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Presented Paper

Dipl. Ing. Joachim Töppler
JENOPTIK JENA GmbH, GDR 69 Jena, Carl-Zeiss-Platz 1

Aerotriangulation with TOPOCART C from Jena.

Abstract:

The considerations and investigations are essentially based on seven requirements which an instrument has to meet, so that it can be used for aerotriangulation by the method of independent models. Major points are the accuracy, the stability of the projection centres both under the influence of phi and omega and over a longer period, the reconstruction of the coordinate system after use of freehand movement and the insurance of a fast relative orientation.

A prerequisite for a stereoplotter to be classified as an equipment being particularly suitable for triangulation work with independent models is that it has to satisfy special requirements to the highest possible degree.

1. The stereoplotting machine must have an accuracy which meets the requirements of the particular tasks.
2. Since in triangulation work the amount of measurement is very low compared with the amount of orientation the equipment should have devices which considerably facilitate model orientation.
3. It must be ensured that the necessary model coordinate measurements can be made in a given coordinate system.
4. Since the projection centres of the plotters are entered into the calculation of the model connections, their determination should be rather simple.
5. During the whole triangulation process the invariance of the projection centres must be ensured or their variations - for example by the utilisation of the base components during the process of relative orientation - must be exactly determinable.
6. So as to record all measuring values the connection of a recording unit must be possible.
7. The left and right photo carriers should be exchangeable.

In the light of these requirements it will be investigated in the following in how far TOPOCART C from Jena (Fig. 1) is suited for triangulations with independent models.

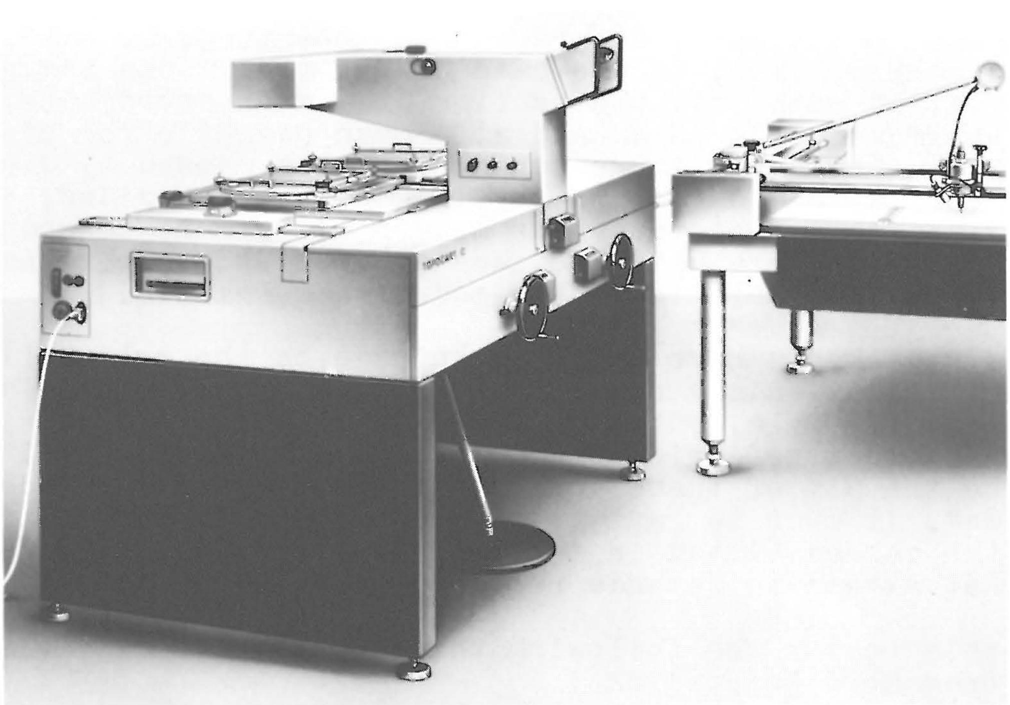

Fig. 1: TOPOCART C Stereoplotter

1. Accuracy

The by far largest percentage of all photogrammetric work still involves the production of line maps or orthophoto-maps. This means, however, in terms of accuracy that generally the mean coordinate error of the drawing in the end product shall not be larger than ± 0.15 mm.

Apart from this planimetric accuracy of the end product the height accuracy to be achieved is of further interest. So as to come to approximate data in this respect our considerations were based on accuracy requirements of the individual map scales for single height points in a terrain with slopes smaller than 10 gon. Since these requirements differ from country to country, a reasonable mean value was used.

A clear survey of the accuracy values is given in Table 1. It is based on three map scales being of interest here; and the photo-flight data refer to an MRB 15/2323 aerial camera. In addition to the data of the image scale and the respective correlated map scale the planimetric and height accuracies are listed illustrating the performance of TOPOCART C with regard to the requirements of practice. From both values a factor is derived, which may be considered as reliability factor giving information on the accuracy reserves of the results.

The accuracy of TOPOCART C defined in this comparison - mean coordinate error of ± 20 µm and mean height error of ± 0.18‰ referred to the photograph - applies to aerial photographic material. It was assumed that an aerial photo restitution is always subject to additional errors, which essentially override the instrumental accuracies as determined by grid measurements; thus, in the case of TOPOCART C the accuracy ascertained with grid plates lies at a mean coordinate error in the image of ± 10 µm and at a mean height error of ± 0.08‰. The error increase is partially caused by distortion, film shrinkage and reduced setting accuracy. Besides, it is an established fact that when modern adjustment methods in triangulations are used the same accuracies are obtained as they are achievable in single model measurements.

A few statements have still to be made on the reliability factor itself. Since not only questions of accuracy play a considerable role, but also economic aspects and, partially, circumstances referring to the particular territory, it cannot be the aim of these considerations to come to a "definite figure". It must be left to the user himself to judge in how far the values listed in Table 1 possess validity for him or to what extent he demands reliability.

For this reason the following three statements of Table 1 are once more pointed out:

1. For each scale mentioned there the reliability factor determined for TOPOCART C is greater than unity both for

the height accuracy and the planimetric accuracy; in other words, there is in any case an accuracy reserve.

2. The planimetric accuracy has more reserves than the height accuracy, which should be noted especially in pure planimetric restitutions.

3. A magnification of the image scale leads of necessity to an increased accuracy reserve.

A general rule is that use can be made of such an instrument for the performance of aerotriangulations which shall also carry out later mapping work.

2. Facilities in orientation work

TOPOCART C - same as its predecessor - has been provided with a freehand movement which considerably helps to accelerate the process of relative orientation. Besides, this type has also for the orientation element omega the same measuring screw as it has already proved most useful for phi tilt. In this way an unproblematic and very sensitive setting possibility offering in addition clear reading has been provided which in conjunction with the other orientation elements allows a quick and straightforward model orientation.

For reasons of the invariability of the coordinates of the projection centres throughout the whole triangulation it is advised here to carry out the process of relative orientation without the utilization of the base components b_y and b_z. Since kappa, phi and omega are available on both sides, this is readily feasible.

3. Restoration of the coordinate system

By means of index marks which can also subsequently be applied in the TOPOCART the exact incorporation, i.e. in the order of 0.01 mm, into the given coordinate system is possible with very slight efforts after conclusion of the model orientation. To this effect, two index marks, one each for x and y, have to be brought into coincidence and under this condition the counters of the recording unit set to certain previously fixed values. Practice-related tests have shown that this is a very reliable and time-saving method.

4. Determination of the coordinates of the projection centres

As will be shown later, the stability of the projection centres in the TOPOCART is so good that during the triangulation work their coordinates have to be determined only at great intervals, so for example after a larger interruption of work or after about 30 to 40 models. The technique which has found world-wide application and which is also recommended by us for this purpose is the determination from intersections of straight lines in space, where equal points at two different levels have to be measured. This problem has already in detail been dealt with in (1), so that only a few additional remarks shall be made in the following.

In the aforementioned publication restrictions were made referring to the position of the measuring points to be used for the determination of the coordinates of the projection centres. These restrictions only apply when the slope angles of the straight-line equations refer to the x and y axes of the spatial coordinate system and go counter-clockwise in the positive direction.

If, on the other hand, the z axis is chosen as reference axis and the rotation is made clockwise, the restrictions referred to above no longer apply and all favourably situated points (Fig. 2) can be used for measurement and calculation. Accordingly, the correction equations have, however, to be changed; they now read

$$v_x = \frac{1}{z_0 - z_2} \cdot dx - \frac{x_0 - x_2}{(z_0 - z_2)^2} \cdot dz + \frac{x_0 - x_2}{z_0 - z_2} - \frac{x_1 - x_2}{z_1 - z_2}$$

$$v_y = \frac{1}{z_0 - z_2} \cdot dy - \frac{y_0 - y_2}{(z_0 - z_2)^2} \cdot dz + \frac{y_0 - y_2}{z_0 - z_2} - \frac{y_1 - y_2}{z_1 - z_2}$$

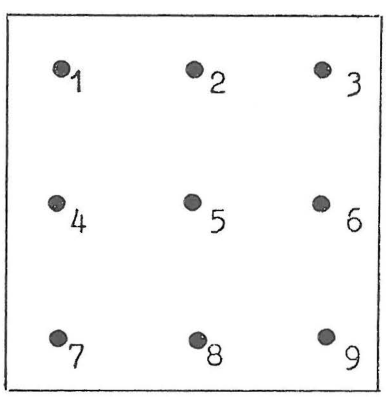

Fig. 2: Arrangement of measuring points for the determination of the projection centres

Variant 1: measuring points 1 through 9

Variant 2: measuring points 2,3,5,7,9

Variant 3: measuring points 1,2,4,5,7,8

On this basis a higher flexibility of the technique discussed in (1) is ensured.

Another point has still to be considered.

The point position given in Fig. 2 calls for a coordinate measurement with the base setting $b_x = 0$, since otherwise the whole image format cannot be traversed. The advantage of such a measuring arrangement is without doubt that favourable conditions of intersection of spatial straight lines in the projection centre are produced. The disadvantage, however, is that in the transition to the measurement of aerial photos a base has to be introduced again, which on its part might bring uncertainties into the previously determined coordinates.

Each introduction of a base component b_x leads, however to a reduction of the x coordinate range and thus to restrictions regarding the x and z coordinates.

With a desired image:model scale ratio of 1:2 and 60 % overlap this practically means for a wide angle camera with 152 mm c.f.l. a model base of about 180 mm. If now at least the half image format is required to be available in the direction of the x coordinate, the shortest projection distance, which can be used is z = 250 mm. Hence, for TOPOCART C with z_{max} = 350 mm the resulting delta z is only 100 mm. Thus, while the "whole image" method both in x and in z can within the equipment ranges be used almost unrestrictedly, the "half image" method is subjected to limitations which have to be considered.

In this connection it is now of interest, to which degree both methods differ with respect to accuracy. For this purpose a comparison of the following variants shall be made (see Fig. 2):

Variant 1:

- All nine points are used for measurement.
- The equipment ranges are optimally used, so that the measurements are made with the following settings:

b_x = 0 $x' = y' = \pm 100$ mm

z_1 = 150 mm

z_2 = 350 mm Δz = 200 mm

Variant 2:

- Same as Variant 1, but referred to the measuring points 1, 3, 5, 7, and 9

Variant 3:

- The measurements are made with the base introduced.
- Points 1, 2, 4, 5, 7, and 8 are measured with
- the equipment settings

b_x	=	180 mm	x'	=	0 and + 100 mm
z_1	=	250 mm	x''	=	0 and − 100 mm
z_2	=	350 mm	y'	=	y'' = $\pm$ 100 mm
Δz	=	100 mm			

For these three variants the weighted coefficients of the unknowns were ascertained on the basis of Equations (1) and (2) and compared with each other, from which the following ratios can be derived:

	Variant 1		Variant 2		Variant 3
Q_{xx}	1	:	1.3	:	1.4 (1.7)
Q_{yy}	1	:	1.3	:	1.2 (1.5)
Q_{zz}	1	:	1.2	:	1.5 (1.8)

This comparison has, however, only full validity, when the same standard errors of unit weight can be expected from all three variants. However, this cannot be assumed. For example, under the condition of constant measuring errors the error of the result increases by a factor of 2.5 when the delta z range is reduced to the half. Because of the low share of the measuring error in the total error it is however not the full amount of magnification that will enter into the result. From comparative investigations an increase in errors by 1.5 times must be expected in the present case, so that for variant 3 the bracketed values are obtained.

Summing up these considerations we can state that for error-theoretical and also economic reasons preference should be given to variant 2. In TOPOCART C it is, of course, also possible to make the necessary measurements with introduced base.

5. Invariability of the projection centres

So as to come to findings regarding the behaviour of TOPOCART in respect of the stability of projection centres measurements were made with the aim of determining the wanted coordinates with different settings of phi and omega. Since, however, large slopes affect very essentially the measuring range of the individual coordinates, these measurements could not be made with the equipment setting which with variant 2 in the previous Section was found to be the most favourable, but a less advantageous setting had to be chosen; mainly the delta z range was affected which had to be reduced to 120 mm. Thus, the accuracies achieved do not correspond to those which would be optimally possible.

It is clear from what has been said above that the projection centres of the TOPOCART have an excellent stability and that scarcely a systematic influence of phi and omega is noticeable. Last but not least, this positiveresult must be attributed to the principle of solution applied in the analogue calculator of the TOPOCART using plane rods which in their working movements transmit scarcely noticeable forces to the projection centres.

The mean error of a single determination referred to the mean value as a characteristic quantity of stability covers

a range from ± 8 µm to ± 13 µm for the planimetric position and

a range from ± 12 µm to ± 17 µm for the height.

Besides this stability test relative to the influence of phi and omega serial measurements were also made with the aim of proving the invariability of the projection centres as well as the stability of the equipment at all over a longer period. So as to provide almost practical conditions the normal orientation and measuring work was carried through between the single necessary measurements; in this procedure use was made of the freehand movement together with the technique described under 3. for restoring the coordinate system and different base sizes were applied. Thus, the results achieved in this way over a period of 19 days correspond to those which would have been obtained under practical conditions. The measurement was made after variant 2 with phi and omega approaching zero. The results obtained are shown in Table 2. They prove once more the excellent stability of the whole equipment system also under the circumstances described above.

All these facts may be considered as evidence that the equipment and its projection centres are stable to an order of magnitude, which is equivalent to the equipment's accuracy referred to the photograph or even better.

6. Connection of a recording unit

Same as all plotters from Jena also TOPOCART C has facilities for the connection of modern electronic recording units, as e. g. COORDIMETER G of our own production.

7. Exchangeability of photo carriers

The photo carriers of all Topocart types are exchangeable, so that in the course of triangulation the centred photograph in a picture carrier can be used as the left or right image of a model.

Practical results

a) A TOPOCART B plotter installed in Canada was used for investigations relative to the stability of its projection centres. In the angular range of ± 2 gon for phi and omega 10 and 6, resp., measuring points distributed across the whole image format were measured in two z planes differing by 150 mm in nine different equipment settings for the left and the right centre. The following mean errors for a single determination were achieved with reference to the mean value.

Left plotting camera

	m_{x_o}	m_{y_o}	m_{z_o}
10 measuring points	± 3 µm	± 3 µm	± 6 µm
6 measuring points	± 3 µm	± 3 µm	± 8 µm

Right plotting camera

	m_{x_o}	m_{y_o}	m_{z_o}
10 measuring points	± 4 µm	± 3 µm	± 9 µm
6 measuring points	± 5 µm	± 2 µm	± 9 µm

Also this result proves that the TOPOCART has very stable projection centres. It further shows that no significant accuracy differences exist between the use of 10 or 6 measuring points, so that 6 measuring points may already be considered as optimum.

b) Also in Canada, but with TOPOCART C, a test triangulation was made with 100 models; use was made of wide-angle photographs of the scale 1:8800 flown for the map 1:2000. Block adjustment was carried out under two aspects:
1. Consideration of the projection centres which had repeatedly been determined in the course of triangulation.
2. Adherence to the projection centres which had been once determined at the beginning of triangulation for the whole block.

The following accuracies referred to the image or the flying height, respectively, were obtained (the bracketed values apply to 2.)

	$m_{x'}$	$m_{y'}$	$m_{z'}$	Point number
- Residual errors of tie points in contrast to geodetic points	± 25.2 µm	± 15.7 µm	± 0.16 ‰	23 planimetric points
	(± 25.2 µm)	(± 15.7 µm)	(± 0.16‰)	65 height points

Of interest are in this connection the results obtained with the STK 1 of the same photo material, reading as follows for the previous last line:

± 19.9 µm   ± 14.4 µm   ± 0.15 ‰.

The results shown here speak for themselves and in favour of the TOPOCART. When considerably higher accuracies have been obtained elsewhere, the reason of this lies primarily in the technique, but less in the equipment used.

Map scale M_k	Image scale M_b	$M_k:M_b$	Height accuracy: 0.18‰ of flying height	Height accuracy: Mean error of single points	Height accuracy: Reliability factor	Planimetric accuracy: 0.15 mm referred to the image	Planimetric accuracy: Reliability factor at 20 µm image accuracy
1: 2000	1: 9000	1:4.5	± 24 cm	± 30 cm	1.2	± 33 µm	1.6
1: 5000	1:12000	1:2.4	± 32 cm	± 65 cm	2.0	± 58 µm	2.9
1:10000	1:17000	1:1.7	± 46 cm	± 110 cm	2.4	± 83 µm	4.2

Table 1:

Survey of the accuracies demanded by the individual map scales in comparison with the efficiency of TOPOCART C from Jena. All values are based on restitutions of aerial photographs and refer to a 15/2323 wide-angle camera.

		m_x	m_y	m_z
Left plotting camera	a)	± 0.010 mm	± 0.010 mm	± 0.014 mm
	b)	± 0.010 mm	± 0.010 mm	± 0.012 mm
Right plotting camera	a)	± 0.013 mm	± 0.009 mm	± 0.017 mm
	b)	± 0.011 mm	± 0.008 mm	± 0.014 mm

Table 2:

Results of the stability tests of the projection centres. Mean errors of the single determination referred to the mean value for

a) image tilts in the range of ± 4 gon and
b) 10 measurements spread over 19 days