SOME ASPECTS OF FORWARD MOTION COMPENSATION IN AN AERIAL CAMERA

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INTRODUCTION

The economics of the entire photogrammetric process is essentially dependent on the information content of the aerial photograph, its interpretability and measurability.

Three basic parameters govern the quality of the aerial photograph: the efficiency of the camera lens, the efficiency of the photographic film as well as the optimum exposure of it including its appropriate further processing. Performance data of an aerial camera, as given in instrument specifications and publications, generally represent an achievable optimum. They are determined under laboratory conditions, where each disturbing influence can largely be eliminated. In practical aerial photographic work, however, a great number of factors have a disturbing influence on the camera and so cause a degradation of quality of the aerial photograph; to this must be added the difficulty in determining optimum exposure parameters.

Essential disturbing factors are the forward motion of the aircraft as well as the vibrations transferred from the aircraft to the camera. In connection with the finite exposure time they give rise to image blurs which may result in a considerable image degradation. Other disturbing influences are of a meteorologic nature. They are merely briefly mentioned here, but are not dealt with in detail. The quality of the image is directly affected by the dust due to its contrast-reducing influence as well as by refraction because of the falsification of the perspective, whereas extreme temperatures and low atmospheric pressure at great heights influence the imaging parameters of the camera's lens. So as to minimize these negative influences on the aerial photograph, particular material combinations are used for the construction of the lenses and lens cones.

When the LMK Aerial Camera System was designed in JENA a twofold aim was pursued: first, optimum conditions of use were created by minimizing the outside dimension and largely reducing the weight and, on the other hand, new functional principles for improving or maintaining the image quality were introduced especially for such instrument units as lens cones and cassettes which have to be

moved by the operator during the flight. The new camera system boasts of having a device for compensating forward image motion and an exposure control on the basis of differential object brightness measurement.
In the following reasons will be given for the introduction of the forward motion compensation into the LMK Aerial Camera System; its technical realization is described and first results of practical tests are reported.

ASPECTS OF INTRODUCTION OF FORWARD MOTION COMPENSATION (FMC)

Under consideration of the basic parameters mentioned at the beginning we may point out three possibilities for increasing the image quality: the improvement of the lens performance, the use of highly resolving film emulsions and the provision of an optimum equipment for determining the exposure parameters.
With the present state of the art of high-performance lenses there is generally no great latitude for further improvements,at least an abrupt enhancement in quality cannot be expected as has yet to be shown.
The film industry, on the other hand, offers photographic materials with considerably increased resolving power, which could, however, so far practically not be used in the field of conventional aerial photography, since because of their low speed long exposure times are necessary. These lead to intolerable image blurs and thus inevitably to the cancelling of the intended effect, namely the increase of the information content. Sufficiently small exposure times have so far been the only possibility of counteracting the intolerably high image motions.
Fig. 1 shows the effect of image motion on modulation transfer and thus the resolving power of an aerial lens. We adopted the representation as used by Brock /1/. Besides the MTF curve of the lens, MTF curves are shown, for which image motion amounts $\Delta e'$ of different sizes were superimposed on that of the lens. For the film emulsion not the appertaining MTF curve has been plotted, but its contrast dependent resolution threshold being related to the film grain. The intersection of appertaining curves allows a prediction of the resolving power for the respective lens/emulsion combination. It is evident that even for a film type of medium speed (Kodak Plus-X Aerographic) as it is generally used and represented here and for image motion amounts as they are today in general actually accepted, an undesirably high reduction of the resolving power is effected. It is demonstrated by the example of the Kodak Panatomic-X Aerographic II that with growing resolving power of the film emulsion the influence of image motion increases so strongly, that

the use of such film emulsions and hence the full utilization of the efficiency of modern high-performance aerial lenses are made possible only by appropriate measures for eliminating image motion.
To which degree the resolving power of the film emulsion has an effect on the lens/emulsion combination is shown by the results of laboratory investigations (Fig. 2), in which the area weighted average resolution (AWAR) of the Lamegon PI 4.5/150 B and Lamegor PI 5.6/300 aerial lenses from JENA was determined by using film emulsions of different speed. As is obvious, an increase of AWAR with decreasing film speed is obtained in the range of 27 DIN to 11 DIN by about 90 % for high contrast ($\log_{10} C = 2.0$) and by about 200 % for low contrast ($\log_{10} C = 0.2$).

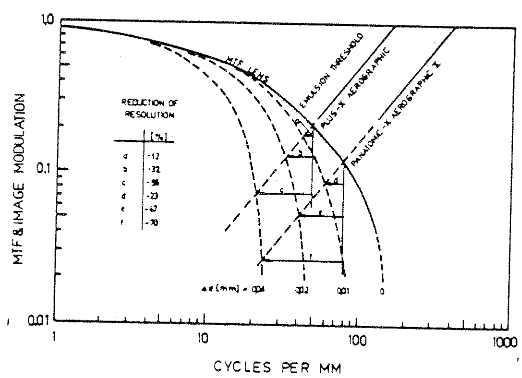

Fig. 1 Effect of image motion ($\Delta e'$) on the resolving power of the lens/film emulsion combination

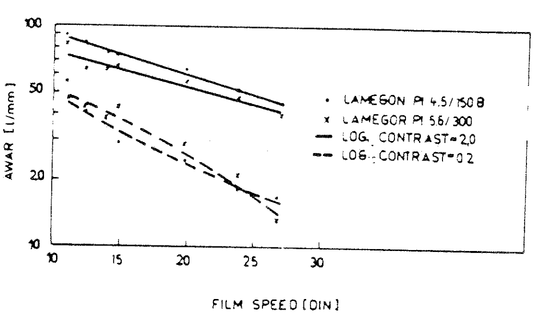

Fig. 2 Effect of film speed on the area weighted average resolution of aerial lenses (laboratory test)

The question remains, how an assumed improvement of lens performance is related to the possibilities of information increase by the use of high-resolution film emulsions. Here, too, a prediction is possible in the above described way. In Figs. 3a) and 3b) a lens A[1] is contrasted with an improved lens B, for which a contrast increase of ≦ 50 % is assumed for frequencies ≧ 30 l/mm. While the representation of the appertaining MTF curves in Fig. 3a) is based on a high input contrast (1000:1), the curve in Fig. 4b) has been plotted for low input contrast (1.6:1), which is of primary interest for practical aerial photography. Superimposed on all curves is an image motion of 0.01 mm (curves A'

1) The diagram shows an area-weighted medium MTF curve of the PI 4.5/150 B Lamegon which is comparable to AWAR in the representation of the mean resolving power.

and B', respectively). This amount probably represents an unavoidable and tolerable residual error, even when an FMC device is used. For three film types of different speed the resolution threshold has been plotted in the way described above. The gain in resolution is represented by arrows and the appertaining percentage values are listed in the Table. One will recognize that when the "standard film" Kodak Plus-X Aerographic is used the improved lens type B in contrast to lens type A leads to an increase in resolving power of about 25 % or 21 %, resp. (arrow a), which due to the assumed image motion is reduced to about 19 % or 16 %, resp. (arrow a'). As compared with this, the resolving power of lens type A with high-resolution films is seen to be increased to a considerably higher degree especially for the low input contrast. The prediction for the High Definition Aerial must, however, be considered with some caution, since the resolution threshold of the film emulsion is known to be no longer linear in the lower region, but approaches the value of the contrast threshold of the eye (roughly between 0.02 and 0.04). Since the values C and, in the case of the low input contrast, also C' were derived in this range, practically achievable values for the combination of the lens with the High Definition Aerial-Film can be expected to lie in each case below those predicted here.

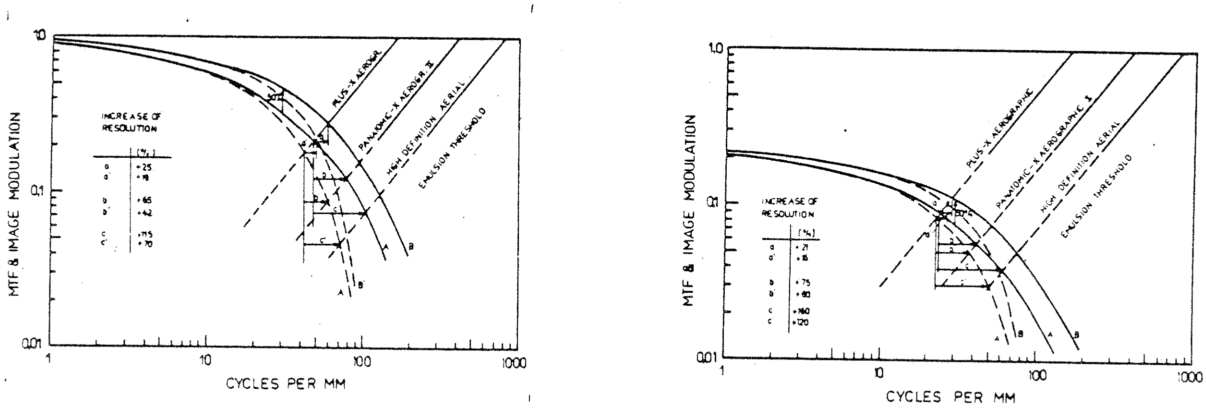

Fig. 3 Possibilities of increasing the information content of the aerial photograph
- by lens improvement or
- by the use of film emulsions with higher resolving power

a) for high input contrast (1000 : 1)

b) for low input contrast (1.6 : 1)

Generally the proof seems to be furnished that through the introduction of forward motion compensation the utilization of the offered high-resolution film emulsions for aerial photography leads to a higher gain than a hypothetic improvement of the aerial camera lenses, if one succeeds in limiting the occurring residual errors of image motion in the order of 0.01 mm.

REALIZATION OF FORWARD MOTION COMPENSATION IN THE LMK AERIAL CAMERA SYSTEM

In the LMK the disturbing image motion caused by the forward motion of the aircraft is compensated in that the film pressure plate together with the vacuum-sucked film is shifted at the same speed as the image in flight direction. The calculation of the compensating speed as well as the synchronization of motion run with shutter release is performed by a microprocessor using the v_g/h_g ratio ascertained in the control unit by means of intervalometric adjustment which has so far merely been used for the realization of the given forward overlap ratio. The maximally compensatable image speed is 32 mm/s. The shift of the film pressure plate represents a rigorous solution being independent of the field angle of the lens, in contrast to the forward motion compensation achieved by tilting the entire camera at the moment of exposure, which is admissible only for narrow field angles. The extra exposure of fiducial marks is performed with an extremely short exposure time at the mid-point of photo exposure. On the one hand, this ensures the sharp imagery of the fiducial marks while, on the other, the conditions of inner orientation of the camera for the whole image contents are strictly adhered to. Maybe the latter is because of the moving information carrier not immediately plausible, but it can easily be verified by a simple theoretical experiment.

The inner orientation of a camera is established by the invariable fixation of the principal point or symmetry point of distortion in the image coordinate system defined by the fiducial marks and serves for the reconstruction of the central projection of the photograph in the plotting process. However, in practical photography a differential multitude of central projections are fixed within the finite exposure period on the film irrespective of whether it has an unvarying position in the image plane as in conventional cameras or whether it is moved synchronously with the image at the moment of exposure. In the blurring figures resulting from the sum of these central projections their centroid is normally taken as measurement reference in plotting, i.e.

Fig. No.	Film	Flying height above ground (feet)	Flying speed (m.p.h.)	Photo scale	Exposure time (sec)	Amount of image motion (mm)	Compensated
4	Double-X Aerographic	1150	155	1:2300	1/500	0.05	no
5	Panatomic-X Aerographic II	1150	135	1:2300	1/125	0.19	yes
6	Panatomic-X Aerographic II	1775	150	1:3550	1/400	0.05	yes
7	High Definition Aerial	3600	150	1:7200	1/70	0.14	yes

Table 1
Parameters of the photographic examples

that central projection is chosen, which was exposed at the mid-point of shutter release. In the case of image motion compensation such blurring figures are of considerably smaller size and generally occur only on objects which are above or below the reference ground plane for which the v_g/h_g-ratio was determined.[2)]
For the imagery of all objects lying within this reference plane the correlation is guaranteed anyway, since the sum of all central projections combined in it in the exposure period also contains the central projection used for plotting, i.e. the one occurring at the mid-point of photo exposure. Hence it is evidenced that the inner orientation in the case of forward motion compensation is fully ensured, when the condition is satisfied that the fiducial marks are exposed at the mid-point of photo exposure. For certain image ranges this condition

[2)] Strictly speaking, the plane for which an exact FMC is ensured, reduces in the multitude of cases to a line due to the unavoidable residual deviations from exact nadir distances.

may perhaps be satisfied even more exactly than with exposures without FMC, since mid-point, and thus positional, displacements in photographs with larger forward motion amounts are avoided on objects with unfavourable contrast distributions as was found out by Mantrow /2/.

A logical consequence of the realization of forward motion compensation is that the high demands placed today on the shutters with regard to their efficiency become practically irrelevant.
The effect of angular vibrations on the image quality remains uninfluenced by the described FMC device. As can easily be realized, only such vibration forms lead to noticeable blurring effects which give rise to tilt motions of the camera during exposure.
Thus, translatory exciting vibrations are detrimental only when they are converted into angular vibrations of the camera, which with sufficient coincidence of centre of gravity and centre of rotation of the vibrating system is largely avoided.
In contrast to this, angular exciting vibrations are in each case converted into angular vibrations of the system; they can only be influenced by the choice of the natural frequency and a suitable attenuation. With a natural frequency of typically 3.5 Hz the LMK is relatively soft-tuned, so that vibrations with frequencies of more than about 5 Hz are efficiently reduced. Frequencies below 5 Hz which essentially result from influences of turbulent air flows and occur as shock vibrations, are forced to decay by additional attenuation elements.

FIRST TEST RESULTS OF THE LMK

The first test flights pursued the main objective of performing basic investigations of forward motion compensation, of the vibration behaviour of the camera and of the automatic exposure system as well as of the gradual optimization of these new facilities. A comprehensive test series was carried out on the initiative of Messrs. J Systems in Mineral Wells/Texas. It was generously supported by Messrs. Kodak/Rochester who supplied a comprehensive collection of aerial films. This made possible especially the use of high-resolution films with low speed; in practical tests and in comparison with "standard emulsions" it could be found out, whether the expectations placed in forward motion compensation on the basis of theoretical prediction would be substantiated. All flights were made with a lens cone which was equipped with the PI 4.5/150 B Lamegon lens type.

The major results will best be illustrated by means of a few selected photographs. So as to enhance recognizability use was not only made of prints at the original image scale but also of enlarged sections with 10 times and 40 times magnification. [3] In all examples the flight direction is from left to right. The major exposure parameters are listed in Table 1.

Fig. 4 shows an exposure on Kodak Double-X Aerographic without compensation of forward motion. The forward motion amount of about 0.05 mm is practically absorbed by the graininess of the emulsion and can only be realized by the blur of the square road marks. The exposure shown in Fig. 5 was made under otherwise equal photographic conditions on Kodak Panatomic-X Aerographic II. The forward motion compensation of about 0.19 mm is fully compensated. The roof of corrugated plate illustrated in Fig. 5c allows a conclusion to be drawn to the realized resolving power, with the roof's structure basically representing an ideal sine test of low contrast. From the negative we derived a wavelength of about 0.025 mm and thus a resolving power of about 40 l/mm, which is approximately in agreement with the prediction made in Fig. 3b) for this lens/emulsion combination. The exposure of Fig. 6 was made on the same emulsion. The compensated forward motion amount is about 0.05 mm. Here a conclusion to the achieved resolving power is possible from both the word "TEXACO" and the structure of the imaged corrugated iron roof. From the letter height of about 180 mm in nature as it was determined from the negative a frequency of about 50 l/mm can be ascertained for the "E" which may rightly be compared to a 3-bar resolution test object. The resolving power as a limiting frequency is to all appearances likely to be higher. In the corrugated iron roof a wavelength of 0.018 mm was measured which corresponds to a resolving power of 55 l/mm. Fig. 7 shows an exposure on Kodak High Definition Aerial. The fact is worthy of note that even at this photo scale (1 : 7200) the square shape of the imaged road marks is scarcely disturbed.
Generally it can be stated that a gain in imaging quality by the High Definition Aerial in contrast to the Panatomic-X Aerographic II could not be ascertained to a degree as it may have been expected due to the higher resolving

[3] These magnification factors may be illustrated by the following example: 10 times corresponds to the mean viewing magnification in stereoplotters or the section of an image of 2.28 m x 2.28 m, 40 times to the section of an image of 9.10 m x 9.10 m side length.

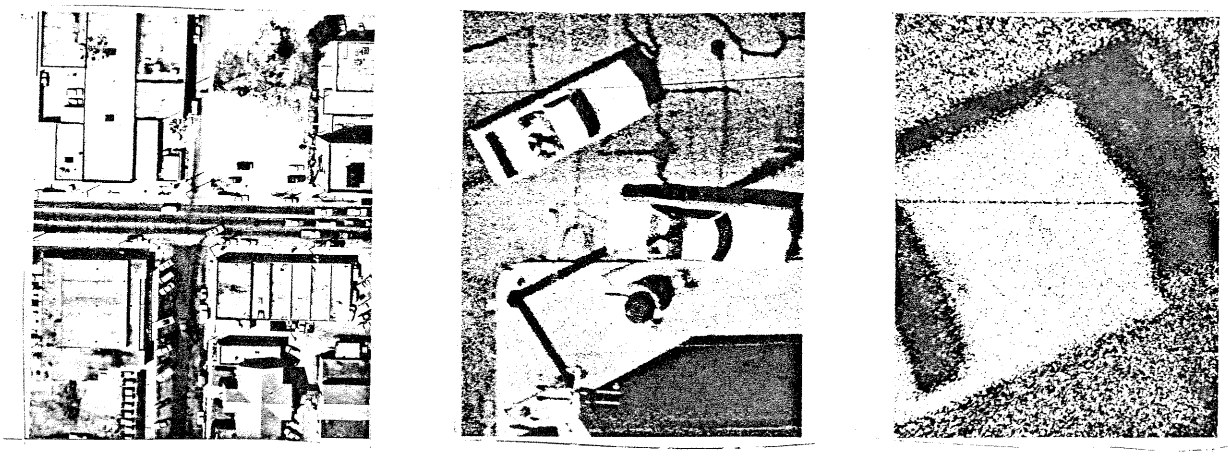

Fig. 4 Aerial photograph on Kodak Double-X Aerographic

a) Original image section b) 10X magnification of section c) 40X magnification of section

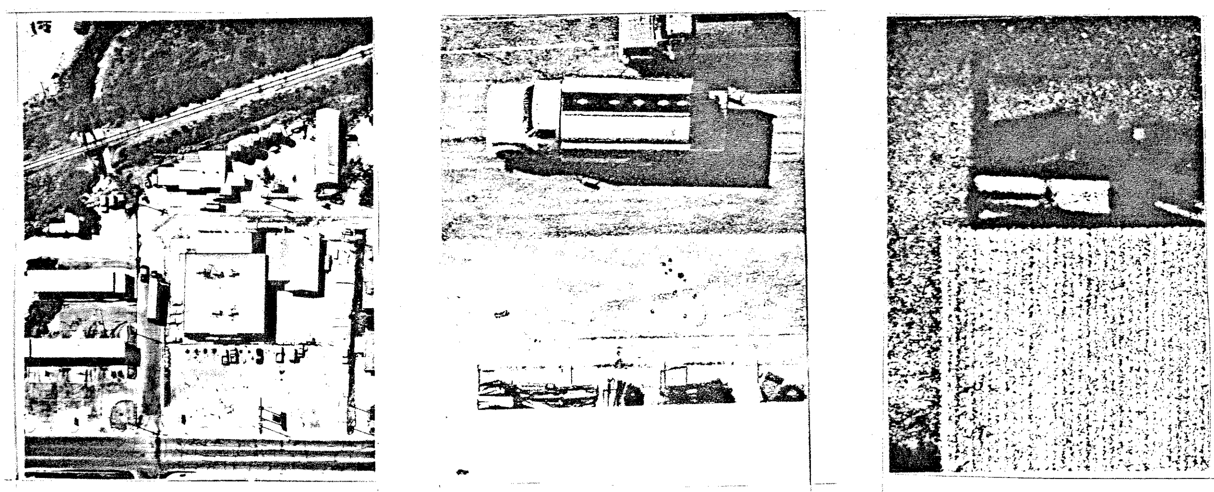

Fig. 5 Aerial photograph on Kodak Panatomic-X Aerographic II

a) Original image section b) 10X magnification of section c) 40X magnification of section

power of 800 l/mm compared with 400 l/mm. Obviously the limits of lens performance make themselves felt in this case. It must be added that the High Definition Aerial owing to its very steep gradation with photographs taken from lower flying heights with inherently larger contrast range offers certain difficulties in the production of positive prints.

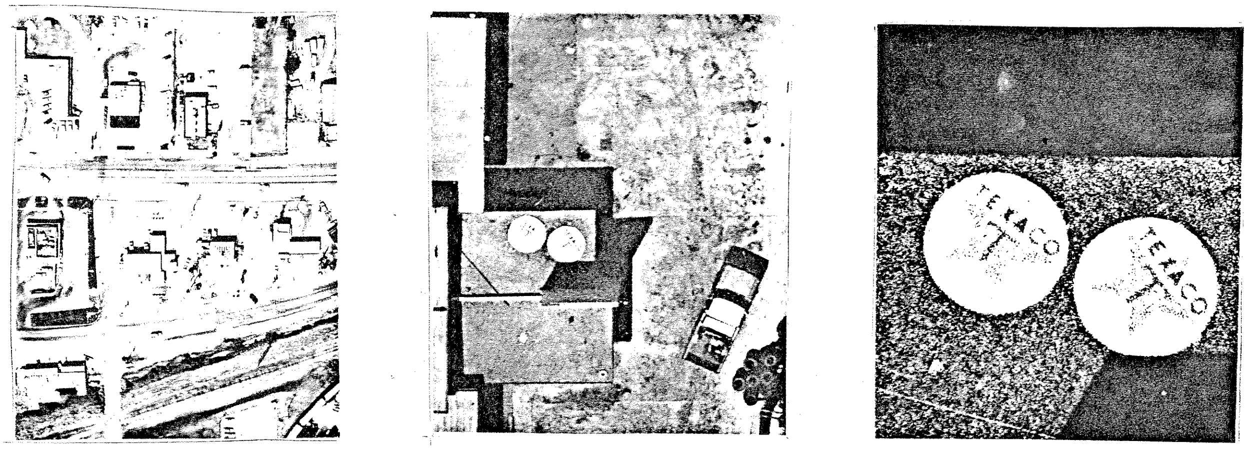

Fig. 6 Aerial photograph on Kodak Panatomic-X Aerographic II

a) Original image section b) 10X magnification of section c) 40X magnification of section

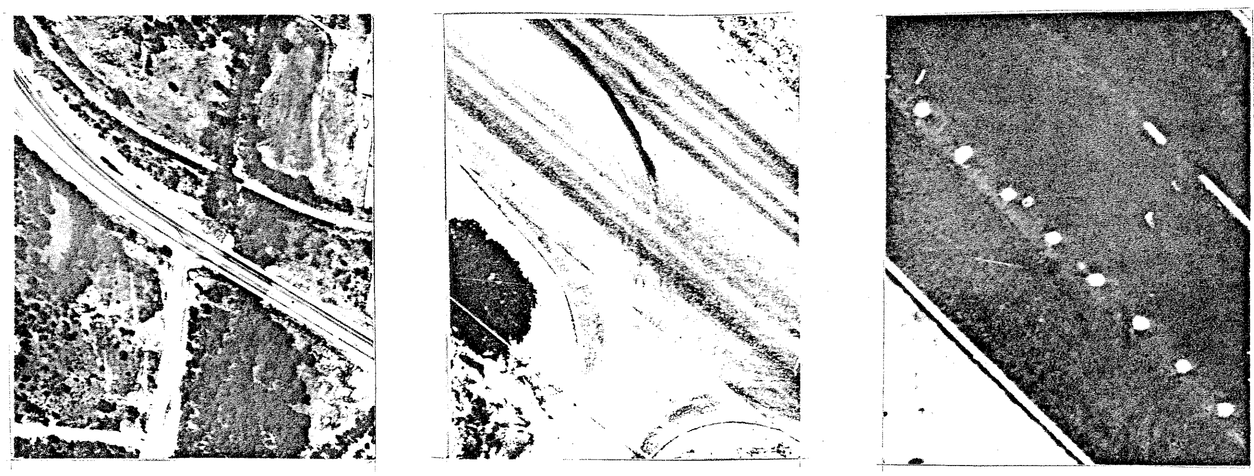

Fig. 7 Aerial photograph on Kodak High Definition Aerial

a) Original image section b) 10X magnification of section c) 40X magnification of section

CONCLUSIONS

The practical advantage of FMC results especially from the essential gain of information through the possible use of higher-resolution film emulsions. Hence the possibility exists to work with smaller photo scales either by taking photographs from larger heights or, where these are limited, by using shorter focal lengths. An increase in economy results in this case from the reduction of the quality of exposures and models to be plotted. If, on the

other hand, the photo scale is retained, the detail recognizability is increased which for large scales leads to a considerable reduction of necessary revision in the field and thus, as is well-known, to an essential increase of economy in the total process. It remains for more comprehensive investigations to find optimum scale ratios for the reasonable utilization of both resulting advantages. Furthermore, one will have to consider, whether the present viewing magnifications in stereoplotting machines suffice for the full utilization of the offered information content.
The useful effect of forward motion compensation is restricted by the amounts of image motion caused by angular vibrations of the camera. Here the practically unavoidable vibrations of the total complex aircraft plus camera produced especially by strong air turbulence and/or unstable aircraft position can have such an unfavourable effect that the long exposure times enabled by forward motion compensation are jeopardized. A remedy may be expected from higher aircraft speeds, i.e. a more stable aircraft position, which had so far not been applicable for cameras without FMC because of the intolerable increase in linear image blur. Owing to the more stable aircraft positions to be expected at larger flying heights the aforementioned restrictions will probably be least there, i.e. the forward motion compensation will in any case be useful in the small-scale range. At low flying heights it may in dependence on the aircraft type and the meteorologic conditions possibly not be recommendable to exceed a maximum exposure time so as to keep the influence of angular vibrations to a minimum; but even at higher-speed film emulsions which might then possibly be used forward motion compensation will in any case be useful thanks to the elimination of the linear portion of image motion.

The subject dealt with in this paper will certainly require further investigations to find the optimum in the interplay of all described effects mutually influencing each other.

REFERENCES

/1/ Brock, G.C. 1970, Image evaluation for aerial photography, London and New York: Focal Press, Chapter VIII.

/2/ Mantrow, A.I. 1981, Einfluß der Bildwanderung auf die geometrischen Eigenschaften der Luftbilder. (Influence of image motion on the geometrical properties of the aerial photographs) Geodesia i Kartographia, Moskau 57, 3, p. 37 - 41.

/3/ Voß, G. and Zeth, U. 1983, Das Aufnahmesystem Luftbildmeßkammer LMK, eine neue Generation von Luftbildmeßkammern aus JENA, (The LMK Aerial Camera System, a new generation of aerial cameras from JENA), Vermessungstechnik 31

ABSTRACT

A new feature of the LMK AERIAL CAMERA from Jena is complete compensation of the linear image motion (FMC) caused by the forward motion of the photographic aircraft. For this purpose the emulsion surface is moved across the image plane in the period of exposure at the same speed as the terrain image itself. The paper is conserned with the increase of the value in use achieved by the FMC as compared with conventional cameras resulting in an expansion of applicabilities.