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Author: Prof. Dr.-Ing. Hans Mohl
Internationales Fortbildungszentrum für Photogrammetrie-Operateure (IPO),
D-7000 Stuttgart

Title: Conception and accuracy of the program system for the STEREOCORD G 2

Abstract:

The STEREOCORD G 2, a plotting system developed by Carl Zeiss, Oberkochen, for the quantitative interpretation of aerial photographs is on the market since 1975. With the introduction of a more advanced desk top computer a new program system has been developed 1977/78. Flexibility, accuracy and handling of the instrument system have been improved considerably.

The conception of the program system for orientation, transformation of the image measuring data to ground coordinates and for measurement of interpretation data will be presented. The precision will be shown by test results.

Titel: Konzeption und Genauigkeitsleistung des Programmsystems zum STEREOCORD G 2

Zusammenfassung:

Das STEREOCORD G 2, ein von Carl Zeiss, Oberkochen, entwickeltes Auswertesystem für die quantitative Luftbildinterpretation, ist seit 1975 auf dem Markt. Mit dem Übergang auf einen anderen Tischrechner wurde 1977/78 ein neues Programmsystem entwickelt. Flexibilität, Benutzerfreundlichkeit und Genauigkeit des Gerätesystems konnten dabei erheblich gesteigert werden.

Die Konzeption des Programmsystems zur Orientierung, zur Transformation der Bildmeßdaten in Geländekoordinaten und zur Messung von Interpretationsdaten wird vorgestellt. Die Genauigkeitsleistung wird durch Testergebnisse belegt.

Titre: La conception et la précision du système de programme pour le STEREOCORD G 2

Sommaire:

Le STEREOCORD G 2, un système de restitution développé par Carl Zeiss, Oberkochen, pour l'interprétation de la photographie aérienne quantitative, est au marché depuis 1975. Avec la prise en charge d'un autre ordinateur à table on a développé un nouveau système de programme en 1977/78. On a amélioré considérablement la flexibilité, la précision et la manoeuvre du système de l'appareil.

On présente la conception du système de programme pour l'orientation, la transformation des données de mesure du cliché dans les coordonnées du terrain et pour le mesurage de données d'interprétation. La précision est prouvée par les résultats des tests.

INTRODUCTION:

The STEREOCORD G 2 has been presented at the 35th Photogrammetric Week in Stuttgart in 1975 [1]. It has been designed for the quantitative photo-interpretation. Coordinates of single points, distances, angles, areas or volumes can be determined and printed out by means of a desk top computer. The connexion of a X-Y-plotter and of other peripheral devices of the calculator is possible.

The principle of the plotting system can be seen in figure 1. The aerial photographs are observed by means of a mirror stereoscope. Two floating marks are fixed on small circular glass plates under which the photo carriage moves in X' and Y' directions. The measuring device consists of a mechanical photo carriage, the X'-and Y'-motions of which are digitized by linear encoders. By these mouvements the coordinates of a point in the left-hand photo can be measured. In order to set the same point in the right-hand photo the motions PX and PY of the right-hand photo carriage with respect to the left one are used. PX is digitized by a rotation encoder.

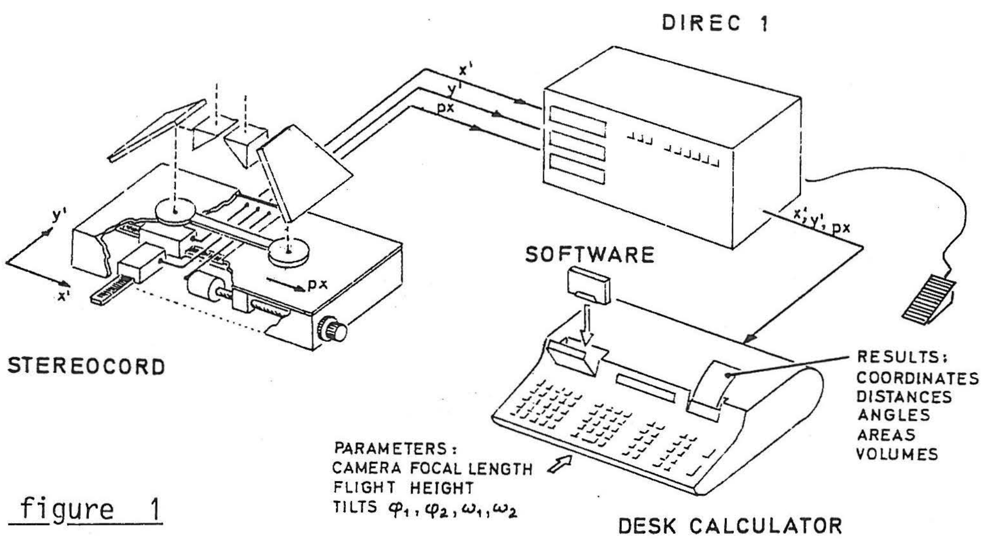

figure 1

The pulses of the X', Y' and PX-motions are counted and displayed in the DIREC 1 interface and control unit. The calculator which is connected with the DIREC by means of an interface cord reads the measured data in a real-time-loop, calculates the actual ground coordinates and displays the elevation above sea level in intervals of about one second. Several measuring programs can be called by the program keys of the DIREC. In running programs the transmission of measuring data from the DIREC to the calculator, the display or the printout of results as well, are triggered by the foot control.

As the photographs remain in their horizontal position, the effects of the tilts are to be taken into account numerically. Only swing is set by aligning the marked and transferred principal points with a straight line - similar to the setting of photographs under a mirror stereoscope. The first program system for the STEREOCORD had been installed in a Hewlett-Packard HP 9810 desk top calculator, which was not supplied with trigonometric functions in its standard outfit. So approximate mathematical solutions in the transformation to the ground system and the orientation procedures had been chosen.

The calculator HP 9815 A, furnished with trigonometric functions and a quick magnetic tape cartridge, gave the chance of improving the transformation formulas, the orientation procedures, as well as the comfort of managing the programs. The system developed by the author in 1977/78 will be outlined now.

ORGANISATION OF THE PROGRAM SYSTEM

The STEREOCORD program system consists of the PILOT program, a set of orientation programs and a set of measurement programs. Each of the programs is stored on a file of the magnetic tape. The computer's integral memory has got sufficient capacity for accepting one of these programs with the corresponding data at a time. As a result, there is an active exchange of tape and computer information while the program system is in use.

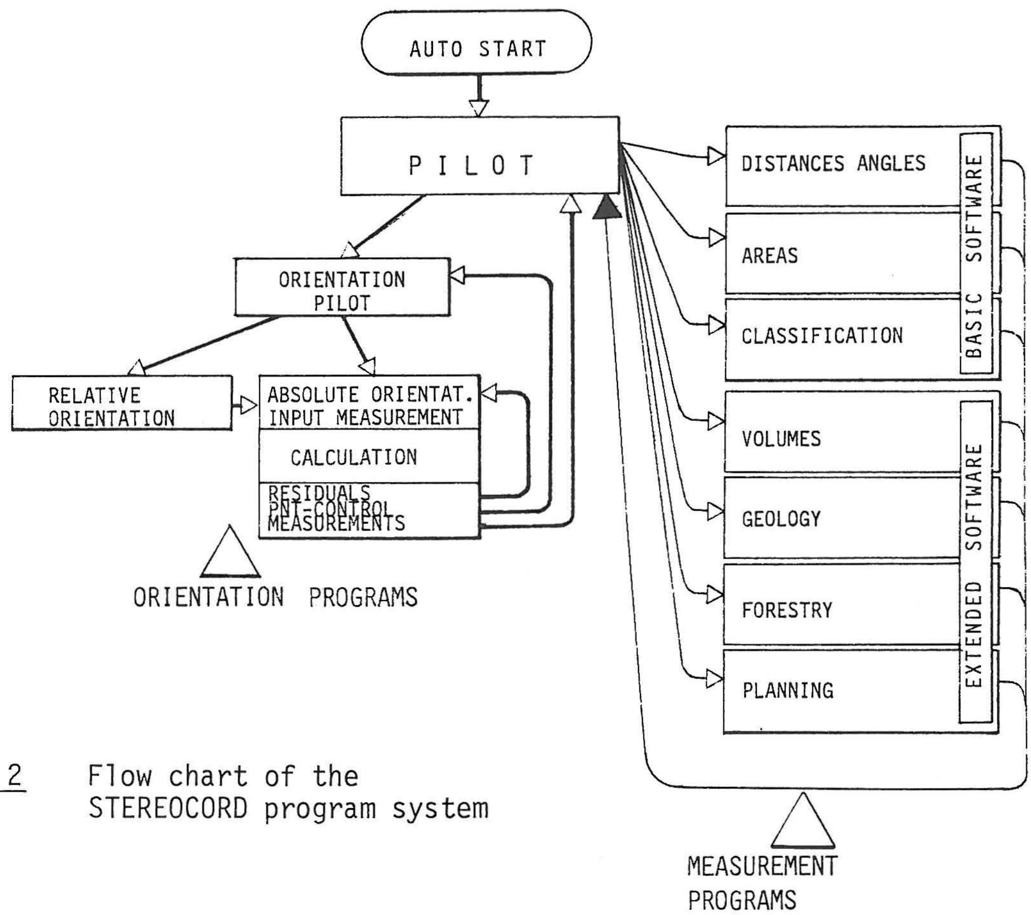

Figure 2 Flow chart of the STEREOCORD program system

The PILOT program takes care of the major chores of organization, which otherwise would be the operator's responsibility. Figure 2 shows the central control function of the PILOT program in a greatly simplified form. After switching on the computer, PILOT is automatically loaded and started. The user gets the informations for handling the system by the printer of the calculator. He decides to go to the orientation programs if a new photopair has been set on the STEREOCORD or if the orientation has to be improved. If the orientation parameters are already stored, the measurement programs can be reached directly from PILOT.

In the basic software cassette some blank files are available, which may be used for recording the user's own programs. At present 30 measurement programs and 6 orientation programs are operative.

THE C O O R D D PROGRAM AND ITS TRANSFORMATION EQUATIONS

The COORD D program calls the X', Y' and PX measurement data from the DIREC and uses them to compute the ground coordinates of the point set in the STEREOCORD. In the following table 1 the sequence of equations is noted down and briefly explained. The used parameters and coefficients shown in table 2 (next page) are entered or calculated during the orientation procedures. In the running REAL-TIME-DISPLAY program the equations (1) through (7) are evaluated in a time of about 0.25 second. The time of display is

List of transformation equations used in COORD D:

INPUT = X', Y', PX measurement data taken over from DIREC

Reduction of DIREC coordinates to principal points:

$$\begin{aligned} x' &= X' - 1000 \\ y' &= Y' - 1000 \\ x'' &= X' - PX - b'' \end{aligned} \qquad (1)$$

Computation of coordinates referred to left-hand photo (x^*, y^*, z^*): true-vertical photos:

$$\begin{aligned} x^* &= a_{11} \cdot x' + a_{13} \\ y^* &= a_{21} \cdot x' + a_{22} \cdot y' + a_{23} \\ z^* &= a_{31} \cdot x' + a_{32} \cdot y' + a_{33} \end{aligned} \qquad (2)$$

right-hand photo (x^{**}, z^{**}):

$$x^{**} = c_{11} \cdot x'' + c_{13} \qquad (3a)$$

$$z^{**} = c_{31} \cdot x'' + c_{32} \cdot y' + c_{33} \qquad (3b)$$

The coefficients a_{ik} and c_{ik} are given below.

Computation of effective $\bar{x}^*$-coordinate in left-hand true-vertical photo:

$$\bar{x}^* = z_o^* \left(\frac{x^*}{z^*} - \frac{x^{**}}{z^{**}} \right) \qquad (4)$$

Computation of level difference between datum H_o and height of the point set in the STEREOCORD:

$$\Delta h = h_G \left[1 - \frac{b^*}{\bar{x}^*} \left(1 + \left(\frac{x^{**}}{z^{**}} - \tan\Delta\Phi\right) \cdot \tan\Delta\Phi\right) \right] \qquad (5)$$

Computation of ground coordinates:

$$X = x^* \cdot \frac{(\Delta h - h_G)}{z^*}$$

$$Y = y^* \cdot \frac{(\Delta h - h_G)}{z^*} \qquad (6)$$

X,Y as referred to left-hand nadir

DISPLAY in RT-DISPLAY

$$H = H_o + \Delta h \qquad (7)$$

OUTPUT: Point number $\bar{X}$ $\bar{Y}$ H upon depression of foot control

$$\bar{X} = X_o + A \cdot X - O \cdot Y$$

$$\bar{Y} = Y_o + A \cdot Y + O \cdot X \qquad (8)$$

$\bar{X}, \bar{Y}$ = state plane coordinates if X_o, Y_o, A,O have been determined by means of ABSORIENT.

In the above mentioned transformation equations b'', b^* and z_o^* are calculated as follows:

$$b'' = X'_{Hr} - PX_{Hr}$$

$$b^* = b' \cdot \cos\varphi_1 - f \cdot \sin\varphi_1 \quad \text{where} \quad b' = X'_{Hr} - 1000$$

$$z_o^* = -(b' \cdot \sin\varphi_1 + f \cdot \cos\varphi_1)$$

Hr = principal point right

Table 1

about 0.75 second. So every second new image coordinates are read from the DIREC counters and are transformed to the ground coordinates, of which the elevation above sea level is displayed. In case the printout of point data has been triggered by pressing the foot control, the equations (8) are evaluated in order to get state plane coordinates $\bar{X}$ and $\bar{Y}$.

Parameters and coefficients in transformation equations of COORD D:

Parameters:

f, h_G, b', b"	Input or determination in OR-PILOT
$\varphi_1, \omega_2, \varphi_2$	Determination in RELORIENT
b^*, z_o^*	Computation according to RELORIENT
$\Delta\Omega$, $\Delta\Phi$, H_o	Determination in ABSORIENT
X_o, Y_o, A, O	Determination in ABSORIENT
$\bar{\omega}_1$, $\bar{\varphi}_1$, $\bar{\omega}_2$, $\bar{\varphi}_2$	Computation after ABSORIENT: (see below)

Coefficients:

$a_{11} = \cos\bar{\varphi}_1$	$c_{11} = \cos\bar{\varphi}_2$
$a_{13} = -f \sin\bar{\varphi}_1$	$c_{13} = -f \sin\bar{\varphi}_2$
$a_{21} = \sin\bar{\omega}_1 \sin\bar{\varphi}_1$	$c_{31} = -\cos\bar{\omega}_2 \sin\bar{\varphi}_2$
$a_{22} = \cos\bar{\omega}_1$	$c_{32} = \sin\bar{\omega}_2$
$a_{23} = f \sin\bar{\omega}_1 \cos\bar{\varphi}_1$	$c_{33} = -f \cos\bar{\omega}_2 \cos\bar{\varphi}_2$
$a_{31} = -\cos\bar{\omega}_1 \sin\bar{\varphi}_1$	
$a_{32} = \sin\bar{\omega}_1$	
$a_{33} = -f \cos\bar{\omega}_1 \cos\bar{\varphi}_1$	

$\bar{\omega}_1 = \Delta\Omega$

$\bar{\varphi}_1 = \varphi_1 + \Delta\Phi$

$\bar{\omega}_2 = \omega_2 + \Delta\Omega$

$\bar{\varphi}_2 = \varphi_2 + \Delta\Phi$

Table 2

Under the given conditions (three measured values X', Y' and PX) the system of transformation equations used in the COORD D program gives optimum results. The coordinate accuracy is above all a function of the relative tilt between the taking axes of the photopair. In equation (3b), table 1, y' should be replaced by y" of the right-hand photo. But as y" is not measured the left-hand y'-coordinate is taken as approximate value. The coordinate accuracy of the STEREOCORD system, as it will be shown later on, is about equivalent to that of a second-B-order stereoplotter for normal photo flights with nearly vertical photography (tilts not exceeding $\pm$ 5 grads). As the tilt of two successive photos in a flight strip usually is less than 2 grads, the measurement of the fourth component (PY $\rightarrow$ y") can be despensed with. - Although the measurement of y-parallaxes would be possible with the aid of a suitable accessory, the higher calculating accuracy could only have a marginal effect because in the case of the COORD D program, the calculating accuracy is already of identical magnitude as the pointing precision attainable in the STEREOCORD.

THE RELATVE ORIENTATION PROCEDURE

The principle of the used relative orientation procedure in the program RELORIENT is shown in table 3. The calculation is carried out iteratively.

Beginning with the measured Y-parallaxes in the six orientation points (according to O.v.Gruber) the tilt corrections $\Delta\varphi_1$, $\Delta\omega_2$ and $\Delta\varphi_2$ are calculated by means of the equations (9) . These corrections are added to the previous values, see (10). With the resulting tilt angles the rigorous residual Y-parallaxes are calculated by equations (11) and (12).

<u>Iterative computation of the elements of the relative orientation</u>:

A) Computation of corrections of the tilt angles from current Y parallax by the equations:

$$\begin{aligned} \Delta\varphi_1 &= \frac{f \cdot \rho}{2 \cdot b \cdot d} \cdot (p_{y_4} - p_{y_6}) \\ \Delta\omega_2 &= \frac{f \cdot \rho}{4 \cdot d^2} \cdot (p_{y_3} + p_{y_4} + p_{y_5} + p_{y_6} - 2\, p_{y_1} - 2\, p_{y_2}) \\ \Delta\varphi_2 &= \frac{f \cdot \rho}{2 \cdot b \cdot d} \cdot (p_{y_3} - p_{y_5}) \end{aligned} \tag{9}$$

where $b = d = 9 0$ mm, $\rho = \frac{200}{\pi}$ grad.

B) Computation of new tilt angles:

$$\begin{aligned} \varphi_1 &= \varphi_1 + \Delta\varphi_1 \\ \omega_2 &= \omega_2 + \Delta\omega_2 \\ \varphi_2 &= \varphi_2 + \Delta\varphi_2 \end{aligned} \tag{10}$$

C) Rigorous computation of residual PY parallax from the new tilt angles, using the equations:

$$\begin{aligned} y^*_i &= y'_i \\ z^*_i &= -x'_i \cdot \sin\varphi_1 - f \cdot \cos\varphi_1 \\ y^{**}_i &= x''_i \cdot \sin\omega_2 \cdot \sin\varphi_2 + y''_i \cdot \cos\omega_2 + f \cdot \sin\omega_2 \cdot \cos\varphi_2 \\ z^{**}_i &= -x''_i \cdot \cos\omega_2 \cdot \sin\varphi_2 + y''_i \cdot \sin\omega_2 - f \cdot \cos\omega_2 \cdot \cos\varphi_2 \end{aligned} \tag{11}$$

The latest parallax of orientation point P_i is:

$$p_{y_i} = f \cdot \left(\frac{y^{**}_i}{z^{**}_i} - \frac{y^*_i}{z^*_i}\right) \tag{12}$$

D) Comparison of angle corrections with the bound:

$$\begin{aligned} |\Delta\varphi_1| &< 1 \text{ mgrad} \\ |\Delta\omega_2| &< 1 \text{ mgrad} \\ |\Delta\varphi_2| &< 1 \text{ mgrad} \end{aligned}$$

If all corrections are smaller than the bound, the relative orientation is finished, if not, jump to A).

<u>Table 3</u>

Before starting another iteration the program compares the absolute values of the tilt corrections with the bound 1 mgrad. The iterative process is broken off, when all tilt corrections are less than this bound. Normally 3 or 4 iterations are sufficient. The results of the relative orientation are automatically stored on a data file of the magnetic tape.

As shown in the flow chart (<u>figure 2</u>) the program for the absolute orientation (ABSORIENT) can be started directly from the relative orientation program. The iterative calculation of the relative orientation takes about 40 seconds, depending on the number of iterations.

THE ABSOLUTE ORIENTATION METHOD

After the relative orientation, the "stereo model" realized in numerical form in the STEREOCORD system is similar to the ground.

The absolute orientation is started with the nominal data input. Up to six control points can be entered. Spatial, planimetric or elevation control points can be mixed in a free sequence. After the control data input from the keyboard of the calculator, the control points are measured in the STEREOCORD in the same sequence as the nominal data have been entered.

The evaluation is carried out according to a spatial similarity transformation with overdetermination. Table 4 explaines briefly the used equations. Planimetric transformations and height adjustments are calculated alternately. When the absolute values of the tilt corrections $\Delta\Omega$ and $\Delta\Phi$ of the model are less than 1 mgrad, the iteration process is broken off and a final planimetric transformation yields the parameters A, O, X_o and Y_o (see equations (8), table 1). In most cases three iterations have proved to be sufficient. The iterations can be observed on the display by counting-up-numbers: 10 / 11 / 12 / 13 // 20 / 21 / 22 / 23 // 30 . . . If the iterative process does not stop as expected (e.g. in case of gross errors), the user terminates the calculation, when X3 is displayed (X = number of iterations).

In the third part of the absolute orientation program (see figure 2), the X-, Y- and H-residuals and their RMS are printed out and the elevation above sea level of the point set in the STEREOCORD appears flashing on the display (RT-DISPLAY). The output of the residuals usually makes it very easy to decide wether the orientation of the photo pair is all right.
The residual corrections are a function of
- photo scale,
- accuracy of control-point data,
- the operator's experience.

The admissible tolerance is determined by the type of work performed:
For absolute measurement (coordinates and elevations), the required accuracy will be higher than in
relative measurement (coordinate differences, distances, angles, slope) since in this case a part of the coordinate errors is eliminated by subtraction.

Depending on the quality of orientation results, various approaches may be used (see figure 2!):
- transfer to PILOT if the results are accepted, from there to the measurement programs,
- if gross control-point errors are suspected, return to the nominal data input,
- if an error is not evident but if doubts persist, it is advisable to go to the ORientation-PILOT program. There the parameterlist can be called. If the results are satisfactory, go to PILOT and the measurement programs, if not, improve the orientation by starting the relative or absolute orientation once more.

USING THE MEASUREMENT PROGRAMS

The package of measurement programs included in the basic software contains a number of elementary programs for measuring distances, angles, slope and areas. The program set DIST/ANGLE (distances/angles) contains the programs VERDIST (level difference), HORDIST (horizontal distance), SPADIST (spatial

Equations for the iterative solution of the absolute orientation:

$$\mu = \frac{1}{\left[\bar{x}_i^2 + \bar{y}_i^2\right]} \sqrt{\left[\bar{x}_i \cdot \bar{X}_i + \bar{y}_i \cdot \bar{Y}_i\right]^2 + \left[\bar{x}_i \cdot \bar{Y}_i - \bar{y}_i \cdot \bar{X}_i\right]^2}$$

horizontal transformation scale factor μ

where

$\bar{x}_i$, $\bar{y}_i$ are the model coordinates reduced to the center of gravity,

$\bar{X}_i$, $\bar{Y}_i$ the nominal coordinates of the horizontal control points reduced to the center of gravity.

The brackets $[\ ]$ are Gaussian sum symbols, so that

$$\left[\bar{x}_i^2 + \bar{y}_i^2\right] = \sum_{i=1}^{i=n} (\bar{x}_i^2 + \bar{y}_i^2) \quad \text{, where}$$

n = number of horizontal control points.

The flying height entered is multiplied by the scale factor μ:

$$\boxed{h_G = \mu \cdot h_G}$$

Leveling:

The corrections of model tilt angles $\Delta\Omega$ and $\Delta\Phi$ are computed by the following formulas:

$$\Delta\Omega = \frac{-\left[\bar{x}_i^2\right] \cdot \left[\bar{y}_i \cdot \bar{l}_i\right] + \left[\bar{x}_i \cdot \bar{y}_i\right] \cdot \left[\bar{x}_i \cdot \bar{l}_i\right]}{\left[\bar{x}_i^2\right] \cdot \left[\bar{y}_i^2\right] - \left[\bar{x}_i \cdot \bar{y}_i\right]^2}$$

$$\Delta\Phi = \frac{-\left[\bar{x}_i \cdot \bar{y}_i\right] \cdot \left[\bar{y}_i \cdot \bar{l}_i\right] + \left[\bar{y}_i^2\right] \cdot \left[\bar{x}_i \cdot \bar{l}_i\right]}{\left[\bar{x}_i^2\right] \cdot \left[\bar{y}_i^2\right] - \left[\bar{x}_i \cdot \bar{y}_i\right]^2}$$

The horizon H_0 is computed by the expression:

$$\boxed{H_o = x_s \cdot \Delta\Phi - y_s \cdot \Delta\Omega + H_s - h_s}$$

In the leveling equations,

$\bar{x}_i$, $\bar{y}_i$ are the model coordinates of the spot heights reduced to the center of gravity,

$\bar{l}_i = \bar{h}_i - \bar{H}_i$, $\bar{h}_i$ being the model heights reduced to the center of gravity and $\bar{H}_i$ the nominal elevations reduced to the center of gravity,

x_s, y_s, H_s, h_s are the coordinates and elevations of the center of gravity.

Final horizontal transformation:

The parameters of the horizontal transformation are computed as follows:

$$A = \frac{\left[\bar{x}_i \cdot \bar{X}_i\right] + \left[\bar{y}_i \cdot \bar{Y}_i\right]}{\left[\bar{x}_i^2 + \bar{y}_i^2\right]}$$

$$O = \frac{\left[\bar{x}_i \cdot \bar{Y}_i\right] - \left[\bar{y}_i \cdot \bar{X}_i\right]}{\left[\bar{x}_i^2 + \bar{y}_i^2\right]}$$

$$X_o = X_s - x_s \cdot A + y_s \cdot O$$

$$Y_o = Y_s - y_s \cdot A - x_s \cdot O$$

Table 4

distance), SLOPE (slope angle) and AZIMUTH (azimuth clockwise from north). The program set AREAS consists of the programs PLANAREA STEP (incremental area determination) and PLANAREA CONT (quasi-continuous area determination). The above mentioned measurements can be classified in the CLASSIFICATION program. At the beginning of every program call, the name of the measurement program is printed out as a heading. A measurement program remains active until the next program is started or until the return to PILOT.

The measurement programs of the basic software cover the most important measurement problems for which the STEREOCORD has been designed. The additional program package I (see "EXTENDED SOFTWARE", figure 2), which is available at a surcharge, contains programs for volume determination, for geological, forestry and planning work.

Users wishing to write their own measurement programs will find the fundamental information required for the purpose in the Operating Instructions delivered with the STEREOCORD.

ABOUT THE ACCURACY OF THE S T E R E O C O R D SYSTEM

To prove the accuracy of the measurement system of the STEREOCORD a pair of grid plates has been measured stereoscopically. The precision of the grid itself has been checked previously by measuring 15 points of the left-hand and the right-hand grid plate in a monocomparator PK 1. The resulting standard errors of the X and Y coordinates have been found as follows: $\sigma_{X,Y} = \pm$ 1.6 µm (left) and $\sigma_{X,Y} = \pm$ 1,8 µm (right). These errors can be neglected in comparison with the accuracy of the STEREOCORD.

Two series of stereoscopical grid measurements have been made on the STEREOCORD. The results are shown below:

Accuracy of the STEREOCORD (checked by stereoscopical grid measurements)						
Series	Number of control points	Number of check points	Results			
			control points		check points	
			μ_{xy}	μ_h	μ_{xy}	μ_h
1	6	9	23µm	24µm $\hat{=}$ 0,016% hg	31µm	30µm $\hat{=}$ 0,020% hg
2	6	39	22µm	23µm $\hat{=}$ 0,015% hg	31µm	28µm $\hat{=}$ 0,018% hg

The following table shows some test results of practical orientations with paper prints on the STEREOCORD:

Test objects ▶ / Data	Eichstätt	Forbach 1	Forbach 2	Schorndorf
focal length flight height photo scale	153,18 mm 2600 m 1:17000	152,55 mm 570 m 1:3740	152,55 mm 595 m 1:3900	139,60 mm*) 20 m 1:145
φ_1 ω_2 grads φ_2	-1,081 0,298 -0,798	-2,094 1,393 -2,648	-0,377 2,918 -0,955	no relative orientation
$\Delta\Omega$ $\Delta\Phi$ grads	1,282 -0,232	1,825 -2,579	-1,804 3,274	29,923 ◀ -0,319
μ_{xy} m	1,1m=65µm	0,22m=59µm	0,42m=108µm	0,007m=48µm
$\mu_h m \hat{=} \% \cdot hg$	0,7m$\hat{=}$0,027%	0,06m$\hat{=}$0,011%	0,16m$\hat{=}$0,027%	0,014m$\hat{=}$0,07%

+) enlarged paper prints (focal length of the camera = 60,60 mm)
architectural photographs with inclined taking axes (see $\Delta\Omega$◀)!

The results shown above give some impression of the attainable accuracy in practical work with the STEREOCORD system. The root mean squares μ_{xy} and μ_h are, of course, affected by the errors of the ground control, which have not been checked particularly. For the purpose of relative measurements (distances or angles between two points) the accuracy has been checked by D. Ruess and L. Weimper in their final thesis at the "Fachhochschule für Technik Stuttgart". They found that the standard errors of distances or angles are only two times higher than in the precision plotter PLANICART.

FINAL REMARKS

With the combination of instruments STEREOCORD G 2 / DIREC 1 / HP 9815 A an appropriate system for measurement and plotting is provided specifically for problems of quantitative photo interpretation in planning, geology and forestry. The new system of formulae combined with systematic orientation procedures gives a mathematical accuracy which corresponds to the measuring precision of the STEREOCORD. The fast cartridge of the calculator permitted a convenient program organization. Thus the user is relieved of laborious subsidiary works and is able to concentrate himself only with actual measurements. After having acquainted himself with his work in a short time even a beginner for photogrammetry will be able to obtain accurate measuring results.

References:

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