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SUBTASK REPORT

PROBLEMS AND POSSIBILITIES OF HIGH ALTITUDE WORLDWIDE MAPPING

Analysis of Existing and Proposed Data Input to Ground Data Reduction

Task 1, Subtask B

20 August 65

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PROBLEMS AND POSSIBILITIES OF HIGH ALTITUDE WORLDWIDE MAPPING

Analysis of Existing and Proposed Data Input to Ground Data Reduction

Task 1, Subtask B

Prepared by [redacted]

Approved by

20 August 65

Itek

Itek Corporation

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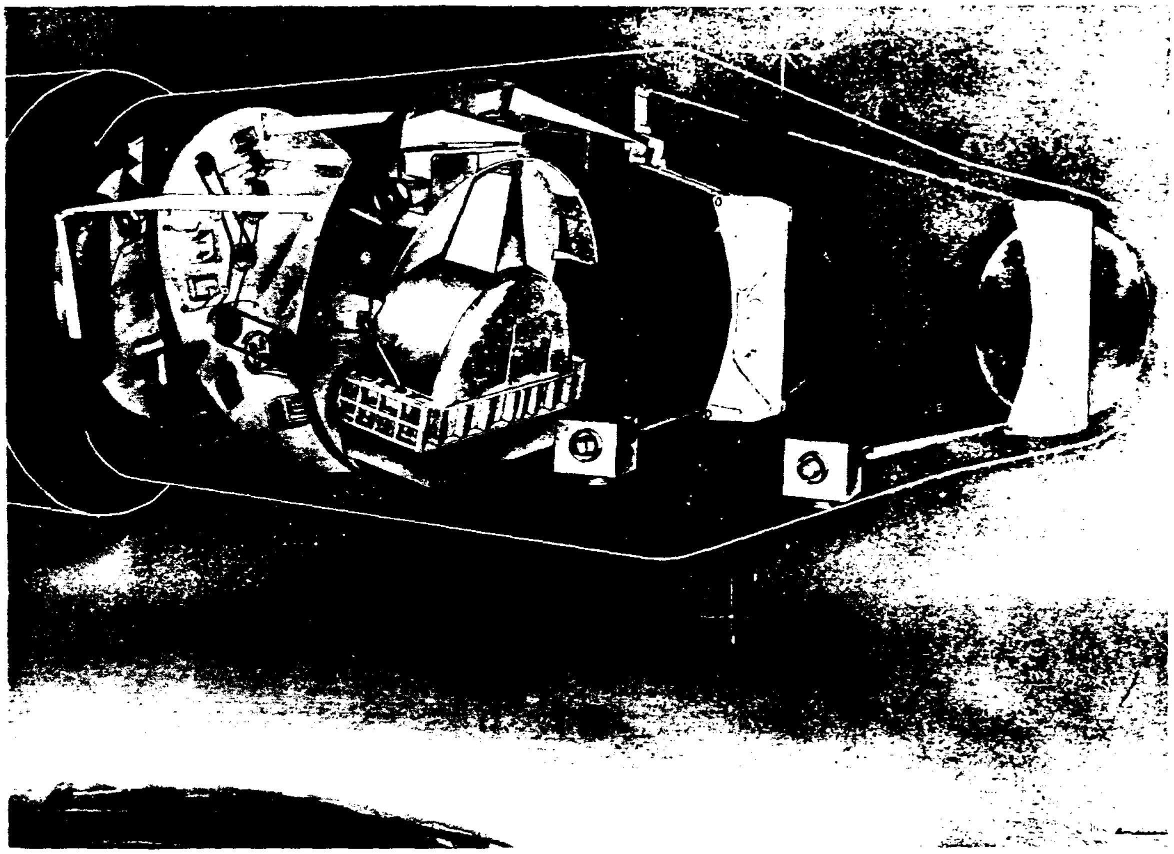


Frontispiece - J-1 Camera System

CONTENTS

CONTENTS (Cont.)

FIGURES

1. INTRODUCTION

The investigation into existing mission data performed under Subtask B of Task I has produced a vast amount of data, both in computer tabulation form, and in various reports by different agencies. A great amount of sifting has been required to ascertain the timeliness and validity of the information, its value in the photogrammetric analysis, and its original source.

A basic understanding of the operation of the J-1 Camera System components is necessary in order to appreciate the full impact of the system on the mapping problem. For this reason a description of the operation of both the J-1 Panoramic Camera and the Stellar/Index Camera has been included as part of this report.

In the Appendix of the Task I Subtask A report is a listing of the mission reports and the computer outputs. This listing has also been incorporated in this document in spite of the redundancy, since it is an important part of the mission data output. Information concerning cycle rates, V/h programmer, and image motion compensation are included. The basis for time referencing and recording is both described and illustrated.

The section on the Stellar/Index Camera is based primarily on the $1\frac{1}{2}$-inch Double Frame Camera. Where definitive information is available on the I.S.I.C. it has been included. Unfortunately, when this report was prepared, the specifications for the camera and its calibration were not available to this organization.

One of the most important portions of this report is the description of the changes to be incorporated in the J-2 Panoramic Camera System that will enable calibration of the internal geometry. Actual samples of the rail fiducials and the collimator images will be made available at the earliest possible date along with the microdensitometric traces so that the user agencies may conduct mensuration evaluations of the imagery.

Section 6 is an attempt, based on this organization's experience, to provide an insight into those aspects of the system which may cause variance in the system output.

Section 7 details the calibration procedures concerning not only the entire system but the component calibrations which tie the various parts of the system together. Calibration procedures intended for the Panoramic Geometry System are described and the Stellar/Index Camera Calibrations are presented in some detail.

The Data Bank principle is discussed in Section 8 of this report. The necessity for applying the maximum information to the Ground Data Reduction, particularly in areas of little or no control, makes it paramount that all available data from a myriad of sources be considered for its value to the mapping problem.

2. MAIN INSTRUMENT ACQUIRED DATA

This section describes the operation of the J Camera System and the data it generates during a mission.

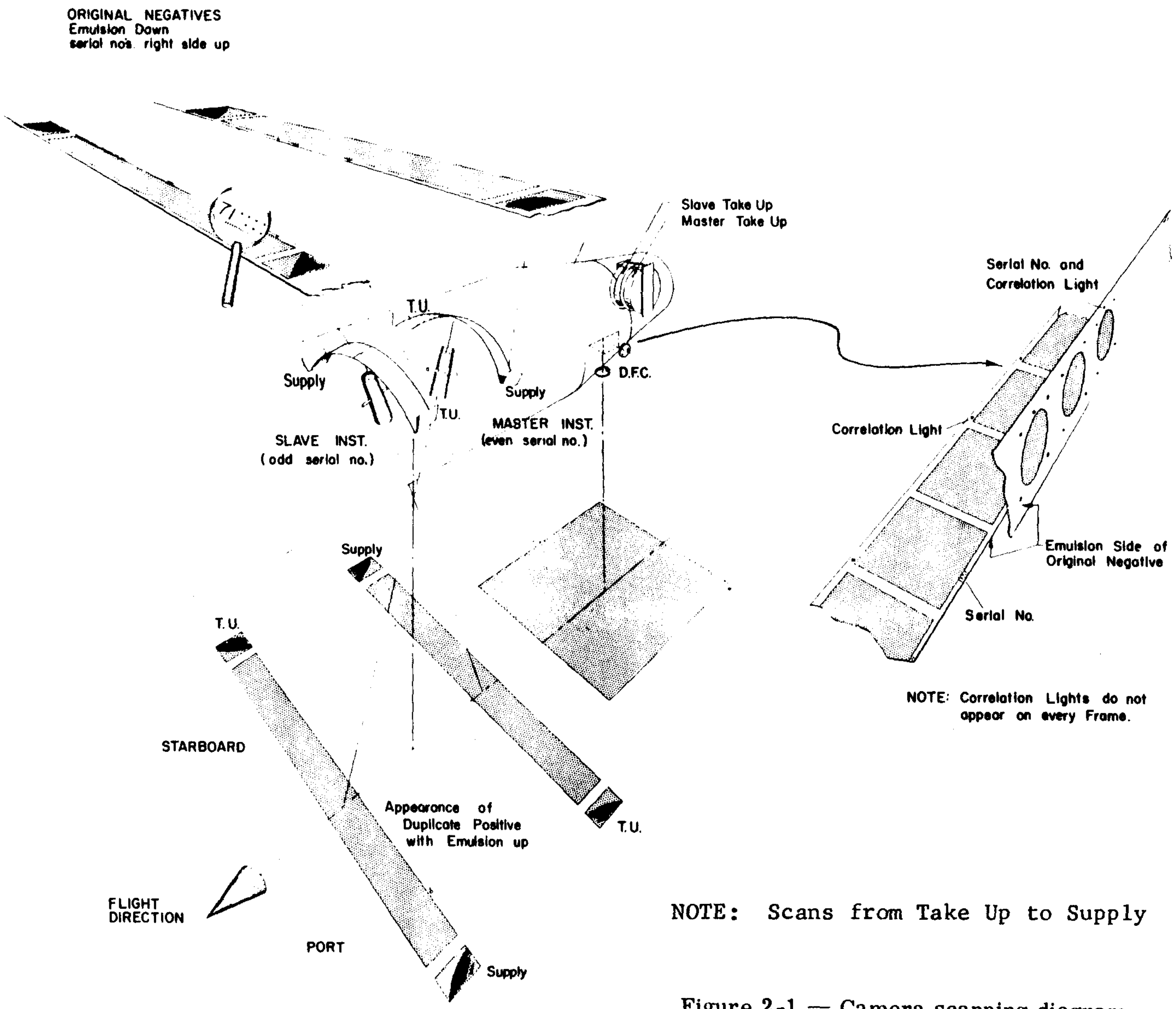
2.1 PANORAMIC CAMERA OPERATION AND COVERAGE

The Mural Panoramic Camera System consists of two high-acuity panoramic cameras with separately contained film supply cassette, two take-up cassettes, ancillary electrical packages, a support frame for the camera system and a support truss for the supply cassette. (See Figure 2-1 and Table 2-1.) In addition, two double frame cameras (Stellar/Index) provide metric information for the panoramic photography. Each S/I Camera provides coverage for each half of a mission.

The panoramic camera consists of a constantly rotating lens synchronized with a velocity matched reciprocating scan head. The lens is rotated about its rear nodal point, and the oscillation axis of the scan arm coincides with the scan axis of the lens. The film is exposed during the exposure portion of the scan and is transported during the return scan. Film guide rails locate the film in the approximate focal plane, and the rollers mounted on the end of the scan arm lift the film slightly above the guide rails to position the film in a precise film plane. This design provides a rigid tie between the axes of rotation, the scan arm oscillation, and the film rails, to minimize any degrading effects of vibration.

The lateral angular coverage of each camera is 70 degrees (± 35 degrees). The two panoramic cameras provide full stereo coverage at a 30 degree convergence angle. The fore and aft angular coverage is slightly over 5 degrees.

While a frame is being metered, the scan arm rotates in a direction counter to the continuous lens rotation. When the scan arm reaches the "start-scan" position the shutter opens, and the arm reverses direction. The scan arm accelerates until it reaches the "start-exposure" position. The scan arm and the lens reach this point simultaneously. At this point, the scan arm and the lens, the velocities of which are now identical, are mechanically coupled by a latching system. The coupled scan arm and lens then sweep at a constant velocity, to expose the film which is being held motionless, until the "end-of-exposure" position is reached, following which the scan arm and the lens unlatch. The scan arm decelerates to the "end-of-scan" position as lens rotation continues, film metering resumes, the scan arm reverses direction and returns to the "start-scan" position and the next cycle begins.



NOTE: Scans from Take Up to Supply

Figure 2-1 — Camera scanning diagram

Table 2-1. J-1 Panoramic Camera Operating Characteristics

Lens type	24-inch, f/3.5 Petzval
Film	Type 3404 thin-base 70-millimeter film (former designation 4404)
Filter	Wratten 21 or 25
Lateral angular coverage	70 degrees (±35 degrees)
Forward angular coverage	5 degrees
Frames/camera	5560
Film length/camera	15,600 feet
Dynamic resolution	Exceeds 130 lines per millimeter at 2:1 contrast
Maximum cycle rate at V/h = 0.043	2.2 seconds
Power consumption/camera	500 watts
Camera weight (master)	122 pounds
Camera weight (slave)	113 pounds
Supply cassette (full)	230 pounds
Twin take-up (empty)	42 pounds
Truss weight (main cameras)	112 pounds
Truss weight (supply cassette)	84 pounds
S/I Camera	15 pounds
Total loaded system weight	703 pounds

Camera cycle rates are a function of the V/h ratio, which is matched through the selection of a pre-programmed ramp function derived for the expected vehicle orbit. In operation this falls within 1 percent of the expected orbit. As the orbit decays, it is possible to make discrete changes in the programmer to correct the cycle rates. The vehicle programmer supplies an analog voltage to the camera servo system drive motor to control the cycle rate. Cycle times range from 6.0 seconds per cycle to 2.15 seconds. A limit is imposed on the system a maximum cycle rate of 2.2 seconds per cycle to assure reliability. Cycle rates of the two cameras are maintained within 1 percent. Image motion compensation is achieved through the IMC cam which is attached to the lens shaft. Lens shaft rotation causes the cam to translate the lens along the line of flight. During the exposure portion of the scan, the cam translates the lens at a velocity which is a function of the scan angle in a direction counter to the direction of flight. Translational velocity is directly proportional to the lens rotation rate, and therefore, to the required V/h.

Table 2-2 lists resolution obtained by the panoramic camera under operational conditions.

2.2 AUXILIARY PHOTOGRAPHIC IMAGERY

In addition to the two panoramic cameras, auxiliary cameras on each main camera photograph the horizon every other frame. These auxiliary optics provide data for pitch, roll, and yaw determination. The Horizon Cameras incorporate 55 millimeter focal length, f/6.3 Aero-Raptar lenses with Wratten No. 25 filters. The assemblies are mounted to the main instrument at a depression angle of 15 degrees. This, combined with the convergence angle of each camera of 15 degrees, places the horizon image across the diagonal of a 2.1 by 0.9-inch format. The quality of the imagery expressed in lines per millimeter is in excess of 125 lines per millimeter on Type 3404 (former designation 4404). Fiducials are provided to facilitate data reduction. A calibration of the angles between the panoramic cameras and the horizon cameras is affected prior to flight to an accuracy of ±6 seconds. This calibration is discussed in detail under Section 7.

2.3 AUXILIARY DATA INPUTS

Also incorporated in the imagery are images of fiducials cut in the film rails to indicate the center-of-format and shrinkage markers. A binary readout is exposed on each frame along with the serial number. In addition to the serial number, an indexing bit is also exposed to aid in alignment of the data block when using automated readout equipment. Associated with the data block, but separately controlled, is an end-of-pass X-mark. This is exposed on the last frame of every photographic pass. The last frame of each such pass does not include a time readout due to interface problems.

In the area just outside the format, a frequency mark is exposed by a neon lamp triggered by a 200 P.P.S. generator. At each scan the center-of-format switch pulses a lamp synchronization unit which instantaneously interrogates the vehicle clock and sends a blanking pulse to the frequency marker. This blanking pulse is thus the basic time reference for the format. (See Figure 2-2.)

Table 2-2. Operational Performance

		Ground Resolved Distance, feet			
		One Sigma		Two Sigma	
Altitude	Direction	Center of Format	30°	Center of Format	30°
100 nautical miles	Along track	9.3	10.7	11.5	13.1
	Across track	10.2	19.5	12.9	24.1
90 nautical miles	Along track	11.8*	12.9*	14.6*	15.6*
	Across track	9.2	18.3	11.6	21.7

*10 percent systematic IMC error.

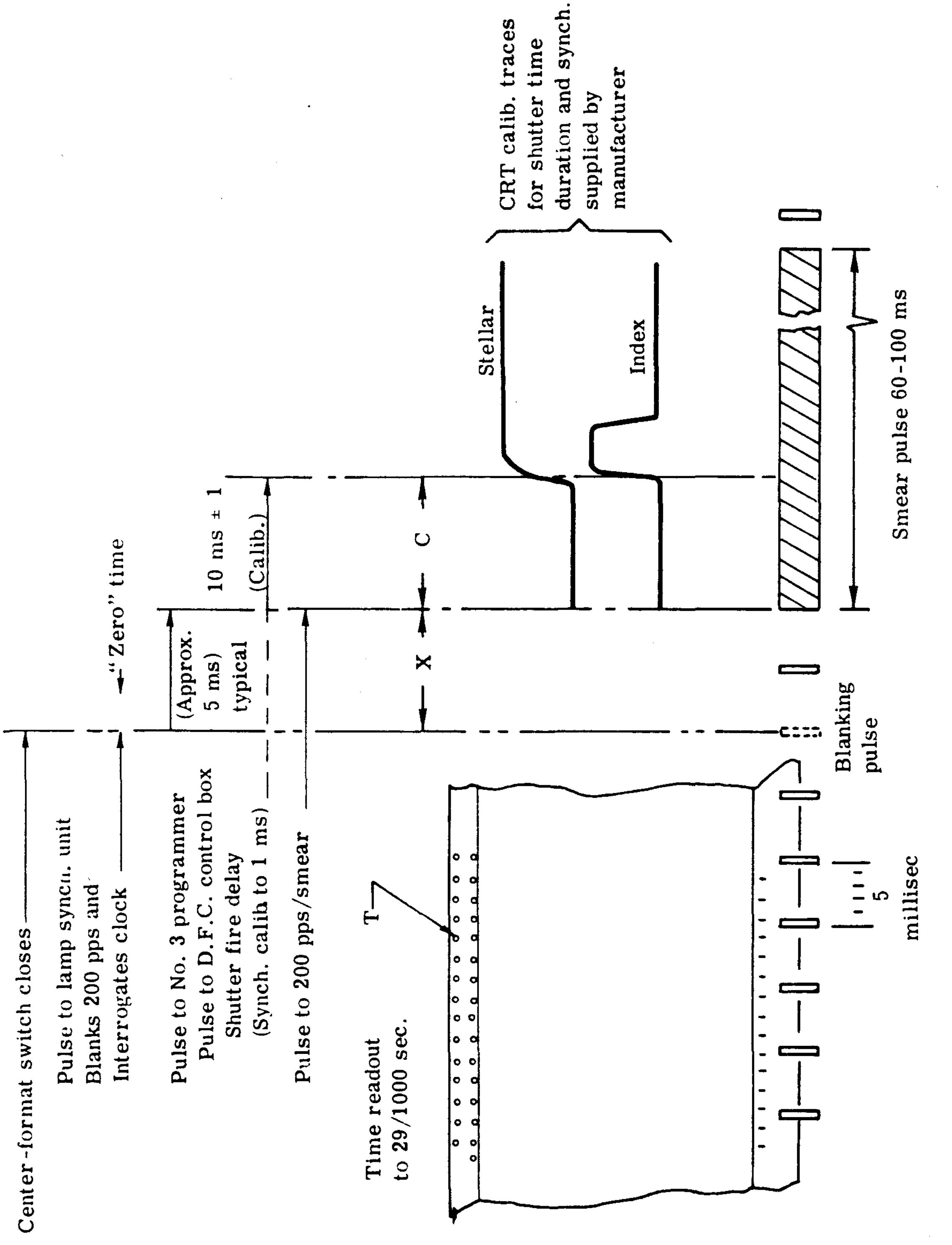


Figure 2-2 — Time reference

3. VEHICLE/INSTRUMENT MISSION DATA

This section describes the mission-generated data that concerns the vehicle and camera system performance. The data are used in referencing and calibrating the photographs obtained by the camera system.

3.1 INSTRUMENT CYCLE RATE

For each photographic pass, a cycle rate and V/h tabulation are prepared from binary data and frequency bit measurement and are correlated with telemetered data obtained from the tracking stations. The nominal cycle rates are listed along with the actual determined rates and the V/h ramp positions. The cycle rates of the two panoramic cameras vary depending upon the V/h programmer. In addition, slight variations (±1 percent) exist between the Master and the Slave Camera. The following nominal cycle rates are based on a sampling of 5 missions and 16 revolutions:

Actual	2.794 seconds/cycle
Nominal	2.784 seconds/cycle

Nominal scan speed over the format (70 degrees) is 0.483 seconds/cycle. Cycle rates and scan speed are proportional to V/h with a 10 percent overlap. The programmer has 121 pre-programmed orbits which can be preset or changed in flight. In practice, there has been less than 1 percent variation between final orbit and the programmed orbit. The ability to change the programmer in flight is necessary to correct for orbital decay.

Several telemetry points are available for evaluating cycle rates, center of format switch pulse, cycle counter, tachometer and others. The minimum cycle rate is limited to 2.15 seconds/cycle and the maximum is 6 seconds/cycle. The nominal rate is 2.5 seconds/cycle for most missions. In many instances the cameras have run slower than predicted, necessitating a change in ramp settings during flight for compensation.

The Flight Cycle Rate Summary includes the following listings:

1. Revolution and Mode
2. Ramp Setting
3. Time Up Ramp
4. Instruments 1 and 2 Actual Rates
5. Nominal Rates (Predicted)
6. Instruments 1 and 2 Deviation
7. Instruments 1 and 2 Difference

3.2 V/h PROGRAMMER

The V/h programmer and transducer are set such that voltages to the panoramic camera drive motors maintain camera cycle rates to within 5 percent of the required value for proper IMC. For a given command, cycle rates of the two cameras are maintained within the specified 3 percent of each other. Operationally, it has been shown that the cycle rates are maintained within 1 percent of each other. Camera cycle rates are a function of the exact V/h ratio which is matched through the selection of pre-programmed ramp functions for the expected vehicle orbit. 121 non-linear ramps are provided to cover a wide spectrum of possible orbit characteristics. Operational cycle rates range from 6.0 to 2.15 seconds per cycle. A programmer limiter circuit assures that the cycle period will be no shorter than 2.15 seconds per cycle. The V/h programmer ramp length is 32 ± 0.5 minutes. Due to the time required for the instruments to get up to speed, the first few frames are not considered when computing cycle rates. Depending upon the ramp position, the instruments reach the top of the ramp either in a few frames at a slow cycle rate, or as much as five frames at a rapid cycle rate.

3.3 IMAGE MOTION COMPENSATION

Image motion compensation is achieved through a fixed IMC cam, which is attached to the lens shaft. Lens shaft rotation causes the cam to translate the lens along the line of flight. During the exposure portion of lens rotation, the cam translates the lens at a velocity which is a function of scan rate angle in a direction counter to the direction of flight. Translational velocity is directly proportional to the lens rotational rate, and, therefore, the required V/h.

The total displacement of the lens during scan is 0.4144 inch. Total displacement per degree is 0.0055 inch. Over the total scan the error is less than 1 percent. (See Figure 3-1.)

3.4 TIME REFERENCING AND RECORDING

Time referencing and recording of the system cameras and other auxiliary instruments is based on an in-flight electronic clock. Both before and during flight, the clock is calibrated to an accuracy of 3 milliseconds. The clock has a drift (maximum) of 1×10^{-6} in 12 hours, but this is corrected. A time word print-out appears on all panoramic frames except for the end-of-pass frame. This time coincides with the blanked frequency pulse generated by the 200 PPS generator. The time read-out is to 1 millisecond. The clock is synchronized to the camera system by a lamp synchronization unit which interrogates the clock when the center-of-format switch is actuated. The center-of-format switch actuation and the physical center of the format do not coincide. The reference is always to the blanked frequency pulse. The time data is stored unambiguously and then printed outllater in the scan sequence by the binary data block. The data block is composed of thirty bits of which four are redundant. In case of lamp failure, the redundant bits may be activated prior to flight.

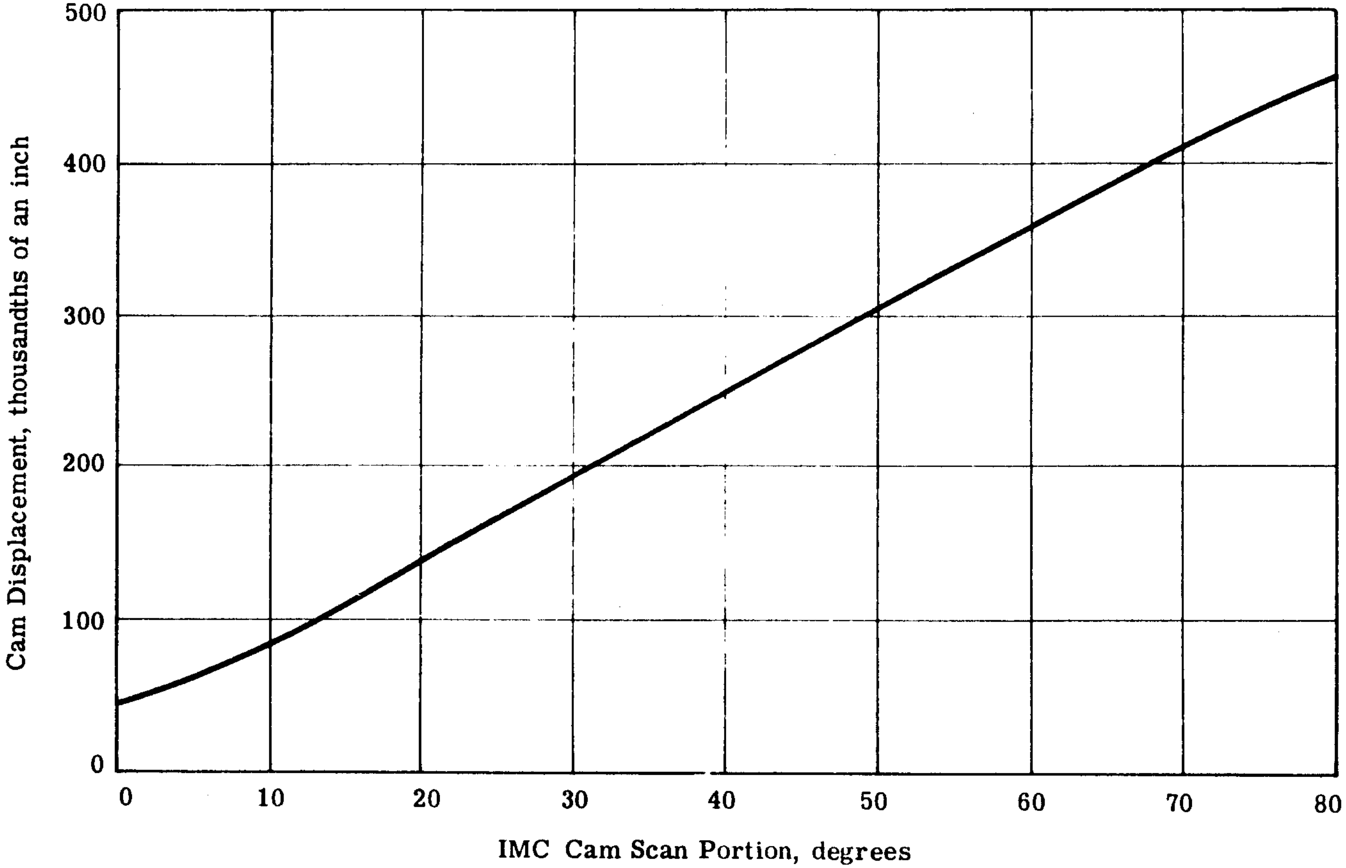


Figure 3-1 — IMC cam displacement

The time of exposure of the Stellar/Index Camera is related to the Main Instruments through a calibration of shutter synchronization, shutter delay and smear pulse calibration. (See Figure 2-2.)

3.5 MISSION DATA

3.5.1 Mission Environment Source Data

Preliminary Report TWX

This report is generated by team from NPIC at the Processing Facility. It is a general report on physical and photographic aspects of the recovered film. While there is no photogrammetric data, this material is useful in checking back on anomalies.

Preliminary Mission Analysis

This report is a more inclusive compilation of data put together by an evaluation team with representatives from both the vehicle and camera manufacturers. It is referred to as the MISSION ANALYSIS REPORT. The following data is reported.

1. Data of launch, time and serial number of instruments.
2. General orbital data comparing predicted to actual (very general in scope).
3. General thermal data with excursions.
4. Comments on clock analysis and correlation (excerpts from correlation tabulation).
5. Cycle rates, fast or slow with tables of actual versus nominal, and what the percent deviation was. This data is generally drawn from cycle rate tabulation and is only general in scope.
6. Tabulation of orbital data for various orbits (drawn from ephemeris tabulation).
    - Period
    - Perigee
    - Apogee
    - Eccentricity
    - Perigee latitude
    - Inclination
7. Comments on image quality and any anomalies are answered to the best of the ability of the team.
8. Attitude information is described (incomplete).

Flight Summary

This summary is a more complete report than the preliminary report mentioned above. It contains tabulations and computer outputs on attitude information and frequency distribution of attitude and rates. It also contains tabulations on cycle rates, time correlation, etc.

NPIC Photo Evaluation Report

This report contains general photographic data; it also includes cloud cover analysis.

SPPL Technical Evaluation Report

This report deals with image quality.

3.5.2 Computer Tabulation Summary

Ephemeris

1. Universal time (accuracy of 3 milliseconds)
2. System time
3. Geodetic latitude (2000 feet in-track)
4. Longitude (1000 feet cross-track)
5. Height (good to 200 feet)
6. Radial distance (based on standard AF surface)
7. Right ascension
8. Inertial velocity
9. Flight path
10. Azimuth
11. Geocentric latitude

Epoch

1. Revolution number
2. Time
3. Long ascending node
4. Inclination
5. Eccentricity
6. Period
7. Decay
8. Perigee
9. Argument of perigee
10. Apogee

Time Correlation

System time correlated to Universal time. Sigma data included.

Cycle Rates and V/h

Supplied for each photographic pass and referenced to time.

Mission Tabulation

NUM
OP (revolution)
NUM (frame
T (reciprocal of exposure)
EL (solar elevation)
AZ (solar azimuth)
VEL (ground velocity)
DTT (distance to target)
CY (V/h error)
PE
RE } (error) (°) every 7th frame rates and error derived for each frame
YE
CE (crab error)
PR
RR } (°hour)
YR
ATE (long track IMC error in percent)
RLA (resolution limit in-track in feet } "Center of Format" only
CTE (cross track error)
RLC (resolution limit in cross-track in feet
DATA NOT AVAILABLE (last line tells what is missing)

4. STELLAR/INDEX CAMERA ACQUIRED DATA

This section contains a detailed description of the Itek Stellar/Index Camera. As part of the Mural Panoramic Reconnaissance System, the Stellar/Index Camera provides the following:

1. A framework for correlating and locating stereoscopic panoramic photography.

2. Geometric data which assists in the elimination of panoramic camera distortion.

3. Photogrammetric information to provide control extension over long distances and position determination when this information is combined with orbital data.

4. Stellar information to aid in the determination of pitch, roll, and yaw during photographic operation.

The Stellar/Index Camera System consists of a downward (terrain) looking frame camera and an integral stellar-looking frame camera. (See Figure 4-1 and Table 4-1.) Stellar/Index operation is controlled by a remotely located programmer pulsed through the center-of-format switch of the Mural System Master Panoramic Camera. The first pulse received by the camera winds both shutters, and subsequent pulses (1) trip the shutters and pulse the correlation and fiducial lamps, (2) lift the platens, (3) meter film, (4) lower the platens, and the cycle is repeated. Telemetered signals verify 35 millimeter and 70 millimeter film transport and terrain shutter firing.

4.1 INDEX CAMERA

The $1\frac{1}{2}$-inch Index Camera incorporates a 38 millimeter, f/4.5 Aeregor lens (Biogon) with a Schott OG-5 filter. Shutter speeds may be preselected from 1/125 to 1/500 second. The camera uses 70 millimeter film and has a capacity of 400 frames. The camera frame length is $2\frac{3}{8}$ inches, and the exposed format is 2.25 inches square. The field angle of the camera is approximately 72 degrees across the frame and 90 degrees across the diagonal. From an altitude of 100 nautical miles, coverage per frame is approximately 150 nautical miles on a side. The camera is capable of providing 55 to 65 percent overlap between adjacent frames for stereo photography. Nominal cycle time based on a nominal cycle rate of the Panoramic Camera System is 17.5 seconds. Minimum AWAR of the Index Camera as defined in MIL-STD-150A is 70 lines per millimeter on Type 4400 film. Operationally, the resolution consistently achieved has been between 85 and 100 lines per millimeter.

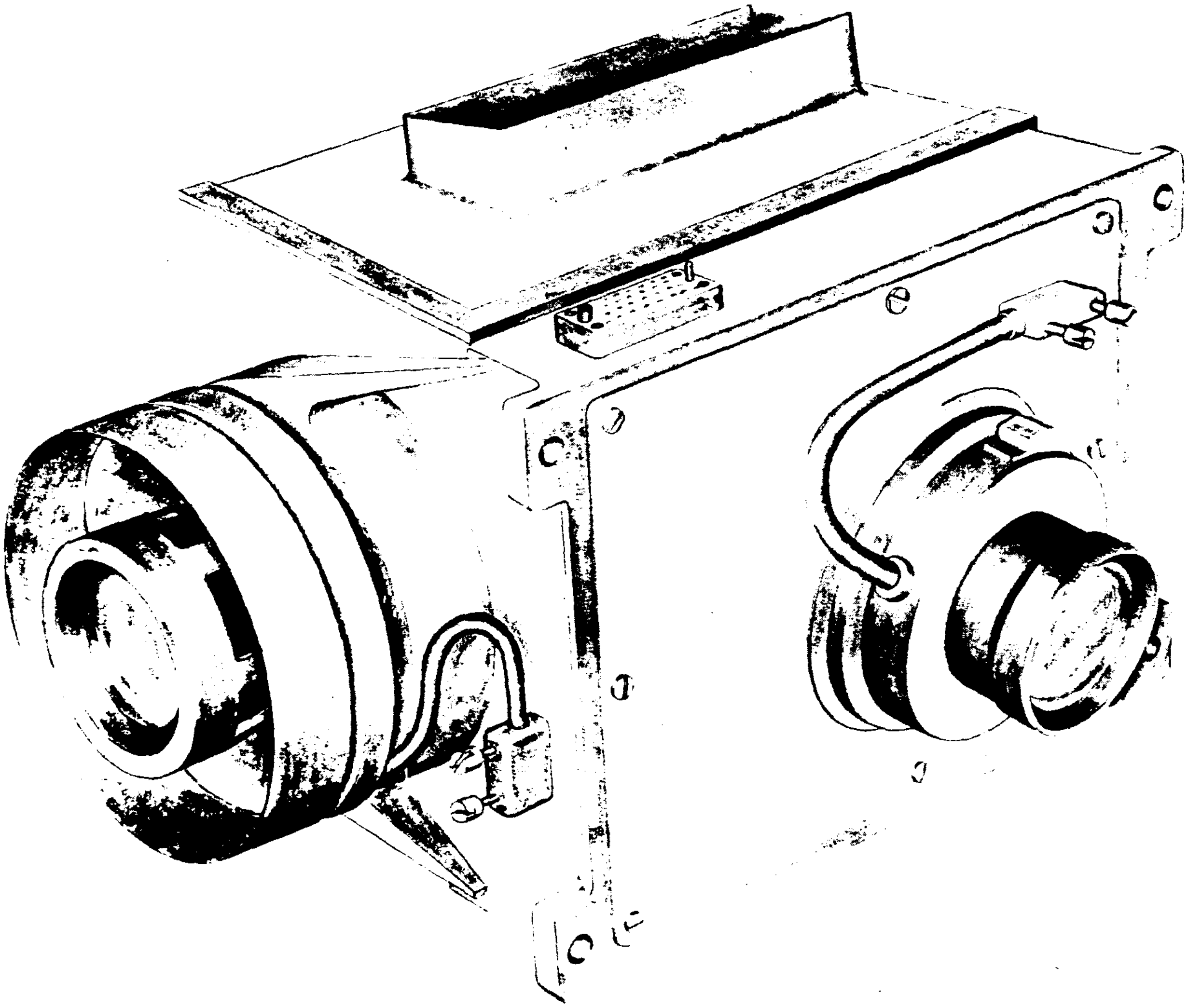


Figure 4-1 — Stellar/Index Camera

Table 4-1. Specification Summary 1½-Inch Focal Length Stellar/Index Camera

Configuration	Polar Type
Lens Type	
Index	38 millimeter Goerz Aeregor f/4.5, with Reseau Schott OG-5 filter
Stellar	85 millimeter Canon f/1.8 reworked, with Reseau
Angular Coverage	
Index	72 degrees across the format, 90 degrees across the diagonals
Stellar	16 degrees
Overlap	Cycled to provide 60 percent overlap
Format Size	
Index	2.25-inch square
Stellar	15/16-inch diameter
Film Capacities	
Index and Stellar	400 frames
Film Type	
Index	Type 4400 Estar Base
Stellar	Type 4401 Estar Base
Reseau Specifications	2.5 millimeter line spacing with 5 micron line weight

4.2 STELLAR CAMERA

The $1\frac{1}{2}$-inch Stellar Camera incorporates an 85 millimeter f/1.8 Canon lens. Shutter speed is limited to 2.0 seconds. The camera uses 35 millimeter film and is capable of providing a minimum of 400 frames of photography when using 0.0035-inch thick triacetate or polyester base films. The camera frame length is $1\frac{3}{16}$ inches and the exposed format is $\frac{15}{16}$-inch in diameter. The field angle of the lens is approximately 16 degrees. However, the field angle is slightly obstructed by a flare baffle designed to reduce earth-flare to a minimum. A typical format is illustrated in Figure 4-2. The Stellar Optical System calibration is described in Section 7. In operation the Stellar Camera records stars to magnitude 6 and 7. There are normally a minimum of 25 star images per frame providing a choice of images for data reduction. Since the S/I Camera is a polar type system, the star images appear to rotate about the format.

4.3 RESEAU SYSTEMS

Reseau grids are incorporated into both the Stellar and the Index optical systems. These reseau lines are nominally five microns in width and are of the evaporated metal type. These reseaus are calibrated so that the residual distortion is less than 2 microns. Complete calibration data reduction is supplied with each system. Identification markings are incorporated in each reseau. The Stellar Camera reseau incorporates four illuminated reseau intersections outside the format area plus an illuminated serial number which is also the correlation mark for matching the Stellar Camera imagery to the Index Camera imagery. The Index Camera serial number is recorded on each frame adjacent to the format at the time of exposure. Also adjacent to the format is the correlation mark which is exposed randomly by the Stellar Camera.

A photocell in the Index Camera optical cell provides telemetry data for shutter-fire monitoring.

NOTE

> The 35 millimeter and 70 millimeter reseau grid serial numbers are not necessarily the same as each other nor the same as the camera body serial number. The complete Stellar/Index Camera serial number consists of the following elements:

camera body serial number
70 millimeter reseau grid serial number
35 millimeter reseau grid serial number

DX / X / X

In addition to the shutter signal, a signal is provided for monitoring film transport.

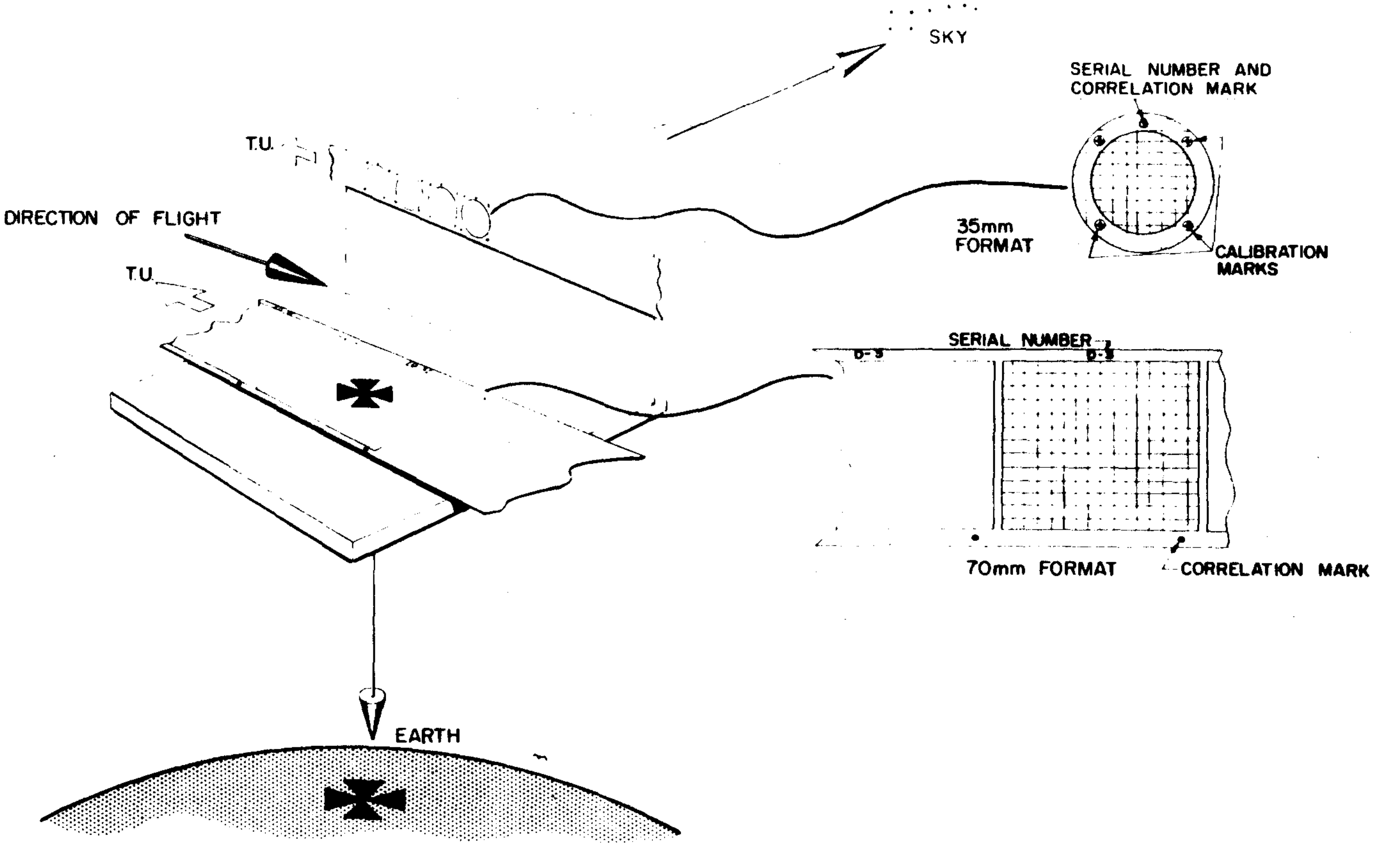


Figure 4-2 — Stellar/Index Camera format

4.4 SHUTTER CALIBRATION

Shutter time-delay calibration data is supplied with each camera. Shutter operation is such that the time delay between the initiation of the shutter-fire signal and the actual opening of the 35 millimeter and 70 millimeter shutters is approximately 2 milliseconds. Oscilloscope traces are recorded and supplied for each camera.

NOTE

> The time delay between the shutter-fire signal and the opening of the 70 millimeter shutter is thus known, as is the delay between the smear pulse and the opening of the shutter, and serves as a time base with the Panoramic Camera exposure where the smear pulse is recorded simultaneously with the shutter fire signal.

4.5 I.S.I.C. STELLAR/FRAME CAMERA

The specifications and calibration data for the I.S.I.C. Stellar/Frame Camera intended for inclusion in the System sometime in the middle of 1966 are not included in this report since they have not been made available to this organization. As soon as they are available they will be reviewed and reported on as to their application to the Ground Data Reduction Task.

It is presently known that the I.S.I.C. Camera will have a 3-inch focal length and will cover a 5-inch format. It will contain a reseau and will be calibrated. The I.S.I.C. Cameras (2) will be oriented to the left and right of the flight path and will provide redundant angular orientation data intended to improve angular knowledge and eliminate poor data due to one side flare, etc.

5. MODIFICATIONS OF f/3.5 PANORAMIC CAMERA FOR PAN GEOMETRY

The following modifications are being included in the Panoramic Mural Cameras to facilitate calibration of the internal geometry and are presented here to provide a basic knowledge of the equipment.

The modifications include (1) incorporation of fiducial lamps in the scan head, (2) incorporation of precision holes in the film guide rails to produce 73 pairs of fiducial marks on the format, and (3) minor revision in the lens design to permit incorporation of a collimator and fiducial lamps in the scan head.

5.1 FIDUCIAL MARKS

The procedure for placing the fiducial marks on the film of the panoramic camera is illustrated in Figures 5-1 and 5-2. In the present system, the film rails guide the film during film transport and locate the film in the approximate focal plane. Rollers mounted on the end of the scan head lift the film off the rails into the exact focal plane during scan. The two rows of fiducial marks spaced approximately one degree apart will be exposed onto the film by attaching a lamp assembly to the scan head on each side of the slit and allowing the light from the lamps to pass through the small holes, 0.0014 to -0.0018, drilled in the guide rails. The rails will be aligned to ensure that a line drawn between any two opposite holes will pass through the smallest exposure slit normally used, i.e., 0.150 inch. This will ensure that the exposed format between any two opposite fiducials and the fiducials themselves will be exposed simultaneously.

Tests conducted on this system prove that sufficient exposure can be provided, and the possibility of the holes becoming plugged with emulsion and/or dirt is minimal.

5.2 LENS WITH COLLIMATOR

The basic 24-inch Petzval lens design will be modified to provide an increase in back focal length from 0.140 to 0.250 inch in order to install the fiducial lamps between the film guide rails and the field flattener. The number of elements and the basic configuration of the lens and the lens cell will not change, but the radius of curvature and the thickness of some of the elements, as well as the air spaces, will be altered to maintain optimum performance.

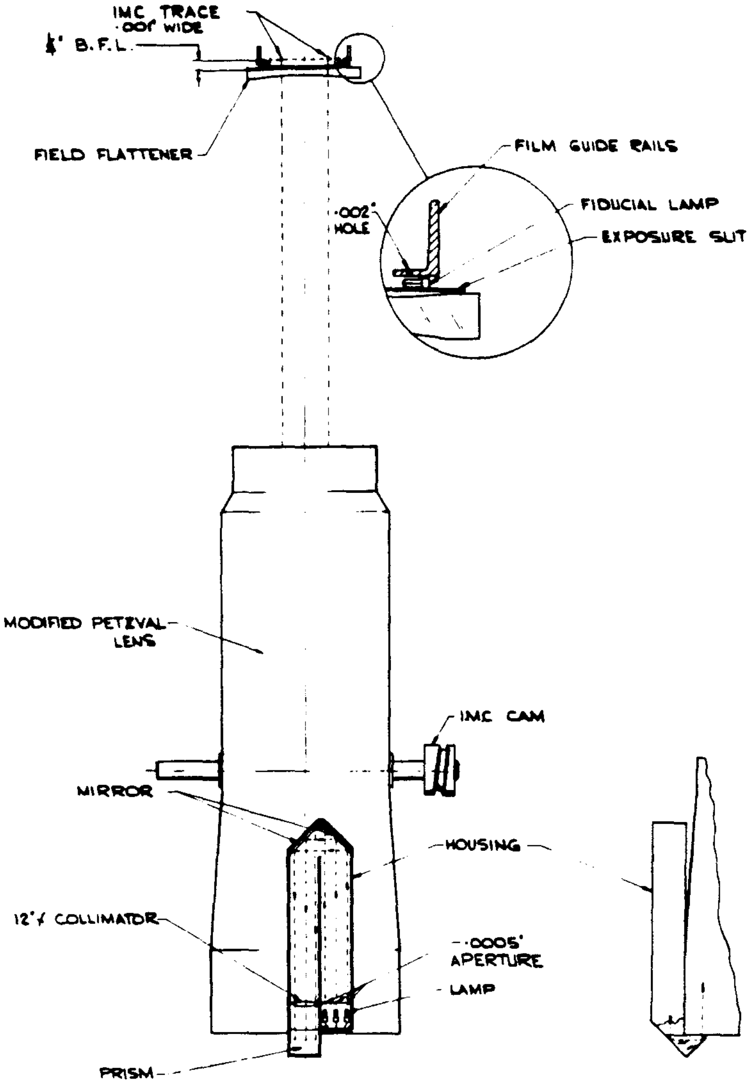


Figure 5-1 — Modifications to provide fiducials

A collimator has been designed to provide a slit image across the scan. This slit image will be presented to the film from three point source targets and will expose the IMC curve on the film. The center image is to be aligned to the optical axis of the lens system and will be effectively a line image of the principle point of the optical system. The collimator is an integral part of the system and will be permanently attached to the lens cell. A slit image is required for adequate exposure.

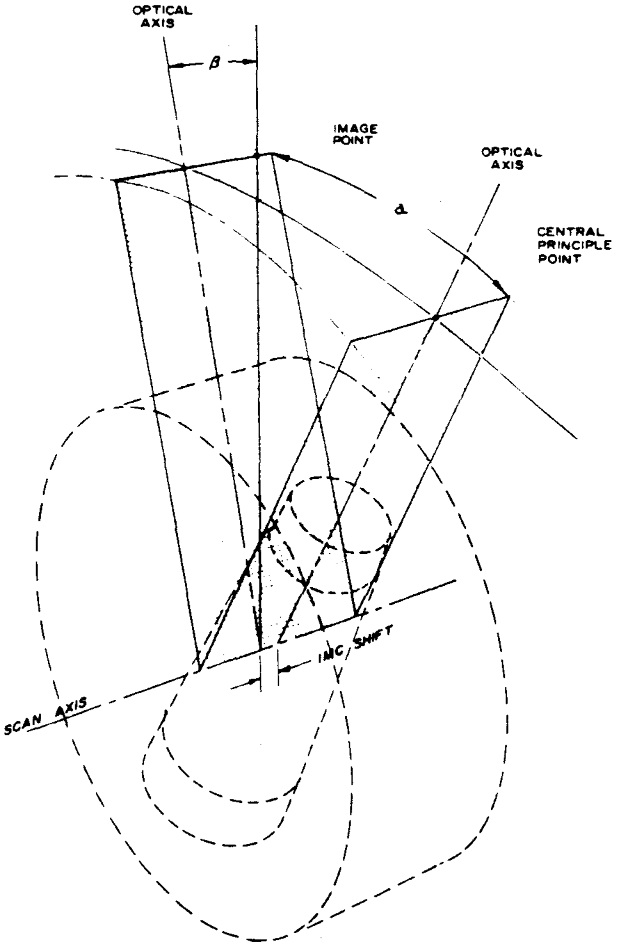


Figure 5-2 — Coordination of image point in terms of scan angle α and cross angle β

6. ADDITIONAL CAMERA GEOMETRY KNOWLEDGE

During the past few years and particularly during the past months, various analyses have been conducted to analyze, and improve the image quality and geometric characteristics of the J Panoramic Camera System. These analyses have resulted in considerably improved image content and hopefully will lead to improved metric fidelity with the future Pan Geometry Camera System. Some of the camera-geometry information more pertinent to this task is contained in the following paragraphs. It is hoped that this data will provide additional insight into the metric aspect of the system.

6.1 SCAN RATE ANALYSIS

An analysis of scan rate was conducted on three instruments. Scan rates were evaluated by measuring the spacing of the 200 PPS marks. During the analysis, effects that produce a displacement of an image ray with respect to the film during exposure were of prime concern.

The analysis of the timing marks indicated that there was a cyclic variation in scan velocity, but because of the continuously rotating lens motion and the cycling motion of the scan head, it is assumed that the velocity change occurs only in the scan head and not in the imaging system (lens) or the image.

If the deviations from a constant velocity involved only the scan head as distinguished from the rotation of the lens cell, the effects would be only those of exposure variation and an imperceptible amount of optical distortion due to the motion of the field flattener. These effects would clearly be very small and have little (submicron) or no effect on image geometry. Exposure variation would appear as banding. This effect is consistent with the velocity profiles collected to date.

The scan velocity data suggests a variety of noise of unresolvable motion elements. Since these elements cannot be directly or analytically related to image ray/film motions, the effects appear as residual degradations.

Velocity patterns developed from measurements of the timing marks vary by more than 10 percent.

The 200 PPS timing marks are generated by a neon lamp controlled by the system clock through an amplifying circuit. The clock signals are accurate to five parts in 10^8. The image quality of the timing marks is, however, relatively poor due to the smearing of the image due to scan.

The spacing of the timing marks is considered to be a direct measure of scan velocity. Strictly speaking, it should be noted that the spacing is the resultant of scan head and film motion. It is also important to note that the frequency lamp trails the actual exposing slit by almost one inch, thus the dynamics of the film/scan head relationship may be different over this distance.

A series of graphs plotting scan rate profiles may be found in Performance Evaluation Report for Mission 1006-1 and 2, dated 26 October 1964, pp. 121-134.

6.2 IMAGE SMEAR ANALYSIS

Computer programs developed by the vehicle manufacturer are utilized to calculate and plot the frequency distribution of the various contributions to image smear in order to permit analysis and correlation of the information content and quality of the acquired photography. (See Figure 6-1.)

The frame correlation tape supplied to A/P by NPIC contains the binary time word for each frame of photography. A computer program has been written which calculates the exposure time of each frame and compares the camera cycle rate with the ephemeris to calculate the V/h mismatch. This data is combined with the vehicle attitude error, the rate values of each frame, and the crab error caused by earth rotation at the latitude of each frame. The program outputs the total in track and cross-track IMC errors and the limit of ground resolution that can be acquired by a camera regardless of focal length and system capabilities. The computer rejects the first six frames of all operations due to the large V/h error induced by camera start-up.

6.3 ASCHENBRENNER TEST

A method known as the Dr. Aschenbrenner Test is used to verify the film flatness during the instant of exposure throughout the format area. A thin format contour is developed by exposing through a series of nine fine transparent lines parallel to the scan plane, using a pair of spaced lamps creating a known triangle (Figure 6-2). Each fine line exposes a pair of lines on the film as the exposure slit scans across the format. A control for measurement of film lift is established by making an exposure on a photographic plate placed on the scan roller plane and a second plate lifted to a known position above the roller surface. This calibration is then applied to the readout of an automatic scanner which scans each pair of lines at one-half inch intervals for the total of nine rows and sixty readings per row. These nine data strips are then assembled as a format and a contour plot is made in one thousandths of an inch increments. The film plane is required to have 90 percent of its area within ±0.001 inch. (This corresponds to the focus depth of the Petzval lens.) The film position is thus optimized to the determined focal length. An illustration of the resulting contour plot is shown in Figure 6-3.

6.4 ERROR BUDGET

Tables 6-1 and 6-2 contain the operation error budget for 3 sigma values for cross-track and along-track conditions.

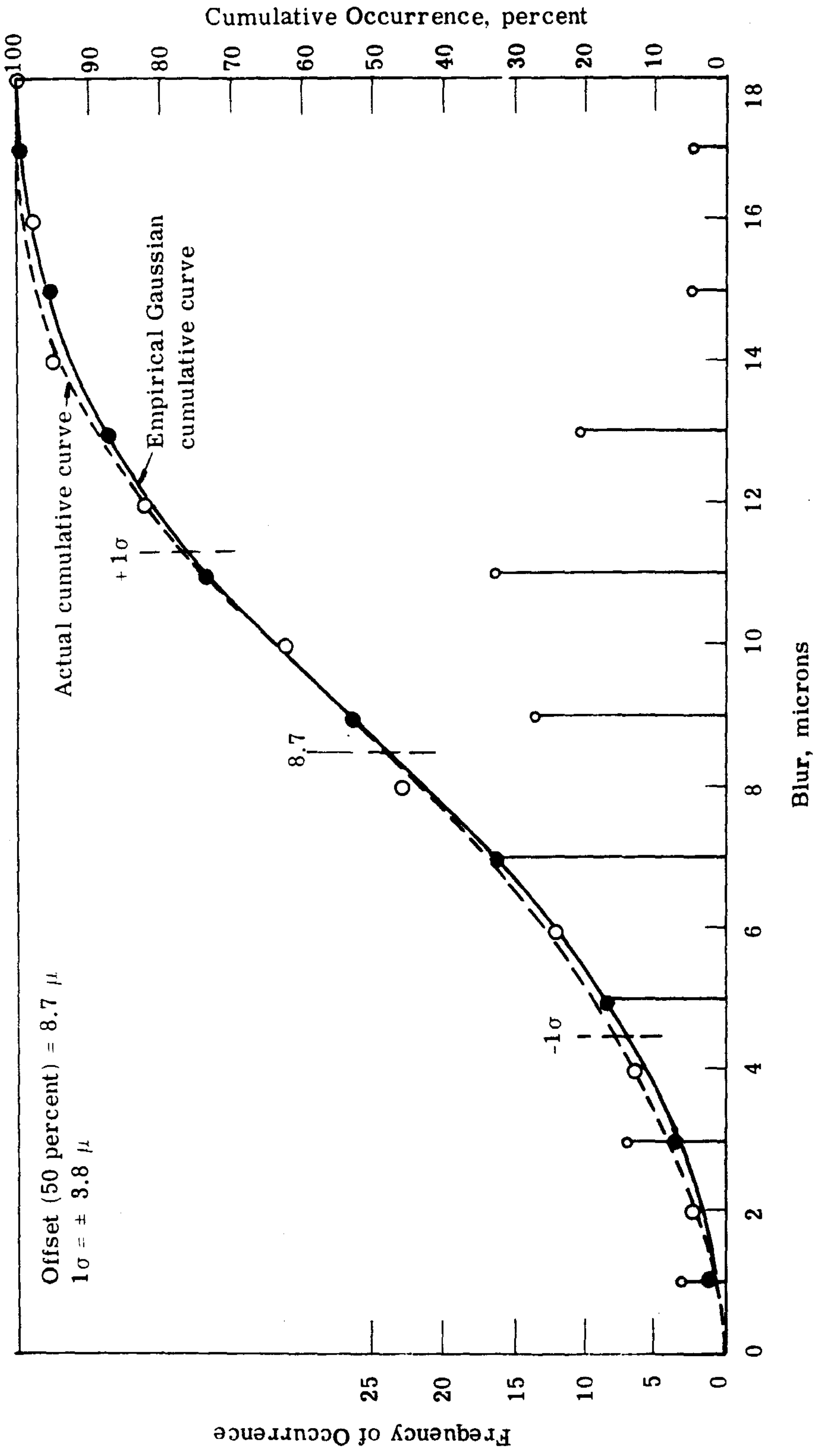


Figure 6-1 — Scan direction frequency versus blur, 90 degrees ± 20 degrees

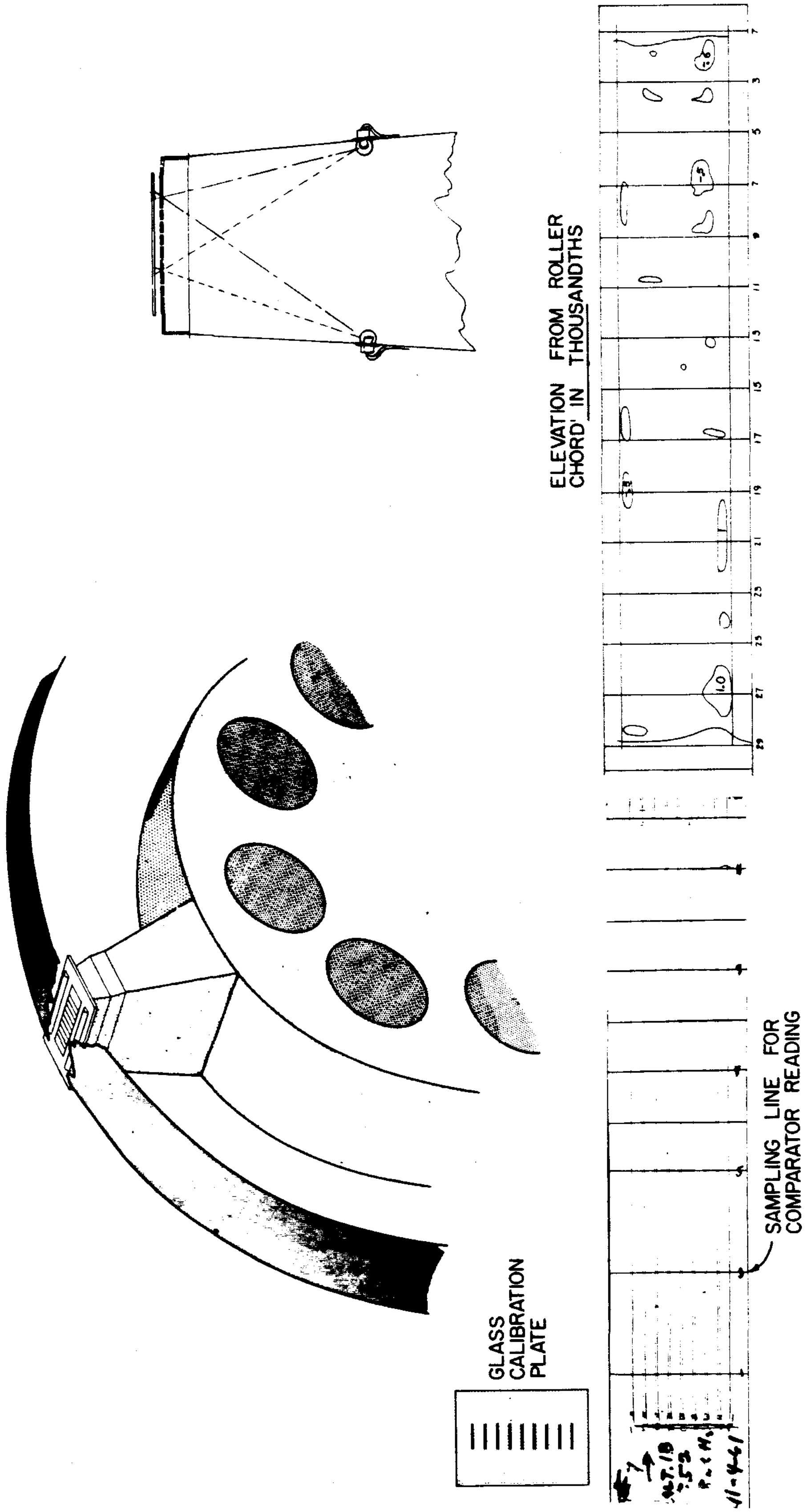


Figure 6-2 — Aschenbrenner test for film position

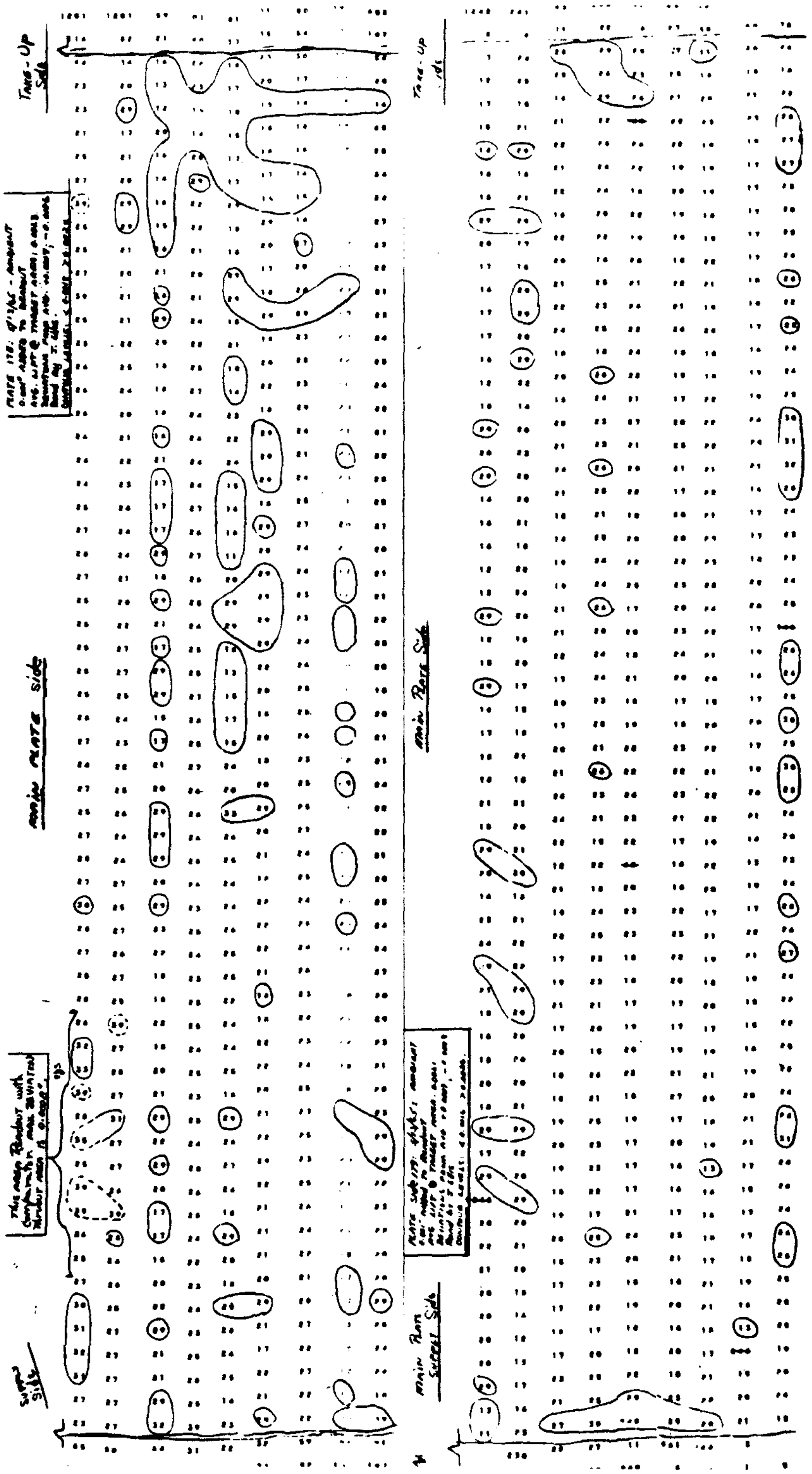


Figure 6-3 — Aschenbrenner test results

Table 6-1. Operation Error Budget

3 Sigma Values

Cross-Track Direction

	Image Blur In Microns	
	Present	Present
Camera Sources	100 nautical miles	90 nautical miles
Vibration	±8.3	±8.3
Field flattener to lens motion	±0.95	±0.95
Motion Due to Film Lift	+2.9	+3.4
Lens distortion	+1.11	+1.23
Nodal point location	±0.92	±1.1
Momentum unbalance (110)	±3.7	±4.1
Vehicle Sources		
Roll attitude	±0.27 cos θ	±0.3 cos θ
Pitch attitude	±0.52 sin 2θ	±0.83 sin 2θ
Yaw attitude	±1.01 cos θ	±1.1 cos θ
Roll rate	±0.72	±0.72
Pitch rate	negl.	negl.
Yaw rate	negl.	negl.
Other Sources		
Stereo angle blur	+7.9 sin 2θ	+8.1 sin 2θ

2.22 millisecond exposure
0.175 inch exposure slit at 100 nautical miles
0.200 inch exposure slit at 90 nautical miles

Table 6-2. Operation Error Budget
3 Sigma Values
Along-Track Direction

	Image Blur In Microns	
	Present	Present
<u>Camera Sources</u>	100 nautical miles	90 nautical miles
Vibration	±4.8	±4.8
IMC	±5.8	±6.3
Field flattener to lens motion	±0.95	±0.95
Uncompensated forward motion	±1.34*	±1.48*
Lens distortion	+0.01	+0.01
Focal length error	±0.01	+0.01
<u>Vehicle Sources</u>		
Roll attitude	±1.02 sin θ	±1.14 sin θ
Pitch attitude	±0.1*	±0.1*
Yaw attitude	negl.	negl.
Roll rate	±0.19 sin θ	±0.195 sin θ
Pitch rate	±0.75 cos θ	±0.83 cos θ
Yaw rate	±0.19 sin θ	±0.195 sin θ
IMC command signal	±4.4	±4.4
<u>Other Sources</u>		
Terrain height variation	±0.3	±0.4

*At edge of format.

2.44 millisecond exposure
0.175 inch exposure slit at 100 nautical miles
0.200 inch exposure slit at 90 nautical miles

7. SYSTEM COMPONENT CALIBRATION

Calibration data is provided with each system describing the parameters of the various optical components and is broken down into the following documents:

1. Complete bench data on each Petzval lens.
2. Dynamic and static resolution data on each panoramic camera.
3. Horizon camera optical data, including resolution and distortion data.
4. Theodolite calibration (West Coast) to provide angular relationship between the horizon cameras and the Petzval lens systems. These calibration films are subsequently measured by the Itek Data Analysis Center in Alexandria, Virginia, and the data is transmitted to Headquarters.

The horizon cameras, while providing data on pitch and roll, are not as precise as the S/I data and thus are not generally used if S/I information is available. However, they are used in the "smoothing" of the S/I data. A discussion of the accuracies achieved by these two systems will be included in this report along with an analysis of the reliability of the data.

Part of the testing procedures performed by the West Coast facility prior to flight is a calibration of the horizon optics assemblies.

The relationship of the horizon cameras to the main lens system is determined by photographing an array of collimators having a fixed angular relationship. The collimators are positioned relative to each other to an accuracy of ±6 arc-seconds.

The reticles used with the collimators are single vertical lines with a circle in the center. The scale of the reticles is such that when they are imaged by the 55 millimeter focal length horizon cameras and the 24-inch focal length lens, the resulting images are the same scale for ease of mensuration. The reticles are orientated vertically to earth gravity zero vector.

The subsequent data reduction establishes the true horizontal to the intersection of the horizon optics fiducials and the angular relationship of the horizon optics to the main lens.

7.1 INITIAL CALIBRATION OF THE PAN GEOMETRY EQUIPMENT

Unlike a conventional frame camera where the basic starting value for calibration is an effective focal length from which all coordinate references and distortions are determined, the panoramic camera has fixed mechanical and optical references. These values are established and determined during the fabrication of the camera system. Essentially these are:

1. The operational effective focal length (f) for ambient and vacuum environments.
2. The optical radial distortions for (f).
3. The mechanical radius (r) of the film surface at rest on the rails, as determined by (f).
4. Deviations from this radius due to uniform and non-uniform lifting of the film by the roller system (film flatness values).
5. The IMC function as determined by a fixed cam at the lens rotation point.

Calibration Procedure

In general, the following procedures, listed sequentially, will be followed to obtain the desired calibration information.

1. A calibrated grid (etched or scribed on glass) will be exposed onto a strip of thick, stable base film. The grid will cover the entire 70 by 750 millimeter format.
2. The pre-exposed (pre-sensitized) piece of film will be loaded onto the camera, making sure that the film edges are in contact with the rails containing the fiducial holes. The film rollers will be removed as the film must stay in contact with the rails and not be lifted from them.
3. The camera will be hand cranked through one scan, thus producing a photographic record consisting of images of the two parallel "S" curves, the fiducial holes, and the pre-exposed grid intersections.
4. The film will be developed taking care to minimize any stresses or strains during the time the film is wet or drying.
5. The grid intersection images, the fiducial hole images, and the "S" curve traces (at 1 cm intervals) on the glass plates will be measured. Using the grid intersection coordinates in the overlap areas, transformation coefficients will be determined by least square adjustment methodologies and used to transform all measurements into a common system. The condition equations for such a transformation are as follows:

$$x_1 - (x_2 - x_p) \cos \xi + (y_2 - y_p) \sin \xi = F_1$$

$$y_1 - (x_2 - x_p) \sin \xi - (y_2 - y_p) \cos \xi = F_2$$

where:

$x_1 y_1$ = Coordinates of grid intersection on Plate 1

$x_2 y_2$ = Coordinates of same grid intersection on Plate 2

ξ = Angle of rotation between the two systems

$x_p y_p$ = Translation in the x and y directions between the two systems

The transformation parameters ξ, x_p, y_p between Plates 1 and 2 will be determined and will then be used to transform all of the Plate 2 measurements into the Plate 1 system. The transformed Plate 2 grid intersection coordinates that overlap with Plate 3 intersections will then be used to determine values for ξ, x_p, y_p that relate Plate 3 measurements with transformed Plate 2 measurements (Plate 1 system) and these measurements will in turn be used to transform Plate 3 measurements into the Plate 1 system. This procedure is continued until all measurements are referenced in the same (Plate 1) system.

6. The magnitudes of the film distortions as indicated by the exposed grid variations will be examined and an appropriate transformation that adequately describes its systematic nature will be determined. The coefficients of this transformation will be found by least square adjustment methodologies using the grid intersection measurements along with their pre-calibrated values. The condition equations for two such transformations are as follows:

$$x_c - (Kx_m - x_p)\cos\theta + (Ly_m - y_p)\sin(\theta + \Phi) = F_1$$

$$y_c - (Kx_m - x_p)\sin\theta - (Ly_m - y_p)\cos(\theta + \Phi) = F_2$$

$$x_c - Ax_m - By_m - Cx_m y_m - Dx_m^2 - Ey_m^2 - Fx_m^2 y_m - Gx_m y_m^2 - Hx_m^3 - Iy_m^3 - J = F_1$$

$$y_c - A'x_m - B'y_m - C'x_m y_m - D'x_m^2 - E'y_m^2 - F'x_m^2 y_m - G'x_m y_m^2 - H'x_m^3 - I'y_m^2 - J' = F_2$$

where:

x_c, y_c = Pre-calibrated coordinate values of a grid intersection

x_m, y_m = Measured coordinate values of the same grid intersection

$K, L, x_p, y_p, \theta, \Phi$ = Coefficients for the first transformation determined by least square adjustment techniques which minimize the quadratic form of the residuals of the measured quantities

$A\ B\ C\ D\ E\ F\ G\ H\ I\ J\ A'\ B'\ C'\ D'\ E'\ F'\ G'\ H'\ I'\ J'$ = Coefficients for the second transformation determined as before

7. The measurements of the "S" curve traces and the fiducial holes will be corrected for film distortion using the coefficients determined in 6, above.

8. The angle that the trace of the scan plane on the film surface makes with the arbitrarily defined measuring axes along with coordinates of the point of inflection of one of the "S" curves in this measuring system are determined using least square adjustment techniques with the following condition equations. The subscripts 1 and 2 refer to "S" curves one and two respectively.

$$(x_1 - x_{p1}) \text{Sin } \mu + (y_1 - y_{p1}) \text{Cos } \mu - C \text{ Sin} \left[\frac{(x_1 - x_{p1}) \text{ Cos } \mu - (y_1 - y_{p1}) \text{Sin } \mu}{r} \right] = F_1$$

$$(x_2 - x_{p1}) \text{Sin } \mu + (y_2 - y_{p1}) \text{Cos } \mu - J \text{ Sin} \left[\frac{(x_2 - x_{p1}) \text{Cos } \mu - (y_2 - y_{p1}) \text{Sin } \mu}{r} \right] = F_2$$

where:

x_1, y_1 = Coordinates of points along the trace of "S" curve one

x_2, y_2 = Coordinates of points along the trace of "S" curve two

x_{p1}, y_{p1} = Coordinates of the point of inflection of the "S" curve one

μ = Angle the trace of the scan plane on the film surface makes with the measuring axes

J = Distance between the two "S" curves. Defining δ and η as the off principle axis angles of each collimator beam, $J = r \tan \delta + r \tan \eta$

r = Radius of curvature of rail system

C = IMC cam constant

F_1, F_2 = Functional values

9. The coordinates of the fiducial holes are rotated and translated using the derived values for μ, x_{pl}, y_{pl} along with J and δ into a system whose origin is at the defined principle point and whose x-axis is the direction of scan.

$$\begin{bmatrix} x_F \\ y_F \end{bmatrix} = \begin{bmatrix} \mathrm{Cos}\ \mu & -\ \mathrm{Sin}\ \mu \\ \mathrm{Sin}\ \mu & -\ \mathrm{Cos}\ \mu \end{bmatrix} \begin{bmatrix} x_{FM} - x_{p1} - r \tan\ \delta\ \mathrm{Sin}\ \mu \\ y_{FM} - y_{p1} - r \tan\ \delta\ \mathrm{Cos}\ \mu \end{bmatrix}$$

where:

x_{pl}, y_{pl}, μ, r and δ are as before in Step 9

x_{FM}, y_{FM} = Measured coordinates of the fiducial holes

x_F, y_F = Final transformed coordinates of the fiducial holes

10. The scan angles α and cross angles β are computed for each fiducial hole using the following relationships:

$$\alpha = \frac{x_F}{r}$$

$$\tan \beta = \frac{{}_{F}{}^{-C\ \mathrm{Sin}\ \alpha}}{f}$$

where:

α, β = Scan and cross angle respectively of a fiducial hole

x_F, y_F = Coordinates of fiducial holes in a system whose origin is at the defined principle point and whose x-axis is the direction of scan

C = IMC cam constant

r = Radius of curvature of the rail system

f = Focal length of camera

This completes the calibration of the internal geometry of the panoramic camera. As random error propagation is a by-product of the proposed data reduction techniques and as it is proposed to weight, inversely as their variances, any a priori known constant, reliable values indicating the statistical validity of the derived values will be available upon completion of the calibration.

7.2 RESEAU CALIBRATION

Because of practical considerations, the actual reseau cannot be measured. Instead, a contact negative of the reseau printed on glass is measured. The grids are measured in four different orientations and locations in the machine coordinate system. These four sets of coordinates are fitted together analytically, allowing only rotation and translation between sets to give the coordinates of the reseau points as the average of the four readings. Finally, the adjusted coordinates are rotated and translated into an arbitrary system.

7.2.1 Measuring Conventions and Procedures

The plate to be measured is placed emulsion side down in the center of the viewing area with the identification number in the lower left corner as one faces the machine. Prior to measuring, the position of each plate is rotated until a given line on the plate is approximately coincident with the line swept out by positioning the measuring reticule at one end of the line and moving the plate by the x-gear only.

Order of Measurements

1. Begin at the print in the lower left corner of the plate and move to the right, measuring each point in turn until the end of the bottom line is reached.

2. Move to the right end point on the line immediately above and move to the left, measuring each point in turn until at the end of the line.

3. Move to the left end point on the line immediately above and repeat the steps 1 and 2 until all points have been measured.

4. Begin at the last point measured and reverse the procedure set forth in 1, 2, and 3.

5. Rotate the plate approximately 180 degrees and repeat steps 1 through 4. This completes measurement of the particular plate under scrutiny.

Point Identification

Each point is uniquely identified by a number scheme that satisfies the requirement that each intersection be placed unambiguously in its appropriate pass of the repetitious measurements. One 9-digit number is used to accomplish this. The digits are assigned as below.

1st digit — 1, if Aerogor
2, if Canon

2nd and 3rd digits — lens number
4th digit — pass number
5th digit — blank
6th and 7th digits — row number from the bottom
8th and 9th digits — column number from the left

Thus, according to this scheme, the number 2293 0610 would represent a point measured from Canon Plate No. 29, pass number 3, in the 6th row from the bottom, 10th column from the left.

Important Attendant Procedures

To ensure consistency in measurements, some of the more important procedures followed, are listed below.

1. Each pass is measured by the same person.

2. The manufacturer's recommendations regarding the operation and maintenance of the machine are followed. For example, the temperature and humidity should be maintained constant within the specified limits.

3. Each point to be measured is always approached in exactly the same manner; i.e., always from the left and up or else by some equivalent scheme.

4. Once started, a pass is never interrupted until all measurements have been made; i.e., the plate remains on the machine untouched until all measurements of the pass begun are complete. If a plate must be removed before a pass is finished, all measurements are deleted and redone.

5. The measurements are treated analytically as described in Section 7.3.2. After the four passes are fitted together and the random error minimized, another transformation is accomplished by translation and rotation, which centers the origin in a particular way. For Aerogor plates, (see Figure 7-1), the origin has its y-axis passing through the point 2312 and perpendicularly intersecting the x-axis, which goes through points 1201 and 1223. The origin for Canon plates (see Figure 7-2) is defined by the perpendicular intersection of a y-axis through the point 1307 with an x-axis through the points 0701 and 0713.

7.2.2 Analytical Treatment of Measurements

The several readings for each plate must be fused into a single coordinate system of reference. At the same time, the random measuring error must be minimized. To accomplish this, each succeeding pass is fitted to the system of the adjusted combination of previous passes. The degree of contribution is such that the first and second

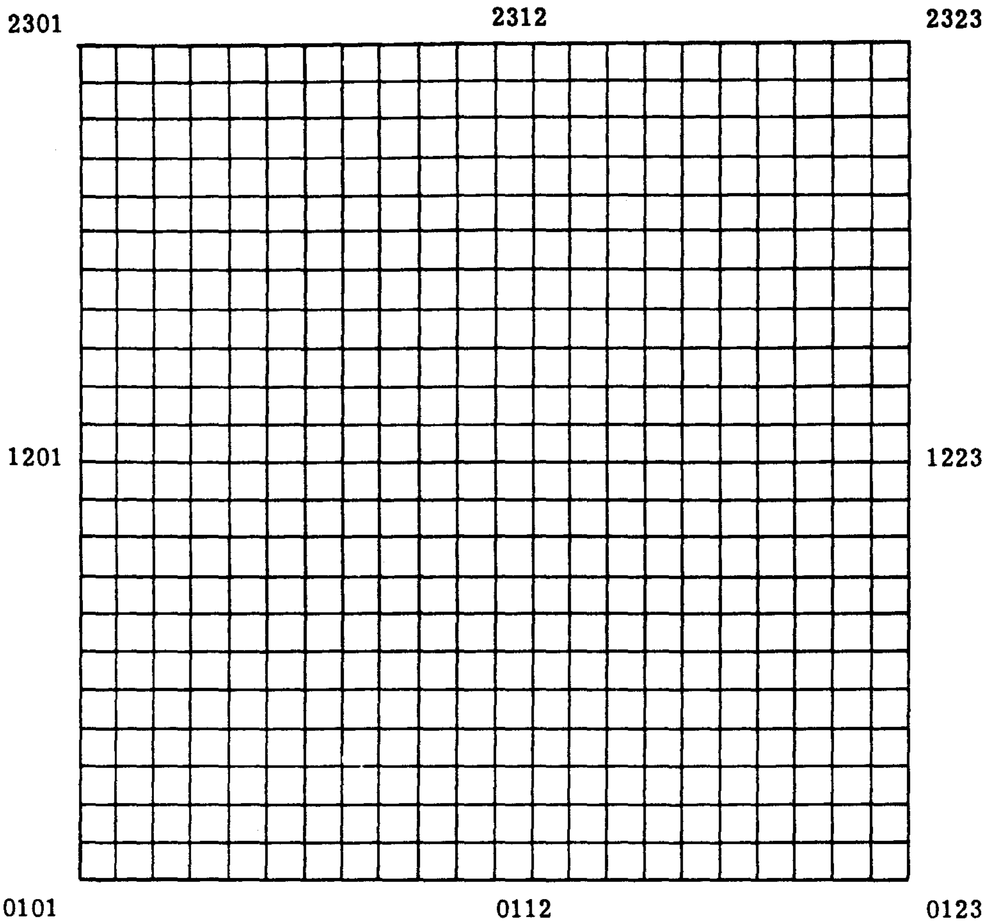


Figure 7-1 — Aerogor reseau; lines represent contact negative with emulsion side down

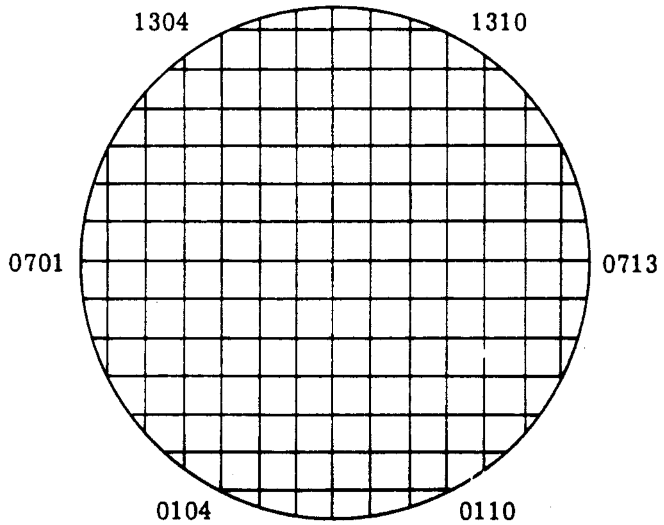


Figure 7-2 — Canon reseau; lines represent contact negative with emulsion side down passes, given equal weight, establish a reference for the third pass with a relative variance ratio of 1 to 2; the first 3 passes have a relative variance ratio of 1 to 3 over the fourth pass, and so on. (See Table 7-1.)

Adjustment Equations

The following equations represent a condition of co-linearity that have to be satisfied during the adjustment procedure.

$$X_c - X_m \cos(s) + Y_m \sin(s) - a = F_1 \qquad (1)$$

$$Y_c - X_m \sin(s) + Y_m \cos(s) - b = F_2 \qquad (2)$$

where the "c" subscripts represent either the initial or control coordinates, and the "m" subscripts represent the uncontrolled coordinates.

The adjustment is carried on under the constraint of (1) and (2), minimizing the weighted sum of the squares of the residuals of the comparator readings and solving for the corrections. The normalized form of the solution is given by

$(B^T WB)\,\delta = -B^T W\epsilon$, where the matrices are defined as

$$B = \begin{bmatrix} \frac{\partial F_1}{\partial s} & \frac{\partial F_1}{\partial a} & \frac{\partial F_1}{\partial b} \\ \frac{\partial F_2}{\partial s} & \frac{\partial F_2}{\partial a} & \frac{\partial F_2}{\partial b} \end{bmatrix}, \delta = \begin{bmatrix} \Delta s \\ \Delta a \\ \Delta b \end{bmatrix}, \epsilon = \begin{bmatrix} F_1(X_c, Y_c, X_m, Y_m, s, a, b) \\ F_2(X_c, Y_c, X_m, Y_m, s, a, b) \end{bmatrix}$$

$$W = (A_c \sigma_c^2 A_c^T + A_m \sigma_m^2 A_m^T)-1$$

$$A_c = \begin{bmatrix} \frac{\partial F_1}{\partial xc} & \frac{\partial F_1}{\partial yc} \\ \frac{\partial F_2}{\partial xc} & \frac{\partial F_2}{\partial yc} \end{bmatrix}, A_m = \begin{bmatrix} \frac{\partial F_1}{\partial xm} & \frac{\partial F_1}{\partial ym} \\ \frac{\partial F_2}{\partial xm} & \frac{\partial F_2}{\partial ym} \end{bmatrix}$$

Table 7-1. Tabulation of Calibration Precisions

Lens	Unit standard deviation from adjustment in mm			Variance-covariance matrix of adjusted coordinates	
	Pass 2 to 1	Pass 3 to 1, 2	Pass 4 to 1, 2, 3		
S9-Aerogor	±0.0013	±0.0011	±0.0007	0.34×10^{-6} 0.0	0.0 0.34×10^{-6}
S9-Canon	±0.0012	±0.0009	±0.0009	0.59×10^{-6} 0.0	0.0 0.59×10^{-6}
S10-Aerogor	±0.0014	±0.0009	±0.0009	0.60×10^{-6} 0.0	0.0 0.60×10^{-6}
S10-Canon	±0.0013	±0.0009	±0.0008	0.48×10^{-6} 0.0	0.0 0.48×10^{-6}
S11-Aerogor	±0.0013	±0.0012	±0.0007	0.38×10^{-6} 0.0	0.0 0.38×10^{-6}
S11-Canon	±0.0015	±0.0011	±0.0008	0.47×10^{-6} 0.0	0.0 0.47×10^{-6}
S12-Aerogor	±0.0013	±0.0010	±0.0009	0.60×10^{-6} 0.0	0.0 0.60×10^{-6}
S12-Canon	±0.0014	±0.0013	±0.0008	0.46×10^{-6} 0.0	0.0 0.46×10^{-6}
S13-Aerogor	±0.0018	±0.0010	±0.0010	0.77×10^{-6} 0.0	0.0 0.77×10^{-6}
S13-Canon	±0.0012	±0.0010	±0.0008	0.47×10^{-6} 0.0	0.0 0.47×10^{-6}

$$\sigma_c^2 = \begin{bmatrix} \sigma_{xc}^2 & \sigma_{xc}\sigma_{yc} \\ \sigma_{xc}\sigma_{yc} & \sigma_{yc}^2 \end{bmatrix} \qquad \sigma_m^2 = \begin{bmatrix} \sigma_{xm}^2 & \sigma_{xm}\sigma_{ym} \\ \sigma_{xm}\sigma_{ym} & \sigma_{ym}^2 \end{bmatrix}$$

Define λ, a multiplier, by

$$\lambda_i = -W_i \epsilon_i$$

The weighted sum of the squares of the residuals is

$$s_i = -\lambda_i^T \epsilon_i$$

The residuals are

$$\begin{bmatrix} V_{xc} \\ V_{yc} \end{bmatrix} = \begin{bmatrix} \sigma_c^2 A_c^T \end{bmatrix} \begin{bmatrix} \lambda \end{bmatrix},$$

$$\begin{bmatrix} V_{xm} \\ V_{ym} \end{bmatrix} = \begin{bmatrix} \sigma_m^2 A_m^T \end{bmatrix} \begin{bmatrix} \lambda \end{bmatrix}$$

This yields a new control combination,

$$X_{cc} = X_c + V_{xc}$$

$$Y_{cc} = Y_c + V_{yc}$$

The adjustment between the first 2 passes is complete, and the third pass must now be fitted to the system, the relative variance of the control being unity and the relative variance of the uncontrolled system being 2.

Error Propagation

The variance-covariance matrix of an adjusted coordinate is computed as

$\sigma_{cci}^2 = \sigma_{ci}^2 = \sigma_{vi}^2$, where the variance of the residuals is given by:

$$\sigma_{vi}^2 = R_{xci} W_i R_{xci}^T - R_{xci} W_i B_i N^{-1} B_i^T W_i^T R_{xci}^T$$

R_{xc} and N are given by

$$R_{xci} = A_{ci}\ \sigma_i^2\ A_{ci}^T, \quad N = \sum_{i-1}^{n} B_i^T W_i B_i$$

An average of the individual relative variance-covariance matrices is taken as the final relative variance-covariance matrix.

Absolute Variance Computations

Relative variances are used throughout the rigorous least squares adjustment. Therefore, the best available estimate of the unit variance comes from the sample as follows:

$$s = \sum_{i=1}^{n} s_i \quad = \quad \text{quadratic form of the residuals, i.e., the function minimized in the adjustment}$$

$$\sigma_o^2 = \frac{s}{2n-p} \quad = \quad \text{unit variance}$$

where n = number of points in adjustment
p = number of parameters solved for.

Using σ_o^2 as a scalar multiplier to the average relative variance-covariance matrix of the adjusted coordinates gives the best available estimate of the absolute variance-covariance for these coordinates.

Additional Transformation of Coordinates

The adjusted coordinates must now be transformed to a system whose origin corresponds to the description at the end of Section 7.3.1, dependent upon whether the plate is Canon or Aerogor. The transformation is accomplished as follows:

$$\begin{bmatrix} X_t \\ Y_t \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \end{bmatrix} - \begin{bmatrix} X_p \\ Y_p \end{bmatrix}$$

where the terms are defined:

X_t, Y_t = transformed coordinates of X, Y, respectively,

X_c, Y_c = untransformed coordinates of X, Y, respectively,

θ = angles of rotation of the transformation, and

X_p, Y_p = translation elements of the transformation.

Further, letting

Xca, Yca = X and Y coordinates of point 1201 for the Aerogor and point 0701 for the Canon,

Xcb, Ycb = X and Y coordinates of point 1223 for the Aerogor and point 0713 for the Canon,

Xcd, Ycd = X and Y coordinates for point 2312 for the Aerogor and point 1307 for the Canon,

the elements of the transformation are computed as follows:

$$\cos\theta = \frac{Xcb-Xca}{R}, \ \sin\theta = \frac{Ycb-Yca}{R}$$

where

$$R = \left((Xcb-Xca)^2 + (Ycb-Yca)^2\right)^{1/2}$$

$$X_p = Xcd\cos\theta + Ycd\sin\theta$$

$$Y_p = -Xca\sin\theta + Yca\cos\theta$$

Final Error Propagation

Since the final coordinates are transformed, random error is propagated through this transformation. The following equations accomplish this propagation:

$$X_t = f_1(X_c, Y_c, \theta, X_p, Y_p)$$

$$Y_t = f_2(X_c, Y_c, \theta, X_p, Y_p)$$

Defining,

σ_{cc}^2 = average variance-covariance matrix of untransformed coordinates,

$$Q = \begin{bmatrix} \frac{\partial f_1}{\partial xc} & \frac{\partial f_1}{\partial yc} \\ \frac{\partial f_2}{\partial xc} & \frac{\partial f_2}{\partial yc} \end{bmatrix} \qquad Q^T = \begin{bmatrix} \frac{\partial f_1}{\partial xc} & \frac{\partial f_2}{\partial xc} \\ \frac{\partial f_1}{\partial yc} & \frac{\partial f_2}{\partial yc} \end{bmatrix}$$

= matrix whose elements are the partial derivatives of functions f_1 and f_2 with respect to X_c and Y_c, respectively.

The variance of θ, X_p, and Y_p is considered to be zero, as they are, in effect, arbitrary values.

σ_{ct}^2 = average variance-covariance matrix of transformed coordinates

$$= Q\sigma_{cc}^2 Q^T .$$

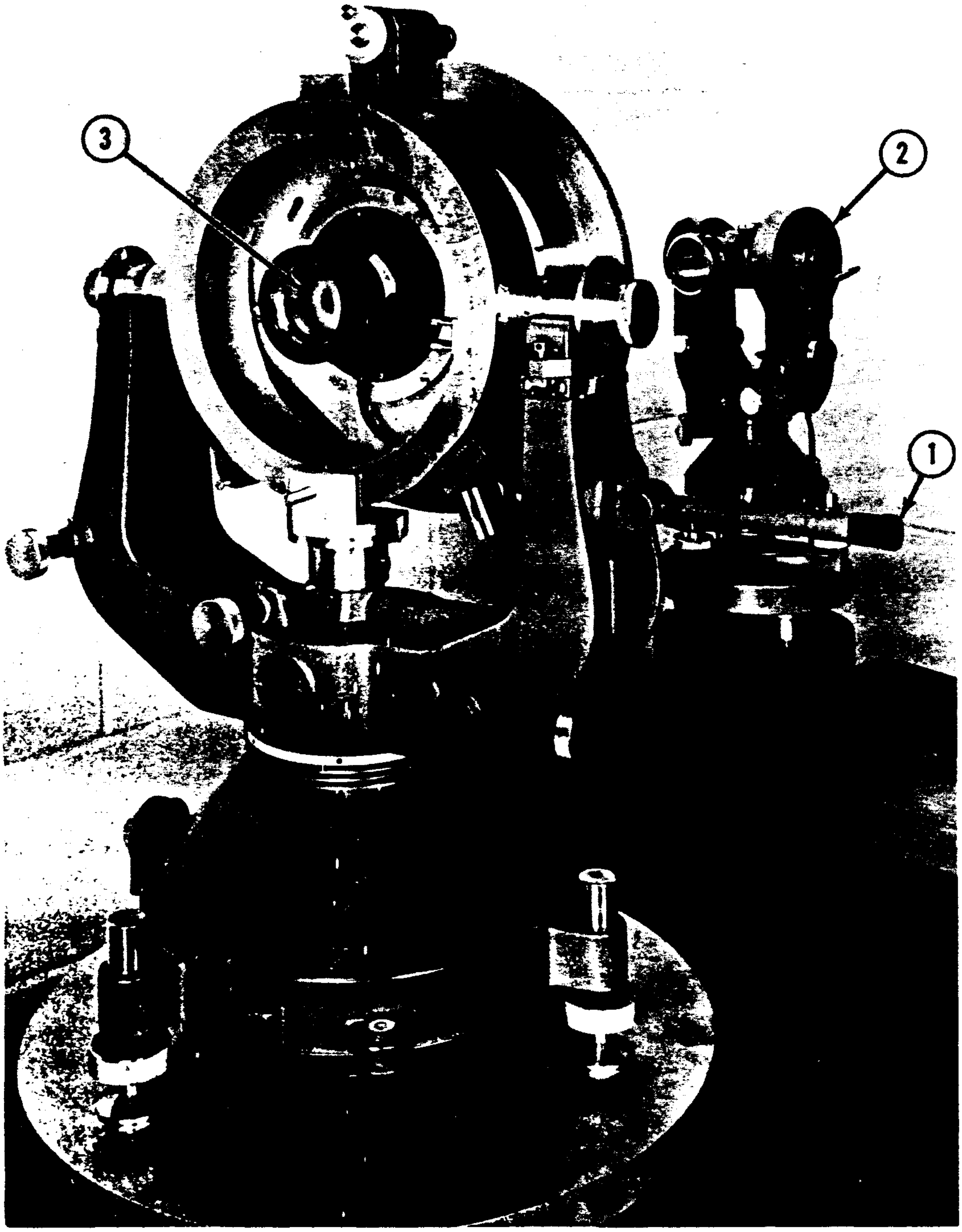
7.3 FRAME CAMERA CALIBRATION

The present lens calibration program involves two basic procedures: (1) the instrumentation procedure, which provides the basic geometric data for each lens, and (2) the computation, or data reduction procedure, which adjusts the basic data and extracts the desired distortion information.

7.3.1 Instrumentation

The instrumentation procedure utilizes the conventional photo-goniometer approach (see Figures 7-3 and 7-4) in which a stationary, collimated target or target pattern is imaged photographically across the field of the lens at known angular positions. The angular separations between successive target images are introduced by rotating the lens through small angles about the axis of the goniometer. Precise measurements of these angles are obtained directly from the goniometer scales.

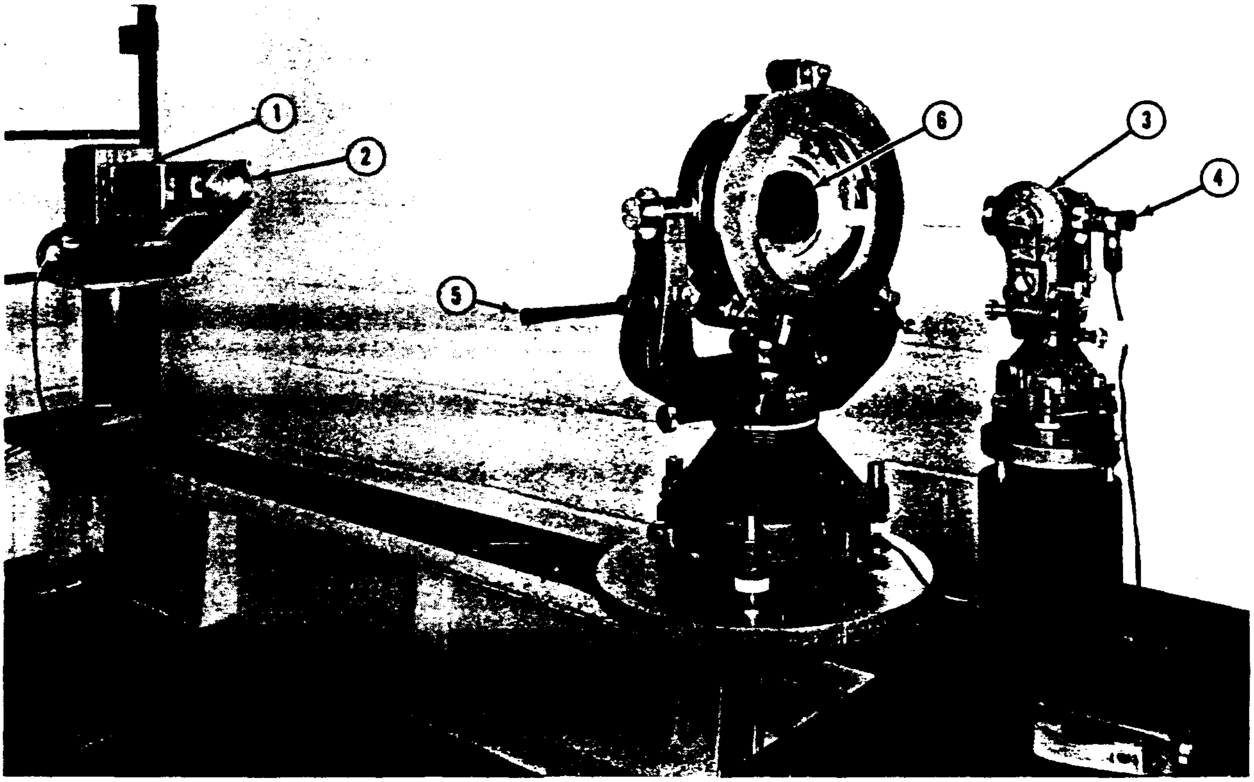
The final step in the instrumentation portion of the photo-goniometer calibration is the measurement on a precision linear comparator of the relative positions of the target images on the photographic record. These measurements, together with the relative angular positions of the target images as set on the goniometer, comprise the input to the computational portion of the calibration procedure.



6945

1. Goniometer reader telescope
2. Collimator telescope (Wild T-2 Theodolite)
3. Lens under test

Figure 7-3 — Goniometer lens test set-up



6946

1. Flash unit and target mount
2. Collimator
3. Collimator telescope (Wild T-2 Theodolite)
4. Autocollimating eyepiece
5. Goniometer reader telescope
6. Lens under test

Figure 7-4 — Goniometer lens test set-up

There are several basic criteria which must be observed in the set-up and alignment of the calibration equipment if the highest precision is to be obtained from the instrumentation procedure. These are:

1. The target or target pattern to be used should be mounted at the focus of the collimating lens and centered on the axis of that lens.

2. The test lens should be mounted in the goniometer yoke so that its entrance pupil is centered on the rotational axis of the goniometer.

3. At the central position (zero setting) of the goniometer, the axes of the collimator lens and the test lens should be colinear.

4. The rotational axis of the goniometer should be normal to the axes of the collimator and test lens.

With the equipment properly aligned, the test lens will be orientated in a position relative to be collimator such that the resulting row of target images will pass very nearly through the center of the field of the lens. By rotating the lens about its own axis and repeating the photographic procedure, any number of rows of target images may be obtained, each crossing the field of the lens in a different direction and intersecting the others close to the lens axis (principal point).

Two variations of the general photo-goniometer approach are possible: (1) the use of either a film or glass plate base for the photographic records, and (2) the use of one common record for all rows, or targets, or the use of individual record for each row. In the present calibration procedure, individual records are made on a film base for each row of targets. The use of the more economical and more easily handled film records is made possible by the fact that the lenses now being tested are supplied with a calibrated reseau grid. By imaging this grid along with the target images, a control of any dimensional instabilities of the film base or emulsion is provided. The seemingly more cumbersome and time-consuming use of individual films for each row of targets also has its advantages. The individual films make it possible to process and check the quality of the images in a given sequence of exposures before the lens is rotated for the next sequence, thus permitting repetitions if necessary. This ability to perform repetitions of each row of targets is utilized in the present technique to provide checks on the precision of the angular settings and readings of the goniometer scales. The individual films also make it possible to have a center target image on each row, close to the principal point of the lens, without overlapping exposures with the other rows of target images.

In the present calibration procedure, a collimated target comprised of a symmetrical pattern of six dots on a transparent background is used. This target is imaged in the vicinity of the reseau intersections, and thus an image of both the intersection and the dot pattern is obtained. This target was selected for two reasons: (1) the symmetrical pattern of several points is more easily and more accurately identified than a single point, and (2), the measurements, either single or repeated, of all points in the pattern (with subsequent distortion computations being based on their center of gravity) are believed to be more precise than repeated measurements on a single, possibly misidentified point. The disadvantage of this target lies in the fact that greater care must be taken in the alignment of the lens and in the selection of the angular separations between exposures in order to ensure that none of the target points fall on the reseau lines, which would make them difficult to see.

7.3.2 Data Reduction

In general, the computation or data reduction portion of any lens calibration procedure receives its input data from the instrument readings, adjusts this data according to specified conditions, and extracts the desired lens distortion information. In the computational procedure now programmed for the CDC 924 computer, the input data is received from the instrumentation procedure previously described and this data adjusted according to the method of least squares. The resultant distortion information includes:

1. The calibrated focal length (CFL) for a desired balance of the radial distortions
2. The radial distortions corresponding to the selected CFL
3. The tangential distortions
4. The point of best symmetry for the radial distortions
5. The line of minimum tangential distortion
6. The function from which the radial and tangential distortions were derived

The proposed least square adjustment is comprised of two condition equations, one each for both the radial and tangential distortions. Each of these conditions equates two different functions of the respective distortions. One is an expression of the theoretically expected shape or form of the distortion, and the other is a first approximation of the distortion (with iterative corrections) based upon the input data and an assumed CFL and point of symmetry. Through several repetitions of the least square adjustments, the input data will be adjusted and the assumed values corrected until a best fit is obtained between these two expressions.

Presently, the theoretical expression for the radial distortion is a four term polynominal function of the radial distance of each point from the point of symmetry. The tangential distortion expression is the product of a quadratic function of the radial distance and a trigonimetric function (sine) of the relative azimuth of the radial about the point of symmetry. Figures 7-5 to 7-8 are typical examples of the computer output.

Calibration Computer Output

The tabulated listings of distortions start at what is indicated as the minus (-) end of each diagonal and continue through to the positive (+) end.

The values preceding the listings are, respectively:

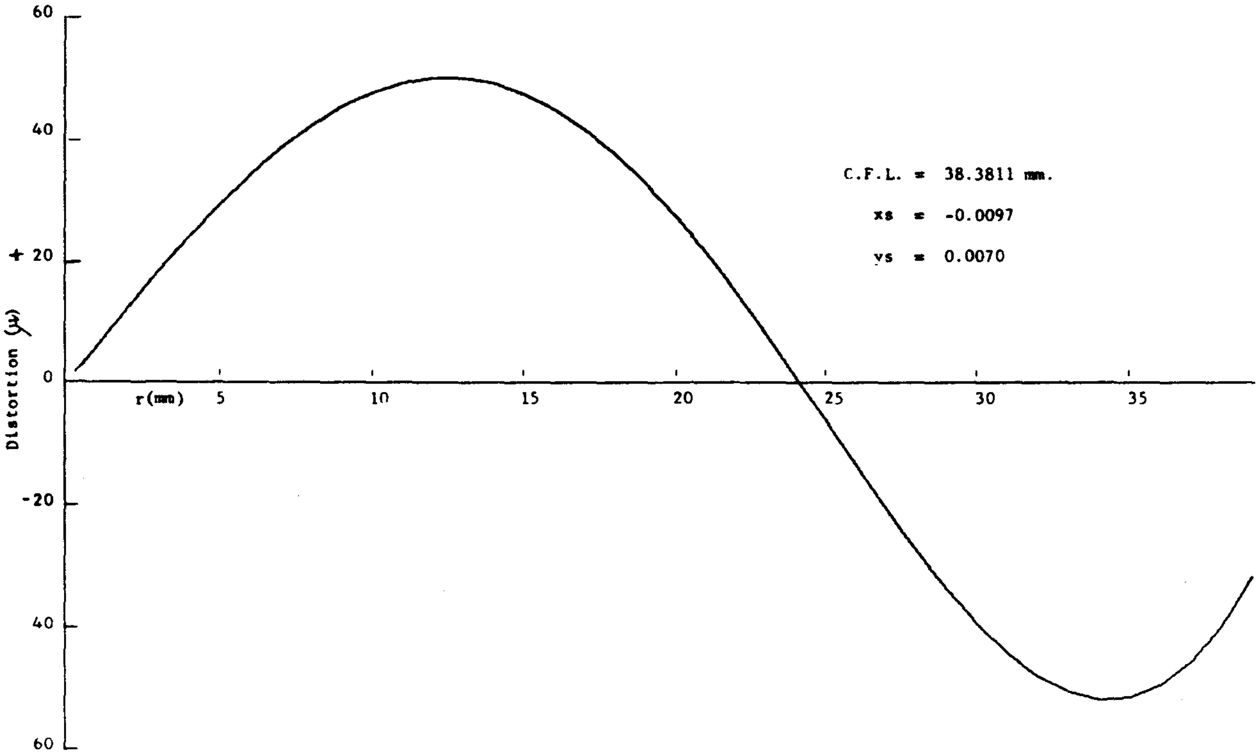


Figure 7-5 — Mean radial distortion

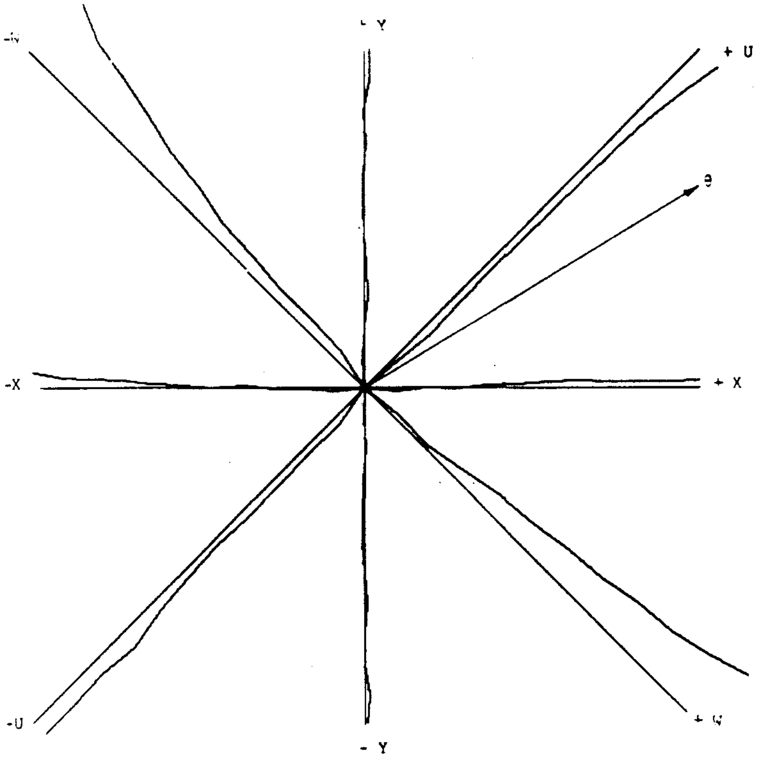


Figure 7-6 — Tangential distortion (1 inch = 20 μ)

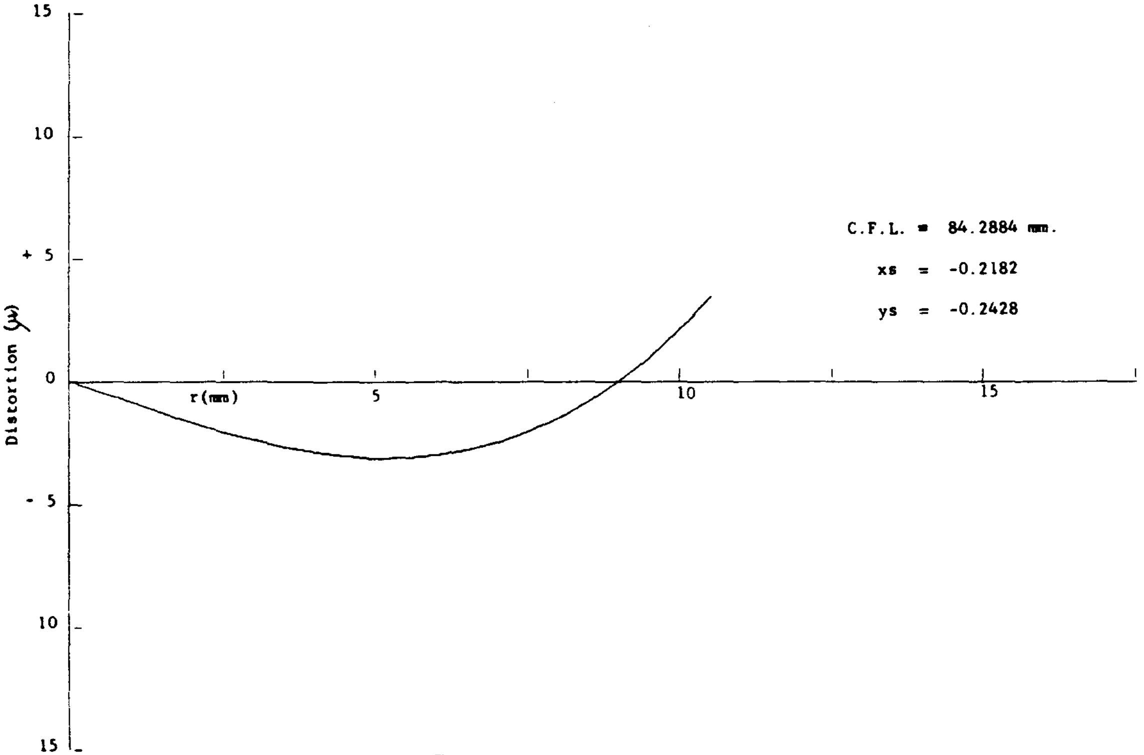


Figure 7-7 — Mean radial distortion

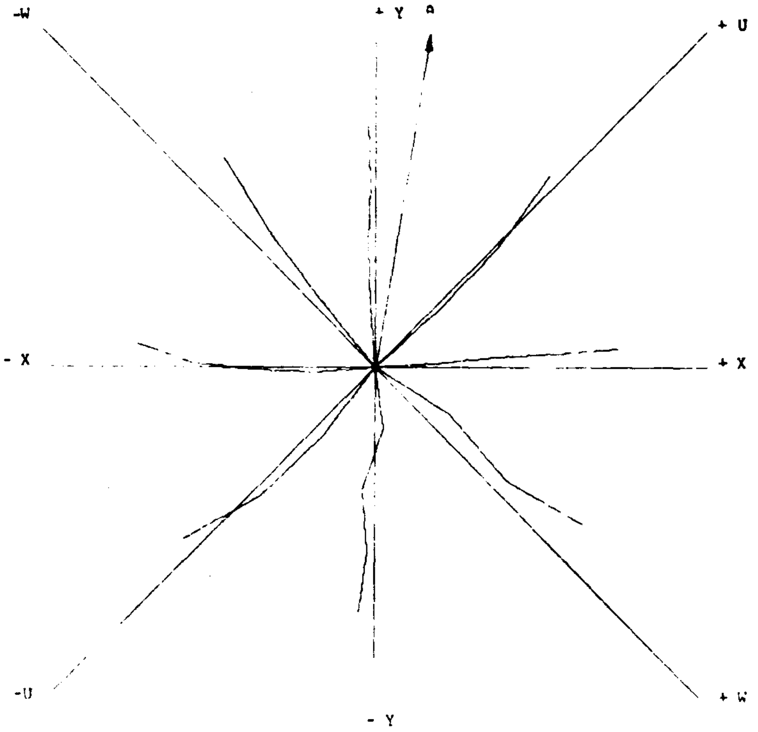


Figure 7-8 — Tangential distortion (1 inch = 5 μ)

- The standard deviations of the twelve individual grid transformations and the identification of any targets rejected from the calibration
- The standard deviation of the measured radial distortions from the theoretical expression

$$D_R = ar_1 + br_1^3 + cr_1^5 + dr_1^7 \qquad \text{(Aerogor)}$$

$$D_R = ar_1 + br_1^3 \qquad \text{(Canon)}$$

where $r_1 = \frac{r(\text{mm})}{100}$

- The standard deviation of the measured tangential distortions from the theoretical expression

$$D_T = Kr_1^2 \sin(\gamma_i \theta)$$

- The coefficients (a, b, c, d) of the radial expression
- The calibrated focal length (CFL)
- The coordinates of the point of symmetry (xs, ys) in the calibrated reseau system, and
- The coefficient (K, θ) of the tangential expression.

7.4 KNEE ANGLE CALIBRATION

The camera manufacturer supplies stellar photographs produced with the Stellar-Index Camera for data reduction of the knee angle or space angle between the stellar optical system and the index optical system. The resultant matrix angles are combined with the camera manufacturers lens calibration information into a final calibration report which becomes a part of the system log.

In the knee angle data reduction, such factors as atmospheric pressure, temperature, humidity, and time are carefully considered as is the correction for atmospheric refraction.

8. DATA BANK AND INPUTS

One goal of this subtask is to provide numerical inputs, along with accuracies and weight factors, to the mathematical systems model. To enable the model to illustrate the ability of our mapping system based on all possible knowledge of interior and exterior imaging space, it has been decided to "play" the model with different theoretical saturations of ground ties or ground data inputs, (geodetic control, maps, conjugate imagery, etc.). All possible conditions can be generated by the introduction and spacing of X, Y, and Z ground coordinate information for 0 to n number of points.

Future Data Bank holdings will be considered in Task II. The up-to-date information on control types, location, accuracies, etc., will be analyzed for the mapping requirements stated.

9. CONCLUSIONS

A great deal of data is obtained for each mission that has a direct and important bearing on the subsequent data reduction and mapping operation. Complete attitude data having a high degree of "goodness" is available as is exposure information such as cycle rate data and time recording and correlation data. All of this information has been generally made available to the Community. However, it has never been listed in one source as in this report.

Continuing liaison with the camera manufacturing group on the mechanical, optical, and electrical aspects of the Panoramic Geometry equipment development and how these aspects relate to the photogrammetric problem is being accomplished. This report is by no means final in that respect. Information will continue to be fed into subsequent reports and in memorandum. In addition, when further information concerning the I.S.I.C. is available, its effects on the data reduction problem will be reported.