Digital Photogrammetric Applications
with the
Prime-Wild S9 Analytical Plotter

David Wilkins

Institute of Geodesy and Photogrammetry
Swiss Federal Institute of Technology
ETH - Hönggerberg
CH - 8093 Zürich
Switzerland

Abstract

In the context of a collaborative project currently underway at the Institute of Geodesy and Photogrammetry of the Swiss Federal Institute of Technology (ETH) in Zürich, a Prime-Wild System-9 Analytical Plotter (S9AP) has been modified to enable the installation of a pair of CCD cameras. Together with appropriate image acquisition hardware and host computer, the S9AP is thus transformed into a general-purpose image scanner for digital photogrammetric applications.

Before the instrument can be used as such, it is necessary to perform a calibration to determine the relationship between the digital image pixel coordinate systems and the S9AP stage coordinate systems. An extensive software package has been written for this, which contains some special components made necessary by the mechanical design of the instrument. As a means to demonstrate the potential accuracy of the system, the signalised points of a photogrammetric test block were digitised, their coordinates determined by template matching and subsequently processed in a bundle adjustment. The results of this investigation are presented, together with a comparison with the results from a manual measurement of the same block on the same instrument.

Key words: analytical plotter, digital photogrammetry, image matching, bundle adjustment.

1. Background

The aims of this paper are twofold. It arises out of the work done over the last two years on a collaborative project between the Institute of Geodesy and Photogrammetry of the Swiss Federal Institute of Technology (ETH) in Zürich and Wild Heerbrugg. The purpose of the project was to develop a system for automatic DTM data generation through image matching, using the analytical plotter System-9 AP (S9AP) as an on-line source for analogue image information. To this end, an S9AP with an adaptation to its optics allowing the attachment of a pair of CCD cameras was installed in Zürich. The work on the project then followed two major paths: calibration of the hardware and algorithms for the image matching. The first aim of this paper is to present the result of the former, that is, to introduce the modified S9AP as a general-purpose image scanner.

The second aim is to present one possible application using such a system - aerial triangulation using image coordinates determined by point location in digital images. This lies outside of the specific aims of the project, but it has always been seen that the modified S9AP could have applications in other areas; the overall aim is to show this.

The paper is organised into two parts reflecting these dual aims. The first part (sections 2 and 3) will describe the system hardware, the procedures for its calibration, and some results therefrom. The second part (section 4) will concentrate on the aerial triangulation investigation - the data acquisition and the results of bundle adjustments thereon.

2. Hardware Introduction - the S9AP

2.1 Analytical Plotters as Image Scanners

Since analytical plotters became generally accepted in the commercial sector in the early 1980's, there have been various attempts at installing them with CCD cameras to enable the digitisation of image sub-scenes. In the most cases, the subsequent processing of the digital imagery was aimed at, but not restricted to, the automatic or semi-automatic generation of height data for DTM applications. Two of the major photogrammetric instrument manufacturers ran projects along these lines. Zeiss Oberkochen of West Germany, in collaboration with Stuttgart University, developed a system on the Planicomp C 100 analytical plotter (Gülch, 1984; Pertl, 1984), whilst Kern of Switzerland introduced the Kern Correlator, based on the DSR11 (Bethel, 1986).

The third major European manufacturer, Wild Heerbrugg of Switzerland, did not attempt similar efforts using any of their range of analytical instruments. However, outside of the commercial field, some work has been done at ETH Zürich on a modified AC1, also mainly with a view to automatic DTM generation (Baltsavias, 1988). The experience gained with this instrument provided a basis for much of the work done on the S9AP.

2.2 Aspects of the S9AP Construction

The S9AP is an integral part of System-9, the geographic information system (GIS) launched by Wild Heerbrugg in 1985. It is well documented in the literature (eg Schneeberger and Burgermeister, 1987), but some aspects of the hardware construction must be outlined as they have implications on the work of the project.

The viewing system of the instrument is of particular interest. The design of the S9AP was based on the existing BC range of instruments, rather than the AC1 which was known to be of slightly higher accuracy. The essential difference between the two is the means of image measurement: in the AC1, the entire optical train remains fixed whilst the photo carriage moves in two directions; in the BC range and in the S9AP, the carriage moves only in the Y direction, whilst measurement in the X direction is effected by translation within the optical train. The major advantage of this is a reduction in the size of the instrument, at the cost of a small reduction in accuracy in the case of measurements by manual operator. The consequences for digital measurements are somewhat more significant, however, as will later be described.

Plate positioning is done via a feedback loop using servo motors and linear encoders of 1 µm resolution. Instrument calibration relates the linear encoder scales to a stage coordinate system defined by a grid of crosses engraved on each photo carriage, the relative positions of which are determined to high accuracy in the factory before installation. The quality of this calibration can be affected by the optical design as described above.

2.3 The S9AP with CCD Cameras

The S9AP at ETH Zürich has a modification allowing the attachment of most types of CCD camera. The optical and structural design and implementation of this modification was carried out by Wild engineers in Heerbrugg, with the consequence that the instrument in its manual use loses nothing in terms of optical quality. The important features of this realisation are:

- The cameras are mounted externally at the rear of the instrument via a C-mount fitting. Any camera using such a standard thread can be simply "screwed on".
- The magnification is approximately unity. It can be changed by a translation of the objective lens, but only within a small range. The lens is, however, not easily accessible.
- The distance of the camera from the stage plate is rather long, having the disadvantage that systematic effects arising from the opto-mechanical design are somewhat magnified. On the other hand, the long focal length of the objective lens (~ 30 cm) means that any effects of distortion are minimised.

Figure 1 shows the relevant part of the S9AP optics and the positioning of the camera (one side only).

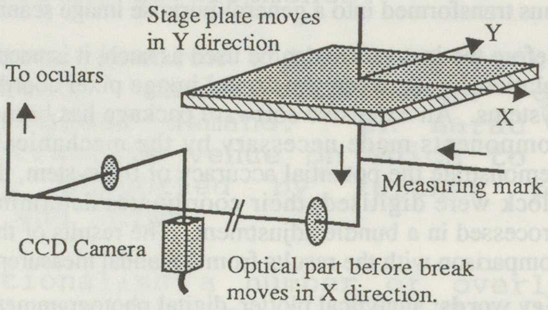

Figure 1. Part of the S9AP optical train showing positioning of the CCD camera mount.

The camera used for the investigations was the Sony XC-77CE, an inter-line transfer device with pixel size 13.6 x 11.1 µm on the stage, giving an image size of 8.0 x 6.4 mm.

The image acquisition hardware used comes from the Maxvideo family of products manufactured by Datacube Inc in the USA. The boards operate on the VMEbus, thereby allowing all system components - host computer, S9AP and image acquisition hardware - to be controlled as a single system from one workstation.

3. System Calibration

3.1 Purpose of Calibration

The primary purpose of calibration in the context of an analytical plotter fitted with CCD cameras is to derive a relationship between the acquired digital images and the analogue imagery being digitised. Once this relationship is determined, it is also necessary to know about its accuracy and stability. Both are influenced by many factors, and hence the whole procedure encompasses many aspects, from instrument calibration through to inner orientation of the analogue imagery.

The core of the calibration, however, is a geometric transformation between the digital image and the stage plate coordinate systems. For a full calibration, a radiometric relationship would also be included, but for the present application and also for on-line DTM generation, this takes on less significance since in general only small areas of the images will be used at any one time. The transformation falls into a local and global part since the pixel coordinate system moves within the stage system. A local stage coordinate system is defined with origin as the current stage position. In an ideal case an invariant transformation between this system and the digital system can be defined, which is equivalent to saying that the measuring mark, if visible, remains at a fixed position in the image, independent of the stage coordinates.

The global part concerns the relationship between the local and the full stage systems, which by definition is only a translation. The accuracy of this relationship is to be found in the instrument calibration.

3.2 S9AP Instrument Calibration

The accuracy of the instrument calibration between the linear encoders and the stage coordinate system is influenced by the opto-mechanical design. It is a limiting factor of the overall calibration.

The calibration is done as a manual procedure, requiring the measurement of all 25 or only 9 stage crosses. An affine transformation is determined by least squares adjustment, resulting in an RMS residual of 1.0 to 1.3 µm. It would be possible to perform this procedure automatically, but it is unlikely that a significant improvement to the accuracy level could be obtained as some systematic tendencies in the residuals are evident.

3.3 Calibration of the CCD Cameras

3.3.1 Position of the Measuring Mark

The ideal case of the local stage and digital image coordinate systems remaining fixed relative to one another for all stage positions does not hold true on the S9AP. This is a consequence of the opto-mechanical design: as the optical unit moves in the X direction, shifts of up to 2 pixels in the position of the measuring mark in the digital image are observed. The movement is systematic in nature and so can be compensated.

The measuring mark movement is determined directly in an automatic procedure known as profile measurement. At constant intervals along the X axis, the position of the mark in the image is determined by least squares template matching, the accuracy of which is high (~ 0.05 pixel) relative to the range of the movement.

The result is handled as a list of the original pixel coordinate measurements. No further modelling is considered necessary if the density of measurement is high enough; an interval of 2 mm is usually used on the S9AP. Corrections are determined by interpolation on these values.

The shapes of the profiles are a characteristic of a stage's measurement system: they remain constant in time. Those for the left stage of the S9AP in Zürich are shown in figure 2, transformed into the stage frame.

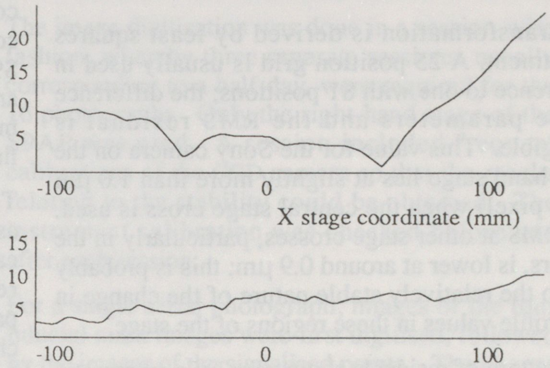

Figure 2. Profiles on the S9AP left stage. Microns on the stage: x above, y below.

There is some similarity between the pattern of these profiles and the instrument calibration residuals, pointing to a possible common source of the observed effects. As the optical unit translates in the X direction, it may also be subject to very small movements in other directions. The remaining five possible movements (ie including rotations) will have different effects, some on the digital image, some on the manual measurements and some on both. Separation into the component movements would, however, be very difficult. This and the acceptable accuracy level of the instrument calibration have justified the relatively simple modelling employed.

3.3.2 Calibration Transformation

The method of deriving a transformation between the digital image frame and a local stage frame is based on a procedure used originally on the AC1 in Zürich (Baltsavias, 1988). One of the engraved stage crosses is used as a fixed point within the stage system; in a grid-wise fashion it is imaged 9, 25 or 81 times, the size of the grid being slightly smaller than the image size projected onto the stage so that all of the sensor is used. The coordinates of the grid positions are taken relative to the central position, which becomes the local system origin. In each position, the coordinates of the cross are determined using a two-stage method of coarse then fine matching: the coarse match will give the cross centre to a resolution of 0.5 pixel, thereafter least squares template matching is used to determine the centre to higher precision (~ 0.05 pixel, or 0.7 μm).

As the camera is being moved relative to the stage system during this procedure, the pixel coordinates must be corrected in accordance with the profile measurements above before a transformation can be derived. Since the physical reality is a perspective relationship between two planes, a two-dimensional projective transformation should be used. However, if the two planes are parallel, then this reduces to a affine transformation; this is in fact the case on the S9AP in Zürich.

The transformation is derived by least squares adjustment. A 25 position grid is usually used in preference to one with 81 positions; the difference in the parameters and the RMS residual is negligible. This value for the Sony camera on the right-hand stage lies at slightly more than 1.0 μm (0.07 pixel) when the central stage cross is used. The RMS at other stage crosses, particularly in the corners, is lower at around 0.9 μm; this is probably due to the relatively stable nature of the change in the profile values in these regions of the stage.

The pattern of residuals show very little systematic tendencies, and hence, for the reason already explained, distortion in the lens system can be discounted.

3.3.3 Application of the Calibration

Using the above derived calibration, and assuming that an affine transformation is sufficient, the relationship between pixel coordinates and full stage coordinates is represented by:

$$\mathbf{x}_s = \mathbf{A}\mathbf{x}_p + \mathbf{t}_p + \mathbf{x}_c + \Delta\mathbf{x}_c$$

where
- $\mathbf{A}$ is the transformation matrix
- $\mathbf{t}_p$ is the transformation shift vector
- $\mathbf{x}_p$ are the pixel coordinates
- $\mathbf{x}_c$ are the camera stage coordinates
- $\Delta\mathbf{x}_c$ are the profile corrections
- $\mathbf{x}_s$ are the full stage coordinates

Note that the profile corrections are expressed in the stage coordinate frame.

3.4 Indicator of Global Accuracy

The accuracy of the derived transformation is only meaningful in the area where the calibration was performed. To determine a global measure, the accuracy of the stage calibration must also be considered. This is achieved using a procedure in which all 25 engraved stage crosses are visited and their coordinates determined by measurement in the digital image, using the same method as in the calibration determination. The resulting pixel coordinates are then transformed back into the full stage frame using all calibration information. The relationship of these coordinates to the factory calibrated values will indicate the global accuracy. This assessment is done by means of an affine transformation determined by least squares adjustment, as this can also reveal factors relating to stability. The residual error of the transformation is a little higher than that of the manual instrument calibration, at around 1.3 μm as compared to 1.0 μm for the right stage.

3.5 Stability of the Calibration

The stability of the calibration relates to its constancy over time. Aspects of stability must consider effects primarily from two sources: the S9AP measurement system and the CCD camera and frame-grabber combination. In both cases, the main cause of instability will be temperature fluctuations.

The stability of the measurement system is assessed by a check procedure on the instrument calibration. The result is an affine transformation representing the change from the current parameters. During periods of rapid temperature change the drift can be significant - 5.0 μm has been observed within a two-hour period. For this reason, digitisation is usually done during periods of temperature stability, when drift within a half-day has been observed to be no more than 1.2 μm, and up to 5.0 μm over a week. Significant changes in the scales or shears have never been observed, and hence any drift is compensated for by an up-to-date calibration of the CCD camera, or by an inner orientation to the analogue imagery.

Drift in the CCD camera and frame-grabber combination is a known phenomenon and hence is expected. Again temperature change - either ambient or directly of the electronic components - is a significant influencing factor (Gülch, 1984; Dähler, 1987). The latter of these can be minimised by starting up the system some time before use, and thereafter running it continuously for as long as the project lasts. Drift due to the ambient temperature may still be observed, however. During the same period of temperature change mentioned above, a drift of the measuring mark coordinates of 0.4 pixel (6 μm on the stage) was observed in the x direction. Otherwise, the characteristic has been observed to be similar to that of the instrument calibration: short-term drift is around the 1 μm level, whilst over a period of some days larger values of up to 10 μm can be observed.

Since a stage cross is used to determine a calibration, any change in the translation parameters will be due to a combination of both of the above instabilities, and will also show up in the result of the global accuracy test (section 3.4). During digitisation, this combined effect of drift can be minimised if the inner orientation to the analogue imagery is done using digital images. In this case, the only significant instabilities are those that occur while the analogue image is being digitised. This was basically the philosophy adopted while digitising for the investigation to be described. The average observed drift of the calibration translations during the digitisation of one photograph was observed to be 0.5 μm. Two values out of a total of thirty-two were observed at over the 1 μm level, the maximum being 1.4 μm. These figures relate to an average time period of thirty minutes.

4. Investigation into Aerial Triangulation using Digital Point Positioning

4.1 The Aim of the Investigation

In this investigation, the S9AP with CCD cameras will be used to relieve a human operator of the point measurement task. Signalised points in a photogrammetric test-block are positioned using image matching and the calibration data as described above. The investigation should shed light onto two aspects: firstly how the accuracy of digital and manual measurements compare, and secondly where the potential problem areas would be in a semi-automatic procedure.

4.2 The Test Area "Heinzenberg"

The data used for the investigation is taken from a test-block flown in August 1986 in an area known as Heinzenberg in eastern Switzerland. A sub-block of the original was used; the relevant details are:

Area covered:	6.0 x 6.0 km
Ground height:	650 m to 2150 m
Flying height:	4000 m
Camera:	Wild RC10, 15/4 UAG
Film:	Kodak Panatomic-X
Photo scale:	1 : 15,000 average
Overlap:	60% / 60%
Block size:	4 x 4

The original film negatives were used; on average there were 17 signalised points per image, with a maximum of 25. The original block was measured on the AC1 at the ETH in Zürich; the results of the subsequent adjustments have been published (Grün and Runge, 1987).

4.3 Manual Measurement of the Block

To get a meaningful comparison with manual measurements, it is necessary to have datasets which are in all other respects equivalent. Hence the block was firstly observed on the S9AP using the Phototriangulation Measurement software of System-9. This was done by the author - not a particularly experienced operator - in two afternoons sessions. The coordinates were not corrected for any distortions since these could be added later if required.

4.4 Digital Measurement of the Block

4.4.1 Outline of the Procedure

The digital measurements were performed as an interactive procedure, divided into two major parts. In the first part, images of the signalised points are acquired; the second part is the off-line matching of these images to obtain the image coordinates.

4.4.2 Digitisation of the Signalised Points

The image digitisation was done in a session-wise fashion, whereby three separate sessions, usually corresponding to a half-day, were required for the 16 photographs. Only the right-hand stage of the S9AP was used. A session included frequent calibrations of the CCD camera so that the results relating to the stability could be obtained. The instrument calibration was checked before and after each session.

For a single aerial photograph, images of the four fiducial mark images were first digitised, followed by the images of the signalised points. The images were stored on disk together with the stage coordinates of the camera position. The time required for digitisation of an image with, say, 20 signalised points was around half an hour, but this was aided by a manual inner orientation and knowledge of the image coordinates already. A complete session of four photographs, including all calibrations, was around three hours.

Image digitisation was done interactively with the Maxvideo system and using software developed in Zürich. For each image, the gain and offset levels of the video signal digitisation were set manually, so that, by visual inspection, the point of interest (fiducial mark or signalised point) had optimum contrast. This optimum depends on the density levels in the aerial photography and hence also on the S9AP illumination. In a few cases, it was also necessary to change this. This all has important implications for the potential of an automatic procedure.

4.4.3 Point Positioning by Template Matching

Within the context of the collaborative project, the constrained least squares image matching (LSM) algorithm has been rewritten in the language C on Sun Workstations. The algorithm is well known and well documented in the literature (eg Grün and Baltsavias, 1988); it is not the intention to elaborate upon it here. For this investigation, the algorithm was used in its unconstrained two-dimensional mode, known as template matching as the one image is then usually an artificial and ideal version of the signal to be located in the other.

The matching was done off-line and interactively using a window-based interface to the algorithm. This allows all algorithm parameters to be set to optimum values for a particular matching problem, plus assessment of the result by visual inspection. The program transforms matched pixel coordinates directly to the photograph frame if the appropriate level of transformation exists.

Different templates were used for the fiducial marks and the signalised points. Both were approximations of Gaussian signals and differed only in size. Consequently, different patch sizes were also used: 7 x 7 and 5 x 5 respectively, such that no background signal was used in the matching. One set of parameters for the matching was selected empirically and thereafter the aim was to use the chosen set in as many cases as possible.

For each photograph, the fiducial marks were first matched and the inner orientation determined as an affine transformation. The fiducial mark signals are usually well defined and the matching can be done without problem. In one or two cases, dirt on the edge of the signal disturbed the solution, but it was possible to overcome this by selection of a different parameter set.

The signalised points were not so straightforward to match; the images displayed a great variety in size, shape and contrast. On the average, the points occupied a circle of 3 pixels diameter (original size on the ground 40 cm). Quality control in this investigation was done by visual inspection: if a point could not be matched satisfactorily with the chosen parameters, then an alternative optimum set was found - usually a smaller patch size or restricted image shaping transformation. Of the 279 points, 74 (27%) were so matched. The final solution was assigned a quality rating between 1 (bad) and 5 (good), which related only to the bias of the solution from the point centre. These classes were reduced to three for the final analysis. For each point, the various statistics resulting from the least squares matching were stored and so a comparison was possible. The results can be summarised as follows:

Table 1. LSM statistics mean values by class

Class	# of points	Sigma σ_0	Standard Devns σ_x (pel)	σ_y (pel)	Corr'n coeff
1/2 Bad	19	16.8	0.112	0.121	0.90
3 OK	69	14.1	0.081	0.082	0.94
4/5 Good	191	12.2	0.064	0.064	0.96

Although an expected improvement in the values does exist, the differences are not distinct. When the distribution of the values is also inspected, it is found that some points classed as 4/5 have values characteristic of class 1/2, and vice-versa. The problem lies in the main with asymmetric signals, where the final matching solution will inevitably be pulled away from the visual optimum. The bias cannot be directly determined from the matching statistics. Asymmetry was found to be due to three sources: noise in the photography (eg dirt); shape and layout of the signal, particularly if the location stripes were too close to the target (see example images); or perspective distortion. The latter of these was not the most significant. It should be stressed that no point could not be matched. Complete failures can usually be trapped, using characteristics such as many iterations or unusually low correlation coefficients, for example. Due to the interaction in the matching, no points were so rejected; the problem here concerns the quality of successful matches, in the sense that matching was possible.

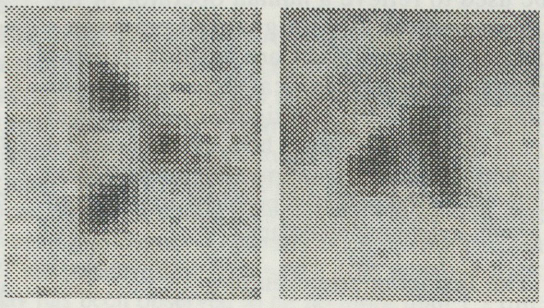

Figure 3. Example signalised point images: on the left a good one, on the right a bad.

4.5 Bundle Adjustment of the Observations

4.5.1 The Datasets and Configurations

The results of bundle adjustment on two datasets will be presented: the manual observations and the digital observations including all matched points. Both datasets had no distortion corrections applied.

Two control point configurations were selected: "PP0" with all points as full control points; and "PP2" with 8 full control points around the block perimeter and 4 height points in the centre (see figures 4a and 4b). The block had a certain asymmetry: the larger size of the original meant that control points on the eastern side of the block were in general only visible in one strip, ie had only two rays. On the opposite side, the perspective centres formed the control point boundary and therefore most points existed in two strips.

Additional parameters were used in the adjustments. Versions with 0, 12 and 44 were computed, using the program Bund of the ETH. In all cases, *a priori* values of 2.5 µm for the image points, and 1 cm in plan, 2 cm in height for the ground control points were used.

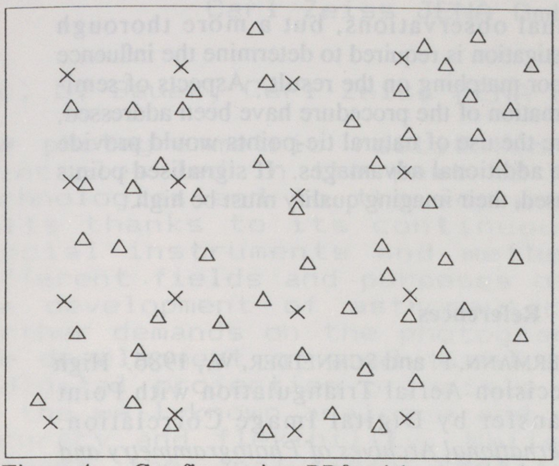

Figure 4a. Configuration PP0 with perspective centres: 53 full points.

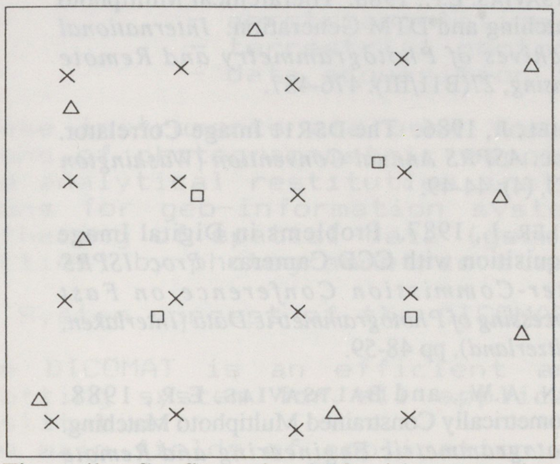

Figure 4b. Configuration PP2 with perspective centres: 8 full points, 4 height points.

4.5.2 Results of the Adjustments

The number of image, control and check points in both configurations was as follows:

Table 2. Numbers of points in the adjustments

	# image points	# control points		# check points	
		plan	height	plan	height
PP0	256	53	53	0	0
PP2	256	8	12	45	41

During the adjustments, gross errors were taken to be observations with a residual greater than $3\sigma_0$. From the manual measurements three points were rejected; from the digital only two.

All values are given in microns at the photograph scale. The average scale of 1:15,000 was used to convert the empirical RMS values (μ_{xy},μ_z) and theoretical standard deviations (σ_{xy},σ_z) of the check points from object space to image space.

Table 3. Result of the MANUAL measurement

	#APs	σ_0 (μm)	μ_{xy} (μm)	μ_z (μm)	σ_{xy} (μm)	σ_z (μm)
PP0	0	3.3	-	-	-	-
	12	2.7				
	44	2.5				
PP2	0	3.0	3.4	5.4	2.7	5.6
	12	2.5	2.5	4.5	2.4	4.9
	44	2.2	2.5	5.1	2.2	4.5

Table 4. Result of the DIGITAL measurement

	#APs	σ_0 (μm)	μ_{xy} (μm)	μ_z (μm)	σ_{xy} (μm)	σ_z (μm)
PP0	0	3.6	-	-	-	-
	12	2.9				
	44	2.7				
PP2	0	3.2	4.2	6.6	2.8	6.0
	12	2.6	2.6	4.9	2.5	5.0
	44	2.3	2.7	4.3	2.3	4.7

4.6 Discussion of the Results

In general, the results from the digital measurements are slightly worse than from the manual. In both cases, the empirical check point RMS values agree quite well with the theoretical standard deviations from the adjustment.

The digital version included all matched points, but there was found to be no correlation between the image space residuals and the matching results. Therefore, it is likely that the biases noted during the matching are not significant, but may contribute to the overall accuracy in the same way as that operator measurements carry a certain error. Adjustments without the badly matched points proved fruitless due to the degradation of block geometry.

The major difference then from the manual observations lies in the calibration. The base accuracy level of the instrument calibration applies to both cases, hence the additional error could be attributed to the calibration of the CCD cameras. In particular, stability may be a crucial factor.

A similar investigation has been done at Stuttgart University (Ackermann and Schneider, 1986). The results were similar, but cannot be compared directly as the aim of that investigation was a comparison between digital measurement of natural points against manual measurements of signalised points.

4.7 The Potential of Semi-Automation

This investigation raises some interesting questions with regard to a potential automation, or semi-automation, of the whole procedure. This does not concern aspects of the hardware - all calibration procedures on the S9AP already run automatically. This concerns more the quality control aspects of obtaining good points.

Two methodologies used in this investigation would be difficult to implement in an automated system: adjustment of the video digitisation gain and offset, and the selection of best matching parameters.

The former may always be a problem, due mainly to the density range in aerial photography. However in this case it was necessary due mainly to the poor contrast exhibited by many of the signalised points used. In a semi-automatic procedure the points to be matched will in general be natural tie-points instead of signalised points. Images in the appropriate positions in the model can be acquired (eg at the von Gruber points) and the tie-points selected automatically based on what image signal there is. The Digital Comparator Correlator System (DCCS) from Helava Associates Inc employs techniques along these lines in its procedures for semi-automatic triangulation (Helava, 1988).

The need to select best matching parameters was also a direct consequence of the signalisation - badly defined points are difficult to match with template matching. This would also to some extent be relieved by the use of natural tie-points: in general, good signal content equates to suitability for matching. If a constant parameter set is used, it may be easier to pick out any failures that do occur, whereupon alternative points could then be selected on-line. It may still be necessary to match signalised points, in which case a higher quality signalisation is required, or the development of supporting or alternative matching methods.

5. Concluding Remarks

The primary aim of the investigation was to use the results of the bundle adjustments as a means to test the quality of the calibration procedures developed for the CCD cameras on the S9AP. The accuracy level achieved with the digital measurements was slightly lower than that for the manual measurements. With the test data used, it is difficult to separate out the exact source of this loss of accuracy: some certainly lies in the image matching techniques used, whilst small instabilities in the calibration may have contributed also. The conclusion for the calibration is that it is at an adequate level for the actual purpose for which it has been developed - DTM generation by image matching.

The secondary aim was an investigation of aerial triangulation with point determination by image matching. The accuracy level is comparable with manual observations, but a more thorough investigation is required to determine the influence of poor matching on the result. Aspects of semi-automation of the procedure have been addressed, where the use of natural tie-points would provide some additional advantages. If signalised points are used, their imaging quality must be high.

6. References

ACKERMANN, F. and SCHNEIDER, W., 1986. High Precision Aerial Triangulation with Point Transfer by Digital Image Correlation. *International Archives of Photogrammetry and Remote Sensing*, 26(3/1): 18-27.

BALTSAVIAS, E.P., 1988. Hierarchical Multiphoto Matching and DTM Generation. *International Archives of Photogrammetry and Remote Sensing*, 27(B11/III): 476-487.

BETHEL, J., 1986. The DSR11 Image Correlator. *Proc. ASPRS Annual Convention (Washington DC)*, (4): 44-49.

DÄHLER, J., 1987. Problems in Digital Image Acquisition with CCD Cameras. *Proc. ISPRS Inter-Commission Conference on Fast Processing of Photogrammetric Data (Interlaken, Switzerland)*, pp 48-59.

GRÜN, A.W., and BALTSAVIAS, E.P., 1988. Geometrically Constrained Multiphoto Matching. *Photogrammetric Engineering and Remote Sensing*, 54(5): 633-641.

GRÜN, A.W., and RUNGE, A., 1987. Projekt «Heinzenberg» - Präzisionsphotogrammetrie im Gebirge. *Vermessung, Photogrammetrie, Kulturtechnik*, 87(7): 271-276.

GÜLCH, E., 1984. Geometric Calibration of Two CCD Cameras used for Digital Image Correlation on the Planicomp C 100. *International Archives of Photogrammetry and Remote Sensing*, 25(A3a): 363-372.

HELAVA, U., 1988. Digital Comparator Correlator System. *International Archives of Photogrammetry and Remote Sensing*, 26(B2): 160-170.

PERTL, A., 1984. Digital Image Correlation with the Analytical Plotter Planicomp C 100. *International Archives of Photogrammetry and Remote Sensing*, 25(A3b): 874-882.

SCHNEEBERGER, R., and BURGERMEISTER, W., 1987. The New Wild System-9 Analytical Stereoplotter Workstation S9AP. *Proc. ASPRS Annual Convention (Baltimore)*, (2): 180-189.