APPENDIX A

CAMERA CALIBRATION SUMMARY

A calibration of the Lunar Mapping Camera Unit SN-004 was performed by the Defense Mapping Agency Aerospace Center (DMAAC) for the National Aeronautics and Space Administration. The following are excerpts from the DMAAC report[3] on this calibration.

Original pre-flight calibration negatives for exposures 2, 4, and 6 PRE were used for the recalibration. Environmental data used in the calibration included the position of the camera mount, time of exposure, temperature and atmospheric pressure.

Camera Mount Position

Latitude	$32^{o}32'00"N$
Longitude	$106^{o}36'00"W$
Height	1501.0 meters

Exposure No.	Time
2	$8^{h}24.0^{m}$ GMT
4	$8^{h}48.0^{m}$ GMT
6 PRE	$5^{h}01.5^{m}$ GMT

Calibration values used for the terrain and stellar reseau coordinate intersections and the terrain fiducial coordinates were obtained from the Raytheon/Autometric Calibration report prepared for Fairchild Space and Defense Systems[6]. The signs of the reseau system and fiducial system coordinates axes were changed however to reflect a right-handed coordinate system required in the software used for calibration. Tables A.1, A.2, and A.3 show the calibrated reseau intersections and fiducial coordinates used to obtain camera system coordinates. The fiducial and reseau system relationship for the terrain and stellar cameras is shown in Figures A.1 and A.2.

The Simultaneous Multi-frame Analytical Calibration (SMAC) Program was used to perform the calibration reduction. This program uses a simultaneous multiple exposure analytical calibration technique using stellar observations from single cameras or arrays of up to five cameras. Description of the (SMAC) program may be found in the report, "Advanced Methods for the Calibration of Metric Cameras," by Duane C. Brown as prepared for U.S. Army Engineering Topographic Laboratories[7].

IKOGON B MASTER GRID PLATE
CALIBRATION DATA
(COORDINATES IN MILLIMETERS)

CROSS	COORDINATES		CROSS	COORDINATES	
	X-	Y-		X-	Y-
X1, Y1	-50.0014	-50.0019	X1, Y4	-50.0014	-20.0015
X2, Y1	-39.9997	-50.0019	X2, Y4	-39.9997	-20.0015
X3, Y1	-29.9977	-50.0019	X3, Y4	-29.9977	-20.0015
X4, Y1	-19.9974	-50.0019	X4, Y4	-19.9974	-20.0015
X5, Y1	- 9.9990	-50.0019	X5, Y4	- 9.9990	-20.0015
X6, Y1	0.0000	-50.0019	X6, Y4	0.0000	-20.0015
X7, Y1	+ 9.9992	-50.0019	X7, Y4	+ 9.9992	-20.0015
X8, Y1	+19.9995	-50.0019	X8, Y4	+19.9995	-20.0015
X9, Y1	+29.9994	-50.0019	X9, Y4	+29.9994	-20.0015
X10, Y1	+40.0019	-50.0019	X10, Y4	+40.0019	-20.0015
X11, Y1	+50.0029	-50.0019	X11, Y4	+50.0029	-20.0015
X1, Y2	-50.0014	-40.0022	X1, Y5	-50.0014	-10.0013
X2, Y2	-39.9997	-40.0022	X2, Y5	-39.9997	-10.0013
X3, Y2	-29.9977	-40.0022	X3, Y5	-29.9977	-10.0013
X4, Y2	-19.9974	-40.0022	X4, Y5	-19.9974	-10.0013
X5, Y2	- 9.9990	-40.0022	X5, Y5	- 9.9990	-10.0013
X6, Y2	0.0000	-40.0022	X6, Y5	0.0000	-10.0013
X7, Y2	+ 9.9992	-40.0022	X7, Y5	+ 9.9992	-10.0013
X8, Y2	+19.9995	-40.0022	X8, Y5	+19.9995	-10.0013
X9, Y2	+29.9994	-40.0022	X9, Y5	+29.9994	-10.0013
X10, Y2	+40.0019	-40.0022	X10, Y5	+40.0019	-10.0013
X11, Y2	+50.0029	-40.0022	X11, Y5	+50.0029	-10.0013
X1, Y3	-50.0014	-30.0030	X1, Y6	-50.0014	0.0000
X2, Y3	-39.9997	-30.0030	X2, Y6	-39.9997	0.0000
X3, Y3	-29.9977	-30.0030	X3, Y6	-29.9977	0.0000
X4, Y3	-19.9974	-30.0030	X4, Y6	-19.9974	0.0000
X5, Y3	- 9.9990	-30.0030	X5, Y6	- 9.9990	0.0000
X6, Y3	0.0000	-30.0030	X6, Y6	0.0000	0.0000
X7, Y3	+ 9.9992	-30.0030	X7, Y6	+ 9.9992	0.0000
X8, Y3	+19.9995	-30.0030	X8, Y6	+19.9995	0.0000
X9, Y3	+29.9994	-30.0030	X9, Y6	+29.9994	0.0000
X10, Y3	+40.0019	-30.0030	X10, Y6	+40.0019	0.0000
X11, Y3	+50.0029	-30.0030	X11, Y6	+50.0029	0.0000

TABLE A.1
(Sheet 1 of 2)

IKOGON B MASTER GRID PLATE
CALIBRATION DATA ------ (COORDINATES IN MILLIMETERS)

CROSS	COORDINATES		CROSS	COORDINATES	
	X-	Y-		X-	Y-
X1, Y7	-50.0014	+10.0000	X1, Y10	-50.0014	+39.9974
X2, Y7	-39.9997	+10.0000	X2, Y10	-39.9997	+39.9974
X3, Y7	-29.9977	+10.0000	X3, Y10	-29.9977	+39.9974
X4, Y7	-19.9974	+10.0000	X4, Y10	-19.9974	+39.9974
X5, Y7	- 9.9990	+10.0000	X5, Y10	- 9.9990	+39.9974
X6, Y7	0.0000	+10.0000	X6, Y10	0.0000	+39.9974
X7, Y7	+ 9.9992	+10.0000	X7, Y10	+ 9.9992	+39.9974
X8, Y7	+19.9995	+10.0000	X8, Y10	+19.9995	+39.9974
X9, Y7	+29.9994	+10.0000	X9, Y10	+29.9994	+39.9974
X10, Y7	+40.0019	+10.0000	X10, Y10	+40.0019	+39.9974
X11, Y7	+50.0029	+10.0000	X11, Y10	+50.0029	+39.9974
X1, Y8	-50.0014	+19.9992	X1, Y11	-50.0014	+49.9969
X2, Y8	-39.9997	+19.9992	X2, Y11	-39.9997	+49.9969
X3, Y8	-29.9977	+19.9992	X3, Y11	-29.9977	+49.9969
X4, Y8	-19.9974	+19.9992	X4, Y11	-19.9974	+49.9969
X5, Y8	- 9.9990	+19.9992	X5, Y11	- 9.9990	+49.9969
X6, Y8	0.0000	+19.9992	X6, Y11	0.0000	+49.9969
X7, Y8	+ 9.9992	+19.9992	X7, Y11	+ 9.9992	+49.9969
X8, Y8	+19.9995	+19.9992	X8, Y11	+19.9995	+49.9969
X9, Y8	+29.9994	+19.9992	X9, Y11	+29.9994	+49.9969
X10, Y8	+40.0019	+19.9992	X10, Y11	+40.0019	+49.9969
X11, Y8	+50.0029	+19.9992	X11, Y11	+50.0029	+49.9969
X1, Y9	-50.0014	+29.9987			
X2, Y9	-39.9997	+29.9987			
X3, Y9	-29.9977	+29.9987			
X4, Y9	-19.9974	+29.9987			
X5, Y9	- 9.9990	+29.9987			
X6, Y9	0.0000	+29.9987			
X7, Y9	+ 9.9992	+29.9987			
X8, Y9	+19.9995	+29.9987			
X9, Y9	+29.9994	+29.9987			
X10, Y9	+40.0019	+29.9987			
X11, Y9	+50.0029	+29.9987			

TABLE A.1
(Sheet 2 of 2)

MASTER FIDUCIAL COORDINATE LIST FOR TERRAIN CAMERA

Lunar Mapping Camera SN-004

$A_x = -60.614$	$A'_x = -60.555$
$A_y = 0.000$	$A'_y = 30.796$
$B_x = +60.627$	$B'_x = +60.475$
$B_y = 0.000$	$B'_y = -30.754$
$C_x = + 0.010$	$C'_x = -30.662$
$C_y = -60.482$	$C'_y = -60.566$
$D_x = - 0.011$	$D'_x = +30.678$
$D_y = +60.439$	$D'_y = +60.580$

Note: All coordinates are in millimeters. Signs on the coordinates have been changed from those provided by Fairchild Company and listed in the Apollo 17 camera calibration report, dated August 1971.

TABLE A.2

IKOTAR B MASTER GRID PLATE
CALIBRATION DATA
(COORDINATES IN MILLIMETERS)

CROSS	COORDINATES		CROSS	COORDINATES	
	X-	Y-		X-	Y-
X1, Y1	-10.0015	-10.0003	X1, Y4	-10.0015	+ 5.0002
X2, Y1	- 5.0004	-10.0005	X2, Y4	- 5.0008	+ 5.0005
X3, Y1	- 0.0003	-10.0000	X3, Y4	- 0.0005	+ 5.0004
X4, Y1	+ 4.9996	-10.0000	X4, Y4	+ 4.9995	+ 5.0000
X5, Y1	+ 9.9996	-10.0000	X5, Y4	+ 9.9996	+ 5.0002
X1, Y2	-10.0015	- 5.0011	X1, Y5	-10.0015	+10.0015
X2, Y2	- 5.0004	- 5.0001	X2, Y5	- 5.0010	+10.0015
X3, Y2	0.0000	- 5.0000	X3, Y5	- 0.0005	+10.0015
X4, Y2	+ 4.9996	- 5.0006	X4, Y5	+ 4.9992	+10.0015
X5, Y2	+ 9.9992	- 5.0004	X5, Y5	+ 9.9992	+10.0015
X1, Y3	-10.0015	- 0.0006			
X2, Y3	- 5.0009	- 0.0002			
X3, Y3	0.0000	- 0.0000			
X4, Y3	+ 4.9993	- 0.0006			
X5, Y3	+ 9.9992	- 0.0004			

TABLE A.3

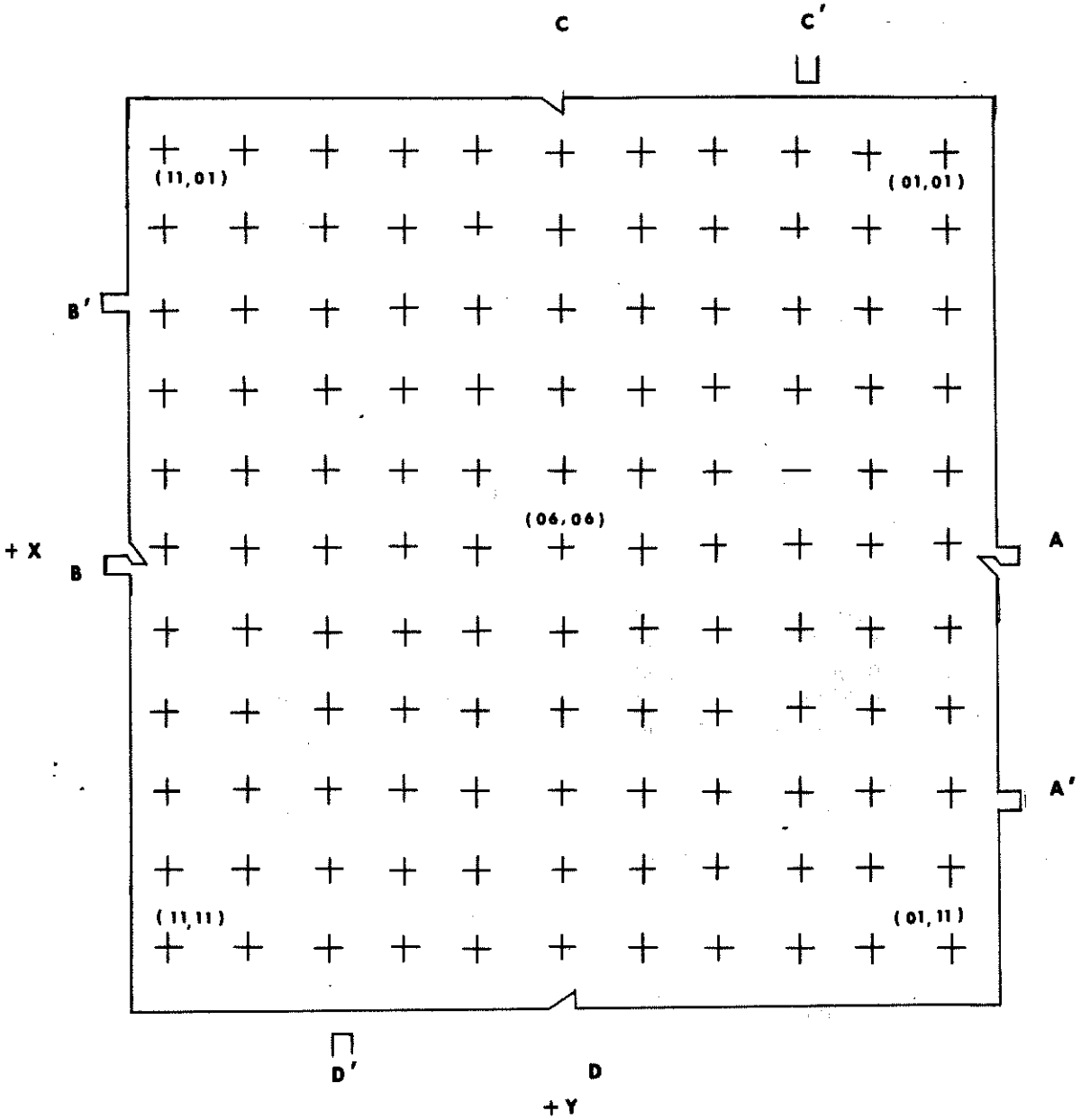
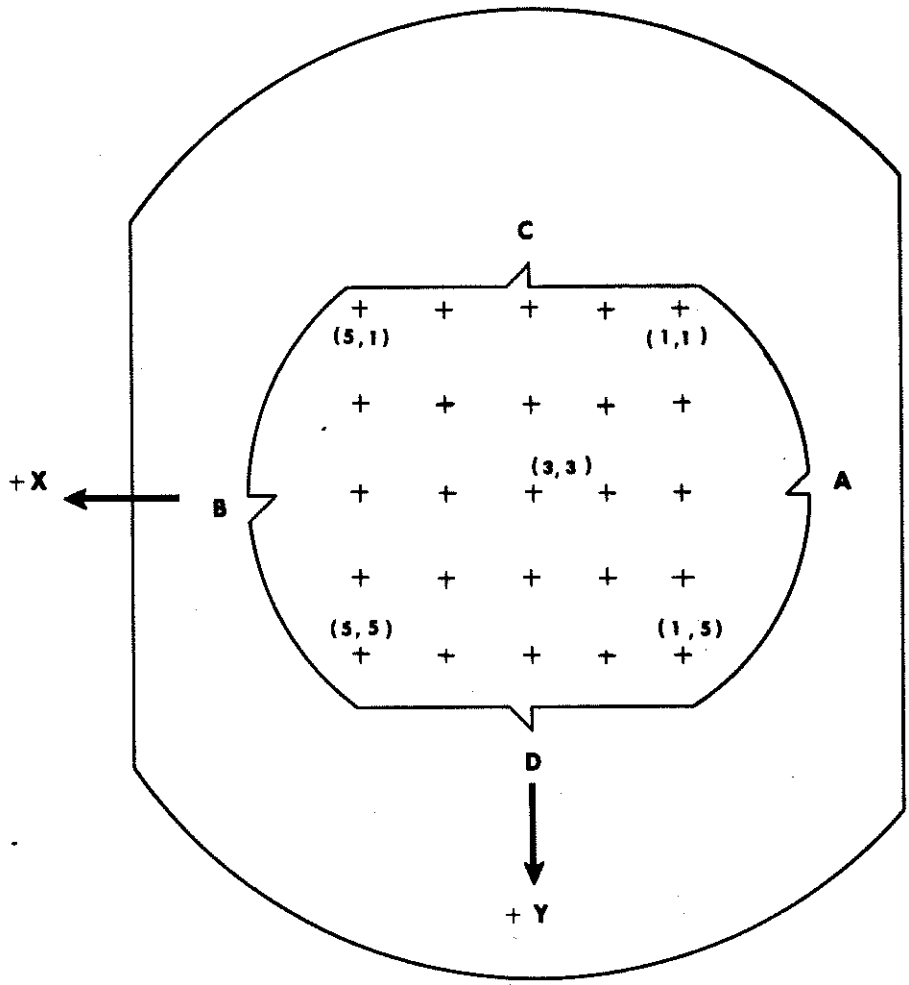


FIGURE A1. IKOGON B MASTER GRID PLATE LAYOUT.



DIRECTION OF FLIGHT

POSITIVE EMULSION UP

FIGURE A2. IKOTAR B MASTER GRID PLATE LAYOUT.

The combined radial and decentering distortion corrections are applied to the x and y image coordinates as follows:

$$\Delta x = x(K_1 r^2 + K_2 r^4 + K_3 r^6) - (J_1 r^2 + J_2 r^4) \left[\left(1 + 2\frac{x^2}{r^2}\right) \text{SIN}\emptyset_o - 2\frac{xy}{r^2}\text{COS}\emptyset_o\right]$$

and

$$\Delta y = y(K_1 r^2 + K_2 r^4 + K_3 r^6) + (J_1 r^2 + J_2 r^4) \left[\left(1 + 2\frac{y^2}{r^2}\right) \text{COS}\emptyset_o - 2\frac{xy}{r^2}\text{SIN}\emptyset_o\right]$$

where x and y are coordinates of the image point referenced to the principal point,

$r = (x^2 + y^2)^{\frac{1}{2}}$ which is the radial distance of an image point from the principal point,

Δx and Δy are the corrections added to the image coordinates,

and K_1, K_2, K_3, J_1, J_2 and $\emptyset_o$ are the correction parameters derived in the calibration.

A total of 581 stars on the terrain camera exposures and 419 stars on the stellar camera exposures were used in determining the principal point offset, lens correction coefficients, and the stellar-terrain camera relationship. The computed calibration of the Inner Cone for the terrain lens (No. 203) and the stellar lens (No. 102) is shown in Tables A.4 and A.5 respectively. The derived relationship of the stellar and terrain camera coordinate systems (Interlock) is shown in Figure A.3. The relative orientation matrix,

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

defines the ω, ϕ, and κ angular orientation relation between the stellar

TERRAIN LENS NO. 203 CONSTANTS OF INTERNAL GEOMETRY

CALIBRATION OF INNER CONE

Coordinates of Principal Point with respect to Indicated Principal Point (Indicated Principal Point X_{ipp} = 0.0 mm, Y_{ipp} = 0.0 mm).

X_p = +0.0074 mm	S.D. = 0.001 mm
Y_p = +0.0094 mm	S.D. = 0.001 mm

Coefficients of Radial Correction

FL = 75.8069 mm	S.D. = 0.0016 mm
K_1 = -0.1278842 -05	S.D. = 0.2619296 -07
K_2 = +0.5264148 -09	S.D. = 0.9402940 -11
K_3 = -0.5259516 -13	S.D. = 0.1021863 -14

Coefficients of Decentering Correction

J_1 = +0.3821279 -06	S.D. = 0.6734721 -07
J_2 = +0.1168324 -19	S.D. = 0.1968640 -17
ϕ_o = 3.371325 radians	S.D. = 0.2906718 radians

TABLE A.4

STELLAR LENS NO. 102 CONSTANTS OF INTERNAL GEOMETRY

CALIBRATION OF INNER CONE

Coordinates of Principal Point with respect to Indicated Principal Point (Indicated Principal Point X_{ipp} = 0.0 mm, Y_{ipp} = 0.0 mm).

X_p = +0.0123 mm	S.D. = 0.0130 mm
Y_p = +0.0145 mm	S.D. = 0.0138 mm

Coefficients of Radial Correction

FL = 75.7790 mm	S.D. = 0.0043 mm
K_1 = -0.1700017 -05	S.D. = 0.9581860 -06
K_2 = +0.2603037 -08	S.D. = 0.6337727 -08
K_3 = +0.3591281 -10	S.D. = 0.1653699 -10

Coefficients of Decentering Correction

J_1 = +0.1120179 -05	S.D. = 0.6479759 -06
J_2 = +0.3580872 -21	S.D. = 0.7633553 -19
ϕ_o = 3.870122 radians	S.D. = 0.5892840 radians

TABLE A.5

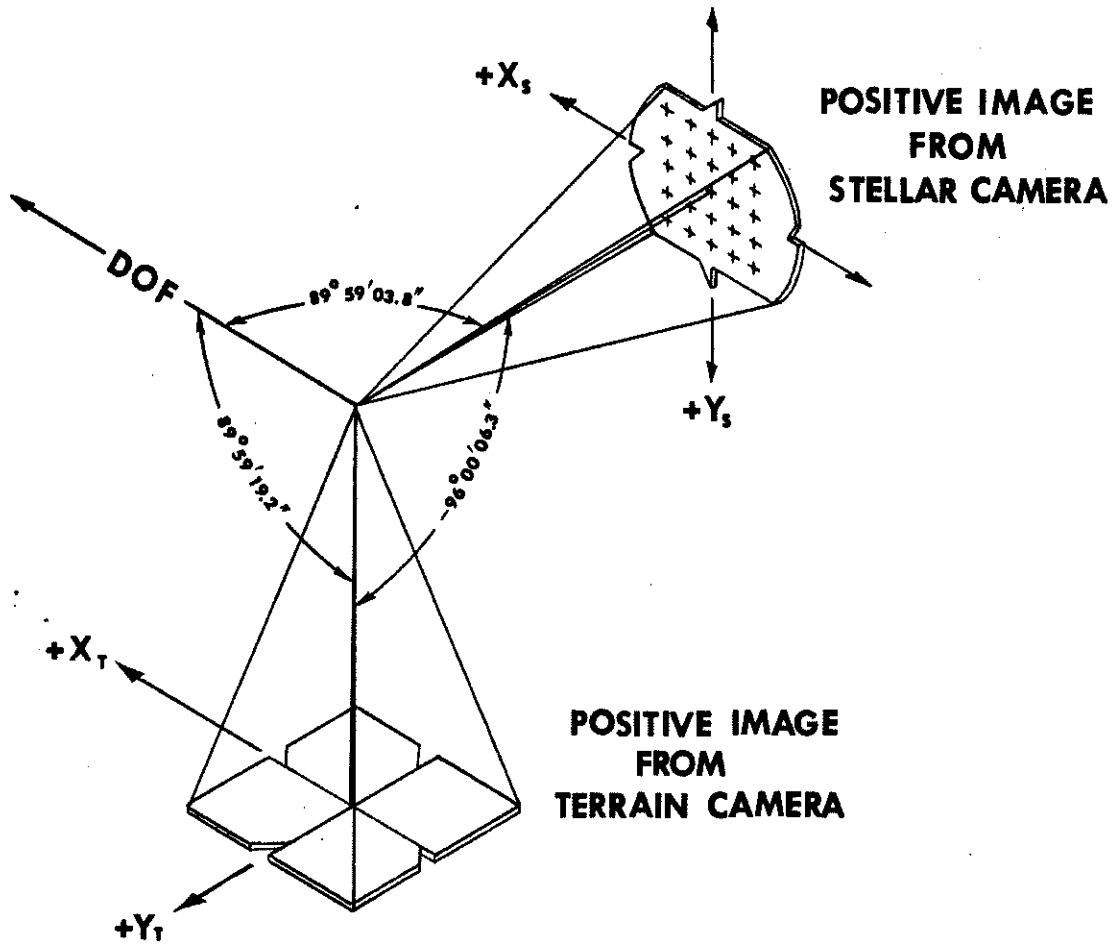


FIGURE A3. INTERLOCK FOR APOLLO 17.

camera and terrain camera. The sequence of the three rotations applied to the stellar camera coordinate axes is ω, ϕ, and κ where;

ω - Rotation about the x axis - Positive ω rotates the +y axis toward the +z axis to produce x' y' z',

ϕ - Rotation about the y' axis - Positive ϕ rotates the +z' axis toward the +x' axis producing x" y" z",

κ - Rotation about the z" axis - Positive κ rotates the +x" axis toward the +y" axis resulting in the final stellar position x_S y_S z_S.

The derived relative orientation matrix, covariance matrix, relative orientation angles, and angular standard deviations defining this transformation from the Terrain Camera to the Stellar Camera are shown in Table A.6.

LUNAR MAPPING CAMERA SN-004 INTERLOCK CALIBRATION

Relative orientation matrix defining a transformation from the Terrain Camera to the Stellar Camera.

+0.99999994	+0.00025051	-0.00022525
-0.00019782	-0.10455878	-0.99451869
-0.00027269	+0.99451868	-0.10455872

Covariance Matrix

+0.21544 -09	-0.30039 -11	-0.58996 -12
-0.30039 -11	+0.12097 -09	-0.79069 -11
-0.58996 -12	-0.79069 -11	+0.27709 -09

Relative Orientation Angles

OMEGA = $-96^{o}00'06\!\!.''276$	S.D. 3".0
PHI = $-\ 0^{o}00'56\!\!.''246$	S.D. 2".3
KAPPA = $+\ 0^{o}00'40\!\!.''803$	S.D. 3".4

Statistical Data from the Multi-Camera Solution

Degrees of Freedom = 1985

Unweighted Mean Error = 0.0028 mm

TABLE A.6