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TECHNICAL MEMORANDUM 2

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INTERIM POST-FLIGHT CALIBRATION REPORT ON APOLLO 9 MULTIBAND PHOTOGRAPHY EXPERIMENT SO65

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INTRODUCTION

This report supplements Technical Memorandum 1[1] and includes the bulk of the spectral analysis on the cameras and filters used in the Apollo 9 S065 multiband photography experiment. Some additional data on registration errors, film flatness, format size, and resolution are included.

This report is divided into three sections. The first includes the spectral transmittance measurements made to date. The second section covers registration and image height errors. The final section summarizes resolution measurements made with the complete camera system.

All work reported here was conducted under contract NAS 9-9333, "Post-Flight Analysis and Calibration of Camera System for Apollo Experiment S065," from the Manned Spacecraft Center, Houston, Texas. Mr. G. L. Kraus is the technical monitor on the contract.

SPECTROPHOTOMETRIC MEASUREMENTS

The data presented in this section were obtained with a 2.4-m, f/8 collimator system or a Cary Model 14 spectrophotometer. The collimator shown in Fig. 2 of Technical Memorandum 1 was used with the integrating sphere replaced by a ground glass screen and the monochromator placed after the light source. The collimator was used for spectral transmittance measurements of the lenses and the filters. These results are given in Fig. 1. No significant difference was noticed among the four lenses. The curves are considered accurate to within ±0.03.

The spectral transmittance curves of the filters were verified by use of a Cary Model 14 spectrophotometer. The check was performed mainly because the transmittance between 600 nm and 650 nm for No. 58 is not typical of Wratten filters. However, these are Photar filters and not Wratten gelatin filters. Photar filters consist of a dye suspended in the cement between two sheets of glass, and the variance from Wratten filters can be attributed to the difference in construction.

The variation of spectral transmittance with field angle was measured using the collimator system. In each band there was no significant variation with wavelength, the only significant variations being due to vignetting and $\cos^4$ losses. The relative illuminance values given in Table 1 are considered accurate to within ±0.03 at all wavelengths of interest.

In Fig. 2 the normalized spectral sensitivity is plotted for the three black-and-white camera systems. The values of relative sensitivity are noted on the figure. These data are believed accurate to ±0.05. Film sensitivity data were taken from Kodak.[2] Kodak ir film 5424 was assumed to be spectrally identical to film type SO-246.

Table 1
Relative illuminance vs field angle

Camera	AA	BB	CC	DD
Lens No.	4488988	4489010	4591824	4593532
Filter	15	58	89B	25A
Aperture	f/8	f/4	f/16	f/4
Field angle	**Relative Illuminance**			
0°	1.00	1.00	1.00	1.00
5°	0.98	0.99	0.99	0.98
10°	0.93	0.94	0.93	0.94
15°	0.85	0.87	0.85	0.86
20°	0.76	0.71	0.76	0.70
25°	0.65	0.46	0.66	0.45

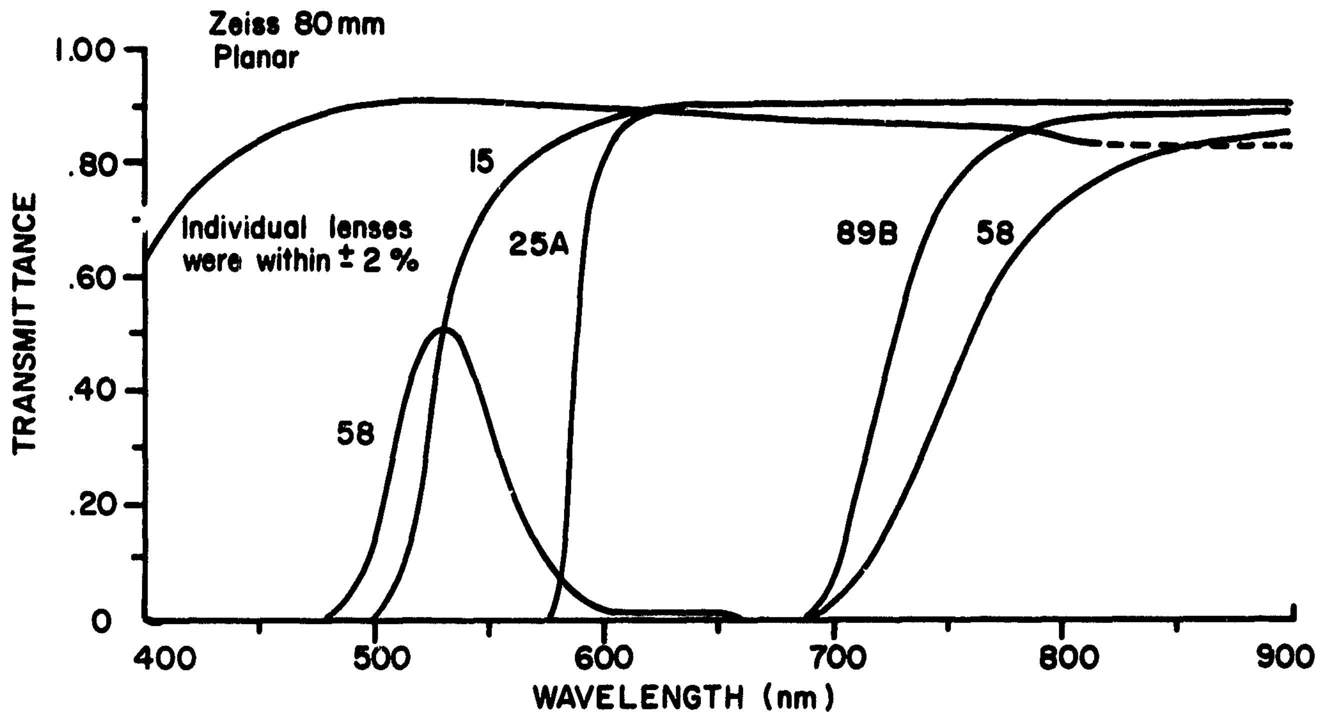

Figure 1. Spectral transmittance of the lens and filters used on Apollo 9 SO65 experiment

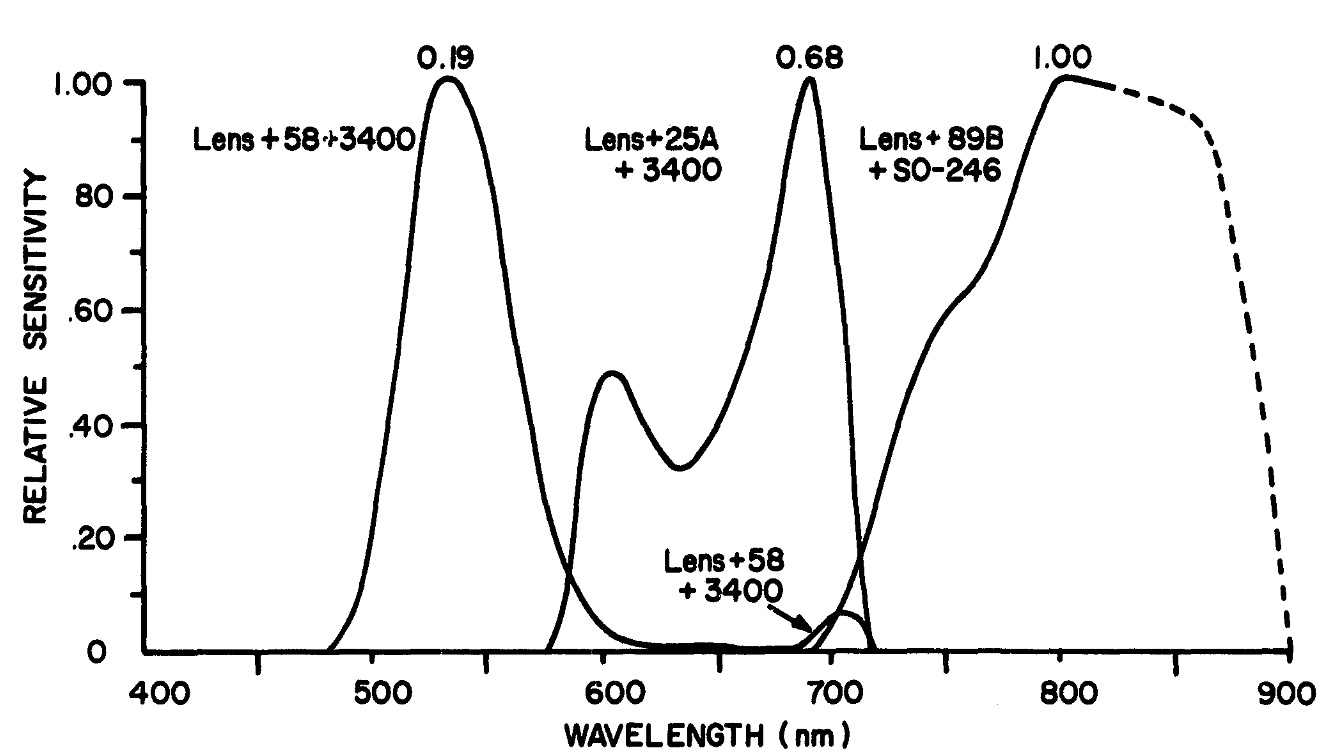

Figure 2. Relative spectral sensitivity of lens, film, and filter combinations for the three monochrome bands used on Apollo 9 SO65 experiment

REGISTRATION ERRORS

Fig. 3 gives the image height error, as a function of field angle, for the lens alone, and Fig. 4 gives the registration error for the lens-film combinations as a function of field angle. These curves were derived from data presented in Technical Memorandum 1.

A large fraction of the image height error for the AA and CC cameras is due to the change of scale resulting from the focus setting used. Plotted in Fig. 5 are the estimated image height errors that would have resulted if all four cameras had been used at infinity focus. The improvement for this is considerable, reducing the maximum registration error by a *factor of four.*

Fig. 6 represents the measured values of registration error for the flight photography. The measurements were supplied by R. Weber,[3] and were made on the four simultaneous exposures of frame AS9-26A-3799. Each frame is effectively superimposed at the center and the numbers represent x-y distances of each point to the corresponding point in the A frame, arbitrarily chosen as the reference frame. Distances labeled + are farther from the center and those labeled – are closer. The frame key is A for color ir, B for green band, C for black-and-white ir band, and D for red band.

Owing to difficulty in determining the location of the same ground feature on each frame, the original data were considered accurate to only ±60 μm. This large error prevents any realistic correlation with the data in Fig. 4.

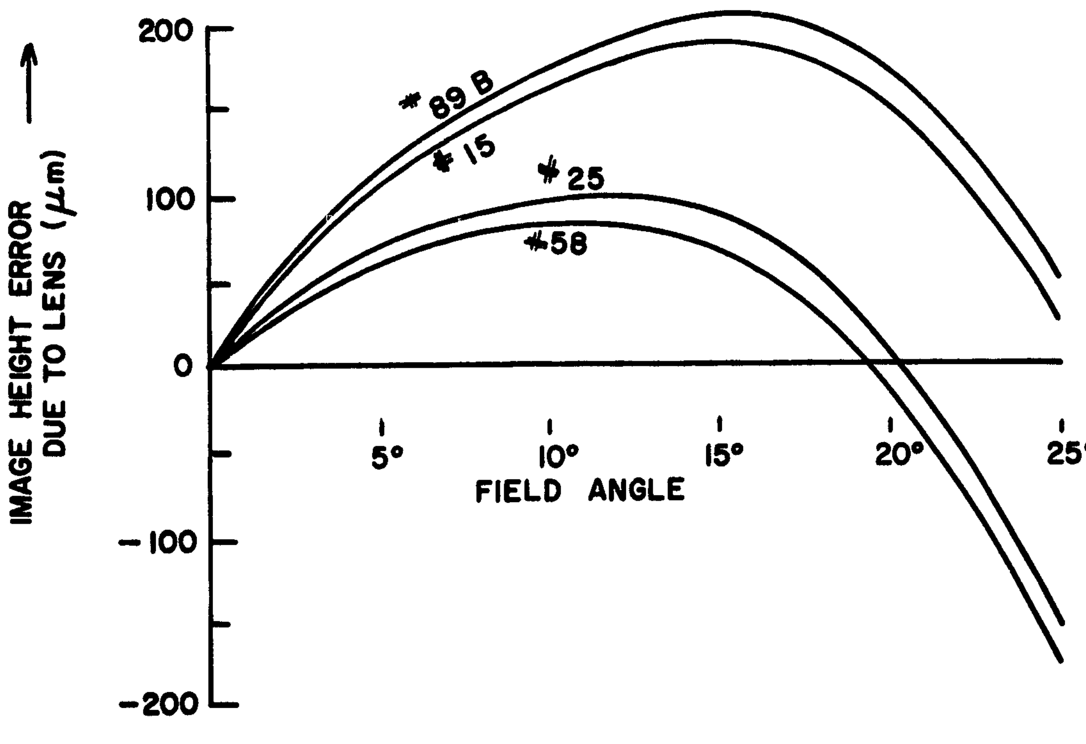

Figure 3. Lens test with plates. Image error is due to lens alone. Values are plotted with respect to distortion-free 80-mm lens

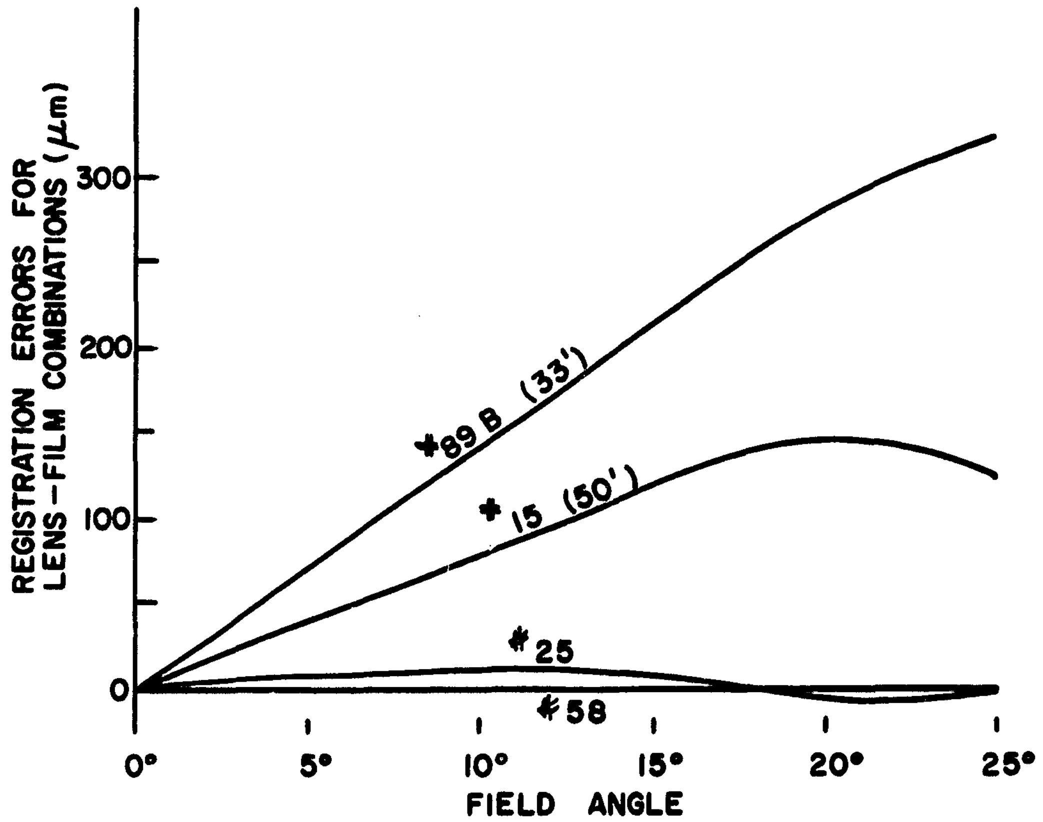

Figure 4. Lens-film combination. Registration errors for flight conditions are plotted with respect to the green (No. 58) camera

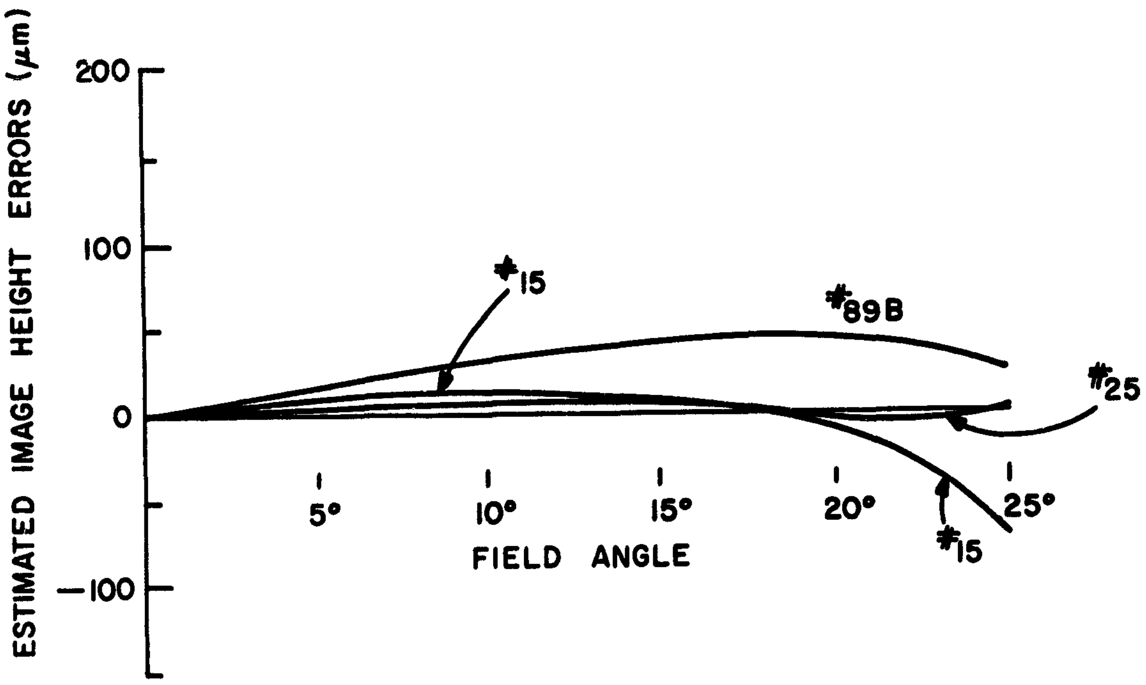

Figure 5. Estimated infinite focus image height errors from center to corner of format for various lens-filter-film combinations are plotted with respect to green (No. 58) band

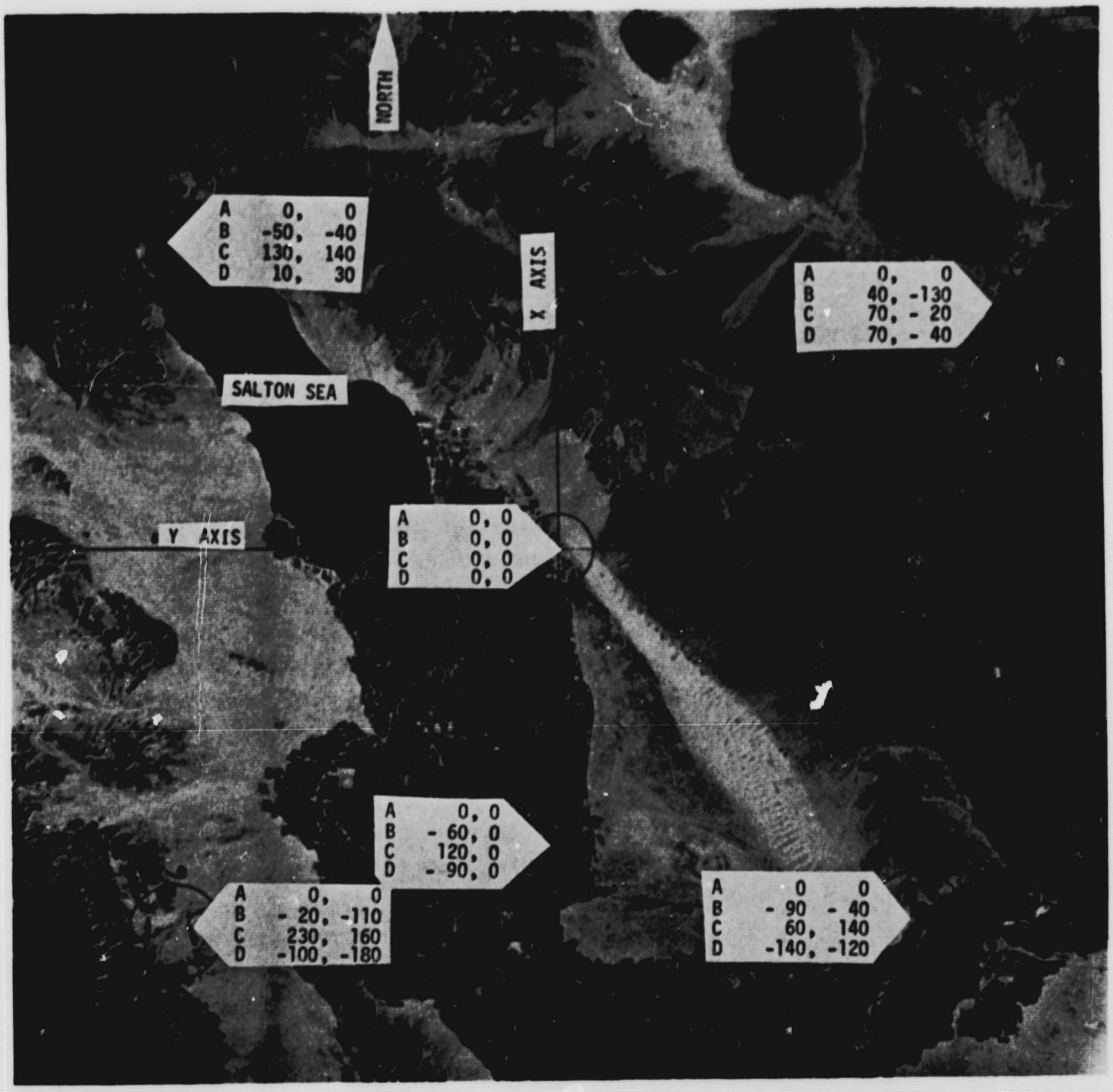

Figure 6. Frames A, B, C, D correspond to magazines AA, BB, CC, DD. Values are the differences (μm) in x-y coordinates of each point from the corresponding point in the A frame

Table 2 gives the expected values of registration error due to various causes. These errors are not necessarily strictly additive and in some instances will tend to cancel with one another, reducing the over-all error.

Table 2
Registration errors (center to corner of format)

Type of error	Typical magnitude of error	Resulting image height error
Chromatic variation in focal length	500 μm	250 μm
Chromatic variation in distortion	12 μm	12 μm
Filter wedge	3 arc min	20 μm
Film flatness	100 μm	50 μm
Boresighting	1°	300 μm

The results of film flatness measurements are presented in Table 3. The data were obtained by loading each magazine with about 1.5 meters of the appropriate film and by focusing a microscope on the emulsion surface at several points over the frame to determine the contour of the film surface. The microscope consisted of a 32X objective and a 6.3X eyepiece; the depth of field was approximately ±1 μm.

The data in Table 3 represent a 5 by 5 array of points across the frame for each magazine. The spacing between the values was 12 mm and extended to within about 3 mm of the flange edge. A reference plane through three corners of the frame was arbitrarily chosen, and the distances from this plane were calculated. The error in the values is about ±10 μm, due to film sag during measurement. The large deviations for magazine AA were attributed by further investigation to the magazine and not the film type. It should be realized that weightlessness and changing temperatures and humidities during the S065 mission preclude accurate predictions of the film contours during the flight.

Finally, the measurements of frame size, shape, and spacing are given in Fig. 7. They were made on simultaneously exposed frames from each magazine, two consecutive frames being averaged for each dimension. The error in measurement is ±0.1 mm, and the edges of the frames are straight within this value. There was little or no variation from the beginning to the end of several feet of film.

Table 3
Vertical distance from the plane defined by the three corners designated 1, 2, and 3 (emulsion up)

	SO-180 2.5 mil base Magazine AA								3400 2.5 mil base Magazine BB					
1 →	0	+35	+55	+40	+15		FILM MOTION ↑	1 →	0	+15	+35	+50	+15	
	-40	-60	-65	-100	-130				-20	-30	-35	-45	-55	
	-60	-90	-110	-150	-190				-30	0	-10	-45	-75	
	+5	-60	-105	-115	-125				-20	-30	-45	-35	-50	
2 →	0	0	+20	+20	0	← 3		2 →	0	-5	+5	+10	0	← 3
	0	+25	+55	+50	0		ADVANCED 1 FRAME		0	+15	+40	+50	+30	
	-35	-30	-65	-85	-130				+20	+20	-5	0	-5	
	-50	-85	-100	-130	-180				+5	-10	-20	-40	-65	
	+15	-40	-100	-130	-125				-5	0	0	-20	-30	
	0	-5	+10	0	0				0	-5	-10	-5	0	
	0	+60	+80	+70	0		ADVANCED 1 FRAME		0	0	+30	+40	+15	
	+20	+15	-20	-60	-120				-20	-20	-30	-35	-50	
	-20	-105	-140	-170	-200				-35	-40	-45	-60	-95	
	+15	-70	-105	-120	-150				-25	-35	-45	-50	-55	
	0	+10	+30	+30	0				0	-5	+5	+10	0	

Table 3 (Continued)
Vertical distance from the plane defined by the three corners designated 1, 2, and 3 (emulsion up)

	SO-246 4 mil base Magazine CC								3400 2.5 mil base Magazine DD					
1 →	0	+25	+45	+45	-10		FILM MOTION ↑	1 →	0	+35	+70	+65	0	
	-5	0	-10	-20	-60				-45	-25	-5	-20	-60	
	-25	+5	-15	-25	-70				-70	-30	-40	-55	-95	
	+20	+35	+10	-5	-10				-50	0	-15	-20	-45	
2 →	0	+30	+30	+15	0	← 3		2 →	0	-10	+20	+15	0	← 3
	0	+20	+45	+40	-20		ADVANCED 1 FRAME		0	+50	+95	+110	+35	
	-15	+5	-20	-35	-70				-40	0	0	+5	-45	
	-25	0	-20	-25	-65				-55	-35	-50	-50	-70	
	+20	+45	+20	+5	-10				-25	+5	+5	+5	0	
	0	+30	+30	+15	0				0	0	+5	+5	0	
	0	+25	+45	+40	-30		ADVANCED 1 FRAME		0	+20	+60	+90	+25	
	-15	+10	-20	-45	-65				-30	-20	-35	-10	-30	
	-30	-10	-10	-30	-55				-40	-15	-25	-45	-65	
	+15	+45	+15	0	-15				-15	+25	0	0	-10	
	0	+20	+25	+15	0				0	+5	+10	+5	0	

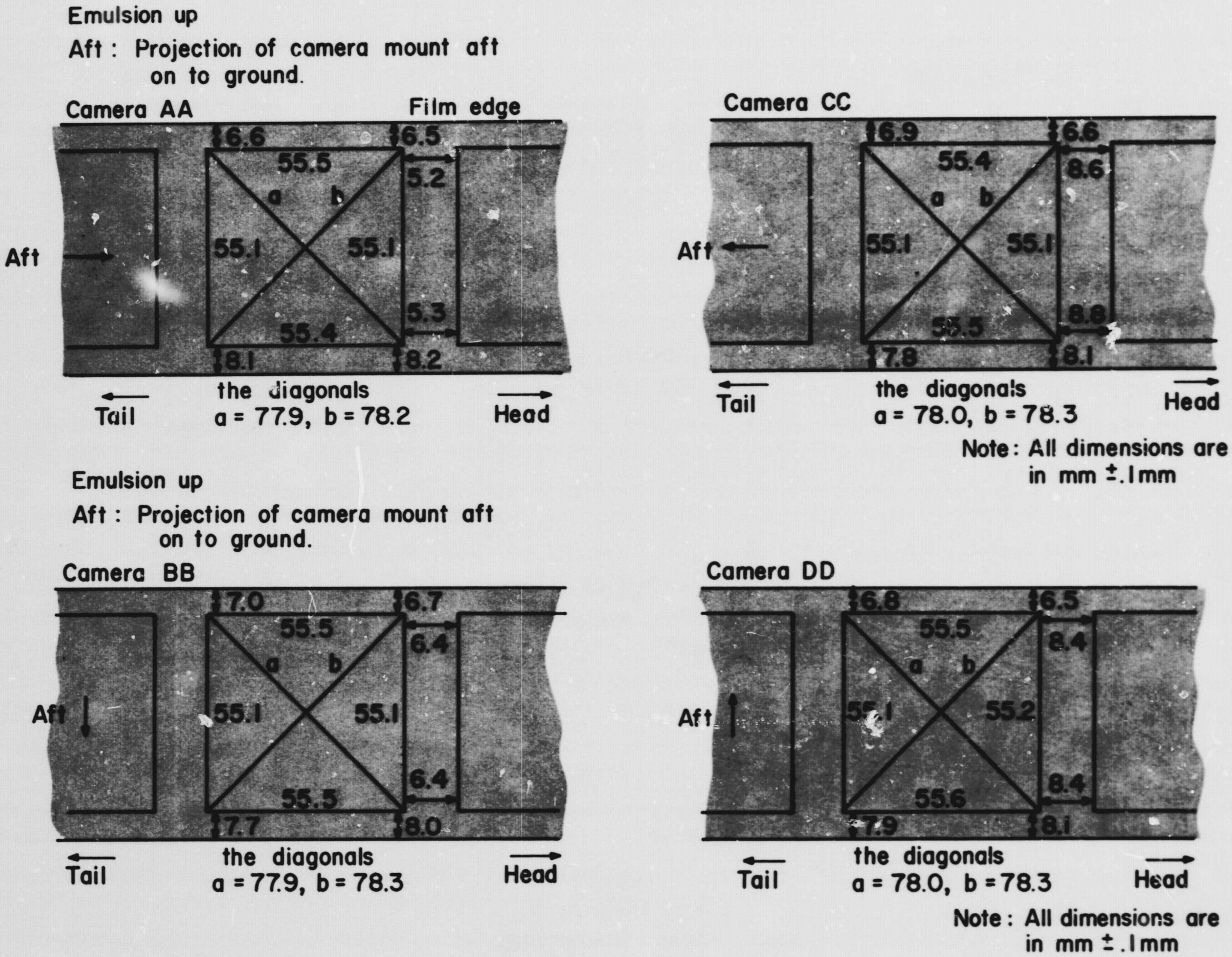

Figure 7. Format size

RESOLUTION

Resolution measurements were made on cameras CC (black-and-white ir band) and DD (red band), with filters, film, f/numbers, etc. identical to flight conditions. Camera BB (green band) was not tested because the film drive motor had failed, necessitating its return to the factory.

The tests were made with a tungsten light source and a USAF 1951 three-bar target. Area-weighted average resolution (AWAR) values were calculated as described in MIL-STD-150A, and ground resolution values are given for an altitude of 200 km (108 n. mi.). The data are given in Table 4. Flight altitudes ranged between 180 km (97 n. mi.) and 246 km (133 n. mi.).

Table 4
Resolution

Target contrast	Camera	Focus setting	Radial or tangential	0°	7.5°	15°	22.5°	AWAR lp/mm	Ground resolution m(ft)
>100:1	DD	∞	R	67	75	41	40	51	50(160)
			T	67	69	53	38		
	CC	33 ft	R	37	36	28	30	31	80(270)
			T	37	35	31	26		
	CC	∞	R	40	38	39	37	36	70(230)
			T	40	37	33	30		
2.6:1	DD	∞	R	54	62	34	34	43	60(190)
			T	54	53	49	34		
	CC	33 ft	R	32	27	24	21	24	100(340)
			T	32	25	24	21		
	CC	∞	R	31	30	30	29	29	85(280)
			T	31	28	29	31		

Using the formula $R_M = R_o M^n$ given by Mayo[4] where R_o is the resolution at a target modulation > 0.98, M is the target modulation, R_M is the resolution at M, and n is an experimental number characteristic of a given lens-film combination, we find that the values of n for the above lenses and films are:

DD, SO-164 $n = 0.23$
CC, SO-246 $n = 0.30$

The estimated values of resolution at a target contrast of 1.6:1 were calculated, and are presented in Table 5.

Table 5
Estimated low contrast resolution

Target contrast	Camera	Focus setting	AWAR (lp/mm)	Ground resolution [m(ft)]
1.6:1	DD	∞	36	70(230)
	CC	33 ft	20	125(400)
	CC	∞	23	110(360)

A through-focus series was made with camera CC, with the highest AWAR occurring at infinity focus. This fact, combined with the misregistration introduced at a focus setting of 33 feet for camera CC, indicates that this camera should have been at infinity focus during the flight.

The above supersedes data previously presented on high-contrast resolution and estimates of low-contrast resolution. It should be emphasized that the ground resolutions listed above are estimates based on *laboratory tests* of the flight equipment. Also the data are given in terms of three-bar resolution, an artificial but generally accepted criterion. There will be departures from the data listed above depending principally on target contrast and shape, film exposure, and processing.

Under an extension of the present contract we will analyze the original photography and up to fourth-generation duplicates. We will then be able to estimate the actual resolution obtained in the flight photography taking into account atmospheric contrast attenuation, spacecraft window degradation, exposure and processing conditions, etc. We will also estimate the resolution loss in each generation copy.

REFERENCES

[1] P. B. Keenan, and P. N. Slater, "Preliminary post-flight calibration report on Apollo 9 multiband photography experiment S065," Optical Sciences Center Technical Memorandum 1, 14 pp., Sept. 1969.

[2] Eastman Kodak Company, 1961 to date, Manual of Physical Properties: Aerial and Special Materials, Data Section 19, Eastman Kodak Company, Rochester, New York.

[3] R. Weber, NASA/Manned Spacecraft Center, Houston, Texas, private communication.

[4] J. W. Mayo III, "Photographic resolving power of aerial reconnaissance lenses as a function of target modulation," Optical Sciences Center Technical Report 28, p. 21, Aug. 1968.

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