PROGRESS BY FORWARD MOTION COMPENSATION FOR ZEISS AERIAL CAMERAS

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1. Introduction

Since the introduction of high-performance lenses in the early fifties, considerable progress has been made regarding the quality of aerial photography. Apart from some outstanding advances such as A characteristics, a large number of small improvements have been made and incorporated in series production without much publicity. As a result, the state of the art is today characterized by extremely high correction with respect to definition and distortion /4/.

The same is true of the films which have been improved considerably in dimensional stability and modulation transfer.

However, the end product "aerial photograph" is not only affected by the lens and the film, but also by image motion, i. e. the motion of image points on the emulsion during exposure. This is due mainly to the longitudinal motion of the carrier (aircraft, satellite), but also to nick and roll and to vibration.

To reduce these influences, indirect countermeasures were taken such as increasing the lens speed and reducing the exposure times by means of highly efficient rotating disk shutters. Direct countermeasures have become possible only recently by the advent of advanced electronic forward motion compensation (FMC) systems.

Such a system has been developed for Zeiss aerial survey cameras during the last years and has now become available. The development work and the performance increases that can be achieved with FMC are described in the following.

2. CC 24 Compensation Cassette

The core of the new system developed for Zeiss aerial survey cameras are the CC 24 Compensation Cassette and the CC Con electronic controller. Fig. 1 shows an RMK with CC 24 and CC Con next to it.

Preserving the mechanical and electronic interfaces was of utmost importance. The CC 24 can therefore be used quite unproblematically with any Zeiss RMK aerial survey camera for standard size 23 cm x 23 cm (9" x 9") film instead of conventional FK 24/120 cassettes.

On the electronics side, the same applies if the RMK is equipped with the ICC Interval Central Computer.

Fig. 2 shows how the CC Con connects to the RMK and the CC 24 by means of cables. A signal contact has to be added to existing series RMK, but only minor modification work is involved.

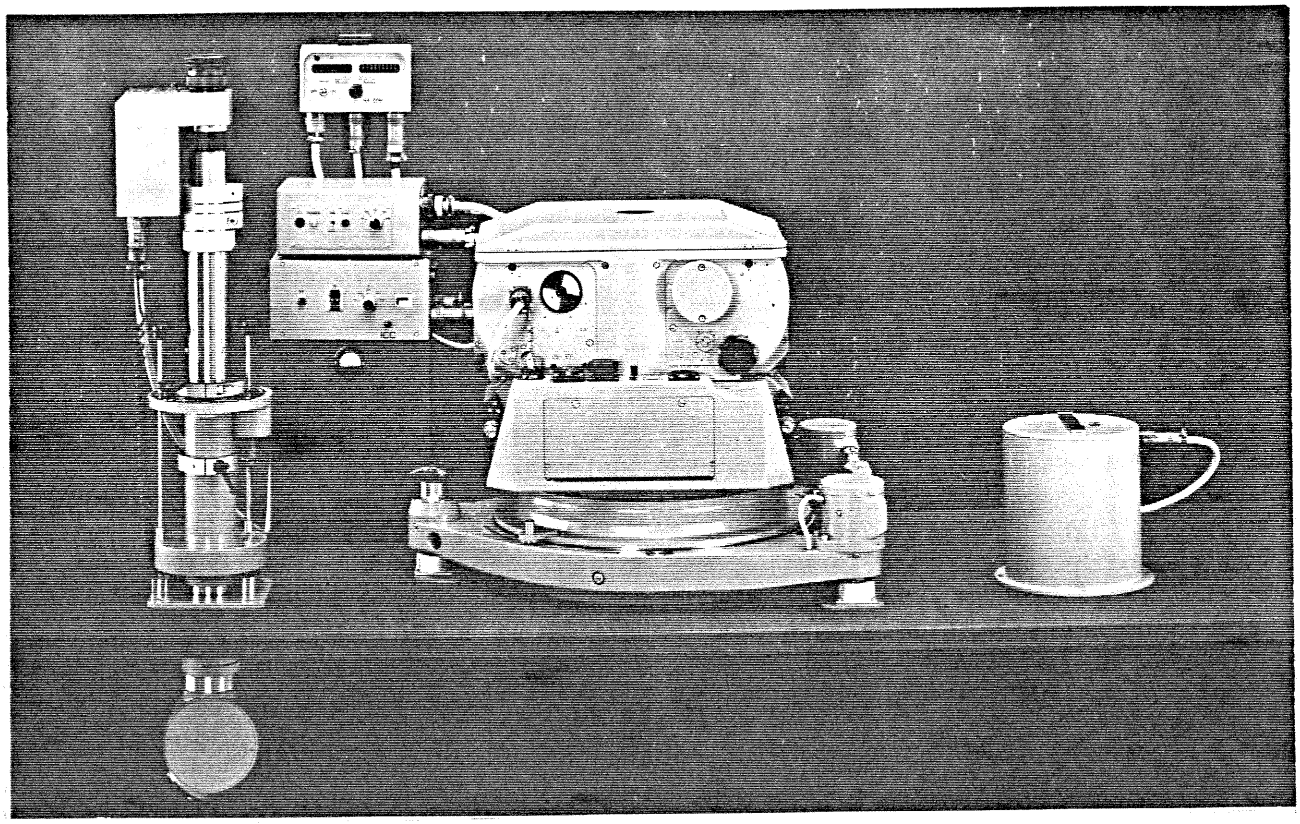

Fig. 1: Zeiss RMK with CC 24 Compensation Cassette and CC Con

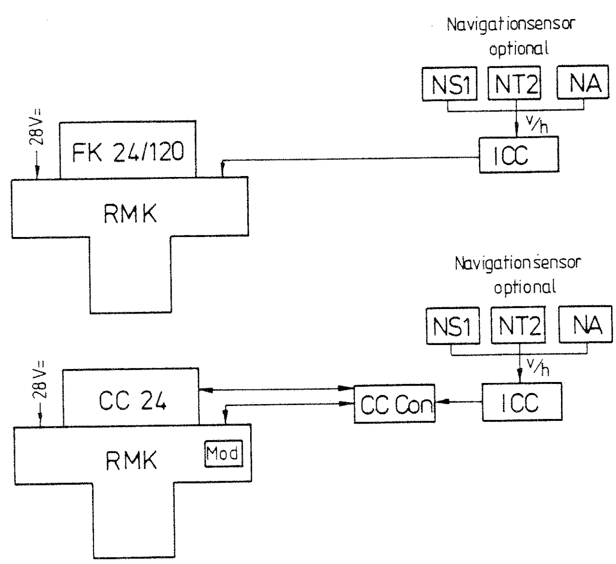

Fig. 2: Integration of the CC 24 Compensation Cassette with CC Con Control Unit in the Zeiss RMK System

The technical data of the CC 24 Compensations Cassette with CC Con are as follows:

Film width	24 cm unperforated (9 1/2")
Film length	120 m for .13 mm film (400 ft, 5 mil)
	150 m for .10 mm film (500 ft, 4 mil)
Film flattening	by vacuum/pressure system in camera body
Film motion	compensated by FMC
- Maximum speed	30 mm/sec.
- Maximum exposure time	1/100 or 1/50 sec.

Operator control is exceedingly easy: The film is inserted as usual. The focal length of the RMK aerial survey camera (8.5 - 15 - 21 - 30 - 60 cm / 3 1/4" - 6" - 8 1/4" - 12" - 24") has to be set at the CC Con, and an On/Off switch has to be operated depending on whether FMC is to be used or not. If required, these settings can be made and changed even during the flight. Finally, careful terrain synchronization is required with the navigation sensor (interactively with the NS 1 or the NT 2, automatically with the NA), because the resulting v/h value now not only affects overlap control but also the FMC film transport speed and thus the photo quality. The selected transport speed is displayed continously by an analog indicator at the CC Con.

3. Photo Quality as a Function of Lens, Film and Forward Motion

3.1 Resolution

The combined influence of the lens, the film and the forward motion on the resolution is given by the following general formula:

$$\frac{1}{R^2_{Total}} = \frac{1}{R^2_0} + \frac{1}{R^2_F} + \frac{1}{R^2_M}$$

where
R_0 is the resolution of the lens,
R_F is the resolution of the film, and
R_M is the forward motion resolution.

The table heading in Fig. 3 contains informations on the resolution of the lens, various films, and different forward motions in lp/mm referred to the image plane. The resolution values listed in the left-hand column were obtained by means of the above general formula for the various combinations indicated in the right-hand columns for high contrast.

The data shows that forward motion, which usually amounts to 20 µm, is currently the weakest link in the imaging chain, and that the resolution can be doubled by means of FMC. However, it also shows that the film then becomes the weakest link. Another considerable increase is possible by abandoning the high-sensitivity 23 DIN/200 AFS film and using the lower-sensitivity 15 DIN/ 40 AFS film, but using the very high resolution 8 DIN/8 AFS film does not yield any significant additional increase.

This intimates that the longer exposure times made possible by FMC allow the use of high-resolution film with a sensitivity that has been too low in the past, e. g. Kodak Panatomic X 2412, and afford considerable quality increases.

R_{Total}	R_0 Lens AWAR 1)	R_F /2/ Film (23 DIN) 200 AFS	(15 DIN) 40 AFS	3) (8 DIN) 8 AFS	R_M Forward Motion 20 µm	10 µm	0 µm
lp/mm	150	100	400	630	50	100	∞
43 ←	X	X			X		
64 ←	X	X				X	
81	X		X			X	
82	X			X		X	
83 ←	X	X					X
140 ←	X		X				X
146 ←	X			X			X

1) AWAR: Aera Weighted Average Resolution

Fig. 3: Combined Resolution of Lens, Film and Forward Motion in Line Pairs per Millimeter (lp/mm)

3.2 Modulation Transfer

The modulation transfer theory is used for a more profound scientific analysis. For this, the modulation transfer functions of the lens (using the area weighted average modulation AWAM 2) shown in Fig. 4.1), of the film /2/ (Fig. 4.2) and of forward motion /3/ (Fig. 4.3) have to be combined in a way that reflects their interaction.

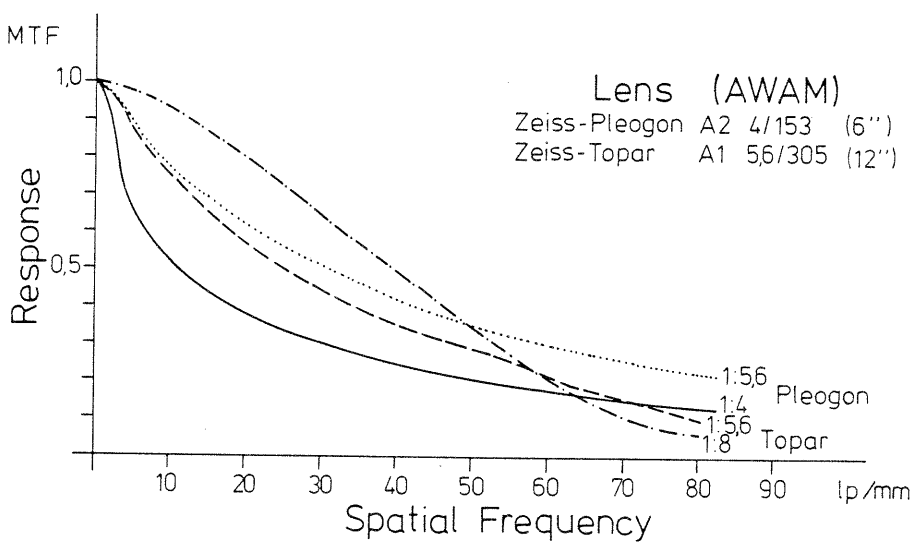

Fig. 4.1: Modulation Transfer of Zeiss Lenses
2)AWAM: Aerea Weighted Average Modulationtransfer

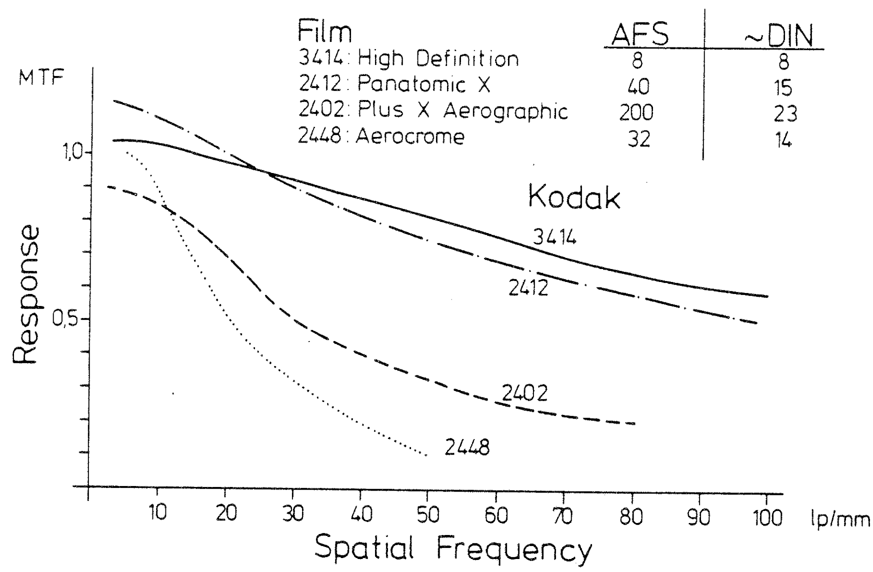

Fig. 4.2: Modulation Transfer of Aerial Film

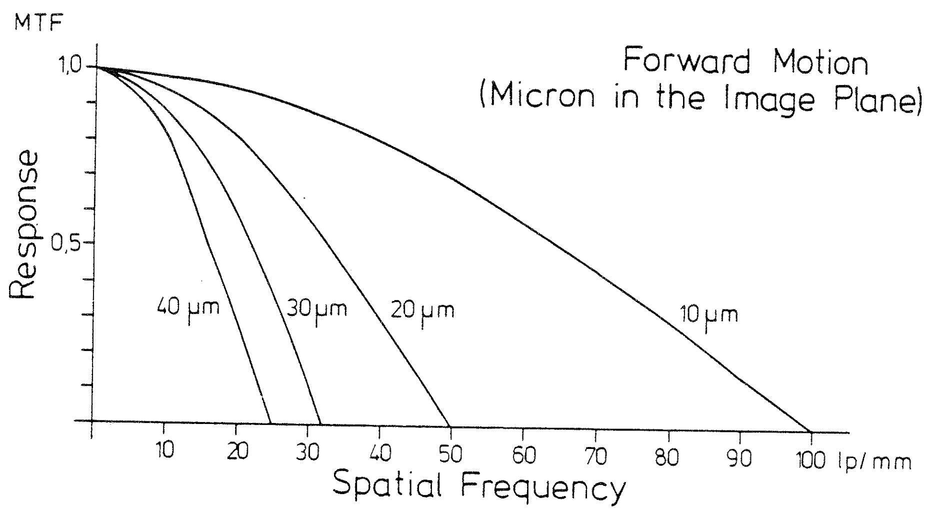

Fig. 4.3: Modulation Transfer of Forward Motion

The resulting overall functions are shown for the Zeiss Pleogon A 2 4/153 (6") wide-angle lens in Fig. 5.1 and for the Zeiss Topar A 1 5.6/304 (12") normal-angle lens in Fig. 5.2 for the maximum aperture and stepped down one f-stop.

The results show that the improvements afforded by FMC alone are rather limited if conventional high-sensitivity film (e. g. Kodak 2402) and the full aperture (Topar A 1 = 1:5.6; Pleogon A 2 = 1:4) are used.

However, when low-sensitivity, high-resolution film is used and the lenses are stepped down one f-stop (Topar A 1 = 1:8; Pleogon A 2 = 1:5.6), the gains are significant.

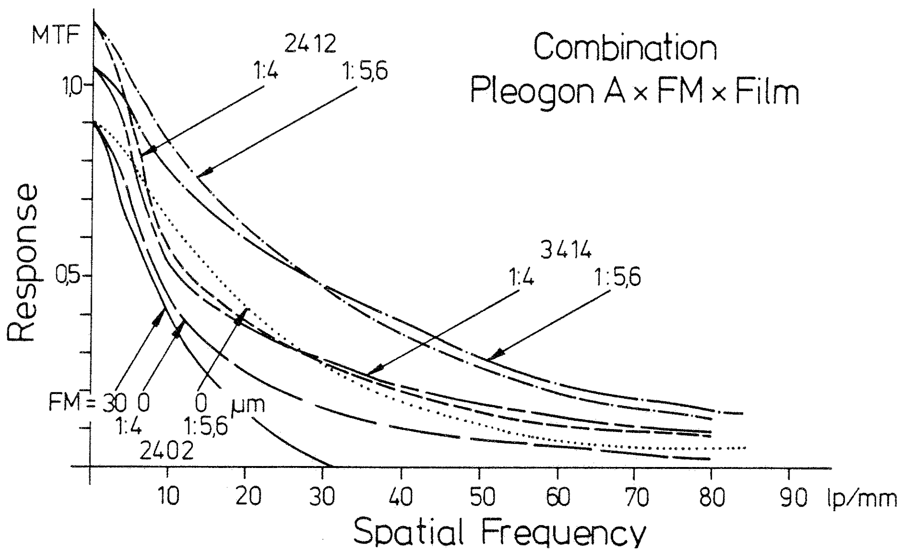

Fig. 5.1: Combined Modulation Transfer 6" Zeiss Pleogon x Forward Motion x Aerial Film

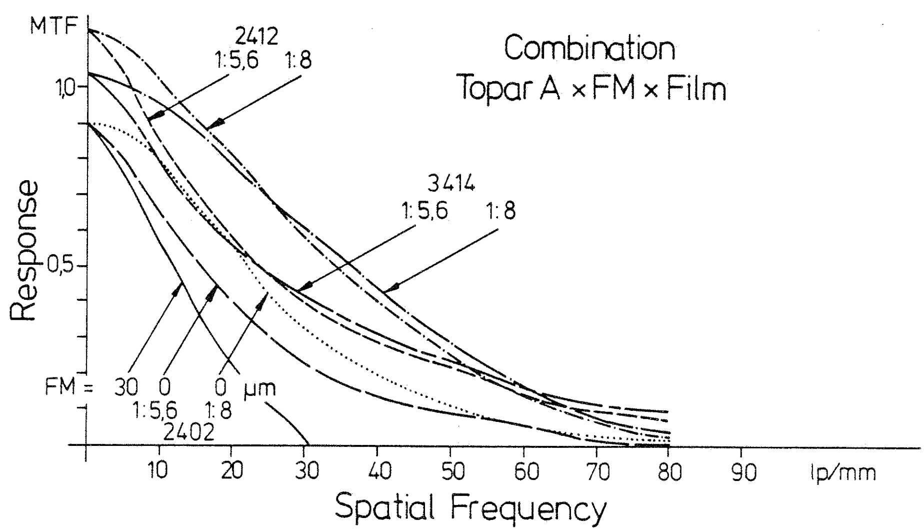

Fig. 5.2: Combined Modulation Transfer 12" Zeiss Topar x Forward Motion x Aerial Film

Only little additional benefits are obtained by the use of very high resolution film (8 DIN/8 AFS, e. g. Kodak 3414) instead of high-resolution film (15 DIN/40 AFS, e. g. Kodak 2412); the resulting loss in sensitivity is not matched by an equivalent quality increase. Therefore, the essential advantage of FMC in day-to-day work is the use of high-resolution film.

In this context it should be noted that there are limits to reducing the sensitivity or increasing the exposure time. The terrain illumination and the maximum exposure afforded by the camera (full aperture, maximum exposure time, no spectral filter) dictate the minimum emulsion sensitivity. Lengthening the exposure time is constrained by the fact that FMC only compensates forward motion, not oscillations and vibration. The adverse effect of the latter increase in proportion with the exposure time extension. Shutter speeds of 1/100 or 1/50 sec. therefore are a lower limit taking into account the focal length.

4. Geometrical Considerations on FMC

Up to now, utmost stability was required regarding film positioning in the image plane of the camera in order to achieve high precision (σ_0 = 3 to 5µm). With the introduction of FMC, however, the film is moved in the image plane; investigations are therefore required on whether and under which conditions this affects the photo geometry.

Publications on this topic are rare. An internal investigation /1/ was therefore made to clarify the basically simple but rather untransparent relationships. Computer-generated "photos" of a synthetic terrain model were used to analytically corroborate these relationships. The results were then checked by means of aerial photos made in summer 1983 with and without FMC and plotted with the Zeiss Planicomp.

The results show that FMC does not adversely affect the photo geometry (central perspective) if

- the forward motion (of the aircraft) and its compensation during exposure are linear and constant in speed;
- the central-perspektive projection center is indicated by fiducial marks in such a way that their location on the moving film defines the perspective at the "center of the exposure time slot" during taking and plotting;
- the center of the object points is set (as usual) during plotting.

Regarding the last point it should be noted that object points are generally not punctiform but linear even with FMC because forward motion and its compensation match only at a specific height. Points above or below this height show a residual forward motion also with FMC which corresponds to the height difference. For height differences of ± 10 % of the average flying height above ground, 90 % of forward motion are compensated and a residual motion of 10 % remains.

In the following, the fact that FMC does not adversely affect the photo geometry will be demonstrated without theoretical deductions:
Assume Fig. 6 to be a strictly central-perspective photo with 4 fiducial marks R and a photo point P, and the overall exposure Δt to consist of a series of consecutive uniform exposures $\Delta t_{1,2...n}$ with the center time Δt_m. By definition each of these exposures is central-perspective. Each exposure has its fiducial marks $R_{1,2...n}$ and object points $P_{1,2...n}$.

In exposures without FMC (i. e. stationary film), the subimages $R_{1,2...n}$ of fiducial marks are imaged at R'_m, i. e. at a single point. Forward motion, however, causes the object point P to be imaged as a series of points P'_1 to P'_n with the center P'_m. Since R'_m and P'_m by definition realize the central perspective, this is also true for $R'_{1,2...n}$ an 1/2 (P'_1 + P'_n) i. e. the center of the object "line" $P'_{1,2...n}$, if forward motion was linear and constant in speed. With this conventional method, strict central perspective is obtained by setting the floating mark to the fiducial mark "point" and the object "line".

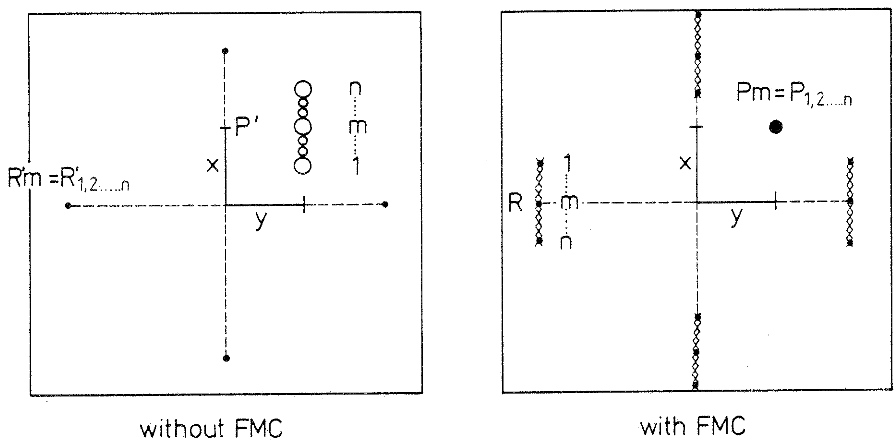

Fig. 6: Influence of Forward Motion and Forward Motion Compensation of Central-Perspective Photography

When photographs are taken with FMC, conditions are reversed. Object point P is now represented in punctiform fashion at P_m as the sum of all part-exposures $P_{1,2...n}$, but the fiducial marks, which are exposed through the lens simultaneously with the photo, are dissolved into a series of points $R_{1,2...n}$ with R_m as the center provided forward motion was linear and constant in speed. Since R_m and P_m by definition realize the central perspective, this is also true for 1/2 (R_1 + R_n) an $P_{1,2...n}$.
If, during plotting, the floating mark is as usual set to the centers of the photo "point" and of the fiducial mark "line", the central perspective remains unaltered regardless of whether the center position R_m of the fiducial mark is obtained by averaging $R_{1,2...n}$ during plotting or by exposure at the time Δt_m.

Zeiss aerial survey cameras are fitted with circular marks with a diameter of 100 µm at the frame sides which are exposed through the lens together with the photo. The fiducial marks are distorted in the flying direction in a defined way by forward motion compensation (FMC). Trials have shown that this does not adversely affect precision setting to the fiducial mark "lines" (σ_0 = 2 µm). An advantage is that the amount of forward motion compensation applied to each photo can later be determined unequivocally. Additional corner marks which will be exposed artificially at the center of the exposure time slot by the shutter are available as an option.

5. Practial Results

In order to empirically check the above theoretical considerations, photo flights were made in summer 1983 with a Zeiss RMK A 30/23 aerial survey camera and the CC 24 Compensation Cassette. Identical flight conditions were aimed at, i. e. same test area, flying height 1,220 meters above ground, photo scale about 1:3800, flying speed v about 200 km/h.

The following Kodak films were used:

Plus X Aerographic Film	2402	AFS 200;	DIN 23[3)]
Panatomic X Film	2412	AFS 40;	DIN 15
Aerocrome Film	2448	AFS 32;	DIN 14
High Definition Film	3414	AFS 8;	DIN 8

The 3414 film could be used only because the lighting conditions were exceptionally favorable in Germany in summer 1983.

The high-sensitivity Plus X 2402 was exposed with and without FMC at 1/350 sec. Without FMC the forward motion was 40 µm. All other films were exposed with 1/100 sec. and FMC. Without FMC the forward motion would have been 140 µm - an impossible amount for aerial photography.
The comparative photo quality assessment results can be given only summarily in this paper.

As could be expected, the 2402 provided better quality photos with FMC than without. The increase was just about discernible at fine detail. Photographs taken with the 2412 and 3414 films were markedly better. Compared to the 2402 the improvement was impressive, but no significant differences were found between the 2412 and the 3414. Finally, the 2448 color film was better than the 2402. Considering the resolution and modulation transfer data published by the manufacturer, this result is surprising (Fig. 4.2) and necessitates further investigation.

To assess the geometrical precision, selected models with identical coverage comprising 21 well-defined natural points were established with the 2402 with and without FMC and with the 3414 (with FMC), measured with the Zeiss Planicomp, and transformed to the conventional configuration, i. e. 2402 without FMC, by Helmert transformation. No significant geometrical deformation through FMC was found for compensation amounts of 40 µm and 140 µm.

In all cases σ_0 of

$$\sigma_{x,y} = 5.7\ \mu m \qquad \sigma_z = 18\ \mu m$$

were found, i. e. high precisions for single model plotting of natural points.

The planimetric setting precision was about 2.2 µm for the floating marks and about 2.0 µm for the natural points with all films, i. e. the setting precision is influenced only little by the photo quality. Further investigation seems necessary in this field.

Finally scale 1 : 1000 and 1 : 500 orthophotos were produced from this photo material with the Zeiss Z 2 Orthocomp. The quality improvement obtained with FMC and high-resolution film was clearly visible particularly in the scale 1 : 500 orthophotos.

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3) The DIN sensitivities have been estimated because the manufacturer only indicates AFS values and a strict relationship between AFS and DIN cannot be established.

6. Conclusions

The quality improvement that can be obtained with FMC in aerial photography in particular by the use of high-resolution, low-sensitivity film made possible by FMC has been shown. The improvement is impressive and becomes clearly visible for example in orthophotos.

In the light of this, the conventional procedural specifications will have to be reconsidered. Photo flight planning, photo scale specifications, photo material selection (e. g. for transparencies), viewing magnification considerations as well as cost and economy factors appear to be affected.

Also, applications are opened up for photogrammetry in further fields, e. g. large photoscales or unfavorable lighting conditions. The hardware required for such applications has been created by Carl Zeiss Oberkochen with the CC 24 Compensation Cassette, which will be available as a series product in spring of 1984.

Literature

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Kodak High Definition Aerial Film 3414

/3/ Meier, H.-K. — Diskussion der Bewegungsunschärfe bei Luftbildern mit Hilfe einer Kontrastübertragungsfunktion
Bildmessung und Luftbildwesen 1960, 65 to 67

/4/ Meier, H.-K. — Über den gegenwärtigen Stand aerophotogrammetrischer Aufnahmesysteme
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Abstract

The CC 24 Compensation Cassette presented by Carl Zeiss Oberkochen expands the RMK system of aerial survey cameras by a forward motion compensation facility. A study of aerial photograph quality illustrates the effects. The improvements directly attributable to the reduction of forward motion are not decisive. Considerably more important are the indirect advances made possible by the use of less sensitive, higher resolution film. This is demonstrated quantitatively by means of modulation transfer functions. It is also shown that forward motion compensation does not adversely affect the central perspective photo geometry.

Photo flights made with conventional high-sensitivity emulsions on the one hand and high resolution and very high resolution film with correspondingly lower sensitivity on the other hand substantiate the quality increase that can be achieved in practice in aerial photography and orthophotos. Comparative evaluations demonstrate that the high precision standard ist maintained.

The CC 24, which can also be integrated in existing RMK systems, will become available as a series product in spring 1984.