

5. 6 GENERAL SERVICE ROUTINES

5. 6. 1 GENERAL COMMENTS

The routines presented in this section include the following general service functions:

- 1) IMU alignment modes
- 2) Basic Coordinate Transformations
- 3) Computer initialization procedures
- 4) Special display routines which can be called by the astronaut
- 5) Automatic optics designate routines

5.6.2 IMU ALIGNMENT MODES

5.6.2.1 IMU Orientation Determination Program

The IMU Orientation Determination Program (P-51) is used during free-fall to determine the present IMU stable member orientation with respect to the Basic Reference Coordinate System by sighting on two navigation stars or known celestial bodies with the sextant (SXT) or the scanning telescope (SCT). At the start of program P-51 the astronaut acquires the desired celestial bodies by maneuvering the spacecraft until they are visible in one of the above optical devices. During this acquisition phase he monitors the FDAI Ball to avoid IMU gimbal lock. He may also have the IMU gimbal angles coarse aligned to zero if he so desires.

Afterwards, the following steps are performed on each of two celestial bodies:

- 1) The Sighting Mark Routine (R-53 of Section 4) is used to sight on one of the celestial bodies. The astronaut performs the sighting by centering the SXT or SCT on the celestial body and presses the MARK button. This mark causes the measurement time and the optics and IMU gimbal angles to be recorded by the computer.
- 2) The identity of the celestial body is indicated by the astronaut by use of a celestial body code. Separate codes are provided for the 37 navigation stars, Sun, Earth, Moon, and a general celestial body. The latter code is referred to as the Planet code.

- 3) The subroutine LOSSEM of Section 5.5.13 is used to compute the correction for aberration of light and the line-of-sight vectors of the Sun, Earth, and Moon in the Basic Reference Coordinate System for the time of the optical sighting (mark). If the Sun, Earth, or Moon code was selected, the vector for that body is set aside for use later.
- 4) If the Planet code was selected, the astronaut is requested to load the coordinates of the desired celestial body in the Basic Reference Coordinate System.
- 5) The unit vector \underline{u}'_{CB} defining the direction of the celestial body as a result of the optical sighting is obtained in the IMU Stable Member Coordinate System as follows:

$$\underline{u}'_{CB} = [NBSM] [SBNB] \begin{pmatrix} \sin TA \cos SA \\ \sin TA \sin SA \\ \cos TA \end{pmatrix} \quad (6.2.1)$$

where $[NBSM]$ is the transformation matrix in Section 5.6.3.2.1 using the IMU gimbal angles stored for the optical mark, $[SBNB]$ is the matrix in Section 5.6.3.1.1, and SA and TA are respectively, the shaft and trunnion angles of the SXT or SCT stored for the optical mark.

- 6) A correction for aberration of light is then applied to the unit vector \underline{u}_{CB}^* defining the direction of the celestial body in the Basic Reference Coordinate System which was either taken from the computer's star catalog in fixed memory, computed by the subroutine LOSSEM in step 3, or loaded by the astronaut in step 4. The light aberration correction is made as follows:

$$\underline{u}_{CB} = \text{UNIT} (\underline{u}_{CB}^* + \underline{a}) \quad (6.2.2)$$

where \underline{a} is the aberration correction vector computed by the subroutine LOSSEM when this subroutine was called after the celestial body sighting, and \underline{u}_{CB}^* and \underline{u}_{CB} are, respectively, the uncorrected and corrected unit vectors to the celestial body in basic reference coordinates. Although this correction is correct only for distant objects such as stars, it is also applied, for reasons of program simplification, to the unit vectors of the Sun, Earth, Moon, or a planet, if any of these bodies are being used. It should be noted that the aberration correction is negligible in comparison to the errors in sighting on the Sun, Earth, or Moon.

When the above steps have been performed for two celestial bodies, the computer has the unit line-of-sight vectors for the two bodies in both IMU stable member and basic reference coordinates. Let \underline{u}_{CBA}^i and \underline{u}_{CBB}^i be the unit vectors for the two celestial bodies (A and B) which are obtained with Eq. (6.2.1)

and let \underline{u}_{CBA} and \underline{u}_{CBB} be the unit vectors for the same bodies obtained with Eq. (6.2.2). At this point in the program the Sighting Data Display Routine (R-54 of Section 4) computes the angle between the unit line-of-sight vectors (\underline{u}_{CBA}^i and \underline{u}_{CBB}^i) obtained for the two bodies in stable member coordinates and the angle between the corresponding unit line-of-sight vectors (\underline{u}_{CBA} and \underline{u}_{CBB}) for the two bodies in basic reference coordinates. The magnitude of the difference between the two angles is displayed to the astronaut and he either accepts the results or repeats the IMU orientation determination process.

If he accepts the results of the Sighting Data Display Routine, the unit vectors \underline{u}_{CBA}^i , \underline{u}_{CBB}^i , \underline{u}_{CBA} , and \underline{u}_{CBB} are used to determine the present stable member orientation and REFSMMAT, using the procedure given in Section 5.6.3.3.1.

5.6.2.2 IMU Realignment Program

The IMU Realignment Program (P-52) is used during free-fall to re-align the IMU to its presently assumed orientation or to align it from a known orientation to one of the desired orientations given in Section 5.6.3.3 and in P-52 of Section 4. This alignment is made by sighting on two navigation stars or known celestial bodies with the sextant (SXT) or the scanning telescope (SCT).

At the beginning of program P-52 the astronaut indicates which of the following stable member orientations is desired:

- 1) Preferred - for thrusting maneuvers
- 2) Landing Site - for LM lunar landing or launch
- 3) Nominal - for alignment with respect to local vertical
- 4) REFSMMAT - for re-alignment to presently assumed orientation

The Preferred, Landing Site, and Nominal orientations are defined in Section 5.6.3.3. If the astronaut selects the Landing Site or Nominal orientation, it is computed by program P-52 in the manner shown in Section 5.6.3.3 and in P-52 of Section 4. The Preferred orientation must be computed prior to entering program P-52. Whenever, the astronaut selects the Preferred, Landing Site, or Nominal orientation, the program also computes and displays the IMU gimbal angles for the desired stable member orientation using the present vehicle attitude. These angles are computed by the routine CALCGA of Section 5.6.3.2.2 where the

inputs to this routine are the unit vectors (\underline{u}_{XSM} , \underline{u}_{YSM} , \underline{u}_{ZSM}) defining the desired stable member axes with respect to the Basic Reference Coordinate System, and the unit vectors (\underline{x}_{NB} , \underline{y}_{NB} , \underline{z}_{NB}) defining the present navigation base axes with respect to the Basic Reference Coordinate System, which are computed as follows:

$$\begin{aligned}\underline{x}_{NB} &= [\text{REFSMMAT}]^T \underline{x}_{NB}^i \\ \underline{y}_{NB} &= [\text{REFSMMAT}]^T \underline{y}_{NB}^i \\ \underline{z}_{NB} &= [\text{REFSMMAT}]^T \underline{z}_{NB}^i\end{aligned}\tag{6.2.3}$$

where $[\text{REFSMMAT}]^T$ is the transpose of the present $[\text{REFSMMAT}]$ and \underline{x}_{NB}^i , \underline{y}_{NB}^i , and \underline{z}_{NB}^i define the navigation base axes with respect to the present Stable Member Coordinate System and are computed by the routine CALCSMSC of Section 5.6.3.2.5.

If the computed IMU gimbals are unsatisfactory, the astronaut maneuvers the vehicle to a more suitable attitude and has the program re-compute and display the new gimbal angles. Once satisfactory angles have been obtained, the astronaut keys in a "PROCEED" and is then requested to indicate whether the IMU is to be aligned to the desired orientation by use of the Coarse Alignment Routine (R-50 of Section 4) or by torquing the gyros. If he elects to have the gyros torqued to the desired orientation, the gyro torquing angles are computed by the routine CALCGTA of Section 5.6.3.2.3 where the inputs to this routine are the unit vectors (\underline{x}_D , \underline{y}_D , \underline{z}_D) defining the desired stable member axes with respect to the present Stable Member Coordinate System which are computed as follows:

$$\begin{aligned}\underline{x}_D &= [\text{REFSMMAT}] \underline{u}_{XSM} \\ \underline{y}_D &= [\text{REFSMMAT}] \underline{u}_{YSM} \\ \underline{z}_D &= [\text{REFSMMAT}] \underline{u}_{ZSM}\end{aligned}$$

where u_{XSM} , u_{YSM} , and u_{ZSM} were previously defined. During the period when the gyros are being torqued, the IMU gimbal angles are displayed to the astronaut so that he may avoid gimbal lock by maneuvering the spacecraft. After the gyro torquing process, the astronaut either terminates program P-52 or performs a fine alignment with optical sightings on two celestial bodies.

If the astronaut elects to have the IMU aligned to the desired orientation by means of the Coarse Alignment Routine (R-50), this routine will command the IMU to the computed gimbal angles if any of the required gimbal angle changes is greater than one degree. If all of the required gimbal angle changes are less than or equal to one degree, routine R-50 will leave the IMU at its present orientation, and it will be assumed by program P-52 that it is at the desired orientation. It should be noted that there is no computation of gimbal angles or coarse alignment of the IMU if the astronaut selects the REFSMMAT orientation at the beginning of program P-52.

Afterwards, the astronaut maneuvers the vehicle to a desired attitude for celestial body acquisition and decides whether to select his own celestial bodies for sighting purposes or to use the Star Selection Routine of Section 5.6.4. If he selects the Star Selection Routine, program P-52 will call the subroutine LOSSEM of Section 5.5.13 prior to calling the Star Selection Routine since LOSSEM computes the directions and the occultation cones of the Sun, Earth, and Moon used in the occultation tests of the Star Selection Routine. When LOSSEM is called for this purpose, the specified input time is the present time plus an additional amount (T_{SS}) in order to insure that the time used in computing the LOS vectors for the Sun, Earth, and Moon is near the middle of the sighting mark process. The time increment T_{SS} is based upon estimates of the time required to do the Star Selection Routine and to perform the optical sightings. The primary purpose of using T_{SS} is to insure that the LOS vector of the primary body used in the occultation test is that which occurs during the sighting mark process.

If the Star Selection Routine is unable to find two satisfactory stars at the present vehicle attitude, the astronaut either repeats the above process of changing the vehicle attitude and using the Star Selection Routine, or decides to select his own celestial bodies.

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Afterwards, the following steps are performed on each of two celestial bodies:

- 1) The celestial body code is established for one of the two bodies which are to be sighted upon (i. e. the astronaut either accepts the celestial body code for one of the stars found by the Star Selection Routine or loads his own celestial body code).
- 2) The subroutine LOSSEM of Section 5.5.13 is used to compute the line-of-sight vectors of the Sun, Earth, and Moon for the current time in case the Sun, Earth, or Moon code was selected. If one of these codes was selected, the vector computed for that body is set aside for use later.
- 3) If the Planet code was selected, the astronaut is requested to load the coordinates of the desired celestial body in the Basic Reference Coordinate System.
- 4) The program then calls the Auto Optics Positioning Routine (R-52) which in turn calls the Sighting Mark Routine (R-53). After the SXT and SCT have been driven to the LOS of the celestial body by routine R-52 the astronaut manually centers the SXT or SCT on the celestial body and presses the MARK button.
- 5) When a satisfactory optical sighting (mark) has been obtained, the same steps (2 through 6) are performed after the optical sighting as are given in Section 5.6.2.1 for the IMU Orientation Determination Program (P-51) except that the unit vector

\underline{u}_{CB} (see Eq. (6.2.2) in step 6 of Section 5.6.2.1) is expressed in terms of the desired IMU Stable Member Coordinate System instead of the Basic Reference Coordinate System as follows:

$$\underline{u}_{CB} = \text{UNIT} \left\{ \left[\text{REFSMMAT} \right]_D (\underline{u}_{CB}^* + \underline{a}) \right\} \quad (6.2.4)$$

where \underline{a} is the aberration correction vector computed by the subroutine LOSSEM, and $\left[\text{REFSMMAT} \right]_D$ is the matrix (Section 5.6.3.3) for transforming vectors from the Basic Reference Coordinate System to the desired IMU Stable Member Coordinate System.

After the above steps have been performed on two celestial bodies, the computer has the unit line-of-sight vectors for the two bodies in both present and desired IMU stable member coordinates. Let \underline{u}_{CBA}^1 and \underline{u}_{CBB}^1 be the unit vectors for the two bodies (A and B) which are obtained with Eq. (6.2.1) and let \underline{u}_{CBA} and \underline{u}_{CBB} be the unit vectors for the same bodies obtained with Eq. (6.2.4). At this point in the program the Sighting Data Display Routine (R-54 of Section 4) computes the angle between \underline{u}_{CBA} and \underline{u}_{CBB} , and the angle between \underline{u}_{CBA}^1 and \underline{u}_{CBB}^1 , and displays the magnitude of the difference between the two angles to the astronaut. If he accepts the results, the four vectors are used in the routine AXISGEN of Section 5.6.3.2.4 to compute the desired stable member axes with respect to the present Stable Member Coordinate System, which are used in the Gyro Torquing Routine

(R-55 of Section 4). Routine R-55 computes the gyro torquing angles required to drive the IMU stable member to the desired orientation by using the above vectors in the routine CALCGTA of Section 5.6.3.2.3. The gyro torquing angles are displayed to the astronaut so that he can decide whether to have the gyros torqued through these angles or not. If he is not satisfied with the results of the Sighting Data Display Routine or the Gyro Torquing Routine, he may repeat the optical sightings without having to terminate the program.

It should be noted that the ground can indicate to the CMC via uplink the present stable member orientation or a desired stable member orientation. If the present orientation is being indicated, this is done by transmitting a REFSMMAT to the CMC. Under normal circumstances, however, it would not be desirable for the ground to indicate the present stable member orientation since this orientation should be determined by the CSM GNCS. However, if an orientation different from the present orientation is desired by the ground, this desired orientation can be transmitted as a Preferred orientation. By treating a desired stable member orientation in this manner, program P-52 will be able to correct for any large differences between the present and desired orientations by coarse alignment. In addition, this approach avoids the introduction of orientation errors which affect celestial body acquisition.

5.6.2.3 Backup IMU Orientation Determination Program

The Backup IMU Orientation Determination Program (P-53) is used during free-fall to determine the present IMU stable member orientation with respect to the Basic Reference Coordinate System by sighting on two navigation stars or known celestial bodies with some optical device other than the sextant or scanning telescope. An optical device which is considered to be a backup to the normal CSM optics is the Crew Optical Alignment Sight (COAS). This program is identical to program P-51 of Section 5.6.2.1 except that the Alternate LOS Sighting Mark Routine (R-56 of Section 4) is used in place of the Sighting Mark Routine (R-53) to sight on the celestial bodies. Whenever routine R-56 is called by program P-53, the astronaut is requested to load the coordinates of the backup optical device before performing the optical sighting. These coordinates are the equivalent SXT shaft and trunnion angles of the device which would be indicated for the SXT if it were possible to direct the SXT along the same direction as the optical device. When an optical sighting is performed using routine R-56, the measurement time, the IMU gimbal angles, and the equivalent shaft and trunnion angles of the backup device are stored by the computer. These angles are used just as in step 5 of Section 5.6.2.1 to obtain a unit vector \underline{u}_{CB}^1 in the IMU Stable Member Coordinate System where SA and TA are now the equivalent shaft and trunnion angles of the backup device.

5.6.2.4 Backup IMU Realignment Program

The Backup IMU Realignment Program (P-54) is used during free-fall to re-align the IMU to its presently assumed orientation or to align it from a known orientation to

one of the desired orientations given in Section 5.6.3.3 and in P-54 of Section 4 by sighting on two navigation stars or known celestial bodies with some optical device other than the sextant or scanning telescope. Such an optical device may be the Crew Optical Alignment Sight (COAS). This program is identical to program P-52 of Section 5.6.2.2 except that the Alternate LOS Sighting Mark Routine (R-56 of Section 4) is used in place of the Sighting Mark Routine (R-53) to sight on the celestial bodies. In addition, the Auto Optics Positioning Routine (R-52) is not used in this program. A description of Alternate LOS Sighting Mark Routine is given in Sections 4 and 5.6.2.3.

5.6.3 IMU ROUTINES

5.6.3.1 Sextant Transformations

5.6.3.1.1 Sextant Base - Navigation Base

To transform a vector from sextant base to navigation base coordinates, use is made of the following transformation matrix:

$$[\text{SBNB}] = \begin{pmatrix} \cos \alpha & 0 & -\sin \alpha \\ 0 & 1 & 0 \\ \sin \alpha & 0 & \cos \alpha \end{pmatrix} \quad (6.3.1)$$

where $\alpha = -32^{\circ} 31' 23.19''$

The above matrix and its transpose $[\text{NBSB}]$ are both present in computer memory.

The sextant base coordinate system referred to above is frequently called the Block I navigation base coordinate system in deference to the present navigation base coordinate system (Block II). Any transformation of vectors between the sextant and the present navigation base requires use of the above transformations.

5.6.3.1.2 Sextant to Navigation Base (SXTNB)

To obtain a unit vector (\underline{u}_{NB}), which specifies the direction of the line-of-sight of the sextant in navigation base coordinates, use is made of the following:

$$\underline{u}_{NB} = [\underline{SBNB}] \begin{pmatrix} \sin TA \cos SA \\ \sin TA \sin SA \\ \cos TA \end{pmatrix} \quad (6.3.2)$$

where $[\underline{SBNB}]$ is the transformation matrix given in Section 5.6.3.1.1, and TA and SA are the trunnion (precision) and shaft angles, respectively, of the sextant.

5.6.3.1.3 Calculation of Sextant Angles (CALCSXA)

Given a unit star vector \underline{s}_{SM} in stable member coordinates, this routine computes the angles SA and TA required to position the optics such that the line of sight lies along the star vector.

The star vector is first transformed to the sextant base coordinate system as follows:

$$\underline{s}_{SB} = [\underline{NBSB}] [\underline{SMNB}] \underline{s}_{SM} \quad (6.3.3)$$

where $\underline{[NBSB]}$ and $\underline{[SMNB]}$ are given in Sections 5.6.3.1.1 and 5.6.3.2.1, respectively.

Next, a unit vector \underline{u}_{TDA} , defining the direction of the trunnion (precision) drive axis in sextant base coordinates, is obtained:

$$\underline{u}_{TDA} = \text{UNIT} \left[\underline{z}_{SB} \times \underline{s}_{SB} \right] \quad (6.3.4)$$

where

$$\underline{z}_{SB} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Using \underline{s}_{SB} and \underline{u}_{TDA} , the angles SA and TA are determined as follows:

$$\begin{aligned} \sin SA &= \underline{u}_{TDA} \cdot (-\underline{x}_{SB}) \\ \cos SA &= \underline{u}_{TDA} \cdot \underline{y}_{SB} \\ SA &= \text{ARCTRIG}(\sin SA, \cos SA) \\ TA &= \cos^{-1} [\underline{z}_{SB} \cdot \underline{s}_{SB}] \end{aligned} \quad (6.3.5)$$

where ARCTRIG implies computing the angle, choosing either \sin^{-1} or \cos^{-1} so as to yield maximum accuracy, and

$$\underline{x}_{SB} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \text{and} \quad \underline{y}_{SB} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

5.6.3.2 IMU Transformations

5.6.3.2.1 Stable Member-Navigation Base

Let IGA, MGA, OGA be the IMU inner, middle and outer gimbal angles, respectively. Define the following matrices:

$$Q_1 = \begin{pmatrix} \cos \text{IGA} & 0 & -\sin \text{IGA} \\ 0 & 1 & 0 \\ \sin \text{IGA} & 0 & \cos \text{IGA} \end{pmatrix} \quad (6.3.6)$$

$$Q_2 = \begin{pmatrix} \cos \text{MGA} & \sin \text{MGA} & 0 \\ -\sin \text{MGA} & \cos \text{MGA} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (6.3.7)$$

$$Q_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos OGA & \sin OGA \\ 0 & -\sin OGA & \cos OGA \end{pmatrix} \quad (6.3.8)$$

Stable Member to Navigation Base Transformation

$$\underline{U}_{NB} = Q_3 Q_2 Q_1 \underline{U}_{SM} \quad (6.3.9)$$

$$[SMNB] = Q_3 Q_2 Q_1$$

Navigation Base to Stable Member Transformation

$$\underline{U}_{SM} = Q_1^T Q_2^T Q_3^T \underline{U}_{NB}, \quad [NBSM] = Q_1^T Q_2^T Q_3^T \quad (6.3.10)$$

5.6.3.2.2 Calculation of Gimbal Angles (CALCGA)

Given a stable member orientation and a navigation base orientation both referred to the same coordinate system, the following procedure is used to compute the corresponding gimbal angles.

$$\underline{a}_{MG} = \text{UNIT} (\underline{x}_{NB} \times \underline{y}_{SM})$$

$$\cos \text{OGA} = \underline{a}_{MG} \cdot \underline{z}_{NB}$$

$$\sin \text{OGA} = \underline{a}_{MG} \cdot \underline{y}_{NB}$$

$$\text{OGA} = \text{ARCTRIG} (\sin \text{OGA}, \cos \text{OGA})$$

$$\cos \text{MGA} = \underline{y}_{SM} \cdot (\underline{a}_{MG} \times \underline{x}_{NB})$$

(6.3.11)

$$\sin \text{MGA} = \underline{y}_{SM} \cdot \underline{x}_{NB}$$

$$\text{MGA} = \text{ARCTRIG} (\sin \text{MGA}, \cos \text{MGA})$$

$$\cos \text{IGA} = \underline{a}_{MG} \cdot \underline{z}_{SM}$$

$$\sin \text{IGA} = \underline{a}_{MG} \cdot \underline{x}_{SM}$$

$$\text{IGA} = \text{ARCTRIG} (\sin \text{IGA}, \cos \text{IGA})$$

where the inputs are three vectors along the stable member axes and three vectors along the navigation base axes.

5.6.3.2.3 Calculation of Gyro Torquing Angles (CALCGTA)

In the fine align procedure, after the present platform orientation is determined, the torquing angles required to move the platform into the desired orientation must be computed. This is achieved as follows:

Let \underline{x}_D , \underline{y}_D , and \underline{z}_D be the desired stable member axes referred to present stable member orientation. The rotations are performed in three steps: (1) rotating through θ_y about the y axis, yielding \underline{x}_D^1 , \underline{y}_D^1 , \underline{z}_D^1 ; (2) rotating through θ_z about the z' axis, yielding \underline{x}_D^1 , \underline{y}_D^1 , \underline{z}_D^1 ; (3) and finally rotating through θ_x about the x'' axis, yielding \underline{x}_D^1 , \underline{y}_D^1 , \underline{z}_D^1 . The relevant equations are as follows:

$$\underline{z}_D^1 = \text{UNIT}(-x_{D,3}, 0, x_{D,1})$$

$$\sin \theta_y = z_{D,1}^1$$

$$\cos \theta_y = z_{D,3}^1 \quad (6.3.12)$$

$$\theta_y = \text{ARCTRIG}(\sin \theta_y, \cos \theta_y)$$

$$\sin \theta_z = x_{D,2}$$

$$\cos \theta_z = z_{D,3}^1 x_{D,1} - z_{D,1}^1 x_{D,3}$$

$$\theta_z = \text{ARCTRIG}(\sin \theta_z, \cos \theta_z)$$

$$\cos \theta_x = z_{D,1}^1 \cdot z_{D,1} \quad (6.3.12 \text{ cont})$$

$$\sin \theta_x = z_{D,1}^1 \cdot y_{D,1}$$

$$\theta_x = \text{ARCTRIG}(\sin \theta_x, \cos \theta_x)$$

The required inputs are the three coordinate axes of the desired stable member orientation referred to the present stable member orientation.

5.6.3.2.4 Coordinate Axes Generator (AXISGEN)

Given two unit vectors (usually star vectors), \underline{s}_A and \underline{s}_B , expressed in two coordinate systems, denoted by primed and unprimed characters, i.e., $\underline{s}'_A, \underline{s}'_B, \underline{s}_A, \underline{s}_B$, this routine computes the unit vectors $\underline{x}, \underline{y}, \underline{z}$ which are the primed coordinate system axes referred to the unprimed coordinate system. This is accomplished by defining two ortho-normal coordinate sets, one in each system, in the following manner:

$$\begin{aligned}\underline{u}'_X &= \underline{s}'_A \\ \underline{u}'_Y &= \text{UNIT}(\underline{s}'_A \times \underline{s}'_B) \\ \underline{u}'_Z &= \underline{u}'_X \times \underline{u}'_Y \\ \underline{u}_X &= \underline{s}_A \\ \underline{u}_Y &= \text{UNIT}(\underline{s}_A \times \underline{s}_B) \\ \underline{u}_Z &= \underline{u}_X \times \underline{u}_Y\end{aligned}\tag{6.3 13}$$

The primed coordinate system axes expressed in terms of the unprimed coordinate system axes are:

$$\underline{x} = u'_{X1} \underline{u}_X + u'_{Y1} \underline{u}_Y + u'_{Z1} \underline{u}_Z$$

$$\underline{y} = u'_{X2} \underline{u}_X + u'_{Y2} \underline{u}_Y + u'_{Z2} \underline{u}_Z \quad (6.3.14)$$

$$\underline{z} = u'_{X3} \underline{u}_X + u'_{Y3} \underline{u}_Y + u'_{Z3} \underline{u}_Z$$

It should be noted that vectors can be transformed from the unprimed to the primed coordinate systems by using the following matrix constructed with the output (Eq. 6.3.14) of AXISGEN:

$$\begin{bmatrix} \underline{x}^T \\ \underline{y}^T \\ \underline{z}^T \end{bmatrix} \quad (6.3.15)$$

5.6.3.2.5 Calculation of Stable Member Coordinates of the
Spacecraft (CALCSMSC)

To determine the directions of the X, Y, and Z axes of the present vehicle coordinate system or the navigation base coordinate system with respect to the IMU Stable Member Coordinate System, use is made of the routine CALCSMSC.

The unit vectors \underline{x}_{NB} , \underline{y}_{NB} , and \underline{z}_{NB} defining the directions of the navigation base coordinate system axes with respect to the IMU Stable Member Coordinate System are determined as follows:

$$\underline{x}_{NB} = \begin{pmatrix} \cos IGA & \cos MGA \\ \sin MGA \\ -\sin IGA & \cos MGA \end{pmatrix}$$

$$\underline{z}_{NB} = \begin{pmatrix} \cos IGA & \sin OGA & \sin MGA \\ + \cos OGA & \sin IGA \\ -\sin OGA & \cos MGA \\ \cos OGA & \cos IGA \\ -\sin OGA & \sin MGA & \sin IGA \end{pmatrix}$$

$$\underline{y}_{NB} = \underline{z}_{NB} \times \underline{x}_{NB}$$

where IGA, MGA, and OGA are the inner, middle, and outer IMU gimbal angles, respectively. It should be noted that the rows of the transformation matrix $[SMNB]$ also give the above vectors.

5.6.3.3 REFSMMAT Transformations

The matrix required to transform a vector from the Basic Reference Coordinate System to the IMU Stable Member Coordinate System is referred to as REFSMMAT. This matrix can be constructed as follows with the unit vectors \underline{u}_{XSM} , \underline{u}_{YSM} , and \underline{u}_{ZSM} defining the orientations of the stable member axes with respect to reference coordinates.

$$\text{REFSMMAT} = \begin{bmatrix} \underline{u}_{XSM}^T \\ \underline{u}_{YSM}^T \\ \underline{u}_{ZSM}^T \end{bmatrix} \quad (6.3.16)$$

5.6.3.3.1 Present REFSMMAT From Star Sightings

The present IMU stable member orientation with respect to the Basic Reference Coordinate System, and the associated REFSMMAT, can be determined by sighting on two navigation stars with the CSM optics. If \underline{s}'_A and \underline{s}'_B are the unit vectors defining the measured directions of the two stars in the present Stable Member Coordinate System, and \underline{s}_A and \underline{s}_B are the unit vectors to the corresponding stars as known in the Basic Reference Coordinate System, then these vectors can be used as the input to the routine AXISGEN (Section 5.6.3.2.4) to obtain the present IMU orientation and REFSMMAT (Eqs. (6.3.14) and (6.3.15)).

5.6.3.3.2 Alignment for Thrusting Maneuvers (Preferred Orientation)

During certain thrusting maneuvers the IMU will be aligned according to the following equations.

$$\begin{aligned} \underline{u}_{XSM} &= \text{UNIT}(\underline{x}_B) \\ \underline{u}_{YSM} &= \text{UNIT}(\underline{u}_{XSM} \times \underline{r}) \\ \underline{u}_{ZSM} &= \underline{u}_{XSM} \times \underline{u}_{YSM} \end{aligned} \quad (6.3.17)$$

where \underline{x}_B is the vehicle or body X-axis at the preferred vehicle attitude for ignition and \underline{r} is the CSM position vector.

The associated transformation matrix (REFSMMAT) is given by Eq. (6.3.16).

5.6.3.3.3 Alignment to Local Vertical in Orbit (Nominal Orientation)

The IMU stable member may be aligned to the local vertical at a specified time. For this type of orientation the stable member axes are found from the following.

$$\begin{aligned} \underline{u}_{XSM} &= (\underline{u}_{YSM} \times \underline{u}_{ZSM}) \\ \underline{u}_{YSM} &= \text{UNIT}(\underline{v} \times \underline{r}) \\ \underline{u}_{ZSM} &= \text{UNIT}(-\underline{r}) \end{aligned} \quad (6.3.18)$$

where \underline{r} and \underline{v} are the position and velocity vectors of the CSM at the specified time. The vectors \underline{r} and \underline{v} are computed by the Coasting Integration Routine of Section 5.2.2.

The REFSMMAT associated with this IMU orientation is found from Eq. (6.3.16).

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5.6.3.3.4 Lunar Landing or Launch Orientation

The proper IMU orientation for lunar landing or launch is defined by the following equations:

$$\begin{aligned} \underline{u}_{XSM} &= \text{UNIT}(\underline{r}_{LS}) \text{ at } t_L \\ \underline{u}_{YSM} &= \underline{u}_{ZSM} \times \underline{u}_{XSM} \\ \underline{u}_{ZSM} &= \text{UNIT}(\underline{h}_C \times \underline{u}_{XSM}) \end{aligned} \quad (6.3.19)$$

where

$$\underline{h}_C = \underline{r}_C \times \underline{v}_C$$

is the orbital angular momentum vector of the CSM, and \underline{r}_{LS} is the landing site position vector at the nominal time of lunar landing or launch, t_L , depending on the alignment mode.

The REFSMMAT associated with this IMU orientation is found from Eq. (6.3.16).

5.6.3.3.5 Earth Pre-launch Alignment

Prior to earth launch the IMU Stable Member is aligned to a local vertical axis system.

$$\begin{aligned} \underline{u}_{ZSM} &= \text{UNIT}(-\underline{r}) \text{ (local vertical)} \\ \underline{u}_{XSM} &= \text{UNIT}(\underline{A}) \text{ where } \underline{A} \text{ is a horizontal vector} \\ &\quad \text{pointed at the desired launch azimuth angle.} \\ \underline{u}_{YSM} &= \underline{u}_{ZSM} \times \underline{u}_{XSM} \end{aligned}$$

The REFSMMAT associated with this IMU orientation is given in Eq. (6.3.16).

5. 6. 4 STAR SELECTION ROUTINE

The Star Selection Routine is used by the IMU Realignment Program (P-52) and the Back-Up IMU Realignment Program (P-54) to select the best pair of stars in the viewing cone of the sextant for fine alignment of the IMU. The logic diagram for this routine is shown in Fig. 6. 4-1.

Each pair from the computer catalog of 37 stars is tested to see if both stars are within a 76 degree viewing cone centered with respect to the shaft drive axis of the sextant (SXT).

Afterwards, the routine checks to see if the angle of separation between the stars is at least 30 degrees.

If a pair passes the above tests, a check is then made to see if either star is occulted by the Sun, Earth, or Moon. The sizes of the occultation cones about each of the three bodies are such as to not only account for true occultation but to also prevent the selection of stars too near the bodies because of visibility problems. The directions and the associated occultation cone sizes of the three bodies are actually computed by the subroutine LOSSEM (Section 5. 5. 13) which is called by the IMU Realignment Programs just prior to calling the Star Selection Routine.

The pair of stars passing the above tests and having the largest angular separation is chosen by this routine. If the routine is unable to find a satisfactory pair of stars after testing all combinations, it is seen in Program P-52 of Section 4 that an Alarm Code is displayed, whereupon the astronaut may either repeat the star selection process at a different spacecraft attitude or select his own stars later.

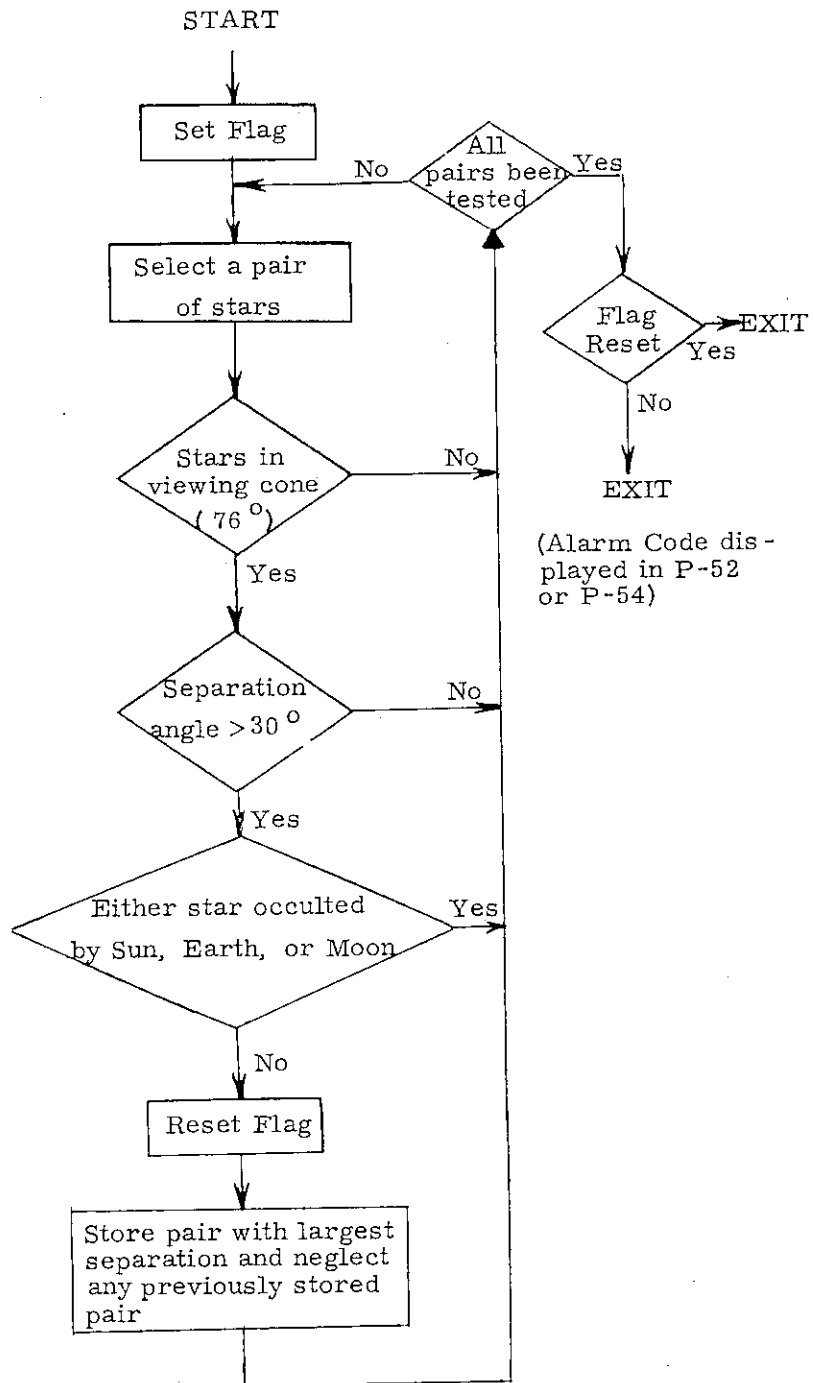


Figure 6.4-1 Star Selection Routine

5.6.5 GROUND TRACK ROUTINE

This routine is used by the astronaut in near-earth or near-moon orbit to obtain CSM or LM trajectory information. The astronaut specifies a time (GET) and a vehicle (CSM or LM). The routine uses the Coasting Integration Routine (Section 5.2.2) to extrapolate the desired vehicle's state vector to the specified time. The resulting estimated position vector is converted to latitude, longitude, altitude coordinates by means of the Latitude-Longitude Subroutine (Section 5.5.3), and these data are displayed. Altitude is defined with respect to the landing site radius for lunar orbit, and the launch pad radius for earth orbit. The astronaut can request the state vector extrapolation to continue in ten minute steps, or to another specified time, and obtain additional displays of the coordinates of points in the spacecraft's orbit. As an additional option, the astronaut can request a display of altitude (to 10 nm), inertial velocity magnitude (to 1 ft/sec), and flight path angle (in degrees) at an astronaut-specified time.

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5.6.6 S-BAND ANTENNA ROUTINE

The S-Band Antenna Routine (R - 05) is used to compute and display 2 angles γ and ρ defined in Fig. 6.6-1. This routine can be initiated by the astronaut during coasting flight only, when the inertial system is operative and when computer activity is at a minimum. Once the program is initiated the computer will automatically update the display at a rate no less than once every three seconds. This updating will continue until S-Band Lock-on is achieved and signaled to the CMC by the astronaut through the DSKY. If the S-Band Routine is interrupted the display of γ and ρ will be stopped until the astronaut reinitiates the routine.

The accuracy associated with the computation and display of γ and ρ does not indicate the pointing accuracy of the associated antenna alignment or the accuracy associated with the antenna gimbal angles.

The angles shown in Fig. 6.6-1 are computed without consideration of any constraints imposed by the actual antenna and therefore, if the present vehicle attitude results in antenna angles beyond the gimbal limit, the CMC will not indicate that the antenna line-of-sight cannot be pointed according to these angles.

The equations and logic flow used to compute γ and ρ are shown in Fig. 6.6-2. With reference to the first portion of this figure, the program will automatically determine whether the Basic Reference Coordinate System is earth or moon centered and will compute the proper values of γ and ρ for either case.

γ is defined as a positive rotation from the plus body X axis about the CSM body Z axis. ($0 \leq \gamma < 360^\circ$)

ρ is defined as a positive rotation about the Y' axis. Y' is an axis in the CSM body XY plane rotated from the CSM Y body axis about the +Z axis direction an amount γ . ($-90^\circ \leq \rho \leq 90^\circ$)

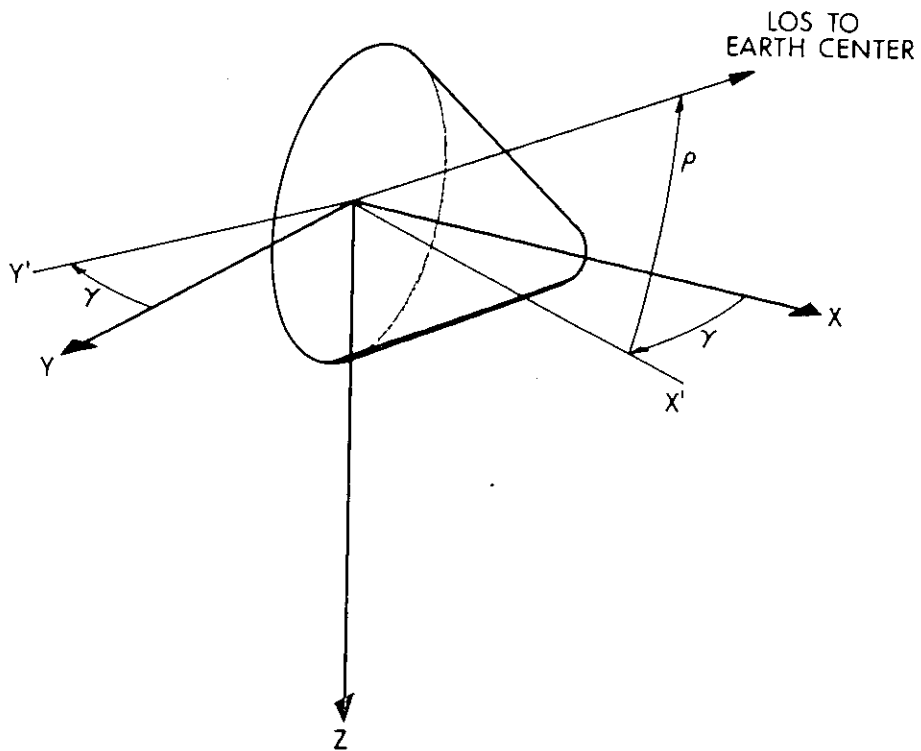


Figure 6.6-1 Definition of CSM S-Band Display Angles

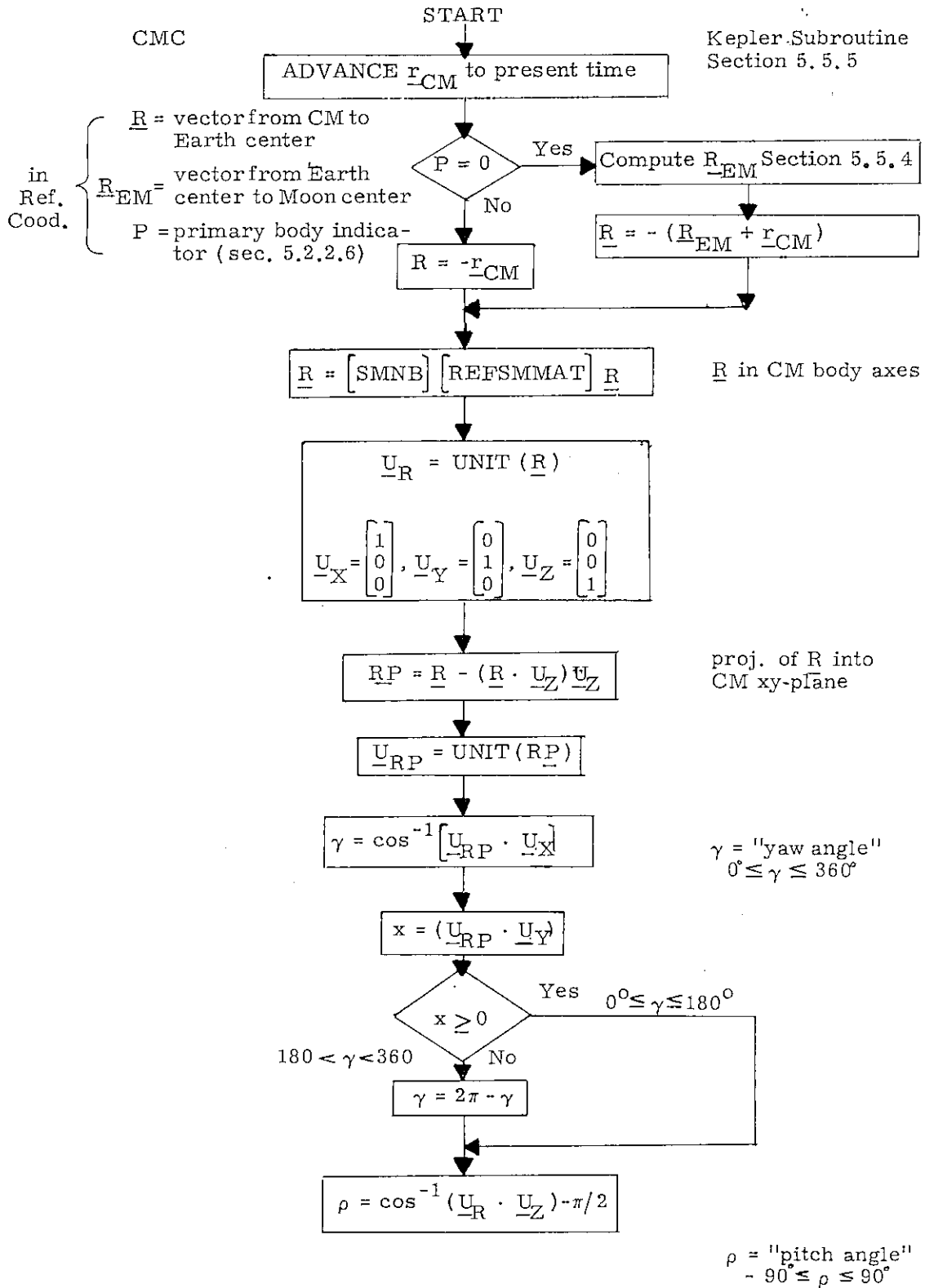


Figure 6.6-2 S-Band Angle Computations and Logic

5.6.7 ADDITIONAL RENDEZVOUS DISPLAYS

During the final phases of rendezvous the following four routines may be called by the astronaut for the purpose of computing and displaying special quantities related to the rendezvous geometry.

5.6.7.1 Range, Range Rate, Theta Display

Routine R-31 may be called upon to compute and display the range and range rate between the two vehicles and an angle θ shown in Fig. 6.7-1.

The angle θ represents the angle between the CSM X-body axis and the local horizontal plane. It is defined in a manner completely analogous to the definition of E in Section 5.4.4.2. Theta, therefore, can have values between 0 and 360°.

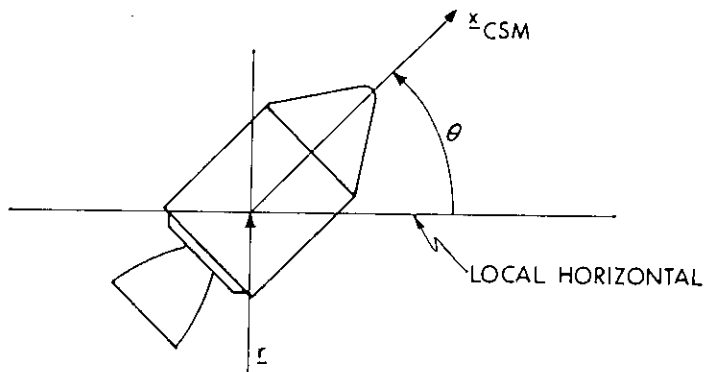


Figure 6.7-1 Definition of Theta

The equations used to compute the display parameters for R-31 are given below.

$$\underline{R} = \underline{r}_L - \underline{r}_C$$

$$\underline{u}_R = \text{UNIT}(\underline{R})$$

$$\text{RANGE} = |\underline{R}| \quad (6.7.1)$$

$$\text{RANGE RATE} = (\underline{v}_L - \underline{v}_C) \cdot \underline{u}_R \quad (6.7.2)$$

To compute θ the following vector is defined

$$\underline{u}_X = [\text{REFSMMAT}]^T [\text{NBSM}] \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

where NBSM and REFSMMAT are defined in Section 5.6.3 and \underline{u}_X is a unit vector along the X-body axis expressed in basic reference coordinates. The angle θ is then found as follows:

$$\begin{aligned} \underline{u} &= \text{UNIT}(\underline{r}_C \times \underline{v}_C) \\ \underline{u}_P &= \text{UNIT} \left[\underline{u}_X - \left(\frac{\underline{u}_X \cdot \underline{r}_C}{r_C^2} \right) \underline{r}_C \right] \\ \theta &= \cos^{-1} [\underline{u}_X \cdot \underline{u}_P \text{SGN}(\underline{u}_P \cdot \underline{u} \times \underline{r}_C)] \quad (6.7.3) \\ &\text{If } \underline{u}_X \cdot \underline{r}_C < 0; \theta = 2\pi - \theta \end{aligned}$$

The three displays of R-31 are automatically updated until R-31 is terminated by the astronaut. The logic flow required to accomplish this update is shown in Fig. 6.7-2.

5.6.7.2 Range, Range Rate, Phi Display

Routine R-34 may be initiated by the astronaut to display the computed range and range rate between the two vehicles as well as an angle ϕ shown in Fig. 6.7-3.

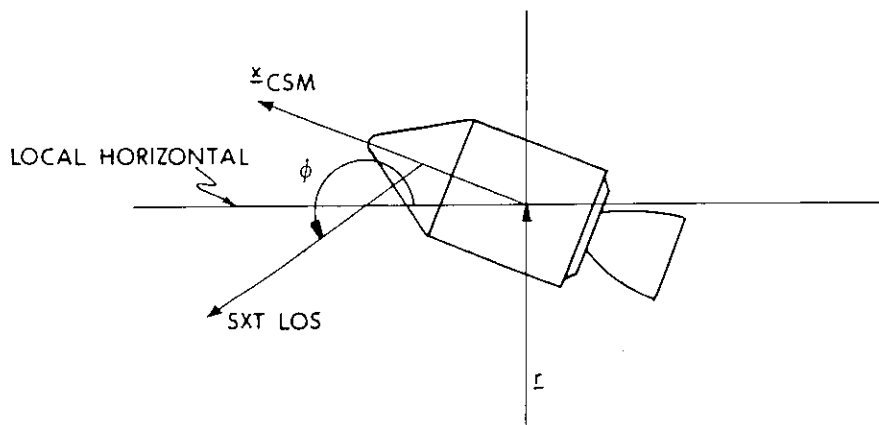


Figure 6.7-3 Definition of Phi

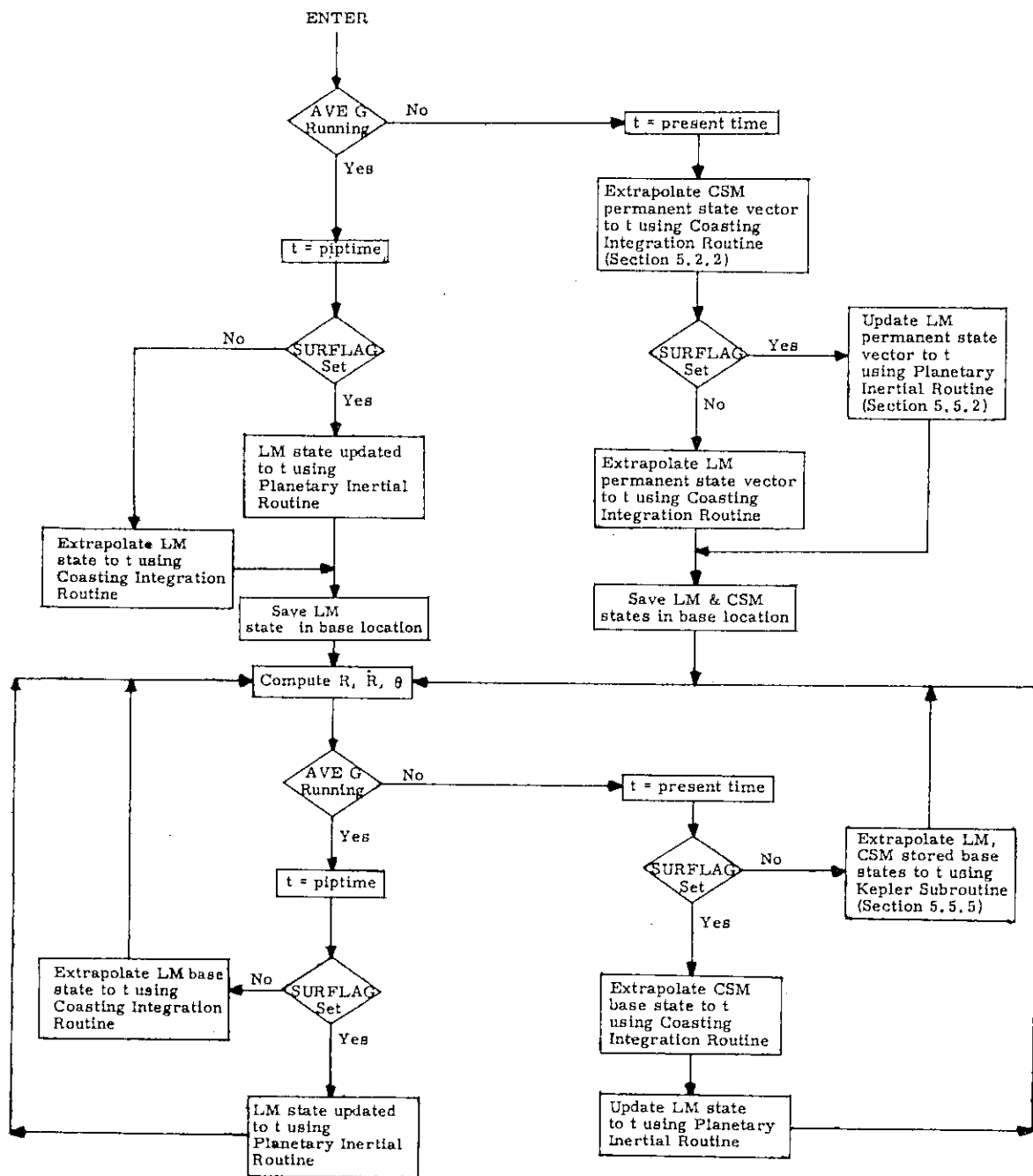


Figure 6.7-2 Range, Range Rate, θ

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The angle ϕ represents the angle between the SXT line of sight and the local horizontal plane. It is determined in the same way as θ in Eq. (6.7.3) except that

$$\underline{u}_X = [\text{REFSMMAT}]^T [\text{NBSM}] \underline{u}_{\text{NB}}$$

where $\underline{u}_{\text{NB}}$ is the sextant line of sight in navigation base coordinates as given in Section 5.6.3.1.2.

The three displays of R-34 are automatically updated in a manner similar to the R-31 update.

5.6.7.3 Final Attitude Display

Routine R-63 may be used to compute and display the gimbal angles required to point the CSM X-axis or the preferred tracking axis defined in Section 5.2.5.1 at the LM. After initiation of this routine the state vectors of both vehicles are extrapolated to the present time plus one minute. Based on these new state vectors the required gimbal angles are computed and displayed.

There is no automatic display update. However, R-63 may easily be recycled to manually accomplish an update of the display.

5.6.7.4 Out-of-Plane Rendezvous Display

Routine R-36 may be used during any phase of the rendezvous sequence to provide information about the out-of-plane geometry of either the CSM relative to the LM orbital plane (CSM option) or the LM relative to the CSM orbital plane (LM option), depending on the option chosen. Three quantities Y , \dot{Y} , and ψ are computed for a given time which is determined by the astronaut. The first two, Y and \dot{Y} , represent the out-of-plane position and velocity in some sense. The third display, ψ , is the angle between the line of sight and the forward direction, measured in the local horizontal plane. It is equivalent to the yaw angle on the FDAI ball, if the ball were aligned to an inplane, local horizontal attitude and the vehicle were rotated so that the forward axis (X-axis on the CSM) were pointed along the line of sight.

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The exact definition of Y , \dot{Y} and ψ is given by the following set of equations.

For the CSM option:

$$\underline{r}_A = \underline{r}_C, \underline{v}_A = \underline{v}_C, \underline{r}_P = \underline{r}_L, \underline{v}_P = \underline{v}_L$$

For the LM option:

$$\underline{r}_A = \underline{r}_L, \underline{v}_A = \underline{v}_L, \underline{r}_P = \underline{r}_C, \underline{v}_P = \underline{v}_C$$

where \underline{r}_L and \underline{v}_L are the position and velocity vectors of the LM and \underline{r}_C , \underline{v}_C the position and velocity vectors of the CSM.

$$\underline{u} = \text{UNIT}(\underline{v}_P \times \underline{r}_P) \quad (6.7.1)$$

$$Y = \underline{r}_A \cdot \underline{u} \quad (6.7.2)$$

$$\dot{Y} = \underline{v}_A \cdot \underline{u}$$

$$\underline{u}_F = \text{UNIT}[(\underline{r}_A \times \underline{v}_A) \times \underline{r}_A]$$

$$\underline{u}_R = \text{UNIT}(\underline{r}_A) \quad (6.7.3)$$

$$\underline{LOS} = \underline{r}_P - \underline{r}_A$$

$$\underline{u}_{LOS} = \text{UNIT}[\underline{LOS} - (\underline{LOS} \cdot \underline{u}_R) \underline{u}_R]$$

$$\psi = \text{COS}^{-1}(\underline{u}_{LOS} \cdot \underline{u}_F) \quad (6.7.4)$$

$$\underline{N} = \underline{u}_{LOS} \times \underline{u}_F$$

$$\text{If } \underline{N} \cdot \underline{r}_A < 0, \psi = 2\pi - \psi \quad (6.7.5)$$

5. 6. 8 AUTOMATIC OPTICS DESIGNATE ROUTINE

5. 6. 8. 1 General

This routine is used during alignment and navigation procedures to automatically point the optics in the direction of a specified tracking target to aid the astronaut in the acquisition of the target. The four target modes available in this routine are as follows:

- 1) Star mode
- 2) LM mode
- 3) Landmark mode
- 4) Advanced ground track mode

The calculations and positioning commands in this routine are repeated approximately every two seconds provided the optics mode switch is set to CMC.

The routine consists of two subroutines, Line-of-Sight and Command. Let t be the time (GET) at the beginning of a cycle and let

$$t_{\delta} = t + \delta t \quad (6.8.1)$$

where δt is a lead term to compensate for system lags. During the first part of the cycle the desired line-of-sight vector at time t_{δ} , \underline{u}_{LOS} , is computed. The Command Subroutine then computes updated values of the desired optics angles from the desired line-of-sight vector, \underline{u}_{LOS} , and the current vehicle attitude. The entire procedure is then repeated. A basic CMC routine drives the optics to the orientation indicated by the desired angles

5. 6. 8. 2 Line-of-Sight Subroutine

5. 6. 8. 2. 1 Star Mode

This mode is used during IMU alignment procedures to point the optics in the direction of a specified star. The desired line-of-sight vector, \underline{u}_{LOS} , is the specified unit star vector stored in the CMC fixed memory.

5. 6. 8. 2. 2 LM Mode

This mode is used during LM tracking phases to point the optics in the direction of the LM. The Kepler Subroutine (Section 5. 5. 5) is used to compute \underline{r}_C and \underline{r}_L , the estimated conic position vectors of the CSM and the LM, respectively, at time t_δ . Then, the desired line-of-sight vector is given by

$$\underline{u}_{LOS} = \text{UNIT} (\underline{r}_L - \underline{r}_C) \quad (6. 8. 2)$$

5. 6. 8. 2. 3 Landmark Mode

This mode is used during the orbit navigation phase to point the optics in the direction of a landmark specified either by

code number for a stored landmark, or by latitude, longitude, altitude for a landmark whose coordinates are not stored in the CMC memory. The Kepler Subroutine (Section 5.5.5) is used to compute \underline{r}_C , the estimated conic position vector of the CSM at time t_δ . Then, \underline{r}_ℓ , the estimated position of the landmark at time t_δ is computed by means of the Latitude-Longitude Subroutine (Section 5.5.3). Finally, the desired line-of-sight is given by

$$\underline{u}_{LOS} = \text{UNIT} (\underline{r}_\ell - \underline{r}_C) \quad (6.8.3)$$

5.6.8.2.4 Advanced Ground Track Mode

This mode is used during the lunar-orbit navigation phase to aid in the surveillance, selection and tracking of possible landing sites by driving the optics to the direction of a point on the ground track of the CSM at a time slightly more than a specified number of orbital revolutions from current time. Let the specified revolution number be N, and assume that N is no greater than four.

Let \underline{r}_C be the estimated CSM position vector at time t_δ . The local vertical vector, \underline{u}_{LV} , at time t_δ is given by

$$\underline{u}_{LV} = - \text{UNIT} (\underline{r}_C) \quad (6.8.4)$$

The desired line-of-sight vector, \underline{u}_{LOS} , is determined such that the angle between the vectors \underline{u}_{LOS} and \underline{u}_{LV} is approximately 60° . Thus, the astronaut can survey the advanced ground track of the CSM, and select a landing site over which the CSM will pass in N orbital revolutions plus about $1/2 (5 - N)$ minutes. After the astronaut selects the landing site, he switches the optics mode to MANUAL in order to obtain navigation data as described in Section 5.2.4.1.

The value of the angle between the vectors \underline{u}_{LOS} and \underline{u}_{LV} is chosen to be 60° in order to ensure that the astronaut will have sufficient time to center the selected landing site in the field of view of the optical instrument before the first navigation sighting should be made. After about one minute of manual tracking, the angle between the line-of-sight to the selected landing site and the current local vertical direction (not the vector \underline{u}_{LV}) will be approximately 45° . At this time it is desirable for accurate tracking conditions to have been attained, and for the MARK button to be pressed. Further navigation sightings of the landing site should then be made at about one minute intervals. The data obtained are processed by the Orbit Navigation Routine (Section 5.2.4).

The desired line-of-sight vector, \underline{u}_{LOS} , is computed by first rotating the local vertical vector about the polar axis of the moon to account for lunar rotation, and then rotating the resulting vector about the normal to the CSM orbital plane to attain the desired 60° angle. The computation sequence is as follows:

- 1 Call the Kepler Subroutine (Section 5.5.5) to determine \underline{r}_C and \underline{v}_C , the estimated CSM conic position and velocity vectors at time t_δ .

- 2 Let

$$\underline{u}_{LOS} = - \text{UNIT} (\underline{r}_C) \quad (6.8.5)$$

- 3 Call the Planetary Inertial Orientation Subroutine to transform the lunar polar vector (0, 0, 1) to the Basic Reference Coordinate System, obtaining the first rotation vector \underline{u}_R .

4 Let the first rotation angle A be

$$A = A_M N \quad (6.8.6)$$

where A_M is the angle through which the moon rotates in one nominal lunar-orbital period.

5 Rotate the vector \underline{u}_{LOS} about \underline{u}_R through the angle A by

$$\begin{aligned} \underline{u}_{LOS} = & (1 - \cos A) (\underline{u}_R \cdot \underline{u}_{LOS}) \underline{u}_R \\ & + \underline{u}_{LOS} \cos A + \underline{u}_R \times \underline{u}_{LOS} \sin A \end{aligned} \quad (6.8.7)$$

6 Compute the second rotation vector from

$$\underline{u}_R = \text{UNIT} (\underline{v}_C \times \underline{r}_C) \quad (6.8.8)$$

7 Let the second rotation angle be

$$A = \frac{\pi}{3} - A \quad (6.8.9)$$

8 Compute the final desired line-of-sight vector \underline{u}_{LOS} by repeating Eq. (6.8.7)

5.6.8.3 Command Subroutine

In this subroutine the line-of-sight vector, \underline{u}_{LOS} , is transformed to stable member coordinates by means of

$$\underline{s}_{SM} = \left[\text{REFSMMAT} \right] \underline{u}_{LOS} \quad (6.8.10)$$

The desired optics trunnion (precision) and shaft angles, TA and SA, respectively, are computed as described in Section 5.6.3.1.3.

5.6.10 ORBITAL PARAMETER DISPLAY COMPUTATIONS

This section presents the CMC computations required for the display of various orbital parameters in the following routines and programs:

a) The Orbital Parameter Display Routine R-30, which is callable by the astronaut via an extended verb.

b) The Splash Error Computation Subroutine DELRSPL, which is automatically called by R-30 when the Earth Orbital Injection Monitor Program P-11 is running.

c) The Maneuver-to-CM/SM Separation-Attitude-Prior-to-Entry Program (P-61) Displays.

d) The CM/SM-Separation-and Pre-Entry-Maneuver Program (P62) Display of the IMU Gimbal Angles.

5.6.10.1 The Orbital Parameter Display Routine R-30

The Orbit Parameter Display Routine R-30 may be called by the astronaut via an extended verb in order to compute and display certain orbital parameters defined below. This display will be automatically updated only when Average G is running. Also the option to select the vehicle for which these orbit parameters are to be displayed will only be available when Average G is not running.

In the normal case the apocenter altitude, pericenter altitude and the time from a reference altitude (300,000 ft. for Earth orbit, 35,000 for Lunar orbit) is displayed. If the chosen orbit does not intercept this altitude, the third display is 59B59. Under certain circumstances explained in Section 4 an additional display of time from pericenter may also be requested by the astronaut. The details of each option and acceptable astronaut responses are discussed in Section 4.

The computational logic and equations used in R-30 are shown in Figs. 6.10-1 and 6.10-2. The following is a list of important parameter definitions which apply to these figures.

\underline{r}	}	:	State vector of the selected vehicle
\underline{v}			
P_C	:	Primary body designator	$\begin{cases} 0 & \text{Earth} \\ 1 & \text{Moon} \end{cases}$
h_a	:	Apocenter altitude	
h_p	:	Pericenter altitude	
r_{LP}	:	Earth launch pad radius	
r_{LS}	:	Lunar landing site radius	
t_{ff}	:	Time from a reference altitude	
t_{PER}	:	Time from pericenter	
SPLERROR	:	See Section 5.6.10.2	

The TFF Subroutines, TFFCONIC, TFFRP/RA, CALCTPER, and CALCTFF, which are called by R-30 to do the mathematical computations, are described in Section 5.6.10.4.

The Splash Error Computation Subroutine DELRSPL which is also called by R-30 if P-11 is running is described in Section 5.6.10.2.

It should be noted that R-30 and DELRSPL use the standard values of the gravitational constants. This is in contradistinction to the "adjusted" values used in the TFF subroutines for the computations involved in the P-61 Displays.

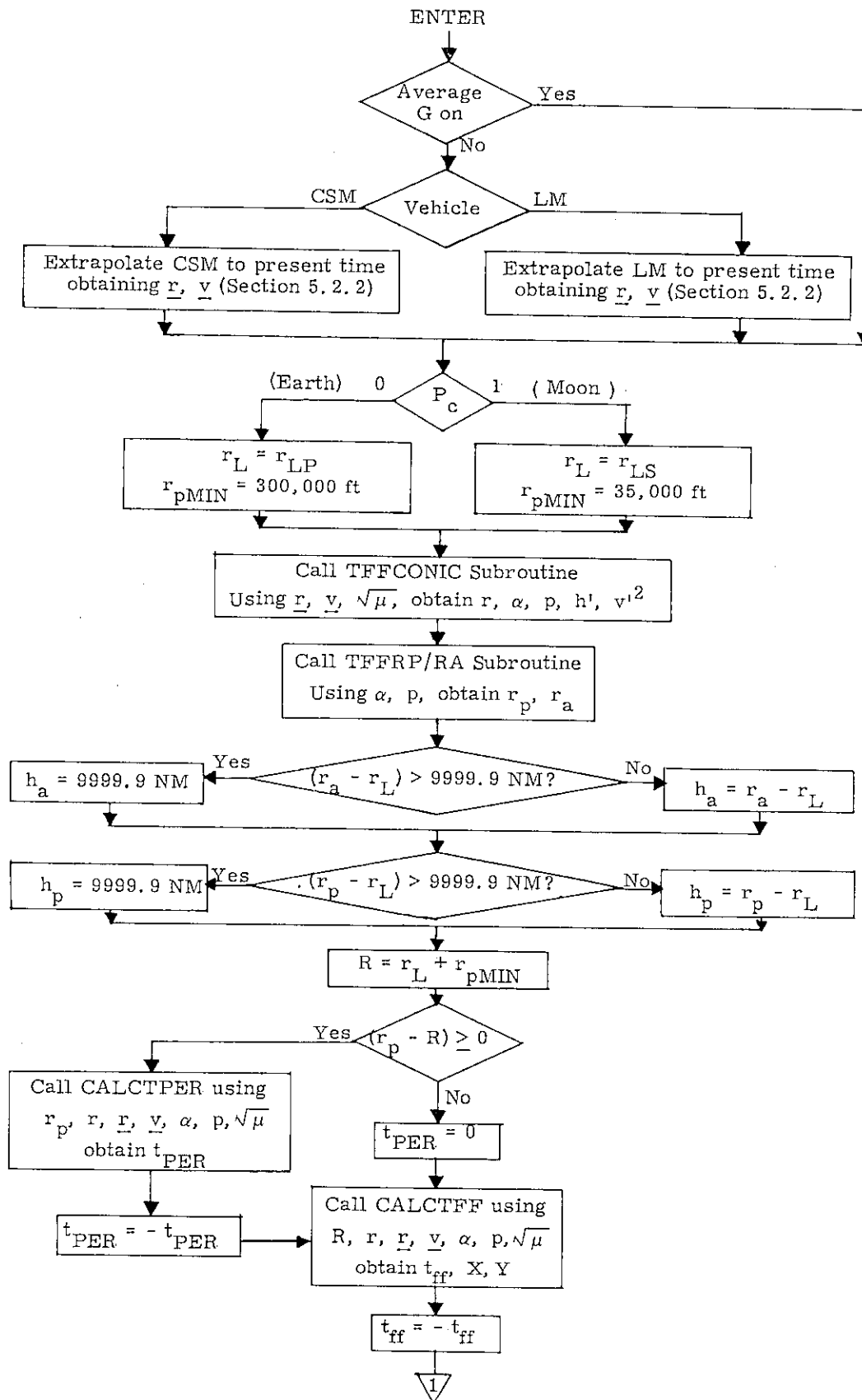


Figure 6.10-1 Orbital Parameter Display Routine
(page 1 of 2)

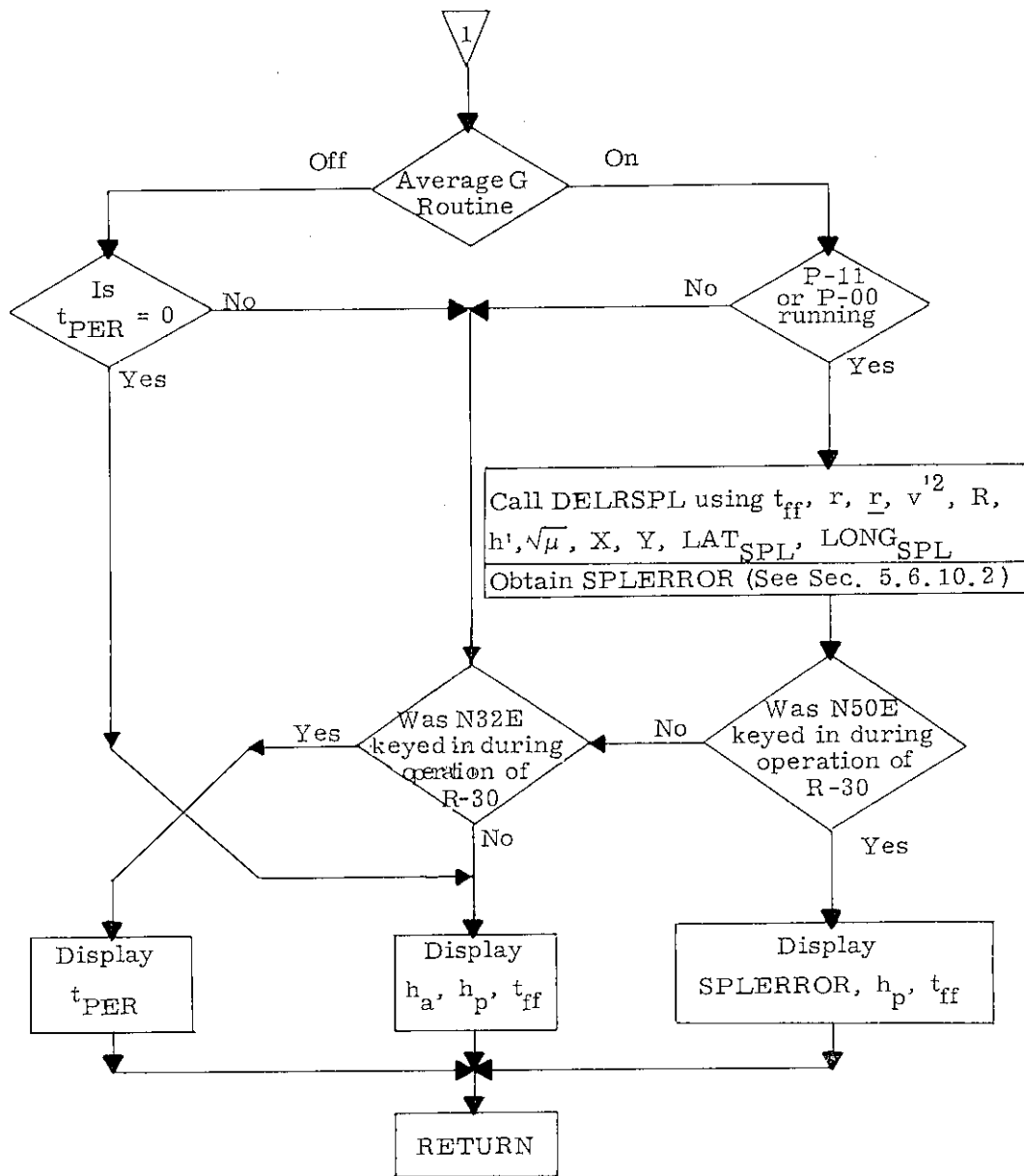


Figure 6.10-1 Orbital Parameter Display Routine
(page 2 of 2)

Note: The values of t_{ff} and t_{PER} are actually made to "count down" every second, i. e. they are automatically updated once a second, although this is not shown explicitly in the above Figure.

5. 6. 10. 2 The Splash Error Computation Subroutine DELRSPL

The Splash Error Computation Subroutine DELRSPL is automatically called by the Orbital Parameter Display Routine R-30 if (and only if) the Earth Orbital Injection Monitor Program P-11 is running.

DELRSPL calculates the quantity SPLERROR which is the miss distance in nautical miles between the abort target landing point and the predicted splash point.

DELRSPL uses the VGAMCALC and TFF/TRIG Subroutines which are described in Section 5. 6. 10. 4. It also uses one of the Latitude-Longitude Subroutines described in Section 5. 5. 3 for converting a known latitude and longitude into a position vector. Further DELRSPL uses the empirical formulas for the entry range and entry time given by the AUGEKUGEL Subroutine.

The coefficient 3437.7468 which is used twice in the DELRSPL calculations is a conversion factor of the reentry calculations, and is defined in Section 5. 7 of this GSOP. (It is called "ATK" in that section).

The parameters LAT_{SPL} and $LONG_{SPL}$ are the geodetic latitude and longitude of the splash point. These quantities are either pad loaded, uplinked, or entered via the DSKY by the astronaut.

It should be noted that the Earth Orbital Insertion Monitor Program P-11 has automatic displays, which are not associated with R-30 or DELRSPL. These are described in Earth Orbital Insertion Monitor Program Section (5. 3. 5. 6).

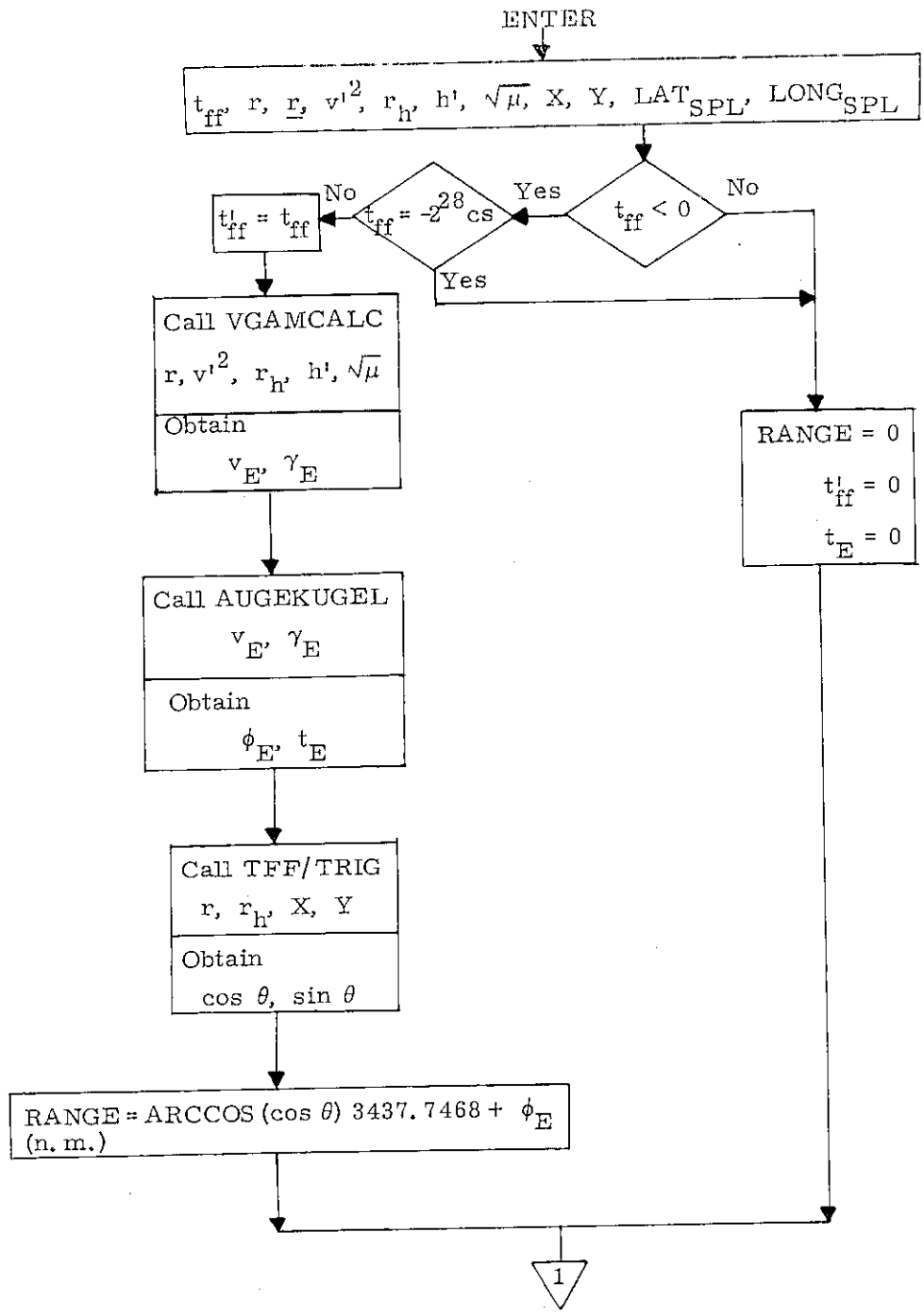


Figure 6.10-2 Splash Error Computation Subroutine
(page 1 of 2)

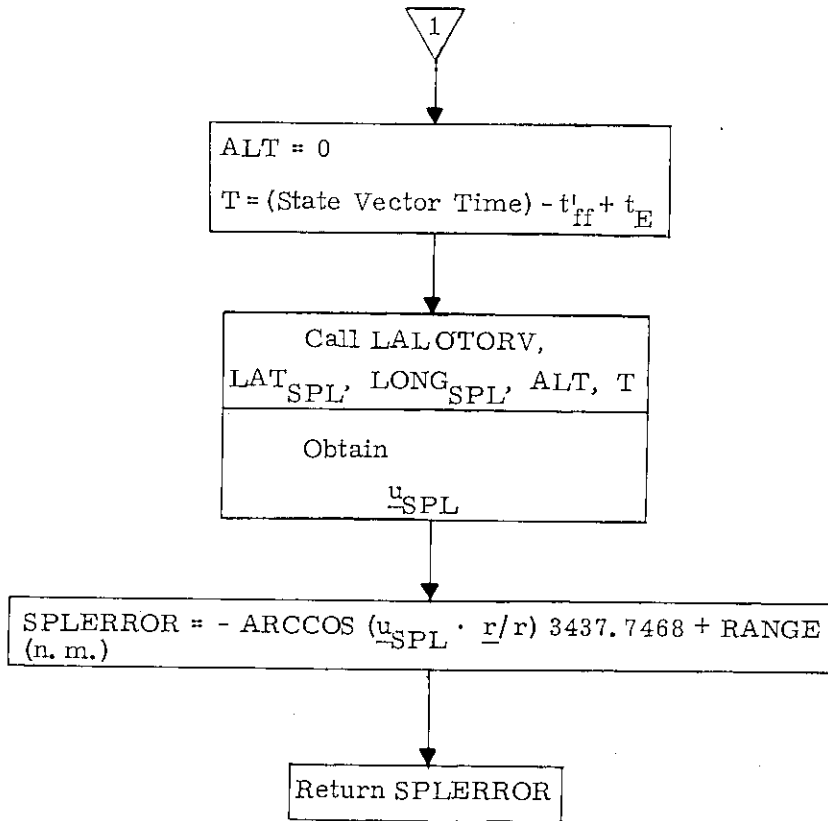


Figure 6.10-2 Splash Error Computation Subroutine
(page 2 of 2)

AUGEKUGEL

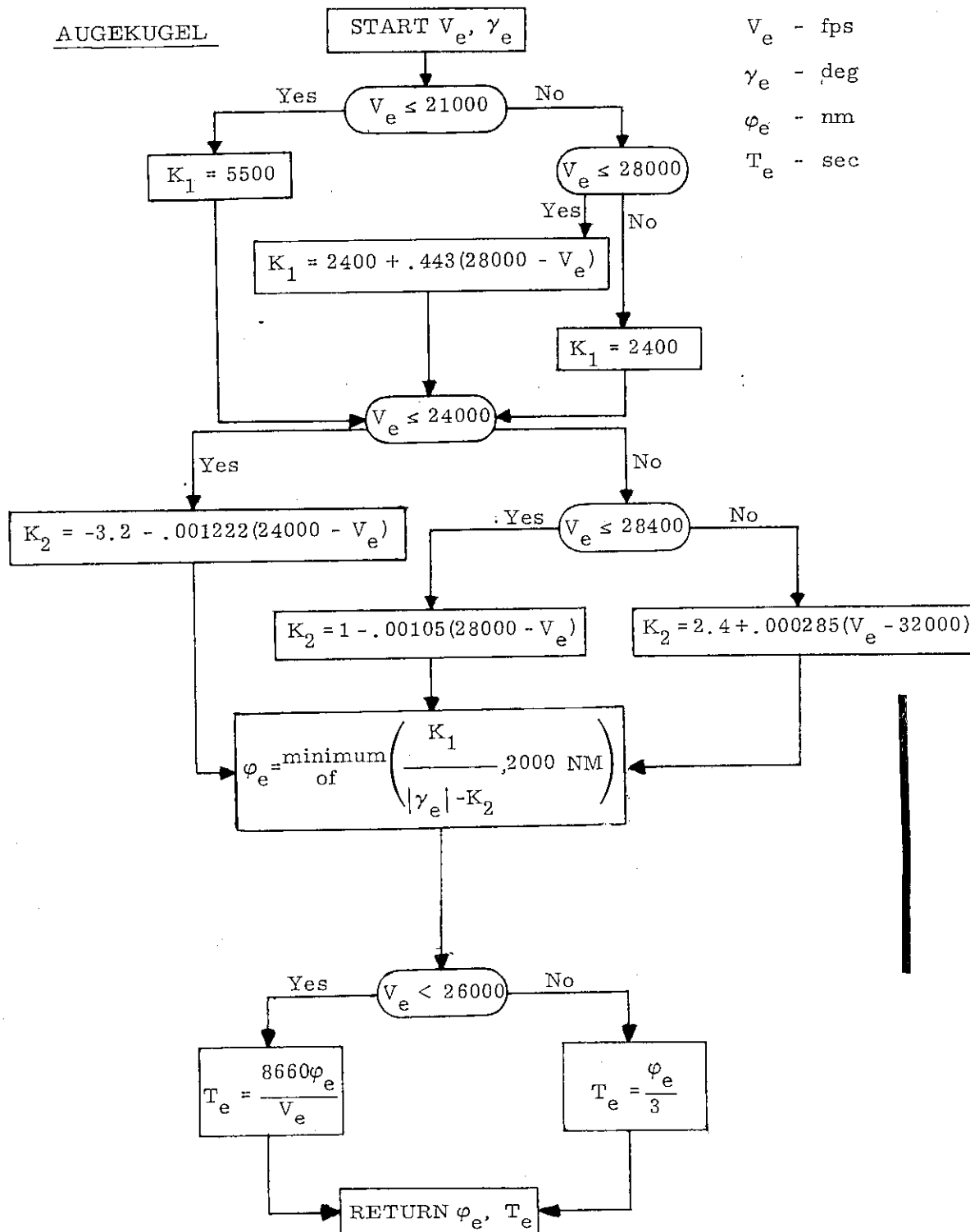


Figure 6.10-3 Empirical Relations for Entry Range & Entry Time

5.6.10.3

The Maneuver to CM/SM Separation Attitude
Prior to Entry Program (P-61) Displays.

The following display computations are made in Program P-61:

- GMAX : Maximum predicted deceleration for entry at the nominal roll angle ($L/D=0.3$).
- VPRED : Predicted inertial velocity at an altitude of 400,000 feet.
- GAMMAEI : Predicted flight path angle between the inertial velocity vector and the local horizontal at an altitude of 400,000 feet.

The altitude of 400,000 feet is referenced to the Fischer ellipsoid, and a two step iteration is made to calculate this radial length.

The following three display parameters are required to initialize the Entry Monitor System, EMS:

- RTGO : Range-to-go from the EMS altitude to the predicted splash point.
- VIO : Predicted inertial velocity at the EMS altitude.
- TTE : Time to go from the current time to the EMS altitude.

The EMS altitude is measured above the Fischer ellipsoid and is stored in erasable memory during the pre-launch erasable load. For earth orbital mission entries, the EMS altitude is 284,643 feet. Lunar mission entries use the EMS altitude of 297,431 feet.

The principal computation required for these display parameters is the conic calculation of time to a radius of specified length. The intersection of a conic with an altitude above the Fischer ellipsoid is a two step iteration. An initial calculation is made using a guess of the radius length. The latitude of the conic with this assumed length is then used to calculate the radius of the Fischer ellipsoid. This is then used to calculate a second radial length, and display quantities are referred to this second radius. Additional iterations are not required to achieve the necessary display accuracy.

The computation logic for the P-61 displays is presented in Fig. 6.10-4. These computations use the TFF Subroutines which are described in Section 5.6.10.4.

The earth gravitation constant used in these calculations is increased recognizing that the missions under consideration are confined to low inclination angles from the equator and oblate earth effects can be significant. The drag loss in reaching the EMS point (0.05 G) is also approximated for these display computations.

Besides the TFF Subroutine symbols (which are defined in Section 5.6.10.4), and the symbols which are defined above, the following additional symbols are used in Fig. 6.10-4:

THETA : The angle between the present position and the initial target vector at the nominal time of arrival. (This is a reentry variable - See Section 5.7).

$\left. \begin{array}{l} \underline{r} \\ \underline{v} \end{array} \right\}$: State vector of the vehicle at the present time

r_G : first guess of the terminal radius
= $r_{PAD} + 284,643$ feet
= 21,194,545 feet
(since $r_{PAD} = 6,373,338$ m = 20,909,902 ft)

μ_1 : Adjusted value of the gravitational constant.
It is .12% greater than the standard value
of the gravitational constant.

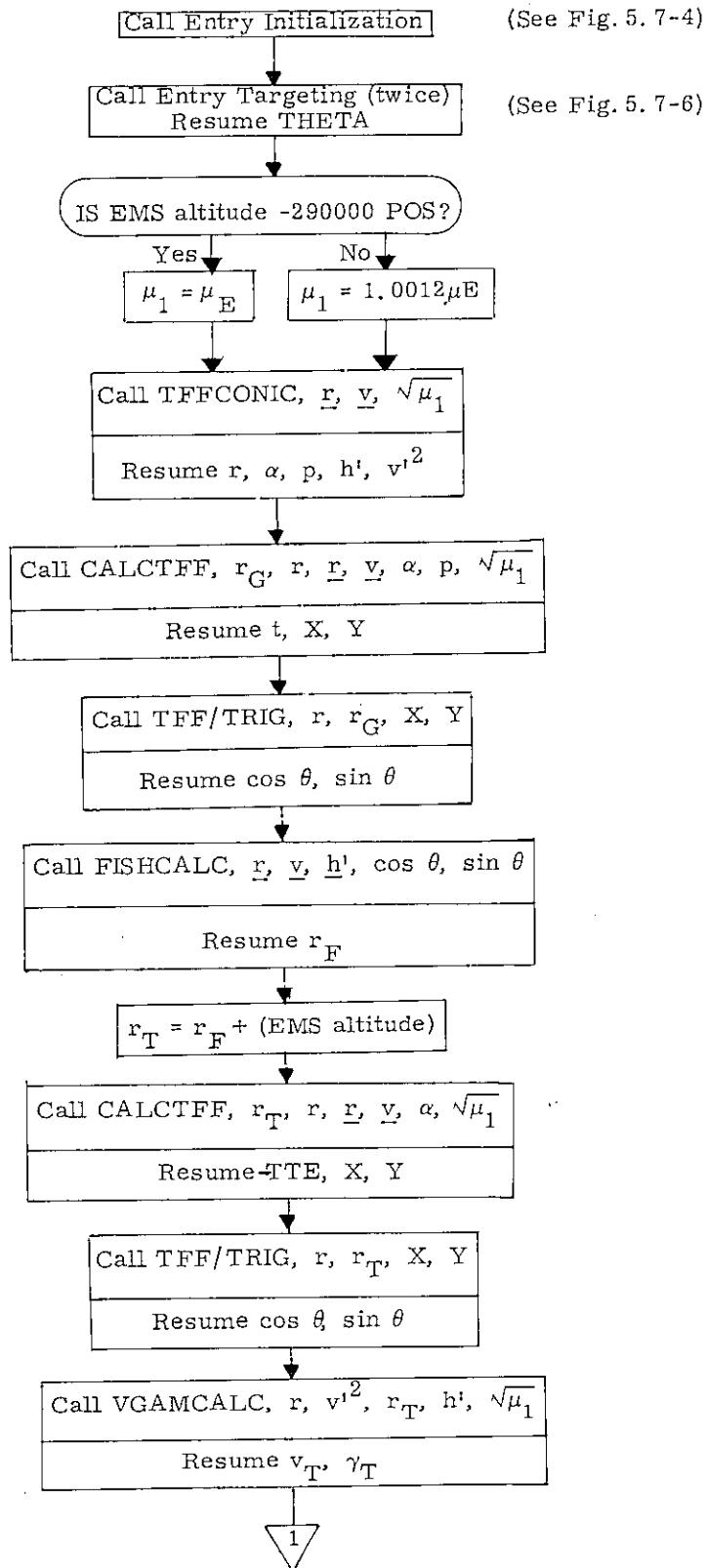


Figure 6.10-4 Display Calculations for P-61
(page 1 of 3)

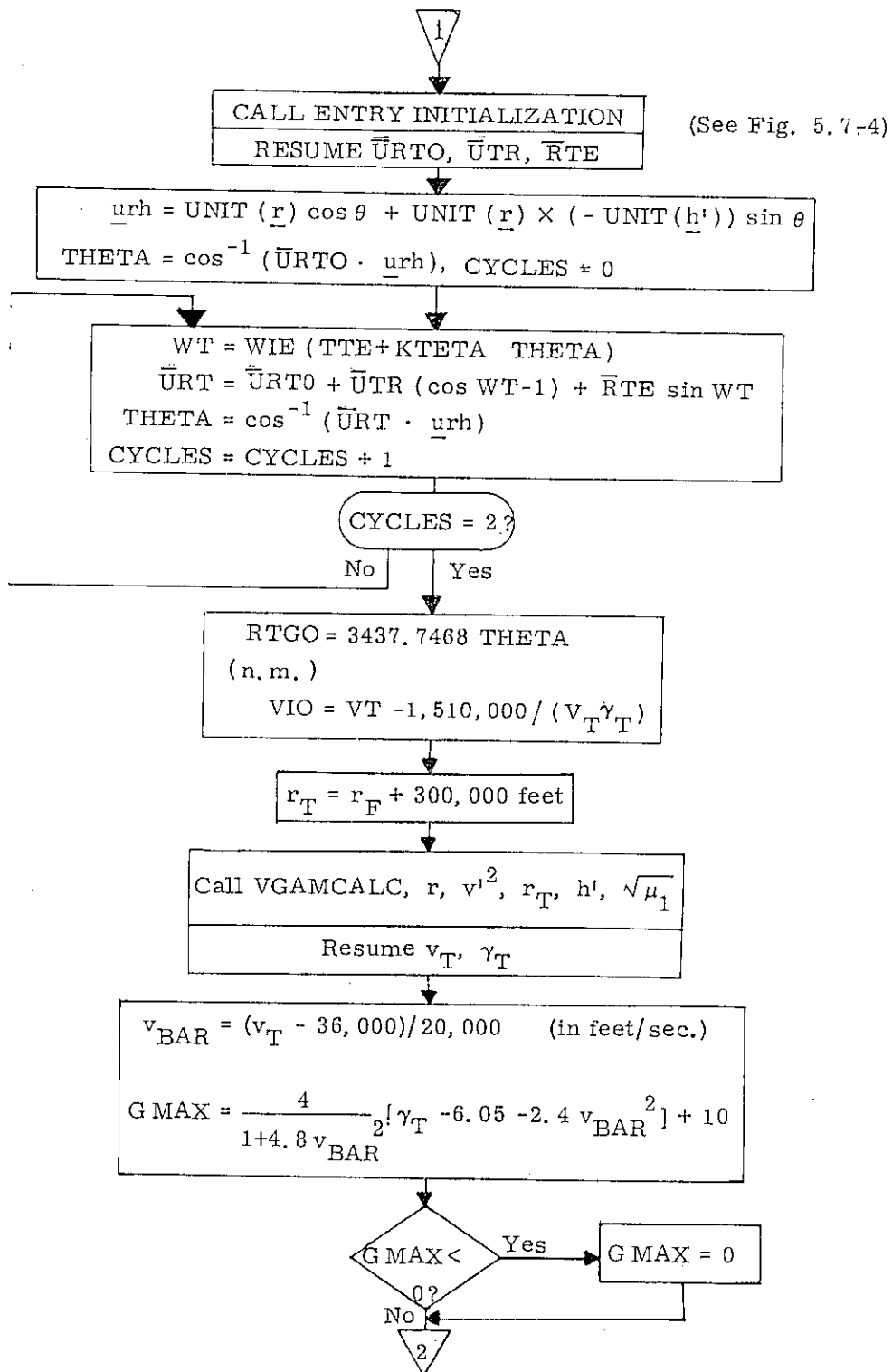


Figure 6.10-4 Display Calculations for P-61
(page 2 of 3)

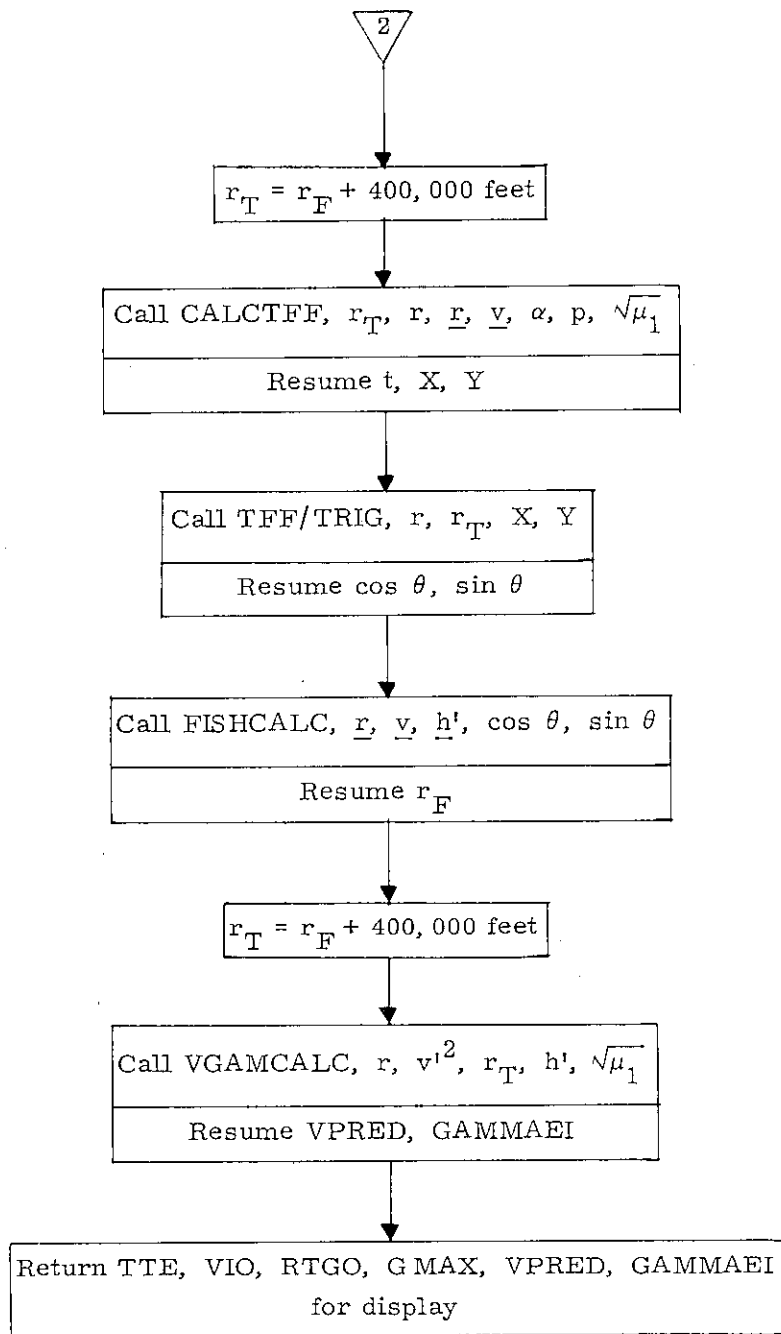


Figure 6.10-4 Display Calculations for P-61
(page 3 of 3)

5.6.10.4 The TFF Subroutines

The TFF Subroutines are used to calculate various conic parameters, such as the semi-latus rectum, the semi-major axis, apocenter and pericenter radii, the transfer time from an initial or present position to specified terminal radii (which may include apocenter and pericenter), the transfer angle of such transfers, and the velocity magnitude and flight-path angle at the terminal position.

It should be noted that the transfer times when displayed on the DSKY are the negative of the calculated values, as in count-down. In the event that the present position lies between perigee and terminal radius, a positive time representing time since terminal point is displayed. When perigee is passed, negative time to terminal radius is displayed once again. However, for outbound hyperbolas or parabolas, positive time since terminal point is displayed.

The TFFCONIC Subroutine (Fig. 6.10-5) calculates various conic parameters and stores them for short-term use. It also computes other intermediate quantities to avoid duplication by following subroutines.

The TFFRP/RA Subroutine (Fig. 6.10-6) calculates pericenter and apocenter radii for the general conic. For hyperbolic or parabolic orbits, or for those elliptic orbits where the apocenter radius exceeds the scaling, r_a is set equal to r_{aMAX} , which corresponds to the largest number expressible in the double precision CMC word.

The CALCTFF/CALCTPER Subroutine (Fig. 6.10-7) calculates the time of free-fall to a given radius or to pericenter depending on the entry point to the subroutine. The subroutine also calculates the quantity Y required by the TFF/TRIG routine in its computation of the transfer angle. In the event that the terminal radius does not lie on the present conic, t is set to the largest time expressible in double precision, $2^{28} - 1$ centiseconds, as a flag. After TFFCONIC has been called, CALCTFF/CALCTPER may be called as desired with different terminal radii to obtain the various times of free fall to these radii for the same conic.

The TFF/TRIG Subroutine (Fig. 6.10-8) calculates the sine and cosine of the transfer angle θ from the initial position vector to the terminal position vector. The computation of the intermediate parameter Y is done during the appropriate branch in CALCTFF/CALCTPER and saved temporarily. Thus the caller of TFF/TRIG may make only one call for each call to CALCTFF/CALCTPER.

FISHCALC Subroutine (Fig. 6.10-9) calculates the sine of the geocentric latitude of the terminal position vector, and then calls the Fischer Ellipsoid Radius Routine (part of the Latitude-Longitude Subroutines of Section 5.5.3) to obtain the radius of the Fischer ellipsoid, using Eq. (5.3.1) of Chapter 5.

VGAMCALC Subroutine (Fig. 6.10-10) calculates the velocity magnitude at the terminal position and the flight-path angle relative to the local horizontal at the terminal position. The user of the subroutine must supply the proper sign to the flight-path angle.

Nomenclature of the TFF Subroutines:

\underline{r} or \underline{r}_0	}	Present or initial state vector
\underline{v} or \underline{v}_0		
μ	:	Gravitational constant
α	:	Reciprocal of the semi-major axis of conic (negative for hyperbolas)
p	:	Semi-latus rectum of conic
e	:	Eccentricity of conic
r_p	:	Pericenter radius
r_a	:	Apocenter radius
r_h	:	Terminal position radius
v_h	:	Velocity magnitude at terminal position
γ_E	:	Flight-path angle relative to local horizontal at the terminal position
S_{TFF}	:	Switch set to 0 or 1 according to whether the transfer time is calculated to the terminal position radius (CALCTFF) or to the pericenter (CALCTPER)
θ	:	Transfer angle
r_F	:	Radius of Fisher ellipsoid along the terminal position unit vector
t	:	Conic transfer time from the present or initial position to the terminal position (CALCTFF) or to pericenter (CALCTPER)
r_{aMAX}	:	The largest apocenter radius expressible in the double precision CMC word at the relevant scaling.

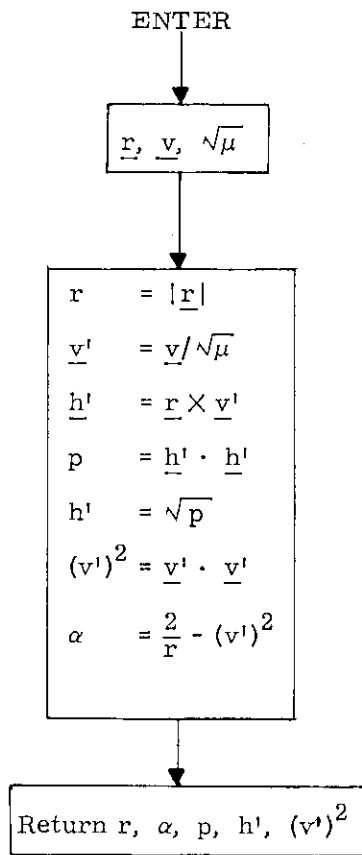


Figure 6.10-5 TFFCONIC Subroutine

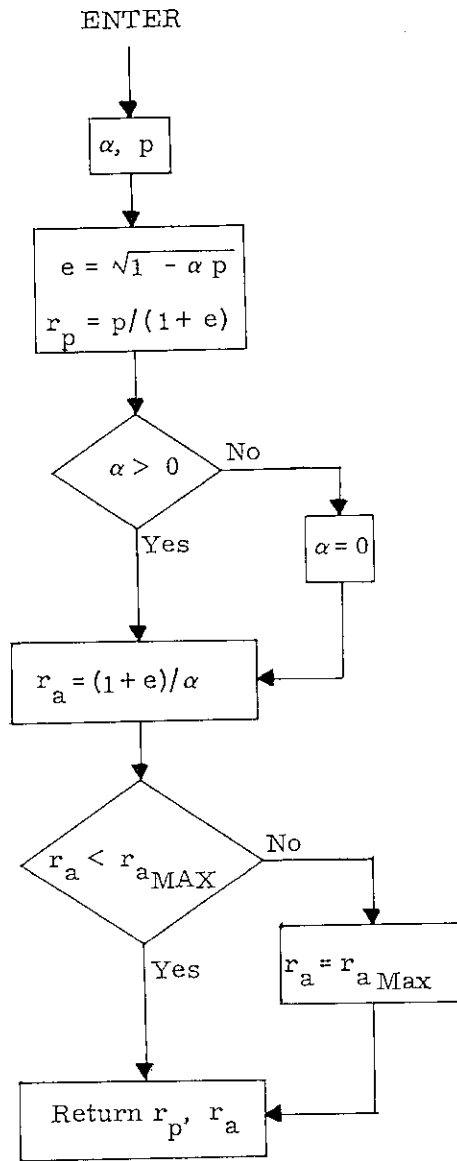


Figure 6.10-6 TFFRP/RA Subroutine

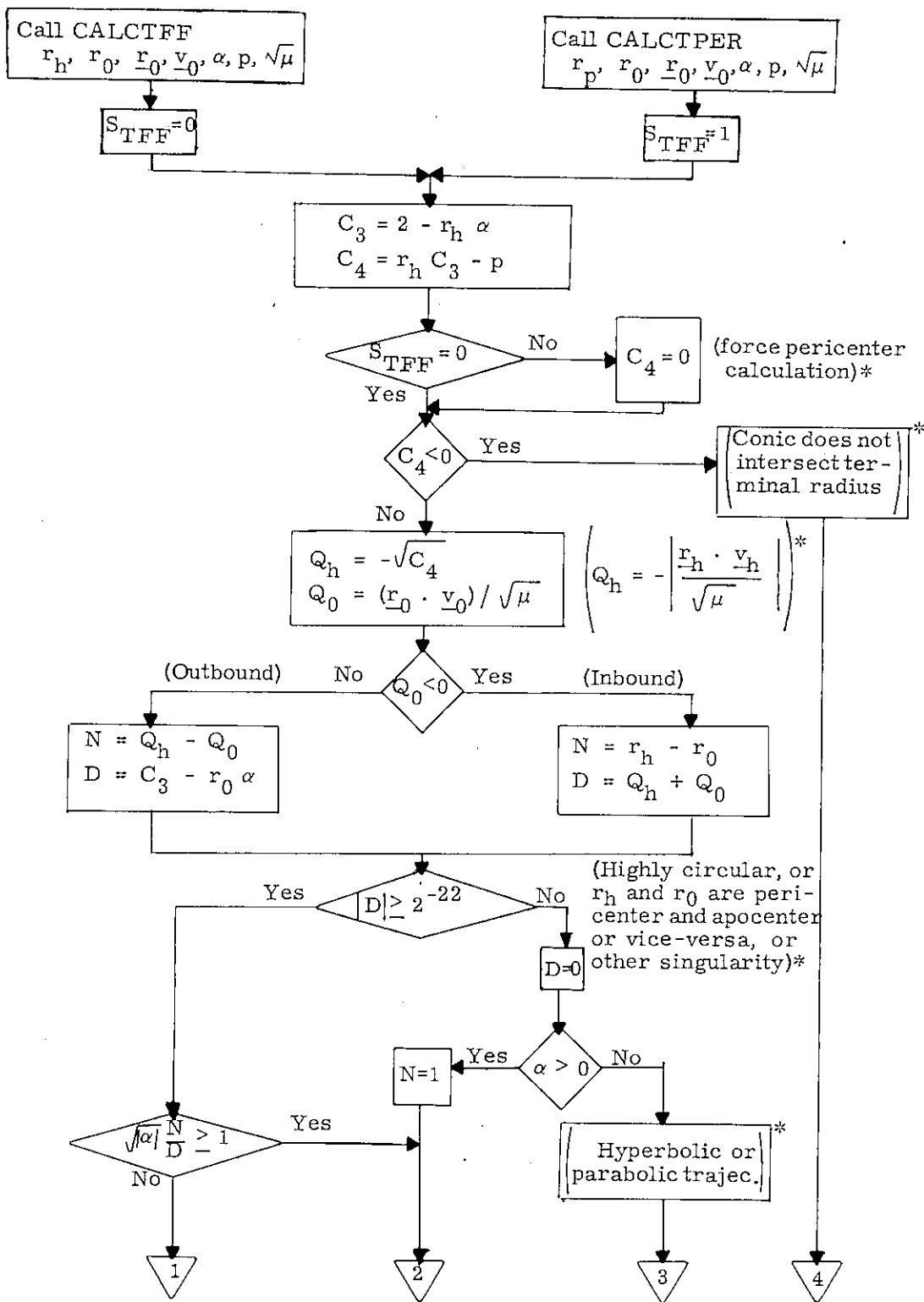


Figure 6.10-7 CALCTFF/CALCTPER Subroutine (page 1 of 2)

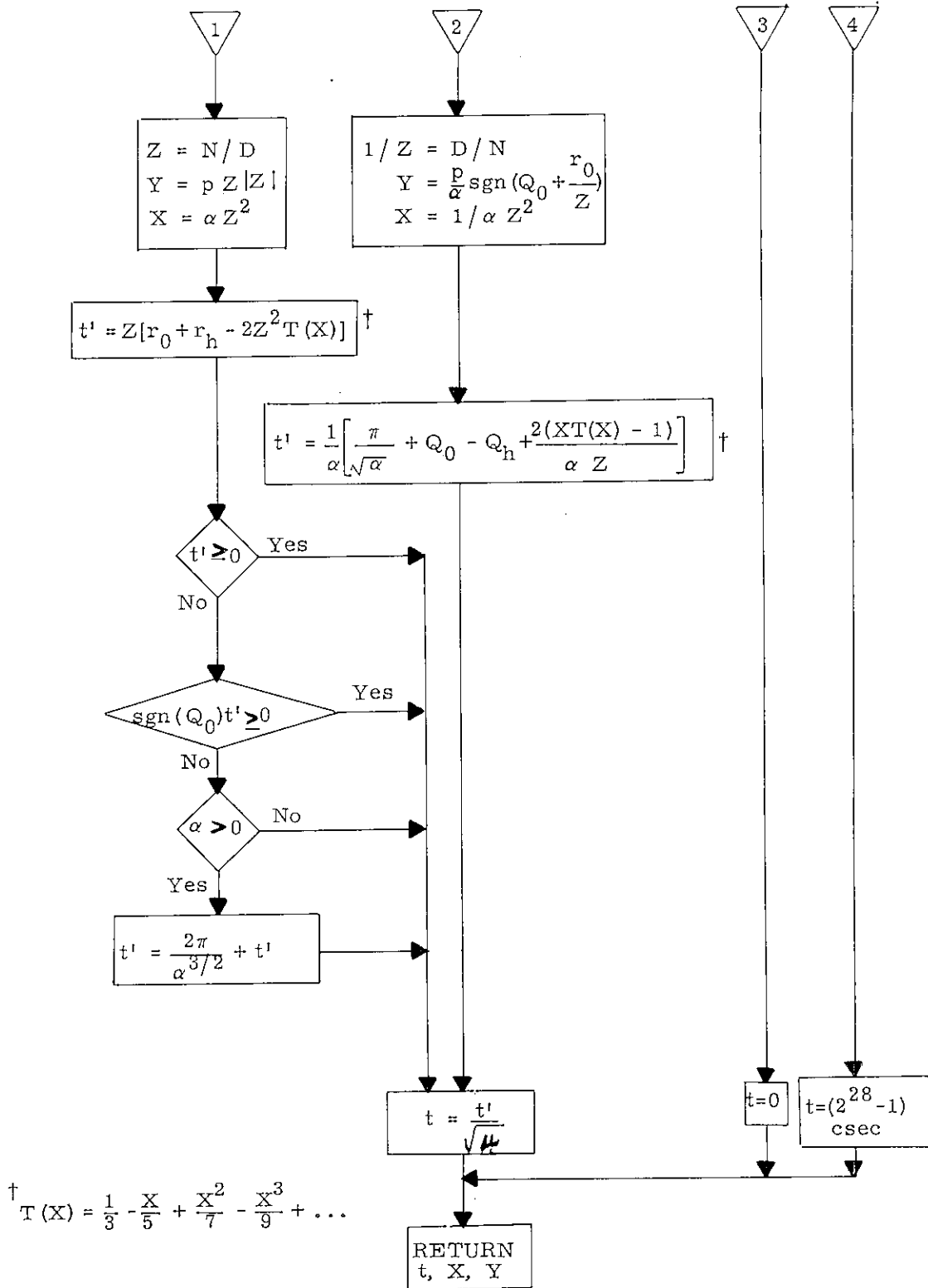


Figure 6.10-7 CALCTFF / CALCTPER Subroutine
(page 2 of 2)

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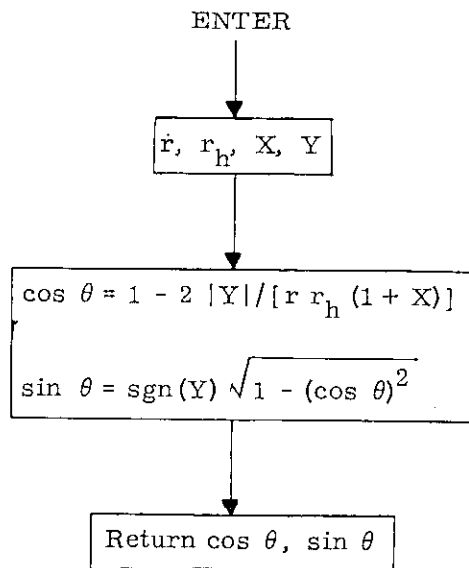


Figure 6.10-8 TFF/TRIG Subroutine

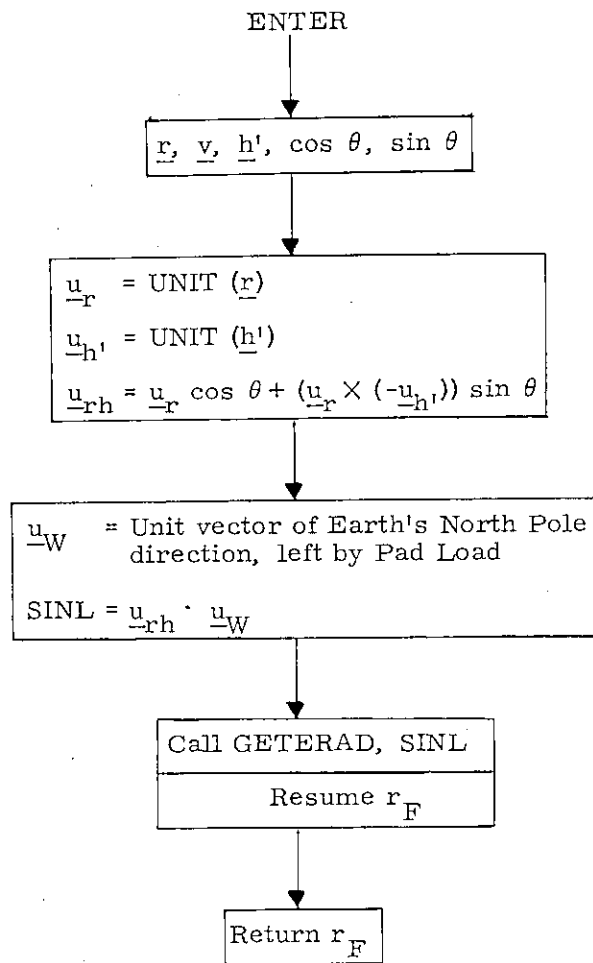


Figure 6.10-9 FISHCALC Subroutine

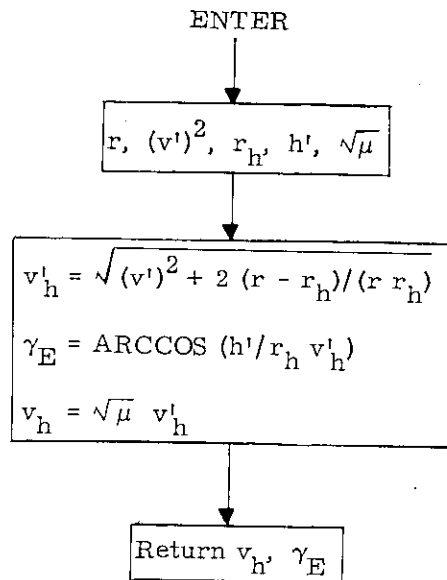


Figure 6.10-10 VGAMCALC Subroutine

5.6.10.5 Equations Used in Calculating the Conic Time of Flight

The time of flight along any conic trajectory proceeding from an arbitrary radius r_0 in the direction of velocity v_0 to a radius of specified length r_h is provided by Kepler's equation. The following formulation, while not quite universal, is explicit and direct. With a single equation, time of flight can be calculated for conic paths that are hyperbolic or parabolic and for those elliptic paths having $|\Delta E| \leq 90^\circ$. An alternate equation is needed for the elliptic paths having $|\Delta E| > 90^\circ$. Highly circular orbits are excluded by the constraint of length for the terminal radius. In the absence of a vector direction, highly circular cases are not treated.

The two conic parameters that appear in the time of flight equations are given by:

Angular momentum: $\underline{H} = \underline{r}_0 \times \underline{v}_0$

Semi-latus rectum: $p = \frac{\underline{H} \cdot \underline{H}}{\mu}$ (6.10.1)

reciprocal semi-major axis: $\alpha = \frac{2}{r_0} - \frac{v_0 \cdot v_0}{\mu}$

The equation for reciprocal semi-major axis α has the usual sign convention: α is negative for hyperbolic orbits, zero for parabolic orbits, and positive for elliptic orbits.

Two intermediate quantities, given in two useful equivalent forms, are:

$$Q_0 = \text{sgn}(\dot{r}_0) \sqrt{r_0 (2 - \alpha r_0) - p} = \underline{r}_0 \cdot \underline{v}_0 / \sqrt{\mu} \quad (6.10.2)$$

$$Q_h = \text{sgn}(\dot{r}_h) \sqrt{r_h (2 - \alpha r_h) - p} = \underline{r}_h \cdot \underline{v}_h / \sqrt{\mu}$$

It is these quantities that exclude highly circular orbits, since being proportional to radial velocity they become uselessly small. For TFF application to reentry, \underline{r}_h is on the returning side, so the sign of \dot{r}_h is chosen as negative. Excepting ellipses for which $|\Delta E| \geq 90^\circ$, the conic time of flight is given by

$$t = (Z/\sqrt{\mu}) (r_0 + r_h - 2 Z^2 T(X)) \quad (6.10.3)$$

where Z is the obtained by one of the following:

if Q_0 and Q_h have opposite signs:

$$Z = (Q_h - Q_0) / (2 - \alpha (r_0 + r_h)) \quad (6.10.4a)$$

if Q_0 and Q_h have like signs:

$$Z = (r_h - r_0) / (Q_h + Q_0) \quad (6.10.4b)$$

and where if

$$\alpha Z^2 < 1.0$$

then

$$X = \alpha Z^2 \quad (6.10.5a)$$

For those elliptic cases having $|\Delta E| \geq 90^\circ$,

then

$$\alpha Z^2 \geq 1.0$$

and

$$X = 1/(\alpha Z^2) \tag{6.10.5b}$$

The conic time of flight is given by

$$t = \left(\frac{1}{\alpha \sqrt{\mu}} \right) \left(\frac{\pi}{\sqrt{\alpha}} - Q_h + Q_0 + \frac{2(XT(X) - 1)}{\alpha Z} \right) \tag{6.10.6}$$

The function $T(X)$ is defined by the series

$$\begin{aligned} T(X) &= \frac{1}{3} - \frac{X}{5} + \frac{X^2}{7} - \frac{X^3}{9} + \dots \\ &= \frac{\sqrt{X} - \arctan(\sqrt{X})}{X\sqrt{X}} \quad \text{if } 0 \leq X \leq 1 \\ &= -\frac{\sqrt{-X} - \operatorname{arctanh}(\sqrt{-X})}{X\sqrt{-X}} \quad \text{if } X \leq 0 \end{aligned} \tag{6.10.7}$$

The equations (6.10.4) are equivalent, except that each has a point of indeterminacy. The selection used in Eq. (6.10.4) excludes the indeterminate point of each from the region of application. The geometric significance of opposite signs for the Q 's is that r_0 and r_h lie on opposite sides of the conic axis of symmetry. For like signs, the radii lie on the same side. In application to spacecraft landing, \dot{r}_h is negative and Eq. (4a) applies to outbound trajectories while Eq. (4b) to inbound ones.

The choice of Eq. (6.10.3) or Eq. (6.10.6) depends on whether αZ^2 is less than or greater than one. Since both Eq. (6.10.3) and Eq. (6.10.6) reduce to the same form when $X = 1.0$, the division made above is arbitrary. Equation (6.10.3) gives both positive and negative values, indicating time to terminal point, and time since terminal point passage. A positive value, time to terminal point, is always provided for the ellipse by replacing negative t by $2\pi/\alpha\sqrt{\alpha\mu} + t$. Equation (6.10.6) yields positive values only.

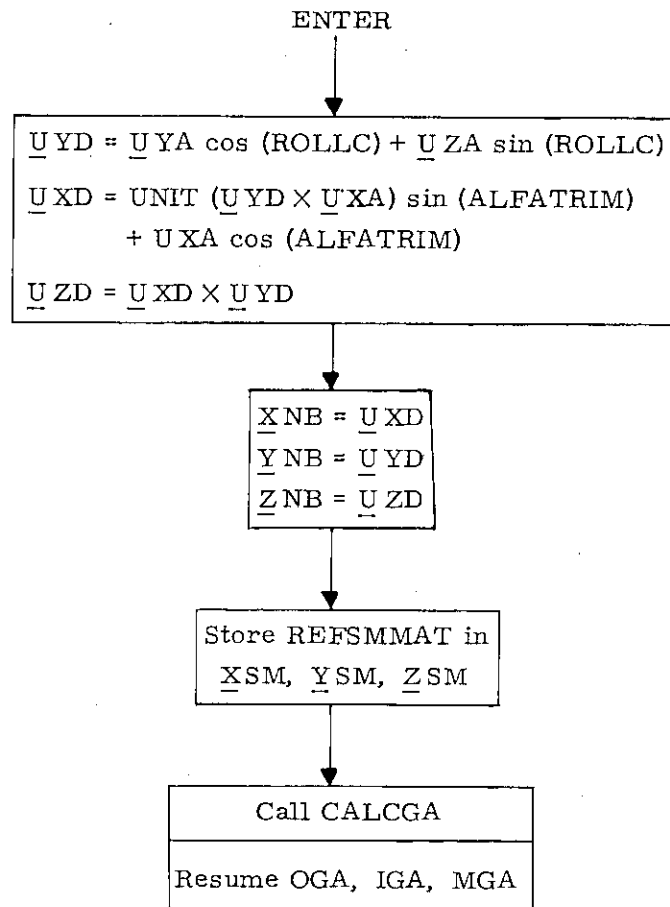
The time of flight equations are exact and involve approximations only to the extent that the function $T(X)$ is represented by a polynomial. Furthermore, Eq. (6.10.3) is continuous as the conic changes from hyperbolic to elliptic.

5.6.10.6 The CM/SM - Separation - and - Pre-Entry - Maneuver Program (P-62) Display of the IMU Gimbal Angles

In the CM/SM - Separation - and - Pre-Entry - Maneuver Program (P-62), the IMU Gimbal Angles corresponding to the entry attitude at the present time are calculated and displayed.

The calculations are shown in Figure 6.10-11. The following nomenclature is used:

- KWE : Equatorial Earth Rate = 1546.70168 ft/sec. (this is a reentry constant - See Section 5.7).
- \underline{u}_W : Unit vector of Earth's North Pole direction, left by pad load.
- \underline{U}_X } : The trajectory triad computed each two seconds
 \underline{U}_Y } : in reference coordinates by CM/ POSE (part of
 \underline{U}_Z } : the DAP calculations).
- \underline{U}_X } : Desired body triad for trimmed flight with respect
 \underline{U}_Y } : to the relative velocity vector, using roll command
 \underline{U}_Z } : and trim angle of attack.
- OGA : Outer Gimbal Angle - Roll
- IGA : Inner Gimbal Angle - Pitch
- MGA : Middle Gimbal Angle - Yaw
- ROLLC : Commanded Roll Angle
- ALFATRIM : Trim Angle of Attack



where:

$$\underline{U} XA = - \text{UNIT} (\underline{V} + KWE (\text{UNIT} (\underline{r}) \times \underline{u}_W))$$

$$\underline{U} YA = - \text{UNIT} (\underline{U} XA \times \text{UNIT} (\underline{r}))$$

$$\underline{U} ZA = (\underline{U} XA \times \underline{U} YA)$$

Figure 6.10-11 Calculation of Gimbal Angles
Corresponding to Entry Attitude

5.6.11 LGC INITIALIZATION

The LGC initialization procedure prior to LM separation is a manual operation which does not involve a numbered CMC program. After the LGC is activated the first requirement is to synchronize the LGC clock with that of the CMC. This is a count-down and mark procedure described in R-33, CMC/LGC Clock Synchronization Routine of Section 4, to obtain an average clock difference which is then used to increment the LGC clock. The CMC and LGC clock synchronization can also be checked by the Mission Ground Control Center using telemetry down-link data, which can provide a more precise difference to increment the LGC clock.

Next, the following parameters are voice-linked from the CSM or uplinked from the earth to the LM to be entered into the LGC:

- 1) \underline{r}_C : CSM position vector
- 2) \underline{v}_C : CSM velocity vector
- 3) t_C : CSM state vector time
- 4) \underline{r}_{-LS} : lunar landing site vector in moon-fixed coordinates
- 5) t_0 : time difference between zero GET and July 1, 0, 1968 universal time.
- 6) P_C : planet identifier

All of the above parameters are in octal, and all are double precision except item 5, t_0 , which is triple precision and item 6, P_C , which is one bit. In the lunar landing mission the above items 1 through 4 are normally determined by the CMC Orbit Navigation Program P-22.

5.6.12 CMC IDLING PROGRAM

This program is used to maintain the CMC in a state of readiness for entry into any other program. While the idling program is in operation, the Coasting Integration Routine (Section 5.2.2) is used to advance the estimated CSM state vector (and the estimated LM state vector when the LM is not on the surface of the moon) to approximately current time. This procedure has the lowest priority of all programs, and is performed only when no other program is active. This periodic state vector extrapolation is not necessary from a theoretical point of view, but does have two practical purposes. First, it is advisable to maintain current (or at least nearly current) state vector estimates in case an emergency situation arises. Second, a significant amount of computation time is transferred from a period of high computer activity (navigation measurement processing, targeting, etc.) to a period of low activity.

The state vectors of both vehicles are extrapolated even if the vehicles are attached. There exists a special DSKY verb by means of which the LM state vector is made equal to the CSM state vector. This verb is used in conjunction with the LM/CSM separation maneuver in order to properly initialize the LM state vector. The use of this verb is followed by astronaut selection of the Target ΔV Routine (Section 5.6.14) to incorporate the LM separation maneuver ΔV .

In order to use the Coasting Integration Routine in an efficient manner, the maximum value for the integration time step, Δt_{\max} , is computed as described in Section 5.2.2.5. The value of Δt_{\max} is a function of radial distance and varies from step to step. Let t_C be the time associated with the estimated CSM state vector and t_1 be the current time. The estimated CSM state vector is extrapolated ahead when

$$t_1 > t_C + 4 \Delta t_{\max} \quad (6.12.1)$$

The integration is terminated when Δt_{\max} is more than the integration time-to-go. In this manner no extra and smaller-than-maximum integration time steps are performed, and the periodic integration is accomplished most efficiently.

The estimated LM state vector (if applicable) is then extrapolated to the CSM state vector time in the same manner.

The error transition matrix W (see Section 5.2.2.4) is extrapolated with the estimated CSM (LM) state vector if ORBWFLAG (RENDWFLG) indicates that the W matrix is valid. ORBWFLAG is defined in Sections 5.2.4.5 and 5.2.6.4, and RENDWFLG in Section 5.2.5.2.

The logic for the periodic state vector extrapolation is illustrated in Fig. 6.12-1. The variables D and V are indicators which control the Coasting Integration Routine. The quantities \underline{x}_C and \underline{x}_L are the estimated CSM and LM state vectors, respectively, and \underline{x} is a temporary state vector used for integration. Refer to Section 5.2.2.6 for precise definitions of these items. The switch SURFFLAG indicates whether or not the LM is on the surface of the moon. This flag is set to one (zero) by means of a special DSKY verb by the astronaut when he receives voice confirmation that the LM has landed on (lifted off from) the lunar surface.

As shown in the figure, time synchronization of the two state vectors is achieved and maintained by this program. The purpose of the state vector synchronization is to guarantee correct W matrix extrapolation during rendezvous navigation.

In order to permit correction of wrong erasable memory parameters which have caused or could cause an invalid and excessively lengthy integration process to begin, there is an emergency special DSKY verb to terminate or inhibit the Coasting Integration Routine. This special verb causes the following to occur:

1. If the Coasting Integration Routine is in operation, it is terminated at the end of the current time step.
2. The current program is terminated.
3. The CMC Idling Program (P-00) is activated.
4. The P-00 state vector test is bypassed so that no state vector integration test occurs until P-00 is reselected.

Note that this operation does not maintain state vector synchronization and can, therefore, cause incorrect W matrix extrapolation in rendezvous navigation.

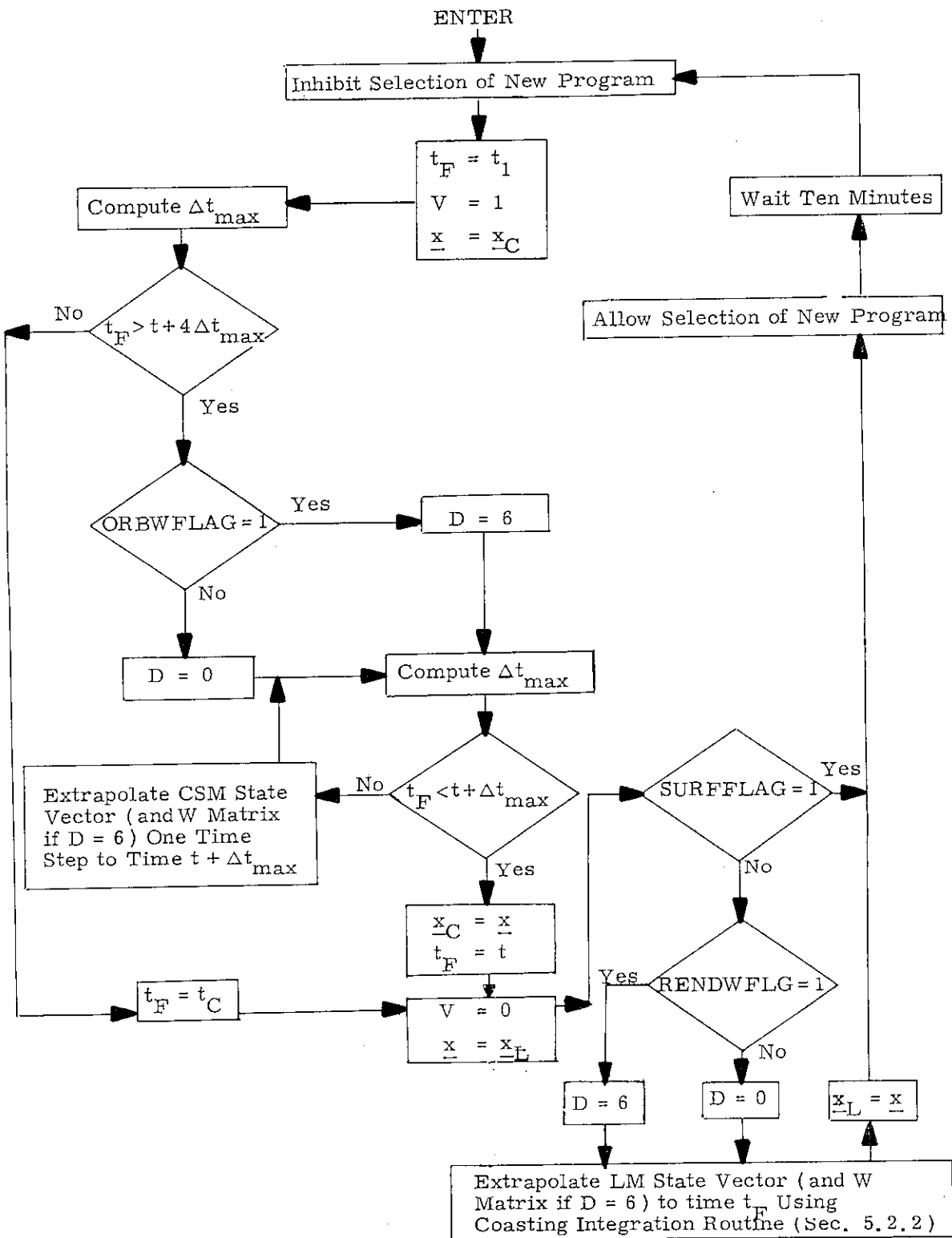


Figure 6.12-1 CMC Idling Program State Vector Extrapolation Logic Diagram

5.6.13 IMU COMPENSATION

The IMU Compensation is designed to compensate for PIPA bias and scale factor error and at the same time accumulate gyro torquing commands necessary to compensate for the associated bias and acceleration caused gyro drifts. The correction to the PIPA's is

$$\text{PIPA}_C = (1 + \text{SFE}_I) \text{PIPA}_I - \text{BIAS}_I \Delta t$$

where

PIPA_C is the compensated data for the I^{th} PIPA denoted PIPAX_C , PIPAY_C , PIPAZ_C

$$\text{SFE} = \frac{\text{SF} - \text{SF}_{\text{nom}}}{\text{SF}_{\text{nom}}} \quad (\text{erasable load})$$

$$\text{SF} = \text{Scale-factor} \frac{\text{CM/Sec}}{\text{Pulse}}$$

BIAS_I is the bias for the I^{th} PIPA (an erasable load)

The compensated data is then used to compute the IRIG torquing necessary to cancel the NBD, ADIA, and ADSRA gyro coefficients. The computations are

$$\text{XIRIG} = -\text{ADLAX} \text{PIPAX}_C + \text{ADSRA} \text{PIPAY}_C - \text{NBDX} \Delta t$$

$$\text{YIRIG} = -\text{ADLAY} \text{PIPAY}_C + \text{ADSRAY} \text{PIPAZ}_C - \text{NBDY} \Delta t$$

$$\text{ZIRIG} = -\text{ADLAZ} \text{PIPAZ}_C - \text{ADSRAY} \text{PIPAY}_C + \text{NBDZ} \Delta t$$

*The term "erasable load" refers to data entered into CMC erasable memory just prior to launch.

where

XIRIG, YIRIG, ZIRIG are gyro drift compensation

NBDX, NBDY, NBDZ are gyro bias drifts (an erasable load)

ADSRAX, ADSRAY, ADSRAZ are gyro drifts due to acceleration in spin reference axis (an erasable load)

ADIAX, ADIAY, ADIAZ are gyro drifts due to acceleration in the input axis (an erasable load)

When the magnitude of any IRIG command exceeds two pulses, the commands are sent to the gyros.

During free-fall only the NBDX, NBDY, NBDZ are the relevant coefficients and the routine is so ordered that only these terms are calculated for the gyro compensation.

5. 6. 14 TARGET ΔV PROGRAM

The purpose of the Target ΔV Program is to update the estimated LM state vector in accordance with the maneuver ΔV which is voice-linked to the CSM from the LM and then entered into the CMC as described in Section 5. 2. 1. The logic for this program is shown in Fig. 6. 14-1. In the figure, ΔV is the maneuver velocity change expressed in a LM local vertical coordinate system and $t_{\Delta V}$ is the time of the maneuver.

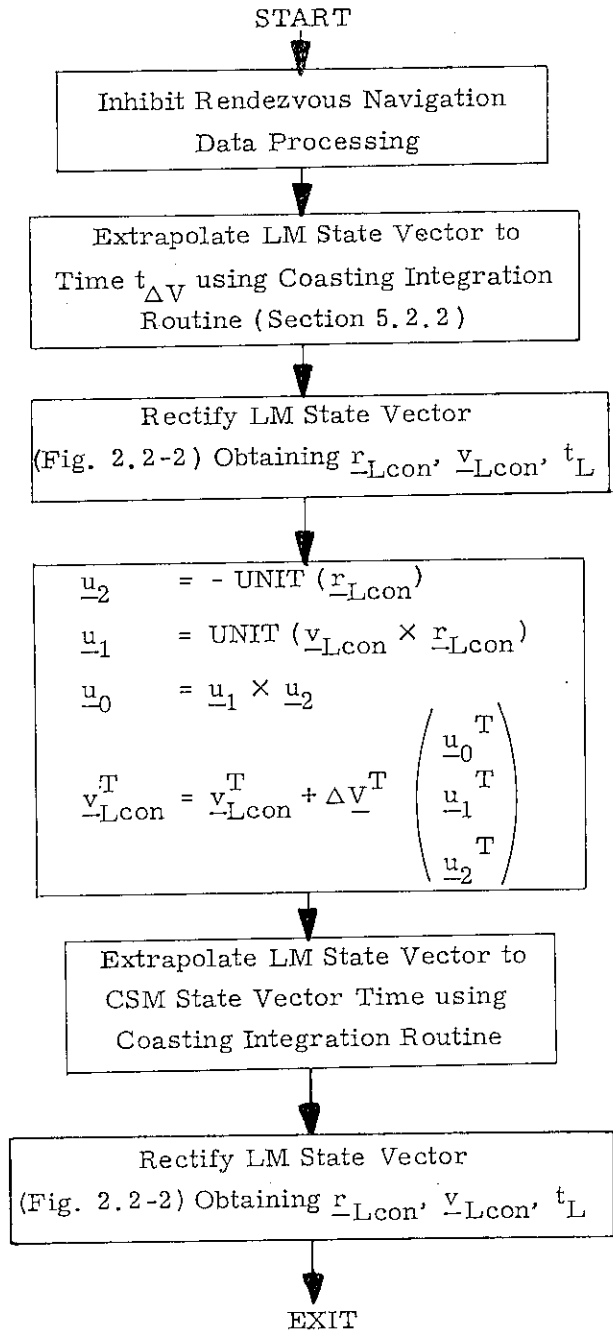


Fig. 6.14-1 Target ΔV Program

5.6.16 RMS POSITION AND VELOCITY ERROR DISPLAY

In order to provide the capability for astronaut monitoring of the G&N system's estimate of state vector accuracy, there exists a special DSKY verb which causes the RMS position and velocity errors to be computed from the W matrix and to be displayed. Based upon the values in this display and the details of the particular mission, the astronaut will elect to stop the navigation that is in progress, to resume or continue with the current navigation procedure, or to reinitialize the W matrix and continue navigating. The capability of selecting the W matrix initialization parameters is also included in this process.

The logic for the RMS position error (Δr_{RMS}) and RMS velocity error (Δv_{RMS}) display is illustrated in Fig. 6.16-1. The vectors w_i are partitions of the W matrix as defined in Eq. (2.2.26) of Section 5.2.2.4. The variables w_{rr} , w_{rv} , w_{lr} , w_{lv} , w_{mr} , and w_{mv} are W matrix initialization parameters, and RENDWFLG and ORBWFLAG are the W matrix validity flags. See Sections 5.2.5.2, 5.2.4.5, and 5.2.6.4 for further definitions and usage of these terms.

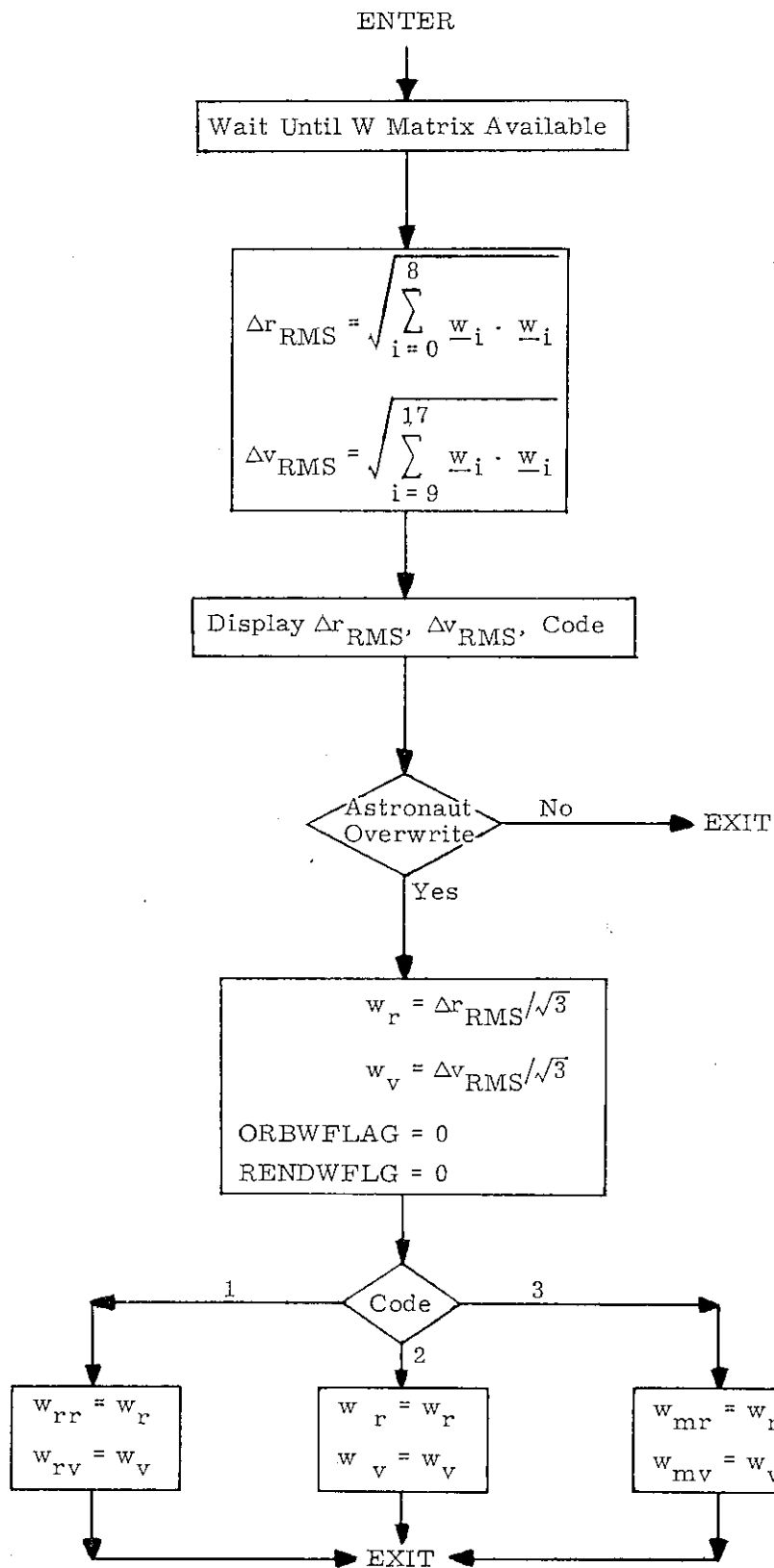


Figure 6.16-1 RMS Position and Velocity Error Display Logic Diagram

5.6-87



5.7 ENTRY GUIDANCE

The entry guidance is used for control of the CM entry vehicle and is described by the logic flow charts in Fig. 5.7-1 thru Fig. 5.7-16. A detailed description of the guidance and steering concept is presented in MIT/IL Report R-532, "Reentry Guidance for Apollo," R. Morth, January 1966.

Figure 5.7-1 illustrates the overall picture of operations during entry. Each block in Fig. 5.7-1 is described in detail in following figures. Figure 5.7-2 defines the symbols which represent computed variables stored in erasable memory. The values and definitions of constants are given in Fig. 5.7-3.

The initialization routine shown in Fig. 5.7-4 is entered only once at the start of entry. Besides setting the appropriate variables to their initial values, this routine presets the variable SELECTOR to INITROLL.

Every pass through the entry equations (done once every 2 seconds) is begun with the section called navigation (see Fig. 5.7-5) and is the same as that presented in Section 5.3.2. This integrates to determine the vehicle's new position and velocity vectors. This navigation routine is started prior to encountering the entry interface at 400,000 feet altitude, and is continuously operated from that time to landing.

Next, the targeting section updates the desired landing site position vector and computes some quantities based on the vehicle's position and velocity and the position of the landing site. (See Fig. 5.7-6).

The mode selector chooses the next sequence of calculations depending upon the phase of entry trajectory that is currently being flown. The initial roll section maintains whatever roll angle was previously selected in the initialization routine and decides when to start the next phase, as shown in Fig. 5.7-7.

The next phase maintains a constant drag trajectory while testing to see if it is time to enter the up-control phase. The testing is presented in Figs. 5.7-8 and 5.7-9. The constant drag equations are given in Fig. 5.7-10. The other phases (up-control, ballistic, and final) are listed in Figs. 5.7-11, 5.7-12, and 5.7-13. (See Fig. 5.7-1.) The final phase is accomplished by a stored reference trajectory with linear interpolation between the stored points. Its characteristics as well as the steering gains are stored as shown in Fig. 5.7-14. The routine that prevents excessive acceleration build-up (G-limiter) is given in Fig. 5.7-15. Finally, the section that does the lateral logic calculations and computes the commanded roll angle is shown in Fig. 5.7-16.

The parameters computed for display purposes only during the entry phase are presented in Section 5.6.10.

For descriptive material about the interaction of Entry Guidance with the Entry DAP and with the mission control programs P61 - P67, see Section 3.

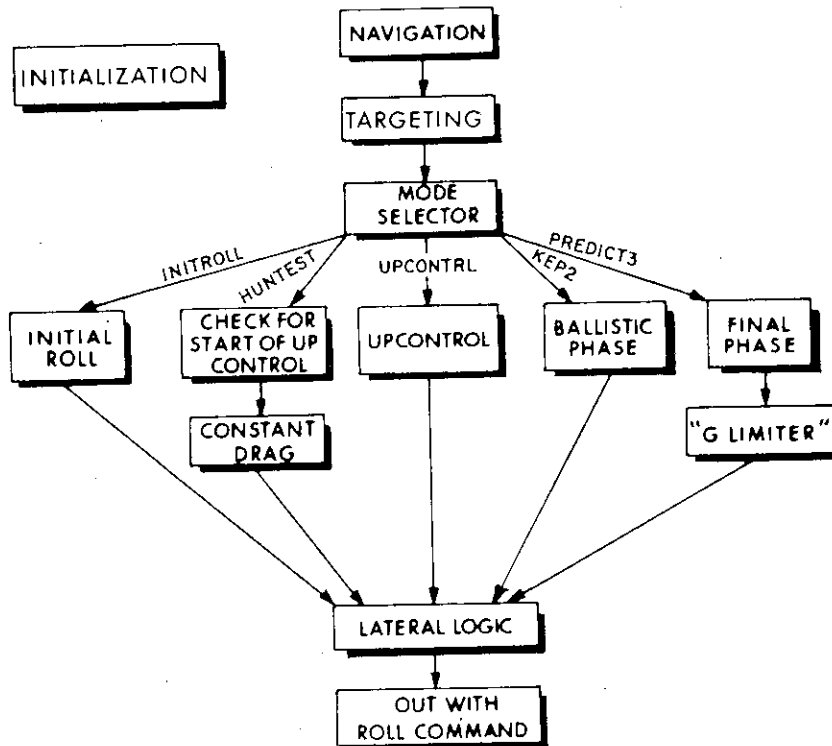


Fig. 5.7-1 Entry Computation

VARIABLE	DESCRIPTION	MAXIMUM VALUE *	COMPUTER NAME
URTO	INITIAL TARGET VECTOR	2 (UNIT VECTOR)	= RTINIT
UZ	UNIT VECTOR NORTH	1	= UNITH
V	VELOCITY VECTOR	2 VSAT	= VEL
R	POSITION VECTOR	2 EXP 29 METERS	= RN
VI	INERTIAL VELOCITY	128 M/CENTISEC	= VN
RTE	VECTOR EAST AT INITIAL TARGET	2	= RTEAST
VTR	NORMAL TO RTE AND UZ	2	= RTNORM
URT	TARGET VECTOR	2	= RT
UNI	UNIT NORMAL TO TRAJECTORY PLANE	2	
DELV	INTEGRATED ACCEL. FROM PIPAS	5.85 16384 CM/S	
G	GRAVITY VECTOR	128 M/CENTISEC	= GDT/2
A0	INITIAL DRAG FOR UPCNTRL	805 FPSS	FPSS=FT/SEC/SEC
AH00KDV	TERM IN GAMMAL CALC. = AH00K DVL	R	
A1	DRAG VALUE IN FACTOR CALCULATION	805 FPSS	
ALP	CONST FOR UPCNTRL	1	
ASKEP	KEPLER RANGE	21600 NM	NM = NAUTICAL MILE
ASPI	FINAL PHASE RANGE	21600 NM	
ASPP	UP-RANGE	21600 NM	
ASP3	GAMMA CORRECTION	21600 NM	
ASPDWN	RANGE DOWN TO PULL-UP	21600 NM	
ASP	PREDICTED RANGE	21600 NM	
CDSG	COSINE(GAMMAL)	2	NOT STORED
D	TOTAL ACCELERATION	2	= COSG/2
DO	CONTROLLED CONSTANT D	805 FPSS	
DHOOK	TERM IN GAMMAL COMPUTATION	805 FPSS	
DIFF	THETNM-ASP (RANGE DIFFERENCE)	805 FPSS	
DIFFOLD	PREVIOUS VALUE OF DIFF	21600X16 NM	
DLEWD	CHANGE IN LEWD	21600X16 NM	
DK	REFERENCE DRAG FOR DOWNCONTROL	1	
DKEEP	REFERENCE DRAG	805 FPSS	NOT STORED
DVL	VSI-VL	805 FPSS	NOT STORED
F	ECCENTRICITY	2 VSAT	
F1	ORANGE/D DRAG (FINAL PHASE)	4	NOT STORED
F2	ORANGE/D ROOT (FINAL PHASE)	2700/805	= FX +5
F3	DRANGE/D (L/D)	2700/2VS NM/FPSS	= FX +4
FACT1	CONST FOR UPCNTRL	805 FPSS	= FX
FACT2	CONST FOR UPCNTRL	1/805 FPSS	
FACTOR	USED IN UPCNTRL	1	
GAMMAL	FLIGHT PATH ANGLE AT VL	1 RADIAN	* MAXIMUM VALUE DENOTES UNSCALED
GAMMAL1	SIMPLE FORM OF GAMMAL	1 RADIAN	VARIABLE VALUE WHEN SCALED
			VARIABLE HAS MAXIMUM VALUE OF ONE.

FIG. 5.7-2 COMPUTER VARIABLES

VARIABLE	DESCRIPTION	MAXIMUM VALUE	COMPUTER NAME
HEADSUP	INDICATOR FOR INITIAL ROLL	1	
KA	DRAG TO LIFT UP IF DOWN	805 FPSS	= KAT (NDM = .0125)
KL	LATERAL SWITCH GAIN	1	
KZROLL	INDICATOR FOR ROLL SWITCH	1	
LAD	MAX L/D (MIN ACTUAL VEHICLE L/D)	1	(NDM = 0.3)
LADPAD	NOMINAL VEHICLE L/D, SP PAD LOAD	4 RADIANS	
LATANG	LATERAL RANGE	128.8 FPSS	
LEO	EXCESS G.F. OVER GRAV=(YSQ-1)G5	1	(NDM = 0.18)
LEWD	UPCONTROL REFERENCE L/D	1	
LLOD	FINAL PHASE L/D	1	
LLODPAD	FINAL PHASE L/D, SP PAD LOAD	1	
L/D	DESIRED LIFT TO DRAG RATIO (VERTICAL PLANE)	1	
L/D1	TEMP STORAGE FOR L/D IN LATERAL	1	
L/DCEMINR	LAD COS(15DEG)	1	(NDM = 0.2895)
PREDANGL	PREDICTED RANGE (FINAL PHASE)	2700 NM	= PREDANG
07	MINIMUM DRAG FOR UPCONTROL	805 FPSS	
ROBT	ALTITUDE RATE	2 VSAT	
RODTREF	REFERENCE ROOT FOR UPCONTROL	2 VSAT	NOT SAVED
ROTR	REFERENCE ROOT FOR DOWNCONT	2 VSAT	= FX +2 NOT SAVED = PIPELINE-TIME/RTO = THETAH
ROLLC	ROLL COMMAND	1 REVOLUTION	
RTOGO	RANGE TO GO (FINAL PHASE)	2700 NM	
SL	SINE OF LATITUDE	1	
T	TIME	8 28 CENTISEC	
THETA	DESIRED RANGE (RADIANS)	2 PI RADIANS	
THETNM	DESIRED RANGE (NM)	21600 NM	
V	VELOCITY MAGNITUDE	2 VSAT	
V1	INITIAL VELOCITY FOR UPCONTROL	2 VSAT	
V1OLD	PREVIOUS VALUE OF V1	2 VSAT	
VCORR	VELOCITY CORRECTION FOR UPCONTROL	2 VSAT	
VL	EXIT VELOCITY FOR UPCONTROL	2 VSAT	
VREF	REFERENCE VELOCITY FOR UPCONTROL	2 VSAT	
VSL	VSAT OR V1, WHICHEVER IS SMALLER	2 VSAT	
VBAKS	VL /VSAT	4	
VSQ	NORMALISED VEL. SQUARED = V /VSAT	2	= VSQUARE
WT	EARTH RATE TIMES TIME	1 REVOLUTION	NOT SAVED = WIE (DTEARROT)
X	INTERMEDIATE VARIABLE IN G-LIMITER	2 VSAT	
Y	LATERAL MISS LIMIT	4 RADIANS	
Z	FINAL PHASE RANGE	21600 NM	
02	COMPUTER VARIABLES (CONT)		NOT SAVED

FIG. 5.7-2A

EXTRA COMPUTER ERASABLE LOCATIONS NOT SHOWN ON FLOW CHARTS

VARIABLE	DESCRIPTION	MAXIMUM VALUE	
GOTOADDR	ADDRESS SELECTED BY SEQUENCER		
XPIPBUF	BUFFER TO STORE X PIPA COUNTS		
YPIPBUF	BUFFER TO STORE Y PIPA COUNTS		
ZPIPBUF	BUFFER TO STORE Z PIPA COUNTS		
PIPCTR	COUNTS PASSES THRU PIPA READ ROUTINE		
JJ	INDEX IN FINAL PHASE TABLE LOOK-UP		
MM	INDEX IN FINAL PHASE TABLE LOOK-UP		
GRAD	INTERPOLATION FACTOR IN FINAL PHASE		
FX	DRANGE/D L/D = F3	2700 NM	
FX + 1	AREF	805 FPSS	
FX + 2	RTDGD	2700 NM	
FX + 3	RDOTREF	VSAT/4	
FX + 4	DRANGE/D ROOT = F2	21600/2VS NM/FPSS	
FX + 5	DRANGE/D DRAG = F1	2700/805 NM/FPSS	
TEMLB	TEMPORARY LOCATION		
TIME/RTO	TIME OF INITIAL TARGET RTINIT	8 28 CENTISEC	
DTEAROT	EST TIME BETWEEN RTINIT AND RT	8 28 CENTISEC	
-			
UNITV	UNIT V VECTOR	2	
-			
UNITR	UNIT R VECTOR	2	
-			
-VREL	NEGATIVE VELOCITY REL TO ATMOSP	2 VSAT	
SWITCHES		INITIAL STATE	CM/FLAGS = STATE + 6
NOSWITCH	INHIBIT LATERAL SWITCH	NON-BRANCH (0)	920, BIT 13
GONEPAST	INDICATES OVERSHOOT OF TARGET	NON-BRANCH (0)	950, BIT 10
RELVELSW	RELATIVE VELOCITY SWITCH	NON-BRANCH (0)	960, BIT 9
EGSW	FINAL PHASE SWITCH	NON-BRANCH (0)	970, BIT 8
HIND	INDICATES ITERATION IN HUNTEST	NON-BRANCH (0)	990, BIT 6
INRLSW	INDICATES INIT ROLL ATTITUDE SET	NON-BRANCH (0)	1000, BIT 5
LATSW	INHIBIT DOWNLIFT SWITCH IF NOT SET	BRANCH (1)	1010, BIT 4
.05GSW	INDICATES DRAG EXCEEDS .05 GS	BRANCH (0)	1020, BIT 3
GONEBY	INDICATES GONE PAST TARGET (SET)	SELF-INITIALIZNG	1120, BIT 8 IN STATE + 7

Figure 5.7-2b Computer Variables (cont)

BODY ATTITUDE QUANTITIES (CM/PDSE)

VARIABLE	DESCRIPTION	MAXIMUM VALUE
-VREL	NEGATIVE VELOCITY REL TO ATMOS.	2 VSAT
OLDUYA	USED FOR UYA BELOW 1000 FPS	2
UAX/2	UNIT VECTOR TRIAD BASED ON THE TRAJECTORY.	2
UYA/2		
UZA/2		
URX/2	UNIT VECTOR	2
URY/2	BODY TRIAD FOR CM.	2
URZ/2		

Figure 5.7-2c Computer Variables (cont)

DISPLAY QUANTITIES

VARIABLE	DESCRIPTION	MAXIMUM VALUE	
GMAX	PREDICTED MAXIMUM ENTRY ACCEL	163.84 GS	N 60
VPRED	PREDICTED VELOCITY AT ALTITUDE	128 M/CENTISEC	N 60
	400K FT ABOVE FISCHER RADIUS.		
GAMMAEI	PREDICTED GAMMA AT ALTITUDE	1 REVOLUTION	N 60
	400K FT ABOVE FISCHER RADIUS.		
D	DRAG ACCELERATION	805 FPSS	N 64
VMAGI	INERTIAL VELOCITY MAGNITUDE(VI)	128 M/CENTISEC	N 64, N 68
THETAH	DESIRED RANGE ANGLE NM	1 REVOLUTION	N 64, N 67
RTOGO	RANGE ANGLE TO SPLASH FROM	1 REVOLUTION	N 63
	EMSALT FT ABOVE FISCHER RADIUS. (IN NM)		
VID	PREDICTED VELOCITY AT ALTITUDE	128 M/CENTISEC	N 63
	EMSALT FT ABOVE FISCHER RADIUS.		
TTE	TIME OF FREE FALL TO ALT	3 28 CENTISEC	N 63
	EMSALT FT ABOVE FISCHER RADIUS.		
BETA	ROLL COMMAND (RDLIC)	1 REVOLUTION	N 66, N 68
XRNGERR	CROSS-RANGE ERROR (LATANG IN NM)	1 REVOLUTION	N 66
DNRRNGERR	DOWN RANGE ERROR *	1 REVOLUTION	N 66
	(PREDANG - THETAH IN NM)		
HDOT	ALTITUDE RATE(RDOT)	128 M/CENTISEC	N 68
DL	EXIT DRAG LEVEL (07)	805 FPSS	
VL	EXIT VELOCITY	2 VSAT	
RTOGO	RTOGO IN P67	1 REVOLUTION	
	(-THETAH IF GONEBY = 0, THETAH IF GONEBY = 1)		
LAT	GEODETTIC LATITUDE OF VEHICLE		
LONG	LONGITUDE OF VEHICLE		

* DNRRNGERR = 99999 IF GONEPAST = 1

Figure 5.7-2d Computer Variables (cont.)

CONSTANTS AND GAINS	VALUE	
C1	1.25	
C16	.01	
C17	.001	FPS
C18	500	FPSS
C20	175	
C21	.25	
CH00K	1	
CH1	.965	
COS(15 DEG)	-.05	
DI	2	SEC.
DLEWDO	257.6	FPSS
GMAX	1.3	GS
KA1	.07F/6S	
KA2	90	FPSS
KA3	40	FPSS
KA4	3.4	
KR1	.0034	
KR2	.5	FPSS
KOMIN	1000	
KTETA	1/24	
KLAT1	19749550	FPS
K44	-.41252961	NM
LATRIAS	.15	
LEW01	.1	
POINT1	.07	NM/FPSS
Q3	7050	NM/RAD
Q5	-.0349	RAD
Q6	6	FPSS
Q7F	40	FPSS
Q7MIN	.5	FPS
Q19	27000	FPS
VFINAL1	26600	FPS
VFINAL	18000	FPS
VLMIN	VSAT/2	
VMIN	700	FPS
VRCONTRL	1000	FPS
VCORLIM	25	NM
Z5NM	1000	FPS
VQUIT	140	FPSS
CZI		
CONVERSION FACTORS AND SCALING CONSTANTS		
ATK	3437.7468	NM/RAD
GS	32.2	FPSS
HS	28500	FT
J	.00162346	FPS
KWE	1546.70168	FPS
MVE	3.98603233	E 14 CUBIC M/ SEC SEC
RE	21202900	FT
REO	20925736.2	FT
VSAT	25766.1973	FPS
WIE	.0000729211505	RAD/SEC

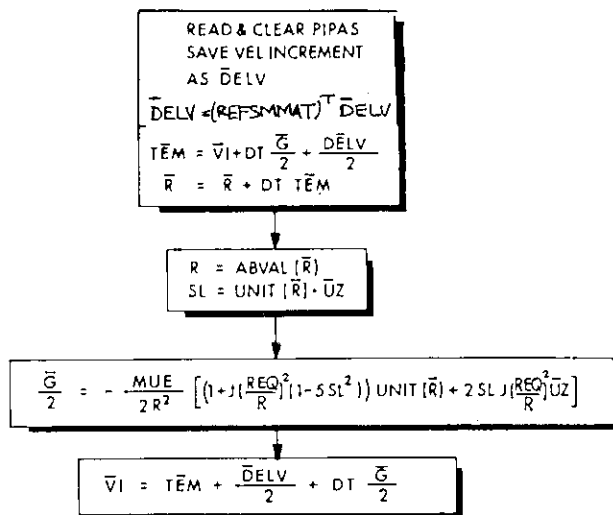
FIG. 5.7-3 CONSTANTS, GAINS AND CONVERSION FACTORS

INITIALIZATION

```
URTO = TARGET VECTOR AT TIME OF INITIALIZATION
RTE = UZ*URTO
UTR = RTE*UZ
URT = INITIAL TARGET VECTOR AT NOMINAL TIME OF ARRIVAL
      (FOR THIS CALCULATION)
      = URTO + UTR(COS WT - 1) + RTE SIN WT
      WHERE WT = W TNOM, TNOM = 500 SEC
UNI = UNIT (V*UNIT(R))
LATANG = URT.UNI
THETA = ARCCOS(URT.UNI(R))
K2ROLL = -SIGN(LATANG)
O7 = 07F
SELECTOR = INITROLL
FACTOR = 1
LOD = LODPAD
LAD = LADPAD
KLAT = KLAT1 LAD
L/DCMINR = LAD COS15
L/D = - LAD SGN(HEADSUP)
DIFFOLD = 0
DLEWD = DLEWDO
LEWD = LEWD1
O2 = -1152 + 500 LAD

INITIALIZE SWITCHES
GONEPAST = 1      RELVELSW = 0      GONEBY = 0
EGSW = 0         .05GSW = 0      NOSWITCH = 0
HIND = 0         INALSW = 0
LATSW = 1
```

Figure 5.7-4 Entry Program Initialization



Note:
This routine is identical
to "Average-G" routine
used elsewhere.

Fig. 5.7-5 "Average-G" Navigation Routine

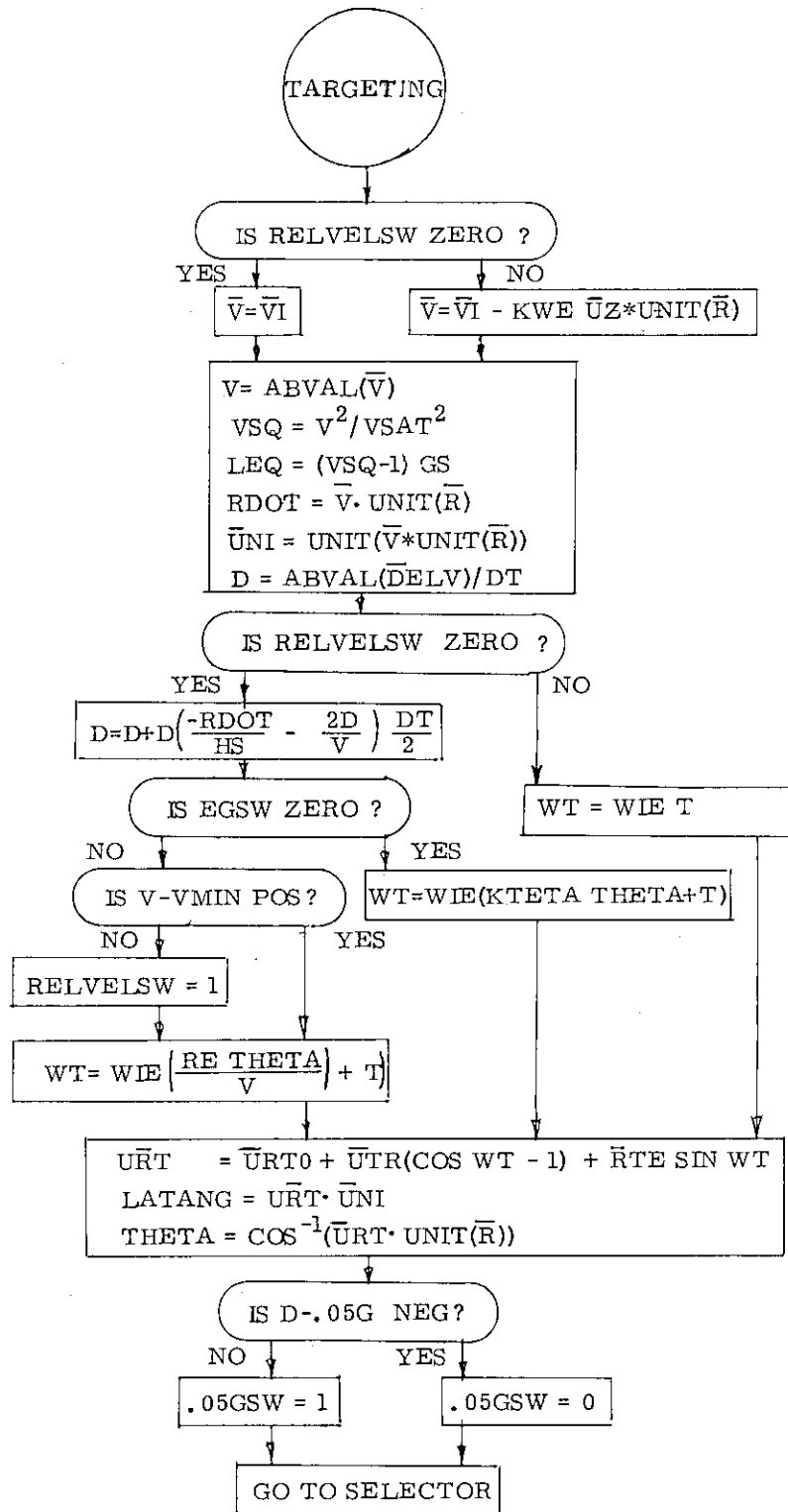


Figure 5.7-6 Targeting

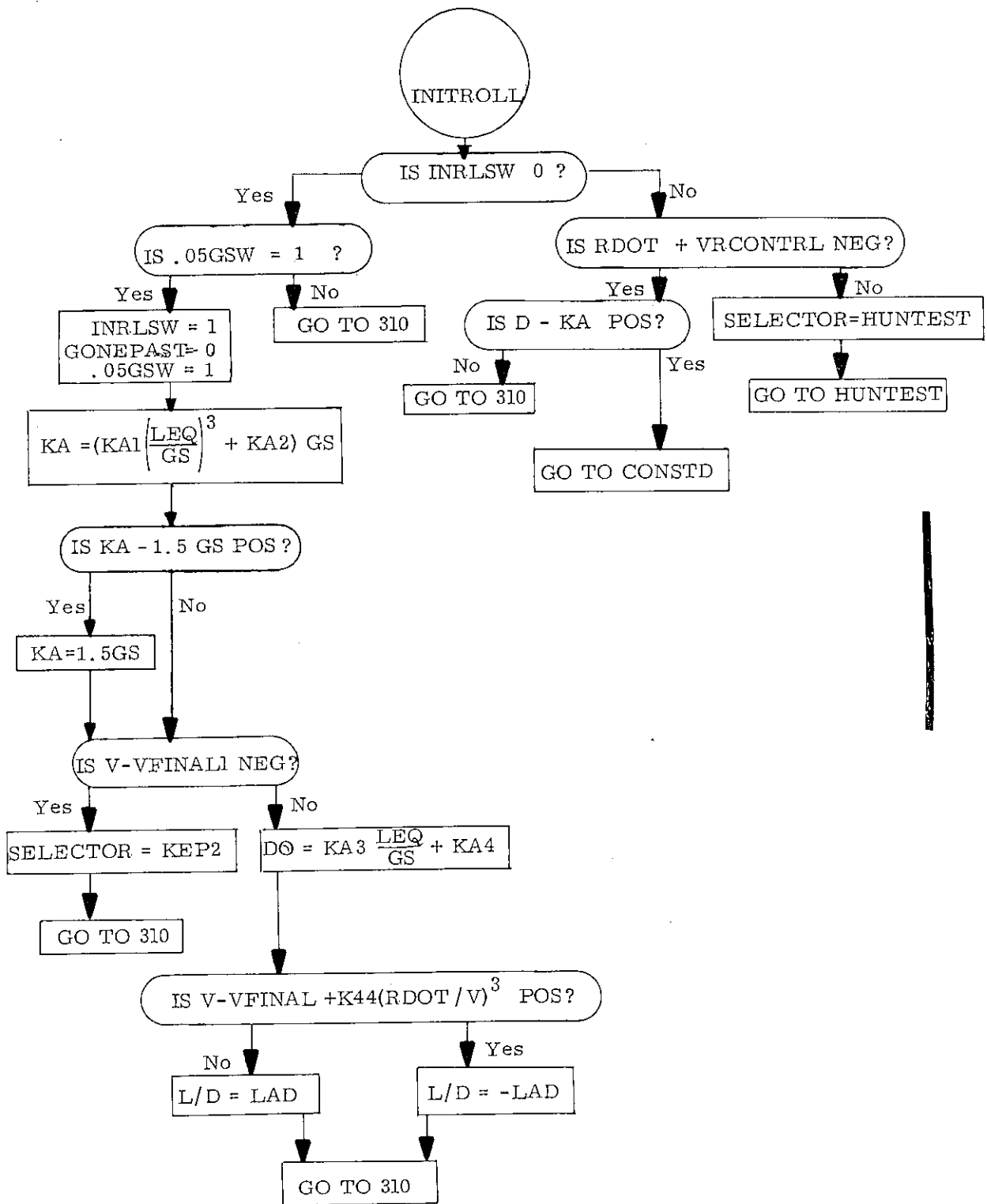


Figure 5.7-7 Initial Roll

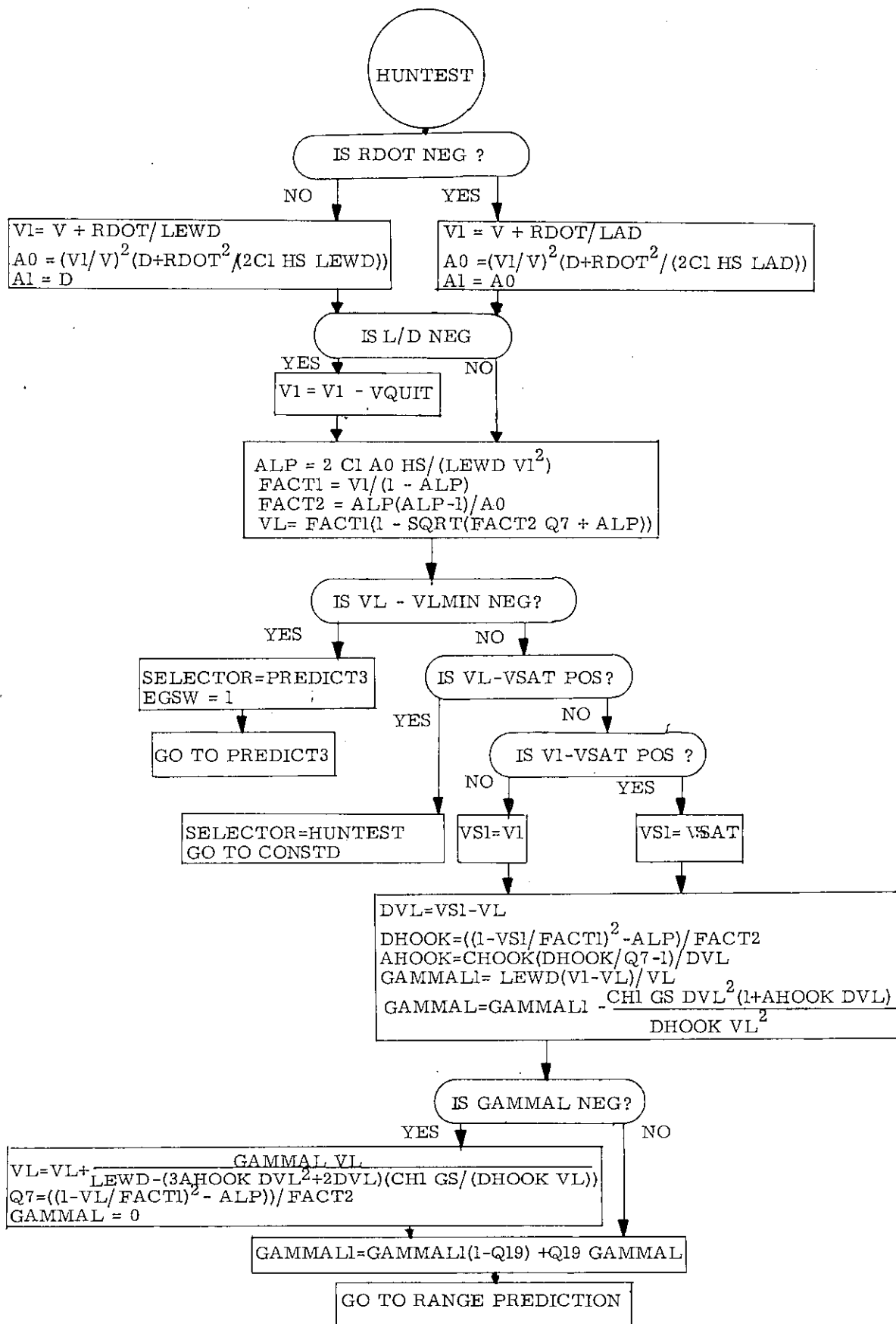


Figure 5.7-8 Hunttest
5.7-14

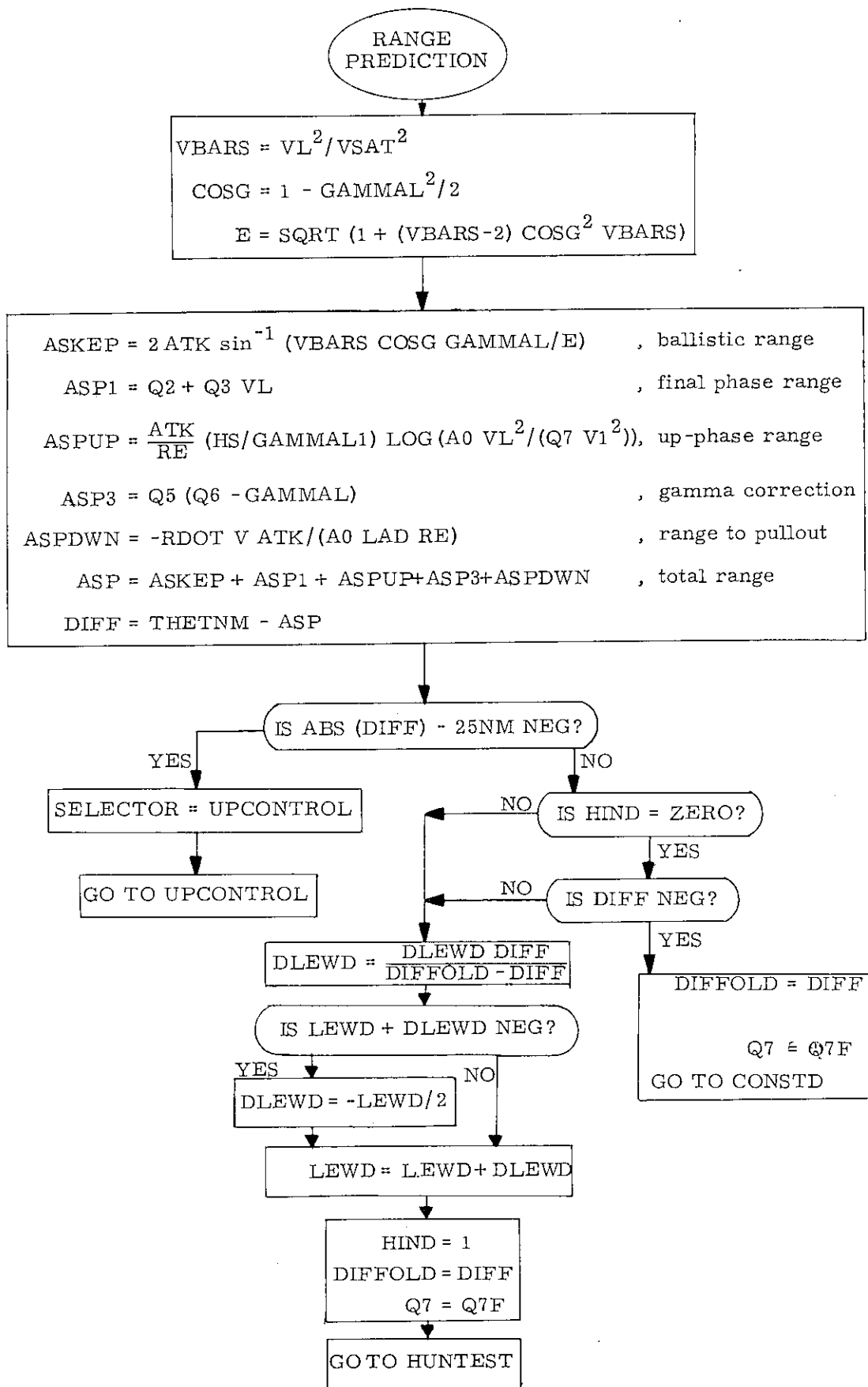


Figure 5.7-9 Range Prediction

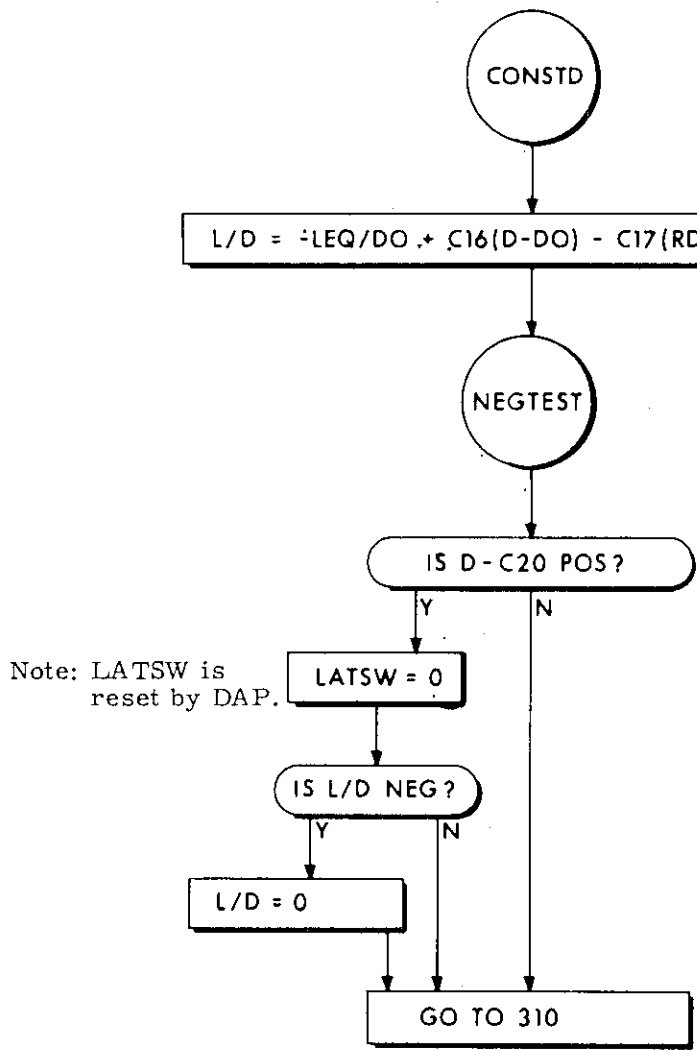


Fig. 5. 7-10 Constant Drag Control

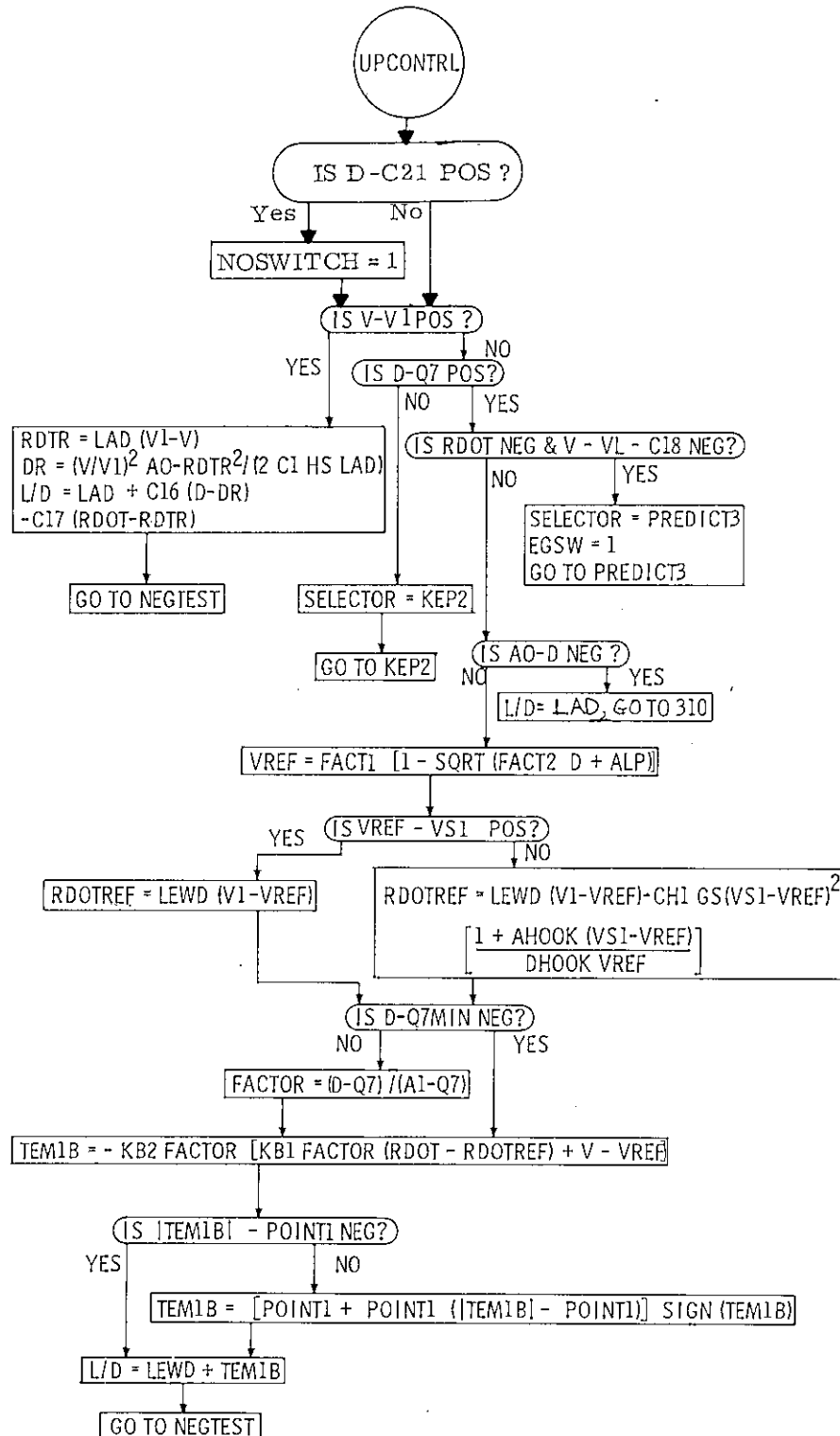


Fig. 5.7-11 Upcontrol

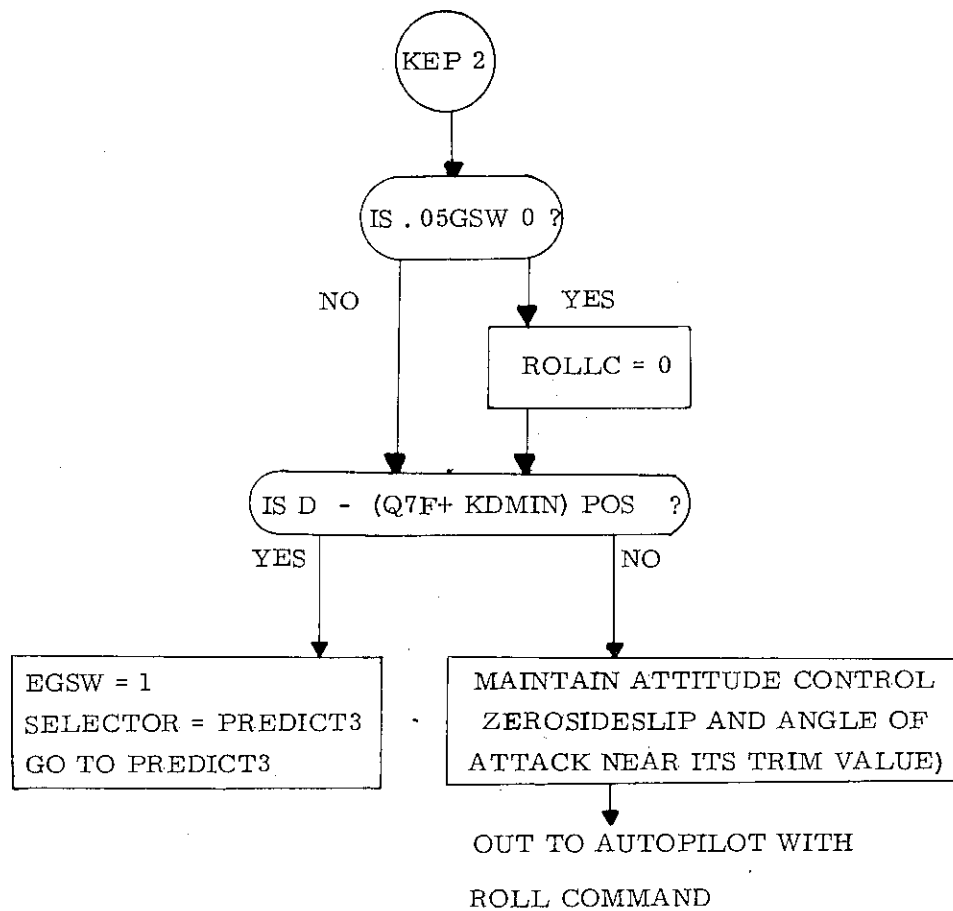


Figure 5.7-12 Ballistic Phase

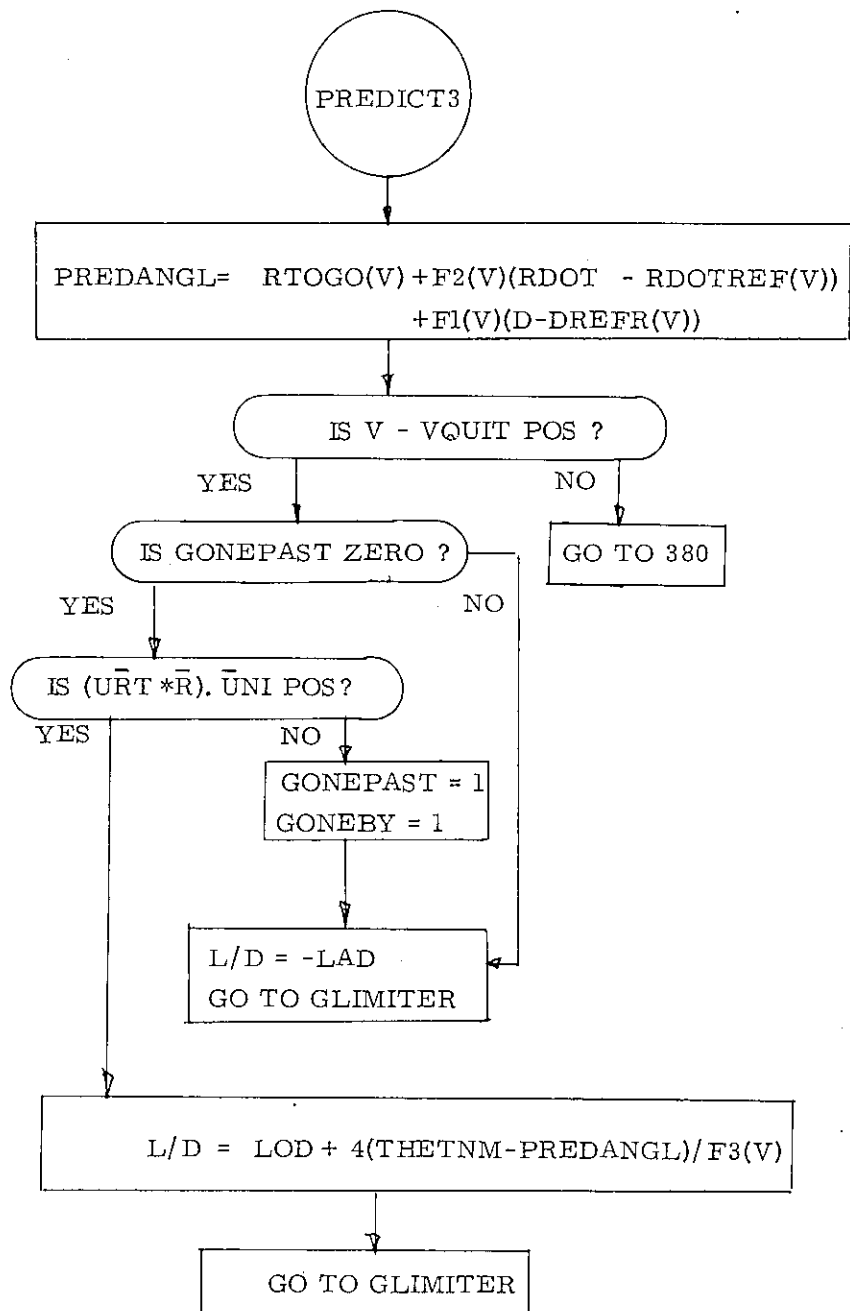


Figure 5.7-13 Final Phase

VREF	RROOTREF	DREFR	DR/DRDOT	DR/DA	RTOGO	DR/DL/D
FPS	FPS	FPSS	F2 NM/FPS	F1 NM/FPSS	NM	F3 NM
994	-690.9	41.15	.002507	-.0346	2.2	6.10 X2
2103	-719	60.	.003582	-.05551	8.9	10.91 X2
3922	-694	81.5	.007039	-.09034	22.1	21.64 X2
6295	-609	93.9	.01446	-.1410	46.3	48.35 X2
8531	-493	98.5	.02479	-.1978	75.4	93.72 X2
10101	-416	102.3	.03391	-.2372	99.9	141.1 X2
14014	-352	118.7	.06139	-.3305	170.9	329.4
15951	-416	125.2	.07683	-.3605	210.3	465.5
18357	-566	120.4	.09982	-.4956	266.8	682.7
20829	-781	95.4	.1335	-.6483	344.3	980.5
23090	-927	28.1	.2175	-2.021	504.8	1385
23500	-820	6.4	.3046	-3.354	643.0	1508
35000	-820	6.4	.3046	-3.354	794.3	1508

Figure 5.7-14a Final Phase Reference

Interpolation Procedure

Start with table entries. See Fig. 5.7-14a.

VREF(i) , i = 1, 13

RDOTREF(i), i = 1, 13

etc

Vary the index i until velocity magnitude lies between two values in the table. That is:

$$VREF(i) < V < VREF(i+1).$$

Save the value i and form the linear interpolation factor

$$GRAD = \frac{V - VREF(i)}{VREF(i+1) - VREF(i)}$$

Then form interpolated values. For example

$$RDOTREF(V) = RDOTREF(i) + GRAD [RDOTREF(i+1) - RDOTREF(i)]$$

Figure 5.7-14b Final Phase Reference

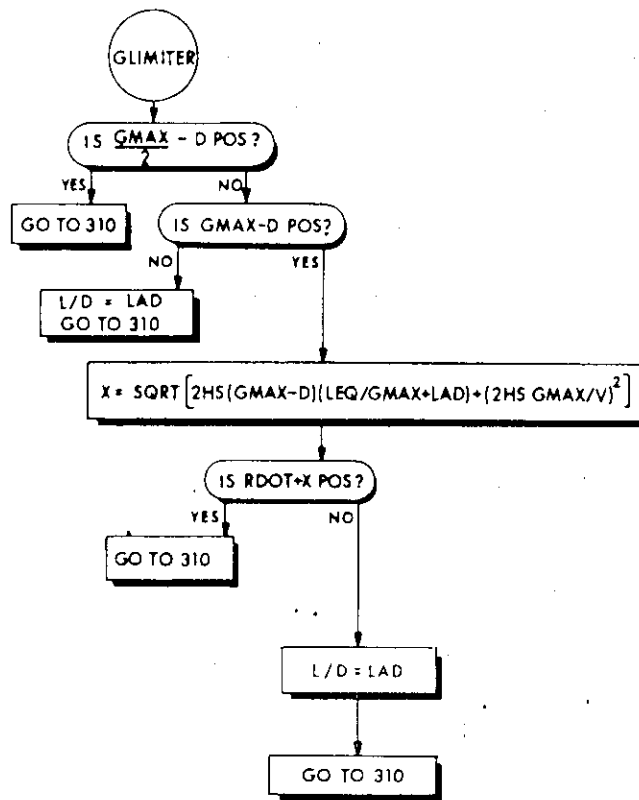


Fig. 5.7-15 G-Limiter

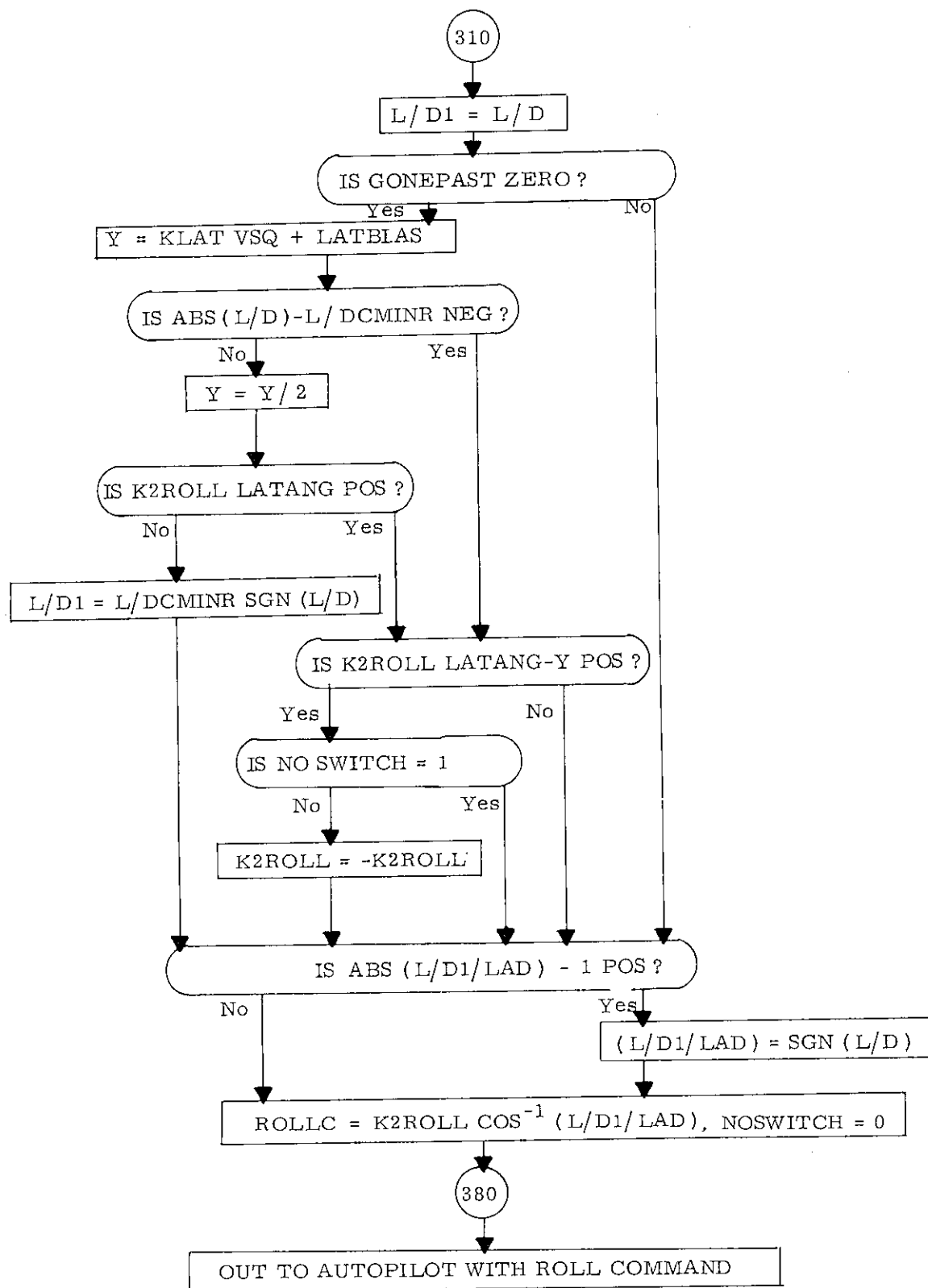


Fig. 5.7-16 Lateral Logic



This section presents a list of selected parameters required for various program operations. It should be noted that this is a very limited CMC erasable parameter list. The objective of this selected list is to identify those parameters that would be stored in erasable memory and are required primarily to initialize the operation of programs and routines. In most cases these parameters can not be originated within the CMC and must be stored prior to the mission. Thus, all of the listed parameters can be initialized before launch, and those that are not applicable will be changed during the mission prior to their usage. Some parameters will vary continually throughout the mission (e. g. vehicle state vectors), others are constant for any one mission phase, but may vary between different mission phases, and finally some may be constant for one mission, but be required to change for subsequent missions that use the same CMC program.

<u>Page</u>	<u>Parameter</u>
5.2-26	r_{C0} , r_{L0}
	v_{C0} , v_{L0}
	$r_{C\text{ con}}$, $r_{L\text{ con}}$
	$v_{C\text{ con}}$, $v_{L\text{ con}}$
	δ_C , δ_L
	ψ_C , ψ_L
	t_C , t_L
	τ_C , τ_L
	x_C , x_L
	P_C , P_L

<u>Page</u>	<u>Parameter</u>
5.2-51	KNOWN L Lat Long Alt Lat ₁ Long ₁ Alt ₁ w _{lr} w _{lv}
5.2-52	OFF w _l var _{RP}
5.2-57	r _{LS}
5.2-70	SC
5.2-71	δ _r MAX δ _v MAX
5.2-77	var _{INT}
5.2-78	var _R var _{Rmin}
5.2-79	w _{rr} w _{rv}
5.2-83	var _{ALT}
5.2-84	Z
5.2-89	h
5.2-85	L w _{mr} w _{mv}

<u>Page</u>	<u>Parameter</u>
5.2-96	H
5.3-3	$\Delta v(\Delta t)$
5.3-18	ΔV_{LV}
	t_{IG}
5.3-19	S_E
	m
5.3-23	$r(t_2)$
	t_2
5.3-24	c
	ec
5.3-28	p
	y
5.3-31	JFLG
	F_{imp}
	K_1
5.3-34	Δv_p (SPS)
5.3-35	K
5.3-48	A_{ZP}
	A_Z
	K_r
	t_{E1}
	t_{E2}
	a_0, a_1, \dots, a_6
5.3-55	Δv_u
5.3-57	δY_B
	δZ_B
5.4-19	t
	E
	ωt
5.4-21	ΔV_{TPI} (LV)
5.4-24	$\delta \tau_3$
	$\delta \tau_7$
5.4-25	ΔV (LV)

5.8-3

<u>Page</u>	<u>Parameter</u>
5.4-27	t_{TPI}
5.4-28	K
5.4-36	t_{IG} ωt S δr
5.4-49	t_1 $\gamma (t_2)_D$ Δv_D
5.4-77	D_1
5.5-13	A_X A_Y A_{Z0} t_0
5.5-16	$\underline{\ell}_M$
5.5-22	r_{LS}
5.5-23	t_{M0} \underline{c}_0 thru \underline{c}_9
5.5-24	\underline{r}_{ES0} \underline{v}_{ES0} ω_{ES}
5.6-54	EMS Altitude

<u>Page</u>	<u>Parameter</u>
5.6-77	r_{LS}
5.6-82	SFE ₁ , SFE ₂ , SFE ₃ BIAS ₁ , BIAS ₂ , BIAS ₃ ADIAX, ADIAY, ADIAZ ADSRAX, ADSRAY, ADSRAZ NBDX, NBDY, NBDZ

5.8-5

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5.9 FIXED MEMORY CONSTANTS

Section 5.9.1 contains a list and the numerical values of those fixed memory constants in Section 5.2 through 5.6 which have not been specified previously. Those constants which are considered to be control type data are indicated by source references which are listed in Section 5.9.2. Explanatory comments are noted in Section 5.9.1 where applicable and listed in Section 5.9.3. It should be noted that only one page number is given for a constant in the list of Section 5.9.1 even though the constant may appear in other parts of Section 5. In these cases the same value is used for the constant as reported in Section 5.9.1.

5.9.1 FIXED CONSTANTS

<u>Page</u>	<u>Constant</u>	<u>Units</u>	<u>Value</u>	<u>Reference (Sec. 5.9.2)</u>	<u>Comments (Sec. 5.9.3)</u>
5.2-13	$\mu_P \left\{ \begin{array}{l} \mu_E \\ \mu_M \end{array} \right.$	m^3/s^2	0.3986032×10^{15}	2, 3, 4	
		m^3/s^2	0.4902778×10^{13}	2, 3, 4	
5.2-16	J_{2E}	-	0.10823×10^{-2}	2, 3, 4	
	J_{3E}	-	-0.23×10^{-5}	2, 3, 4	
	J_{4E}	-	-0.18×10^{-5}	2, 3, 4	
	r_E	m	6,378,165	2, 3, 4	
5.2-17	J_{2M}	-	0.207108×10^{-3}	2, 3, 4	
	J_{3M}	-	0	2, 3, 4	
	J_{4M}	-	0	2, 3, 4	
	J_{22M}	-	0.207160×10^{-4}	2, 3, 4	
	r_M	m	1,738,090	2, 3, 4	
5.2-18	μ_S	m^3/s^2	$0.132715445 \times 10^{21}$	2, 3, 4	
5.2-27	ϵ_t	csec	3.0		1
5.2-29	r_{ME}	m	7,178,165		2
	r_{MM}	m	2,538,090		2
5.2-30	r_{SPH}	m	64,373,760	14	3
5.2-31	r_{dE}	m	80,467,200		4
	r_{dM}	m	16,093,440		4

<u>Page</u>	<u>Constant</u>	<u>Units</u>	<u>Value</u>	<u>Reference</u> <u>(Sec. 5.9.2)</u>	<u>Comments</u> <u>(Sec. 5.9.3)</u>
5.2-54	var _{SCT}	(mr) ²	1.0	4	
	var _{IMU}	(mr) ²	0.04	5	
5.2-73	k _{RL}	nm/bit	0.01	6	
5.2-77	var _{SXT}	(mr) ²	0.04	4	
5.2-86	c	ft/sec	9.835712 x 10 ⁸	2, 3, 4	
5.2-95	var _{TRUN}	(mr) ²	0.0025	4	
	var _L	(nm) ²	1		15
5.3-21	F _{SPS}	pounds	20,000	9	
	F _{RCS}	pounds	200 or 400	9	
5.3-31	m(SPS)	pounds/sec	63.8	10	
	F _L	pounds	197	9	10
	K ₂	pound-sec	5000	20	
	K ₃	pounds	25500	20	
5.3-33	Δt _{Tail-off} (SPS)	sec	0.57	17	
5.3-34	V _e (SPS)	m/sec	3151.0396	20	
5.3-49	ω _E	rad/sec	7.29211515 x 10 ⁻⁵	8	
5.3-49	(b/a) ²		0.993306578	2, 3, 4	
5.3-50	t _{KS}	sec	163.84		11
5.4-51	ε ₂	m	100.0		7
	ε ₃	-	0.001		7
5.4-52	ε ₇	m	1000		7
	ε ₈	-	0.002		7

5.9-2

Revised COLOSSUS

Added GSOP #R-577 PCR # 734 Rev. 5 Date _____

<u>Page</u>	<u>Constant</u>	<u>Units</u>	<u>Value</u>	<u>Reference</u> (Sec. 5.9.2)	<u>Comments</u> (Sec. 5.9.3)
5.4-61	ϵ_1	-	.99966		7
	C_0	m	1.81000432×10^8		7
	C_1	-	1.5078514		7
	C_2	1/m	$-6.49993054 \times 10^{-9}$		7
	C_3	$1/m^2$	$9.769389245 \times 10^{-18}$		7
5.4-62	ϵ_4	-	0.00001		7
5.4-63	ϵ_6	-	0.000007		7
5.4-65	k_1	m	7.0×10^6		7
	k_2	m	6.495×10^6		7
	k_3	-	-.06105		7
	k_4	-	-.10453		7
	k_5	m	107		7
	E_3	m	121920		7
	D_2	s/m	$-4.8760771 \times 10^{-4}$	19	7
	D_3	s^2/m^2	4.5419476×10^{-8}	19	7
	D_4	s^3/m^3	$-1.4317675 \times 10^{-12}$	19	7
5.4-68	MA_1	m	8.0×10^8		7
5.4-69	ϵ_9	-	2^{-20}		7
5.4-70	ϵ_{10}	m/s	0.01		7
5.4-73	V_c (SPS)	m/s	3151.0396	20	
	V_c (RCS)	m/s	2706.64	10	8
	m(RCS)	kg/s	0.16375	10	

<u>Page</u>	<u>Constant</u>	<u>Units</u>	<u>Value</u>	<u>Reference</u> <u>(Sec. 5.9.2)</u>	<u>Comments</u> <u>(Sec. 5.9.3)</u>
5.4-85	C_t	-	0.5		16
5.5-8	(Kepler) ϵ_t	-	2^{-22}	12	
	(Lambert) ϵ_t	-	2^{-19}	12	
	ϵ_x (moon)	$m^{1/2}$	2^{-13}	12	
	ϵ_x (earth)	$m^{1/2}$	2^{-12}	12	
	ϵ_c	-	2^{-23}	12	
5.5-11	k_1	-	2^{-2}	12	
5.5-16	B_0	rad	0.409164173	7,8	5
	Ω_{I0}	rad	-6.03249419	7,8	5
	F_0	rad	2.61379488	7,8	5
	\dot{B}	rad/sec	$-7.19756666 \times 10^{-14}$	7,8	5
	$\dot{\Omega}_I$	rad/sec	$-1.07047016 \times 10^{-8}$	7,8	5
	\dot{F}	rad/sec	$2.67240019 \times 10^{-6}$	7,8	5
5.5.17	C_I	-	0.99964115	7,8	5
	S_I	-	0.02678760	7,8	5
5.5-18	a	m	6,378,166	2,3,4	
	b	m	6,356,784	2,3,4	
5.5-22	r_{LP}	m	6,373,338	11	
5.6-8	T_{SS}	sec.	360		6
5.6-39	δt	sec.	1.3		
5.9-5	Star Table	sec.	See Fig. 9-1		17

Catalogue No. (total)	Star Name	Vis. Mag.	X Coordinate	Y Coordinate	Z Coordinate
1	α Andromedae (Alpheratz)	2.1	+ 8749183324	+ 0258916990	+ 4835778442
2	β Ceti (Diphda)	2.2	+ 9342726691	+ 1732973829	- 3116128956
3	γ Cassiopeiae (Navi)	2.2	+ 4776746280	+ 1164935557	+ 8707790771
4	α Eridani (Achernar)	0.6	+ 4917355618	+ 2203784481	- 8423950835
5	α Ursae Minoris (Polaris)	2.1	+ 0131955837	+ 0078043793	+ 9998824772
6	θ Eridani (Acamar)	3.4	+ 5450662811	+ 5313738486	- 6484940879
7	α Ceti (Menkar)	2.8	+ 7033883645	+ 7074274193	+ 0692188921
10	α Persei (Mirfak)	1.9	+ 4107492871	+ 4987190610	+ 7632590132
11	α Tauri (Aldebaran)	1.1	+ 3509587451	+ 8925545449	+ 2831507435
12	β Orionis (Rigel)	0.3	+ 2013426456	+ 9689888101	- 1432544058
13	α Aurigae (Capella)	0.2	+ 1373948084	+ 6813398852	+ 7189566241
14	α Carinae (Canopus)	-0.9	- 0614360769	+ 6031700106	- 7952430739
15	α Canis Majoris (Sirius)	-1.6	- 1818957154	+ 9405318128	- 2869039173
16	α Canis Minoris (Procyon)	0.5	- 4116502629	+ 9066387314	+ 0924676785
17	γ Velorum (Regor)	1.9	- 3611937602	+ 5748077840	- 7342581827
20	ζ Ursae Majoris (Dnoces)	3.1	- 4656165921	+ 4775804724	+ 7450624681
21	α Hydrae (Alphard)	2.2	- 7741360248	+ 6154234025	- 1482142053
22	α Leonis (Regulus)	1.3	- 8606970465	+ 4638127405	+ 2099484122
23	β Leonis (Denebola)	2.2	- 9656240240	+ 0528067543	+ 2545224762
24	γ Corvi (Gienah)	2.8	- 9525633510	- 0591313500	- 2985406935
25	α Crucis (Acrux)	1.0	- 4524416631	- 0492700670	- 8904319187
26	α Virginis (Spica)	1.2	- 9171065276	- 3500098785	- 1908106439
27	η Ursae Majoris (Alkaid)	1.9	- 5811943804	- 2907877154	+ 7600365758
30	θ Centauri (Menkent)	2.3	- 6899901699	- 4180817959	- 5908647707
31	α Bootis (Arcturus)	0.2	- 7862552143	- 5216265404	+ 3312227199
32	α Coronae Borealis (Alphecca)	2.3	- 5328042377	- 7159448596	+ 4511569595
33	α Scorpis (Antares)	1.2	- 3518772846	- 8239967165	- 4440853383
34	α Trianguli Austr. (Atria)	1.9	- 1147906312	- 3399437395	- 9334138229
35	α Ophiuchi (Rasalhague)	2.1	- 1126265542	- 9694679589	+ 2178236347
36	α Lyrae (Vega)	0.1	+ 1216171923	- 7703014754	+ 6259751556
37	σ Sagittarii (Nunki)	2.1	+ 2067145272	- 8720349419	- 4436486945
40	α Aquilae (Altair)	0.9	+ 4535361097	- 8780537171	+ 1527307006
41	β Capricorni (Dabih)	3.2	+ 5518160037	- 7934422090	- 2568045150
42	α Pavonis (Peacock)	2.1	+ 3200014224	- 4436740480	- 8371095679
43	α Cygni (Deneb)	1.3	+ 4540570017	- 5393383149	+ 7091871552
44	ε Pegasi (Enif)	2.5	+ 8138753897	- 5559063490	+ 1690413589
45	α Piscis Austr. (Fomalhaut)	1.3	+ 8341953207	- 2394362567	- 4967780649

Figure 9-1 Unit Vectors of the Navigational Stars

5.9.2 REFERENCES FOR FIXED CONSTANTS

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2. Natural Environment and Physical Standards for the Apollo Program, NASA M-DE-8020-008B, April, 1965.
3. Directory of Standard Geodetic and Geophysical Constants for Gemini and Apollo, NASA General Working Paper No. 10,020B, April 6, 1966.
4. Apollo Missions and Navigation Systems Characteristics, Apollo Navigation Working Group Technical Report No. AN-1.3, December 15, 1967.
5. Airborne Guidance and Navigation Equipment - Block II For Apollo Command Module, Part I, MEI No. 2015000, MIT, June 21, 1965, (C).
6. Command Module Guidance Computer Electrical Interfaces - Block II NAA-MIT, MHO1-01380-216, North American Aviation, Inc.
7. Inertial Orientation of the Moon, R. C. Hutchinson, MIT Instrumentation Laboratory, Report No. R-385, October, 1962.
8. Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac, 1961.
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10. Performance Data Supplement to Mission Modular Data Book-Block II Earth Orbital Mission, SID 66-1501 A, North American Aviation, Inc., Revised March 15, 1967.
11. NASA letter of direction to MIT 67-FS55-91-329.
12. The Fixed Memory Constants in the Conic Subroutines, W.M. Robertson, MIT SGA Memo No. 8-68, March 26, 1968.
13. NAR-MIT Interface Document, MHO1-01301-116 (Rev. B) Block II G & N Navigation Base and Optics Assembly to Command Module Structure.
14. Astronautical Guidance, Richard H. Battin, McGraw Hill Book Co., 1964.
15. The American Ephemeris and Nautical Almanac, Nautical Almanac Office, U.S. Naval Observatory, 1969.
16. Apollo Spacecraft Weight and Mission Performance Definition, Manned Spacecraft Center, NASA, December 12, 1967.
17. Apollo Mission Data Specification, TRW 2131-H005-R8-000, Thompson Ramo Wooldridge, June 9, 1966.
18. Fixed Memory Lunar Landmarks for COLOSSUS (Mission D) Ropes, 68-FS55-21, June 11, 1968.
19. NASA Letter of Direction to M. I. T. 68-FS55-19-172.
20. CSM/LM Spacecraft Operational Data Book, Volume I, CSM Data Book, NASA, SNA-8D-027, May, 1968.

5.9.3 COMMENTS ON FIXED CONSTANTS

1. The quantity ϵ_t is the limit used for the minimum time step in the Coasting Integration Routine. When the time step drops below ϵ_t , the routine is terminated.
2. The quantities r_{ME} and r_{MM} are the radii used by the Coasting Integration Routine to define a cislunar midcourse orbit inside of which the only gravitational force considered is that of the primary body. Outside these radii the gravitational attraction of the Earth, Moon, and Sun are all taken into account.
3. The quantity r_{SPH} is the radius of a sphere that approximates the surface of influence of the Moon as given in Fig. 1.3 of Reference 14.
4. The quantities r_{dE} and r_{dM} are the radii outside of which only the central force term of the gravitational attraction of the primary body is used.
5. The values given for the fixed constants used in the Planetary Inertial Orientation Subroutine (Section 5.5.2) are obtained by using Chapter 4 of Reference 7 and Sections 4C and 11D of Reference 8.
6. The quantity T_{SS} is a rough estimate of the time between the initiation of the Star Selection Routine in the IMU Realignment Program (P-52) or the Back-up IMU Realignment Program (P-54) and the midpoint of the optical sightings on the two celestial bodies.

7. The following comments are made with respect to the indicated quantities:

- ϵ_1 criterion used to determine whether the pre-return position and velocity vectors are nearly collinear ($\epsilon_1 = \cos 1.5^\circ$).
- ϵ_2 criterion used to determine whether the conic portion of Return to Earth has converged upon a suitable reentry radius.
- ϵ_3 criterion used to determine whether the conic portion of Return to Earth has converged upon a suitable reentry angle (although the test is made on the cotangent of the angle it is equivalent to $.058^\circ$).
- ϵ_4 criterion used to determine whether the precision portion of Return to Earth final state vector computation has reached the desired reentry angle (although the test is made on the cotangent of the angle it is equivalent to $.00058^\circ$).
- ϵ_6 criterion used to determine whether the final state vector computation has already reached the best possible reentry angle.
- ϵ_7 criterion used to determine whether the precision portion of Return to Earth has converged upon the reentry radius selected in the conic portion.
- ϵ_8 criterion used to make a final check on the reentry angle reached by the precision portion of Return to Earth (although the test is made on the cotangent of the angle it is equivalent to $.116^\circ$).

- ϵ_9 criterion used to determine whether the $x(t_1) - \Delta v$ iterator has reached a minimum value.
- ϵ_{10} criterion used to determine whether the $x(t_1) - \Delta v$ iterator has reached the desired Δv .
- C_0, C_1, C_2, C_3 polynomial coefficients used to determine the maximum allowable major axis of return trajectories with a positive radial component based on the radius magnitude.
- MA_1 Maximum allowable major axis of return trajectories with a negative radial component
- k_1 radius used to determine which estimate of reentry angle should be used.
- k_2 initial estimate of reentry radius.
- k_3 initial estimate of the cotangent of the reentry angle used when the initial radius is less than k_1 (equivalent to $-3^\circ 29.5'$).
- k_4 initial estimate of the cotangent of the reentry angle used when the initial radius is greater than k_1 (equivalent to $-5^\circ 58'$).
- k_5 radius below which $-\Delta v$ option not available
- D_1, D_2, D_3, D_4 polynomial coefficients used to determine the cotangent of the reentry angle based on reentry velocity magnitude
- E_3 entry altitude above the Fischer Ellipsoid (equivalent to 400,000 ft).

The RCS exhaust velocity was computed by using the nominal specific impulse of the reference document and an acceleration of gravity of $32.174048 \text{ ft/sec}^2$.

10. The quantity F_L is ullage thrust using two RCS jets where consideration has been made for the 10° offset of these jets.
11. The quantity t_{KS} is the elapsed time from lift-off to when the attitude error display is disabled.
12. These landmarks do not fit the mapping pattern assumed and required by the Lunar Landmark Selection Routine, Section 5.6.9
15. The quantity var_L is a rough estimate of the landmark or horizon error variance during cislunar midcourse navigation.

16. The constant C_t when multiplied with the estimated length of the burn gives the adjustment made to compute the actual ignition time from the impulsive maneuver time. The presently adopted value is 0.5.
17. The direction of each of the 37 navigation stars in Fig. 9-1 is expressed as the components of a unit vector in the Basic Reference Coordinate System. These star directions are the mean places of the stars at the beginning of the Besselian year 1969. The term "mean place" is defined in Reference 8. The star directions are computed by MIT using essentially the same technique employed by the Nautical Almanac Office. Although there are slight differences between the directions of some of the stars in Fig. 9-1 and those given in the American Ephemeris and Nautical Almanac for 1969 (Reference 15), they are considered negligible in comparison to the other errors associated with a star sighting.
18. The precise value of thrust is not available. This value is a good working number.

R-577 COLOSSUS 2
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Section 5

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