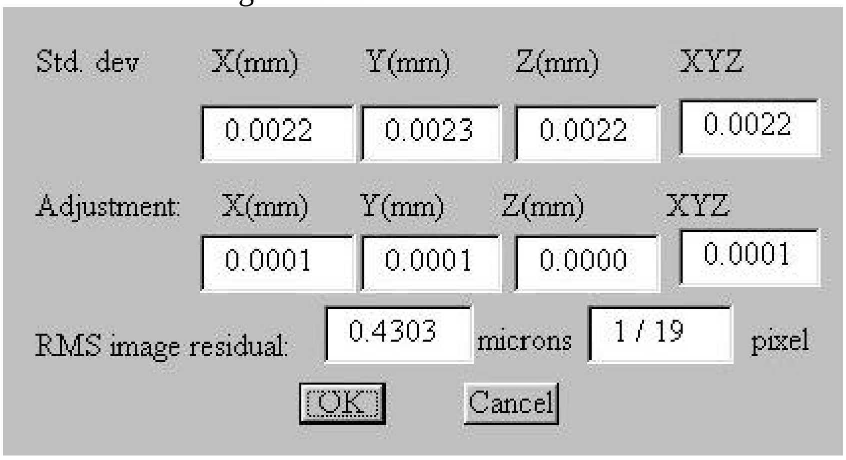


Figure 4.10. Self-calibration output window

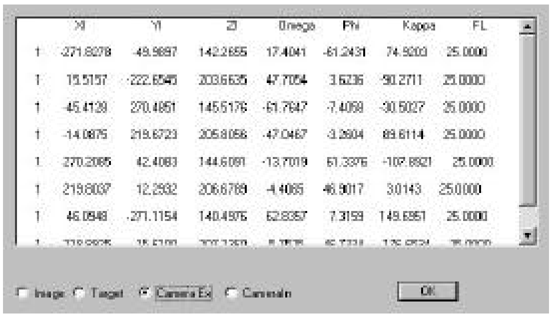
In this particular example the overall error has been reduced dramatically to 1/20 of the previous value. To get to this point does require some further explanation however.

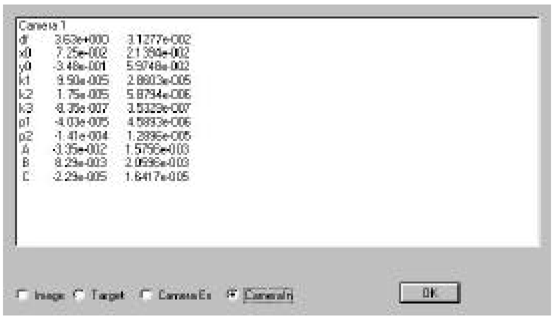
The adjustment process is relatively fine and the first step will only begin the convergence process. The number of times the adjustment button needs to be pressed in dependent upon, amongst other things, the geometry. The users should repeat the process until convergence to the lowest value in terms of 3-D precision and rms image residual has been reached.

The adjustment process can fail and diverge in some circumstances such as when a flat calibration object is used or when long focal length lenses are used. In these cases it may still be possible to obtain a solution but more care is needed. The user should make changes to the relaxation factor selecting a value of 0.2. In addition for the majority of steps it is useful to fix the focal length and principal point location to reasonable value

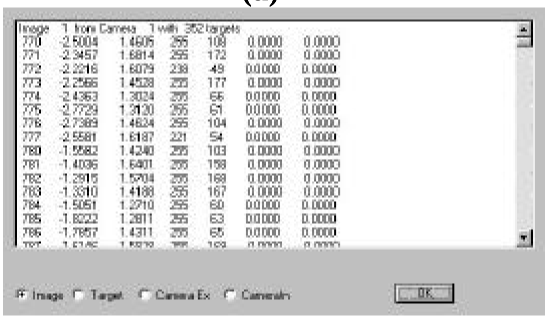
4.3.10. Viewing results

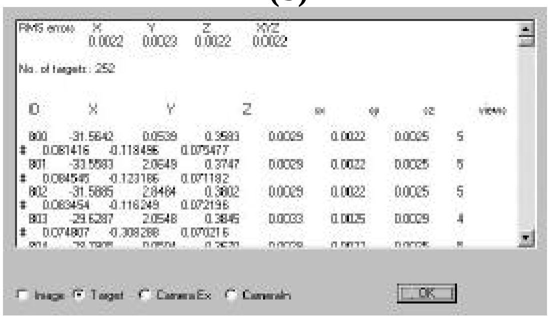
Following a successful calibration which is generally indicated by the convergence of the solution to an image residual of between 1/10 and 1/80 of a pixel, the user can view the data using View - Data option in the pull down menu. The information available is illustrated in the following figures.





(a) **(b)**





(c) **(d)**

Figure 4.11. Output from the calibration process

The output data consist of the original input image data (c), the exterior parameters (a), the interior parameters (b) and the 3-D co-ordinates of the object points. In the case of the interior parameters the standard deviations are also given which indicate how well the parameters have been estimated. Each of these sets of data can be saved to a file for later use.

4.3.11. System settings - Adjustment

The user is able to vary the default settings of the software and the way in which certain functions are carried out. These settings are grouped under three pages. The adjustment parameters page is illustrated in figure 4.12.

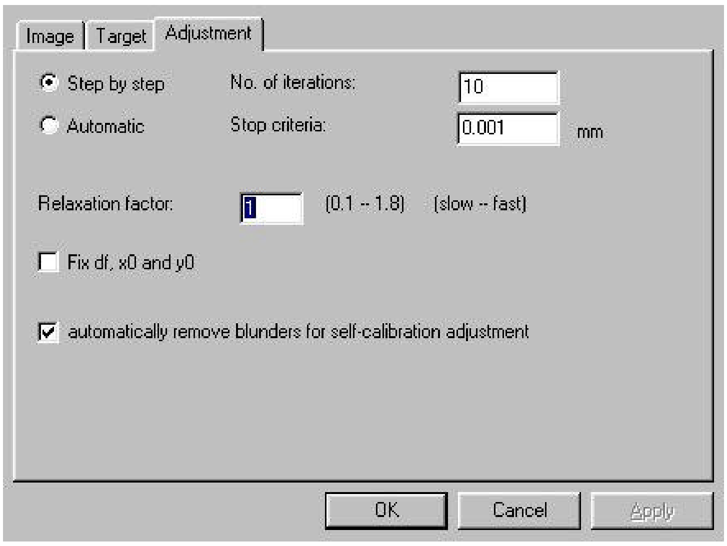


Figure 4.12. Adjustment parameters

The number of steps that the adjustment performs per button press can be changed from the default of 10. It may be useful to change this number to 30 for instance which will lessen the number of button presses necessary but length the time for the computations to take place. Alternatively the user can select a stopping criteria for the adjustment so that it will progress until this value is reached and then stop.

The relaxation factor relates to the speed of convergence. Fast convergence is only possible if the geometry of the images is strong, slow convergence is necessary if the image geometry is weak. A factor of 1.0 would be normal and a factor of 0.2-0.4 would be suitable for a weak geometry. This value can be changed on the fly. For instance once convergence appears to be inevitable the value can be increased.

For situations where a long focal length lens is being used or when a flat calibration object is used the option to fix the values of the focal length and the principal point distance exists. The user should create a input .CIP file with the desired values for principal distance and principal point location and read this in to the system using the FILE - OPEN - CAMERA INTERIORS pull down menu option. With the button ticked these values will be used and not adjusted. In many instances, even with weak geometry, it is sometimes possible to adjust these values slightly in the last few steps of the process when the other parameters have been established. However, care should be taken to see that the values that are estimated are reasonable. For instance, the principal point location should not be more than 100 pixels from the nominal centre of the image and often will be around 10-30 pixels maximum value.

Where there is sufficient redundancy of measurements it is reasonable to test the residuals for outliers and remove them. This option is usually selected but can be turned off. The user should check that this scheme does not remove all of the outer targets for instance as this would be undesirable. Another problem can be if the scheme removes all of the 3-D points leaving a plane that is also undesirable.

4.3.12. System settings - Target

The user can vary some settings related to the targets. This page is illustrated in figure 4.13.

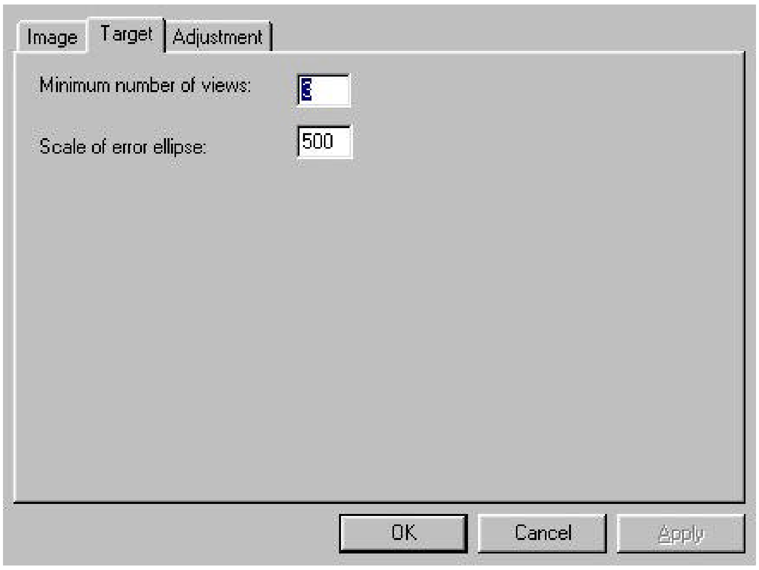


Figure 4.13 Target settings

The user can select how many views of a target are required from a minimum of two to the maximum number of camera views available. In general terms it is better if the number of views equals the number of targets but this will in practice leave many legitimate groups of targets unused. It is recommended that two views are not used for camera calibration unless deemed absolutely necessary.

In the VIEW - 3D pull down menu option the user can view error ellipses for each target measured. The scale of the error ellipse will sometimes need to be changed to obtain the best magnification of the error ellipses.

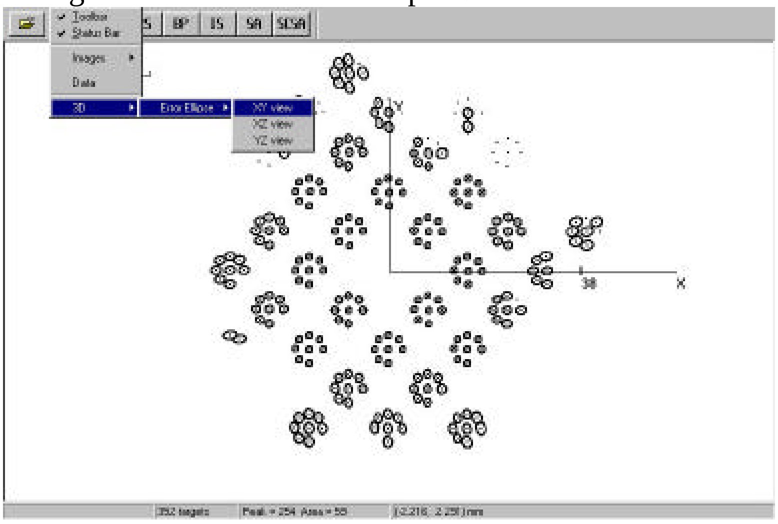


Figure 4.14. Error ellipse display XY viewpoint

This display can be viewed from three orthogonal axes as a parallel projection. The user should be aware that this viewpoint may result in varying sized error ellipses being plotted on top of each other. The example given in figure 4.14 illustrates the case where the errors are larger for outer targets that are not viewed by as many images as the inner targets.

4.3.13. System settings - Image

The **Image** page of the systems settings are illustrated in figure 4.15.

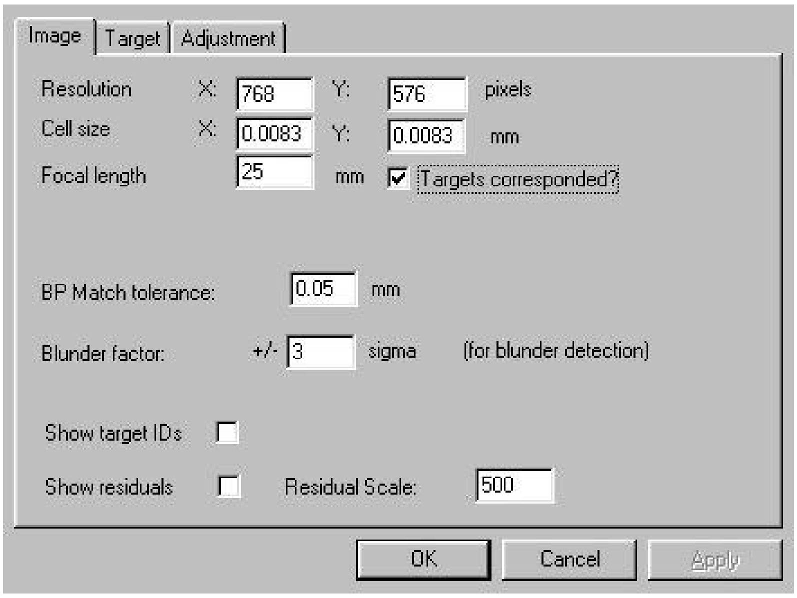


Figure 4.15. Image settings page

In this page the nominal image size in pixels and pixel size are defined as well as the focal length. These values can either be set manually - and they have to be correct for any reasonable calibration - or input in the project file. The focal length can be artificially moved from its nominal manufacturers value which may be necessary when the user is fixing the principal distance. However, it should be noted that this change in setting only comes into effect if the user starts the calibration procedure again - i.e. by going back to the resection stage.

The tick box indicating Targets Corresponded will determine whether the BP and IS buttons are available or just the BP which implies that the user has not corresponded the targets by any other means.

The back projection tolerance relates to how close the back projected ray can be away from a image target for it to be considered a legitimate match.

The blunder detection value used in the adjustment is set here to +/- 3 sigma which will ensure that only a few blunders are removed. This value could be increased.

The user can display either the ID’s for the targets or the error vectors after an adjustment process or even during the adjustment process. The scaling for the error vectors can also be changed here. However, updating the screen can be a bit time consuming and if the error vectors are extremely large - as they are at the beginning of the adjustment or if the solution diverges - there is no checking at present and plotting these points may cause unacceptable delays or a software crash. It is therefore recommended that the residuals are displayed at the end of the process as illustrated in figure 4.16.

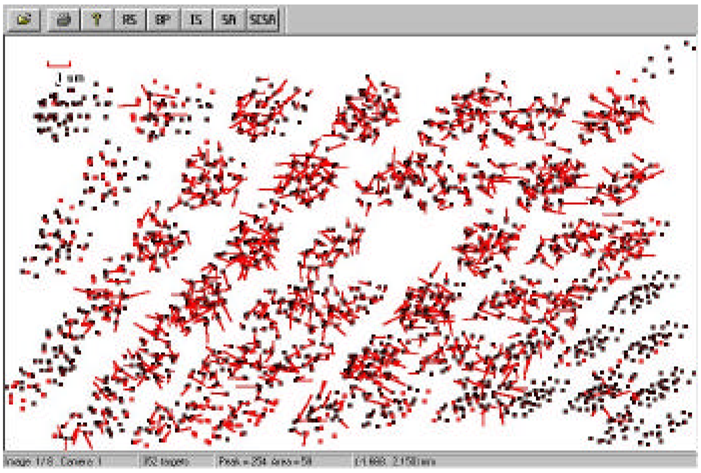


Figure 4.16. Error vector display

The user should look at the vectors to establish that no systematic effects are in evidence, or if there are systematic effects that these are not too large or consistent across a whole image.

The ID display is illustrated in figure 4.17.

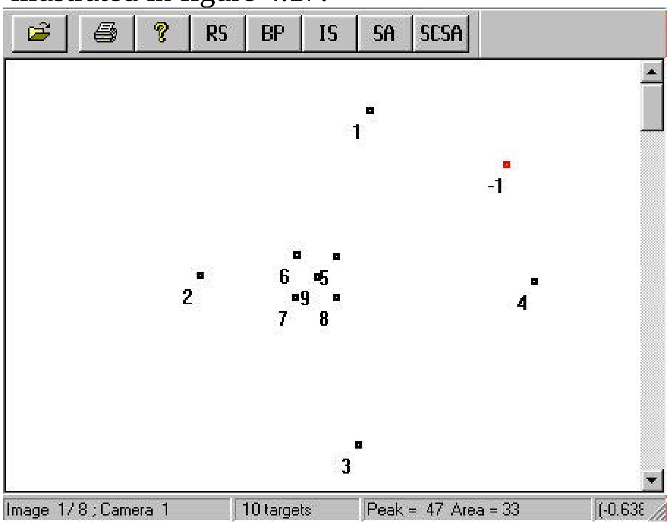


Figure 4.17. ID display

Where there a large number of targets this display may be too cluttered to identify individual targets clearly. In this case the user can look at the status bar and determine the ID by placing the cursor over the target. In this case the cursor will change shape into a cross and the ID of the target will be displayed on the status bar information. A -1 indicates that this particular target is not corresponded and therefore no measurements will be made using this target in this image.

4.4. Practical calibration examples

The software allows the user to perform the calibration process in a number of ways. One of the most important first steps is the unique labeling of the targets from each view. Several schemes are possible and two of them are illustrated in the following sections.

4.4.1. Regular array of target points

A calibration artifact was produced by sticking a number of 5 mm retro-reflective targets to blue paper according to a regular grid pattern (blue was used in preference to white due to its low response to the red light used to illuminate the retro-reflective targets. The arrangement is illustrated in figure 4.18.

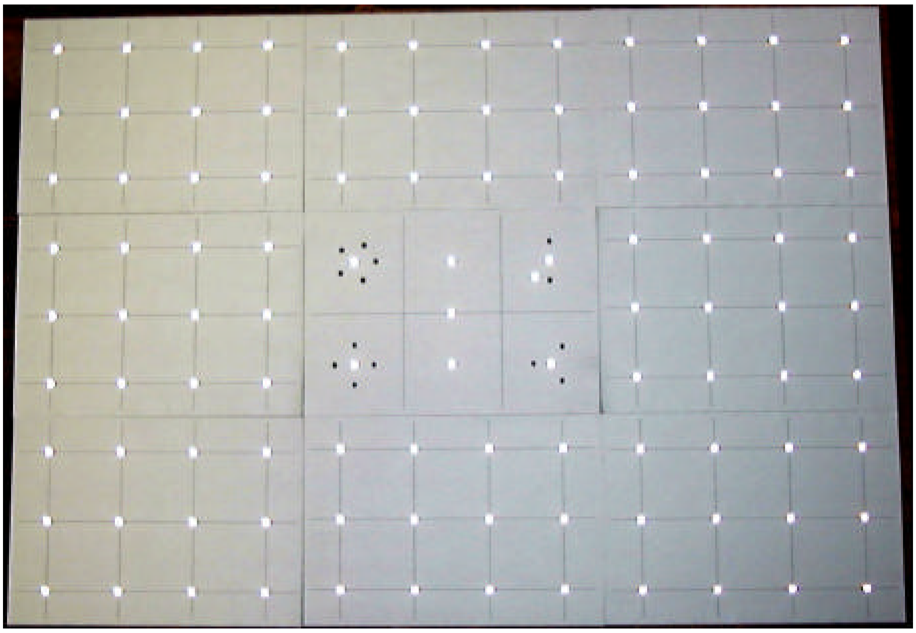
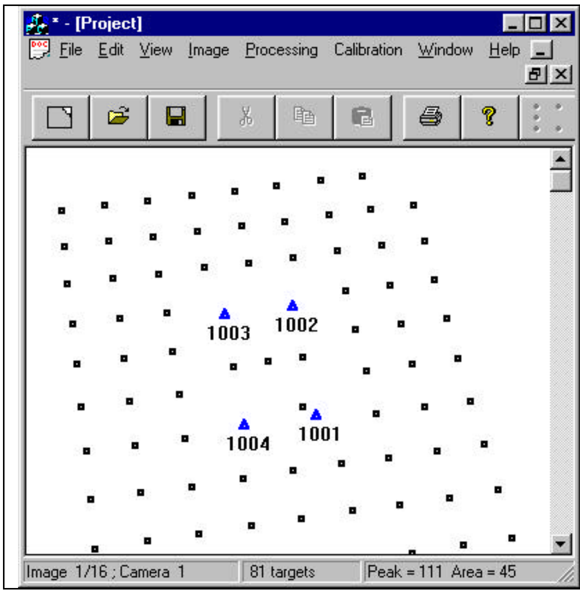


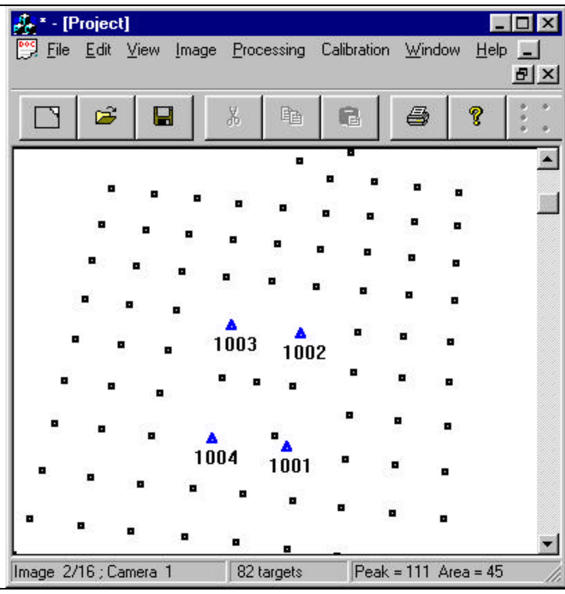
Figure 4.18. Calibration artifact

A camera was placed on a tripod as illustrated in figure 4.19 and images were taken as discussed previously.

Figure 4.19. Arrangement of the target test field and camera

The resulting images were processed and four identical points in each image were manually marked to enable the camera positions to be estimated. The resulting images are illustrated in table 4.1.





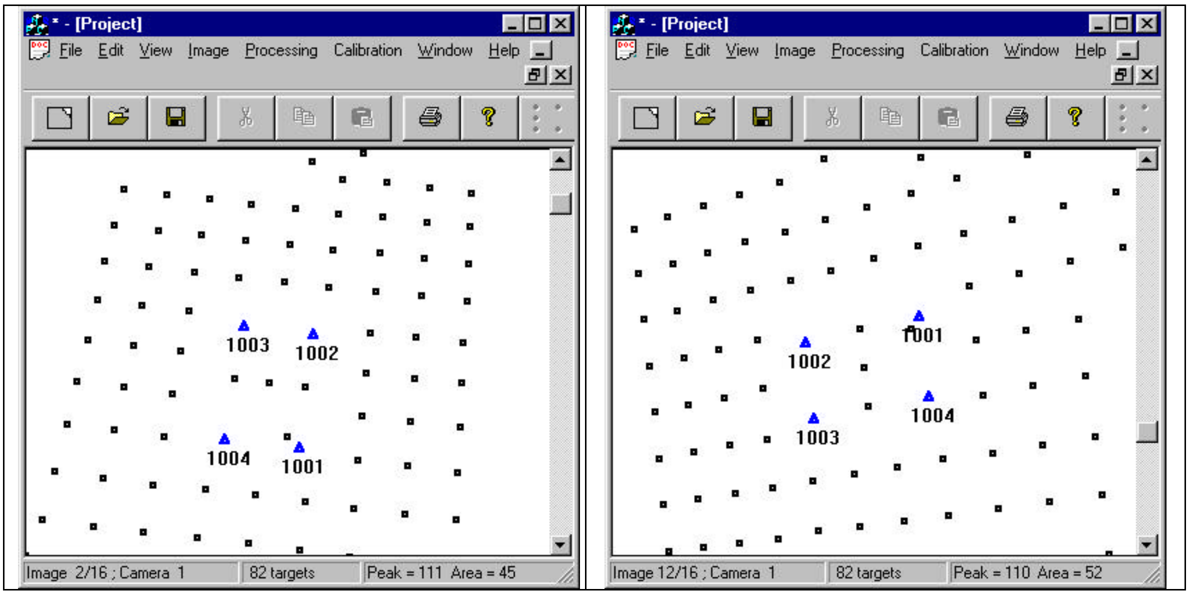
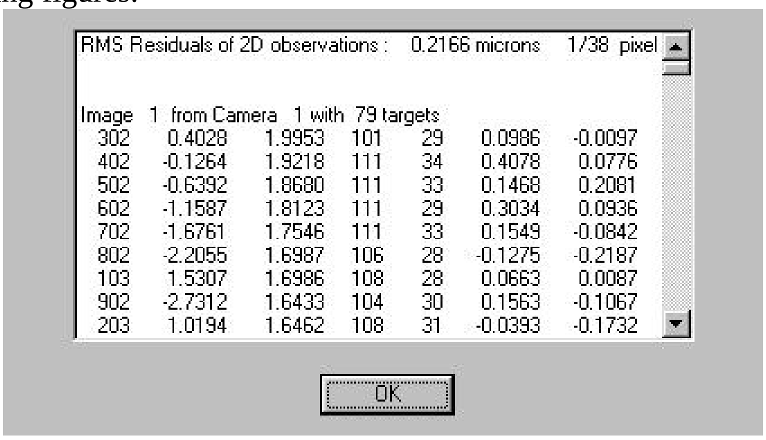


Table 4.1. Four examples of the 2-D visualisation of the target co-ordinates from the set of 16 used in the calibration

Using the initial estimates the 3-D co-ordinates the unmatched targets were projected onto the images and the targets were therefore uniquely corresponded between images. There were a number of further steps required to complete the calibration of the camera:

1. Intersect the corresponded targets to create initial 3-D estimates
2. Adjust the exterior orientation and 3-D co-ordinates without estimating the interior parameters
3. Adjust all parameters
4. Remove obvious blunders
5. Adjust all parameters again

All of these operations can be carried out automatically if no problems are encountered. Further work will allow all of the operations to be carried out automatically. The results available after the calibration consist of various screens that can be interrogated and files that can be saved. The information available is illustrated in the following figures:



RMS Residuals of 2D observations : 0.2166 microns 1/38 pixel

Image 1 from Camera 1 with 79 targets

302	0.4028	1.9953	101	29	0.0986	-0.0097
402	-0.1264	1.9218	111	34	0.4078	0.0776
502	-0.6392	1.8680	111	33	0.1468	0.2081
602	-1.1587	1.8123	111	29	0.3034	0.0936
702	-1.6761	1.7546	111	33	0.1549	-0.0842
802	-2.2055	1.6987	106	28	-0.1275	-0.2187
103	1.5307	1.6986	108	28	0.0663	0.0087
902	-2.7312	1.6433	104	30	0.1563	-0.1067
203	1.0194	1.6462	108	31	-0.0393	-0.1732

OK

Figure 4.20. 2-D image data

Figure 4.21. provides a summary of the 2-D image residuals in microns and the overall subpixel accuracy. The 2-D co-ordinates for each of the targets are grouped by camera and contain the target ID, x and y co-ordinates, peak intensity, area, x and y residual.

RMS STDV of	X	Y	Z	XYZ
	0.0083	0.0081	0.0129	0.0100

No. of targets : 92

	X	Y	Z	stdv_x	stdv_y	stdv_z	No. of view
202	-341.0654	216.0141	1.9501	0.0092	0.0094	0.0149	9
302	-341.1320	145.1100	1.6400	0.0083	0.0080	0.0128	12
402	-338.1066	71.0510	1.4732	0.0082	0.0077	0.0128	12
502	-338.1475	0.5124	1.6989	0.0086	0.0082	0.0133	11

OK

Figure 4.21. 3-D data

Figure 4.6. gives a summary and details of the 3-D data that is a by-product of the calibration process. The rms error in the 3-D co-ordinates are given for all of the targets and the individual results in the order of: target ID, X Y Z co-ordinates, std dev for the X Y Z co-ordinates, and the number of views of each target. The exterior parameters for the camera stations are illustrated in figure 4.22.

	XI	YI	ZI	Omega	Phi	Kappa	FL
1	1152.9574	-233.1191	1573.8439	8.0705	34.0166	78.2649	16.0000
1	1139.4127	102.0365	1571.9122	-3.4592	34.8199	98.3937	16.0000
1	159.3428	1164.9073	1582.3158	-34.2824	4.4622	176.1927	16.0000
1	-188.6401	946.0410	1572.0509	-29.5192	-4.4115	-168.9738	16.0000
1	-1114.4116	-154.9963	1571.6435	4.1752	-33.6521	-79.4552	16.0000
1	-1135.3392	215.5904	1572.5012	-6.9707	-33.0929	-99.6307	16.0000

OK

Figure 4.22. Camera station exterior parameters

These parameters can be checked to establish whether there are any unreasonable values computed if problems are encountered. The interior parameters (the objective of the camera calibration process) together with standard deviations are illustrated in figure 4.23.

	xp	yp	df	k1	k2	k3	p1	p2	A	B
1	-2.0e-001	-6.8e-001	1.1e-001	4.5e-004	2.0e-005	-7.3e-007	5.5e-005	-9.8e-005	1.2e-002	-1.3e-003
1	8.2e-003	7.9e-003	1.2e-002	1.0e-005	1.5e-006	6.6e-008	5.0e-006	4.9e-006	3.4e-005	3.3e-004	5.

OK

Figure 4.23. Interior camera parameters and standard deviations

The results from this calibration are extremely good for the type of camera being around 1/40 of a pixel rms error overall.

4.4.2. Coded targets

In this example coded targets are used which are identified by the separate image processing software. The coded targets have a unique geometric and radiometric signature that is recognised by the software such that each target is identified in each image separately.

4.4.1. 2-D Calibration artifact

A two-dimensional calibration artifact provides the maximum ease of construction, maintenance and use. Figure 4.24 shows a 2-D calibration artifact with the camera in the normal and rolled positions.

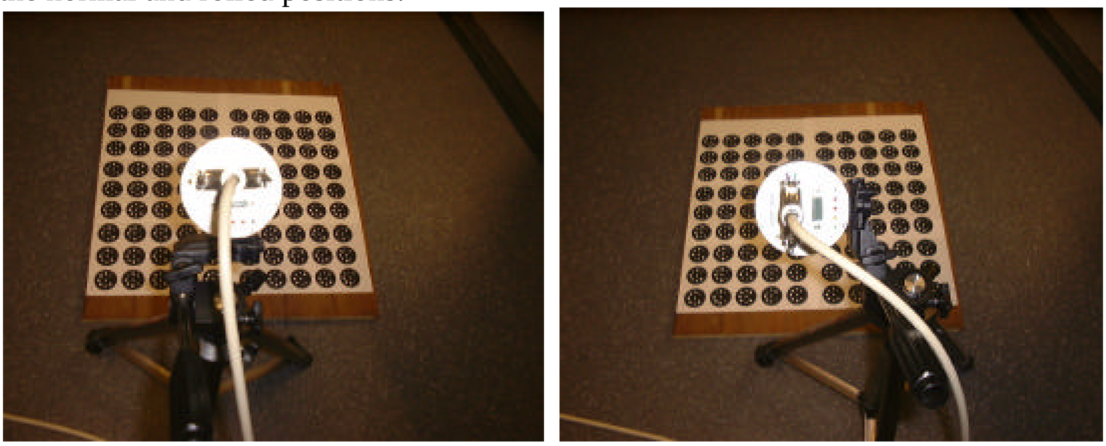


Figure 4.24. Camera in normal (left) and rolled (right) positions

In this example the artifact has been made of 20 mm block board and the printed coded target sheets have been glued to the board in an appropriate pattern. The board must be rigid or must be left in a stable position and the camera moved around the object. It should be noted that there can be some problems with a flat object for the highest accuracy calibration due to similarities in the lens model with the flat object especially when the cameras are all pointing towards the centre of the object. This is particularly true with longer focal length lenses where use of a flat calibration object becomes impossible due to the lack of perspective distortion that is usually required to resect the camera positions accurately. To get around this problem an object with three dimensions should be used.

4.4.2. 3-D Calibration artifact

The three dimensional artifact in figure 4.25 is constructed from anodized steel with a number of coded targets mounted on the end of rods at varying heights.

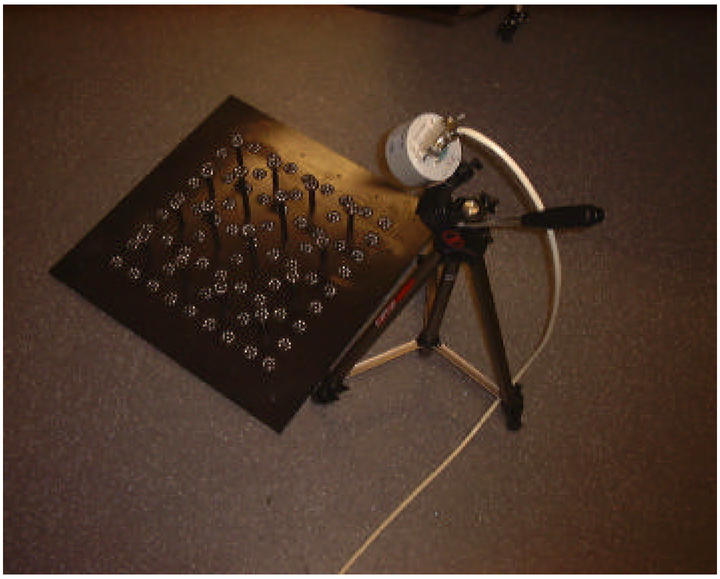


Figure 4.25. 3-D calibration artifact

Problems can be encountered with objects of this type due to coded targets being partially or completely obscured. However, the artifact does allow for the highest accuracy camera calibrations to be performed.

4.4.3. Relative orientation with more than one camera

The relative orientation of stereo, trinocular, or multi-camera systems is an important factor in the calibration process. While it is only briefly touched upon here the OMC software has some useful characteristics for this process where the relative orientation is derived for all cameras at the same time as a 3-D measurement thus giving the maximum accuracy due to the added redundancy of the scheme.

To achieve this type of calibration it is necessary to collect image pairs, or triplets etc with pre-calibrated cameras. The images should be corrected for distortion and then the 3-D of the object should be computed using the Separated Adjustment without self-calibration. After this process the optimum camera exterior parameters can be extracted from the exterior data set that will contain multiple sets of parameters - any set can be chosen.

It may be necessary, depending upon how the 2-D data was collected to manually edit the 2-D data file to ensure that the right cameras are identified and used. The format is as follows

```
Image-ID1    Cam-ID1          No_targets
ID1  X  Y  peak area
ID2  X  Y  peak area
-
Image-ID2    Cam-ID2          No_targets
ID1  X  Y  peak area
ID2  X  Y  peak area
-
Image-ID3    Cam-ID1          No_targets - etc.
```

Figure 4.26. Data format for i2D data (stereo case)

4.4.4. Calibration of a stereo system using a 3-D calibration artifact

A stereo system may, in some cases, be calibrated in an all-in-one procedure that results in the interior and exterior parameters being available at the same time. The following example outlines the calibration of a fixed configuration stereo system. The usual requirements of obtaining images from four directions and also further images with a significant angle roll still applies. However, creating the roll angle can be a problem for some viewpoints.

A stereo measurement system using two VDS cameras is used an examples system. This cameras are rigidly constructed using a rectangular steel tube. The stereo system consists of two VDS cameras (1280 by 1024 pixels, 6.7 by 6.7 microns, focal lengths = 8.5 mm, base distance = 530 mm, convergence angle = 70 degrees). Two Matrox Meteor digital frame grabber were used for the image acquisition.

A 3-D test field with 81 coded targets (648 targets in total) was used for calibration and relative orientation of the system. 22 images were captured with the stereo system (11 images from each camera). The configuration of the test field and the camera system is illustrated in figure 4.27.

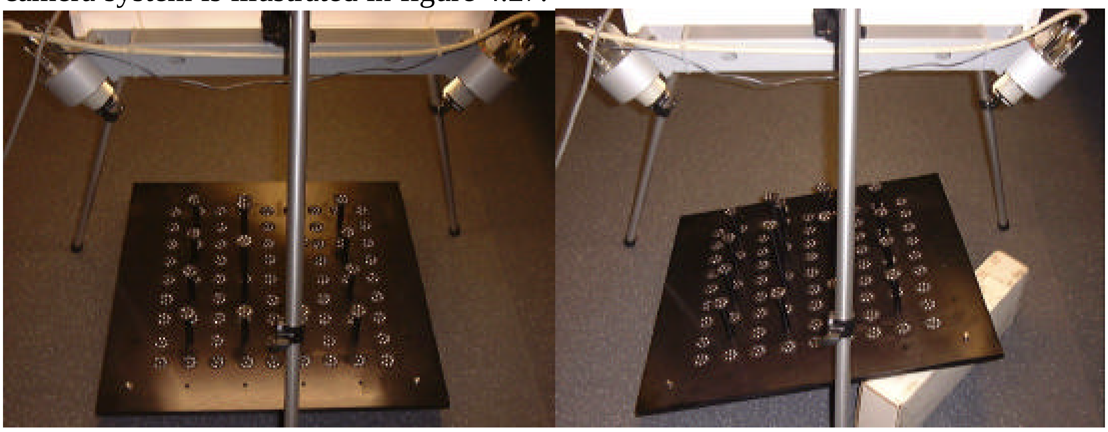


Figure 4.27. Calibration configuration for normal and roll positions

In each configuration, i.e. as illustrated in the left or right hand image, the artifact is rotated through approximately 90 degrees. In the case of the right hand image, where an approximation to a 90 degree roll in the camera has been improvised, a similar set of images would be required which would be mover favourable to the right hand camera.

The overall image 2-D accuracy is was 0.2 microns or 1/33 pixel after the self-calibration. The camera interior parameters were saved in file camera.cip. Calibration results are saved in file calibration-results.dat. The details are given on the next page.

```
Number of Images:       22
Number of Targets:      560


3D Standard errors:      SX        SY        SZ          SXYZ  (mm)
                      0.0041    0.0038    0.0069      0.0051

RMS 2D Image Residuals:   0.2041 microns  (1/32 of a pixel)

Camera  1 :
Camera Interior Parameters:  Estimated Values      Standard Deviations
                        pd:      8.5307e+000           1.1685e-004
                        x0:      1.0033e-001           2.0409e-004
                        y0:     -4.1587e-002           2.0125e-004
                        k1:      2.8426e-003           2.7199e-006
                        k2:     -1.4824e-005           2.6762e-007
                        k3:     -7.9310e-007           7.9438e-009
                        p1:      5.1211e-005           7.1135e-007
                        p2:     -4.7827e-005           6.2416e-007
                         A:     -4.8784e-005           3.6779e-006
                         B:     -1.6045e-005           3.2424e-006
                         C:     -5.7425e-006           2.1168e-006
Correlations between parameters:
  x0     y0     k1     k2     k3     p1     p2     pd     A      B      C
  1.000
 -0.005  1.000
  0.015 -0.079  1.000
 -0.032  0.076 -0.970  1.000
  0.054 -0.082  0.916 -0.983  1.000
 -0.894  0.001 -0.000  0.009 -0.019  1.000
  0.045 -0.424  0.003 -0.047  0.054 -0.054  1.000
  0.027 -0.212  0.478 -0.449  0.412 -0.004 -0.035  1.000
  0.024  0.104 -0.071  0.021 -0.001 -0.020  0.388  0.186  1.000
  0.028  0.005 -0.006  0.006 -0.003 -0.213  0.026 -0.042 -0.011  1.000
 -0.082 -0.627  0.080 -0.068  0.055  0.072 -0.021 -0.033 -0.372  0.016  1.000

Camera  2 :
Camera Interior Parameters:  Estimated Values      Standard Deviations
                        pd:      8.5455e+000           1.1689e-004
                        x0:      4.9345e-002           1.9050e-004
                        y0:     -1.8241e-001           2.0330e-004
                        k1:      3.0014e-003           2.2821e-006
                        k2:     -2.1092e-005           2.0190e-007
                        k3:     -6.7727e-007           5.2814e-009
                        p1:      3.9662e-005           6.8948e-007
                        p2:     -6.4637e-005           6.6551e-007
                         A:     -1.2589e-004           3.9915e-006
                         B:      3.2706e-004           3.3000e-006
                         C:      7.0956e-005           2.0341e-006
Correlations between parameters:
  x0     y0     k1     k2     k3     p1     p2     pd     A      B      C
  1.000
  0.006  1.000
  0.116 -0.057  1.000
 -0.149  0.041 -0.966  1.000
  0.167 -0.053  0.910 -0.983  1.000
 -0.875  0.001 -0.062  0.073 -0.082  1.000
  0.047 -0.450 -0.016 -0.058  0.077  0.001  1.000
  0.057 -0.164  0.436 -0.412  0.385 -0.083 -0.028  1.000
  0.129  0.158 -0.089  0.027 -0.005 -0.118  0.446  0.158  1.000
  0.124  0.069  0.053 -0.039  0.032 -0.337 -0.128  0.065  0.016  1.000
 -0.066 -0.609  0.082 -0.067  0.056  0.068  0.029 -0.093 -0.478 -0.096  1.000
```

Analysis of this report shows that an overall result for both cameras of 1/32 of a pixel was achieved and (from experience) the values of the parameters are reasonable for the type of lens used. In addition the correlations between the parameters indicate that no unexpectedly high values were present (over 90%) except in cases where high correlations are expected such as between the K parameters.

Following the calibration analysis of the image residuals by averaging the results from the 21 images with respect to one of the camera still showed some systematic effects that remained unmodelled by the system (figure 4.28).

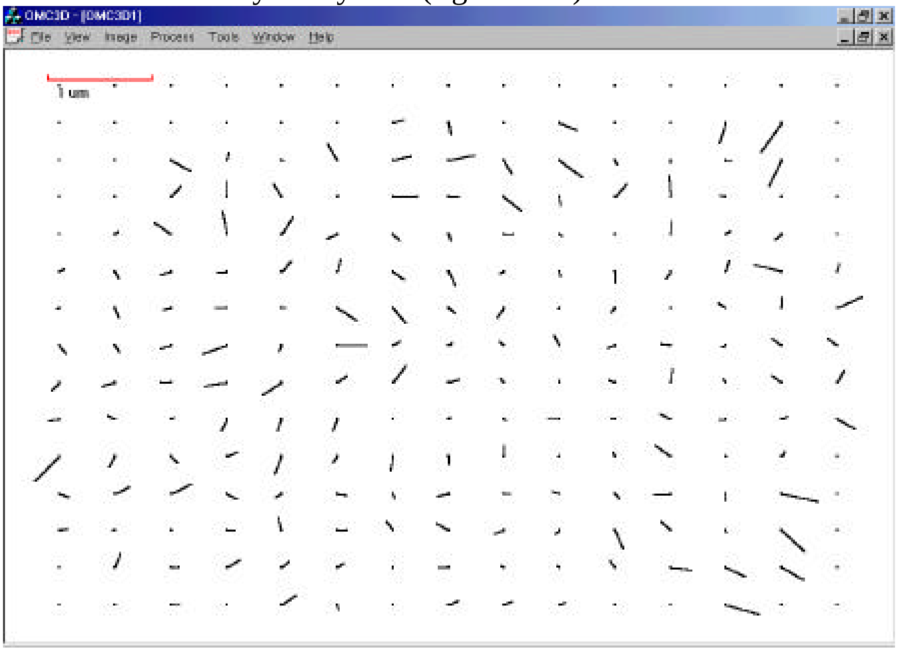


Figure 4.28. Systematic errors after calibration

The systematic errors, although noticable, are not large enough to cause major problems. After self-calibration adjustment the camera exterior parameters were saved in file camera.cep. The first pair of the camera exterior parameters was used to define the relative orientation of the stereo system.

4.4.5. Generic procedure for independent calibration of a set of cameras

To calibrate a set of cameras and obtain their exterior parameters the following procedure is recommended:

- Calibrate each camera in turn and save their interior calibration parameters into individual files
- Create a new interior calibration file with a different camera number for each set of calibration parameters
- Take a series of images of an array of target that can be viewed by all cameras if possible rotating the target array by 90 degrees for each set.
- Combine the resulting images into one file and ensure that the camera number is the same as for step 2 and the image number increments.
- Load the images into the calibration software and correct the images for distortion.
- Perform a typical calibration by resection, intersection followed by Separated Adjustment. Remove any blunders and check that the subpixel accuracy is similar to that encountered in step 1. Do not attempt to self-calibrate.
- Scale the 3-D data as described in the next section.
- Take any group of camera exterior parameters - e.g. the first pair of parameters and create a file with just these parameters. These parameters must be loaded along with the interior parameters whenever that set of cameras is to be used in pre-calibrated mode.

4.4.6. Imposing scale

Photogrammetry measures the shape of objects and does not have a direct means of determining scale. If a camera is to be used on its own then scale is not important. If the exterior orientation of the cameras will be used then it will be important to establish scale. Hence, the final step in the calibration process is to scale the 3-D data and perform one final iteration of the resection intersection process to ensure that the scale of the exterior orientation parameters is correct.

- Measure the distances between points that are likely to fall in all images
- Create a file of the following type:

ID1 ID2 Distance (mm)

```
1260 1270 8
1270 1280 8
1280 1130 8
1130 980 8
980 970 8
970 960 8
960 1110 8
1110 1260 8
```

with an extension “.SCL”

- Select the Rescale option from the ***Process*** pull down menu and select the file you have created containing scale distances.
- Perform one iteration of resection (from the saved 3-D data) followed by intersection to establish a new set of exterior parameters which should then be used.

5. Conclusions

This guide has explained the principles and operation of the OMC software package for camera calibration. The user of the software will be able to calibrate a wide range of normal cameras. Some limitations may exist for very long or very short focal length lenses.

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