Total System for Evaluating Aerial Survey Cameras

Takeshi Hirai, Shintaro Yagi and Hiroshi Masaharu

Geographical Survey Institute of Japan (GSI)

Commission I, W.G. 1/2

Abstract

The study on the calibration of aerial survey cameras has been carried out for seven years since 1977 with the cooperation of scientists and experts of universities, institutes and surveying companies in the fields of optical instruments, photogrammetry and image technology.
The committee was made up of these menbers discussing methods of calibration of geometric optical performance which directly influences the results of aerial photogrammetry and of image-forming performance which affects the quality of the photographic image. The method of measuring each performance was studied and some instruments for calibration were developed on an experimental basis. After examining almost all kinds of aerial survey cameras, now used in Japan, by using these instruments, it was certified that the total performance of them could be clarified quantitatively.
In addition to laboratory methods, some field methods have also been studied for the purpose that aerial survey cameras whose performances are under a certain standard level should be discovered mainly using black-and-white film.

1. Introduction

It is well known that the quality of photographs which determines the photogrammetric accuracy mainly depends on the performance of the camera system. Camera performance can be classified into three groups, i.e. geometric optical performance, image-forming performance and photometric performance. GSI of Japan has studied the methods of measuring these performances and developed a total system for evaluating aerial survey cameras on an experimental basis.
The system consists of a collimator array camera calibrator, a moiré flatness tester, an exposure distribution measurement instrument, a glare spots measuring instrument and a lens analyzer in laboratories and an aerial resolution target placed on the roof of the GSI's building.
Through many experiments using these instruments in laboratories, it was certified that the total performance of any aerial survey camera could be clarified to some extent by laboratory methods.
Periodical examination seems to guarantee the performance of each aerial survey camera. It is important, at the same time, to test a camera under a complete working condition for finding any aerial survey camera which might cause trouble in the photogrammetric work. For this purpose, the field calibration methods have also studied and some experiments have been carried out at GSI.

2. Items of Calibration

After discussing what items should be calibrated and what methods should be emplyed for calibration, the following items were decided to be calibrated.

A. Geometric optical performance
- Focal length
- Distortions
- Flatness of the film surface during exposure

B. Image-forming performance
- Resolving power
- Modulation Transfer Function (MTF)

C. Photometric performance
- Uniformity of image illuminance
- Exposure time
- Glare spots

And several instruments were developed and installed at GSI to measure the following items of calibration.
The relation between items of calibration and the instruments developed is summarized as in Table 1.

Item	Instrument
A. Geometric optical performance	
(1) Optical characteristics of aerial survey cameras	
a. Frame center, PPA and PPS	·Collimator array camera calibrator
b. Effective calibrated focal length	
c. Distortion	
(2) Flatness of the film surface	
a. Film surface	·Moiré flatness tester
b. Film pressure plate	·3-dimensional coordinats measuring instrument
B. Image-forming performance	
(1) Resolving power	·Collimator array camera calibrator
(2) MTF	·Lens analyzer
C. Photometric performance	
(1) Exposure time	·Exposure distribution measuring instrument
(2) Uniformity of image illuminance	
(3) Glare spots	·Glare spots measuring instrument

Table 1. Items of calibration and their corresponding instruments

3. Geometric Optical Performance

3.1 Optical characteristics of aerial survey camera

The optical quality of aerial survey cameras, characterized by the accuracy of perspective projection achievement, is an essential requisite in photogrammetry, and, calibration of this item can be accomplished by measuring the effective focal length, distortions and the coordinates of principal point of symmetry (PPS). The collimator array calibrator has been developed mainly for this purpose.
This instrument consists of a collimator array, a supporting table and an autocollimator. The collimator array consists of 81

collimators, 80 of which are hemispherically arranged on the six plain located next to each other at angle of 30°, from vertical to 52.5° or 60.0° at every 7.5° fastened by iron arms. The other collimater, the central collimator, is fixed at the center of the array. The test chart, the cross lines for measuring distortions and standard three-bar test patterns for measuring the resolving power, is kept on the focal plane, which is illuminated by a light source with a lamp. Seven kinds of filter can be inserted between the light and the test chart. Collimators are arranged so that their optical axes converge at one point.
The camera table made of steel is supported by poles and is situated at the center of the upper part of the collimator array and can be rotated freely with an attached camera around the axis of the central collimator.
Diagrams of the collimator array camera calibrator and the target images recorded by a wide-angle camera on a glass-plate negative are shown in Fig. 1 and 2. The resolving power of a photographic emulsion is about 2,000 lp/mm.

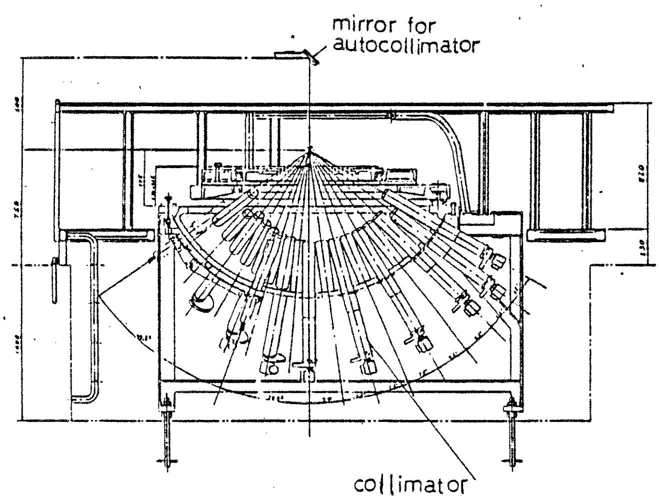

Fig.1 Structure of Collimator Array Camera Calibrator

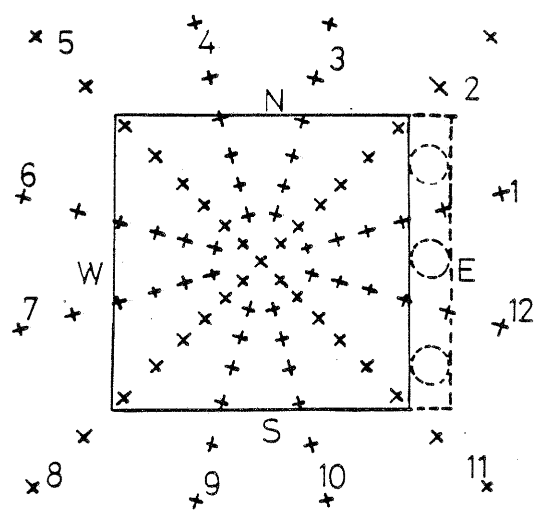

Fig.2 Target images on a glass-plate negative

The following is the procedure of calibration using the collimator array camera calibrator.

(1) Measurement of collimator angles
A special theodolite is used to determine the angles between the center collimator and the other collimators. The theodolite, Nikon NT-5, is modified so that measurement in upside-down attitude can be performed accurately. Although each angle is measured several times and standard errors are checked, certain accidental errors may occur. Therefore, each angle is verified statistically using the results of 12 sets of plate measurements.
In order to verify each angle, glass-plate negatives are exposed 12 times so that rotational value, kappa, for the image plane increase at angle of 30° at each exposure, and radial distortion of each lens point is measured at most 12 times with different collimators. The correction of each collimator angle can be performed on condition that these 12 values of radial distortion should be the same. As above-mentioned, camera system attached on the camera table can be rotated freely and collimator array arms are located next to each other at angle of 30°.

(2) Measurement of image coordinates
When an unknown camera is calibrated, two or four glass-plate negatives are exposed varying the relative horizontal angle between the camera and the collimator array. The camera table is rotated at angle of 180° or 90° at the next exposure.
The coordinates of each target are measured two times and each measurement is repeated if the residual of two measurement exceeds 5μm. The mean of two measurements is adopted as coordinates of each image of the target.

(3) Tilt correction of image plane
When an aerial camera is positted on the collimator array for calibration, a thick optical-parallel plate which has a mirrored top surface is placed on the focal plane of the camera and the position of the camera is adjusted so that the camera lens axis coincide with the axis of the central collimator and the focal plane is normal to this axis. Usually this condition, however, is not achieved wholly and a small tilt of the focal plane is left. This tilt causes errors in the values of lens distortion.
In practice, the tilt correction is carried out by determining a maximum likelihood principal point of autocollimation (PPA). The coordinates of PPA, (Xp,Yp), are that cordinates which make

$$\sum_i \sum_k \left(\cos\theta_{ki} - \sum_{k'} \cos\theta_{k'i} / \sum_{k'} 1 \right) = \text{minimum} \qquad (1)$$

where

$$\cos\theta_{ki} = \frac{(X'_{ki} - X_P)\cdot(X'_{kj} - X_P) + (Y'_{ki} - Y_P)\cdot(Y'_{kj} - Y_P)}{\sqrt{(X'_{ki} - X_P)^2 + (Y'_{ki} - Y_P)^2}\sqrt{(X'_{kj} - X_P)^2 + (Y'_{kj} - Y_P)^2}} \qquad (2)$$

$$X'_{ki} = X_{ki} + X_{ki}\cdot\Delta\alpha, \quad Y'_{ki} = Y_{ki} + Y_{ki}\cdot\Delta\alpha \qquad (3)$$

$$\Delta\alpha = \left\{ X_{ki}(X_P - X_{ko}) + Y_{ki}(Y_P - Y_{ko}) \right\} / f_o^2 \qquad (4)$$

(X_{ki}, Y_{ki}) : Coordinates of the i-th point on the k-th negative, and the j-th point is the next tangential point of the i-th point
f_o : Assumed focal length

And the tilt correction can be given by transforming the image coordinates of each target using the next equation:

$$\left.\begin{aligned} x_{ki} &= X_{ki} - \Delta r_k \cos\varphi_k - \frac{\Delta r_k}{f_o^2} X_{ki}(X_{ki}\cos\varphi_k + Y_{ki}\sin\varphi_k) \\ y_{ki} &= Y_{ki} - \Delta r_k \sin\varphi_k - \frac{\Delta r_k}{f_o^2} Y_{ki}(X_{ki}\cos\varphi_k + Y_{ki}\sin\varphi_k) \end{aligned}\right\} \qquad (5)$$

where

$$\Delta r_k = \sqrt{(X_{ko} - X_P)^2 + (Y_{ko} - Y_P)^2} \qquad (6)$$

$$\varphi_k = \cos^{-1}\left(\frac{X_{ko} - X_P}{\Delta r_k}\right) = \sin^{-1}\left(\frac{Y_{ko} - Y_P}{\Delta r_k}\right) \qquad (7)$$

(4) Determination of focal length
The values of a calibrated focal length is determined so that radial distortion over the area of the plate is minimized. For this poupose, the following equation is used for determining the correction in focal length.

$$\Delta f_k = \frac{\sum \tan\theta_i \left\{ \sqrt{(x_{ki} - X_P)^2 + (y_{ki} - Y_P)^2} - f_o \tan\theta_i \right\}}{\sum_i \tan^2\theta_i} \qquad (8)$$

where θ_i is the angle between the central collimator and the i-th collimator. For a calibrated focal length we have

$$f_c = f_o + \sum_k \Delta f_k / \sum_k 1 \qquad (9)$$

(5) Determination of PPS and Radial Distortion
As a matter of fact, the distortion around PPA is not necessarily symmetrical and it is necessary to compute the coordinates of the principal point of symmetry (PPS) in order to minimize the effect of asymmetrical distortion over the whole plate.
If the coordinates of PPS could be written as (Xs,Ys), the radial distortion of each lens point can be computed by the following equation:

$$D_i = \frac{\sum_k \left[\sqrt{(x_{ki}-x_{k0})^2+(y_{ki}-y_{k0})^2} - f_c \tan\theta_i + \frac{\tan\theta_i}{f_c}\left\{x_{ki}(X_s-X_p)+y_{ki}(Y_s-Y_p)\right\}\right]}{\sum_k 1} \qquad (10)$$

The values, Xs and Ys, are determined so as to satisfy the least squares condition that:

$$\sum_k \sum_i (D_{ki} - D_{ki'})^2 = \text{minimum} \qquad (11)$$

Where i'-th point is the symmetrical point of i-th point on the negatives. As example, the lens distortion curves of Zeiss RMK-A and Wild RC-10 measured according to the above mentioned procedure are shown in Fig.3 and 4.

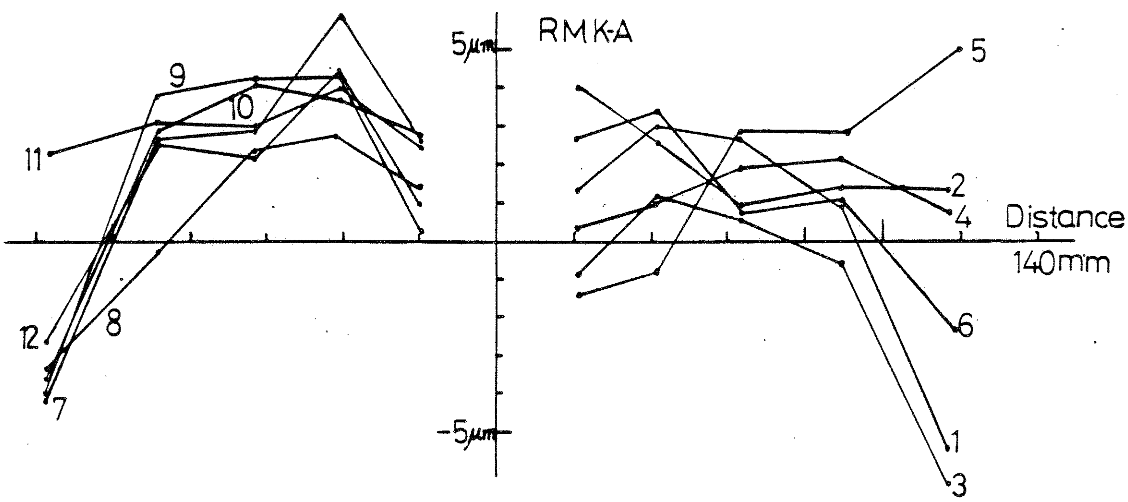

Fig. 3 Radial distortion along the radial lines (RMK-A 15/23 Pleogon 124293)

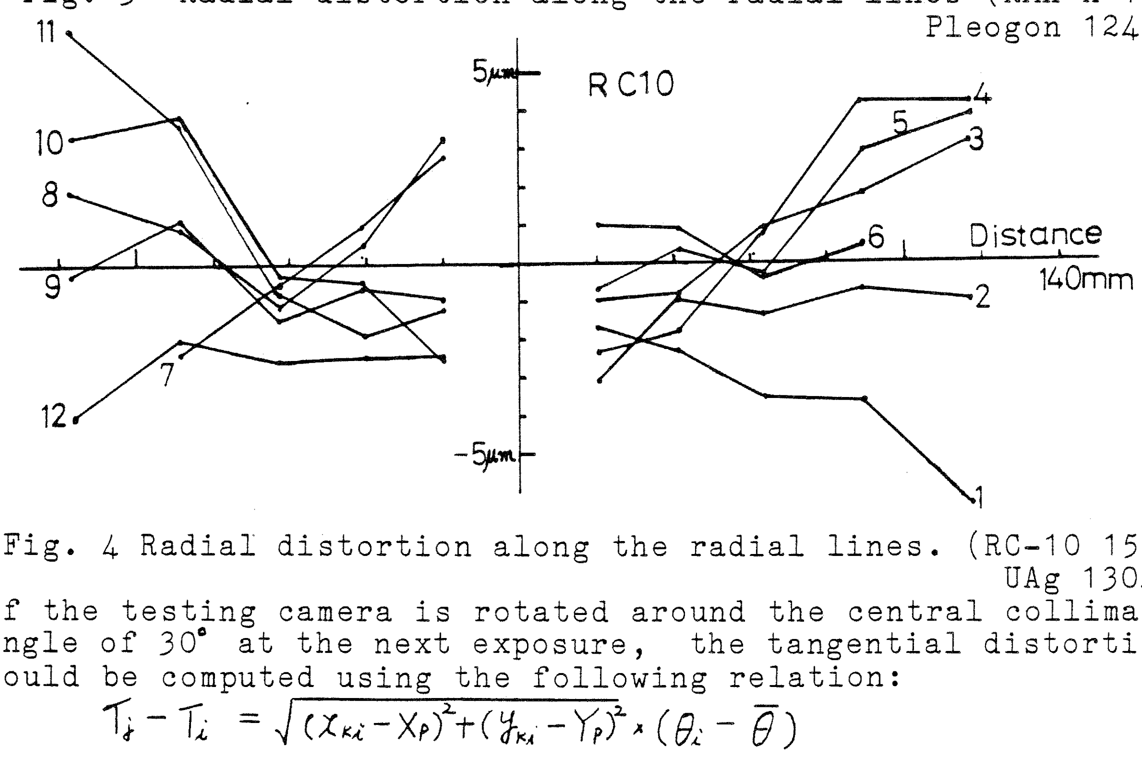

Fig. 4 Radial distortion along the radial lines. (RC-10 15/4 UAg 13041)

If the testing camera is rotated around the central collimator at angle of 30° at the next exposure, the tangential distortion could be computed using the following relation:

$$T_j - T_i = \sqrt{(x_{ki}-X_p)^2+(y_{ki}-Y_p)^2} \times (\theta_i - \bar{\theta}) \qquad (12)$$

where T_i is the tangential distortion at the i-th lens point, the j-th point is the next tangential point of the i-th point,

$$\bar{\theta} = \frac{\sum_i \theta_i}{\sum_i 1} \quad (13) \quad \text{and} \quad \theta_i = \cos^{-1}\left\{\frac{(x_{ki}-X_p)(x_{k+1,j}-X_p)+(y_{ki}-Y_p)(y_{k+1,j}-Y_p)}{\sqrt{(x_{ki}-X_p)^2+(y_{ki}-Y_p)^2}\sqrt{(x_{k+1,j}-X_p)^2+(y_{k+1,j}-Y_p)^2}}\right\} \quad (14)$$

But it has been quite difficult to know the probable values until now becouse the values of tangential distortion seemed to be much smaller than those of the measurement error at least in case of RMK-A 15/23 Pleogon 124293 or RC-10 15/4 UAg 13041.

3.2 Flatness of the film surface

As the flatness of the film surface is one of the important factor influencing the accuracy in photogrammetry, aerial survey cameras are made so as to keep the film flat by connecting a vacuum pump which sucks the film with all of the many small holes in the pressure plate. But it was difficult to measure the flatness of the film surface directly when the film was sucked. Then the film surface was assumed flat if the flatness of the pressure plate was accurate enough.
Under these considerations, a film flatness tester has been developed. Principles of moiré topography are applied to this instrument. The step of moiré contours is set as 20μm and the moiré fringes are photographed with a 35mm camera.
Two kinds of measuring methods are applied. One is the parallel method in which adjustment is made so that the film surface is as parallel as possible to the reference grating. The other is the tilting method in which the reference grating is slightly tilted to the film surface. The former method is useful in clarifying the shape of the film surface with slight undulation, and the latter method is useful in determining the shape as well as convexity or concavity of the film surface.
Examples of the moiré fringes are shown in Fig.5 and 6. Although the film flatness of more than ten cameras was examined, there was only one camera whose film flatness was problematic. The moiré fringes of that camera are shown in Fig.7. After measuring the flatness of the film pressure plate as shown in Fig.8, it was reaffirmed that there was a strong correlation between the flatness of a pressure plate and that of a film surface.

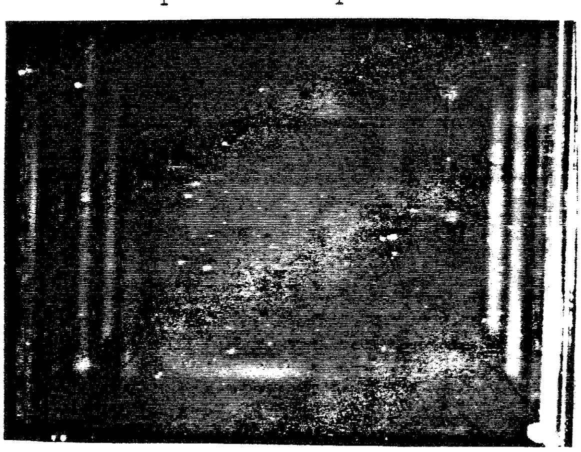

Fig. 5 Moiré fringes of a film surface measured by the parallel method

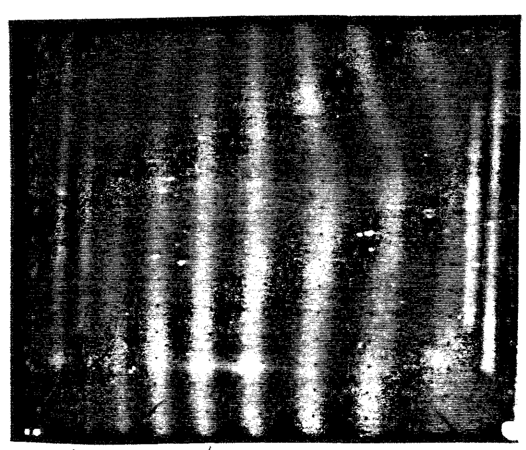

Fig. 6 Moiré fringes of a film surface measured by the tilting method

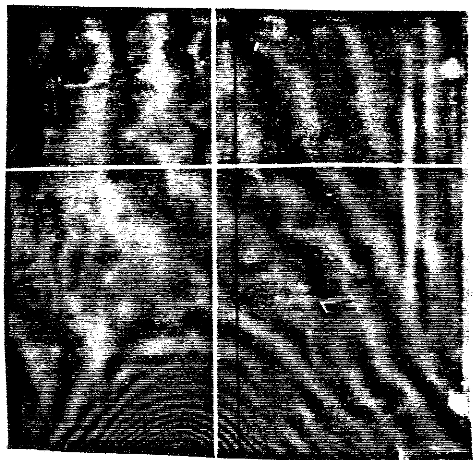

Fig.7 Moiré fringes of the problematic film surface

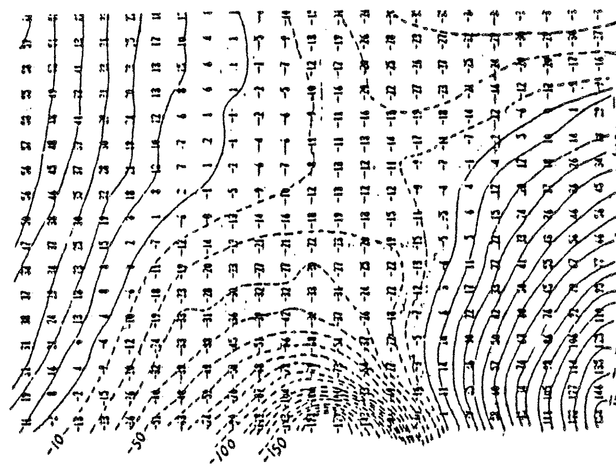

Fig.8 Contours of the pressure plate surface measured with 3-dimensional coodinates measuring instrument

4. Image-Forming Performance

4.1 Resolving power

Resolving power of a camera lens is determined visually by measuring the test chart images of the collimator array which are exposed on glass-plate negatives under x 30 microscope. The negatives used for measuring distortions are also used for measuring resolving power. This method was adopted in 1979 and there has been no significant change since then.

4.2 Modulation transfer function (MTF)

The use of MTF instead of resolving power has been proved to be a highly valuable method in evaluating the quality of optical system.
GSI developed a lens analyzer to measure MTF in 1979. This instrument adopted the method of digital Fourier transformation. When the line spread function (LSF) is measured for discrete sampling points with a scanner, the optical transfer function (OTF) is calculated by discrete Fourier transformation. That is

$$F(f_j) = \sum_{k=1}^{N} L(X_k) \exp\left(i \frac{2\pi f_j X_k}{N}\right) \qquad (15)$$

Where f_j is j-th spatial frequency and $L(X_k)$ is the intensity distribution of k-th sampling point on the image of a line object formed by the optical system which is examined.
Then the MTF at spatial frequency f_j is given as:

$$MTF(f_j) = \sqrt{Re^2(F(f_j)) + Im^2(F(f_j))} \qquad (16)$$

Where Re and Im denote real and imaginary parts respectively. Structure of the lens analyzer, detailed measuring methods and some experimental results were described at the conference four years ago (Reference 1).

5. Photometric Performance

5.1 Exposure distribution and exposure time

It is unavoidable optical characteristics of wide angle lenses that there is significant underexposure at the periphery and corners of the picture due to a decrease in illuminance as the fourth power of the cosine of the (image) field angle and vignetting of the lens. Modern wide-angle lenses for aerial survey cameras are designed so that they show almost no vignetting and A.V.filters are usually used with the lenses to obtain even illuminance over the picture format. However, the unevenness of exposure distribution is not been sufficiently corrected in a few types of camera. For that reason, an exposure measuring instrument was developed. The composition of the instrument is shown in Fig.9.

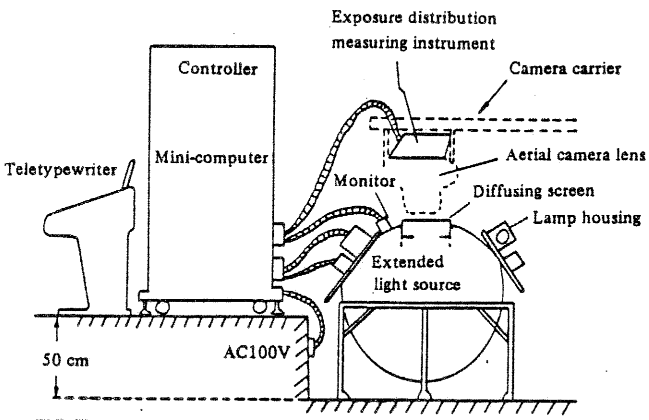

Fig.9 Composition of the exposure measuring instrument

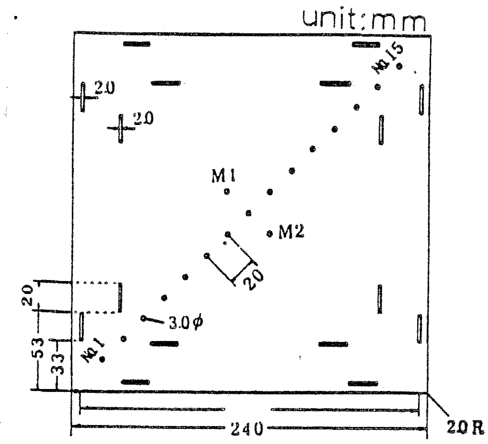

Fig.10 Photodiode arrangement
M1,M2:monitoring detector

Control of the instrument, scanning, data acquisition and data processing are aided by a minicomputer. Fifteen silicon photodiodes, used as detectors, are located on one of the diagonals of the picture format, one at the principal point and the others at 20 mm intervals as shown in Fig.10. All 15 detectors can be used for cameras with a 230 x 230 mm format. And it is possible to measure the exposure distribution, the illuminance distribution and the effective exposure time distribution of any aerial survey camera having the following specifications:

Camera lens F No.	: F/4 - F/11
Focal length of lens	: f = 80 - 700 mm
Half angular field	: 5° - 55°
Camera shutter speed	: 1/20 - 1/1,000 seconds
Film format size	: 23 cm x 23 cm , 18 cm x 18 cm
Filter	: any kinds of A.V.filter having about 50% transmittance on optical axis

After an exposure under the condition of the actual operation, numerical values regarding three kinds of distribution is calculated automatically in accordance with following procedures.

(1) Illuminance distribution : Measured illuminance values at 15 points are normalized by the illuminance measured at the principal point and are expressed as a percentage, as shown in equation (17) below;

Relative illuminance at point "d" on the film plane

$$= \frac{\text{Illuminance at point "d" (lx)}}{\text{Illuminance at the principal point (lx)}} \times 100\ (\%) \qquad (17)$$

(2) Exposure distribution : Exposure is measured in the same way as shown in equation (18) below;

Relative exposure at point "d" on the film plane

$$= \frac{\text{Exposure at point "d" (lx·s)}}{\text{Exposure at the principal point (lx·s)}} \times 100\ (\%) \qquad (18)$$

(3) Effective exposure time distribution: Effective exposure time at a point "d" can be caluculated by dividing the exposure at the point "d" by the illuminance at the same point, as shown in the next equation.

Effective exposure time at point "d"

$$= \frac{\text{Exposure at point "d" (lx.s)}}{\text{Illuminance at point "d" (lx)}} \quad (S) \qquad (19)$$

A diagram of the photocurrent versus exposure time can be described as shown in Fig.11, and it can be watched on a CRT. As an example, the results of calibration are shown in Table 2.

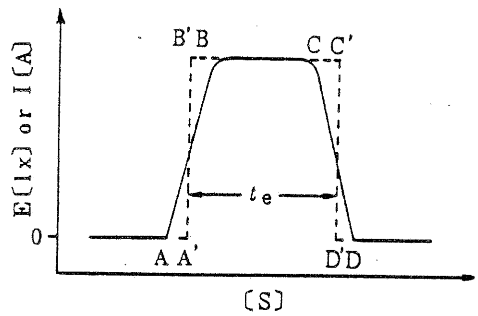

Fig. 11 Exposure diagram
Practical exposure(——)
normalized exposure(------)

Table 2 Results of exposure distribution measurement

FOCAL PLANE EXPOSURE DISTRIBUTION TEST
FOR AERIAL SURVEY CAMERA

CALIBRATION DATA

DATE	80-03-26
TEST ROOM TEMPERATURE	18.5 °C
RELATIVE HUMIDITY	50%

CAMERA TYPE:	RMK 21/18	S/NO.	2027
LENS TYPE:	TOPAR	S/NO.	9240
MAX APERTURE:	F/4.0	FOCAL LENGTH	F = 209.91
FILTER TYPE:	NO FILTER	S/NO.	–
FILM FORMAT:	180 x 180		

TEST POSITION: APERTURE F/8
SHUTTER IND I/0100 EFFICIENCY 93.5%

CH	RADIUS (MM)	ANGLE (DEG)	ILLUMINANCE DSTRBT(%)	EXPOSURE LVL DSTRBT(%)	EXPOSURE TIME(MSEC)
1	140	33	0.0	0.0	
2	120	29	2.9	0.0	0.000
3	100	25	47.1	45.0	9.641
4	80	20	63.5	61.9	9.331
5	60	15	74.6	73.5	9.938
6	40	10	87.7	87.1	10.01
7	20	5	97.5	97.1	10.04
8	0	0	100.0	100.0	10.08
9	20	5	97.2	97.1	10.06
10	40	10	89.9	90.0	10.10
11	60	15	78.0	77.6	10.04
12	80	20	64.6	63.6	9.932
13	100	25	52.7	50.8	9.721
14	120	29	38.6	37.6	9.304
15	140	33	0.0	0.0	

LUMINANCE: 7068. (CD/MM) 7071. (CD/MM)

ACCURACY OF MEASUREMENT 10%
PRECISION OF MEASUREMENT 5%

After examining more than ten cameras, it is certified that exposure distribution measurement is useful in evaluating the focal plane illuminance distribution of wide-angle lenses and is necessary in order to check a deterioration of the A.V.filter transmission and a change in exposure time.

5.2 Glare spots

Blue glare spots were sometimes observed at the center of color aerial photographs mainly taken by some old types of aerial cameras when the brightness conditions are even in the field.
It is presumed that such glare spots are caused by reflections at the lens surface and the film surface and the color of a glare spot is presumed to depend on the color of the lens coating. The procedure of measuring glare spots with the glare spots measuring instrument which was developed to measure and analyze real glare spots is the follwing.
A light source as large as the picture format of the camera, with a circular detector of 30 mm in diameter placed at the center of the light source, is placed on the film plane. The illuminace at the center of the picture due to the reflected light from the lens surface is measured while the camera shutter is opening. This illuminance is compared with the illuminance

caused by the reflection at the reference surface:the plane glass plate. The data are thus given in terms of the relative illuminance. The measurement is performed in three spectral regions: blue, green and red spectral regions, and the relative illuminance in each region: B,G and R are calculated. The data are then illustrated in terms as defined below:

$$b = B/(B+G+R),\ g = G/(B+G+R),\ r = R/(B+G+R)$$

The overall intensity w is calculated from the equation:

$$w = (B^2 + G^2 + R^2)^{\frac{1}{2}}$$

Results for 22 aerial survey cameras are shown in Fig.12.

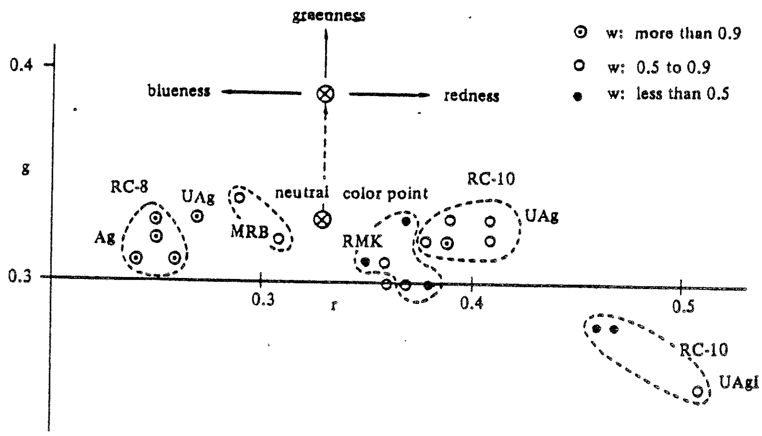

Fig. 12 Intensity and color properties of the glare spots

6. Camera Calibration by Photographing from Aircraft

One advantage of this method is that the condition of calibration closely resembles those of the practical aerial photograph, compared with laboratory methods.
Photometric performance can be evaluated without any artificial target. However it is necessary to establish air-photo signals and resolution targets in order to calibrate geometric optical and image-forming performances.
In attempt to realize this method, GSI has established two kinds of testfields for the calibration of geometric performance and a resolution target, and been carrying out some experiments.

6.1 Geometric optical performance

It is necessary to establish in advance a large number of air-photo signals with a uniform distribution over a certain large area in order to calibrate geometric optical performance, such as flatness of the film surface, coordinates of the principal point, radial distortion and a calibrated forcal length.
For this purpose, two kinds of testfields have been established. One is the testfields for bundle block adjustment with self-calibration parameters, and the other is the testfield mainly for orientation of a single photograph with self-calibration parameters. The former fields can be established rather easily because triangulation points and leveling routes distributs densely in many areas in Japan, and have been proved to be very useful to find out cameras whose performances don't satisfy a certain standard level. The latter field has been established on the Mt. Omuro area as shown in Fig.13 by carrying out precise control point survey. Calibration of geometric optical performance can be

performed with a single photograph taken at a scale of 1:8,000, in case of 23cm x 23cm frame camera by determining self-calibration parameters satisfying the least square condition.

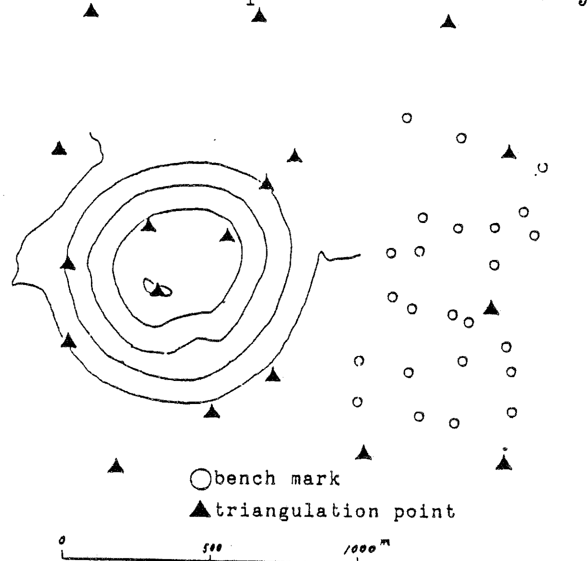

Fig.13 Mt. Omuro testfield

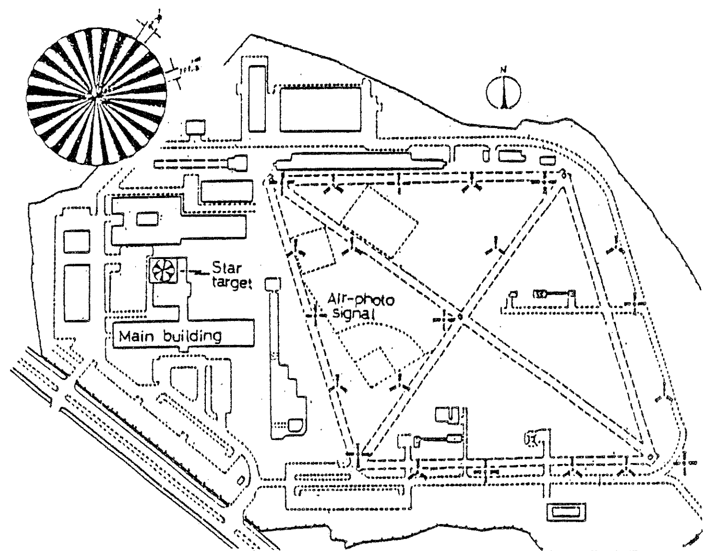

Fig.14 Resolution target at GSI

6.2 Resolving power

The resolving power of photographs taken by actual operation is usually much inferior to that of glass-plate negatives exposed with the collimator array camera calibrator. And this phenomenon is presumed for the sake of aircraft motion and the lower resolving power of the film. Therefore, aerial resolution targets are very useful to determine the actual resolving power of aerial survey cameras.

GSI has constructed a Siemens star target. The target, located on the roof of GSI building as shown in Fig.14, has a diameter of 17 meters and the average contrast ratio is 2.5 : 1.

Any organization can take photographs of the star target and air-photo signals which have also constructed in the grounds of GSI to evaluate the actual performance of each camera system.

7. Conclusion

Total performance of any aerial camera can be calibrated quantitatively enough to guarantee usual photogrammetric work in Japan with the facilities installed at GSI. But it seems very difficult to evaluate effectively the geometric optical performance of some types of cameras which have been manufactured recently because their lens distortions seems to be smaller than the amount of measuring errors (2-3μm).

Periodical calibrations are necessary to detect deteriorations of camera systems after long periods of use. And field calibration methods are usuful to complement them.

References

(1) Hirai,T. and J. Kaneko,1980:Total System of Evaluating Aerial Survey Cameras of G.S.I.,Tsukuba (presented at the ISPRS commission I symposium in Humburg, July 1980)

(2) Kaneko, J. 1981: "Calibration of Aerial Survey Cameras", Bulletin of Geographical Survey Institute, Tsukuba:GSI