A NEW METHOD OF CALIBRATION FOR ANALYTICAL PHOTOGRAMMETRIC WORKSTATIONS

Wilfried Müller
R&D Photogrammetry

Alain Chapuis
Product Manager

Leica Heerbrugg AG - Photogrammetry & Metrology Unterentfelden
CH-5035 Unterentfelden, Switzerland

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Abstract

A new method for compensation of systematic instrument errors by means of dense correction grids is integrated into the real-time program of the Leica SD line. The factory calibration procedures are based on totally automated measurements of precision grid plates using CCD cameras. This approach permits the use of less stringent tolerances in the mechanical construction than in previous generations of analytical stereoplotters, thereby preventing a growth of the maufacturing costs.

Keywords : Analytical Plotters, System Design, Calibration, Algorithms, Real-Time Program

1. INTRODUCTION

Analytical plotters consist of various mechanical, optical and electronic components. Because of unavoidable tolerances during manufacturing and mounting the measuring system delivers coordinates which do not refer to an ideal cartesian coordinate system as needed in photogrammetric applications. The main sources for systematic deviations (instrument errors) are :

- non-orthogonality of the measuring system axes,
- different scale factors and non-regularities of the scales,
- non-straightness of movements parallel to the coordinate axes,
- hysteresis (drag) errors because of mechanical tensions,
- prejection errors because of deviations from Abbé's comparator principle,
- temperature effects.

In the past manufacturers of high precision analytical plotters tried to keep these errors small by costly mechanical constructions. Usually the remaining errors could be sufficiently compensated by e.g. an affine transformation. Although prices for electronic components have dropped in the last years, a rise of production costs can only be prevented if the mechanical construction can be simplified. The storage capacity and performance of processors used for the real-time control of the photo carriers now allow to compensate larger and higher order instrument errors by more sophisticated calibration functions. In case of the Leica SD series dense correction grids are used.

Since the design of analytical plotters very much influences the calibration procedures, section 2 compares the Kern/Leica DSR and the Leica SD2000. Section 3 explains how instrument errors are compensated in the real-time programm. Section 4 describes the method of automatic measurement with CCD cameras and standard calibration procedures which will be performed for every instrument. In section 5 results from further investigations are presented which are performed from time to time for some instruments.

2. DESIGN OF DSR AND SD2000

The type of correction model for instrument errors and the calibration procedures are very much depending on the design of the analytical plotter. This shall be demonstrated by comparing the design of Kern/Leica DSR digital stereo restitution instrument *(Chapuis, 1984)* and the Leica SD2000 stereo digitizer *(Cogan at al. 1991, Cogan & Hinsken 1992)*.

In both instruments the photo carriers are on top of each other. In the DSR these carriers are driven by spindles. The straightness of movements parallel to the coordinate axes is made possible by cutting two sides of the glas plates at very high precision. The optical system of the DSR is fixed and the measuring marks are injected into beam splitting cubes which are a few milimeters underneath the glass plates of the photo carriers (fig. 1), thus meeting Abbé's comperator principle nearly perfectly. Influences of environment temperature changes are compensated by a special patented construction such that the effect is zero for the center of the photos.

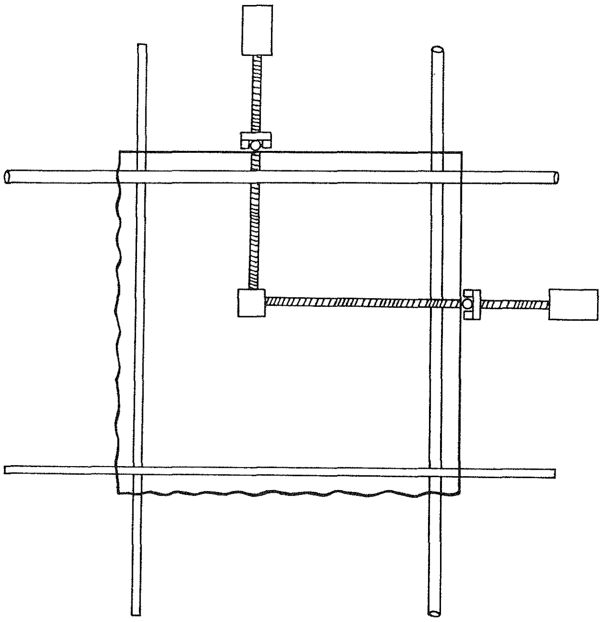

Fig. 1 : DSR driving and measuring system

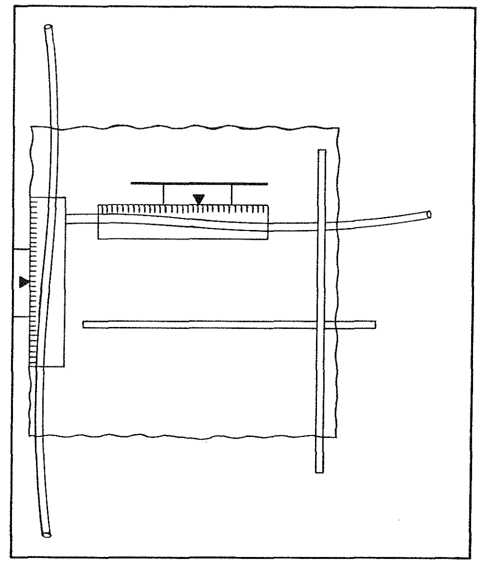

Fig. 2 : SD2000 driving and measuring system

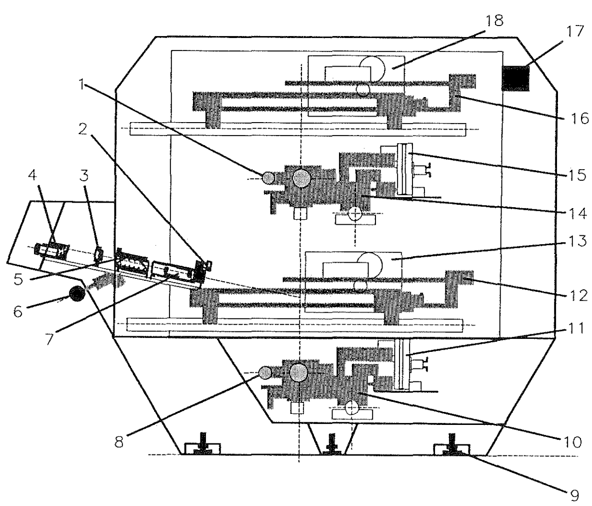

Fig. 3 : Overview of the SD2000

1	Measuring mark left	10	Optic carrier XR
2	Zoom motor	11	Drive XR
3	Centering lens	12	Photo carrier YR
4	Eyepiece	13	Drive YR
5	Dove prism	14	Optic carrier XL
6	Dove prism drive	15	Drive XL
7	Zoom	16	Photo carrier YL
8	Measuring mark right	17	Ventilator
9	Leveling screw	18	Drive YL

It is obvious that this design requires a lot of space for the movement of the carriers and leads to high production costs. In the SD2000 the photo carriers are driven only in y-direction while optic carriers which contain the ilumination- and measuring mark injection systems are moving in x-direction (fig. 2 & 3). This leads to a very compact shape of the instrument. Glass scales and linear encoders are used instead of spindles and rotation encoders. The measuring heads of the encoders are fixed on the steel frame (with exception of the optic carrier of the lower plate). The movements of both carrieres are guided by steel rails. No sharp restrictions were made for the straightness of the guide rails to keep the production costs low. In order to obtain a large field of view of 60 mm at the lowest zoom magnification, the distance between the injected measuring marks and the photo carriers had to be 150 mm. Instead of a welded steel frame a base made of polymer-mineral cement gives the instrument the required stability.

3. Correction of Instrument Errors

In case of the DSR the scale factors and non-linearities of the spindles were calibrated in the factory using a special device. The correction values are stored in a 'spindle calibration file' on the host computer (P1) and are downloaded to the P2 computer together with the real-time program. Since in this way non-orthogonalities of the plate coordinate system axes are not corrected the model setup software package DSR1B contains a calibration program (DSRCAL). It supports measurements of a precise grid plate (5 x 5 crosses, delivered with the instrument) and computes parameters of a conformal or affine transformation between the nominal grid coordinates and the measured 'raw' plate coordinates. The parameters are stored in a 'calibration file' on P1 and are combined and downloaded with the inner orientation parameters.

In case of the SD2000 there are no spindles. The 'spindle calibration file' is replaced by a file named RTP_P2.CAL which is stored on the disk of the P2 real-time processor and contains 'correction grids'. For a dense grid of plate positions (dx = dy = 10 mm) RTP_P2.CAL contains correction values for the x- and y-plate coordinates of the upper and lower plate. The real-time program reads this file at start and computes corrections for the actual plate positions by a bilinear transformation using the correction values for the actual mesh of the correction grids. The way of generating the correction grids during factory calibration is explained in the next section. Here it should be noted that with the correction grids all possible instrument errors are corrected. There is not need to repeat the factory calibration unless one of the guide rails has to be exchanged (which is very unlikely).

With DSRCAL / DSR1B the user has furthermore the possibility to check the accuracy of the instrument. A conformal transformation without scale should already lead to small root mean squares of residuals (< 4 microns). In case of significant global effects upon the axis system there is also the possibility of improving the factory calibration by accepting the results of an affine transformation. Such global effects could for example be very large temperature difference (e.g. > 10^{0} C) between the temperature of factory calibration and the mean temperature in the users office.

4. SD2000 FACTORY CALIBRATION

4.1 Use of CCD Cameras

The grid crosses of a high quality calibration grid plate can be measured either manually or in the case of the SD2000 automatically. The advantages over manual measurements are as follows :

- The measurements are independent from individual pointing accuracies of human operators.
- The accuracy is independent from the number of crosses to be measured, whereas an operator can keep up a high power of concentration for this monotonous work only for a short period of time.
- Each cross can be measured many times in order to mean out inaccuracies caused by the encoder resolution of ± 1 micron.
- For manual measurement of a minimum of 8 x 8 grid crosses (forward and reverse, upper and lower plate) at least 45 minutes are required. The system for automatic measurement can be set up in 5 minutes.
- Measurements can also be done overnight and during weekends, allowing long-term stability investigations.
- Measurements can be done under extreme temperature conditions.

4.2 Hardware Configuration

The system for SD2000 calibration consists of the following hardware components (fig. 4) :

P1 - P1-Processor (386 PC, 20 MHz, 40 MB HD, VGA) running the measurement and analysis programs.
P2 - P2-Processor (386 PC, 20 MHz, 40 MB HD, VGA) running the 'Leica Mapping Terminal' program (Real-Time Loop).
C - 2 CCD-cameras (Phillips NXA 1011) with 25 mm optics fixed in front of the eyepieces using a special mounting which prevents any movements of the cameras.
F - Frame grabber board (LFS-AT from Leutron Vision AG) allowing input from 2 b&w CCD cameras.
M - B&W video monitor for manual measurement of 3 initial crosses.
P - 12 V power supply.
G - Gain control box to distribute the power to 2 cameras and switch off the automatic gain control of the CCD cameras.

Two precision grid plates with 25 x 25 grid croses at a distance of 10 mm are used as reference for the calibration. According to the calibration certificates for the grid plates the root mean square deviation of the crosses from an ideal squared grid is between :

0.4 microns < = RMSX, RMSY < = 0.7 microns

The system is installed in a room which can be temperature stabilized at 1.5^{0} C .

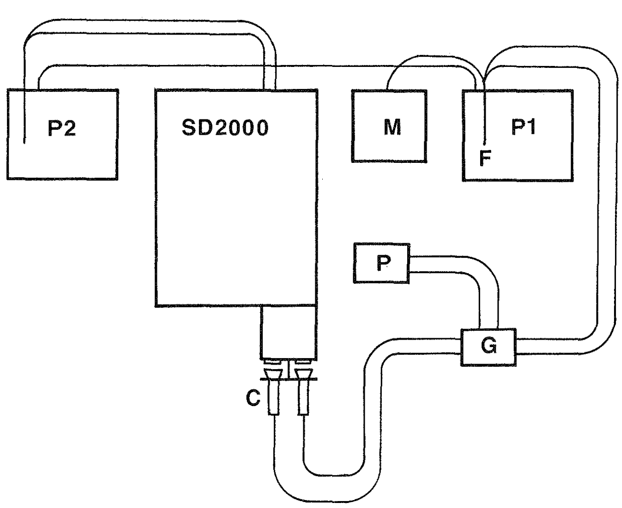

Fig. 4 : System for SD2000 calibration

4.3 Automatic measurement of a cross

Automatic measurement of a cross is a basic function which is used by all calibration procedures described in the following sections. At the beginning of the measurements the CCD cameras are geometrically calibrated, i.e.

the parameters of an affine transformation from video- (pixel-) into plate coordinates and vice versa are determined. However only the scale and rotation coefficients are used, while the shift values are obtained by alternately measuring the center of the cross and the center of the floating mark. For this purpose it is very helpful that the SD2000 allows to set among others the transparent ilumination and the floating mark ilumination to any value between 0 and 100 % by an application program on P1.

The center of gravity is used to compute the location of the floating mark. The pixel coordinates of a cross are derived by computing the axis of the cross bars for each image line (column), representing the axis points by adjusted straight lines and intersecting these straight lines. By means of error propagation it has been found that the mean coordinate errors of the cross coordinates are < 0.05 pixel (< 0.21 microns). The errors resulting from transformation into the plate coordinate system are not bigger than 0.3 microns. The resolution of the encoders of $\pm$ 1 micron finally leads to an estimated accuracy of the cross coordinates of ± 1.5 microns.

4.4 Generation of Correction Grids

In order to derive the correction grids 13 x 13 crosses of the grid plate are measured. A random number generator is used to determine the sequence of the crosses. This leads to a non-uniform movement of the grid plates and thus avoids hysteresis effects. The random number generator works in a way that for all crosses the same number of measurements are obtained. Each cross is measured at least three times, allowing to compute standard deviations for the plate coordinates of the crosses and to eliminate gross errors. If the mean of the standard deviations in x and y is greater than 2.0 microns the measurements have to be repeated.

A conformal transformation without scale (only shifts and rotation) is computed with the measured plate coordinates (source) and the known coordinates of the grid plate (target). The elements of the correction grids are interpolated from the residuals of this transformation. The mean square of the differences rx_i - cx_i resp. ry_i - cy_i is used as an internal accuracy of the correction grids, with rx_i , ry_i being the residuals and cx_i , cy_i the corrections for the plate coordinates of the crosses, computed in the same way as in the real-time program. If the internal accuracy is worse than 2.0 micron, again the measurements have to be repeated but now with 25 x 25 grid crosses instead of 13 x 13 croses.

The correction grids are stored in file SDxxxx.CAL, where xxxx is the instrument number. During installation of the P2 software the file is renamed into RTP_P2.CAL .

4.5 Control of Correction Grids

After installing the file with the correction grids on P2 and rotating the grid plates by approximately 85^{0} an independend control measurement is made to check the quality of the correction grids. The measurements are performed in the same way as the previous measurements for deriving the correction grids with the only difference that now the correction grids are active and the measured plate coordinates are corrected because of instrument errors.

Theoretically a conformal transformation without scale should now lead to residuals of zero. In practice the encoder resolution of $\pm$ 1 micron and small deviations of the grid crosses from a perfectly rectangular grid cause the residuals to be non-zero (fig. 5). The accuracy of the correction grids is accepted if the root mean square of the residuals is less than 3.0 microns. Otherwise both the measurements to derive the correction grids and the control measurments have to be repeated. In case that again the required accuracy is not achieved, parts of the instruments have to be reassembled (e.g. the carriers) or replaced (e.g. encoders). Up to now all manufactured SD2000's have passed this test excellently. For 96 % of the instruments the root mean square of the residuals was even less than 2.0 microns.

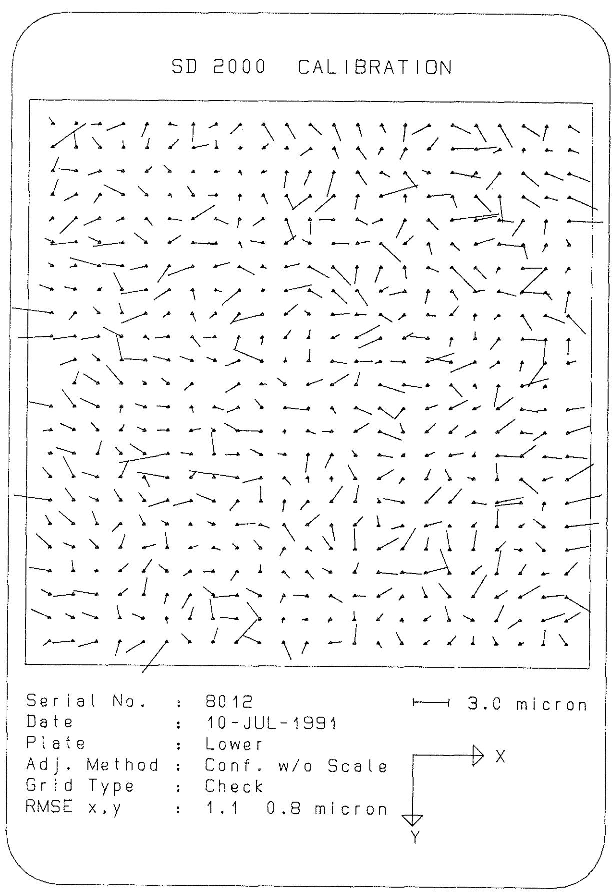

Fig. 5 : Residuals after control measurement

4.6 Hysteresis Effects

Hysteresis effects are present in all instruments with moving mechanical parts. The aim is to design the instrument in a way the effects are as small as possible. The standard factory calibration of the SD2000 includes measurements to check the magnitude of hysteresis effects. Instead of a random movement of the plates, the sequence of the crosses being measured is meandering (fig. 6) . After all crosses are measured once (forward), a further measurement is made in a reverse sequence. These types of measurements are made with the main direction of movement both in x and y.

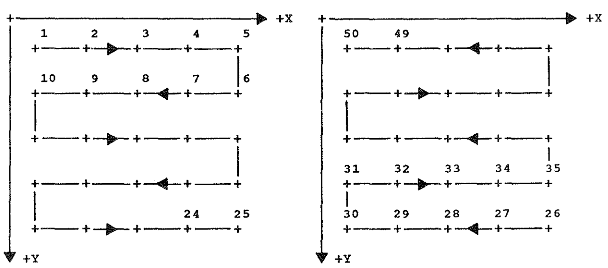

Fig. 6 : Sequence of measurements for hysteresis test

Although the SD2000 does not contain elements with any play or looeseness, significant hysteresis effects are present (fig. 7) . The reason for this is not quite clear. A first assumption was, that an inprecise adjustment of the tiny rolls, which are used to move the carriers along the guide rails, would lead to tensions if the movement is parallel to one of the coordinate axes. But also differences in the acceleration and braking function can lead to momentums which act upon the guide rails. From fig. 7 it can be seen that most of the tensions are released if the direction of movement changes.

An SD2000 will pass the hysteresis test if the root mean square of the differences from forward and reverse measurements are less than 5 microns. Otherwise a reassembly of the carriers will be done. The results from the test represents the worst case which can ever happen. In practice hysteresis effects are of minor importance. During map compilation the floating mark is moved randomly within the photogrammetric model and tensions are not generated. Even when a grid measurement for DTM data collection is performed tensions are released when the floating mark is set on the ground.

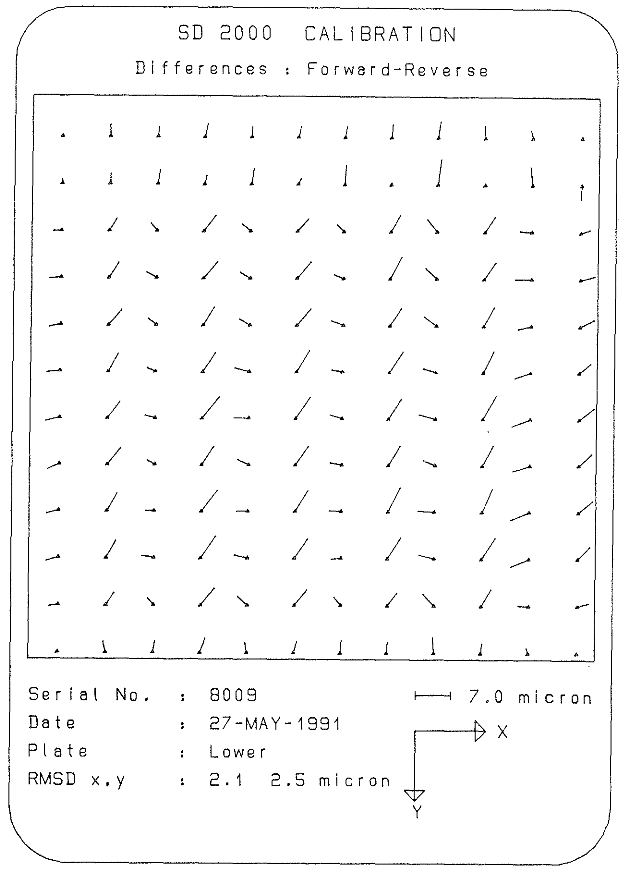

Fig. 7 : Results from hysteresis test

5. Further Investigations

5.1 Warm-up Phase

A problem with previous types of analytical plotters was their instability in the warm-up phase just after switching the instrument on. With some instruments the operator had to wait up to 60 minutes *(Lahio & Kilpelä, 1988)* until the normal accuracy was reached and no more drifts of coordinates could be observed. In the design of the SD2000 special care has been taken to avoid internal heating up of the instrument. The heat generated by the bulbs of the photo ilumination and the drive system has been minimized and will be completely absorbed by a ventilator.

In the measurment program for the factory calibration a warm-up period can be defined. During this period five crosses of the grid plate (corners and middle) are continuously measured in a random sequence and the plate coordinates are stored on file for evaluation on request. Fig. 8 shows the typical behaviour of an SD2000 during the warm-up time. In this plot the differences of the x-plate coordinates against their mean value are plotted. It can be seen that also in the first 90 minutes after switching the instrument on the pointing accuracy is better than 2 microns. The systematic drift of coordinates in the first 15 - 30 minutes is rather small. The systematics for the rest of the warm-up time are even smaller and might also be caused by a change of the room temperature. That means that in most cases the operator can immediately start with measurements.

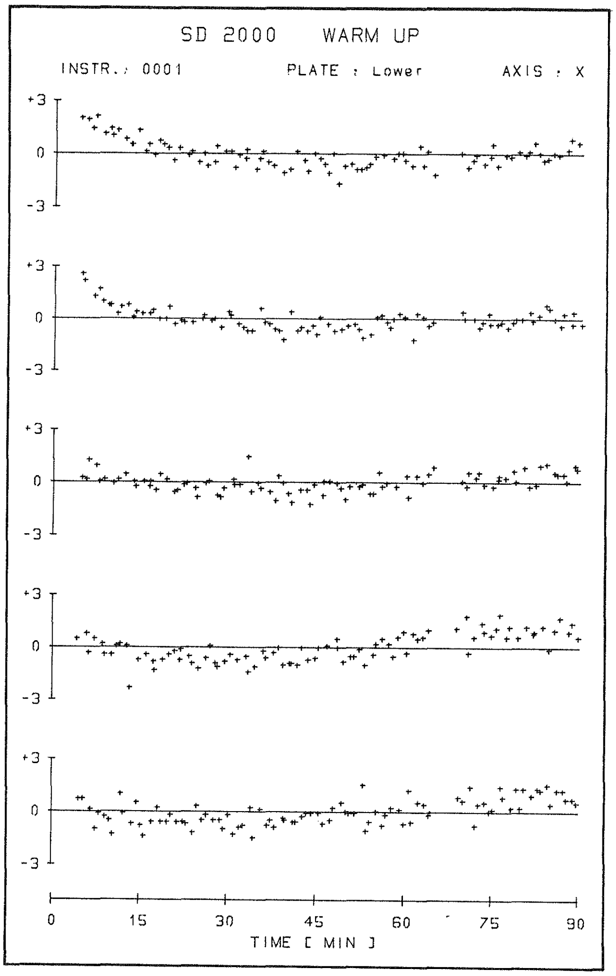

Fig. 8 : Drift of coordinates during a warm-up period

5.2 Influence of Temperature Changes

Any analytical plotter contains parts of different material of which each has its specific coefficient of expansion. In case of the SD2000 these are :

- polymer-mineral cement (base) $12.0 * 10^{-6}$
- steel (frame, guide rails, carriers) $11.5 * 10^{-6}$
- glass (encoder scales) $9.5 * 10^{-6}$

Changes of the environment temperature will be taken over by the instrument but differently fast by the different materials. For two instruments the influence of environment temperature changes has been investigated by performing measurements in a special test room where the temperature could be adjusted from outside and kept stable to ± 0.5° C . For each instrument 4 series of measurements were made where the temperature was changed every two hours by 2° C from 14° C to 34° C resp. from 34° C to 14° C . In a period of 4 hours before starting the measurements, the intruments could adapt to starting temperature of 14° C resp. 34° C . During the automatic measurements the plate coordinates of 5 x 5 grid crosses were continuously registrated.

The evaluation of the aquired data has shown that the changes of environment temperature caused mainly a shift of the origin of the plate coordinate system. For the upper (lower) plate the shift was not larger than 1 (3) microns per ° C . The larger values for the lower plate result from fixing the guide rails for the photo- and optic carrier directly on the polymer-mineral cement base instead of the steel frame as in case of the upper plate. By computing an affine transformation with the mean of coordinates from measurements at 14° C and those at 34° C it was found that there were also small changes of the scale factors. The rotation of the plate coordinate system was not significant. For the lower plate temperature changes seem to be the cruical factor of the SD2000 accuracy. However it should be considered that temperature changes also lead to expansions of the photo emulsion and therefore it must be anyway in the users interest to keep the room temperature as stable as possible. It is clear that the instrument should not be installed in on such a place where it is exposed to the sun (window) or in temperature sensitive areas (radiator). Unavoidable temperature effects can always be compensated by repeating the innner orientation.

5.3 Long-term Stability

Long-term stability tests are performed whenever the production process is interrupted, e.g. in the period between Christmas and New Year, at Easter etc. and during the factory holidays. During this test 3 x 3 or 5 x 5 crosses are continuously measured in an endless loop and the plate coordinates are stored together with a time stamp. The process is terminated by operator intervention on his return.

From the measurements the mean of standard deviations for different time periods (2 h, 4 h, 8 h, 16 h, 24 h) are computed and a check for gross errors or any abnormal behavior of the instruments is made. Up to April 1992 eight instruments have been tested 5 days or longer. Only in one test 3 pairs of false coordinates could be detected. Within a 2 hour period the mean of standard deviations was always smaller than 2.5 microns. Slightly larger values for greater intervals (e.g. < 5 microns for 8 hours) could be traced back to temperature changes.

5.4 Repetition of Control Measurements

With the instruments installed in the demo rooms and laboratories of Leica at Heerbrugg and Unterentfelden, Switzerland, control measurements were repeated approximately every 3 month. Since two years up to April 1992 a reduction of accuracy could not be detected. After conformal transformation without scale the root mean square of the residuals was always smaller than 3.0 microns.

6. ACCURACY OF THE SD3000

In order to fulfill some market demands Leica has decided to further develop the SD2000 into an SD3000 which will be presented at the ISPRS Congress in Washington. The SD3000 will have an improved viewing system with the option to switch between stereoscopic base-in, stereoscopic base-out, monoscopic binocular-left and monoscopic binocular-right. Another major difference is the increased instrument accuracy. This will be achieved by using components from sub-suppliers with better quality and by small changes in the construction of the instrument. It is aimed that an SD3000 has to meet the following accuracy citerias :

a) control measurement -
   root mean square of residuals < 2.0 microns,
b) hysteresis test -
   root mean square of differences < 3.0 microns,

Furthermore it is anticipated that the influence of temperature changes can be restricted to less than 1 micron per 1^0 C .

7. CONCLUSIONS

Although the SD2000 does not use high precision guidings for the carriers and Abbé's comparator principle is heavily violated, the SD2000 has been proven to be one of the most accurate analytical plotters currently on the market. The accuracy is sufficiently good enough for all photogrammetric standard applications such as aerial triangulation, map compilation and DTM data aquisition. This high level of accuracy is achieved by correcting all kinds of instrument errors via dense correction grids and new methods for calibration. The accuracy is proven by strict tests which have to be passed before an instrument can leave the factory. The SD3000 with improved accuracy will be the ideal solution for all applications (e.g. in close range photogrammetry, aerotriangulation) where highest precision is required.

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