INCREASED IMAGE QUALITY RESULTING FROM NEW TECHNOLOGIES IN AERIAL CAMERAS

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ABSTRACT:

A link in terms of image resolution is developed between new optics for the Leica RC30 Aerial Camera with forward image motion compensating device and the new PAV30 Gyro-stabilized camera mount. Moreover the progress in reduction of distortion and improvement of resolution of the Wild / Leica lens cones f = 153 mm and f = 303 mm in the last three decades is shown.
Theoretical evaluations illustrate the improvements through compensation of forward motion and angular camera rotations, essentially for large-scale photography.
The parameters qualifying image resolution and geometric accuracy in mapping are given for the new 15/4UAG-S and 30/4NAT-S lenses with laboratory measurements: modulation transfer function (MTF), resolution for high and low contrast targets, homogeneity of spectral transmission and distortion.
Geometric accuracy is illustrated by results of test flights performed by Leica with very large image scale (1:2 500, flying height 380 m and 760 m). Even for longest exposure times (1/100 s) and intentionally disturbed aircraft stability in pitch, roll and yaw, the small residuals on control points (East and North ± 1.5 cm, height ± 3 cm) confirm the theoretical expectations. The dramatic improvement of system quality is obtained at full aperture f:4.

RÉSUMÉ:

Il est développé le lien en qualité d'image entre la résolution de nouveaux objectifs pour chambre aérienne Leica RC30 avec compensation du filé d'image et nouvelle suspension gyro-stabilisée PAV30. Une rétrospective illustre le progrès en réduction de distorsion et accroissement de résolution des objectifs Wild / Leica f= 153 mm et f= 303 mm durant les trois dernières décennies.
Une évaluation théorique montre l'amélioration en résolution par compensation du filé d'image suite par déplacement de l'avion et rotations de la chambre aérienne, en particulier pour les grandes échelles.
Les paramètres déterminant qualité image et géométrie sont quantifiés pour les nouveaux objectifs 15/4 UAG-S et 30/4 NAT-S: transfert de contraste (MTF), résolution pour mires fort et faible contraste, homogénéité de transmission spectrale, distorsion.
Finalement, la précision géométrique est documentée par des vols à très grande échelle (1:2 500, hauteur de vol 380 m et 760 m) effectués par Leica. Même avec temps d´obturation maximal (1/100 s) et déstabilisation intentionnelle de l'avion en roulis / tangage / lacet, les faibles résidus sur les points de contrôle (Est et Nord ±1.5 cm, altitude ±3 cm) confirment les pronostics théoriques. Un accroissement considérable de qualité du système est obtenue déjà à pleine ouverture f:4.

INTRODUCTION

In the last decade the increasing demand for both large scale aerial surveys and economic high-altitude photography with highest image quality led to extremely stringent specifications for nearly all links in the quality chain of aerial camera systems. New technologies used in the Leica RC30 Aerial Camera System now make it possible to profit from the higher image quality of a new lens generation.

EVOLUTION OF DISTORTION AND RESOLUTION OF LEICA AERIAL CAMERAS

Figure 1 illustrates the progress in resolution and distortion of the standard wide-angle lens cone f=153 mm (6") and the narrow-angle f=303 mm (12"). The latter being the lens mostly dedicated to large-scale photography. The maximum distortion is given for the maximum lens aperture, the AWAR resolution („Area Weighted Average Resolution") in linepairs / mm for the optimal aperture f:4 or f:5.6 (older lenses max. f:5.6).

All values are related to high-contrast targets (contrast 100:1 or log k = 2) imaged in the image frame of the lens cone by collimators spaced at 5°. The typical high-resolution film for high-altitude survey flights Kodak Panatomic-X 2412, also used for the lens Calibration Certificate, has been taken as a reference.

At f:4, the mean AWAR for Panatomic-X at high contrast exceeds clearly 120 Lp/mm for the new generation lens 15/4UAG-S and 105 Lp/mm for the 30/4NAT-S type. AWAR values of the same magnitude have also been obtained when calibrating the 15/4UAG-S on the multicollimator of the U.S. Geological Survey (USGS), which included the use of other test parameters such as the emulsion type (Spectroscopic V-F) and the size gradation of the test targets.

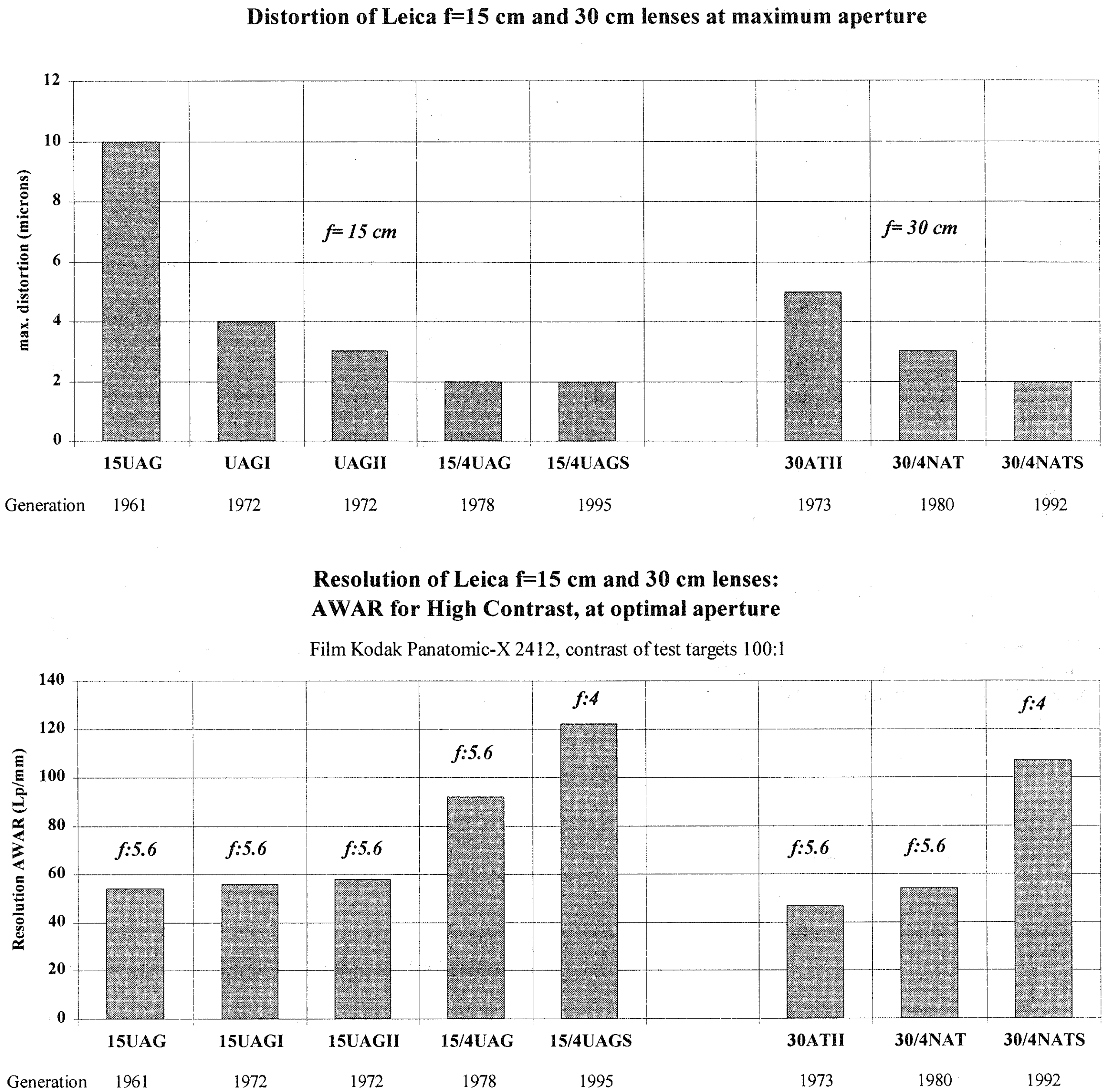

Figure 1

In the early eighties, the demand for large scale maps for planning and GIS increased and it became obvious for camera manufacturers that without forward motion compensation (FMC) and angular motion compensation (AMC), no relevant improvement concerning image quality could be expected. On the one hand, speculations about designing lenses with larger aperture were not realistic, since the weight of the 23" x 23" lens cones had already attained the very limits of practical use. On the other hand the aerial film industry was producing high resolution emulsions for photogrammetric purposes with low filmspeeds which demanded higher spatial stability over longer exposure times.

IMAGE QUALITY DEGRADATION BY FORWARD MOTION AND CAMERA ROTATIONS

Effect of forward motion

The most critical degradation of image quality in large-scale aerial photography is due to forward image motion. Flying at low altitude with longer focal lengths (f=303 mm, 12") and long exposure times results in a nearly uniform longitudinal blur of all points of the image, varying only slightly with the height differences of the terrain.

The compensation by FMC devices is decisive for both following cases:
-medium and small-scale photography flown at high altitudes and high aircraft speeds using black and white emulsion with

very high resolution, high contrast and low speed, requiring longer exposure time (e.g. Kodak Panatomic-X 2412 or Agfa Aviphot Pan 50);
-large-scale photography essentially flown at low altitudes and low aircraft speeds in poor light conditions (low sun altitude), normal-resolution black and white emulsion (e.g. Kodak Plus-X 2402 or Agfa Aviphot Pan 100 or 150).

Figure 2 illustrates the amount of image motion corrected for in the lens cones of RC20 / RC30 by the FMC device:

$$ds = v/h * c * t * 10^3 \qquad [1]$$

ds	image motion (microns)
v/h	flying height (m) to speed (m/s) ratio
c	camera focal length (mm)
t	exposure time (s)

Examples of typical parameters for large-scale photography are:

image scale	1:5000
flight speed	V= 90 kts, 120 kts, 150 kts
exposure time	1/200 s (max. 1/100 s)

FMC is implemented since 1987 in the drive unit and in the f:4 lens cones of the Leica cameras. Besides better image quality at all image scales, camera systems with FMC can be amortised in a much shorter time period due to it's usefulness, in reduced or poor light conditions throughout the whole year.

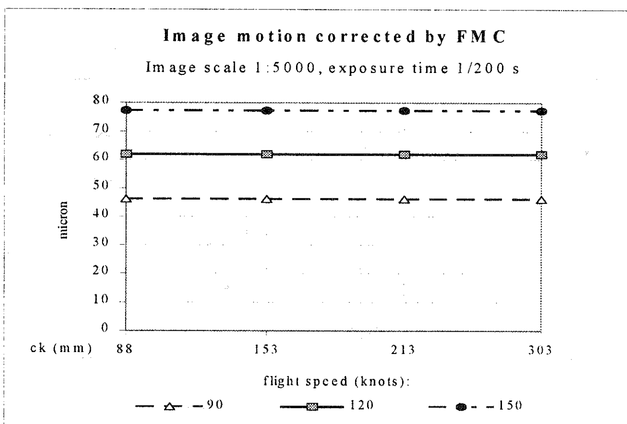

Figure 2

Effect of angular camera rotations

Aerial photography flown at low altitudes in turbulent atmospheric conditions with small relatively unstable aircraft (single engine) and long exposure times causes blurred images in cameras without stabilization. The purpose of the newly introduced Leica PAV30 Gyro-stabilized camera mount is -in terms of image quality- to counteract by active means the image blur resulting from pitch, roll and yaw camera rotations during exposure time.

Image blurring increases with the radial distance in the image plane and with the exposure time.

$$ds(x) = t*[-W_p*c(1+x^2/c^2) + W_r* xy/c + y*W_d] \qquad [2]$$
$$ds(y) = t*[-W_p*xy/c + W_r*c(1+y^2/c^2) - x*W_d] \qquad [3]$$

$$ds(r) = [ds(x)^2 + ds(y)^2]^{1/2} \qquad [4]$$

where:

ds (x)	image motion in x (flight direction, in microns)
ds (y)	image motion in y ((lateral direction, in microns)
ds(r)	resulting image motion (vector, in mm)
t	exposure time (s)
c	camera focal length (mm)
x,y	image coordinates (mm)
W_p	angular velocity in pitch, around y axis (mrad/s)
W_r	angular velocity in roll, around x axis (mrad/s)
W_d	angular velocity in yaw (drift), around vertical (mrad/s)

Figure 3 shows for typical large-scale 1:5000 photography the resulting image motion in the film plane at three radial distances (centre, at a radius of 100 mm and in the corner at 151 mm), for exposure time 1/200 s and angular velocities of 2°/s (35 mrad/s) corresponding to a typical turbulence. It has been assumed that the three rotations pitch / roll / yaw occur simultaneously and added absolutely.

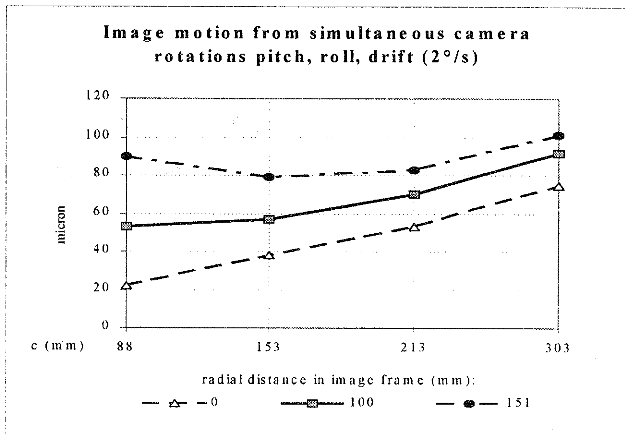

Figure 3

Combined effects of forward motion and angular motion

To illustrate the reduction of image quality caused by this effect, both above evaluated image blurs have been combined in Figure 4, using:

$$[(FM)^2 + (AM)^2]^{1/2} \qquad [5]$$

as motion parameter.

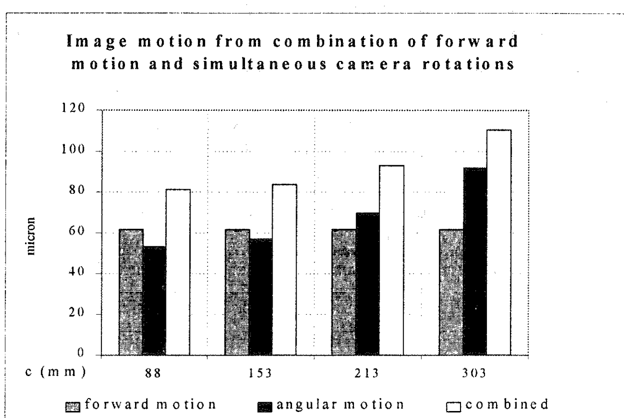

Figure 4

For Figure 4 the following has been assumed:

image scale	1:5000
focal lengths	c = 88 mm, 153 mm, 213 mm, 303 mm
flight speed	V= 120 knots (220 km/h)
exposure time	1/200 s (maximum would be 1/100 s)
angular velocities	pitch, roll and yaw = 2°/s (35 mrad/s)
radial distance	100 mm (at film plane)

Worst case situation occurs with t= 1/100 s in the image corner (at r=151 mm).

Major improvements in the chain of critical features which in practice determine the global image quality of the Leica camera system began in 1987 with the integration of FMC into the RC20, followed by the redesign of the 30/4NAT-S and the 15/4UAG-S lens cones and finally in 1995 with introduction of the PAV30 Gyro-stabilized camera mount.

The f=12" lens cone is especially useful for large and very large image scales at not too low flying heights, an appreciated advantage for urban surveying.

Improvements due to FMC and AMC (camera stabilization) is illustrated in Figure 5 for image scale 1: 5000.

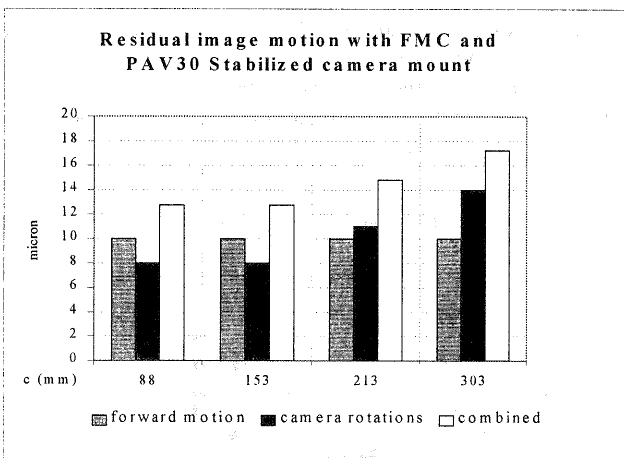

Figure 5

Note: a *forward motion* residual error of 10 microns takes into account terrain height differences, adjustment error of v/h by the operator and smaller residual errors of the camera FMC control device.

Residual *camera rotations* after AMC *(angular motion compensation)* is based on the following assumptions:

exposure time	1/200 s
aircraft angular velocities	2° /s (35 mrad/s) (simultaneous in the 3 rotations axes)
PAV30 stabilization	0.3°/s
radial distance at film	100 mm

Again formula [5] has been used for the combination of FMC and AMC.

High-tech optical design and manufacturing

Sophisticated technologies in optical design, manufacturing, coating, and individual optical adjustment and calibration have been developed for these new lens types. Most important of all this high level of image resolution is achieved in serial production. Special attention has been given to achieving highest resolution even for very low object contrast. These new lenses are therefore also the best choice for high altitude flights.

OPTICAL PERFORMANCE OF THE 15/4UAG-S AND 30/4NAT-S LENSES

Modulation transfer function (MTF)

The modulation transfer function of each serial version of the new lenses has been measured in the laboratory, for maximum aperture f:4 and for f:5.6.

Illumination	Standard white lamp Type A
Filter	420 nm
Incidence angles	every 5°
Spatial frequency	0 to 130 Lp/mm
Focusing distance	15/4UAG-S: at infinity (standard) 30/4NAT-S: at 850 m (standard)

In the usual *photographical method*, image resolution is related to the smallest figure of a series of 3-bars test patterns which can be resolved by experienced operators. It is given for radial (R_i) and tangential (T_i) directions in line pairs/mm and also as mean value by the *AWAR* (Area Weighted Average Resolution). The geometric mean of R_i and T_i at each incidence angle is taken and weighted with the respective coefficient k_i in terms of its share of image surface (%).

$$AWAR = [k_i * (R_i * T_i)^{½}] /100 \qquad [6]$$

In the *MTF method*, image quality is measured directly on-line in a more objective manner (excluding photography and visual interpretation) over the whole range of spatial frequencies required for aerial surveying *[Tiziani]*. From the numerous data and curves resulting from MTF measurement, the contrast values for three particularly representative spatial frequencies, 20 Lp/mm, 40 Lp/mm and 80 Lp/mm, have been extracted in radial (R_i) and tangential (T_i) directions of the format. As in the method with resolution test targets, the average value taken across the film is given by the *AWAM* (Area Weighted Average Modulation transfer function).

$$AWAM = [k_i * (R_i * T_i)^{½}] /100 \qquad [7]$$

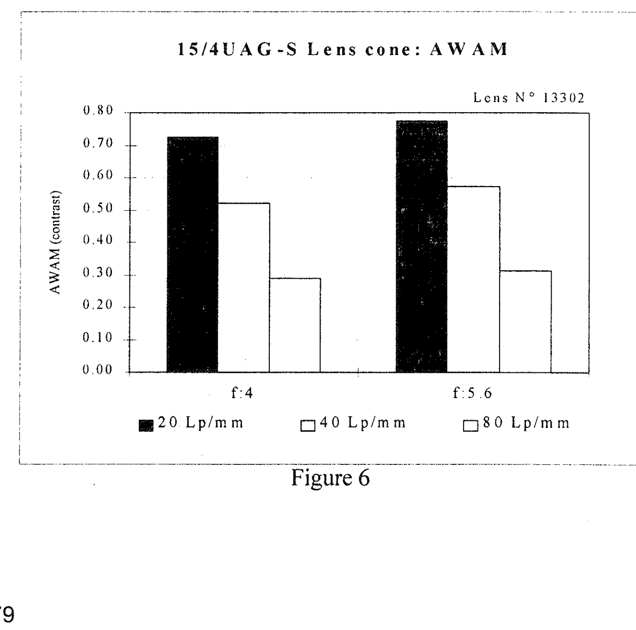

Figure 6

Figures 6 and 7 show for both lens cones the AWAM for f:4 and f:5.6, for 20 Lp/mm (larger terrain features), 40 Lp/mm (medium features) and 80 Lp/mm (smallest features).
Note, that there is only a minimal performance improvement from f:4 to f:5.6, therefore the full quality potential is available already for the largest aperture.

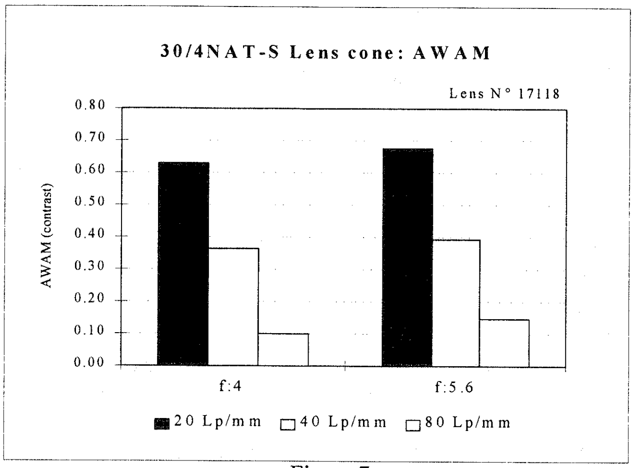

Figure 7

Spectral transmission and intensity homogeneity

Light distribution in the film plane should be as homogeneous as possible over the whole spectral range covered by the usual emulsions used in practice. This is important for medium or small-scale photography with high-contrast colour reversal emulsions (diapositives) over flat contrastless terrain. Also for large-scale photography this physical optical characteristic plays a major role in the image registration, as directly related to the contrast and sharpness rendition.

Figure 8 shows the polychromatic transmission of both lens types (for max. aperture f:4) as a function of the radial distance across the film plane. The transmission values are deduced from measurements taken between 380 nm and 900 nm.

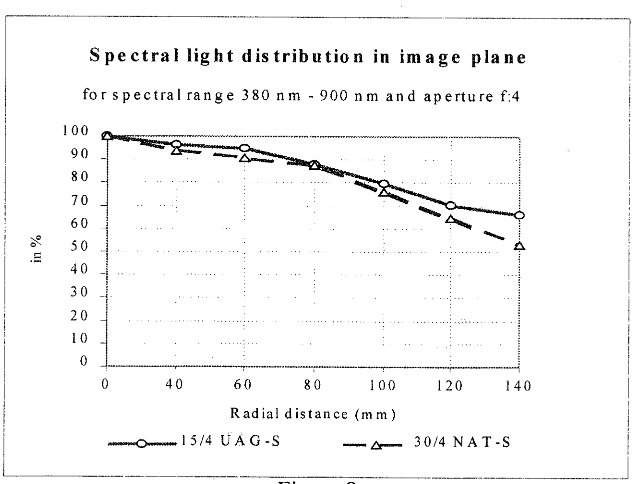

Figure 8

A partial compensation of the light fall-off in aerial lens cones is realised by an "antivignetting (AV) layer", which is a neutral light absorbing layer whose transmission increases from the optical axis to the image corners. In the 15/4 UAG-S such a layer with a standard AV factor 2x is applied on all filters, whereas in the 30/4 NAT-S an AV 1.4x layer is applied as a coating on the inside surface of the upper front lens.

The remaining intensity drop is further attenuated by the "skylight", as a non-image-forming diffusing atmospheric effect which increa-ses with the incidence angle. Note that for critical conditions (essentially for colour reversal emulsions) depending on terrain type, illumination contrast and haze, higher factor AV 3x filters are available on request for the 6" lens.

The intensity drop should not vary for different spectral bandwidths, otherwise shifts in colour rendition result between image centre and image corners.

Resolution of the new lenses

When designing the new lenses 15/4 UAG-S and 30/4 NAT-S *Dr Klaus Hildebrand* placed special emphasis on low contrast rendition. This quality is essential for small-scale photography with hazy atmosphere and for large or medium scales, where details in shadows can be perceived with more accuracy and reliability in the restitution phase, thus reducing mapping time and costs.

Figure 9 shows the mean AWAR values for Panatomic-X 2412 emulsion determined with:
- high contrast test targets (3-bars test targets according to ANSI PH3.609-1980 R1987), contrast 100:1 (log k=2), at f:4 and f:5.6.
- low contrast targets, contrast 1.6:1 (log k= 0.2) at f:4.

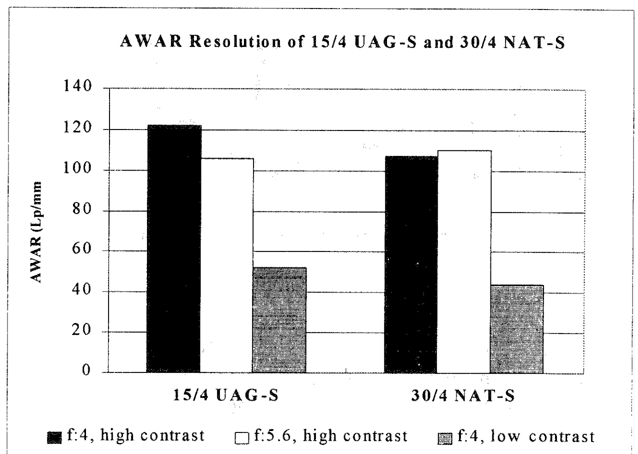

Figure 9

Terrain features with total contrast (object * illumination) 100:1 are rare in current survey flights, whereas contrastless objects with short shadows at high sun angles (e.g. desert regions) or high-altitude flights with hazy atmosphere require the highest possible low-contrast AWAR, which why for both lenses the highest AWAR is already made available at full aperture f:4.

TEST FLIGHTS WITH 15/4UAG-S AND 30/4NAT-S LENS

Three test flights realised on 06.09.94, 01.09.95 and 25.10.95 with the very large image scale 1:2500 made it possible to assess the image quality and geometric accuracy of a serial production 15/4UAG-S and 30/4NAT-S lens cone. In the flights with the 15/4UAG-S, the PAV30 Gyro-stabilized mount assured verticality and rotational stabilization of the RC30 camera.

Positioning and navigation of the aircraft over the nominal waypoints were realised with the Leica GPS MX 9212 which is an integral part of the Leica ASCOT / ACU30 Aerial Survey Navigation System.

Test site	
Location	Buchs SG, Switzerland
Dimensions	length 1.4 km, width 0.6 km
Type	flat terrain with residential, industrial and railway zones
Used control points	100 to 122
Type of points	mostly round man-hole covers on street
Flight data	
Aircraft type	Pilatus Porter PC-6
Flying height/gnd.	f= 153 mm: nominal 382 m f= 303 mm: nominal 762 m
Flying speed	about 90 kts
Mission data	
Nominal image scale	1:2 500
Longitudinal overlap	70%
Number of models	3x 1 strip with 8 models
Film type	Kodak Plus-X 2402
Filter	Haze 420 nm
Exposure time	1/100 s to 1/300 s (for f=153 mm)
Aperture	f:4
Restitution	
Photo material	diapositive contact prints on Agfa Avitone P3p
Equipment	SD 2000 Analytical instrument
Method	independent models
Magnification	18 fold
Photogrammetric results	
Residuals on control points:	
Eastings	± 1.5 cm
Northings	± 1.5 cm (flight nearly N-S and S-N)
Height	± 3 cm

These residuals are in the same magnitude as the accuracy of the geodetic coordinates. They correspond at image scale to x,y errors of ± 6 microns and in altitude to 0,08 per thousand of the flying height above ground. These good results were achieved even for long exposure times (max. 1/100 s) and / or intentionally disturbed aircraft stability in terms of rotation angles pitch / roll / drift.

Furthermore, first high-altitude flight tests with 15/4 UAG-S (with Panatomic-X 2412 emulsion) have already confirmed the high image quality and geometric accuracy, in flight conditions with less critical influence of both FMC and camera rotations. This opens new possibilities for small-scale mapping.

CONCLUSIONS

One of the major aims when developing the new generation of lens cones was to achieve full optical quality at maximum aperture f:4. This assures best imaging conditions for low-contrast targets. In small-scale missions the inherent capabilities of high-resolution films are enhanced. Also for large and medium image scales, there is no need for a compromise between optimal aperture and short exposure time. Higher resolution makes it possible to fly at higher altitudes which reduces flying time and costs. On the other hand the possibility to fly in difficult light conditions thanks to high image quality at f:4 increases profitability. This challenge of overcoming opposing physical conditions has been fulfilled with the new „S" lens generation together with the RC30 camera equipped with FMC and AMC.

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