# THE SEMIMETRIC 6×6 RESEAU CAMERA FOR THE CLOSE RANGE PROJECTS OF HIGH ACCURACY

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**ABSTRACT:**

The way of adaptation of photo-camera Pentacon Six TL for recording of reseau pictures is presented. An economic and accurate way of reduction of photocoordinates to the reseau pattern as well as results of camera calibration are described. This non-expensive camera is meant as a tool for industrial and architectural close-range applications.

**KEY WORDS:** Instrument Design, Camera-reseau, Close range, Non-metric, Accuracy.

## 1. INTRODUCTION

Semimetric cameras, being accurate, inexpensive and easy to use, are each year more often used in various engineering and scientific applications and in recording of historic monuments. At the Photogrammetric Research of The University of Mining & Metallurgy (AGH) in Cracow a semimetric camera was constructed. It was built on the basis of the Pentacon Six TL photographic camera, by equipping it with the 1.6 mm thick glass plate with reseau crosses. Furthermore a circular level was attached to the camera body and a mark was introduced to the field of view of the camera view finder to enable more accurate angular camera orientation in the field. There also was corrected the position of the zero-mark of the distance scale on the camera objective due to the change of optical properties after a glass plate was inserted to the optical system. Some changes were done to the film flattering device to make there more room for glass-plate which was added up.

The camera to which the reseau plate had been inserted not only better flattens the film in the fiducial reseau plane, but also registers on each picture the shadows of 49 (7×7) crosses (fig.2) which correspond to the reseau master pattern in the camera. No doubt, the most accurate reduction of the photograph errors would result from the transformation of each measured point onto the nearest four reseau crosses. From the point of view of the economy of time, however, it would be better to reduce the number of reseau active crosses which are to be measured on each semimetric photograph. It was proofed that 9 reseau active crosses give the most convenient configuration. The pictures made using semimetric-reseau camera fit well for high precision surveys, can be evaluated using analytical plotting techniques and also the old analogue-type plotters (Boroń & Jachimski,1991).


Fig.1 The Pentacon Six TL photographic camera

## 2. THE ADAPTATION OF CAMERA

### 2.1. Introductory assumptions

In the professional periodicals there are several reports about good surveying results achieved using 6×6 cm amateur cameras, or even using 24×36 mm cameras.

In our case, as the result of the survey of available cameras, three of them were selected as more or less suitable for adaptation for precise photogrammetric works. This were 6×6 cameras: Pentacon Six

TL, Kiev 80 and Lubitiel. It seems to be difficult to fasten the reseau plate in the Kiev 80 camera body, because of its fiducial frames exchangeable together with film magazines (Kiev is similar to Hasselblad). On the other hand the simple and rather inexpensive Lubitiel (the two objective still 6x6 camera, no exchangeable optics) seemed to be too simple for our first approach to the adaptation problem. So we decided finally to choose the Pentacon Six TL camera (fig.1), provided with exchangeable objectives, build-in exposure mater, and a focal-plane shutter of wide range of exposure times. Also very important was the conclusion of the camera inspection which assured us that it will be comparatively easy to build in a reseau glass plate.

The insertion of the glass plate between objective and camera fiducial plane causes changes of the image distortion and image resolution. The resultant image distortion after adaptation will consist of the objective distortion and of the optical flat glass distortion. The optical flat glass causes always distortion of equal sign (displacements toward the image center), while the sign of the objective distortion can vary along the image radius.The resultant image distortion effected by this two factors can decrease or increase in comparison with distortion caused by the objective only.

The quality (resolution) of image created in the camera depends on the objective aberrations and the aberrations of the flat glass inserted to camera in front of the fiducial plane. The flat glass plate will generate such aberrations, as astigmation or the curvature of the image field. So the resultant image resolution can be different than that of objective alone. So, the insertion of the flat glass plate to the camera optical system can cause change of the distortion and usually decrease of the resolution power. In exchange we are gaining minimalisation of errors caused by film nonflattness and by the film shrinkage (here must be used the reseau grid). Better film flatness is gained by pressing it to the flat glass plate. On the film which fits better the fiducial plane the sharper image can be recorded.

The flat glass plate must first be attached to a special metal frame-mount, and glass in the mount can then be inserted and fixed to the camera body (to fiducial frame). The frame-mount with the flat glass plate must be adjustable to fulfill the condition of its perpendicularity to objective axis. One must consider that the flat glass plate inserted to a camera can cause a change of the zero position of the distance scale on the objective. In such case also inequality of distances from objective to fiducial plane and to the ground glass of the view finder will appear.

And again, there appears the problem of physical room for the glass. Even very thin glassplate captures some space inside of camera. It is comparatively easy to fix the glass plate atop of the original fiducial frame of the camera, but this will reduce the space reserved for film on the back of the camera. Since the film must shift smoothly in the camera (bigger tight of the film in the camera can cause unpredictable deformations of recorded picture), the necessity of constructional changes of the back camera cover appears.

### 2.2. The reseau plate

In 6×6 medium format cameras there is variety of designs of shape and size of reseau grid. For example in the Hasselblad MK 70 camera there is 25 crosses which create regular 10mm×10mm net (the crosses cover only picture of 40mm×40mm size); in Rolleiflex SLX Reseau there is reseau grid of 121 crosses (5×5mm grid covering 50×50mm picture area) (Wester-Ebbinghaus,1983).

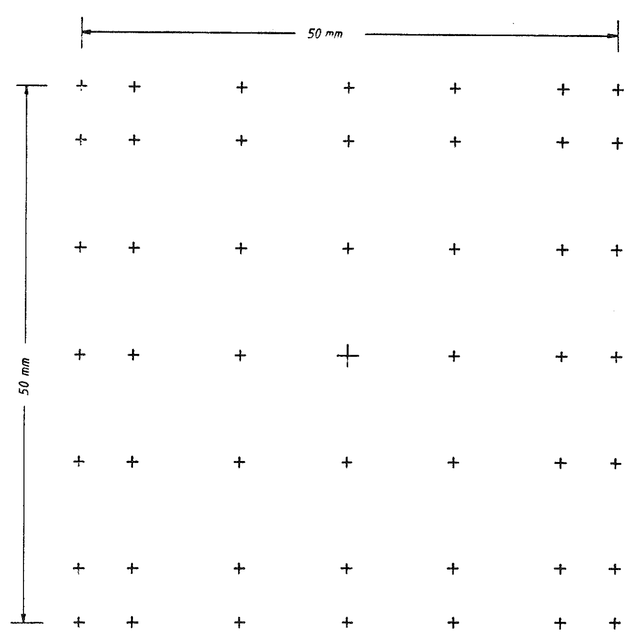


Fig.2 The reseau grid

We decided that 5×5mm grid is too dens, be cause crosses can interfere with the image contents making it less clearly readable; it is also to difficult to survey so many crosses. In the opinion of the reseau camera users, rather only generalized grid is measured in practice (Meid & Hasch, 1984), and no great loss of accuracy is noted. For our camera we designed a grid of 49 crosses (fig.2) which covers 50×50mm area. Our reseau grid consist of 16 squares 10×10mm and additionally each net line is 5mm extended at the edges what densifies the grid at the picture limits, where image errors can be biggest. Reseau crosses are of 1×1mm size (only central cross is 2×2mm), the line sickness is 40$\mu$m. The reseau grid was recorded on the 1.6mm thick glass and measured on the precise monocomparator (Ascorecord of Zeiss Jena) with the accuracy greater than $\pm 1\mu$m.

### 2.3 Fitting up the reseau plate to the camera body

First of all we have to assume that the film active surface will be flattened on the exterior surface (surface with crosses marked on it) of the reseau plate in the camera. To record the sharp image existing in the camera fiducial plane, after inserting glass plate between the objective and fiducial plane one must shift fiducial plane away from the camera objective on $\Delta l = (n-1)d/n$ (where: n - coefficient of light refraction in the glass, d - thickness of the glass plate). If it would be possible, no other adaptational changes in the camera would be necessary. In our Pentacon-Six and for our 1.6mm thick glass plate the above described $\Delta l$ value would be equal to 0.5mm ($\Delta l = 0.5$mm for $d = 1.6$mm, $n = 1.5$). But this means, that our glass plate should plunge into the camera metal fiducial frame by 1.6-0.5 = 1.1mm, what would involve a serious cutting of the very delicate and precise metal fiducial frame of the Pentacon Six camera. Therefore in our case the reseau glass plate was fixed in the camera in the most convenient position from the point of view of mechanical camera reshaping (fig.3). This resulted in the shift of the camera fiducial plane (exterior plane of reseau plate) not by 0.5mm but by 1.2mm away from the camera objective.

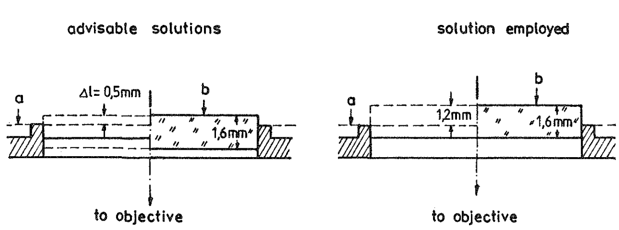


Fig.3 Fitting up the reseau glass plate to the camera:
a) the camera original fiducial plane
b) the exterior surface of the reseau glass plate (on which the reseau crosses are marked)

The reseau glass plate was glued to the special metal frame. This metal frame was lain on 4 pins of Ø = 1.5mm which were screwed to the camera metal fiducial frame (they can be regulated). Metal frame with the reseau glass is fixed to the camera body with 2 screws, what enables easy assemblage and disassemblege. The 4 pins ensure the stable position of the reseau plate in the camera and make the adjustment possible.

### 2.4. The Further Camera Modifications.

The mechanical assemblage of the reseau glass plate (1.6mm thick) to the camera body caused a shift of the camera fiducial plane (exterior reseau plate surface) by 1.2mm (fig.3) away from the objective, instead of 0.5mm (due to the glass plate). This will effect the position of the camera objective, which must be shifted by 0.7mm towards the fiducial frame, to enable the proper use of the distance scale existing in the camera. This was achieved by shortening (mechanical cutting by 0.7mm) of the metal cylinder assembling the lenses. The change of the objective position developed the need for adjustment of the ground glass surface of the camera viewfinder. It had to be shifted away from the camera body on 0.7mm (this was achieved using a spacer washer). In the Pentacon Six camera the film is pressed against the fiducial frame using flat plate contact spring, which is connected on the interior side of the camera lid. The spring is pushing film continuously to the slide bearings on the camera fiducial frame. The maximum distance available between slide bearings and plate spring is around 1.5mm. After the reseau glass plate has been assembled this distance was reduced to 0.3mm, what is far too little for the easy shifting of normal film. To prevent the film deformations caused by too tight sliding, the whole lid of the camera (together with the plate spring) was displaced from the fiducial frame by 1.0mm (the hinges and the lock were offset on 1mm). To enable approximate exterior camera orientation in the field a circular level was attached to the camera body and a mark was introduced to the field of view of the camera view finder (it points out the direction of the camera axes).

## 3. THE ADAPTED RESEAU CAMERA PHOTOGRAPHIC RESOLUTION

The examination of the camera photographic resolution ranged over the pictures taken using: non-adapted camera and camera with the 1.6mm thick reseau plate, and using two objectives: normal angle Biometar 2.8/80 (for the f-stops: 2.8, 8, 22) and wide angle Flectogon 4/50 (for the f-stops: 4, 8, 22). Pictures made without and with the reseau glass-plate were taken for this purpose on the photographic glass-plates TO1 ORWO. The greatest losses of the camera resolving power were noticed at the biggest entrance pupils of the objective. For the normal-angle Biometar 2.8/80 at the relative aperture 1:2.8 the resolution without the reseau-glass was around 37 l/mm at the picture centre and 24.6 l/mm at the picture edges. The 1.6mm reseau plate caused the drop of the resolution by 9.5 l/mm in the middle of the image field and by the 2.4 l/mm at the image field edges. Relatively resolution dropped to the level of 75% at the centre, and to 90% at the edges of the original camera resolution. For the wide angle Flectogon 4/50 at the relative aperture 1:4 the image resolution without the reseau-glass was 37 lines at the centre of the field of view and 10.5 l/mm at the edges. The glass-plate caused the resolution drop by 8.7 l/mm at the centre and by 0.6 l/mm at the edges. Relatively resolution dropped to the level of 76% at the centre and 94% at the edges comparing with the original camera resolution (without the 1.6mm reseau glass plate).

## 4. GEOMETRY OF PICTURES TAKEN WITH THE ADAPTED RESEAU CAMERA

### 4.1. The reseau transformation accuracy

The first, very important step of processing of photographs taken with a reseau camera, it is elimination of systematic errors appearing during image recording on the film. These systematic errors are due to the film differential shrinkage, film non-flattness in the moment of exposure, and by recording of the image slightly out of the plane of fiducial frame. The elimination, or at least reduction of those systematic errors can be achieved by transformation of photo-coordinates onto the reseau fiducial frame. The transformation coefficients can be calculated by fitting the coordinates of reseau-crosses surveyed on the photograph onto the coordinates of crosses of reseau master pattern surveyed directly on the reseau plate (the reseau master pattern was surveyed with the accuracy $\pm 0.8\mu m$ using Zeiss Jena Ascorecord).

In the presented experiment we have examined 12 photographs taken with our 6×6 reseau camera, to get answer to the following questions:

- by what value of deformation are influenced the photographs,
- which type of transformations would be the best for photo-coordinates refinement,
- how the number and distribution of the reseau active crosses influences the accuracy of refinement procedure (as an active reseau cross is meant such a cross of the reseau pattern which is actually used as a control point in the coordinate refinement procedure).

To get answer to the above questions the experimental 12 photographs selected from three films (ORWO NP 20) have been measured. On each photograph there should be registered 49 reseau crosses, but on a few pictures one cross could be omitted if imaged on the black image fragment and badly visible, and such picture could be partially excluded from the analysis. The reseau crosses were surveyed with the accuracy $\pm 2\mu m$ using the Zeiss - Jena Stecometer. The information about the size of errors caused by the above described deformations can be achieved by isometric transformation of coordinates of all the 49 crosses of the photograph onto the coordinates of all the 49 crosses of the reseau master pattern. The residual deviations on all this active points will describe optimally the quality of the identity of the both compared sets of points, as the isometric transformation does not change size or shape of the transformed picture. The results of this isometric transformations shows the average standard error calculated for the 12 experimental frames is $\pm 36.3\mu m$. The analysis of errors shows that the residual deformations fluctuate up to 50% of average standard deviation even for pictures recorded within one piece of film. There was found experimentally that the best description of deformations give: bilinear transformation and projective transformation. Comparing the results of those two transformations when applied to our test photographs it was noticed that the average standard deviations are in both cases identical avr. $m_x = \pm 2.4\mu m$, avr. $m_y = \pm 2.7\mu m$, avr. $m_p = \pm 3.7\mu m$. However, the bilinear transformation is less sensitive to noises and can be used to describe the photograph deformations. To check the property of the deformation there were calculated separately the bilinear transformations for the points distributed over the area of each quarter of the frame. The calculations ranged over only those quarters of each of the 12 experimental photographs on which there was possible to measure all the 16 reseau crosses (all the 16 crosses were active in the transformation). The calculation results are shown in table 1. And below are the average values of standard deviations, and their errors, for the separate quarters:

- for the I quarter avr.$m_p = \pm 1.9\mu m$, $\sigma = \pm 0.4\mu m$,
- for the II quarter avr.$m_p = \pm 2.3\mu m$, $\sigma = \pm 0.6\mu m$,
- for the III quarter avr.$m_p = \pm 1.8\mu m$, $\sigma = \pm 0.3\mu m$,
- for the IV quarter avr.$m_p = \pm 3.1\mu m$, $\sigma = \pm 0.4\mu m$.

The results show that the average value of standard deviations taken from the separate transformation of each quarter is smaller than the one for the full frame transformed at once. The best result was achieved for the I-th quarter, and the poorest for the IV-th quarter.

For average case of practical applications of the reseau camera it would be rather costly to measure all the 49 crosses on each reseau frame. So the experimental bilinear transformation was made for all the 49 crosses, using exclusively 9 regularly distributed active crosses, but only 4 of them at a time. When transforming separately each quarter area of the photograph, we got different results, which points out on differences of the physical model of errors on different portions of the photograph.

Table 1.

Bilinear transformation in the reseau frame quarters for 16 active crosses or 4 active crosses (only in the corners of each quarter).

| Name of photo | N° of film | BILINEAR TRANSFORMATION: 16 active crosses — standard deviation for 16 active crosses $m_x$ [µm] | $m_y$ [µm] | $m_p$ [µm] | 4 active crosses — standard deviation for 4 active and 12 passive crosses $m_x$ [µm] | $m_y$ [µm] | $m_p$ [µm] |
|---|---|---|---|---|---|---|---|
| The first quarter of photograph | | | | | | | |
| DP2 | III | 0.9 | 0.9 | 1.3 | 1.2 | 1.0 | 1.6 |
| GS2 | III | 1.0 | 1.4 | 1.7 | 1.1 | 1.9 | 2.3 |
| DL4 | III | 1.0 | 1.3 | 1.7 | 1.2 | 1.5 | 1.9 |
| DP4 | III | 1.5 | 1.0 | 1.8 | 2.0 | 1.0 | 2.3 |
| GS4 | III | 1.1 | 1.2 | 1.7 | 1.6 | 1.3 | 2.1 |
| L2 | II | 1.9 | 1.3 | 2.3 | 2.1 | 1.5 | 2.6 |
| P2 | II | 1.2 | 1.6 | 2.0 | 1.6 | 1.9 | 2.4 |
| S2 | II | 1.1 | 1.1 | 1.6 | 1.2 | 1.7 | 2.1 |
| L4 | II | 0.6 | 1.6 | 1.7 | 0.7 | 1.7 | 1.9 |
| P4 | II | 1.3 | 2.6 | 3.0 | 1.6 | 4.5 | 4.8 |
| S4 | II | 0.9 | 1.4 | 1.7 | 1.0 | 1.9 | 2.2 |
| L24 | I | 1.6 | 1.4 | 2.1 | 1.9 | 2.2 | 2.9 |
| $\frac{[m]}{n}$ | | 1.2 | 1.4 | 1.9 | 1.4 | 1.8 | 2.4 |
| $\sigma$ | | ± 0.3 | ± 0.4 | ± 0.4 | ± 0.4 | ± 0.9 | ± 0.8 |
| The second quarter of photograph | | | | | | | |
| DP2 | III | 1.0 | 1.2 | 1.5 | 1.0 | 1.3 | 1.6 |
| GS2 | III | 1.5 | 1.6 | 2.2 | 2.2 | 2.3 | 3.1 |
| DP4 | III | 1.5 | 1.3 | 1.9 | 2.5 | 1.4 | 2.9 |
| GS4 | III | 1.0 | 1.8 | 2.0 | 1.3 | 1.8 | 2.2 |
| L2 | II | 1.5 | 1.2 | 2.0 | 1.6 | 1.6 | 2.3 |
| P2 | II | 1.5 | 1.3 | 2.0 | 2.1 | 1.6 | 2.6 |
| S2 | II | 1.9 | 2.7 | 3.3 | 2.9 | 3.1 | 4.2 |
| P4 | II | 1.8 | 2.7 | 3.2 | 2.5 | 3.6 | 4.3 |
| S4 | II | 1.8 | 1.6 | 2.4 | 3.0 | 2.5 | 3.8 |
| P24 | I | 1.6 | 2.4 | 2.9 | 2.1 | 2.5 | 3.3 |
| $\frac{[m]}{n}$ | | 1.5 | 1.8 | 2.3 | 2.1 | 2.2 | 3.0 |
| $\sigma$ | | ± 0.3 | ± 0.6 | ± 0.6 | ± 0.6 | ± 0.7 | ± 0.8 |
| The third quarter of photograph | | | | | | | |
| DP2 | III | 0.9 | 1.4 | 1.7 | 1.4 | 1.6 | 2.1 |
| GS2 | III | 1.6 | 1.3 | 2.0 | 2.2 | 1.5 | 2.6 |
| DP4 | III | 0.9 | 1.6 | 1.9 | 1.2 | 1.8 | 2.2 |
| GS4 | III | 1.0 | 1.7 | 2.0 | 1.4 | 2.4 | 2.8 |
| L2 | II | 1.3 | 1.6 | 2.0 | 1.6 | 2.2 | 2.7 |
| P2 | II | 1.2 | 1.5 | 1.9 | 1.5 | 1.8 | 2.3 |
| S2 | II | 1.4 | 1.7 | 2.2 | 1.8 | 2.4 | 3.0 |
| P4 | II | 0.8 | 0.9 | 1.2 | 1.0 | 0.9 | 1.4 |
| S4 | II | 1.2 | 0.9 | 1.6 | 1.5 | 1.1 | 1.8 |
| $\frac{[m]}{n}$ | | 1.1 | 1.4 | 1.8 | 1.5 | 1.7 | 2.3 |
| $\sigma$ | | ± 0.3 | ± 0.3 | ± 0.3 | ± 0.3 | ± 0.5 | ± 0.5 |
| The fourth quarter of photograph | | | | | | | |
| DP2 | III | 1.8 | 2.7 | 3.2 | 2.2 | 3.3 | 4.0 |
| GS2 | III | 1.9 | 2.5 | 3.2 | 2.6 | 3.2 | 4.2 |
| DL4 | III | 1.4 | 2.5 | 2.9 | 1.9 | 3.1 | 3.6 |
| DP4 | III | 1.7 | 2.1 | 2.7 | 2.5 | 2.9 | 3.9 |
| GS4 | III | 2.7 | 2.6 | 3.8 | 3.4 | 2.9 | 4.5 |
| L2 | II | 2.0 | 2.6 | 3.3 | 2.8 | 3.7 | 4.7 |
| P2 | II | 2.1 | 3.2 | 3.8 | 3.2 | 4.2 | 5.3 |
| S2 | II | 1.4 | 2.6 | 2.9 | 2.1 | 3.6 | 4.1 |
| L4 | II | 1.3 | 2.3 | 2.6 | 1.9 | 3.3 | 3.7 |
| P4 | II | 2.2 | 1.8 | 2.8 | 2.9 | 2.6 | 4.0 |
| S4 | II | 1.4 | 2.6 | 3.0 | 2.2 | 3.3 | 4.0 |
| L24 | I | 1.9 | 2.2 | 2.9 | 2.5 | 2.9 | 3.8 |
| $\frac{[m]}{n}$ | | 1.8 | 2.5 | 3.1 | 2.5 | 3.3 | 4.2 |
| $\sigma$ | | ± 0.4 | ± 0.3 | ± 0.4 | ± 0.5 | ± 0.4 | ± 0.5 |

For all the 12 passive crosses in a quarter which were not used as the control-points the residuals were calculated and analyzed together with the four v = 0 which were obtained on active crosses. The following average standard deviations for each quarter were achieved:

- for the I quarter avr.$m_p = \pm 2.4 \mu m$, $\sigma = \pm 0.8 \mu m$
- for the II quarter avr.$m_p = \pm 3.0 \mu m$, $\sigma = \pm 0.8 \mu m$
- for the III quarter avr.$m_p = \pm 2.3 \mu m$, $\sigma = \pm 0.5 \mu m$
- for the IV quarter avr.$m_p = \pm 4.2 \mu m$, $\sigma = \pm 0.5 \mu m$.

The average standard deviation for the full reseau frame in such case of calculations amounts in $\pm 3.0 \mu m$, what would be satisfactory for many applications. The differences of accuracy which are shown in above quoted average mean errors were calculated from individual deviations of each measured reseau cross. The values of individual deviations $V_x$, $V_y$ are shown in the table 2 for the best and the worth quarter of the pictures (quarter I and quarter IV). The average deviations (bilinear transformation on 4 active crosses) for each quarter of the reseau frame are shown on fig.4.

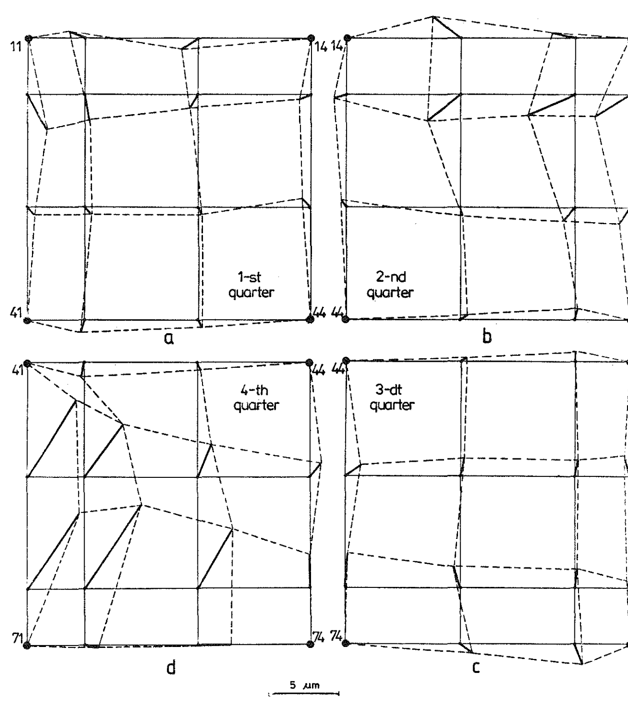


Fig.4 a,b,c,d. The average deviations of coordinates of each reseau cross, calculated using bilinear transformation with 4 active crosses in separate reseau frame quarters.

It is noticeable, that biggest deviations appear close to the limits of the frame (fig.4). The average values of $V_x$ or $V_y$ fixed for certain reseau cross (the mean systematic residuals) could be used as the systematic corrections to improve the accuracy of determination of image coordinates.

Table 2.

The deviations $V_x, V_y$ of 16 crosses in the 1-st and 4-th quarter of the photograph which result from the bilinear transformation made on 4 active crosses placed in the corners of each quarter.

| 1) | Names of surveyed photographs | | | | | | | | | | | | 2) [μm] | 3) [μm] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DL4 | DP2 | DP4 | GS2 | GS4 | L24 | L2 | L4 | P2 | P4 | S2 | S4 | | |
| | 1-st quarter - Vx [μm] | | | | | | | | | | | | | |
| 11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 12 | -2.4 | -0.4 | -3.8 | -1.3 | 0.9 | -2.6 | -2.1 | -1.0 | -1.0 | 0.6 | 1.3 | -1.4 | -1.2 | ±1.4 |
| 13 | -0.6 | -1.6 | -4.8 | 1.5 | 0.0 | 0.8 | -0.5 | -0.5 | -2.5 | -0.7 | 1.2 | -0.1 | -0.7 | ±1.6 |
| 14 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 21 | 0.7 | 0.7 | 0.0 | -2.0 | 3.2 | 3.2 | 2.9 | 0.8 | 0.6 | 2.1 | 0.5 | 1.3 | 1.2 | ±1.4 |
| 22 | -1.3 | 0.9 | -1.5 | -0.7 | 3.2 | 2.9 | -2.6 | -1.0 | 0.0 | 1.5 | 1.8 | 0.9 | 0.3 | ±1.7 |
| 23 | -0.2 | -0.1 | -0.6 | 1.4 | -0.1 | 1.0 | 0.3 | 0.1 | -2.4 | -2.0 | -2.5 | -2.1 | -0.6 | ±1.3 |
| 24 | -0.9 | -3.0 | -1.5 | 0.7 | 1.9 | 2.5 | -0.6 | -1.0 | -3.1 | -2.4 | -1.4 | -1.8 | -0.9 | ±1.7 |
| 31 | 1.1 | 2.6 | -2.8 | -2.3 | 2.8 | -1.6 | 3.7 | 1.1 | 3.0 | 0.5 | -1.8 | 1.1 | 0.6 | ±2.1 |
| 32 | -0.4 | 0.1 | -3.2 | -1.7 | 2.5 | 2.5 | 4.5 | 0.2 | 2.2 | 3.4 | -0.5 | -0.8 | 0.7 | ±2.2 |
| 33 | 0.9 | 0.1 | -1.0 | -0.3 | 0.0 | 2.9 | 2.7 | -0.3 | 0.1 | -0.3 | -2.0 | -0.2 | 0.2 | ±1.3 |
| 34 | 0.9 | -0.2 | -1.0 | -1.3 | -0.8 | 1.1 | -2.7 | -1.4 | -1.2 | -1.7 | 1.3 | 1.1 | -0.5 | ±1.2 |
| 41 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42 | -1.4 | 1.4 | 1.2 | -0.4 | 0.0 | 2.2 | -0.8 | -0.1 | -1.0 | -1.6 | -0.6 | -1.0 | -0.2 | ±1.1 |
| 43 | 2.9 | 1.2 | -1.4 | 0.9 | 1.0 | 0.6 | 1.6 | -0.8 | 0.0 | -2.3 | -0.5 | -0.5 | 0.2 | ±1.4 |
| 44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 1-st quarter - Vy [μm] | | | | | | | | | | | | | |
| 11 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 12 | 0.8 | -0.8 | 2.1 | -0.3 | 4.2 | -1.0 | 1.4 | 0.1 | -0.2 | -3.1 | 1.4 | 1.0 | 0.5 | ±1.7 |
| 13 | -2.2 | -1.0 | -1.6 | 1.1 | 0.0 | -1.6 | -1.7 | -0.9 | 4.6 | -4.7 | 0.1 | -1.9 | -0.8 | ±2.1 |
| 14 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 21 | -3.3 | -2.6 | -0.6 | -3.6 | 0.3 | -2.8 | -3.1 | -2.5 | -1.6 | -7.6 | 0.9 | -2.1 | -2.4 | ±2.1 |
| 22 | -0.1 | -1.2 | -2.1 | -3.4 | -0.8 | -2.0 | -2.6 | 3.2 | -1.9 | -10. | 1.7 | -2.8 | -1.8 | ±3.1 |
| 23 | -1.6 | 0.0 | -0.8 | 0.2 | -0.7 | -2.1 | -1.3 | 3.4 | 0.8 | -6.3 | 1.0 | -4.8 | -1.0 | ±2.5 |
| 24 | 1.9 | -1.6 | -0.4 | 1.0 | -0.7 | -6.0 | 0.7 | 2.2 | 2.0 | -5.5 | 3.5 | -0.7 | -0.3 | ±2.8 |
| 31 | 0.5 | 0.3 | 0.3 | -1.7 | -1.8 | -1.8 | -0.5 | -0.9 | 1.8 | -4.4 | 2.3 | 0.3 | -0.5 | ±1.7 |
| 32 | 1.0 | 1.1 | -0.4 | -2.5 | -1.8 | -1.0 | -2.0 | 0.9 | 0.7 | -5.4 | 3.6 | -0.2 | -0.5 | ±2.2 |
| 33 | -1.0 | 0.6 | -1.8 | 1.7 | 1.2 | -2.5 | -0.2 | -1.0 | 1.0 | -2.2 | 0.8 | -1.7 | -0.4 | ±1.4 |
| 34 | 0.3 | 0.5 | 0.1 | 4.3 | 0.5 | -2.7 | 2.5 | 2.4 | 3.1 | -1.2 | 1.3 | -2.3 | 0.7 | ±2.0 |
| 41 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42 | -0.7 | -1.6 | 0.4 | -1.5 | -0.5 | -0.9 | -0.2 | -0.2 | -3.0 | -2.4 | 1.8 | -2.4 | -0.9 | ±1.3 |
| 43 | -2.8 | -0.4 | 0.7 | -0.4 | -0.3 | -0.5 | -1.0 | -2.4 | 0.7 | 0.0 | 2.1 | -1.5 | -0.5 | ±1.3 |
| 44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 4-th quarter - Vx [μm] | | | | | | | | | | | | | |
| 41 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42 | -1.3 | 1.4 | 1.2 | -0.4 | 0.0 | 2.3 | -0.9 | -0.1 | -1.0 | -1.6 | -0.6 | -1.0 | -0.2 | ±1.2 |
| 43 | 3.0 | 1.2 | -1.4 | 0.7 | 0.9 | 0.6 | 1.4 | -0.8 | 0.0 | -2.3 | -0.6 | -0.5 | 0.2 | ±1.4 |
| 44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 51 | 0.6 | 4.9 | 3.4 | 1.1 | 4.8 | 6.3 | 4.5 | 2.1 | 6.2 | 3.1 | 2.5 | 2.9 | 3.5 | ±1.8 |
| 52 | 0.7 | 4.2 | 1.0 | 2.2 | 4.7 | 2.6 | 1.9 | 2.0 | 4.9 | 4.2 | 4.1 | 1.4 | 2.8 | ±1.4 |
| 53 | 0.9 | 2.9 | 2.5 | 3.7 | -0.6 | 1.1 | 3.1 | 0.0 | 1.4 | -3.0 | -1.1 | 1.0 | 1.0 | ±1.9 |
| 54 | 0.5 | 0.3 | -0.5 | 4.7 | -2.2 | -2.7 | 3.0 | 1.5 | 1.4 | -1.2 | 1.8 | 3.2 | 0.8 | ±2.1 |
| 61 | 0.1 | -0.1 | 6.1 | 2.5 | 5.9 | 4.0 | 4.0 | 5.6 | 6.3 | 3.1 | 2.8 | 4.7 | 3.8 | ±2.1 |
| 62 | 3.3 | 1.1 | 5.0 | 4.9 | 5.4 | 3.1 | 5.6 | 2.9 | 4.5 | 7.7 | 2.6 | 2.6 | 4.1 | ±1.7 |
| 63 | 1.4 | 4.0 | 3.6 | 4.5 | -1.0 | 2.9 | 5.1 | 2.0 | 4.0 | -0.5 | 1.7 | 2.8 | 2.5 | ±1.8 |
| 64 | -0.7 | -1.3 | 1.0 | 1.1 | -3.5 | -0.4 | -1.7 | 0.0 | 3.3 | -0.9 | 2.2 | -0.1 | -0.1 | ±1.7 |
| 71 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 72 | 4.1 | -1.8 | 0.8 | -1.6 | -1.1 | -1.8 | 1.5 | 0.6 | 1.6 | 5.0 | 2.0 | 2.4 | 1.0 | ±2.2 |
| 73 | 3.6 | 1.2 | 1.0 | 3.7 | 7.5 | -1.8 | 1.4 | 0.9 | 2.9 | 1.1 | 3.6 | 2.8 | 2.3 | ±2.2 |
| 74 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 4-th quarter - Vx [μm] | | | | | | | | | | | | | |
| 41 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 42 | -0.7 | -1.6 | 0.4 | -1.6 | -0.6 | -0.9 | -0.3 | -0.2 | -3.0 | -2.4 | 1.8 | -2.4 | -1.0 | ±1.3 |
| 43 | -2.8 | -0.4 | 0.7 | -0.4 | -0.4 | -0.5 | -1.0 | -2.4 | 0.7 | 0.0 | 2.1 | -1.5 | -0.5 | ±1.3 |
| 44 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 51 | 5.8 | 6.6 | 4.8 | 4.5 | 4.2 | 5.9 | 6.3 | 4.8 | 7.8 | 4.2 | 4.3 | 6.5 | 5.5 | ±1.1 |
| 52 | 7.1 | 2.1 | 2.5 | 3.5 | 3.3 | 4.2 | 3.4 | 4.4 | 6.2 | 3.3 | 2.0 | 3.8 | 3.8 | ±1.5 |
| 53 | 1.8 | 0.5 | 2.0 | 4.9 | 3.0 | 1.1 | 4.0 | 2.3 | 2.7 | -0.1 | 4.3 | 1.0 | 2.3 | ±1.5 |
| 54 | 1.3 | -1.0 | 2.6 | 3.3 | 0.7 | 2.0 | 1.2 | -1.2 | 2.3 | -1.1 | 1.0 | 0.3 | 1.0 | ±1.4 |
| 61 | -0.5 | 4.1 | 6.5 | 7.7 | 5.2 | 2.5 | 6.9 | 7.5 | 9.0 | 3.8 | 5.0 | 6.4 | 5.3 | ±2.5 |
| 62 | 5.5 | 6.5 | 5.1 | 5.0 | 5.8 | 4.9 | 6.6 | 6.7 | 5.5 | 6.7 | 8.4 | 6.1 | 6.1 | ±1.0 |
| 63 | 4.2 | 7.2 | 3.1 | 1.9 | 3.1 | 4.5 | 5.2 | 2.9 | 5.6 | 2.6 | 5.2 | 4.9 | 4.2 | ±1.4 |
| 64 | -0.1 | 2.2 | 4.4 | 3.0 | 0.4 | 4.2 | 5.7 | 1.3 | 4.3 | 0.5 | 4.7 | -1.2 | 2.5 | ±2.1 |
| 71 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 72 | 1.7 | 0.1 | -0.7 | -0.1 | -3.9 | -0.9 | 2.3 | 1.7 | -0.6 | 2.6 | -1.8 | -1.6 | -0.1 | ±1.8 |
| 73 | 2.4 | -2.0 | 0.6 | -0.7 | -3.1 | 0.0 | -0.7 | -0.7 | 0.4 | 1.0 | 1.6 | 1.9 | 0.1 | ±1.5 |
| 74 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

1) reseau cross number

2) average deviation for each reseau cross

3) mean error of the average deviation ($\sigma$)

It must be considered, however, that - as it is shown in the table 2 - the coordinates after bilinear transformation do not always deviate very regularly (eg.P4-$V_y$-22). Therefore, sometimes the correction of coordinates by the interpolated mean systematic residual value can rather deteriorate than to improve the accuracy. It would be advisable in our case, therefore, to neglect such corrections for the I-III quarters of the image, considering the fact that the value of the mean error of the average deviation are close to the eventual correction. So, only systematic corrections to the coordinates after bilinear transformation would be applied to the IV quarter and partially to III quarter (see fig.4 and table 2). Nevertheless, for the top accuracy projects where single microns are of the great importance, there would not be enough to measure only 9 active crosses in each reseau frame. In such cases which require the top accuracy the image coordinates must be transformed individually in each little quadrangle formed by crosses around the image surveyed point. Sometimes the correction procedure could require the measurement of all the 49 reseau crosses.

## 4.2. Calibration of the semimetric reseau camera

The camera was calibrated using pictures of the special flat test-field. It is 2.28×2.28 m grid of squares consisting of 161 targets and 40 additional targets placed to thicken control points on the 4 symmetry axes. The test-field was enriched with 5 control points placed in the space in front of the flat test grid. The spatial coordinates of the test field were determinated with the accuracy ±0,2mm applying mixed direct and photogrammetric methods. There were taken 2 triplets of photographs so oriented to secure the best possible geometry crossing of the projection rays (2 photographs were taken from left and right site from the for level, and the third was taken frontally, but from just under the ceiling). Both triplets were taken using Biometar 2.8/80, one within the distance of 2 m, the other within the distance of 4m from the flat grid test. The calibration calculations made with the use of bundle adjustment program (by A.Tokarczyk, AGH) gave excellent accuracy of 0.1÷0.3 mm on the 9 control points (5 on the flat test-grid and other 4 in the space in front of the flat test) and provided the interior and exterior orientation elements. For D = 2 m we received $C_k$ = 87.79±0.018 mm, $x_o$ = -0.08 ±0.020 mm, $y_o$ = -0.52±0.023 mm, $m_o$ = ±0.0033 mm. For distance D = 4 m the following elements were evaluated: $C_k$ = 85.64±0.009 mm, $x_o$ = 0.01±0.008 mm, $y_o$ = -0.49±0.008mm, $m_o$ = ±0.0014mm. The calculations in both cases were performed under condition that the interior orientation elements are stable for pictures of the triplet. All the targets of the test field were used to calculate distortion of the camera objective. The radial distortion of the reseau pictures (recorded on film) compared with the distortion of the camera before adaptation (pictures recorded on the glass plate) changed very little due to the additional glass-plate within the camera optical system (see fig.5). The maximal radial distortion is greater by 10% on the picture taken with the reseau glass in comparison with picture taken with non adapted camera.

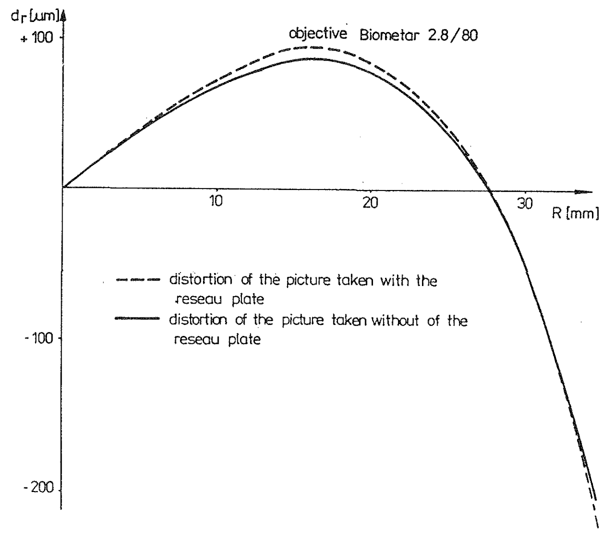


Fig.5 Radial Distortion Diagram

## 5. CONCLUSIONS

The adapted semimetric reseau camera with the 1.6mm thick reseau glass plate provides the high accuracy pictures and is suitable for various industrial, architectural and other applications. The correction of film deformation using only 9 crosses of the reseau grid provides the image coordinates accuracy $m_p = \pm 3.0 \mu m$. The described adaptation procedure makes it possible to perform the adaptation for the similar amateur camera types even without the need to use the very highly specialized laboratories.

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