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Metric or Non-Metric Cameras

Non-metric cameras may be sufficiently accurate if narrow cone angles, and analytical methods are employed.

(Abstracts on next page)

INTRODUCTION

VARIOUS PROBLEMS in engineering require high precision measurements. In many cases photogrammetric methods have proved to be extremely useful. Special advantages of this measuring technique are its high precision and great versatility; furthermore, the object itself is not touched by the measuring tool.

Special cameras (mono- and stereocameras) and measuring devices (Wild A-40, Zeiss Terragraph, and others) have been developed to take and restitute the photographs. These instruments are conceived for the production of plans, profiles, or contour maps and demand very few numerical computations. The restitution instruments can be considered as analog computers and are constructed for specific camera arrangements. These limitations simplify considerably the handling of the equipment and permit an efficient operation. In general only photographs with parallel camera axes can be used (e.g., Zeiss Terragraph) and consequently the base-to-height ratio and the accuracy in depth is very limited.

The standard outputs of analog restitution instruments are in a graphical form. Besides the graphical representation of the measurements, digital methods are increasingly used for the description of an object. The data are very flexible and suitable for further processing with electronic computers. Although automatic coordinate registration devices can be connected to analog plotters, it is advisable to use mono- or stereocomparators for the measurements. Comparators offer a higher measuring accuracy than the analog plotters, and furthermore there are practically no limitations for the camera arrangement. Deviations from the normal case of photogrammetry do not cause any time delay in the restitution phase, as the orientation of the stereo model is achieved analytically by the computer. Consequently, convergent photographs can be used without restrictions, and systematic errors of the picture coordinates caused by lens distortion, film shrinkage, etc. can be taken into account.

Under these conditions photogrammetric measurements are no longer restricted to pictures taken with metric cameras. This is of great importance because for many applications appropriate cameras are not available, such as in close-range photogrammetry for distances of less than 2 meters. The optical industry has also developed several highly specialized cameras for various applications which can be used for metric applications as well. Then photogrammetric measuring techniques are not bound to specific surveying instruments, which might give impetus to a wider application of these methods.[1]

In this paper the accuracy limitations which are caused by the properties of non-metric cameras are discussed and the differences in application of metric and non-metric cameras are pointed out. In the beginning a definition is given for the term "metric cameras", and accuracy tolerances for the

ABSTRACT: *For a comparison of metric and non-metric cameras the reproducibility of the principal distance and the principal point are of primary interest. Such a comparison should take into account the precision requirements for these parameters. Tolerances for the parameters of the elements of inner orientation can be derived from a fictitious camera calibration. The estimations show that the computed values depend only on the opening angle of the camera and the extension of the test field, whereas the size of the camera format is immaterial. Because the tolerances are much larger for normal-angle cameras than for wide-angle or super-wide-angle cameras, it is suggested that, for precision measurements, cameras with long focal lengths be applied. A comparison of the computed tolerances with the reproducibility of the principal distance and the principal point indicate that non-metric cameras do fulfill the requirements within certain limits. Problems may arise under certain conditions for the principal point. An accuracy discussion also should include the parameters of exterior orientation. For example, an unfavourable base-to-height ratio or vibrations of the stereocamera might reduce the final measuring precision considerably. Under these conditions small errors of the inner orientation are of minor importance. In general, about the same measuring precision can be reached with metric and non-metric cameras. The data processing for photographs taken with non-metric cameras is practically bound to analytical methods, and sophisticated computer programs are needed. Pictures taken by metric cameras can be restituted with analog plotters. Therefore it is more a question of the restitution method than a matter of precision whether metric or non-metric cameras should be used.*

RÉSUMÉ: *C'est le degré de reproductibilité du point principal et de la distance principale qui constitue le critère essentiel d'une comparaison entre chambres métriques et non-métriques. Les exigences de précision importent alors. On calcule donc des tolérances appropriées à l'aide d'une calibration fictive de la chambre. Les résultats dépendent du champ angulaire de la chambre, de la grandeur du terrain d'essai, de la précision des mesures sur les clichés, mais non du format ou de l'échelle photographique. A égalité de champ angulaire, on a donc les mêmes tolérances pour un appareil de petit format que pour une chambre aérienne métrique. Il est conseillable d'employer, pour les tâches photogrammétriques, des chambres non-métriques de champ angulaire aussi faible que possible. Les exigences de précision sont alors plus facilement remplies. La comparaison des tolérances calculées avec leur reproductibilité montre que les chambres non-métriques répondent elles aussi assez bien aux exigences. La reproductibilité du point principal demeure imparfaite, mais elle n'est pas meilleure dans les chambres métriques. Il convient, dans ces considérations sur la précision, de tenir compte aussi des éléments de l'orientation externe. L'article montre sur la base d'exemples pratiques que la précision finale dépend beaucoup plus d'une bonne disposition de la chambre, et de l'absence de vibrations, que d'une orientation interne raffinée. On arrive en général à atteindre avec des chambres non-métriques la même précision qu'avec des chambres métriques. La restitution de clichés non-métriques présuppose à vrai dire l'emploi exclusif de procédés analytiques, alors que les clichés métriques se prêtent à la stéréorestitution. Le choix entre chambre métrique et non-métrique ne dépend donc pas tant de la précision désirée que du matériel restituteur disponible ou préférable.*

ZUSAMMENFASSUNG: *Beim Vergleich von Messkammern und Nicht-Messkammern interessieren primär die Reproduzierbarkeit von Bildhauptpunkt und Kammerkonstante; dabei sollten die Genauigkeitsanforderungen an diese Parameter mitberücksichtigt werden. Mit Hilfe einer fiktiven Kammerkalibrierung werden daher Toleranzen für die Kammerkonstante und den Bildhauptpunkt berechnet. Massgebend für die berechneten Werte sind der Oeffnungswinkel der Aufnahmekammer, die Ausdehnung des Testfeldes und die Koordinatenmessgenauigkeit im Bild. Dagegen kommen dem Bildformat der Kammer und den Abbildungsmassstab keine Bedeutung zu. Es gelten somit zahlenmässig die gleichen Toleranzwerte für eine Kleinbildkammer als auch für eine Luftbild-Messkammer, vorausgesetzt dass der Oeffnungswinkel für beide Kammern gleich gross ist. Wegen der erheblich geringeren Genauigkeitsanforderungen bei Kammern mit kleinem Oeffnungswinkel empfiehlt es sich möglichst langbrennweitige Nicht-Messkammern für metrische Aufgaben zu verwenden. Ein Vergleich der berechneten Toleranzen mit der Reproduzierbarkeit dieser Werte zeigt, dass auch Nicht-Messkammern den Anforderungen grösstenteils genügen. Einige Diskrepanzen ergeben sich bei Nicht-Messkammern als auch bei Messkammern bei der Reproduzierbarkeit des Bildhauptpunktes. Bei derartigen Genauigkeitsüberlegungen sollten die Elemente der äusseren Orientierung nicht ausser acht bleiben. An Hand einiger praktischer Beispiele wird aufgezeigt, dass die Messgenauigkeit am Objekt viel empfindlicher durch eine ungünstige Kammeranordnung oder durch Vibrationen der Stereokammer beeinflusst werden kann als durch eine ungenaue innere Orientierung. Im allgemeinen gelingt es mit Nicht-Messkammern die gleiche Genauigkeit zu erreichen wie mit Messkammern. Die Auswertung von Bildern, die mit Nicht-Messkammern aufgenommen wurden, setzt allerdings die Verwendung analytischer Methoden voraus. Dagegen können Aufnahmen von Messkammern an Stereokartiergeräten ausgewertet werden. Entscheidend für die Verwendung einer Messkammer oder einer Nicht-Messkammer ist daher nicht so sehr die angestrebte Messgenauigkeit als die Wahl des Auswerteverfahrens.*

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inner orientation are computed. These estimates are based on fictitious camera calibrations. The next part deals with the reproducibility of the elements of inner orientation for various cameras, and finally the influence of the elements of the exterior orientation is pointed out.

Characteristic of Metric Cameras

For precision measurements some highly specialized cameras are on the market (Wild P 31, Zeiss-Oberkochen TMK, Zeiss-Jena UMK, Galileo-Santoni, etc.). Their construction differs considerably from amateur cameras, but the differences become less distinct if e.g., the Hasselblad MK 70 is compared with the Hasselblad 500 El, especially should glass plates be used.

By definition a metric camera has a known inner orientation and a calibrated radial distortion.[2] This definition could be misleading, because every camera calibrated by a test field could consequently be considered a "metric camera." Also, the specifications that a metric camera has certain facilities to define the elements of inner orientation does not help very much. In general, the edge of the picture can be used to determine the position of the principal point, and the position of the image plane must be fairly constant, otherwise the picture would get out of focus. Of course the requirements for proper image quality do not cope completely with the requirements for precision measurements. Additionally, with metric cameras one may dispense with facilities to determine the orientation of the camera axis in space or to fix the relative orientation of two conjugate pictures.

Consequently, it should be stated that

photographs taken with *metric cameras* can be used for precision measurements or for restitution in analog plotters without additional control of the elements of inner and relative orientation. The measuring precision should be limited only by unavoidable errors of the photographic material. Furthermore the lens distortion should be small enough so that it can be neglected for plotting on analog restitution instruments.

Tolerances for the Principal Point and the Principal Distance

The tolerances for the inner orientation depend on a number of factors such as the opening angle of the camera, the size of the object, or the type of photographic material to be used (roll film, plane film, or glass plates). Therefore it is not possible to give figures which are applicable under all circumstances. These tolerances will also help to judge under which conditions non-metric cameras can be used for precision measurements without any loss of accuracy.

Such an accuracy evaluation can be performed by a simulated camera calibration. If one assumes that the object to be measured includes control points, then the principal distance, the coordinates of the principal point, and eventually the distortion can be computed. The precision of the calculated parameters is obtained from the system of inverted normal equations. In case the control points are unfavorably distributed, the unknowns are fairly inaccurate. This does not effect the precision of the points to be measured *within* the area defined by the control points, provided that the camera calibration is restricted to the principal distance and the coordinates of the principal point.

The simulated camera calibration has been based on the projection equations of Hallert,[3] extended for the elements of the inner orientation.

$$x' = x'_o + \Delta r'_x + c \cdot \frac{(x-x_o)(\cos\phi\cos\kappa - \sin\phi\sin\omega\sin\kappa) - (y-y_o)\cos\omega\sin\kappa + (H-h_o)\cdot(\sin\phi\cos\kappa + \cos\phi\sin\omega\sin\kappa)}{(x-x_o)\sin\phi\cos\omega - (y-y_o)\sin\omega - (H-h_o)\cos\phi\cos\omega} \quad (1)$$

$$y' = y'_o + \Delta r'_y + c \cdot \frac{(x-x_o)(\cos\phi\sin\kappa + \sin\phi\sin\omega\cos\kappa) + (y-y_o)\cos\omega\cos\kappa + (H-h_o)\,(\sin\phi\sin\kappa - \cos\phi\sin\omega\cos\kappa)}{(x-x_o)\sin\phi\cos\omega - (y-y_o)\sin\omega - (H-h_o)\cos\phi\cos\omega} \quad (2)$$

In the formulae x' and y' are the picture coordinates (measured in the comparator); x, y, and H the corresponding coordinates of the points in the test field; c the principal distance; x'_o and y'_o the coordinates of the principal point; and x_o, y_o, and h_o the coordinates of the projection center. The rotation elements are the swing κ, the tip ϕ, and the tilt ω. The lens distortion is taken into account by $\Delta r'_x$ and $\Delta r'_y$.

The form of the projection equations and the sequence of the axes of the rotation elements is immaterial; it is of importance only that the physical imaging process is approximated sufficiently. The inclusion of the radial distortion or the principal point of symmetry as unknowns would degrade the precision of the estimated parameters considerably. The increase of the variances is then combined with a strong correlation between the unknowns. The high correlation between the orientation elements means that an error of one of these parameters can be compensated by a proper choice of the other variables. This compensation is possible only if at least one of two highly correlated values can be chosen freely.

For the study of the reproducibility of the elements of inner orientation it is assumed that these parameters are considered constant and only the elements of the exterior orientation are variable. Therefore the accuracy estimations should be performed for each orientation element separately. Because the correlation between the principal point and the principal distance is small, this precaution is not necessary for these three parameters, but it would not be correct to introduce more parameters of the inner orientation as stochastic variables.

The size of an object or the size of the test field for a calibration is physically limited by the characteristics of the camera. Its lateral extension is restricted by the opening angle of the camera, and the depth extension in general by the depth of focus. Especially for short imaging distances the depth of focus can be very narrow. Figure 1 gives a survey of the depth of focus for cameras with different focal lengths. It has been assumed for the computation that the circle of confusion should not be larger than 30μm and the smallest admittable aperture stop has been fixed at 1 : 16. These limitations might appear rather narrow but less severe restrictions would cause a serious degradation of the image quality, which is intolerable for precision measurements. Nevertheless the diagram can be used for other values; the resulting depth of focus has only to be multiplied by the factor to the initial values of the aperture stop or the diameter of the circle of confusion.

The accuracy estimation has been performed with a fictitious test field of eight control points. These points were located in the corners of a quadratic prism (see Figure 2). The side length of the prism should be chosen so that it might fill four fifths of the picture format. The height of the prism is variable and is expressed as a fraction of the imaging distance. The computation was stopped when the depth of the fictitious test field was equal to its lateral extension.

Finally a figure for the mean square error of unit weight σ_o must be assumed in order to compute the variances for the principal point and the principal distance. This term σ_o indicates the measuring precision in the picture and can be determined from the residual errors of a camera calibration. According to various experiments[4,5,6] a measuring accuracy of $\sigma_o = \pm 3\ \mu m$ can be achieved with glass plates or plane film, and for roll film a $\sigma_o = \pm 10$ to $12\ \mu m$ must be expected.

The simulated camera calibration was performed on an electronic computer (CDC 6400). The program was run for various focal lengths and opening angles of the camera. The computation showed that the accuracy requirements for the principal distance and the principal point are independent of the focal length and depend only on the opening angle of the camera and the extension of the testfield. This means that the numerical values for the tolerances of the inner orientation would be the same for a small-size camera as for an aerial camera with a picture format of 23 × 23 cm as long as the opening angle of the lenses are the same.

The computed variances are presented in Figures 3 and 4. The graphs show that a high precision for the parameters of the inner orientation is necessary only for objects with considerable depth extension. If the object is fairly flat, then the tolerances for these parameters are obviously less severe. In the extreme case, for a completely flat object and vertical photographs, the values for the principal distance and the principal point can be arbitrary. Deviations from the nominal values are completely compensated by a proper

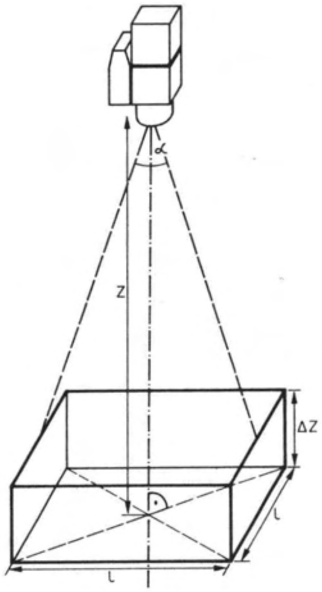

FIG. 2. For the determination of tolerances for the principal distance and the principal point, a simulated camera calibration is used. The figure shows the distribution of the control points and the dimensions of the fictitious test field. Normally the test field has the shape of a cube. For close-range photographs the depth-of-focus can get very narrow. Then the depth extension ΔZ of the test field has to be adapted to the depth-of-focus (α is the angle under which the test field is photographed, Z the maximum distance of the object points).

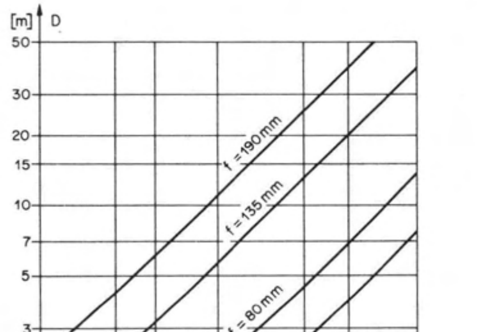

FIG. 1. Ratio between the depth-of-focus and the maximum object distance ΔZ/Z. This value can be used to enter in the graphs of Figure 3 and Figure 4. (admitted circle of confusion, 30 μm; aperture 1:16; *D*, focusing distance)

choice of the projection distance. As the depth of the test field increases, the correlation between the principal distance and the projection distance diminishes and the precision requirements become more severe.

This is of importance for close-range photogrammetry because the depth of focus is very narrow for imaging distances of 2–1 m or less (see Figure 1). Consequently, the depth extension of an object is severely restricted and the accuracy requirements on the parameters of inner orientation need not be so high. Therefore it seems unrealistic to demand special metric cameras for such short imaging distances.

The computed tolerances are surprisingly large for narrow-angle cameras whereas they become very strict for wide-angle and super-wide-angle cameras. The precision of the principal distance should be on the order of ± 0.1 mm for the Hasselblad camera with Planar 1:3.5/100 (c = 100 mm, s = 27 × 27 mm) whereas the tolerance for a wide-angle camera like the Zeiss TMK (c = 60 mm, s = 8 × 10 cm) gets reduced to ± 25 μm for film (σ_o ± 10 μm). The corresponding values for glass plates (σ_o ± 3 μm) are smaller by a factor of 3 and would be ± 30 μm for the Hasselblad and ± 8 μm for the TMK. Therefore, it should be recommended that non-metric cameras are mainly applied with narrow opening angles and, consequently, long focal lengths. The precision requirements for wide-angle cameras are on the order of ± 10 to ± 30 μm for film and ± 3 to ± 10 μm for plates. These tolerances are very narrow and it seems doubtful whether these values are always met by metric cameras.

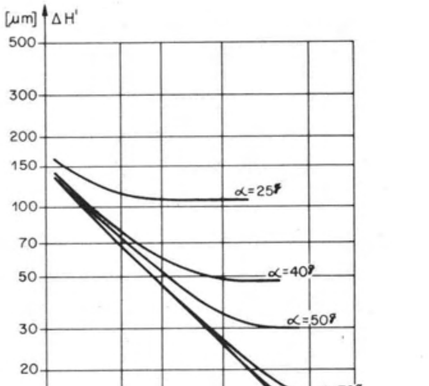

FIG. 3. Tolerances for the mean square coordinate error of the principal point according to a simulated camera calibration. The measuring precision in the picture has been assumed to be $\sigma_o = \pm 10$ μm. α is the angle under which the test field is seen from the camera.

Lens Distortion

The principal distance and the location of the principal point are liable to certain changes from photograph to photograph. These variations are caused by erroneous positioning of the plate or film during exposure. The lens distortion should not be influenced by this effect. Nevertheless the lens distortion determined by a camera calibration might show considerable differences when the calibration procedure is repeated. This is due mainly to a superposition of the lens distortion with various other imaging errors such as atmospheric refraction, film shrinkage, or lack of flatness of the image plane. In general the symmetrical lens distortion can be separated by a study of the reproducibility. The precision of the distortion curve should be at least of the same order as the measuring precision.

An extension of the mathematical model for affinity or for the tangential and asymmetric lens distortion should not be necessary for small- or medium-format cameras[1,7]. The only exception would be for the principal point of symmetry, and it is advisable to control its location in a camera calibration. This point is defined only for lenses with a noticeable distortion (more than ± 5 to ± 20 μm). The precision of this point determined by a camera calibration varies from ± 1 mm

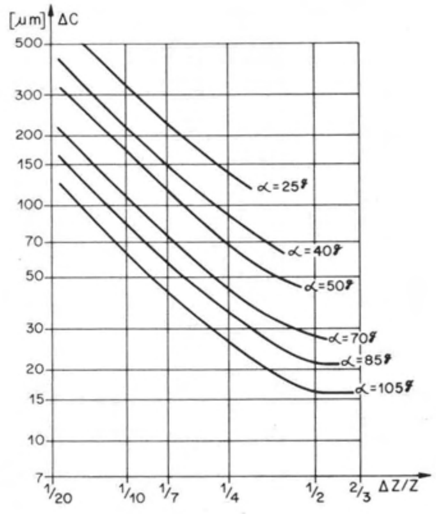

FIG. 4. Tolerances for the principal distance.

for a nearly distortion-free lens (Topogon with ancillary lens and a maximum distortion of about 5 μm) to ± 0.2 mm for the Planar 1 : 2.8/80 mm lens (maximum distortion about 0.4 mm). The definition and the reproducibility of the principal point of symmetry should not cause any problems in a pre-calibrated camera as the tolerances are consequently rather large.

Reproducibility of the Elements of Inner Orientation

The investigations have shown that the tolerances for the parameters of inner orientation are not uniform and that they depend on various factors. Especially for long focal lengths the tolerances are very large and it seems possible that these values could be met even by non-metric cameras. In a photographic camera the position of the image plane is defined by optical conditions. If the photographic material deviates from its prescribed position, then the image quality might deteriorate. For the estimation of tolerances again the circle of confusion can similarly be used as for determination of the depth of focus. For this computation the largest possible aperture stop should be taken into account. For the Hasselblad camera with the Planar 1 : 2.8/80 mm lens a circle of confusion of 30 μm is already reached by a displacement of the image plane of 84 μm for the aperture of 1:2.8. In this case an object point at the nominal focusing distance would be out of focus. From a statistical point of view this deviation should not be reached in 95 per cent or even 99 per cent of the cases. The calculated tolerances for the principal distance have been standard errors (with a significance level of 68 per cent). Consequently, the standard error for the positioning of the picture plane should be only one-half or even one-third of the computed tolerance: that means ± 30 to ± 40 μm.

A positioning error of the image plane in general also will affect the location of the principal point (see Figure 5). With some simplifications the displacement of the principal point can be computed. For the derivation of a mathematical relation it is assumed that the photographic material is completely flat and pressed with its edge against the frame of the camera. Due to imperfections of the contact surface the plate has a varying distance (Δd_u,Δd_l) to the upper and lower edge of the camera. From these differential values the error of the principal point and the principal distance can be computed.

$$\Delta c = \frac{\Delta d_u + \Delta d_l}{2} \; ; \Delta H = \frac{c}{s} \, (\Delta d_u - \Delta d_l) \quad (3)$$

The distance between the two contact points is s and should coincide with the diagonal of the plate format. For the computation of the variances the differential values Δd_l and Δd_u have to be replaced by their standard deviation m_d. According to the law of error propagation one gets the following relations:

$$m_c = \frac{m_d}{\sqrt{2}}; \; m_H = \frac{\sqrt{2} \cdot c}{s} \cdot m_d \quad (4)$$

Thus

$$m_H = \frac{2c}{s} \cdot m_c \quad (5)$$

The computation becomes more complex if it is taken into account that the film or plate in the camera does not form a plane but has the shape of a cylinder or an arbitrary, higher-order surface. Therefore the formula can give only a rough approximation and indicates a certain ratio between the reproducibility of the principal point and the principal distance. For the Hasselblad camera equipped with the Planar 1:2.8/80 lens one would expect an accuracy of the principal point of ± 60 to ± 80 μm according to the assumed variance of the principal distance of ± 30 to ± 40 μm. This computation coincides fairly well with the practical experiences in camera calibration[4,6] (see Table 1, Columns 5,8). The

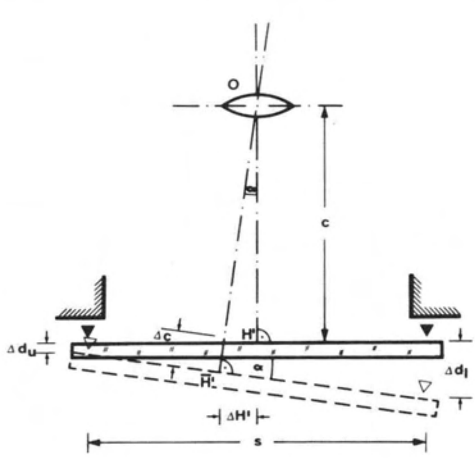

Fig. 5. Falsification of the principal point and the principal distance by an erroneous positioning of the photo plate (ΔH, Δc errors of the principal point and the principal distance; Δd_u, Δd_l displacement of the edge of the plate from the camera frame, and α tilt of the plate).

same estimations should be valid for the larger format cameras such as the Linhof-Technika and the Phototheodolite. The variation of the principal point also should be approximately twice the value for the principal distance. The reproducibility of the principal distance seems slightly less accurate according to the figures in Table 1, which might be due to deformations of the image plate.

A comparison of these figures with the tolerances discussed earlier shows that the reproducibility of the principal distance is rather satisfying whereas the precision of the principal point is adequate only for an assumed measuring accuracy of $\sigma_o = \pm 10\ \mu m$. This is valid for non-metric cameras and to some extent also for the tested metric cameras. Again, the tendency can be seen that narrow-angle cameras are better fitted for precision measurements than wide-angle cameras. Although the reproducibility of the principal point becomes less accurate for cameras with long focal lengths, the tolerance for this parameter increases even more rapidly.

Model Accuracy

The accuracy discussion has assumed that the measuring precision should be limited only by uncontrollable components, such as film shrinkage or lack of flatness of the photographic plate, whereas errors of the orientation elements should be small enough to be neglected. Up to now the discussion has concentrated on the elements of inner orientation, but would be incomplete without the inclusion of elements of exterior orientation. In the following, an example is given in which the overall precision was decisively limited by vibrations of the stereocamera whereas the use of metric cameras would not have contributed to any increase of the measuring precision.

At the Swiss Forest Research Institute an investigation has been undertaken to perform a forest inventory with extremely large-scale photographs taken from helicopters. The task was to measure tree height, stem diameter, and a few other parameters in deciduous woods with the help of stereophotographs. The required precision was ± 1 m for the tree height and ± 1 to ± 2 cm for the stem diameter. The base length chosen could be relatively small because the precision requirements in depth were not very severe and the use of a stereocamera became feasible.

After a few experiments, a base of 4.5 m was adopted, and two Hasselblad 500 EL cameras with Planar 1:2.8/80 mm lenses equipped with film were used; the flying height chosen was 100m (see Figure 6). It was of great importance that the model scale be kept constant within about ± 1 per cent because a signalization of control points seemed unreasonable. The observation of this tolerance proved to be very difficult. Theoretically, scale errors can be caused by a varying base length, an inferior *definition* of the principal point (for the indicated measurements, the principal point used for the reconstruction of the pencil of rays must not exactly coincide with the principal point of autocollimation), and by a variation of the angle of convergency of the two cameras during flight (see Figure 7). To avoid scale errors in the model of more then 1 per cent, the tolerance for the base length would be ± 5 cm, or ± 30 to 40 μm for the definition of the assumed principal point (picturescale 1:1200) and ± 3^c for the angle of convergency. The observation of the convergency proved

Table 1. Comparison of the Tolerances for the Principal Point and the Principal Distance with the Reproducibility of These Parameters for Plate Cameras[4,6]. (A: Non-Metric Cameras, M: Metric Camera, α Opening Angle Computed for a Reduced Plate Format of 80%, the Tolerances in Brackets are Valid for a Depth of Field of $\Delta z/z = 1/10$).

Camera	α	Principal Point			Principal Distance		
		Tolerances		Reprod.	Tolerances		Reprod.
		$\sigma_0 = \pm 10\ \mu m$	$\sigma_0 = \pm 3\ \mu m$		$\sigma_0 = \pm 10\ \mu m$	$\sigma_0 = \pm 3\ \mu m$	
Hasselblad 500 C (A)	34^g	65	20	70	85	25	31
f = 80 mm, 5.5 × 5.5 cm		(100)	(30)		(290)	(87)	
Linhof Technika (A)	36^g	60	18	70	80	24	50
f = 135 mm, 9 × 12 cm		(95)	(28)		(270)	(81)	
Photo-Theo (M)	37^g	55	17	46	75	22	32
f = 190 mm, 13 × 18 cm		(90)	(27)		(260)	(78)	
SMK (M)	69^g	15	5	10	27	8	10
f = 60 mm, 9 × 12 cm		(75)	(22)		(115)	(34)	

FIG. 6. Stereocamera in a helicopter taking photographs for a forest inventory. (A: Base beam, length 4.5 m; B, C: Hasselblad cameras 500 EL)

to be most difficult due to the vibrations of the base beam of the stereocamera. These vibrations were caused by the movements of the rotor of the helicopter and air turbulence. The camera suspension vibrates like a beam supported in its central part. The movements are extremely critical if the vibrations of the helicopter match the self-frequencies of the camera suspension. A great stiffness is necessary so that the bending of the axis of the beam does not exceed the given tolerance, which means that the deflection in the central part should remain within 0.3 mm. Laboratory tests on a vibrating table have shown that a framework in combination with shock absorbers is necessary for the camera suspension whereas a tube would render less favorable results. This effect is due to the better damping property of a framework.

The example shows that it is not useful to discuss the metric behavior of non-metric or metric cameras alone, but the whole camera set-up has to be taken into consideration. In this special case, the application of metric cameras would not have contributed to any increase of the measuring precision because the accuracy limitations originate from a completely different source. The requirements for the depth precision were extremely low in this case, but this is not the rule for photogrammetric measurements and very often this is the limiting factor for the choice of the photoscale.

In several investigations the advantage of convergent photographs compared with photographs taken by stereocameras has been pointed out (see Table 2)[1,6,9]. The increase of precision is considerable and it should be noted that erroneous elements of inner orientation degrade the overall precision less than an unfavourable base-to-height ratio. Earlier, tolerances for the elements of inner orientation were computed. It has been pointed out that the test field should include the whole object so that the determination of the object coordinates can be considered as a sort of interpolation. The point determination gets more critical if the measurements are extended outside the area defined by the control points. The deterioration of the point accuracy can be estimated with the help of the law of error-propagation. The coordinates of an object point are a function of the image coordinates and the orientation elements. The variances of these point coordinates are computed from the linearized determination equation and the variance and covariance matrix of the orientation elements. With the covariance matrix taken from a camera calibration, these variances have been computed for several points within and outside the test field (see Figure 8). According to this estimation the measurements can be extended up to a factor of three outside the

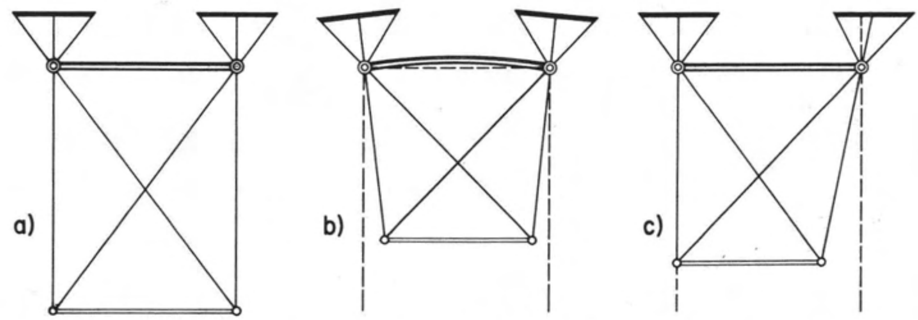

FIG. 7. Factors affecting the measuring precision of distances, in pictures taken by a stereocamera. A convergency of the two cameras (b) or an erroneous definition of the principal point (c) will cause systematic scale errors. For a stereocamera mounted in a helicopter it proved more difficult to get the camera suspension sufficiently stable and to avoid vibrations of the base beam than to reconstruct the principal point in a non-metric camera with sufficient accuracy (see Figure 6).

TABLE 2. MODEL ACCURACY FOR METRIC CAMERAS (PHOTO-THEO, SMK-40) AND NON-METRIC CAMERAS FROM PRACTICAL TESTS.

Camera Arrangement	Convergent Photographs						Vertical Photos
Calibration Reference	Selfcalibration (6)				Test Field (4)	(9)	(10)
Camera	Photo-Theo	Linhof	Hasselblad	Contarex	Hasselblad	SMK 40	SMK 40
Picture scale	1 : 22	1 : 25	1 : 44	1 : 45	1 : 36	1 : 43	1 : 45
Principal distance	204	141	82	53	82	60	60
Base to height ratio	1 : 1.5	1 : 1.5	1 : 1.5	1 : 1	1 : 1.5	1 : 1.5	1 : 6.5
Object size	2.7 × 3.9 m	2.0 × 2.5 m	2.4 × 2.4 m	1.1 × 1.6m	2.0 × 2.0m	2 × 2 m	4.2 × 4.2 m
Number of control points	30	27	22	23	120	64	16
Residual parallaxes (mm)	0.08	0.10	0.14	0.13			
Co-ordinate errors (mm)	0.11	0.10	0.20	0.15	0.19	0.16	0.10
	Co-ordinate Errors Reduced to a Picture Scale of 1 : 20						
m_o (mm)	0.10	0.08	0.09	0.07	0.10	0.08	0.49
m_x (mm)	0.08	0.06	0.08	0.06	0.06	0.05	0.39
m_y (mm)	0.06	0.05	0.06	0.06	0.06	0.07	0.39
m_z (mm)	0.15	0.12	0.12	0.11	0.16	0.10	0.65

area of the control points until the coordinate errors exceed the influence of the unavoidable measuring errors by a factor of two. These reflections point out that the question of metric or non-metric cameras is even inferior to the problem of using a favorable camera arrangement.

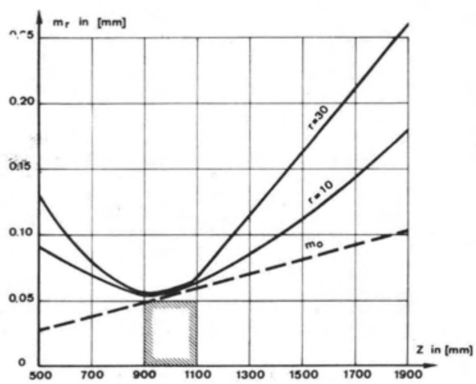

FIG. 8. Estimated planimetric errors in radial direction for photogrammetric point determination. It is assumed that the camera is calibrated by a test field located within the marked area (Z = 900 to 1100 mm). As the depth of the test field is very narrow the precision of the parameters of the inner orientation is relatively low. Nevertheless the influence of these errors is completely compensated within the area of the test field. The measuring precision decreases for points closer to or further from the camera (camera: Hasselblad with Planar 1 : 2.8/80; the calibration was performed with 74 control points and included the radial distortion and the principal point of symmetry; $\sigma_o = \pm 4.4 \mu m$, $m_c = \pm 53\ \mu m$, $m_H = \pm 37\ \mu m$, maximum correlation coefficient 0.95, *r* *r* indicates the distance of the image point from the principal point, m_o the effect of the measuring precision).

CONCLUSIONS

The aim of this paper was to show tolerances for the parameters of inner orientation and to compare these figures with the potentials of various cameras. The differences in precision between metric and non-metric cameras are smaller than one would expect. To a great extent the model accuracy depends on factors other than the use of metric or non-metric cameras. Nevertheless, the application of non-metric cameras is coupled with a number of problems which are not expressed by such figures. The user of non-metric cameras has to calibrate the camera by himself and should investigate the reproducibility of the principal point and the principal distance. Sophisticated computer programs are needed for the calibration of the cameras and for the data reduction of the photographs, whereas for metric cameras the manufacturer delivers the calibration report. Photographs taken with metric cameras can be restituted on analog plotters due to the smaller lens distortion and the controlled relative orientation. Consequently it is more a question of comfort than a matter of precision whether metric or non-metric cameras should be used. But this comfort requires a considerable capital investment.

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(Continued from page 80)

the entire Birdseye Family which feels so greatly honored by the gallant action of the photogrammetric community.

In her place we have the pleasure to welcome one of Lt. Col. and Mrs. Bert Sweigart's eight children, namely Col. Birdseye's grandson, Karl Sweigart, who came to bring us the message of the Birdseye Family.

Postscript:

Following the dedication ceremony at Hopi Pont, an enterprising group consisting of Heinz Gruner, Fred Doyle, and Karl Sweigart, accompanied by a pilot and photographer, took off in a helicopter from the Grand Canyon airfield. They flew down the canyon to Birdseye Point north of the river and circled the point several times, with everybody taking pictures.

—*M. M. Thompson*