

Calibration Stability of the Kodak DCS420 and 460 Cameras

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ABSTRACT

Portable digital image cameras such as the Kodak DCS420 and 460 are widely used for metric applications of close-range photogrammetry. The use of these cameras is typically in one of two forms, either as a mobile single camera for offline industrial measurement applications, or in a multi-camera system for online operation in a "work-cell" environment. In common with any metric system, the calibration of the cameras is of paramount importance to maintain the fidelity of the collinearity solution, and therefore the maximum possible accuracy. Any variation in the calibration during image capture for an offline or an online system will inevitably have a deleterious effect on the measurement accuracy. This paper describes a series of experiments concerning the calibration stability of DCS420 and 460 cameras in offline and online configurations. The calibration strategy is described and the effect of a minor modification to the CCD sensor mounting is presented. The variations in RMS image residuals and calibration parameters are quantified in terms of magnitude and significance for the different modes of operation.

Keywords: digital still cameras, camera calibration, calibration stability, vision metrology, industrial inspection

1. INTRODUCTION

Vision metrology (VM) systems for high-precision optical three-dimensional measurement have gained wide acceptance for industrial inspection and large-scale metrology in manufacturing and engineering¹. The acceptance of these systems is based principally on the efficiency and accuracy levels which can be achieved. The cornerstone of the efficiency is the use of digital images, which can be rapidly acquired and processed. In particular, advances in the automation of systems² would not be feasible without the use of cameras which capture digital still or video-rate images.

A digital still image camera which has proved to be extremely popular for metric applications is the Kodak DCS series³. This camera series is designed essentially for photo-journalism, but has many desirable features for a digital image, photogrammetric camera. The high resolution of the CCD sensor combined with high image storage capacity and ready availability has made the DCS the common choice for vision metrology applications where system portability is important. Though there are other digital still cameras with similar features⁴, the DCS series is certainly the most widely used camera for industrial inspection and large-scale metrology.

The accuracy of VM systems is dependent on the image resolution, image scale, image measurement precision and a number of other factors, such as network design⁵. The principal influence on accuracy for the DCS series is the resolution of the CCD sensor. Utilizing a 1536 by 1024 element CCD array, the DCS420 and its predecessors are widely used for measurement tasks which require proportional accuracies in the range 1:50,000 to 1:80,000⁵. Accuracies well in excess of 1:100,000⁶ can be achieved with the DCS460, which has an image resolution of 3096 by 2048 pixels but is commensurately more expensive.

However, the assumption of equivalency between precision and accuracy for VM applications can be invalidated by errors or variations in the calibration of the camera. The appropriate modeling and compensation of systematic errors in the collinearity solution is essential to maintain the fidelity of the triangulation and the derived object space coordinates. Any deficiency in the calibration model will have a propagated effect on accuracy within the object space. It is well known that the design of the DCS series of cameras is not conducive to consistent internal geometry because of the nature of the CCD sensor mounting and the camera body to digital back connection⁷. This paper describes a series of experiments designed to determine the magnitude of instability of the calibration of Kodak DCS420 and 460 cameras.

2. SYSTEM MODES, CALIBRATION AND APPLICATIONS

The initial use of digital still cameras was generally as a single roving camera, which in essence is in the manner of traditional semi-metric or metric film cameras used for industrial metrology. The wide range of applications for Kodak DCS cameras in this mode of operation include industrial inspection¹, large scale engineering metrology⁵, architectural recording⁸ and low altitude mapping⁹.

In the fields of engineering metrology and industrial inspection, targeted points of interest combined with self-calibration is the normal mode of operation. To ensure an accurate and reliable solution for the object space coordinates of the targets, there are a series of well known characteristics required for the photogrammetric network. The two most important characteristics are a multi-station, convergent network configuration to obtain multiple, optimally intersecting rays to the targets, and the requirement for a distribution of orthogonal camera roll angles within the network to minimize correlations between exterior orientation and calibration parameters¹⁰. Due to the high capacity of image storage available with the DCS cameras, it is typical that many images will be captured to ensure a very high level of reliability. High levels of redundancy used in conjunction with orthogonal roll angles will generally lead to an extremely robust network and therefore a reliable calibration for the camera.

The single roving camera mode of operation is now often known as “offline” mode, as opposed to “online” mode where multiple cameras are used at fixed locations in a work cell or laboratory environment^{11,12}. The cameras are pre-calibrated or are calibrated in-situ prior to the actual measurements made to define the object. The exterior orientation of the cameras is determined using fixed reference targets, either initially as part of the set up routine or continuously if the reference targets are at stable locations and can be maintained within the field of view of the cameras.

Rather than placing targets on the object to be measured, a probe or hand tool is used to manually locate points of interest. The hand tool commonly has a number of replaceable measuring probe tips which can be selected to suit the type and location of the measurements. This mode of operation is adopted when the object has a complicated shape or many hidden areas which would make it unsuitable for offline measurement. Although it is often the case that the object will be transported to the work cell, portable online systems can be set up in virtually any environment. The measurements gathered are used for purposes such as tool or fixture verification, quality control and surface shape characterization.

Fixed work cell systems generally adopt video-rate CCTV cameras and/or high resolution “scientific” CCD cameras, such as the Kodak Megaplug series, for reasons of versatility. Portable online systems tend to use high resolution digital still cameras or scientific cameras in order to balance accuracy requirements against the practical limitations on the number of cameras which can be deployed^{13,14}. Stereo online systems are widely used, although most commercial systems are capable of utilizing four or more cameras simultaneously. Applications in the aerospace and manufacturing industries demand minimum proportional accuracies of approximately 1:50,000, which in turn demands that stereo online systems must use cameras with sensor resolutions at least equivalent to the DCS420.

3. STABILITY ISSUES

There are a number of stability issues associated with offline and online systems. For instance, offline systems require that the object being measured is static, or at least rigid, so that changes in shape do not occur whilst the single camera is roving to capture sufficient images to build a photogrammetric network. Similarly, online systems are dependent on the consistency of the camera platforms, as instability may invalidate the exterior orientation established during the set up and initialization phase. If fixed reference targets are continuously available the camera platform stability can be ignored with an additional, albeit very small, computational overhead to continuously update the orientation.

However, the emphasis here is on calibration, and certainly both modes of operation are critically dependent on the stability of the camera calibration parameters. Further, the considerations for offline and online systems are quite different, specifically with digital still cameras such as the DCS series.

As previously noted, the DCS camera was designed for photo-journalism and the design shows no deference to metric stability. The body of the camera is a standard 35mm SLR type which can exhibit shape variations with handling. Although the camera body must be rigid enough to maintain sharp focus on the focal plane, small variations in body shape can be significant. In addition, the camera body is fixed to the digital back by a simple lip and screw-in arrangement which does not constrain the physical relationship between the two components (figure 1). Therefore, there is the distinct possibility of relative movement between the lens of the camera, attached to the SLR body, and the CCD sensor at the focal plane, attached to the digital back. As a further complication, the mounting of the CCD array to the

digital back is a flexible spring arrangement, in order to protect the sensor against shock transmission in the event of the camera being dropped or knocked. This leads to even greater potential for variations to the calibration during handling for offline use.

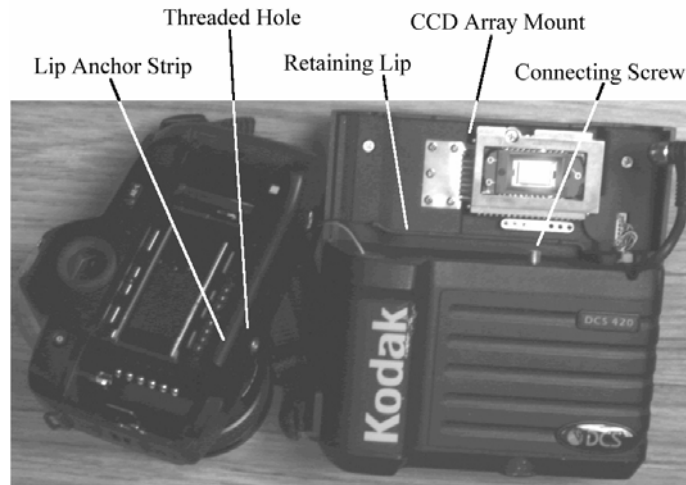


Figure 1. Camera body to digital back connection for the Kodak DCS420.

Clearly, movement of the CCD array within the focal plane may lead to variations in the location of the principal point. Movement of the focal plane with respect to the lens may lead to variations in the principal distance, although the magnitude of changes to the principal distance is likely to be small as substantial movement would lead to visible defocussing of the image. Based on this knowledge of the internal structure of the camera, it would be predicted that all of the other calibration parameters with a physical manifestation would be relatively unaffected. For example, assuming the focus of the lens does not change during the capture of the images, lens distortions would be consistent. Similarly, affinity and orthogonality terms, although often insignificant, are a function of image transfer or lens misalignment¹⁵, and again should not be subject to variation. A confounding factor here is the potential for optical effects from the cover glass of the CCD array, but the nature and magnitude of any distortions introduced by this component have not been investigated to the knowledge of the authors.

In the case of offline use of the DCS cameras, the continual handling of the camera and the necessity for orthogonal rolls of the camera are likely to lead to transient calibration variations within a single network. Testing and analysis of offline networks should therefore concentrate on the effect of the variations and modification of the camera and/or the roll strategy to ameliorate the variations in the calibration during the image capture. It is assumed that in all cases the camera is handled carefully to minimize distortions associated with all camera components.

Online use of the camera raises different issues with respect to calibration stability. As the camera is mounted on a tripod or similar support, there is no handling or rolling of the camera. It could therefore be expected that the physical calibration and calibration parameters should be significantly more stable. The more important issue for online use of DCS, or indeed any other camera type, is that the calibration is consistent over the short to medium term. The testing and analysis of online systems should emphasize the significance of variations of calibration changes over periods of minutes or hours, rather than individual exposures. A comprehensive quantification of the level of variation would define guidelines for the frequency with which online systems must be re-calibrated.

4. TESTING STRATEGY

Automation of industrial inspection systems based on vision metrology has enabled very rapid set up and measurement times. The automation of the process is based on the use of coded targets¹⁶ at known locations, image processing techniques to detect all targets within the images (on the basis of an initial threshold and a series of other tests to eliminate false targets¹⁷), and closed form resection algorithms¹⁸ to robustly compute the exterior orientations of the cameras. Targets with a known layout are generally provided by a rigid frame, also known as an "orientation cross", which is introduced into the field of view of all camera stations (figure 2). Once the exterior orientations of a majority of camera stations are established, all images can be scanned for epipolar line matches of all unknown targets. A network

solution can then be computed and the process repeated to, if necessary, improve the number of correctly matched targets from searches based on more accurate camera calibration and camera station exterior orientation data.

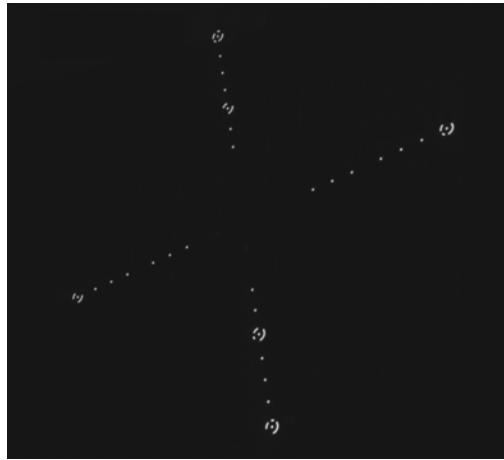


Figure 2. Image of an Imetric SA orientation cross with coded targets.

Using the rapidity of processing of photogrammetric networks, many calibrations of digital still cameras can be conducted during a short period of time. Typically, a photogrammetric network of 10-20 camera stations and a virtually unlimited number of targets can be independently measured 6-12 times in the space of 2-4 hours. Target arrays can be constructed on an ad hoc basis to suit the image format and desired image scale, rather than using a fixed target field which has pre-established coordinate values¹⁹, because of the efficiency with which networks can be processed. The experimental testing carried out for this research project was conducted using the Imetrics software suite, however products from other vendors are capable of similar rapidity in terms of set up and measurement.

Taking advantage of the speed with which calibrations can be carried out, the testing strategy adopted for the experimental work was to conduct many groups of 6-12 rapid calibrations of Kodak DCS cameras in the offline and online modes of operation. Comparison of calibration parameters within the groups or across groups can be used to test the consistency of the calibration of cameras for both modes of operation. For the roving camera or offline mode of operation, the effects of different roll strategies and modifications to the camera can be investigated by comparisons of groups of calibrations. The comparison of the RMS image space errors between offline and online modes of operation will also provide an insight into the degradation expected from the handling of the camera and the CCD array movement within the focal plane.

In all cases the calibration parameter set incorporated only the primary physical parameters comprising :

- principal point location
- principal distance
- radial distortion (2-4 terms depending on the lens)
- decentring distortion
- orthogonality and affinity

and all terms were unconstrained in the photogrammetric network solution.

Three standard Kodak DCS cameras were used, two DCS420s (identified as 420-1 and 420-2) and a DCS460. In accordance with common practice within industrial inspection tasks carried out by Imetric SA, the cameras were used with 18mm and 24mm Nikkor lenses for the 420s and 460 respectively.

In an attempt to further analyse the effects of camera body distortion, relative movement between the camera body and the digital back, and movement of the CCD array, 420-2 was modified during the testing. The camera body was clamped to the digital back, which reduces the flexing of the body whilst simultaneously minimising any movement between the body and back. At the same time, a corner of the CCD array mount was fixed to the digital back to minimise the movement of the sensor within the focal plane.

5. EXPERIMENTS

Table 1 details the calibration tests conducted for the online mode of operation. In this mode the camera was mounted on a tripod and not disturbed in any way during the calibrations. The number of calibrations in each set varies primarily because of the availability of the equipment and the efficiency with which the calibrations proceeded. However in no case is there less than six calibrations, which was deemed to be the minimum required for a representative data set. The online calibrations used DCS420 cameras in all but one instance, as the 420 was the camera type usually used for online measurement with Imetrics systems at the time of the experimental work. Although higher resolution cameras are being introduced to online systems, cameras of the resolution of the DCS420 remain common due the relatively high cost of providing multiple, high resolution cameras.

Camera	Date	Number of Calibrations
420-1	August 30	6
420-1	September 16	12
420-2	September 17	8
420-2	September 26	8
420-2	September 27	6
460	November 11	7

Table 1. Calibration tests in online mode.

The networks for the online calibrations consisted of 12 camera stations and 36 targets on a single orientation cross similar to the example shown in figure 2. A convergent multi-station network with two orthogonal roll angles was configured by appropriately presenting the orientation cross to the tripod-mounted camera. As the orientation cross is manufactured from a carbon fibre composite there is no question of lack of rigidity of the target array along the arms of the cross. The distances between the targets along the arms of the cross were included in the network solution as constraints to control the scale of the network and generally enhance the reliability and accuracy of the network, and as a consequence, the confidence with which the calibration parameters can be derived. Note that it was not necessary for the relative angle between the two cross arms to remain constant, as all networks were processed with an internally constrained datum, also known as the free network solution.

Due to the rectangular format of the DCS cameras, the cross cannot readily fill the field of view of the cameras. As filling the format is desirable to illicit maximum confidence in parameters such as the lens distortion terms, the location of the cross was randomised through the format during the image acquisition sequences. A second concern for the online calibrations was the two dimensional nature of the target array, as three dimensional target arrays are preferred for camera calibrations to minimise correlations between parameters. To at least partially ameliorate any influence of a two dimensional target field, the camera to cross distance was also randomly varied within an envelope of acceptable image scales.

Camera	Date	Number of Calibrations	Roll Strategy
420-1	September 11	12	Quad
420-1	September 12	8	None
420-1	September 13	10	Dual
420-2	September 18	10	Dual
420-2	September 23	8	Quad
420-2	September 26	12	Dual
420-2	October 14	10	Quad
420-2	October 15	9	Quad
460	October 16	7	Quad
460	October 17	6	Dual

Table 2. Calibration tests in offline mode.

The calibration tests conducted for the offline mode of operation are listed in Table 2. The emphasis here was initially again with the DCS420 in order to make comparisons between the online and offline modes, however later tests shifted to the DCS460. The offline calibration tests generally comprised 12 camera stations, however some networks contain as

few as 8 and as many as 24 camera stations to accommodate different roll strategies whilst maintaining reasonable consistency in the layout of camera stations. The target arrays were manufactured using the orientation cross and some additional carbon fibre rods in order to provide more targets and a three dimensional span for the array (figure 3). Once more distances were used as constraints in the network.

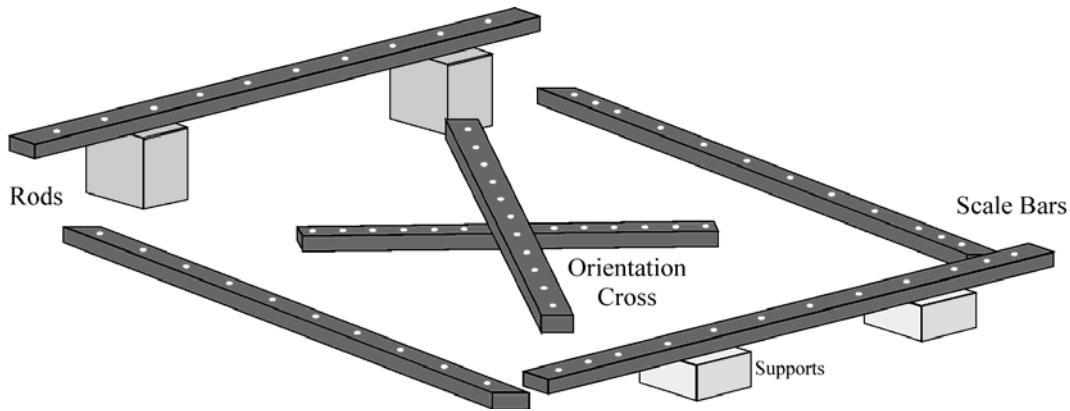


Figure 3. Typical target field layout for an offline calibration test.

Three different types of roll strategy were used as indicated in Table 2. In one case the camera was always used in the upright mode, so no rolls were used. The dual mode of operation uses the camera in the upright position and a 90° roll which corresponds to the CCD array “hanging” from the strongest area of the mounting. The quad mode of operation employs the upright, 90° , 180° and -90° roll positions.

All offline mode networks included a camera station vertically above the target array, with the camera held horizontally, at which four orthogonal roll angles were exposed to ensure that all calibration parameters could be recovered regardless of the roll strategy used for the other camera stations in the multi-station, convergent image set. The mounting of the CCD array is such that it is unlikely that there would be any CCD array movement within the focal plane whilst the camera is carefully and consistently held in a horizontal orientation.

6. ANALYSIS OF RESULTS

6.1 Offline versus Online

Figures 4 and 5 show comparisons of calibration sequences for the 420-1 and 460 cameras respectively. The graphs highlight the differences in the RMS image space residuals from the self-calibrating, free network solutions for the calibration sequences. The RMS values can be interpreted as a measure of the internal consistency of the networks and demonstrate that in general there is a substantive improvement for the online calibrations. The implication of this result is that handling and rolling of the cameras does have a significant influence on the consistency of the calibration of the camera, in this case within each image set captured for a network.

For the DCS420 there is a clear difference between the results for the offline and online cases. For the DCS460 the result is less consistent. The dual roll strategy produces results which, on average, are only marginally degraded when compared to the online case. Experience with the DCS series of cameras suggests that there is some variation in the stiffness or inertia of the CCD array mounting, or the level of variation may be correlated with whether the camera body and digital back have been separated for inspection or repair. Regardless of the physical mechanism involved, the available evidence from a small sample of cameras would suggest that some DCS cameras realise more favorable results than others when the dual roll strategy is used (see also figure 8), however the online approach does demonstrably improve the network consistency and calibration stability.

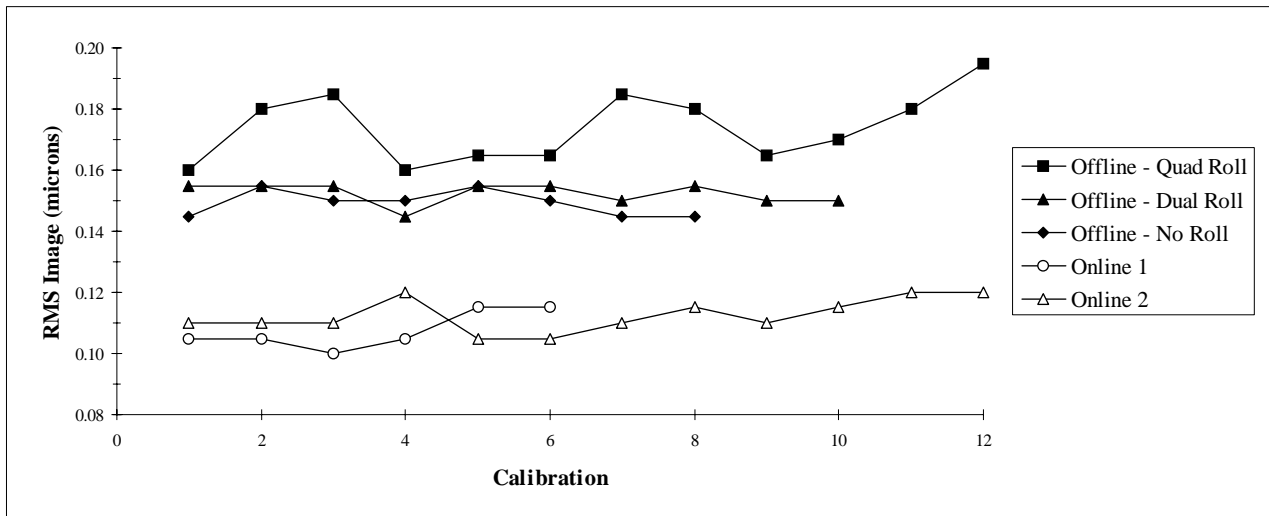


Figure 4. RMS image space residuals for various calibrations of camera 420-1.

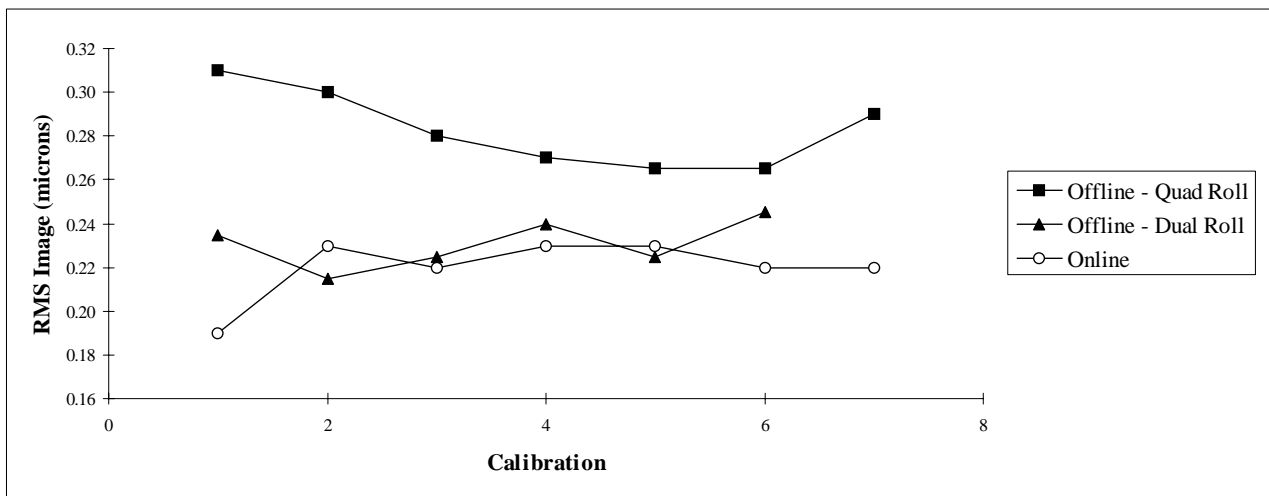


Figure 5. RMS image space residuals for various calibrations of camera 460.

Figures 6 and 7 reinforce the supposition that there are physical changes in the camera calibration of the DCS cameras from handling and rolling of the camera. These graphs show the significance of changes to the calibration parameters for camera 420-1 for the offline, quad roll and second online cases respectively. The significance values are computed from :

$$c_s = |\delta_p| / q_p$$

where c_s = change significance
 δ_p = change in the parameter between calibrations i and $i+1$
 $q_p = (qq_i + qq_{i+1})^{0.5}$
 qq_i = a posteriori variance of the parameter from epoch i

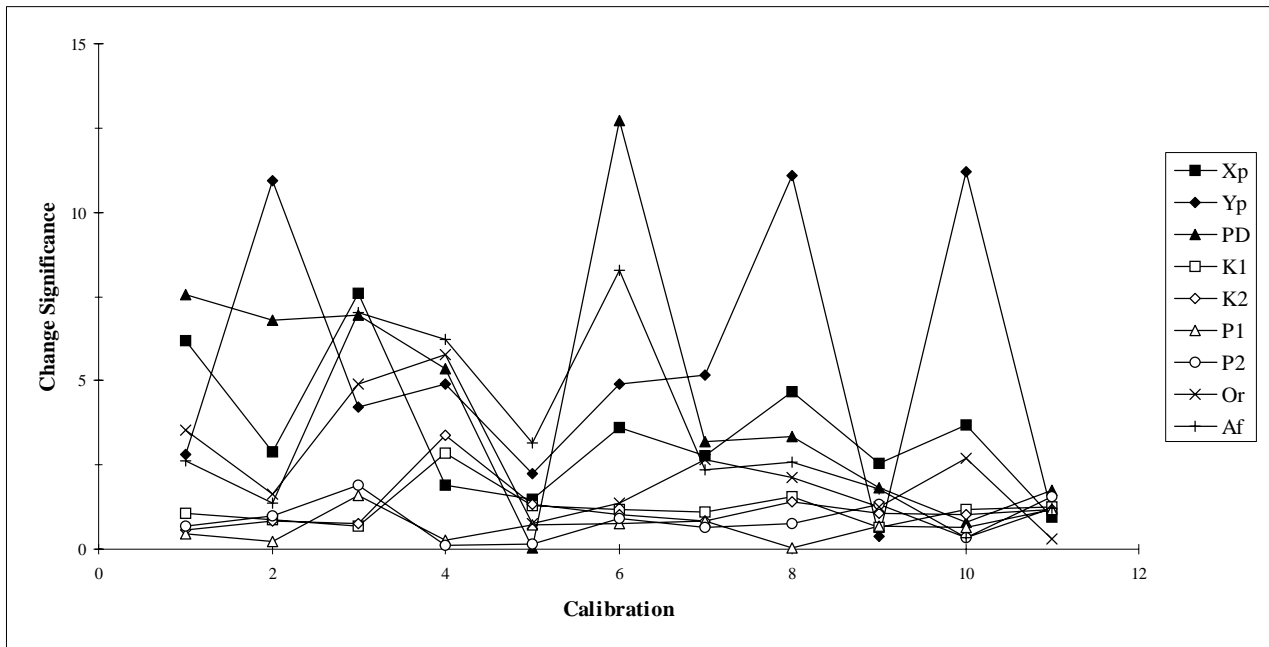


Figure 6. Calibration parameter changes for the offline, quad roll calibration set for camera 420-1.

The contrast between the parameter variations shown in figures 6 and 7 is representative of most cases for the DCS420 and 460 cameras calibrated in offline and online modes. In general the variation for the offline modes is greater for the quad roll calibrations than the dual and no roll cases, which are approximately equal in variation. The dominant parameters in the offline cases tend to always be the principal point coordinates and the principal distance. The affinity term also shows large variations in some cases, however this effect is due to the inevitable correlations between the affinity term and the principal point and principal distance terms. Similarly, in the online cases occasional large variations are present in the radial distortion terms, also due to high correlations between parameters. The consequent effect on the calibration is generally insignificant.

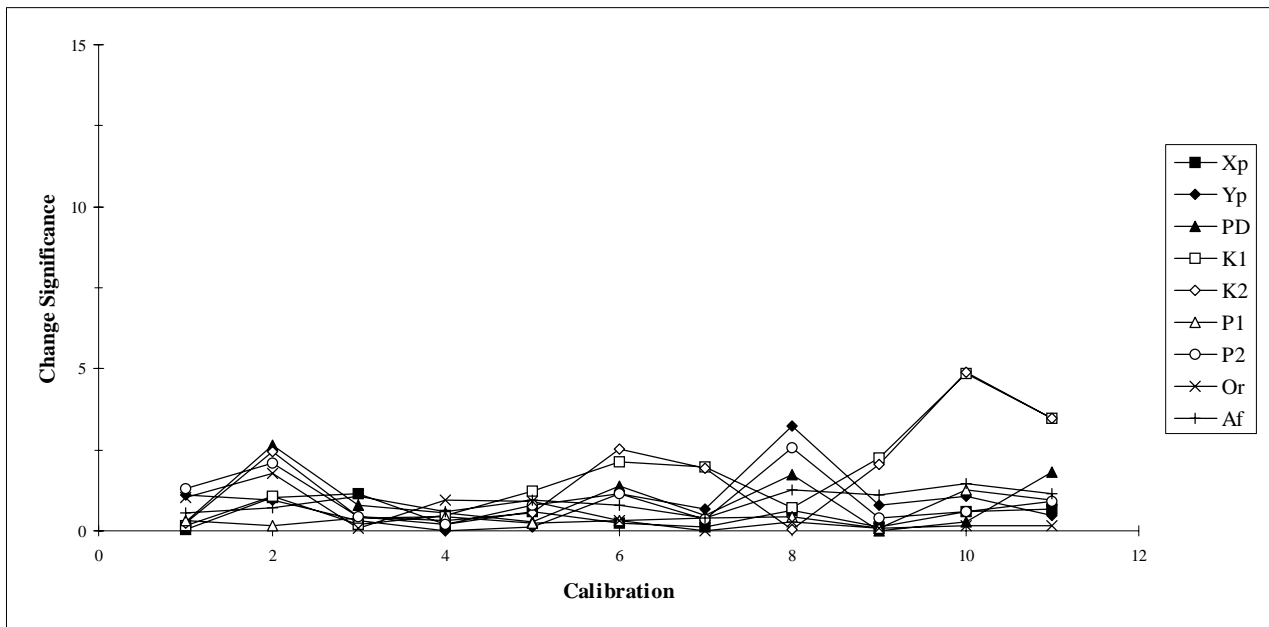


Figure 7. Calibration parameter changes for the second online calibration set for camera 420-1.

6.2 Effectiveness of Camera Modifications

The modifications to camera 420-2 were effective in stabilising the camera. As can be seen from figure 8, the RMS image residuals for the offline testing after modification of the camera are reduced to approximately the same level as the online calibrations. Whilst there is a slight improvement in the RMS image residuals for the online calibrations after the modification, as could be expected, the effect is relatively small.

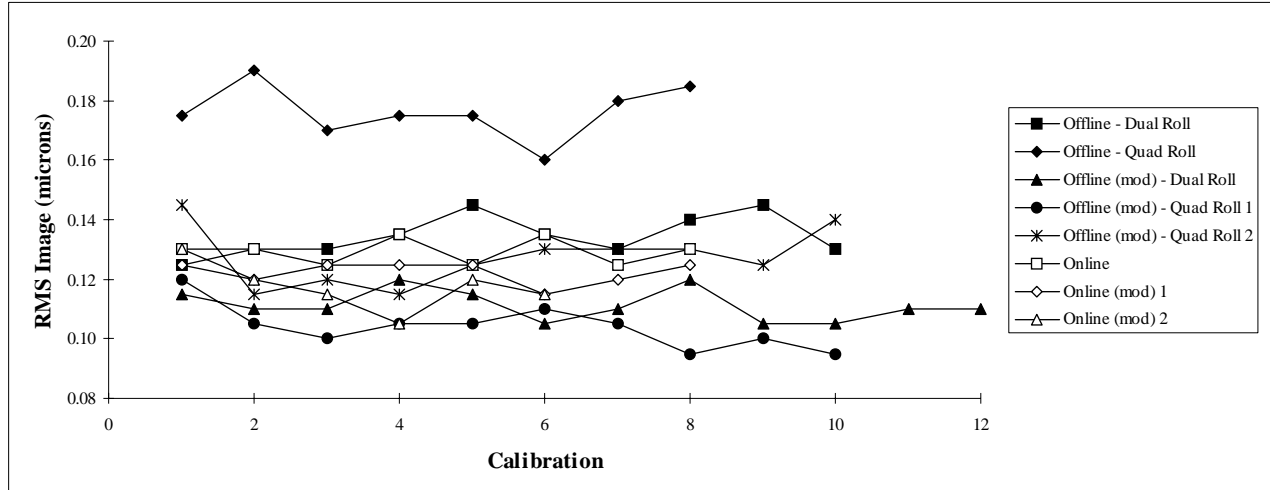


Figure 8. RMS image space residuals for various calibrations of camera 420-2.

As previously noted, the dual roll strategy for the offline use of the camera is apparently quite effective at reducing instabilities of the CCD array within the focal plane, therefore minimising the influence of variations of the principal point coordinates on the network solution. The improvement may well be enhanced by correlations between the principal point coordinates and parameters of the exterior orientation of the camera stations. Such correlations would tend to mask the effect and simultaneously reduce the influence of this systematic error on both the internal consistency of the network and the accuracy of the object space coordinates of the targets.

6.3 Average Parameter Values

The longer term trends for the two DCS420 cameras are shown in figures 9 and 10 in the form of data averages from the calibration sets. The graphs show the numerical changes in the most significant parameters, namely the principal point coordinates, the principal distance and the radial distortion at a radius of 6mm. The parameters show trends in these physical parameters against time, using day one as the first calibration sets carried out. The data points in the graphs include both offline and online calibration sets.

Although there is probably insufficient data to draw any decisive conclusions, some observations can be made. The most obvious effects for the cameras are the sudden changes at 14 days for 420-1 and 10 days for 420-2. These changes correspond to the dates of disassemblies of the cameras, for an inspection of 420-1 and the modification of 420-2. Camera 420-1 appears to be quite stable prior to the inspection, and soon thereafter regains its stability for the principal point location and the principal distance. The implication is that the CCD array is held in a consistent position and the camera body retains a consistent shape, at least on average over a set of calibrations. Predictably, the radial distortion value is unchanged as it is primarily associated with the lens, rather than the camera body or CCD array.

The trends for camera 420-2 are more variable for the principal point location and principal distance, whilst again the radial distortion is virtually constant. Not only is the camera not consistent prior to the modifications made on day 10, but clearly there are some residual effects from the clamping of the camera body and the fixing of the CCD array, especially for the principal point location. Although the modifications may have been successful in improving the stability of the camera within a set of photographs for a calibration, the camera has not yet reached equilibrium at more than two weeks after the modifications.

An additional observation which can be made from the longer term trends is a further confirmation of the variability of calibration parameters, and therefore the stability of the cameras, within offline calibration sets. For a stable camera, a

near unity ratio would be expected between the mean calibration parameter precisions derived from the bundle solutions within a calibration set, and the standard deviations computed directly from the calibration parameters resulting from the calibration sets. In other words, the bundle solutions should correctly predict the variability of the calibration parameters if the only contributing influence is Gaussian noise. Unmodelled systematic errors, such as those caused by instability, will inevitably produce predicted values which are under-estimates when compared to the actual variations.

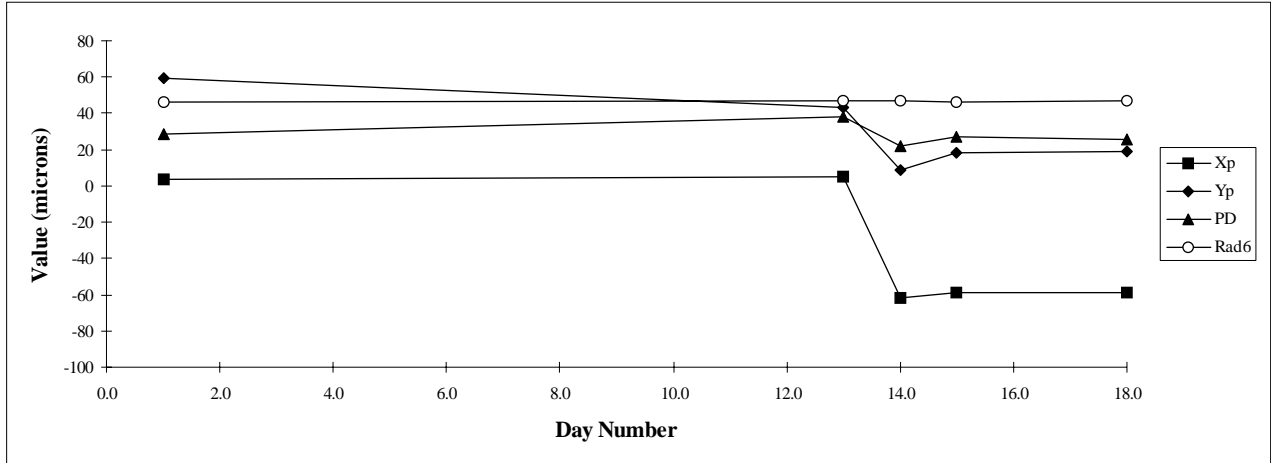


Figure 9. Variations in the mean of selected parameters for camera 420-1

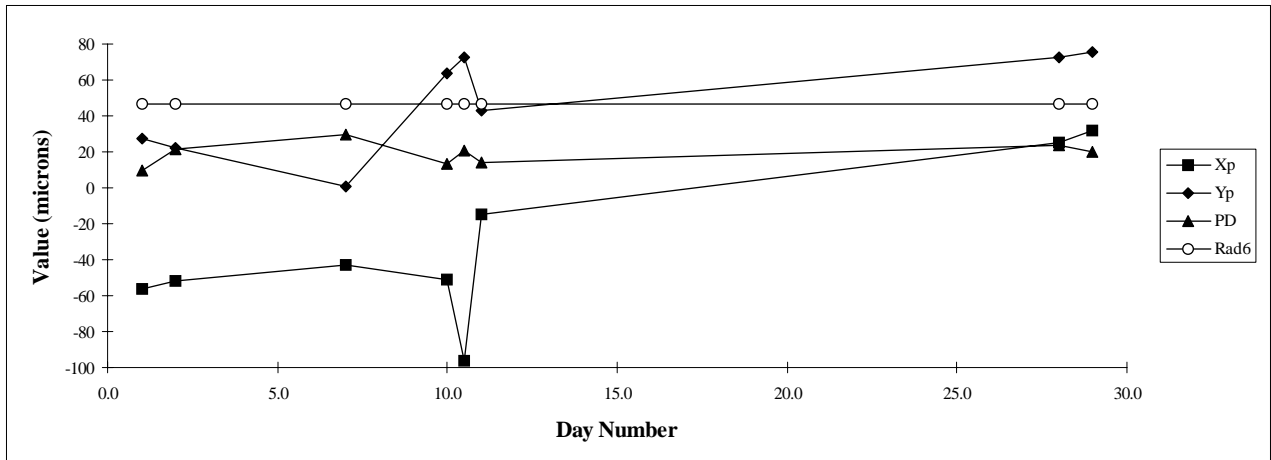


Figure 10. Variations in the mean of selected parameters for camera 420-2

For the six online cases shown in table 1, the average ratio for the calibration parameters was 1.5 with little difference between the principal point location and principal distance parameters as compared to the lens distortion parameters. The greater than unity value can be explained by the time span of 2-4 hours for the acquisition of the 6-12 calibrations for the calibration sets, which may conceivably introduce some metric variation in the cameras even in the online cases.

Hence, the bundle solutions are consistently under-estimating the variability of the parameters by a factor of 0.67 for the online cases. In stark contrast, for the ten offline cases shown in table 2 the average ratios are 6.1, 3.5 and 1.3 for the principal point location, principal distance and lens distortion parameters respectively. This clearly indicates the under-estimation of the variability of the principal point and principal distance by the bundle solutions for the offline cases.

This data also provides support for the supposition that there is some projective compensation present in the calibration networks employing the dual roll strategy. The ratios for these cases show no propensity for lower values, despite the reduction in the RMS values shown in figures 4, 5 and 8.

7. CONCLUSIONS

The experiments described in this paper provide conclusive evidence that CCD chip movement within the focal plane and relative movement between the camera body and digital back are significant for the standard Kodak DCS420 and DCS460 cameras. Previous experience and the data analysis conducted here indicate that some DCS cameras are more stable than others, although a larger sample of cameras would improve the confidence of this assertion. However, constraining the camera body and fixing the CCD array are at least partly successful in improving the characteristics of the camera. The family of 35mm SLR type cameras are considered to be non-metric cameras, and digital still cameras, due to the monolithic nature and relative flatness of the CCD array at the focal plane, are generally considered more stable. If specialist actions such as the dual roll strategy and modification of the camera are taken, then the Kodak DCS series can be considered sufficiently stable to be categorised as semi-metric cameras.

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