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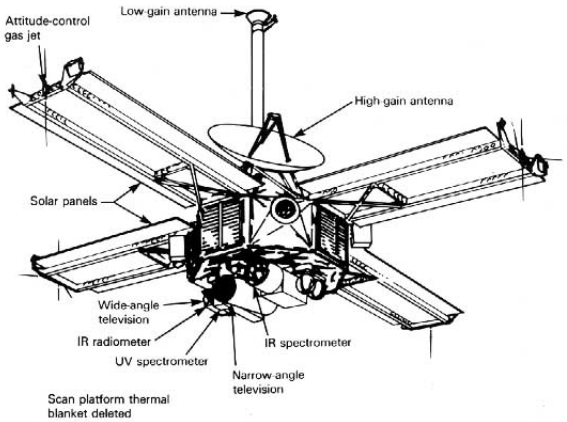
Mariner Mars 1969 Spacecraft Orientation and Camera Pointing: the basis for NAIF SPICE Frames and Attitude/Pointing Kernels



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1 Introduction

The Mariner Mars 1969 Mission (NASA, 1969) had two spacecraft, Mariner 6 and Mariner 7, whose inertial / celestial attitudes were controlled by Sun and star sensors. The spacecraft roll axes were pointed toward the Sun and the roll attitudes around the Sun lines were controlled by star sensors that tracked the bright southern star Canopus. Each spacecraft had a narrow and a wide angle camera (Danielson and Montgomery, 1971, Reindfleisch, *et. al.*, 1971) that were mounted on two degree-of-freedom scan platforms to point the cameras at Mars while the spacecraft maintained their celestially-fixed orientation.

A thorough search was made in archival libraries and with ex-operational personnel in an attempt to locate the telemetered spacecraft attitude control angles of pitch, yaw and roll as well as the scan platform clock and cone pointing angles. These data were not located but a document (Campbell, 1970) was found in the JPL Regional Planetary Image Facility (RPIF) that contained approximate clock and cone pointing angles for each camera when images were taken. These data were used as initial guesses when determining the actual camera pointing angles.

Current flight missions create many different "C" kernels for defining the orientation of systems / frames in coordinate systems. The primary "C" kernel defines the spacecraft frame orientation. Other "C" kernels, for example, define the orientation of antennae, pointing platforms, scan mirrors and instruments. This specific document gives the equations needed to define two "C" kernels, one for the spacecraft orientation in celestial space and one for camera pointing. The nominal spacecraft celestial attitude is based upon the spacecraft-centered apparent directions to the Sun and Canopus in Earth Mean Equator and Vernal Equinox of J2000.0 (referred to as J2000). This was the basis of computing NAIF SPICE frames and spacecraft orientation kernels (Acton, 1996, Acton, *et. al.*, 2017) for the inertial attitudes of Mariner 6 and 7 during the Mars encounter time periods.

Equations are also given to relate the scan platform / camera pointing relative to the spacecraft axes in the nominal celestially-fixed attitude and also relative to J2000. Without the telemetered attitude and scan platform pointing data, the mounting alignments of the two cameras on each platform could not be determined. Therefore, the equivalent right ascension, declination and twist camera pointing angles, relative to J2000, and equivalent clock, cone and twist camera pointing angles, relative to the nominal celestially-fixed spacecraft attitude, were computed in the form of quaternions to produce NAIF SPICE spacecraft attitude and camera pointing C kernels.

2 Mariner 6 and 7 Celestially-fixed Orientations

The nominal spacecraft roll axes were pointed at the Sun and the orientation about the roll axes were controlled by the direction to Canopus. At an image time, the spacecraft-centered, apparent unit direction vector $\hat{\mathbf{c}}$ (1-way light time and stellar aberration effects included) to the Sun and to Canopus, $\hat{\mathbf{C}}$ (stellar aberration effects included), both in J2000, define the celestial orientation of the spacecraft-fixed **abc** axes (Figure 1) using

$$\hat{\mathbf{c}} = \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} \tag{1}$$

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$$\hat{\mathbf{b}} \;=\; \frac{\hat{\mathbf{c}} \times \hat{\mathbf{C}}}{|\,\hat{\mathbf{c}} \times \hat{\mathbf{C}}\,|} \;=\; \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \tag{2}$$

$$\hat{\mathbf{a}} \;=\; \frac{\hat{\mathbf{b}} \times \hat{\mathbf{c}}}{|\,\hat{\mathbf{b}} \times \hat{\mathbf{c}}\,|} \;=\; \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \tag{3}$$

where $|\ |$ is the vector magnitude operator and $\times$ is the vector cross product operator.

The 3 x 3 unitless transformation $\mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}}$ from J2000 to spacecraft-fixed **abc** is given by

$$\mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}} \;=\; \begin{bmatrix} \hat{\mathbf{a}}^t \\ \hat{\mathbf{b}}^t \\ \hat{\mathbf{c}}^t \end{bmatrix} \;=\; \begin{bmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \end{bmatrix} \tag{4}$$

where ^{t} denotes the transpose of the unit vector.

For this analysis to restore the Mariner Mars 1969 Far and Near Encounter images, the direction to Canopus in J2000 was defined by

$$\hat{\mathbf{C}} \;=\; \begin{bmatrix} \cos\alpha_c & \cos\delta_c \\ \cos\alpha_c & \sin\delta_c \\ & \sin\delta_c \end{bmatrix} \tag{5}$$

where α_c, δ_c are the right ascension and declination direction angles, respectively, in J2000. The angles α_c, δ_c were computed with proper motion applied to 01 August 1969, mid-way between the Mariner 6 and Mariner 7 encounters with Mars, but with parallax and elliptic aberration ignored since the Mariner 6 and 7 orientations relative to the Sun and Canopus are uncertain to 0.05 deg without the telemetered spacecraft attitude data. At the epoch 01 August 1969

$$\alpha_c \;=\; 95.9876787; \quad \delta_c \;=\; -52.6958608 \;\; \text{deg} \tag{6}$$

Because the precision was not needed, stellar aberration effects were not applied to the roll reference (Canopus) unit vector in equation 5 using the heliocentric velocity in J2000 of the spacecraft at each image time.

Given a SPICE .bsp file (**S** kernel) for Mariner 6 or 7 trajectories and a SPICE .bsp file for the planetary orbits to compute $\hat{\mathbf{c}}$ and $\hat{\mathbf{C}}$ in equations 1 and 5 with 1-way light time and stellar aberration applied, the transformation $\mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}}$ from J2000 to spacecraft-fixed **abc** was computed at each Far and Near Encounter image time and the equivalent quaternions were extracted to produce spacecraft attitude **C** Kernels relative to J2000 during the Mariner 6 and 7 encounters with Mars.

3 Scan Platform / Camera Pointing Geometry

The Scan Platform pointing was controlled by commanded clock α_p and cone β angles relative to the spacecraft-fixed **abc** axes (Figure 1). Since these commanded scan platform pointing angles were not found, the similar clock and cone angles listed in Campbell, 1970 were used as the initial guess for the platform/camera pointing angles. Camera pointing is defined relative to camera-fixed coordinates **xyz** defined in the camera focal planes with axis $\bar{\mathbf{x}}$ in the direction of increasing sample

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number, axis $\bar{\mathbf{y}}$ in the direction of increasing line number and axis $\bar{\mathbf{z}}$ completing the orthogonal right-handed system and in the direction of the camera optical axis (Figure 1 - Duxbury, 2017). The transformation $\mathbf{T}^{\mathbf{abc}}_{\mathbf{xyz}}$ from spacecraft-fixed **abc** to camera fixed **xyz** coordinates is given by

$$\mathbf{T}^{\mathbf{abc}}_{\mathbf{xyz}} = [\ \gamma\ ]_3\ [\ \beta\ ]_2\ [\ \alpha_p\ ]_3 \tag{7}$$

The form $[\ \theta\ ]_i$ for $i = 2$ or 3 represents a unitless 3 x 3 rotation matrix given by

$$[\ \theta\ ]_2 = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}, \tag{8}$$

and

$$[\ \theta\ ]_3 = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{9}$$

The nominal value of γ is 180 deg for all images and the initial values of α_p, β were taken from Campbell, 1970 for each image. The transformation T^{J2000}_{xyz} from inertial J2000 to camera-fixed **xyz** is given by

$$T^{J2000}_{xyz} = \mathbf{T}^{\mathbf{abc}}_{\mathbf{xyz}}\ \mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}} = [\ \kappa\ ]_3\ [\ 90-\delta\ ]_2\ [\ \alpha+90\ ]_3 = \begin{bmatrix} 1,1 & 1,2 & 1,3 \\ 2,1 & 2,2 & 2,3 \\ 3,1 & 3,1 & 3,3 \end{bmatrix} \tag{10}$$

where i, j in equation 10 are the 9 unitless elements of the matrix. The equivalent inertial camera pointing angles of α, δ, κ in J2000 for an image are computed from these i, j matrix elements having values of 1, 2 or 3 by

$$\alpha = \tan^{-1}\ \frac{(\ 3,1)}{(-3,2)}\ - 90 \tag{11}$$

$$\delta = 90\ -\ \cos^{-1}\ (3,3) \tag{12}$$

$$\kappa = \tan^{-1}\ \frac{(1,3)}{(2,3)} \tag{13}$$

Also the equivalent quaternions that represent equation 10 were computed to form the basis of the narrow and wide angle camera pointing **C** Kernels relative to J2000 and **abc**.

4 Computing Camera Pointing Angles

For a given image (Leighton, *et. al.*, 1969, Leighton, *et. al.*, 1971, Collins, 1971), the time tag was used to compute the appropriate spacecraft roll axis direction $\hat{\mathbf{c}}$ and the Mars apparent position relative to the spacecraft from SPICE **S** Kernels to compute $\mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}}$. The initial camera pointing angles, take from Campbell, 1970, were used as the initial guess to compute $\mathbf{T}^{\mathbf{abc}}_{\mathbf{xyz}}$. It is noted that 7F02 was not found and is not listed in the Collins, 1971 document. The Mariner 7 Tape Recorder could only hold 33 full frame images and images 7F34 and 7F68 were not recovered. The time tag and trajectory parameters for 7F00 were not included in Campbell, 1971. Collins, 1971 states

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that this image was taken about 5 hours earlier than 7F01. Therefore the time tag for 7F00 was set to 5 hours earlier than 7F01 and viewing / lighting / trajectory parameters were computed at this time. The camera analytic geometric model (Duxbury, 2017) was then used to map project an illuminated Mars MOLA digital terrain model (DTM) to make a digital image model (DIM) and computed Mars limb and terminator through $\mathbf{T}^{\mathbf{J2000}}_{\mathbf{abc}}$ and $\mathbf{T}^{\mathbf{abc}}_{\mathbf{xyz}}$ into sample and line image coordinates. The angles $\alpha_p,\ \beta$ were adjusted until the computed limb / terminator overlay was registered to the image as seen in Figure 2. With no telemetered attitude / platform data, γ was held fixed at 180 deg for all images and only $\alpha_p,\ \beta$ were varied for each image.

After registering each image, the angles $\alpha_p,\ \beta,\ \gamma$ and equivalent quaternions for equation 7 were used to make a camera pointing **C** Kernel relative to the spacecraft-centered and fixed, celestial **abc** system and the angles $\alpha,\ \delta, \kappa$ and equivalent quaternions for equations 10 were used to make a camera pointing **C** Kernel relative to the spacecraft-centered and J2000-fixed system frame.

The NAIF SPICE spacecraft ID numbers for the Mariner 1969 spacecraft and cameras are given in Table 1. The camera pointing angles $\alpha_p,\ \beta,\ \gamma$ are given in Table 2 for Mariner 6 and in Tables 4 and 5 for Mariner 7. The camera pointing angles $\alpha,\ \delta,\ \kappa$ are given in Table 3 for Mariner 6 and in Tables 6 and 7 for Mariner 7. The **C** kernels giving the spacecraft attitude in inertial J2000 coordinates are

*mr*6*_sc_*690729_690730*_tcd_v*10.*bc* and

mr7_sc_690802_690804_tcd_v10.bc, s

The **C** Kernels giving narrow angle camera pointing in inertial J2000 coordinates (Duxbury and Semenov, 2017) are

mr6_na_690729_690730_tcd_v10.bc and

*mr*7*_na_*690802_690804*_tcd_v*10.*bc*,

The related Mariner Mars 1969 NAIF SPICE Kernel collection includes the meta-kernel, making the use of the Mariner 69 kernels collection much easier

mariner69_v02.tm

Spacecraft Trajectory S Kernels (Duxbury and Jacobson, 2017)

mr6_690721_690810_ssd_v10.bsp and

mr7_690726_690815_ssd_v10.bsp,

Instrument I Kernels (Duxbury, 2017)

mr6_na_tcd_v10.ti and

mr7_na_tcd_v10.ti,

Spacecraft Frames F and C Kernels (Duxbury and Semenov, 2017)

mr6_v10.tf and

mr7_v10.tf

and Spacecraft Clock Correlations Kernels (Duxbury and Semenov, 2017b)

m6_fict.tsc and

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m7_fict.tsc

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Table 1: Mariner Mars 1969 SPICE Spacecraft and Camera Identification Numbers

S/C	S/C (S & SCLK) Kernels	S/C (C, F & I) Kernels	Narrow Angle Camera	Wide Angle Camera
Mariner 6	-530	-530000	-530101	-530102
Mariner 7	-531	-531000	-531101	-531102

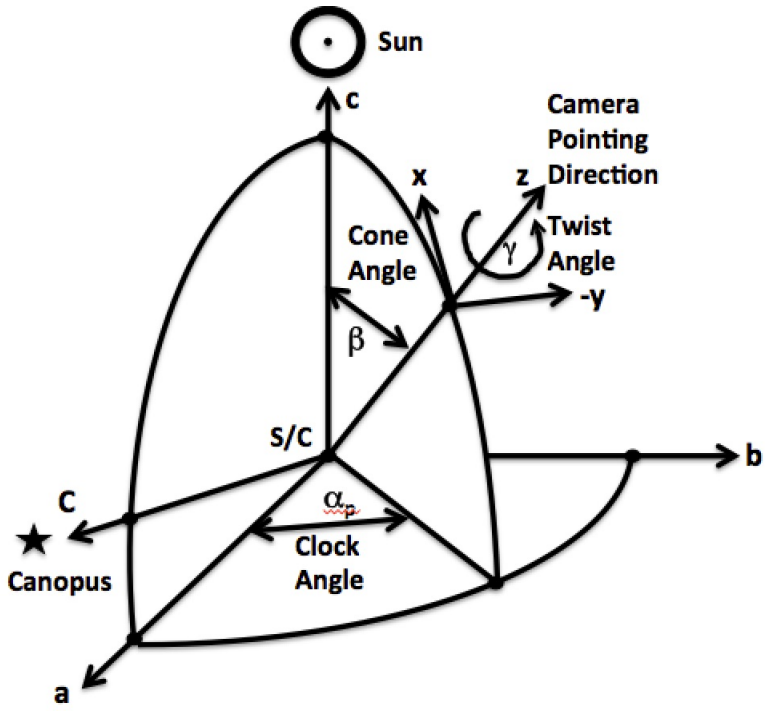

Figure 1: The spacecraft - centered celestial **abc** and camera - fixed **xyz** coordinate systems

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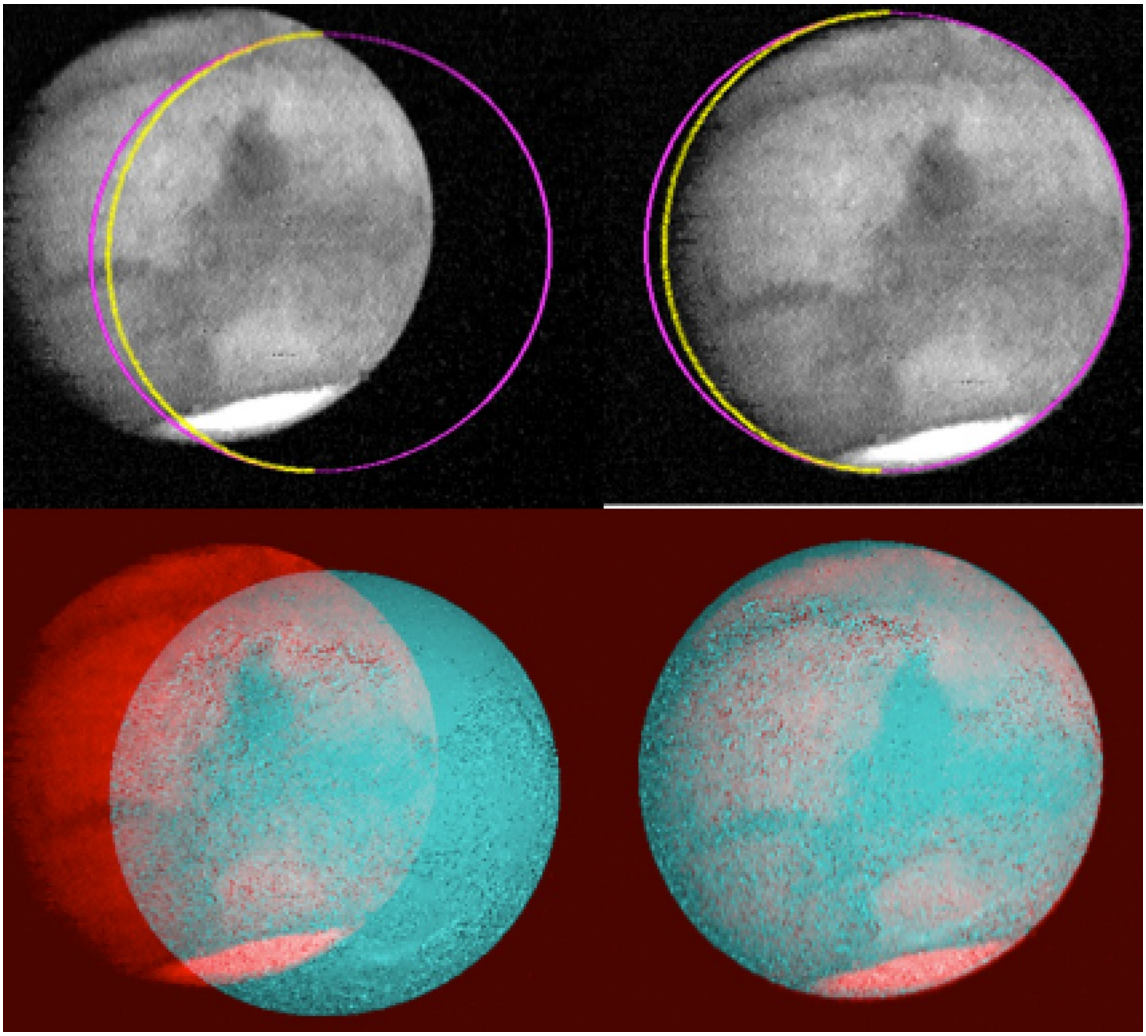

Figure 2: Actual camera pointing was computed by changing the scan platform angles α_p and β to register the predicted limb / terminator (top) and MOLA DIM (bottom) to each image.

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Table 2: M6 camera pointing angles relative to the spacecraft-centered and celestial $\hat{\mathbf{a}}\hat{\mathbf{b}}\hat{\mathbf{c}}$ frame

PICNO	Camera	UTC	α_p	β	γ
6F01	NA	1969-JUL-29 05:28:48.130	111.0650	158.6710	180.0000
6F02	NA	1969-JUL-29 06:05:24.763	111.0317	158.6671	180.0000
6F03	NA	1969-JUL-29 06:42:01.395	111.0432	158.6543	180.0000
6F04	NA	1969-JUL-29 07:18:38.028	111.0320	158.6885	180.0000
6F05	NA	1969-JUL-29 07:56:39.146	111.0722	158.6819	180.0000
6F06	NA	1969-JUL-29 08:33:15.778	111.0090	158.6235	180.0000
6F07	NA	1969-JUL-29 09:09:52.411	111.0170	158.6617	180.0000
6F08	NA	1969-JUL-29 09:46:29.043	111.0037	158.6510	180.0000
6F09	NA	1969-JUL-29 10:24:30.160	111.0510	158.6092	180.0000
6F10	NA	1969-JUL-29 11:01:06.794	110.9860	158.5905	180.0000
6F11	NA	1969-JUL-29 11:39:46.145	111.0367	158.6269	180.0000
6F12	NA	1969-JUL-29 12:15:44.544	110.9747	158.5692	180.0000
6F13	NA	1969-JUL-29 12:52:21.176	111.0320	158.6146	180.0000
6F14	NA	1969-JUL-29 13:28:57.808	110.9840	158.5615	180.0000
6F15	NA	1969-JUL-29 14:05:34.440	111.0082	158.5534	180.0000
6F16	NA	1969-JUL-29 14:43:35.559	110.9490	158.5547	180.0000
6F17	NA	1969-JUL-29 15:20:12.191	111.0007	158.5903	180.0000
6F18	NA	1969-JUL-29 15:56:48.824	110.9697	158.5397	180.0000
6F19	NA	1969-JUL-29 16:34:49.942	110.9337	158.5329	180.0000
6F20	NA	1969-JUL-29 17:11:26.575	110.9785	158.5538	180.0000
6F21	NA	1969-JUL-29 17:48:03.207	110.9182	158.5325	180.0000
6F22	NA	1969-JUL-29 18:24:39.838	110.9102	158.5280	180.0000
6F23	NA	1969-JUL-29 19:02:40.957	110.9155	158.5640	180.0000
6F24	NA	1969-JUL-29 19:39:17.589	110.9322	158.5162	180.0000
6F25	NA	1969-JUL-29 20:15:54.221	110.9285	158.5572	180.0000
6F26	NA	1969-JUL-29 20:52:30.855	110.9407	158.5114	180.0000
6F27	NA	1969-JUL-29 21:30:31.972	110.9027	158.5444	180.0000
6F28	NA	1969-JUL-29 22:07:08.605	110.9005	158.5142	180.0000
6F29	NA	1969-JUL-29 22:43:45.237	110.9430	158.4849	180.0000
6F30	NA	1969-JUL-29 23:21:46.356	110.9417	158.4748	180.0000
6F31	NA	1969-JUL-29 23:58:22.988	110.8942	158.5132	180.0000
6F32	NA	1969-JUL-30 00:35:06.458	110.8947	158.5184	180.0000
6F33	NA	1969-JUL-30 01:11:36.253	110.8862	158.4806	180.0000
6F34	NA	1969-JUL-30 07:31:47.435	110.9307	158.5310	180.0000
6F35	NA	1969-JUL-30 08:36:33.785	110.9840	158.5465	180.0000
6F36	NA	1969-JUL-30 09:39:55.647	111.0000	158.5581	180.0000
6F37	NA	1969-JUL-30 10:44:41.998	110.9825	158.5340	180.0000
6F38	NA	1969-JUL-30 11:48:03.861	111.0092	158.5991	180.0000
6F39	NA	1969-JUL-30 12:52:50.210	111.0457	158.6334	180.0000
6F40	NA	1969-JUL-30 13:56:12.075	111.1105	158.6307	180.0000
6F41	NA	1969-JUL-30 13:57:36.560	111.1100	158.6316	180.0000
6F42	NA	1969-JUL-30 14:53:55.994	111.1130	158.6721	180.0000
6F43	NA	1969-JUL-30 15:50:15.430	111.1895	158.7224	180.0000
6F44	NA	1969-JUL-30 16:46:34.864	111.2117	158.7826	180.0000
6F45	NA	1969-JUL-30 17:41:29.813	111.2960	158.8895	180.0000
6F46	NA	1969-JUL-30 18:37:49.247	111.3033	158.9747	180.0000
6F47	NA	1969-JUL-30 19:34:08.681	111.3658	159.0660	180.0000
6F48	NA	1969-JUL-30 20:30:28.116	111.5480	159.1819	180.0000
6F49	NA	1969-JUL-30 21:26:47.550	111.6168	159.2941	180.0000

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Table 3: M6 camera pointing angles relative to the spacecraft-centered and inertial J2000 frame

PICNO	Camera	UTC	α	δ	κ
6F01	NA	1969-JUL-29 05:28:48.130	263.5344	-17.1300	156.8516
6F02	NA	1969-JUL-29 06:05:24.763	263.5394	-17.1411	156.8889
6F03	NA	1969-JUL-29 06:42:01.395	263.5425	-17.1337	156.8838
6F04	NA	1969-JUL-29 07:18:38.028	263.5875	-17.1524	156.9123
6F05	NA	1969-JUL-29 07:56:39.146	263.6014	-17.1379	156.8839
6F06	NA	1969-JUL-29 08:33:15.778	263.5495	-17.1376	156.9323
6F07	NA	1969-JUL-29 09:09:52.411	263.6012	-17.1514	156.9448
6F08	NA	1969-JUL-29 09:46:29.043	263.6026	-17.1532	156.9624
6F09	NA	1969-JUL-29 10:24:30.160	263.5837	-17.1225	156.9177
6F10	NA	1969-JUL-29 11:01:06.794	263.5697	-17.1385	156.9789
6F11	NA	1969-JUL-29 11:39:46.145	263.6268	-17.1373	156.9535
6F12	NA	1969-JUL-29 12:15:44.544	263.5754	-17.1370	157.0008
6F13	NA	1969-JUL-29 12:52:21.176	263.6414	-17.1370	156.9717
6F14	NA	1969-JUL-29 13:28:57.808	263.5968	-17.1339	157.0080
6F15	NA	1969-JUL-29 14:05:34.440	263.6064	-17.1241	156.9930
6F16	NA	1969-JUL-29 14:43:35.559	263.6130	-17.1461	157.0550
6F17	NA	1969-JUL-29 15:20:12.191	263.6688	-17.1440	157.0280
6F18	NA	1969-JUL-29 15:56:48.824	263.6291	-17.1362	157.0500
6F19	NA	1969-JUL-29 16:34:49.942	263.6314	-17.1473	157.0891
6F20	NA	1969-JUL-29 17:11:26.575	263.6719	-17.1418	157.0642
6F21	NA	1969-JUL-29 17:48:03.207	263.6561	-17.1553	157.1203
6F22	NA	1969-JUL-29 18:24:39.838	263.6643	-17.1578	157.1349
6F23	NA	1969-JUL-29 19:02:40.957	263.7140	-17.1715	157.1497
6F24	NA	1969-JUL-29 19:39:17.589	263.6841	-17.1488	157.1300
6F25	NA	1969-JUL-29 20:15:54.221	263.7368	-17.1675	157.1538
6F26	NA	1969-JUL-29 20:52:30.855	263.7082	-17.1470	157.1387
6F27	NA	1969-JUL-29 21:30:31.972	263.7486	-17.1742	157.1909
6F28	NA	1969-JUL-29 22:07:08.605	263.7328	-17.1647	157.1931
6F29	NA	1969-JUL-29 22:43:45.237	263.7246	-17.1405	157.1559
6F30	NA	1969-JUL-29 23:21:46.356	263.7288	-17.1386	157.1633
6F31	NA	1969-JUL-29 23:58:22.988	263.7725	-17.1710	157.2251
6F32	NA	1969-JUL-30 00:35:06.458	263.7914	-17.1743	157.2349
6F33	NA	1969-JUL-30 01:11:36.253	263.7673	-17.1640	157.2405
6F34	NA	1969-JUL-30 07:31:47.435	263.9646	-17.1837	157.3066
6F35	NA	1969-JUL-30 08:36:33.785	264.0117	-17.1743	157.2793
6F36	NA	1969-JUL-30 09:39:55.647	264.0489	-17.1759	157.2837
6F37	NA	1969-JUL-30 10:44:41.998	264.0473	-17.1751	157.3078
6F38	NA	1969-JUL-30 11:48:03.861	264.1377	-17.1937	157.3179
6F39	NA	1969-JUL-30 12:52:50.210	264.2004	-17.1972	157.3108
6F40	NA	1969-JUL-30 13:56:12.075	264.2310	-17.1768	157.2677
6F41	NA	1969-JUL-30 13:57:36.560	264.2323	-17.1774	157.2688
6F42	NA	1969-JUL-30 14:53:55.994	264.2929	-17.1942	157.2912
6F43	NA	1969-JUL-30 15:50:15.430	264.3737	-17.1902	157.2511
6F44	NA	1969-JUL-30 16:46:34.864	264.4562	-17.2082	157.2620
6F45	NA	1969-JUL-30 17:41:29.813	264.5922	-17.2236	157.2308
6F46	NA	1969-JUL-30 18:37:49.247	264.6965	-17.2562	157.2622
6F47	NA	1969-JUL-30 19:34:08.681	264.8148	-17.2730	157.2463
6F48	NA	1969-JUL-30 20:30:28.116	264.9741	-17.2601	157.1305
6F49	NA	1969-JUL-30 21:26:47.550	265.1133	-17.2833	157.1148

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Table 4: M7 camera pointing angles relative to the spacecraft-centered and celestial $\hat{\mathbf{a}}\hat{\mathbf{b}}\hat{\mathbf{c}}$ axes

PICNO	Camera	UTC	α_p	β	γ
7F00	NA	1969-AUG-02 04:32:42.224	102.9875	157.8128	180.0000
7F01	NA	1969-AUG-02 09:32:42.223	103.0628	157.8893	180.0000
7F03	NA	1969-AUG-02 10:27:37.036	103.0015	157.8818	180.0000
7F04	NA	1969-AUG-02 10:54:22.202	103.0055	157.7211	180.0000
7F05	NA	1969-AUG-02 11:21:07.368	103.0602	157.7626	180.0000
7F06	NA	1969-AUG-02 11:47:52.533	102.9785	157.7719	180.0000
7F07	NA	1969-AUG-02 12:14:37.699	102.9895	157.7650	180.0000
7F08	NA	1969-AUG-02 12:41:22.863	103.0155	157.7478	180.0000
7F09	NA	1969-AUG-02 13:09:32.512	103.0615	157.6729	180.0000
7F10	NA	1969-AUG-02 13:36:17.678	102.9945	157.7668	180.0000
7F11	NA	1969-AUG-02 14:03:02.843	103.0568	157.7200	180.0000
7F12	NA	1969-AUG-02 14:29:48.008	102.9960	157.8004	180.0000
7F13	NA	1969-AUG-02 14:56:33.173	102.9887	157.8007	180.0000
7F14	NA	1969-AUG-02 15:23:18.339	102.9885	157.6903	180.0000
7F15	NA	1969-AUG-02 15:51:27.986	103.0517	157.6142	180.0000
7F16	NA	1969-AUG-02 16:18:13.153	103.0510	157.6301	180.0000
7F17	NA	1969-AUG-02 16:44:58.318	102.9965	157.6101	180.0000
7F18	NA	1969-AUG-02 17:11:43.484	102.9912	157.7695	180.0000
7F19	NA	1969-AUG-02 17:38:43.648	103.0671	157.5790	180.0000
7F20	NA	1969-AUG-02 18:05:13.814	102.9872	157.5888	180.0000
7F21	NA	1969-AUG-02 18:33:23.461	103.0670	157.7237	180.0000
7F22	NA	1969-AUG-02 19:00:08.627	102.9863	157.5690	180.0000
7F23	NA	1969-AUG-02 19:26:53.792	102.9870	157.5657	180.0000
7F24	NA	1969-AUG-02 19:53:38.959	103.0488	157.6690	180.0000
7F25	NA	1969-AUG-02 20:20:24.124	103.0755	157.5330	180.0000
7F26	NA	1969-AUG-02 20:48:33.771	103.0642	157.5438	180.0000
7F27	NA	1969-AUG-02 21:15:18.937	103.0668	157.5490	180.0000
7F28	NA	1969-AUG-02 21:42:04.103	103.0050	157.5310	180.0000
7F29	NA	1969-AUG-02 22:08:49.268	103.0028	157.6334	180.0000
7F30	NA	1969-AUG-02 22:35:34.434	103.0678	157.5158	180.0000
7F31	NA	1969-AUG-02 23:02:19.599	103.0110	157.5644	180.0000
7F32	NA	1969-AUG-02 23:30:29.247	103.0665	157.6554	180.0000
7F33	NA	1969-AUG-02 23:57:14.411	103.0771	157.5181	180.0000
7F35	NA	1969-AUG-03 06:00:30.869	103.1092	157.3926	180.0000
7F36	NA	1969-AUG-03 06:35:42.929	103.1218	157.4226	180.0000
7F37	NA	1969-AUG-03 07:12:19.470	103.1150	157.3677	180.0000
7F38	NA	1969-AUG-03 07:47:31.530	103.0660	157.4846	180.0000
7F39	NA	1969-AUG-03 08:24:08.072	103.1314	157.4959	180.0000
7F40	NA	1969-AUG-03 08:59:20.132	103.1445	157.4692	180.0000
7F41	NA	1969-AUG-03 09:35:56.674	103.1440	157.3670	180.0000
7F42	NA	1969-AUG-03 10:12:33.216	103.0850	157.3603	180.0000
7F43	NA	1969-AUG-03 10:47:45.277	103.1045	157.4066	180.0000
7F44	NA	1969-AUG-03 11:24:21.819	103.1540	157.4391	180.0000
7F45	NA	1969-AUG-03 11:59:33.879	103.1205	157.3837	180.0000
7F46	NA	1969-AUG-03 12:36:10.421	103.1260	157.3150	180.0000

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Table 5: M7 camera pointing angles relative to the spacecraft-centered and celestial $\hat{\mathbf{a}}\hat{\mathbf{b}}\hat{\mathbf{c}}$ axes

PICNO	Camera	UTC	α_p	β	γ
7F47	NA	1969-AUG-03 13:11:22.481	103.1977	157.4095	180.0000
7F48	NA	1969-AUG-03 13:47:59.023	103.1380	157.3746	180.0000
7F49	NA	1969-AUG-03 14:24:35.566	103.1754	157.3424	180.0000
7F50	NA	1969-AUG-03 14:59:47.625	103.2167	157.2730	180.0000
7F51	NA	1969-AUG-03 15:36:24.168	103.2347	157.2932	180.0000
7F52	NA	1969-AUG-03 16:11:36.227	103.2330	157.2259	180.0000
7F53	NA	1969-AUG-03 16:48:12.770	103.1922	157.2479	180.0000
7F54	NA	1969-AUG-03 17:23:24.828	103.2422	157.3584	180.0000
7F55	NA	1969-AUG-03 18:00:01.372	103.2560	157.2139	180.0000
7F56	NA	1969-AUG-03 18:36:37.914	103.2164	157.2733	180.0000
7F57	NA	1969-AUG-03 19:11:49.973	103.2095	157.1954	180.0000
7F58	NA	1969-AUG-03 19:48:26.515	103.2647	157.2802	180.0000
7F59	NA	1969-AUG-03 20:23:38.575	103.2583	157.2109	180.0000
7F60	NA	1969-AUG-03 21:00:15.117	103.2482	157.2068	180.0000
7F61	NA	1969-AUG-03 21:34:27.176	103.2325	157.1940	180.0000
7F62	NA	1969-AUG-03 22:12:03.720	103.3143	157.2510	180.0000
7F63	NA	1969-AUG-03 22:47:15.779	103.2927	157.2998	180.0000
7F64	NA	1969-AUG-03 23:23:52.322	103.3006	157.2146	180.0000
7F65	NA	1969-AUG-04 00:00:28.864	103.3145	157.2701	180.0000
7F66	NA	1969-AUG-04 00:35:40.924	103.4075	157.2858	180.0000
7F67	NA	1969-AUG-04 01:12:17.466	103.3930	157.2447	180.0000
7F69	NA	1969-AUG-04 08:06:15.288	103.6940	157.2827	180.0000
7F70	NA	1969-AUG-04 08:54:07.690	103.7400	157.1706	180.0000
7F71	NA	1969-AUG-04 09:40:35.610	103.7542	157.2093	180.0000
7F72	NA	1969-AUG-04 10:28:28.011	103.8461	157.2810	180.0000
7F73	NA	1969-AUG-04 11:14:55.930	103.9252	157.2215	180.0000
7F74	NA	1969-AUG-04 12:01:23.849	103.9825	157.3063	180.0000
7F75	NA	1969-AUG-04 12:49:16.249	104.0405	157.2001	180.0000
7F76	NA	1969-AUG-04 13:35:44.168	104.1184	157.2263	180.0000
7F77	NA	1969-AUG-04 14:23:36.570	104.2668	157.3358	180.0000
7F78	NA	1969-AUG-04 15:10:04.488	104.3660	157.3299	180.0000
7F79	NA	1969-AUG-04 15:56:32.408	104.4374	157.3010	180.0000
7F80	NA	1969-AUG-04 16:44:24.809	104.5969	157.3851	180.0000
7F81	NA	1969-AUG-04 17:30:52.728	104.7618	157.3871	180.0000
7F82	NA	1969-AUG-04 18:17:20.647	104.9028	157.5367	180.0000
7F83	NA	1969-AUG-04 19:05:13.049	105.0995	157.6212	180.0000
7F84	NA	1969-AUG-04 19:51:40.968	105.3608	157.6043	180.0000
7F85	NA	1969-AUG-04 20:39:33.369	105.6446	157.6611	180.0000
7F86	NA	1969-AUG-04 21:26:01.288	105.9527	157.9777	180.0000
7F87	NA	1969-AUG-04 22:12:29.207	106.3757	158.0201	180.0000
7F88	NA	1969-AUG-04 23:00:21.607	106.9090	158.2334	180.0000
7F89	NA	1969-AUG-04 23:11:37.466	106.9731	158.2654	180.0000
7F90	NA	1969-AUG-04 23:24:17.809	107.0880	158.3220	180.0000
7F91	NA	1969-AUG-04 23:35:33.668	107.4442	158.3524	180.0000
7F92	NA	1969-AUG-04 23:48:14.009	107.3870	158.3612	180.0000
7F93	NA	1969-AUG-04 23:59:29.869	107.8117	158.4171	180.0000

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Table 6: M7 camera pointing angles relative to the spacecraft-centered and inertial J2000 frame

PICNO	Camera	UTC	α	δ	κ
7F00	NA	1969-AUG-02 04:32:42.224	264.1281	-20.0370	165.2969
7F01	NA	1969-AUG-02 09:32:42.223	264.3312	-20.0432	165.3296
7F03	NA	1969-AUG-02 10:27:37.036	264.3386	-20.0663	165.3949
7F04	NA	1969-AUG-02 10:54:22.202	264.1839	-20.0255	165.3411
7F05	NA	1969-AUG-02 11:21:07.368	264.2426	-20.0172	165.3134
7F06	NA	1969-AUG-02 11:47:52.533	264.2542	-20.0508	165.3960
7F07	NA	1969-AUG-02 12:14:37.699	264.2586	-20.0463	165.3903
7F08	NA	1969-AUG-02 12:41:22.863	264.2540	-20.0337	165.3676
7F09	NA	1969-AUG-02 13:09:32.512	264.1925	-19.9992	165.3070
7F10	NA	1969-AUG-02 13:36:17.678	264.2927	-20.0488	165.4062
7F11	NA	1969-AUG-02 14:03:02.843	264.2612	-20.0154	165.3408
7F12	NA	1969-AUG-02 14:29:48.008	264.3483	-20.0592	165.4297
7F13	NA	1969-AUG-02 14:56:33.173	264.3582	-20.0632	165.4428
7F14	NA	1969-AUG-02 15:23:18.339	264.2549	-20.0368	165.4105
7F15	NA	1969-AUG-02 15:51:27.986	264.1939	-19.9957	165.3342
7F16	NA	1969-AUG-02 16:18:13.153	264.2206	-20.0013	165.3469
7F17	NA	1969-AUG-02 16:44:58.318	264.2048	-20.0176	165.3948
7F18	NA	1969-AUG-02 17:11:43.484	264.3788	-20.0609	165.4623
7F19	NA	1969-AUG-02 17:38:43.648	264.2008	-19.9863	165.3341
7F20	NA	1969-AUG-02 18:05:13.814	264.2130	-20.0195	165.4150
7F21	NA	1969-AUG-02 18:33:23.461	264.3710	-20.0255	165.3984
7F22	NA	1969-AUG-02 19:00:08.627	264.2138	-20.0175	165.4222
7F23	NA	1969-AUG-02 19:26:53.792	264.2209	-20.0177	165.4268
7F24	NA	1969-AUG-02 19:53:38.959	264.3440	-20.0222	165.4148
7F25	NA	1969-AUG-02 20:20:24.124	264.2170	-19.9793	165.3496
7F26	NA	1969-AUG-02 20:48:33.771	264.2379	-19.9875	165.3702
7F27	NA	1969-AUG-02 21:15:18.937	264.2539	-19.9892	165.3762
7F28	NA	1969-AUG-02 21:42:04.103	264.2394	-20.0088	165.4312
7F29	NA	1969-AUG-02 22:08:49.268	264.3551	-20.0366	165.4759
7F30	NA	1969-AUG-02 22:35:34.434	264.2509	-19.9843	165.3831
7F31	NA	1969-AUG-02 23:02:19.599	264.3056	-20.0188	165.4571
7F32	NA	1969-AUG-02 23:30:29.247	264.4159	-20.0226	165.4467
7F33	NA	1969-AUG-02 23:57:14.411	264.2859	-19.9854	165.3953
7F35	NA	1969-AUG-03 06:00:30.869	264.3007	-19.9592	165.4103
7F36	NA	1969-AUG-03 06:35:42.929	264.3465	-19.9638	165.4183
7F37	NA	1969-AUG-03 07:12:19.470	264.3034	-19.9542	165.4138
7F38	NA	1969-AUG-03 07:47:31.530	264.4324	-20.0034	165.5069
7F39	NA	1969-AUG-03 08:24:08.072	264.4649	-19.9838	165.4616
7F40	NA	1969-AUG-03 08:59:20.132	264.4524	-19.9739	165.4491
7F41	NA	1969-AUG-03 09:35:56.674	264.3612	-19.9501	165.4224
7F42	NA	1969-AUG-03 10:12:33.216	264.3624	-19.9722	165.4813
7F43	NA	1969-AUG-03 10:47:45.277	264.4257	-19.9782	165.4888
7F44	NA	1969-AUG-03 11:24:21.819	264.4784	-19.9697	165.4651
7F45	NA	1969-AUG-03 11:59:33.879	264.4315	-19.9699	165.4838
7F46	NA	1969-AUG-03 12:36:10.421	264.3755	-19.9524	165.4636

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Table 7: M7 camera pointing angles relative to the spacecraft-centered and inertial J2000 frame

PICNO	Camera	UTC	α	δ	κ
7F47	NA	1969-AUG-03 13:11:22.481	264.4938	-19.9511	165.4417
7F48	NA	1969-AUG-03 13:47:59.023	264.4659	-19.9663	165.4912
7F49	NA	1969-AUG-03 14:24:35.566	264.4507	-19.9460	165.4555
7F50	NA	1969-AUG-03 14:59:47.625	264.3971	-19.9148	165.4030
7F51	NA	1969-AUG-03 15:36:24.168	264.4339	-19.9149	165.4029
7F52	NA	1969-AUG-03 16:11:36.227	264.3781	-19.9002	165.3893
7F53	NA	1969-AUG-03 16:48:12.770	264.4106	-19.9228	165.4420
7F54	NA	1969-AUG-03 17:23:24.828	264.5431	-19.9336	165.4449
7F55	NA	1969-AUG-03 18:00:01.372	264.4100	-19.8938	165.3909
7F56	NA	1969-AUG-03 18:36:37.914	264.4811	-19.9253	165.4555
7F57	NA	1969-AUG-03 19:11:49.973	264.4138	-19.9100	165.4429
7F58	NA	1969-AUG-03 19:48:26.515	264.5210	-19.9124	165.4324
7F59	NA	1969-AUG-03 20:23:38.575	264.4625	-19.8990	165.4223
7F60	NA	1969-AUG-03 21:00:15.117	264.4714	-19.9035	165.4387
7F61	NA	1969-AUG-03 21:34:27.176	264.4698	-19.9078	165.4563
7F62	NA	1969-AUG-03 22:12:03.720	264.5514	-19.8933	165.4128
7F63	NA	1969-AUG-03 22:47:15.779	264.6130	-19.9153	165.4575
7F64	NA	1969-AUG-03 23:23:52.322	264.5403	-19.8926	165.4294
7F65	NA	1969-AUG-04 00:00:28.864	264.6129	-19.9031	165.4454
7F66	NA	1969-AUG-04 00:35:40.924	264.6523	-19.8740	165.3768
7F67	NA	1969-AUG-04 01:12:17.466	264.6226	-19.8708	165.3841
7F69	NA	1969-AUG-04 08:06:15.288	264.8524	-19.7872	165.2299
7F70	NA	1969-AUG-04 08:54:07.690	264.7605	-19.7436	165.1617
7F71	NA	1969-AUG-04 09:40:35.610	264.8196	-19.7503	165.1736
7F72	NA	1969-AUG-04 10:28:28.011	264.9213	-19.7365	165.1285
7F73	NA	1969-AUG-04 11:14:55.930	264.8865	-19.6938	165.0489
7F74	NA	1969-AUG-04 12:01:23.849	264.9974	-19.6965	165.0386
7F75	NA	1969-AUG-04 12:49:16.249	264.9130	-19.6495	164.9620
7F76	NA	1969-AUG-04 13:35:44.168	264.9660	-19.6293	164.9131
7F77	NA	1969-AUG-04 14:23:36.570	265.1125	-19.6048	164.8308
7F78	NA	1969-AUG-04 15:10:04.488	265.1349	-19.5684	164.7519
7F79	NA	1969-AUG-04 15:56:32.408	265.1308	-19.5363	164.6898
7F80	NA	1969-AUG-04 16:44:24.809	265.2525	-19.5015	164.5886
7F81	NA	1969-AUG-04 17:30:52.728	265.2903	-19.4431	164.4542
7F82	NA	1969-AUG-04 18:17:20.647	265.4762	-19.4333	164.3911
7F83	NA	1969-AUG-04 19:05:13.049	265.6023	-19.3860	164.2565
7F84	NA	1969-AUG-04 19:51:40.968	265.6316	-19.2876	164.0299
7F85	NA	1969-AUG-04 20:39:33.369	265.7394	-19.2016	163.8083
7F86	NA	1969-AUG-04 21:26:01.288	266.1134	-19.1807	163.6513
7F87	NA	1969-AUG-04 22:12:29.207	266.2219	-19.0427	163.2999
7F88	NA	1969-AUG-04 23:00:21.607	266.5170	-18.9166	162.9065
7F89	NA	1969-AUG-04 23:11:37.466	266.5610	-18.9037	162.8625
7F90	NA	1969-AUG-04 23:24:17.809	266.6362	-18.8803	162.7817
7F91	NA	1969-AUG-04 23:35:33.668	266.7126	-18.7643	162.4765
7F92	NA	1969-AUG-04 23:48:14.009	266.7196	-18.7876	162.5335
7F93	NA	1969-AUG-04 23:59:29.869	266.8302	-18.6560	162.1754