5.6 GENERAL SERVICE ROUTINES

5.6.1 GENERAL COMMENTS

The routines presented in this section are used for 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

5.6.2 IMU ALIGNMENT MODES

5.6.2.1 Orbital Alignment

5.6.2.1.1 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 Alignment Optical Telescope (AOT) or the Crew Optical Alignment Sight (COAS). At the start of program P-51 the astronaut acquires the desired celestial bodies by maneuvering the spacecraft until they are visible in the optical device which he intends to use. During the above operation he checks to insure that gimbal lock does not occur. Afterwards, the Inflight Sighting Mark Routine (R-53) is used twice to sight upon each of two celestial bodies. Prior to sighting on each body, the astronaut indicates to the computer which optical device he is going to use and which celestial body he is going to sight on. The method of selection and operation of the AOT and COAS is given in Section 5.6.3.1.1 and in the Inflight Sighting Mark Routine (R-53) of Section 4. The identity of the celestial body is indicated by the astronaut at the beginning of the Inflight Sighting Mark Routine by use of a star (or 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. If the astronaut selects the Sun, Earth, or Moon code, the subroutine LOSSEM of Section 5.5.13 will be called after optical sightings have been made on the body to compute the line-of-sight vector to that body in the Basic Reference Coordinate System. If he selects the Planet code, the computer will request after the optical sightings that he load in the coordinates of the desired celestial body in the Basic Reference Coordinate System.

After optical sightings have been made on both 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 $\underline{u}'_{CBA}$ and $\underline{u}'_{CBB}$ be the unit vectors in IMU stable member coordinates for the two celestial bodies (A and B) which are computed as shown in Section 5.6.3.1.1, and let $\underline{u}_{CBA}$ and $\underline{u}_{CBB}$ be the unit vectors for the same bodies in basic reference coordinates which are either taken from the computer's star catalog in fixed memory, computed by the subroutine LOSSEM, or loaded by the astronaut. At this point in the program the Sighting Data Display Routine (R-54 of Section 4) computes the angle ϕ' between the unit line-of-sight vectors ($\underline{u}'_{CBA}$ and $\underline{u}'_{CBB}$) obtained for the two bodies in stable member coordinates and the angle ϕ between the corresponding unit line-of-sight vectors ($\underline{u}_{CBA}$ and $\underline{u}_{CBB}$) for the two bodies in basic reference coordinates. The angular difference $\phi' - \phi$ 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 $\underline{u}'_{CBA}$, $\underline{u}'_{CBB}$, $\underline{u}_{CBA}$, and $\underline{u}_{CBB}$ are used to determine the present stable member orientation and REFSMMAT, using the procedure given in Section 5.6.3.4.1.

5.6.2.1.2 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 5.6.3.4 and in P-52 of Section 4. This alignment is made by sighting on two navigation stars or known celestial bodies with the AOT or the COAS.

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 5.6.3.4. If the astronaut selects the Landing Site or Nominal orientation, it is computed by program P-52 in the manner shown in Section 5.6.3.4 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:

$$\underline{x}_{NB} = [\text{ REFSMMAT}]^T \, \underline{x}'_{NB}$$

$$\underline{y}_{NB} = [\text{ REFSMMAT}]^T \, \underline{y}'_{NB}$$

$$\underline{z}_{NB} = [\text{ REFSMMAT}]^T \, \underline{z}'_{NB}$$

where $[REFSMMAT]^T$ is the transpose of the present [REFSMMAT] and $\underline{x}'_{NB}$, $\underline{y}'_{NB}$, and $\underline{z}'_{NB}$ 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 gimbal angles 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 IMU gyro 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:

$$\underline{x}_D = [REFSMMAT]\ \underline{u}_{XSM}$$

$$\underline{y}_D = [REFSMMAT]\ \underline{u}_{YSM}$$

$$\underline{z}_D = [REFSMMAT]\ \underline{u}_{ZSM}$$

where $\underline{u}_{XSM}$, $\underline{u}_{YSM}$, and $\underline{u}_{ZSM}$ 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.

At this point in program P-52 the Fine Alignment Routine (R-51 of Section 4) is used to perform the necessary optical sightings for fine alignment. This routine performs the alignment by using various other routines. Initially, the astronaut decides whether or not to use the Star Selection Routine of Section 5.6.4. If he selects the Star Selection Routine, Routine R-51 will call the subroutine LOSSEM of Section 5.5.13 prior to calling the Star Selection Routine since LOSSEM computes certain parameters which are used in the occultation tests of the Star Selection Routine. 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 selects his own celestial bodies. It should be noted that the Star Selection Routine only selects stars for the forward viewing position of the AOT. However, the astronaut may select stars or celestial bodies with the intention of using one of the other viewing positions described in Section 5.6.3.1.1.

Prior to performing the optical sightings on each celestial body, the astronaut is given the option of either maneuvering the vehicle himself to place the celestial body at the desired sighting position or having the Auto Optics Positioning Routine (R-52 of Section 4) command the vehicle attitude so as to place the celestial body at the desired sighting position. The sighting position is established by the astronaut at the beginning of the Auto Optics Positioning Routine in the same manner as is done at the start of the Inflight Sighting Mark Routine. By selecting the appropriate detent code as described in Section 5.6.3.1.1 and in routines R-52 and R-53 of Section 4, the sighting position can be the center of the field-of-view of the COAS or any of the six fields-of-view of the AOT. In addition to establishing the sighting position, the astronaut can also specify the celestial body (star, etc.) which is to be used in the Auto Optics Positioning Routine just as is described for the Inflight Sighting Mark Routine in Section 5.6.2.1.1. If he selects the Sun, Earth or Moon Code, the subroutine LOSSEM is called prior to positioning the spacecraft to compute the line-of-sight vector to that body. If he selects the Planet code, the computer will request that he load in the coordinates of the desired celestial body just before positioning the spacecraft. Once the celestial body is properly positioned in the field-of-view, the Inflight Sighting Mark Routine is used to perform the sightings on the body.

After sightings have been made on 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 $\underline{u}_{CBA}$ and $\underline{u}_{CBB}$ be the two unit vectors in IMU stable member coordinates for the two celestial bodies (A and B) which are computed as shown in Section 5.6.3.1.1, and let $\underline{u}''_{CBA}$ and $\underline{u}''_{CBB}$ be the unit vectors for the same bodies in basic reference coordinates which are either taken from the computer's star catalog in fixed memory, computed by the subroutine LOSSEM, or loaded by the astronaut. The vectors $\underline{u}''_{CBA}$ and $\underline{u}''_{CBB}$ are next transformed to the desired IMU Stable Member Coordinate System as follows:

$$\underline{u}'_{CBA} = [\text{REFSMMAT}]_D \; \underline{u}''_{CBA}$$

$$\underline{u}'_{CBB} = [\text{REFSMMAT}]_D \; \underline{u}''_{CBB}$$

where $[\text{REFSMMAT}]_D$ is the matrix (Section 5.6.3.4) for transforming vectors from the Basic Reference Coordinate System to the desired IMU Stable Member Coordinate System. At this point in the program the Sighting Data Display Routine (R-54) of Section 4) computes the angle ϕ between $\underline{u}_{CBA}$ and $\underline{u}_{CBB}$, and the angle ϕ' between $\underline{u}'_{CBA}$ and $\underline{u}'_{CBB}$ and displays the angular difference $\phi' - \phi$ 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

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☐ Added GSOP # 567 PCR # 972 Rev. 7 Date 11/69

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 LGC 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 LGC. 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 PGNCS. 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.

5.6.2.2 Lunar Surface Alignment

5.6.2.2.1 General

There are several methods or techniques of IMU alignment available to the astronaut in the Lunar Surface Alignment Program (P-57). These techniques are denoted as Alignment Techniques 0 through 3.

In order to align the IMU stable member to a desired orientation with respect to the Basic Reference Coordinate System with any of the four techniques, it is necessary to determine two separate line-of-sight (LOS) directions with respect to both the Basic Reference Coordinate System and the present IMU Stable Member Coordinate System. It should be noted that the present orientation of the IMU Stable Member Coordinate System with respect to the Basic Reference Coordinate System does not have to be known in order to perform the alignment. The two directions in both of the above coordinate systems are specified by four unit LOS vectors where $\underline{s}_A$ and $\underline{s}_B$ denote the unit vectors for the directions A and B in present stable member coordinates, and $\underline{s}'_A$ and $\underline{s}'_B$ are the unit vectors for the corresponding directions in basic reference coordinates. For example, if A and B are two navigation stars and the alignment is made with technique 2 of P-57, the unit vectors $\underline{s}_A$ and $\underline{s}_B$ in present stable-member coordinates would be those obtained by optical sightings with the AOT, and $\underline{s}'_A$ and $\underline{s}'_B$ would be the unit vectors for A and B in basic reference coordinates which are obtained from the computer's star catalog.

If one of the other techniques (0, 1, or 3) is used, at least one of the directions A and B is not that of a star (or celestial body) and is determined by other means.

The sources of the four unit LOS vectors (or IMU alignment vectors) for each technique in program P-57 are given in Fig. 6.2-1. If Technique 0 is used, $\underline{s}_A$ and $\underline{s}_B$ represent the present directions of the LM Y and Z axes with respect to the IMU stable member and $\underline{s}'_A$ and $\underline{s}'_B$ represent the directions of these axes in basic reference coordinates as determined from stored information of their directions in the Moon-Fixed Coordinate System (MFCS) which were computed from the previous alignment of the IMU.

Technique 1 in Fig. 6.2-1 differs from Technique 0 in that vector $\underline{s}_A$ represents the direction of lunar gravity as determined by the Gravity Vector Determination Routine and $\underline{s}'_A$ is the direction of the landing site position vector in basic reference coordinates based upon its stored vector in moon-fixed coordinates. It is assumed that the gravity and landing site position vectors represent the same direction in space.

Technique 3 in Fig. 6.2-1 uses the gravity vector approach of Technique 1 in conjunction with one celestial body sighting with the AOT to obtain the four IMU alignment vectors. Additional information on the manner in which these vectors are computed for each technique is given later.

Alignment Technique	Sources of IMU Alignment Vectors			
	Basic Reference Coordinate System		Present IMU Stable Member Coordinate System	
	$\underline{s}'_A$	$\underline{s}'_B$	$\underline{s}_A$	$\underline{s}_B$
0	LM Y-axis stored in MFCS	LM Z-axis stored in MFCS	Present LM Y-axis	Present LM Z-axis
1	Landing Site stored in MFCS	LM Z-axis stored in MFCS	Gravity Vector Determination Routine	Present LM Z-axis
2	One or more of the following: 1. LGC star catalog 2. Loaded by astronaut 3. Ephemeris (i.e., SUN, EARTH)		AOT Sighting	AOT Sighting
3	Landing Site stored in MFCS	Same as Technique 2 above	Gravity Vector Determination Routine	AOT Sighting

Fig. 6.2-1 Sources of IMU Alignment Vectors in Program P-57

Whenever the IMU is aligned by Techniques 1, 2, or 3, one of the last functions performed by P-57 before termination is to determine and store the orientations of the LM Y and Z axes with respect to the Moon-Fixed Coordinate System. These orientations are indicated as unit vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$ and completely specify the attitude of the LM (or the navigation base) with respect to the Moon Fixed Coordinate System. This procedure is generally referred to as storing the LM attitude. The LM attitude is stored primarily for backup purposes so that the IMU can be aligned at a later time using just the stored LM attitude data in case the IMU orientation is not known and there is insufficient time to perform an alignment by other means, such as in emergency launch. In addition to storing the LM attitude after each alignment with Techniques 1, 2, or 3, the LM attitude is also stored by the Landing Confirmation Program (P-68) after the vehicle has come to rest on the lunar surface. Whenever the LM attitude is stored, the Attitude flag is set to denote this fact. It should be noted that the vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$ will always represent the correct orientations of the LM Y and Z axes with respect to the Moon-Fixed Coordinate System as long as there is no change in the vehicle attitude since the time when the vectors were computed.

To determine the vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$, the LGC first computes the unit vectors $\underline{u}_{YREF}$ and $\underline{u}_{ZREF}$ defining the directions of the LM (or navigation base) Y and Z axes with respect to the Basic Reference Coordinate System as follows:

$$\underline{u}_{YREF} = [\ REFSMMAT\ ]^T \underline{y}_{NB}$$

$$\underline{u}_{ZREF} = [\ REFSMMAT\ ]^T \underline{z}_{NB} \qquad (6.2.1)$$

where $[\ REFSMMAT\ ]^T$ is the transpose of $[\ REFSMMAT\ ]$ defined in Section 5.6.3.4 and $\underline{y}_{NB}$ and $\underline{z}_{NB}$ define the directions of the navigation base Y and Z axes with respect to the present IMU Stable Member Coordinate System and are computed by the routine CALCSMSC of Section 5.6.3.2.5. The vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$ are obtained by transforming $\underline{u}_{YREF}$ and $\underline{u}_{ZREF}$, respectively, to the Moon-Fixed Coordinate System using the Planetary Inertial Orientation Subroutine of Section 5.5.2 where the time specified to this subroutine is the present time. It should be noted that it is not necessary to record the time of storage of these vectors. Whenever it is desired to use the stored vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$ to obtain the orientations of the LM Y and Z axes with respect to the Basic Reference Coordinate System for a given time, it is only necessary to transform the stored vectors to the Basic Reference Coordinate System using the Planetary Inertial Orientation Subroutine with the desired time as one of the inputs.

The logic associated with the Lunar Surface Alignment Program (P-57) is shown in Fig. 6.2-2. At the beginning of program P-57 the astronaut indicates the desired IMU stable member orientation just as is done for the IMU Realignment Program (P-52 of Section 5.6.2.1.2) except that the Nominal orientation is not used in P-57. If the Landing Site Orientation Option is selected, a time t_L must be specified by the astronaut which defines the desired IMU orientation in the manner shown in Section 5.6.3.4.4. In Fig. 6.2-2 it is seen that the initial value of t_L displayed to the astronaut is equal to the time of ignition t_{IG} for powered ascent. This value of t_L may be changed by the astronaut if he so desires. However, note that the following steps are taken in the program when the following values are loaded for t_L:

1)	$t_L = 0$	The program will set t_L equal to the present time.
2)	$t_L >$ Present Time	The program will set t_{IG} equal to t_L. This feature permits the astronaut to load a new value for t_{IG} in P-57 without having to use P-12 prior to P-57 for this purpose. It should be noted that this value of t_{IG} will be that displayed to the astronaut at the start of P-12.

After the desired IMU orientation has been selected, the astronaut indicates which of the four previously mentioned techniques he wishes to use to align the IMU. In addition, the status of the REFSMFLAG, and Attitude flags are displayed in a data code. This is followed by a check on the status of REFSMFLAG and possibly the Attitude Flag as shown in Fig. 6.2-2 to see if any previous IMU alignment information is available. The REFSMFLAG is a flag which is set whenever the computer knows the present orientation of the IMU stable member with respect to the Basic Reference Coordinate System, which also implies that the computer has the correct matrix REFSMMAT for transforming vectors from the Basic Reference Coordinate System to the present IMU Stable Member Coordinate System. Since REFSMFLAG is set only if the IMU is on and at a known orientation, its presence at the start of an alignment program generally implies that the IMU has previously been aligned and has remained in this condition except for IMU drift until

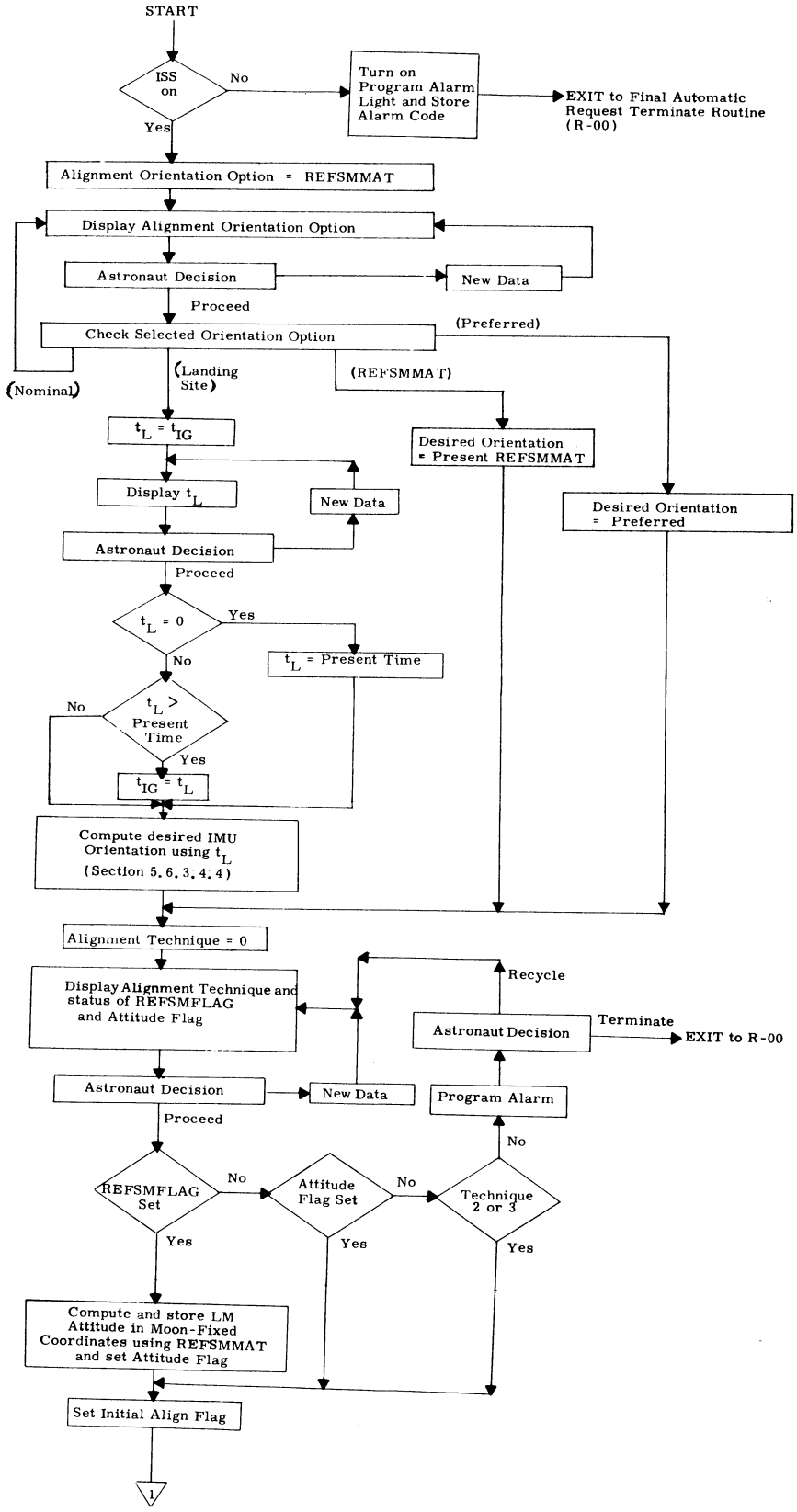


Figure 6.2-2 Lunar Surface Alignment Program

(page 1 of 3)

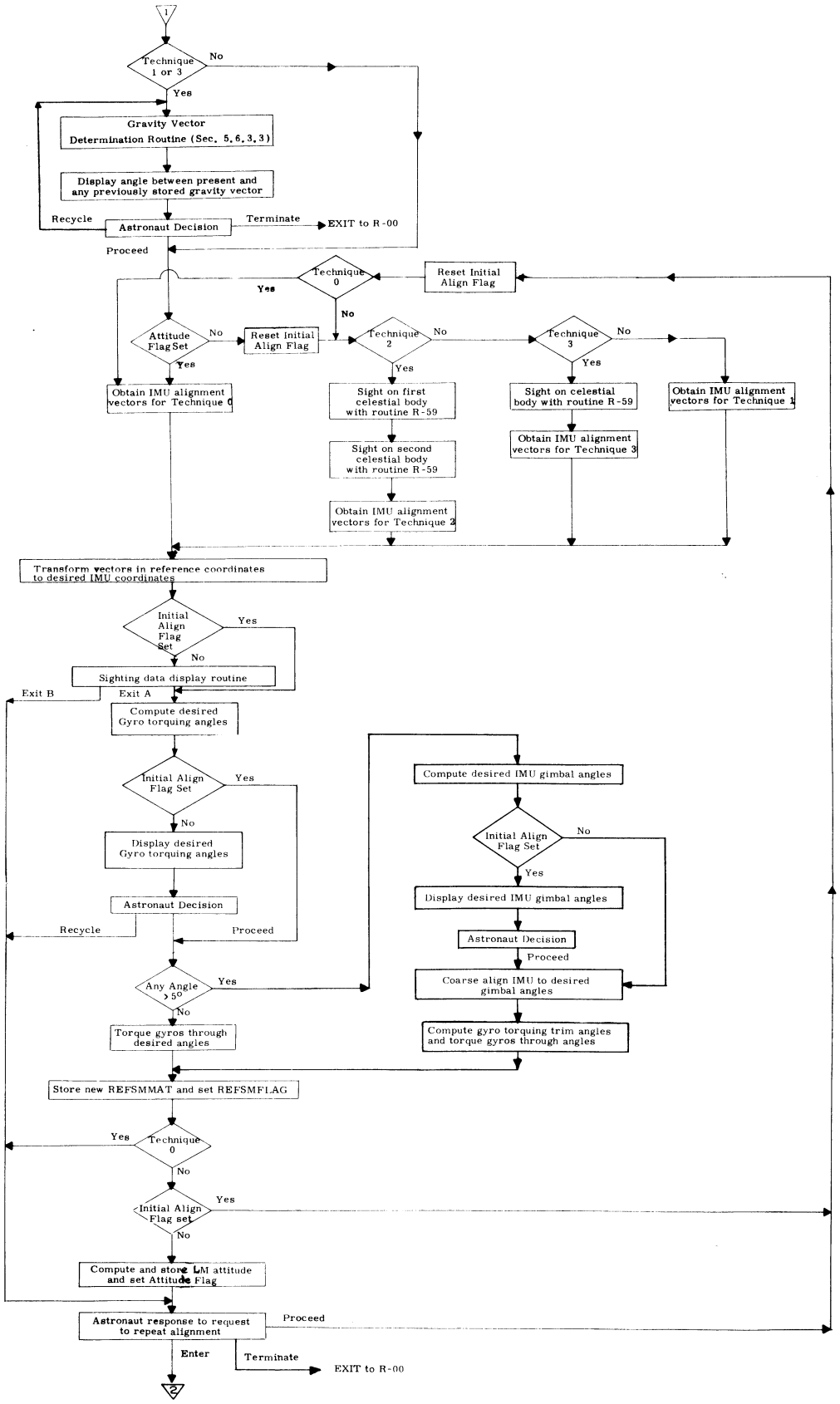


Figure 6.2-2 Lunar Surface Alignment Program (Page 2 of 3)

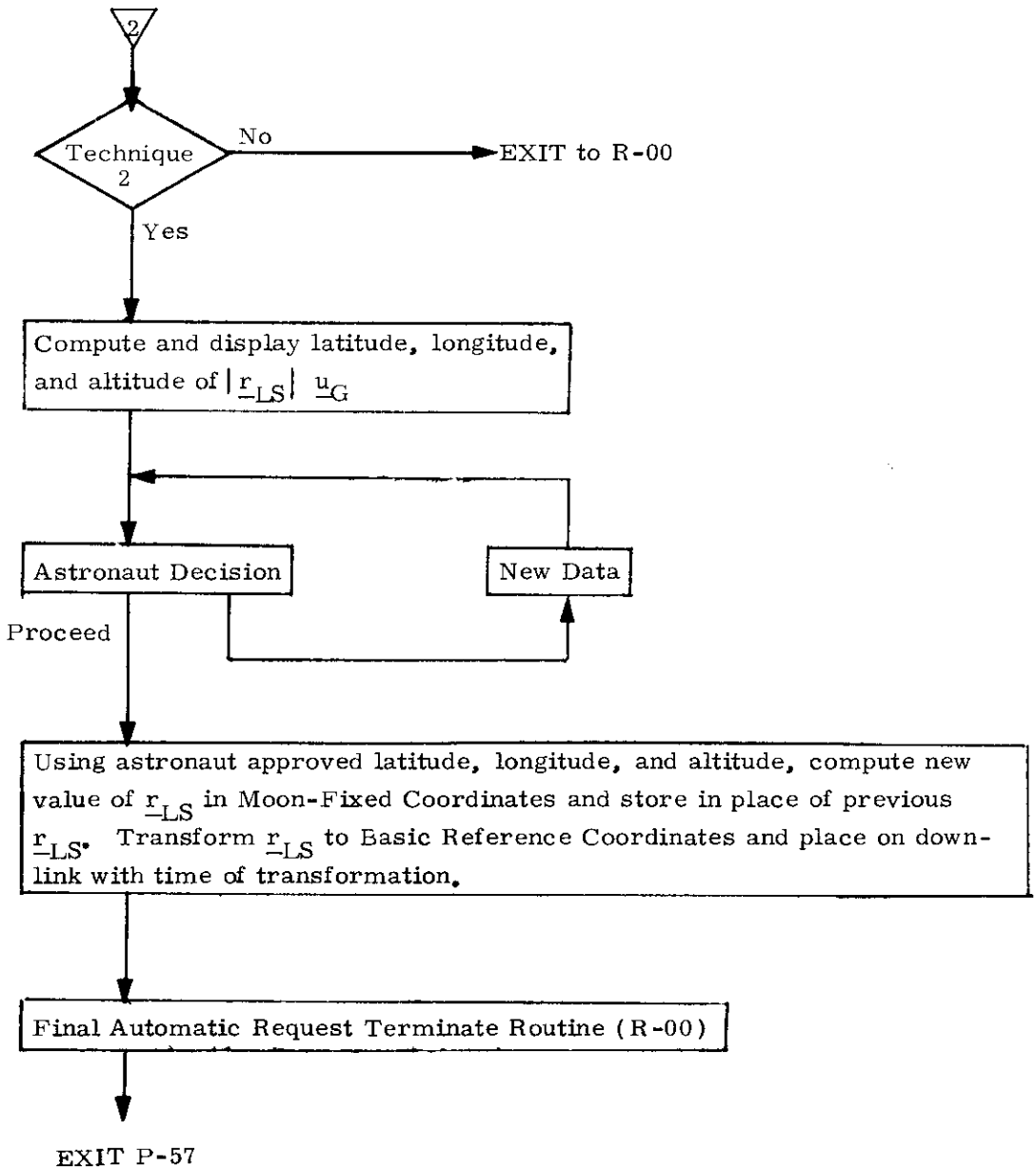


Figure 6.2-2 Lunar Surface Alignment Program (Page 3 of 3)

the present alignment process. However, it is possible that the correct REFSMMAT could have been determined on earth in one of the backup situations described later and entered into the LGC without a previous alignment having been made with P-57. If the REFSMFLAG is set, the program will compute and store new LM attitude vectors based upon the present alignment of the IMU. The new attitude vectors replace any previously-stored attitude vectors and are used in the initial IMU alignment described later. It should be noted that the new LM attitude vectors and the subsequent alignment with these vectors will have the same error as present between the REFSMMAT and the IMU orientation when entering the program. If the REFSMFLAG is not set and the Attitude flag is set, the program will use the attitude vectors computed and stored in the previous use of P-57 or P-68. If the REFSMFLAG and Attitude flags are not set and Technique 0 or 1 is selected, it is seen in Fig. 6.2-2 that a program alarm is issued since these techniques require the use of stored LM attitude data.

The details associated with the alignment procedure for each technique in the remaining portion of Fig. 6.2-2 are presented in the following sections. One important feature which should be noted in Techniques 1, 2, and 3 is that an initial alignment is made to the desired IMU orientation prior to the final alignment if the Attitude flag is set. The initial alignment is made with the LM attitude data just as in Technique 0 and the final alignment is made using the regular alignment vectors for Techniques 1, 2, or 3. Since the initial alignment can be as good as the final alignment the gyro torquing angles displayed to the astronaut in the final alignment process should be near zero if an initial alignment was made. In this case, the gyro torquing angles are a direct indication of the difference between the alignment obtained with the LM attitude data and the final alignment obtained with Techniques 1, 2, or 3. If these angles are not near zero (i.e. within acceptable tolerances, such as the desired IMU alignment accuracy) this either indicates that the final alignment may not be acceptable because of bad star sightings, etc. and/or the LM attitude data is in error because of errors in the previous

alignment used to compute the LM attitude data and/ or errors due to settling of the spacecraft since the time when the LM attitude data was computed. In Fig. 6.2-2 it is seen that the astronaut can repeat the final alignment if he so desires. It should be noted that the astronaut can determine changes in the LM attitude with respect to the local gravity vector by using the Gravity Vector Determination Routine in Techniques 1 and 3.

5.6.2.2.2 Technique 0 - IMU Alignment Using the LM Attitude Data

Technique 0 is selected by the astronaut if he wants the IMU to be driven to the desired orientation using the stored LM attitude data or the present REFSMMAT. Note in Fig. 6.2-2 that if REFSMFLAG is set, the program will use the present REFSMMAT to compute a new set of LM attitude data for use in this technique. This technique provides a quick means of alignment for emergency launch in case there is insufficient time to perform the alignment by other means. If neither the Attitude flag or the REFSMFLAG is set at the beginning of this technique, it is seen in Fig. 6.2-2 that a program alarm is issued.

To obtain the four IMU alignment vectors ($\underline{s}_A$, $\underline{s}_B$, $\underline{s}'_A$, $\underline{s}'_B$) indicated in Fig. 6.2-1 for Technique 0, the following is done. The stored LM attitude vectors $\underline{u}_{YMF}$ and $\underline{u}_{ZMF}$ are transformed from moon-fixed to basic reference coordinates using the Planetary Inertial Orientation Subroutine with the present time being specified to this subroutine, and are denoted as $\underline{s}'_A$ and $\underline{s}'_B$, respectively. The unit vectors $\underline{y}_{NB}$ and $\underline{z}_{NB}$ defining the orientations of the LM Y and Z axes with respect to the present IMU Stable Member Coordinate System are computed by the routine CALCSMSC of Section 5.6.3.2.5 and are denoted as $\underline{s}_A$ and $\underline{s}_B$, respectively.

After the four IMU alignment vectors ($\underline{s}_A$, $\underline{s}_B$, $\underline{s}'_A$, and $\underline{s}'_B$) have been collected for Technique 0, it is seen in Fig. 6.2-2 that the same procedure is used to align the IMU with these vectors as is done with the alignment vectors for any other technique. The vectors $\underline{s}'_A$ and $\underline{s}'_B$ are transformed to the desired IMU Stable Member Coordinate System as follows:

$$\begin{aligned} \underline{s}''_A &= [\text{ REFSMMAT }]_D \, \underline{s}'_A \\ \underline{s}''_B &= [\text{ REFSMMAT }]_D \, \underline{s}'_B \end{aligned} \qquad (6.2.2)$$

where $[\text{REFSMMAT}]_D$ denotes the desired REFSMMAT. If the Initial Align flag is set, as is the case for the first pass through Technique 0, the Sighting Data Display Routine (R-54 of Section 4) and the display of gyro torquing angles are by-passed as shown in Fig. 6.2.2. However, the program does compute the gyro torquing angles required to drive the IMU stable member from the present to the desired orientation. These angles are computed by the routine CALCGTA of Section 5.6.3.2.3 using the unit vectors $\underline{x}$, $\underline{y}$, and $\underline{z}$ defining the orientations of the desired stable member axes with respect to the present Stable Member Coordinate System, which are computed by the routine AXISGEN of Section 5.6.3.2.4 using the previously computed vectors $\underline{s}_A$, $\underline{s}_B$, $\underline{s}''_A$, and $\underline{s}''_B$. Afterwards, a magnitude check is made on each angle as shown in Fig. 6.2-2 to determine whether the IMU should be aligned by torquing the gyros through the above angles or should first be coarse aligned to the desired IMU gimbal angles and then trimmed to the desired orientation by torquing the gyros.

The desired gimbal angles used in the coarse alignment are computed by the routine CALCGA of Section 5.6.3.2.2 where the inputs to this routine are the unit vectors $\underline{x}$, $\underline{y}$, and $\underline{z}$ previously

computed by the routine AXISGEN, and the unit vectors $\underline{x}_{NB}$, $\underline{y}_{NB}$, and $\underline{z}_{NB}$ defining the orientations of the navigation base axes with respect to the present Stable Member Coordinate System, which are computed by the routine CALCSMSC of Section 5.6.3.2.5. The desired gimbal angles are displayed to the astronaut so that he can approve the resulting IMU orientation before coarse aligning to it during the initial alignment (or first pass) in P-57.

The gyro torquing trim angles are computed as follows: The unit vectors $\underline{x}_{NB}$ and $\underline{y}_{NB}$ defining the orientations of the navigation base X and Y axes with respect to the present IMU Stable Member Coordinate System are computed by the routine CALCSMSC of Section 5.6.3.2.5. The unit vectors $\underline{x}'_{NB}$ and $\underline{y}'_{NB}$ defining the orientations of the same two axes with respect to the desired IMU Stable Member Coordinate System are computed as follows:

$$\underline{x}'_{NB} = [\,NBSM\,]_D \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$\underline{y}'_{NB} = [\,NBSM\,]_D \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \qquad (6.2.3)$$

where $[NBSM]_D$ is the matrix for transforming vectors from navigation base to desired stable member coordinates using the desired IMU gimbal angles computed previously for coarse alignment. Once the vectors $\underline{x}_{NB}$, $\underline{y}_{NB}$, $\underline{x}'_{NB}$, and $\underline{y}'_{NB}$ have been computed, they are used in the routine AXISGEN of Section 5.6.3.2.4 to compute the vectors $\underline{x}$, $\underline{y}$, and $\underline{z}$ defining the orientations of the desired stable member axes with respect to the present IMU Stable Member Coordinate System, which are used by the routine CALCGTA to compute the gyro torquing trim angles.

After the IMU has been aligned to the desired orientation with Technique 0, it is seen at the bottom of Fig. 6.2-2 that the program stores the new REFSMMAT and sets REFSMFLAG before requesting the astronaut to repeat the alignment with Technique 0 if he so desires. If he keys in "PROCEED", it is seen in Fig. 6.2-2 that the same

alignment will be made with Technique 0 except that the Initial Align flag will not be set, thereby causing the Sighting Data Display Routine and the display of gyro torquing angles to not be by-passed. The purpose of the Sighting Data Display Routine is to compute and display the angular difference $\phi' - \phi$ where ϕ' is the angle between $\underline{s}_A''$ and $\underline{s}_B''$ and ϕ is the angle between $\underline{s}_A$ and $\underline{s}_B$.

5.6.2.2.3 Technique 2-IMU Alignment Using Two Celestial Bodies

Technique 2 is selected by the astronaut whenever a complete alignment or realignment is to be made by sighting on two celestial bodies (usually stars) with the Alignment Optical Telescope (AOT). No program alarm is issued when selecting this technique if the Attitude flag or REFSMFLAG is not set. However, if either of these flags is set, it is seen in Fig. 6.2-2 that the IMU is initially aligned with the LM attitude data just as in Technique 0. If neither of these flags is set, the IMU remains at its present orientation and sightings are made on two celestial bodies with the Lunar Surface Sighting Mark Routine (R-59) which is described in Sections 4 and 5.6.3.1.2.

It should be noted that the astronaut can select the same celestial body codes at the beginning of routine R-59 which are described for the Inflight Sighting Mark Routine (R-53) in Section 5.6.2.1.1. The same methods are used in routine R-59 to obtain a line-of-sight vector to the Sun, Earth, Moon, or a Planet in basic reference coordinates, although the Moon would not be used in this case. If the astronaut selects one of the 37 navigation stars stored in the computer's catalog, the Lunar Surface Star Acquisition Subroutine of Section 5.6.3.1.3 will check to see if the star is within the field-of-view of the AOT for any of its six viewing positions and, if successful, will compute the reticle rotation angles needed to acquire the star. The AOT viewing position and the reticle rotation angles are displayed to the astronaut to aid him in acquiring the star.

The four IMU alignment vectors used by Technique 2 to perform the final IMU alignment are obtained as a direct result of using routine R-59 twice to sight on two celestial bodies, where $\underline{s}_A$ and $\underline{s}_B$ are the measured directions of the two bodies in the present IMU Stable Member Coordinate System and $\underline{s}_A'$ and $\underline{s}_B'$ are the directions of the celestial bodies in basic reference

coordinates, which are either obtained from the computer's star catalog, loaded by the astronaut, or computed from ephemeris data such as for the Sun or Earth.

Once the alignment vectors have been obtained for Technique 2, it is seen in Fig. 6.2-2 that the remaining steps in the alignment process are the same as described for Technique 0 in Section 5.6.2.2.2 except that Technique 2 also computes and stores the LM attitude in moon fixed coordinates and sets the Attitude Flag. The astronaut can repeat the final alignment if he so desires. At the bottom of page 2 of Fig. 6.2-2, it is seen that the astronaut can repeat the final alignment by keying in a "PROCEED". If he wishes to establish a new landing site position vector as described in Section 5.6.2.2.6, he must key in an "ENTER" after the final alignment with Technique 2.

5.6.2.2.4 Technique 3-IMU Alignment Using the Gravity Vector and One Celestial Body

Technique 3 is selected when the complete alignment is to be made by determining the lunar gravity vector with the IMU accelerometers and sighting on one celestial body with the AOT. As will be discussed later, this technique may be selected by the astronaut if he is only interested in determining the direction of the gravity vector. No program alarm is issued by program P-57 when selecting this technique if the Attitude flag or REFSMFLAG is not set.

In Fig. 6.2-2 it is seen that Technique 3 initially uses the Gravity Vector Determination Routine of Section 5.6.3.3 to obtain a unit vector $\underline{u}_G$ defining the direction of lunar gravity in navigation base coordinates. The angle between this vector and any previously stored gravity vector is displayed to the astronaut so that he may judge whether there has been any tilt of the vehicle since the previous gravity vector was stored. If no previous gravity vector was stored, the angle between the present vector $\underline{u}_G$ and the LM + X-axis is displayed. At this point the astronaut may terminate P-57 if he is only interested in obtaining the gravity vector. However, if he is interested in making a complete IMU alignment with Technique 3, he keys in a "PROCEED".

If the Attitude flag is set, it is seen in Fig. 6.2-2 that the IMU is initially aligned to the desired orientation with the LM attitude data before the celestial body sighting is made for the final alignment.

After the optical sighting has been made with the Lunar Surface Sighting Mark Routine (R-59), the computer collects the four IMU alignment vectors ($\underline{s}_A$, $\underline{s}_B$, $\underline{s}'_A$, and $\underline{s}'_B$) used by Technique 3 to perform the final alignment where $\underline{s}_B$ and $\underline{s}'_B$ were previously obtained with routine R-59 and $\underline{s}_A$ and $\underline{s}'_A$ are computed as follows:

$$\begin{aligned} \underline{s}_A &= \left[\mathrm{NBSM}\right] \underline{u}_G \\ \underline{s}'_A &= \mathrm{UNIT}\left[\underline{r}_{LS}\right] \end{aligned} \qquad (6.2.4)$$

where $\underline{u}_G$ is the gravity vector stored in navigation base coordinates and $\underline{r}_{LS}$ is the landing site position vector in basic reference coordinates at the present time, which is obtained from moon-fixed coordinates with the Planetary Inertial Orientation Subroutine of Subsection 5.5.2.

Once the alignment vectors have been obtained for Technique 3, it is seen in Fig. 6.2-2 that the remaining steps in the alignment process are the same as described for Technique 0 in Section 5.6.2.2.2 except that Technique 3 also computes and stores the LM attitude in moon fixed coordinates, and sets the Attitude Flag. The astronaut can repeat the final alignment if he so desires.

It should be noted in Technique 3 that Routine R-54 will display the angular difference $\phi' - \phi$ where ϕ' is the angle between the landing site position vector $\underline{r}_{LS}$ and the catalogued star vector in desired stable member coordinates, and ϕ is the angle between the gravity vector $\underline{u}_G$ and the measured star vector in present stable member coordinates. This angular difference (except for errors in the star sighting) represents that component of the angular difference between $\underline{r}_{LS}$ and $\underline{u}_G$ in the plane defined by $\underline{r}_{LS}$ and the star vector. Repeating this process on a second star in a different direction produces another component of the angular difference, thereby enabling one to obtain an estimate of the latitude and longitude of the gravity vector which is assumed to be the true site. Further improvement in the estimate can be obtained by performing extra sightings on the same and/or other stars. A convenient way of repeating star sightings is to use Exit B of the Sighting Data Display Routine and key in a PROCEED response to the request to repeat alignment (see Fig. 6.2-2).

☐ Revised LUMINARY
☐ Added GSOP # 567 PCR # 972 Rev. 7 Date 11/69

If the astronaut terminates Technique 3 after having determined only the gravity vector with the Gravity Vector Determination Routine, this may have been done in order to implement another technique of aligning the IMU which involves having the rendezvous radar (RR) track the CSM and transmitting the RR and IMU CDU angles to earth via down-link. In addition, the stored gravity vector in vehicle (or navigation base) coordinates is transmitted to the earth. It should be noted that the gravity vector could be transmitted by voice-link instead of down-link in such an improbable situation since the direction of gravity remains fixed in the navigation base coordinate system as long as there is no settling of the vehicle. With the above data and the knowledge of the positions of the CSM and the landing site, the present stable member orientation with respect to the Basic Reference Coordinate System can be determined at the earth. The associated REFSMMAT can then be voice-linked to the astronaut and entered into the LGC.

5.6.2.2.5 Technique 1-IMU Alignment Using the Gravity Vector and the LM Attitude Data

Technique 1 is selected by the astronaut when a complete alignment is to be made by using the lunar gravity vector and the stored LM attitude data. A program alarm is issued when selecting this technique if the attitude flag or REFSMFLAG is not set.

In Fig. 6.2-2 it is seen that Technique 1 initially uses the Gravity Vector Determination Routine just as in Technique 3 to determine the unit gravity vector $\underline{u}_G$ in navigation base coordinates. Afterwards, the IMU is aligned to the desired orientation using only the LM attitude data. The final alignment is then made with the regular IMU alignment vectors for Technique 1 where $\underline{s}_A$ and $\underline{s}'_A$ are the same as for Technique 3 and $\underline{s}_B$ and $\underline{s}'_B$ are the same as for Technique 0.

5.6.2.2.6 Determination of Landing Site Position Using the Gravity Vector and a Technique 2 Alignment

After the final IMU alignment with Technique 2, it is possible for the astronaut to have a new landing site position vector $\underline{r}_{LS}$ determined in P-57 by using the latest lunar gravity vector $\underline{u}_G$ stored in navigation base coordinates. This approach is based upon the assumption that $\underline{r}_{LS}$ is in the same direction as $\underline{u}_G$. When performing this function, it is assumed that a gravity vector was previously obtained through use of Technique 1 or 3. Since the gravity vector is stored in navigation base coordinates and is therefore affected by settling of the spacecraft, it is desirable that this vector be determined just prior to performing an alignment with Technique 2.

The logic associated with the determination of $\underline{r}_{LS}$ with the gravity vector is shown on page 3 of Fig. 6.2-2. To obtain the latitude, longitude, and altitude of the proposed $\underline{r}_{LS}$ for display to the astronaut, use is made of the Latitude-Longitude Subroutine of Section 5.5.3 where the inputs to this subroutine are the present time and the vector

$$\underline{r}'_{LS} = |\underline{r}_{LS}|[\text{REFSMMAT}]^T[\text{NBSM}]\underline{u}_G$$

where $\underline{r}'_{LS}$ and $\underline{r}_{LS}$ are respectively the proposed and present landing site position vectors. If the astronaut approves the displayed latitude, longitude, and altitude, they are used in the Latitude-Longitude Subroutine to compute the new $\underline{r}_{LS}$. In addition, this $\underline{r}_{LS}$ is transformed to the Moon-Fixed Coordinate System through use of the Planetary Inertial Orientation Subroutine of Section 5.5.2 and replaces the previously-stored $\underline{r}_{LS}$.

It should be noted in Fig. 6.2-2 that the astronaut can establish a new $\underline{r}_{LS}$ by loading his own values of latitude, longitude, and altitude instead of using those based upon the gravity vector $\underline{u}_G$ and the magnitude of the present $\underline{r}_{LS}$. This feature permits him to conveniently establish a new $\underline{r}_{LS}$ based upon data from sources such as from optical tracking of the LM by the CSM during an overhead pass, or from correlation of observed lunar terrain features with onboard lunar maps.

5.6.3 IMU ROUTINES

5.6.3.1 AOT and COAS Transformations

5.6.3.1.1 Determination of the Star Line-of-Sight During Free-Fall

To perform IMU alignment during free-fall it is necessary to determine the lines-of-sight to two separate navigation stars or known celestial bodies in stable member coordinates. As a matter of convenience all celestial bodies used for this purpose shall be referred to as stars in this section. The line-of-sight to a star is determined during free-fall by making optical sightings on the star with the Alignment Optical Telescope (AOT) or the Crew Optical Alignment Sight (COAS). These optical sightings are made by varying the LM attitude so that the star crosses the X and Y reticle lines of the AOT or the equivalent X and Y lines of the COAS. The astronaut depresses the X or Y mark button whenever the star crosses the corresponding reticle line. When the star coincides with one of the reticle lines, this defines a plane containing the star. Once the location of the star has been established in two separate planes, the line-of-sight to the star can be obtained by solving for the intersection of these two planes.

The AOT is a unity power telescope with a field-of-view (FOV) of 60 degrees and can be rotated to six distinct positions about an axis parallel to the navigation base X-axis. These positions are accurately obtained by the use of detents. The center of the FOV for each of the viewing positions is defined by the azimuth (AZ_N) and elevation (EL_N) angles shown in Fig. 6.3-1 where the subscript N denotes the viewing position being used. The approximate values of these angles for the six viewing positions are:

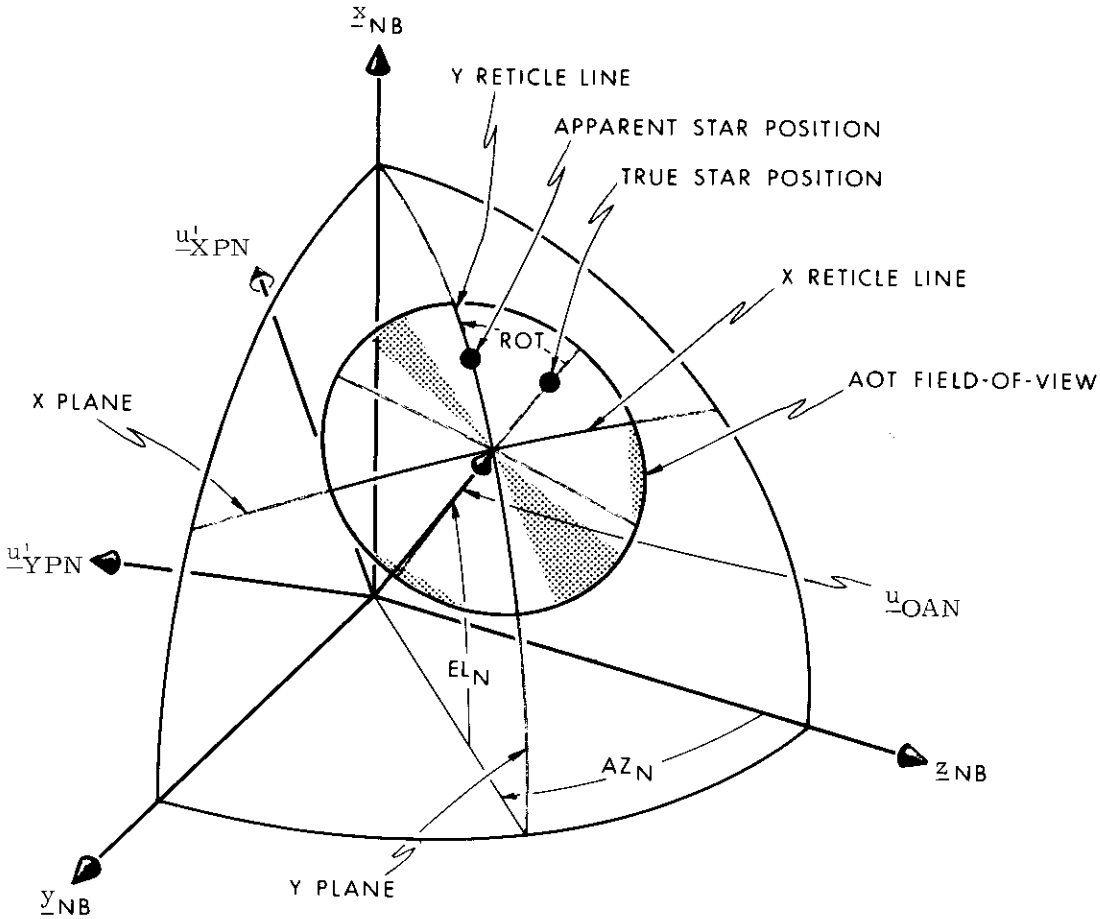


Fig. 6.3-1 AOT Alignment Geometry

Position 1 (left forward)	$AZ_1 = -60^\circ$, $EL_1 = 45^\circ$
Position 2 (forward)	$AZ_2 = 0^\circ$, $EL_2 = 45^\circ$
Position 3 (right forward)	$AZ_3 = 60^\circ$, $EL_3 = 45^\circ$
Position 4 (right rear)	$AZ_4 = 120^\circ$, $EL_4 = 45^\circ$
Position 5 (rear)	$AZ_5 = 180^\circ$, $EL_5 = 45^\circ$
Position 6 (left rear)	$AZ_6 = -120^\circ$, $EL_6 = 45^\circ$

At the beginning of the Inflight Sighting Mark Routine (R-53) and the Auto Optics Positioning Routine (R-52) the astronaut indicates whether he is going to use one of the viewing positions of the AOT or the COAS by selecting one of the following detent codes:

Detent Code	Use
0	COAS (R-52 only)
1	AOT Position 1
2	AOT Position 2
3	AOT Position 3
4	AOT Position 4
5	AOT Position 5
6	AOT Postion 6
7	COAS

For detent codes 1 through 6, the computer uses the angles AZ_N and EL_N which have been pre-stored in erasable memory for the corresponding AOT viewing positions. The angles for each AOT viewing position must be stored in erasable memory since the exact values vary slightly from one AOT to another and are not known until the final AOT installation. These angles completely specify the AOT position to the computer. If detent code 7 is selected the astronaut must load-in the correct angles AZ and EL for the COAS. If the COAS is pointed along the LM+Z axis when used in this application, its AZ and EL angles are approximately zero.

Detent code 0 is only used to calibrate the COAS with Routine R-52. When this code is used by the astronaut, R-52 requests that the angles AZ and EL for the COAS be loaded just as for detent code 7. Afterward, R-52 commands the LM attitude to establish coincidence between the line of sight specified by AZ and EL and the direction of a previously-specified celestial body. The astronaut then notes any corrections that should be made in AZ and EL by observing the celestial body through the COAS. For detent code 0, R-52 will repeat its data request (i.e., detent code and COAS angles) and perform automatic optics positioning until the astronaut is satisfied with the values of AZ and EL and has indicated this by using detent code 7.

The direction of the center of the FOV (or optical axis) for each AOT viewing position and the COAS can be expressed in navigation base coordinates by the following unit vector:

$$\underline{u}_{OAN} = \begin{bmatrix} \sin(EL_N) \\ \cos(EL_N) \quad \sin(AZ_N) \\ \cos(EL_N) \quad \cos(AZ_N) \end{bmatrix} \qquad (6.3.1)$$

where N denotes the viewing position of the AOT (N = 1 through 6) or the COAS (N = 0 or 7).

The X and Y reticle lines of the AOT (shown in Fig. 6.3-1) and those of the COAS define two planes perpendicular to each other. The orientation of these planes with respect to the navigation base for each viewing position of the AOT and the COAS are given by the following vectors:

$$\underline{u}'_{YPN} = \begin{bmatrix} 0 \\ \cos(AZ_N) \\ -\sin(AZ_N) \end{bmatrix} \qquad (6.3.2)$$

$$\underline{u}'_{XPN} = \underline{u}'_{YPN} \times \underline{u}_{OAN}$$

where N denotes the viewing position of the AOT or the COAS (N = 7). Note that the X and Y reticle lines of the COAS are assumed to be in the planes defined by the respective vectors $\underline{u}'_{XPN}$ and $\underline{u}'_{YPN}$ in Eq. (6. 3. 2). Since the AOT reticle can be rotated about the AOT optical axis by means of a knob near the eyepiece, it is necessary for the astronaut to set the reticle rotation angle to zero when performing optical sightings during free-fall in order for the vectors in Eq. (6. 3. 2) to correctly define the X and Y reticle planes.

At this point it is necessary to consider one important difference between the AOT and the COAS which is the following. When the AOT is rotated from one viewing position to another, the apparent star field observed through the instrument rotates about the optical axis. This effect is due to the optical design of the AOT and does not occur for the AOT reticle lines. In the forward position (Position 2) the apparent star field is the same as the true star field. As the AOT is rotated through a given azimuth angle from Position 2 to 3, the apparent star field rotates with respect to the true star field by an equal amount in a clockwise direction about the AOT optical axis. For Position 3 the relationship between the apparent and true positions of a star would be as shown in Fig. 6.3-1 where the amount and sense of rotation is shown as ROT. Consequently, when an apparent star coincides with the Y reticle line, as shown in Fig. 6.3-1, the true location of this star is in a plane obtained by rotating the Y plane about the optical axis by an amount ROT in the reverse direction. If it is

assumed that the azimuth angle, AZ_N, is positive as shown in Fig. 6.3-1, then the correct sense and magnitude of the rotation (R_N) which is applied to the X and Y planes for a given AOT viewing position is

$$R_N = AZ_2 - AZ_N \quad (N = 1 \text{ thru } 6) \qquad (6.3.3)$$

Therefore, the correct orientation in navigation base coordinates of the planes represented by the AOT X and Y reticle lines is

$$\begin{aligned} \underline{u}_{XPN} &= \cos(R_N)\, \underline{u}'_{XPN} + \sin(R_N)\, \underline{u}'_{YPN} \\ \underline{u}_{YPN} &= -\sin(R_N)\, \underline{u}'_{XPN} + \cos(R_N)\, \underline{u}'_{YPN} \end{aligned} \qquad (6.3.4)$$

The orientations of the corresponding planes for the COAS are obtained by setting the rotation angle R_N to zero in Eqs. (6.3.4).

Since the above planes ($\underline{u}_{XPN}$ and $\underline{u}_{YPN}$) are fixed with respect to the Navigation Base Coordinate System it is only necessary to compute them once when using a given AOT viewing position or the COAS; regardless of the number of marks made on a star.

The orientations of the vectors $\underline{u}_{XPN}$ and $\underline{u}_{YPN}$ are obtained in stable member coordinates by

$$\underline{u}_{XP} = [NBSM]_X \, \underline{u}_{XPN}$$
$$\underline{u}_{YP} = [NBSM]_Y \, \underline{u}_{YPN} \qquad (6.3.5)$$

where $[NBSM]_X$ and $[NBSM]_Y$ are the transformation matrices based upon the IMU CDU readings stored during the X and Y marks and are defined in Section 5.6.3.2.1.

The vector describing the line-of-sight to the star in stable member coordinates is

$$\underline{s}_{SM} = \text{UNIT}\,(\underline{u}_{XP} \times \underline{u}_{YP}) \qquad (6.3.6)$$

To achieve greater accuracy in determining the line-of-sight to a star, a multiple mark capability is provided, whereby the astronaut can make up to five pairs of marks. This is accomplished by storing the IMU CDU readings for each pair of X and Y marks until the marking process is completed for the star and then using the CDU readings for each pair of marks to obtain a star vector $\underline{s}_{SM}$ as indicated in Eqs. (6.3.5) and (6.3.6). As each star vector $\underline{s}_{SM}$ is computed it is averaged with the previously computed star vectors to obtain an average star vector $\underline{s}_n$ as follows:

$$\underline{s}_n = \frac{1}{n}\,[(n-1)\,\underline{s}_{n-1} + \underline{s}_{SM}] \qquad (6.3.7)$$

where n is the number of $\underline{s}_{SM}$ accumulated.

5.6.3.1.2 Determination of the Star LOS during Lunar Stay

When optical sightings are made to align the IMU with the Lunar Surface Alignment Program (P-57), use is made of the Lunar Surface Sighting Mark Routine (R-59). At the beginning of routine R-59 the astronaut selects one of the detent codes for the AOT just as described in Section 5.6.3.1.1 for the Inflight Sighting Mark Routine (R-53). However, the manner in which optical sightings are made with the AOT in routine R-59 is

different from that used in routine R-53. Instead of using the entire X and Y reticle lines of the AOT, use is made of only half of the Y line and a spiral, which also exist on the AOT reticle. The complete reticle pattern is shown at the left of Fig. 6.3-2. The spiral is so constructed as to depart radially from the center as a linear function of rotation about the center. Both the spiral and that half of the Y line used during the lunar stay period have been constructed as double lines to aid the astronaut in placing them on a star. The doubled portion of the Y line is sometimes referred to as the cursor. The entire reticle pattern can be rotated about its center by turning a knob near the eyepiece. A micrometer type readout is provided near the knob to indicate the amount of reticle rotation.

When optical sightings are made during free-fall the reticle rotation angle is set to zero. On the lunar surface, however, the astronaut must rotate the reticle pattern so as to establish coincidence of the star with both the cursor and the spiral as shown at the right of Fig. 6.3-2 and record the indicated angle of the micrometer dial for each. During these two measurements the X or Y MARK button must be depressed once (preferably midway between the two measurements) so that the LGC will store the IMU CDU angles for later use. After making the mark and the second measurement, the astronaut loads the two angles into the LGC.

The two angles, which are shown as YROT and SROT in Fig. 6.3-2, completely define the direction of the star with respect to the center of the field-of-view (FOV) of the AOT for the particular viewing position being used. The direction or azimuth of the star with respect to the center of the FOV is indicated by YROT. The angular separation between the star and the center of the FOV is given by

$$SEP = \frac{360^{\circ} + SROT - YROT}{12} \qquad (6.3.8)$$

except for the case when SROT = YROT = 0 where SEP is set to zero. This special case is necessary when the star is at the center of the FOV since Eq. (6.3.8) does not give the correct value for SEP. It should be noted that the astronaut must load zero values for YROT and SROT when he wishes to indicate that the star is at the center of the FOV.

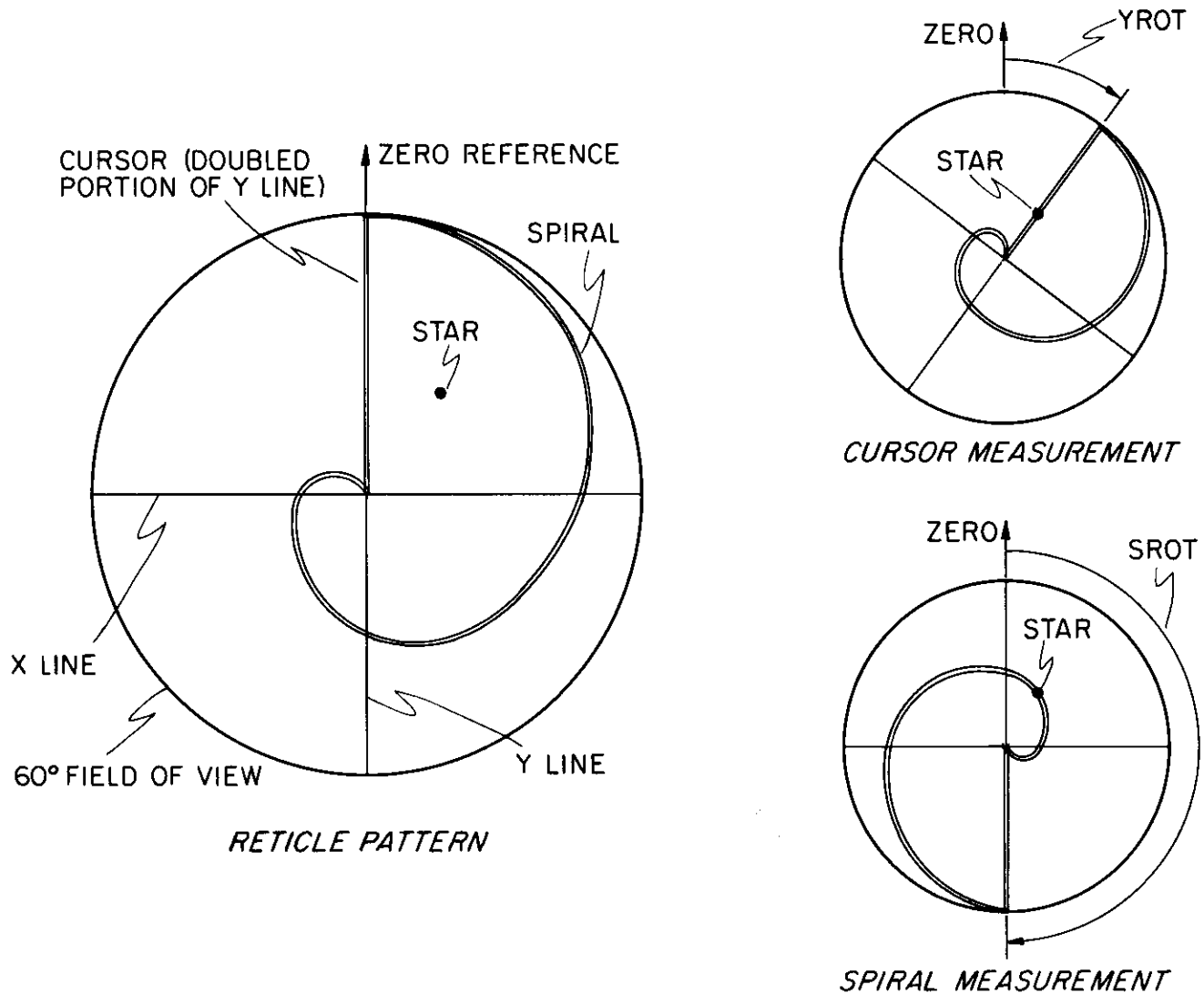


Fig. 6.3-2 AOT Reticle Pattern and Use on Lunar Surface

To determine a unit vector $\underline{s}_{NB}$, which represents the direction of the star in navigation base coordinates, use is made of the vectors $\underline{u}_{OAN}$, $\underline{u}_{YPN}$, and $\underline{u}_{XPN}$ given in Section 5.6.3.1.1 for the free-fall case. $\underline{u}_{OAN}$ is the direction in navigation base coordinates of the center of the FOV for the particular AOT viewing position being used. $\underline{u}_{YPN}$ and $\underline{u}_{XPN}$ are normal to the planes associated with the Y and X reticle lines for the AOT viewing position being used and define the orientations of these planes in navigation base coordinates. However, it should be noted that the planes specified by $\underline{u}_{YPN}$ and $\underline{u}_{XPN}$ are correct only if the reticle rotation angle is zero.

If the reticle is rotated through the angle YROT in order to place the cursor on the star, the vector defining the orientation of the plane containing both the star and $\underline{u}_{OAN}$ is

$$\underline{u}''_{YPN} = - \sin(YROT)\, \underline{u}_{XPN} + \cos(YROT)\, \underline{u}_{YPN} \qquad (6.3.9)$$

To obtain $\underline{s}_{NB}$ it is only necessary to rotate $\underline{u}_{OAN}$ about $\underline{u}''_{YPN}$ through the angle SEP:

$$\underline{s}_{NB} = \cos(SEP)\, \underline{u}_{OAN} + \sin(SEP)\, (\underline{u}''_{YPN} \times \underline{u}_{OAN}) \qquad (6.3.10)$$

The line-of-sight to the star in stable member coordinates is:

$$\underline{s}_{SM} = [NBSM]_X \, \underline{s}_{NB} \qquad (6.3.11)$$

where $[NBSM]_X$ is the transformation matrix derived from using the IMU CDU angles stored when the X or Y MARK button was depressed.

To achieve greater accuracy in determining the line-of-sight to a star during the lunar stay period, a multiple mark capability is provided just as during free-fall. The star vectors $\underline{s}_{SM}$ obtained from the star sighting process are combined to obtain an average star vector $\underline{s}_n$ as described in Section 5.6.3.1.1.

5.6.3.1.3 Lunar Surface Star Acquisition Subroutine

The purpose of the Lunar Surface Star Acquisition Subroutine is to assist the astronaut in locating a navigation star with the AOT when the celestial body code (or star code) has been selected by him at the beginning of the Lunar Surface Sighting Mark Routine (R-59). The subroutine is bypassed when the astronaut selects the Sun, Earth, Moon, or Planet code, and when there is no REFSMMAT just prior to entering the subroutine.

Initially, the subroutine checks to see if the star is within 30 degrees of the center of the AOT field-of-view (FOV) for any one of the six AOT viewing positions defined in Section 5.6.3.1.1. If successful, the subroutine then computes the reticle rotation angles needed to place the cursor and spiral of the AOT reticle onto the star. The parameters computed by this subroutine for display to the astronaut are the following:

N	AOT viewing position as defined in Section 5.6.3.1.1.
YROT	Reticle rotation angle in order to place the cursor on the star for viewing position N.
SROT	Reticle rotation angle in order to place the spiral on the star for viewing position N.

If the star is not within 30 degrees of the FOV center for any AOT position, a Program Alarm is issued and the astronaut must respond as shown in Fig. 6.3-3. If the star is within 0.5 degrees of the FOV center for one of the AOT positions, the values of YROT and SROT displayed to the astronaut are zero.

The logic associated with this subroutine is shown in Fig. 6.3-3. After transforming the selected unit star vector from basic reference to navigation base coordinates, a test is made for each AOT viewing position N to see if the star vector $\underline{s}_{NB}$ is within 30 degrees of the unit vector $\underline{u}_{OAN}$ defining the optical axis or the center of the field-of-view for that viewing position. The parameters $\underline{u}_{OAN}$ and C_1 are computed for each position as follows:

$$\underline{u}_{OAN} = \begin{bmatrix} \sin 45^{\circ} \\ \cos 45^{\circ} \sin AZ_N \\ \cos 45^{\circ} \cos AZ_N \end{bmatrix}$$

$$C_1 = \underline{u}_{OAN} \cdot \underline{s}_{NB} \qquad (6.3.12)$$

where AZ_N is the approximate azimuth angle for the AOT viewing position N which is given in Section 5.6.3.1.1.

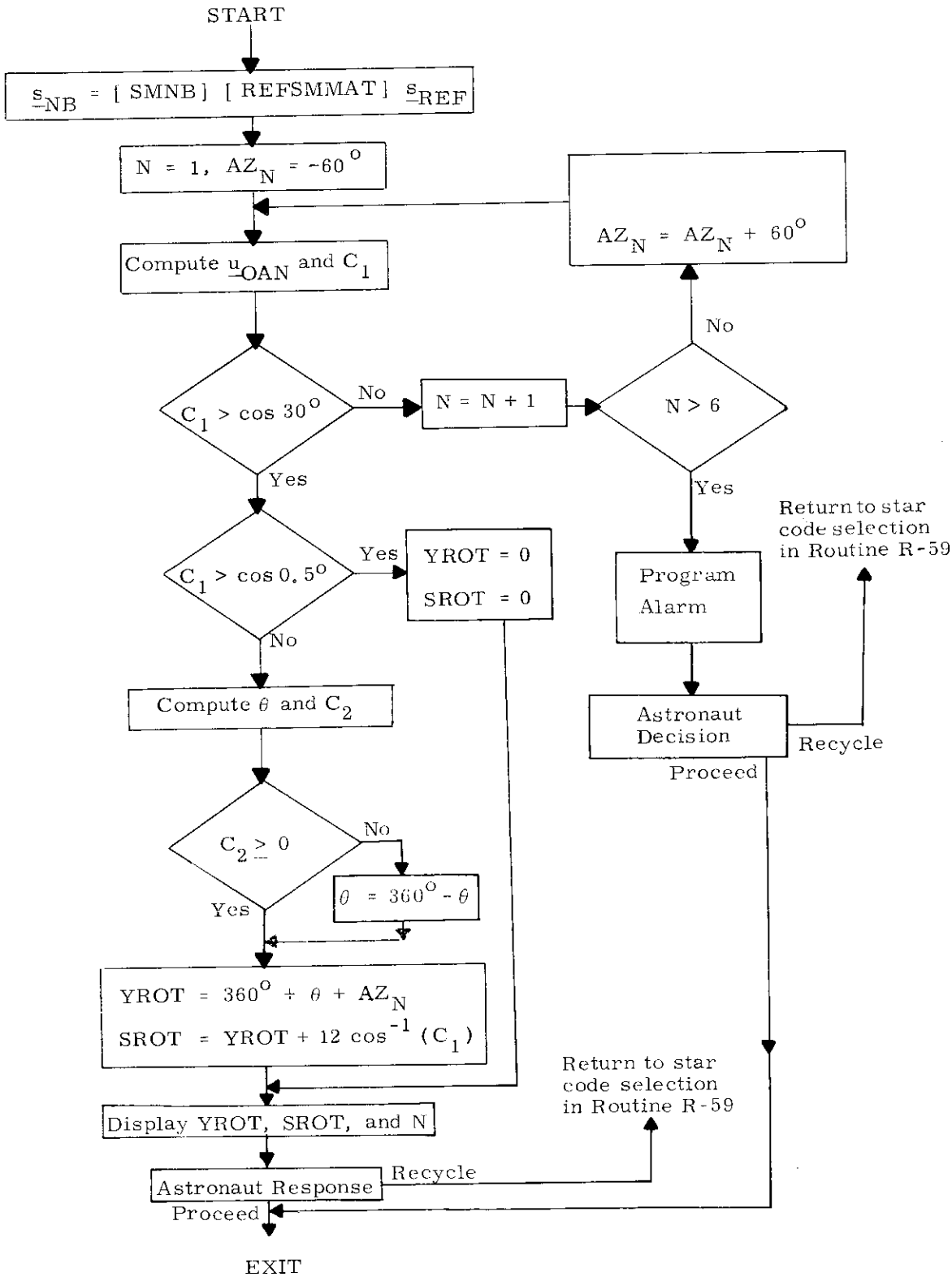


Figure 6.3-3 Lunar Surface Star Acquisition Subroutine

If the star is found to be within 30 degrees of $\underline{u}_{OAN}$, the reticle rotation angles YROT and SROT are computed as shown in Fig. 6.3-3 where:

$$\theta = \cos^{-1}\left\{ [\, \underline{u}_{OAN} \times \underline{s}_{NB}] \cdot [\, \underline{u}_{OAN} \times \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}] \right\}$$

$$C_2 = (\underline{u}_{OAN} \times \underline{s}_{NB}) \cdot \left\{ \underline{u}_{OAN} \times [\, \underline{u}_{OAN} \times \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}] \right\} \tag{6.3.13}$$

Note in Fig. 6.3-3 that 360° is added to the angle YROT to insure that YROT and SROT will always be positive. In addition, the LGC insures that the angles YROT and SROT displayed to the astronaut are not greater than 360° since the AOT reticle rotation dial is only capable of indicating values between 0° and 360°.

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:

$$Q_1 = \begin{pmatrix} \cos IGA & 0 & -\sin IGA \\ 0 & 1 & 0 \\ \sin IGA & 0 & \cos IGA \end{pmatrix} \qquad (6.3.14)$$

$$Q_2 = \begin{pmatrix} \cos MGA & \sin MGA & 0 \\ -\sin MGA & \cos MGA & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (6.3.15)$$

$$Q_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos OGA & \sin OGA \\ 0 & -\sin OGA & \cos OGA \end{pmatrix} \qquad (6.3.16)$$

Stable Member to Navigation Base Transformation

$$\begin{aligned} \underline{u}_{NB} &= Q_3 Q_2 Q_1 \, \underline{u}_{SM} \\ \left[SMNB\right] &= Q_3 Q_2 Q_1 \end{aligned} \qquad (6.3.17)$$

Navigation Base to Stable Member Transformation

$$\underline{u}_{SM} = Q_1^T Q_2^T Q_3^T \underline{u}_{NB}$$
$$[NBSM] = Q_1^T Q_2^T Q_3^T \qquad (6.3.18)$$

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.

$$\underline{a}_{MG} = \text{UNIT}\,(\underline{x}_{NB} \times \underline{y}_{SM})$$
$$\cos OGA = \underline{a}_{MG} \cdot \underline{z}_{NB}$$
$$\sin OGA = \underline{a}_{MG} \cdot \underline{y}_{NB}$$

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

$$\cos MGA = \underline{y}_{SM} \cdot (\underline{a}_{MG} \times \underline{x}_{NB}) \qquad (6.3.19)$$
$$\sin MGA = \underline{y}_{SM} \cdot \underline{x}_{NB}$$

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

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

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

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

where the inputs are three vectors along the stable member axes and three vectors along the navigation base axes. In the above equations ARCTRIG implies computing the angle, choosing either $\sin^{-1}$ or $\cos^{-1}$ so as to yield maximum accuracy.

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 $\underline{x}'_D$, $\underline{y}_D$, $\underline{z}'_D$; (2) rotating through θ_z about the z' axis, yielding $\underline{x}''_D$, $\underline{y}'_D$, $\underline{z}'_D$; (3) and finally rotating through θ_x about the x'' axis, yielding $\underline{x}''_D$, $\underline{y}''_D$, $\underline{z}''_D$. The relevant equations are as follows:

$$
\begin{aligned}
\underline{z}'_D &= \text{UNIT}\,(-x_{D,3},\ 0,\ x_{D,1}) \\
\sin\theta_y &= z'_{D,1} \\
\cos\theta_y &= z'_{D,3} \\
\theta_y &= \text{ARCTRIG}\,(\sin\theta_y,\ \cos\theta_y) \\
\sin\theta_z &= x_{D,2} \\
\cos\theta_z &= z'_{D,3}\,x_{D,1} - z'_{D,1}\,x_{D,3} \\
\theta_z &= \text{ARCTRIG}\,(\sin\theta_z,\ \cos\theta_z) \\
\cos\theta_x &= \underline{z}'_D \cdot \underline{z}_D \\
\sin\theta_x &= \underline{z}'_D \cdot \underline{y}_D \\
\theta_x &= \text{ARCTRIG}\,(\sin\theta_x,\ \cos\theta_x)
\end{aligned}
\qquad (6.3.20)
$$

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:

$$
\begin{aligned}
\underline{u}'_X &= \underline{s}'_A \\
\underline{u}'_Y &= \text{UNIT}\,(\underline{s}'_A \times \underline{s}'_B) \\
\underline{u}'_Z &= \underline{u}'_X \times \underline{u}'_Y \\
\underline{u}_X &= \underline{s}_A \\
\underline{u}_Y &= \text{UNIT}\,(\underline{s}_A \times \underline{s}_B) \\
\underline{u}_Z &= \underline{u}_X \times \underline{u}_Y
\end{aligned}
\qquad (6.3.21)
$$

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

$$
\begin{aligned}
\underline{x} &= u'_{X1}\,\underline{u}_X + u'_{Y1}\,\underline{u}_Y + u'_{Z1}\,\underline{u}_Z \\
\underline{y} &= u'_{X2}\,\underline{u}_X + u'_{Y2}\,\underline{u}_Y + u'_{Z2}\,\underline{u}_Z \\
\underline{z} &= u'_{X3}\,\underline{u}_X + u'_{Y3}\,\underline{u}_Y + u'_{Z3}\,\underline{u}_Z
\end{aligned}
\tag{6.3.22}
$$

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. (6.3.22)) of AXISGEN:

$$
\begin{bmatrix} \underline{x}^T \\ \underline{y}^T \\ \underline{z}^T \end{bmatrix}
\tag{6.3.23}
$$

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:

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

(6.3.24)

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

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

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 Gravity Vector Determination Routine

The gravity vector determination routine, see Fig. 6.3-4, measures the gravity vector twice, to minimize the error due to accelerometer bias. For the first measurement the IMU is coarse-aligned to gimbal angles of: OGA = 42°, MGA = 35.25°, IGA = -42°. In this orientation, the accelerometer (PIPA) axes are approximately at equal angles from the spacecraft X-axis, which should be roughly parallel to the gravity vector. The PIPA's are then monitored for 40 seconds, giving a gravity vector $\underline{g}$ in stable member co-ordinates. The gravity vector UNIT ($\underline{g}$) is transformed to navigation base co-ordinates, using the SMNB routine, and stored as $\underline{g}_1$.

A rotation matrix, Q, is then constructed, see Eqs. (6.3.25) and (6.3.26), which essentially defines the new orientation of the stable member axes with respect to the present stable member axes if the stable member were to be rotated 180° about the gravity vector.

$$\underline{u}'_X = \text{UNIT}\ (\underline{g})$$

$$\underline{u}'_Y = \text{UNIT}\ \left[\underline{u}'_X \times (0,\ 1,\ 0)\right] \qquad (6.3.25)$$

$$\underline{u}'_Z = \underline{u}'_X \times \underline{u}'_Y$$

$$Q = \begin{bmatrix} \underline{u}'_X & \underline{u}'_Y & \underline{u}'_Z \end{bmatrix} \begin{bmatrix} \underline{u}'^{T}_X \\ -\underline{u}'^{T}_Y \\ -\underline{u}'^{T}_Z \end{bmatrix} \qquad (6.3.26)$$

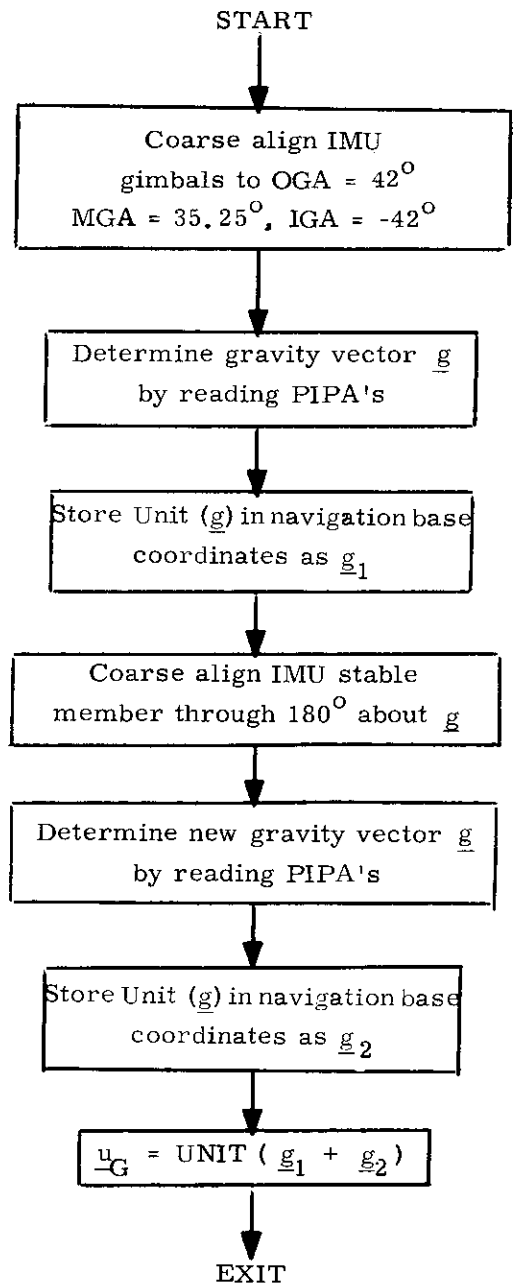


Figure 6.3-4 Gravity Vector Determination Routine

The coordinates of the desired stable member axes with respect to the present stable member axes are present in matrix Q:

$$Q = \begin{bmatrix} \underline{x}_{SM}^{T} \\ \underline{y}_{SM}^{T} \\ \underline{z}_{SM}^{T} \end{bmatrix} \qquad (6.3.27)$$

and the coordinates of the navigation base axes ($\underline{x}_{NB}$, $\underline{y}_{NB}$, and $\underline{z}_{NB}$) with respect to the present stable member axes are computed by the routine CALCSMSC of Section 5.6.3.2.5.

With $\underline{x}_{NB}$, $\underline{y}_{NB}$, $\underline{z}_{NB}$ and the vectors in (6.3.27), the routine CALCGA can be used to determine the desired gimbal angles for the new orientation, and the PIPA's are again monitored for 40 seconds, giving another gravity vector $\underline{g}$ in stable member co-ordinates. The gravity vector UNIT ($\underline{g}$) is transformed to navigation base co-ordinates with the SMNB routine, and stored as $\underline{g}_2$.

The unit vector in the direction of the gravity vector is calculated from:

$$\underline{u}_G = \text{UNIT}\,(\,\underline{g}_1 + \underline{g}_2\,) \qquad (6.3.28)$$

By using the above procedure, the error in estimating the direction of the gravity vector because of accelerometer biases is reduced.

5.6.3.4 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 the Basic Reference Coordinate System:

$$\text{REFSMMAT} = \begin{bmatrix} \underline{u}_{XSM}^{T} \\ \underline{u}_{YSM}^{T} \\ \underline{u}_{ZSM}^{T} \end{bmatrix} \qquad (6.3.29)$$

5.6.3.4.1 Present REFSMMAT From Star Sightings

The present IMU stable member orientation with respect to the reference coordinate system, and the associated REFSMMAT, can be determined by sighting on two navigation stars with the AOT. 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 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. (6.3.22) and (6.3.23)).

5.6.3.4.2 Alignment for Thrusting Maneuvers (Preferred Orientation)

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

$$\underline{u}_{XSM} = \underline{u}_{TD}$$

$$\underline{u}_{YSM} = \begin{cases} \text{UNIT}\,(\underline{u}_{XSM} \times \underline{r}) & \text{If } \underline{r} \text{ not parallel to } \underline{u}_{TD} \\ \text{UNIT}\,(\underline{u}_{XSM} \times \underline{v}) & \text{If } \underline{r} \text{ parallel to } \underline{u}_{TD} \end{cases} \qquad (6.3.30)$$

$$\underline{u}_{ZSM} = \underline{u}_{XSM} \times \underline{u}_{YSM}$$

where $\underline{u}_{TD}$ is the unit vector in the desired thrust direction at ignition and $\underline{r}$ and $\underline{v}$ are the LM position and velocity vectors.

The associated transformation matrix (REFSMMAT) is given by Eq. (6.3.29).

5.6.3.4.3 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.

$$\begin{aligned} \underline{u}_{XSM} &= \text{UNIT}\,(\underline{r}) \\ \underline{u}_{YSM} &= \text{UNIT}\,(\underline{v} \times \underline{r}) \\ \underline{u}_{ZSM} &= \text{UNIT}\,(\underline{u}_{XSM} \times \underline{u}_{YSM}) \end{aligned} \qquad (6.3.31)$$

where $\underline{r}$ and $\underline{v}$ are the position and velocity vectors of the LM at the specified time, t_{align}.

The REFSMMAT associated with this IMU orientation is found from Eq. (6.3.29).

5.6.3.4.4 Lunar Landing and Launch Orientations

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

$$\underline{u}_{XSM} = \text{UNIT}\left\{ \underline{r}_{LS}\left[t_L \right] \right\}$$

$$\underline{u}_{YSM} = \underline{u}_{ZSM} \times \underline{u}_{XSM} \qquad (6.3.32)$$

$$\underline{u}_{ZSM} = \text{UNIT}\left\{ \underline{h}_C \times \underline{r}_{LS}\left[t_L \right] \right\}$$

where $\underline{u}_{XSM}$, $\underline{u}_{YSM}$, and $\underline{u}_{ZSM}$ represent the directions of the respective stable member axes expressed in the Basic Reference Coordinate System.

$\underline{h}_C$ is the orbital angular momentum vector of the CSM given by $(\underline{r}_C \times \underline{v}_C)$.

$\underline{r}_{LS}$ is the landing site position vector in the Basic Reference Coordinate System at a specified time t_L.

In Section 4 the time t_L may either be the nominal time of lunar landing referred to in IMU Realignment Program (P-52) or a time specified by the astronaut at the beginning of the Lunar Surface Alignment Program (P-57). It should be noted that no program exists in the LGC to determine the lunar landing time, and this parameter must be supplied by RTCC.

Since the landing site moves in the Basic Reference Coordinate System because of lunar rotation, it is more convenient to store its position vector $\underline{r}_{LS}$ in the Moon-Fixed Coordinate System where it does not change with time. Whenever it is desired to express $\underline{r}_{LS}$ in the reference coordinate system for a given time (i.e., t_L) use is made of the Planetary Inertial Orientation Routine of Section 5.5.2.

The REFSMMAT associated with the landing site alignment in Eq. (6.3.32) is given by Eq. (6.3.29).

5.6.4 STAR SELECTION ROUTINE

The Star Selection Routine is used by the Fine Alignment Routine (R-51) to select the best pair of stars in or near the forward AOT field of view 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 100 degree viewing cone centered with respect to the optical axis of the Alignment Optical Telescope (AOT) when in the forward viewing position (Detent 2). Although this viewing cone is larger than the actual field of view (60 degrees) of the AOT, it is used to enhance the probability that a star pair will be found with sufficient angular separation so as to insure accurate IMU alignment.

Afterwards, the routine checks to see if the angle of separation between the stars is at least 50 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 Fine Alignment Routine (R-51) 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 Routine R-51 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 in the Fine Alignment Routine (R-51).

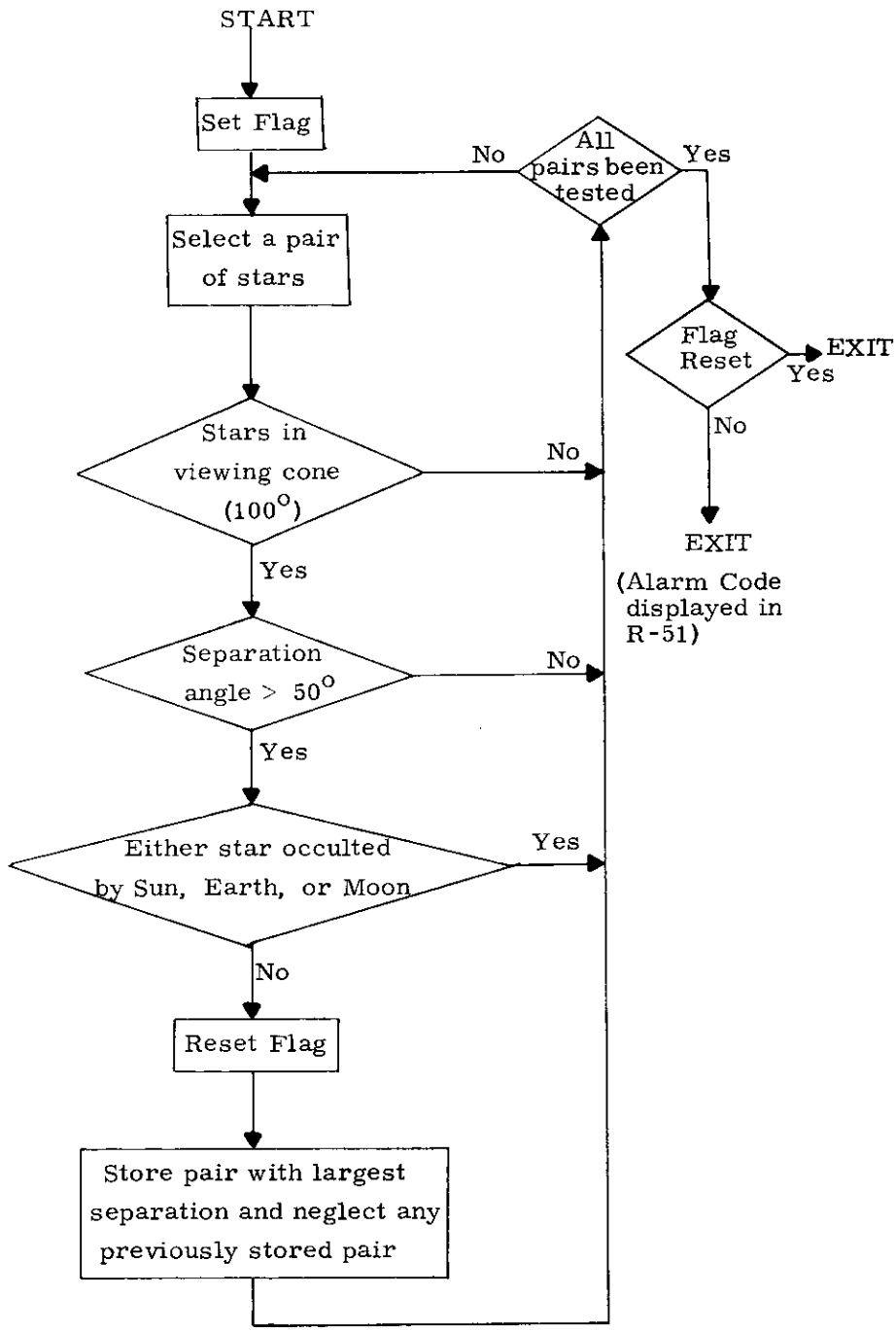


Figure 6.4-1 Star Selection Routine

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.

In order to decrease the computer time required to do recycled computations of latitude, longitude, and altitude, the routine saves the results of its initial integration of the state as a base vector which is used as input for recycling requests.

As an additional option, the astronaut may request a display of altitude (to 10 N.M.), inertial velocity magnitude (to 1 ft/sec), and flight path angle (in degrees) at an astronaut-specified time.

5.6.6 S-BAND ANTENNA ROUTINE

The S-Band Antenna Routine (R-05) in the LGC is used to compute and display the two antenna gimbal angles which will point the antenna toward the center of the Earth, using the present LM position and body attitude. The gimbal angle definitions and their relation to the LM body axes are shown in Fig. 6.6-1.

Once the program is initiated by the astronaut the computer will automatically update the display at a rate of no greater than once per second depending on other computer activity. This update will continue until terminated by the astronaut via the DSKY. If the S-Band Antenna Routine is interrupted, the display and computation will be terminated until the astronaut reinitiates the routine.

The computational accuracy of the antenna gimbal angles is $\pm$ 1.0 degrees. This accuracy reflects only the level of accuracy of the displayed angles and does not indicate the pointing accuracy of the associated antenna alignment.

The angles computed and displayed (see Fig. 6.6-1) cover the entire range of possible gimbal angles. There is no attempt to restrict these angles to those constrained by gimbal limits or to indicate that a vehicle attitude change is required to achieve S-Band lock-on.

[x] Revised LUMINARY
[ ] Added GSOP # 567 PCR # 832.2 Rev. 7 Date 11.69

Rotation order α, β

α, pitch angle is rotation about the + pitch gimbal axis ($-90 < \alpha \leq 270$)

β, yaw angle is rotation about the yaw gimbal axis fixed to the antenna ($-90 \leq \beta \leq 90$)

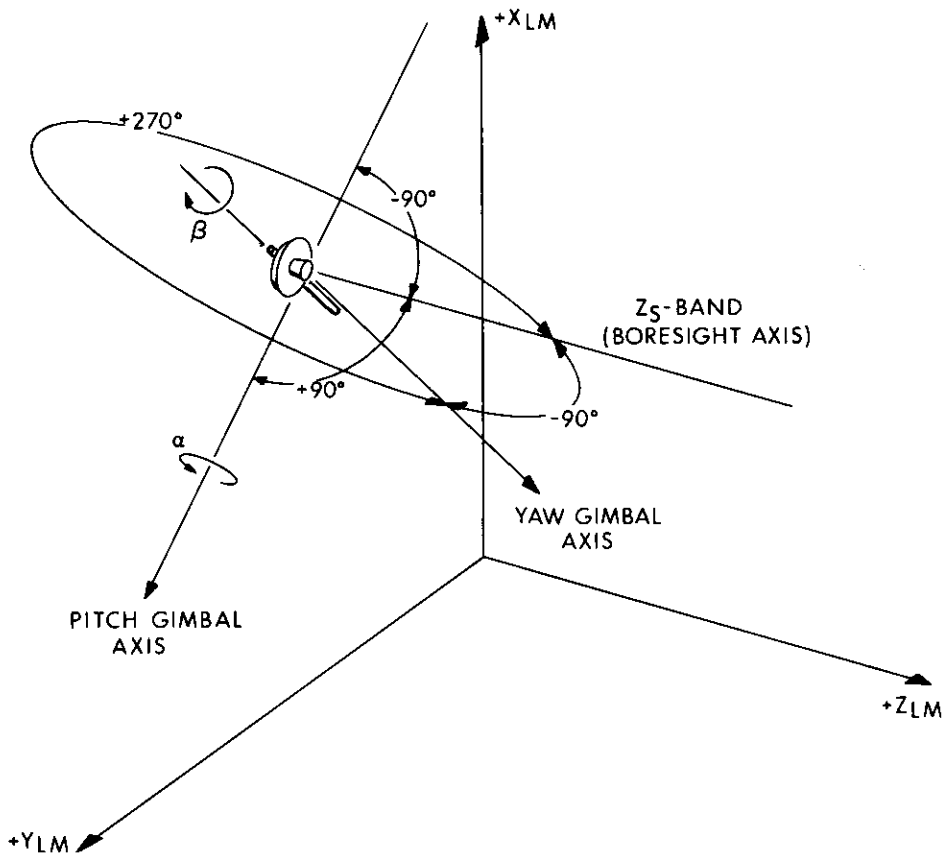


Figure 6.6-1 Definition of LM S-Band Gimbal Angles

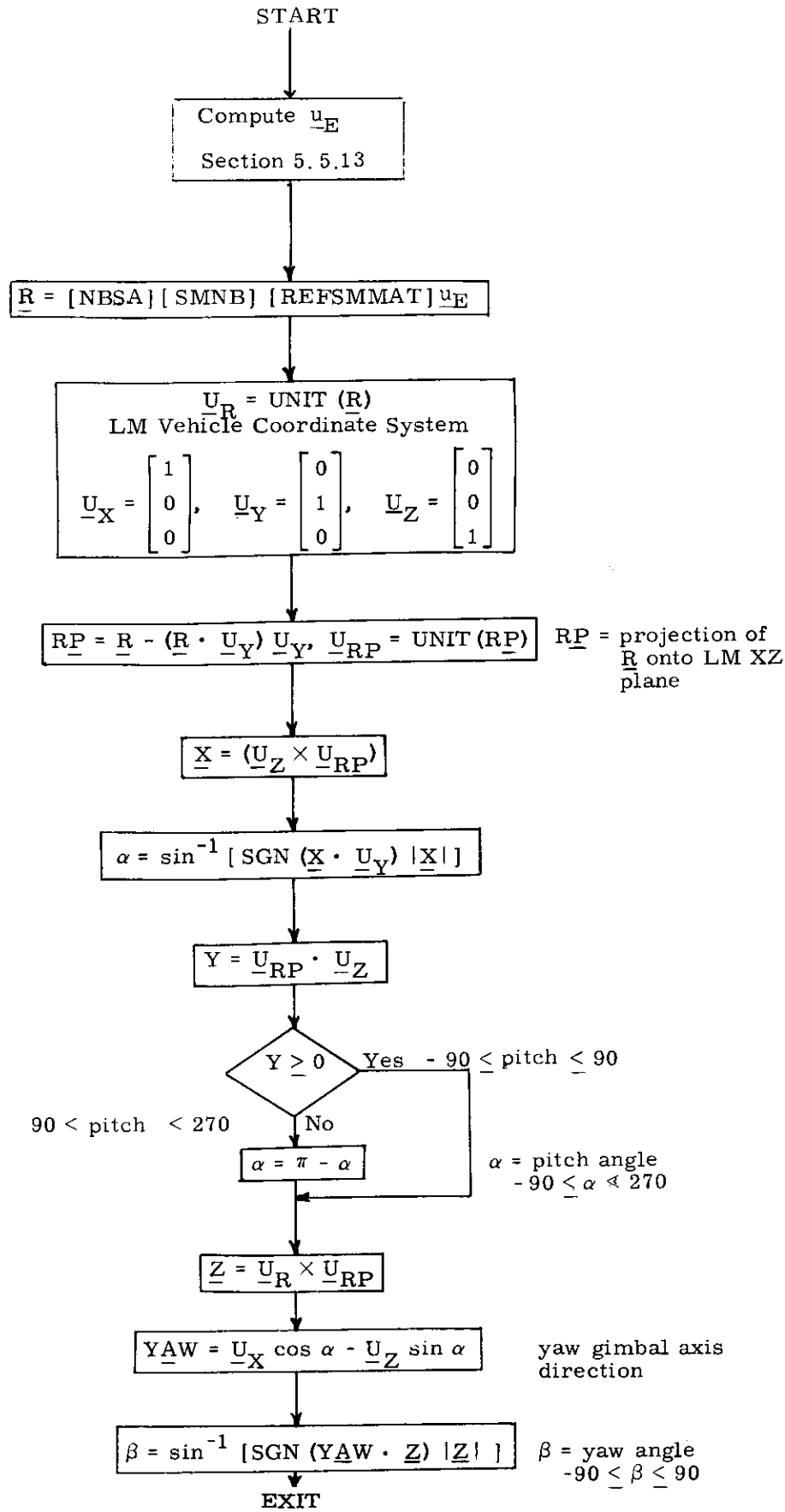


Figure 6.6-2 S-Band Angle Computations and Logic

The equations and logic used to compute the LM antenna gimbal angles are shown in Fig. 6.6-2. The vector $\underline{R}$ from LM to Earth as determined by the unit vector $\underline{u}_E$ of the LOSSEM subroutine of Sec. 5.5.13 is transformed to navigation base coordinates then rotated by the transformation matrix [NBSA] to account for the orientation of the S-band antenna mount with respect to the navigation base or LM coordinates. The relation between $\underline{U}_R$ and ($U_{X_{LM}}$, $U_{Y_{LM}}$, $U_{Z_{LM}}$) determines the S-band antenna gimbal angles in the subsequent computations. The transformation matrix [NBSA] is defined as follows:

$$[NBSA] = \begin{bmatrix} \cos 45^\circ & \sin 45^\circ & 0 \\ -\sin 45^\circ & \cos 45^\circ & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

5.6.7 ADDITIONAL RENDEZVOUS DISPLAYS

During the rendezvous sequence the following 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 in order to display the computed range and range rate between the two vehicles and an angle θ shown in Fig. 6.7-1.

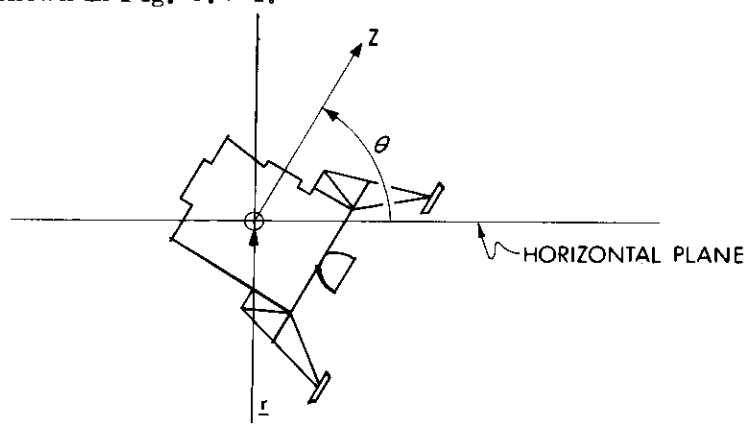


Figure 6.7-1 Definition of Theta

The angle θ represents the angle between the LM Z-body axis and the local horizontal plane of the LM. It is defined in a manner completely analogous to the definition of E in Section 5.4.2.2 and, therefore, has limits of 0 to 360 degrees.

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

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

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

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

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

To compute θ the following vector is defined

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

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

$$\begin{aligned} \underline{u} &= \text{UNIT}\,(\underline{r}_L \times \underline{v}_L) \\ \underline{u}_P &= \text{UNIT}\left[\underline{u}_Z - \left(\frac{\underline{u}_Z \cdot \underline{r}_L}{r_L^{\,2}}\right)\underline{r}_L\right] \\ \theta &= \cos^{-1}\left[\underline{u}_Z \cdot \underline{u}_P\,\text{SGN}\,(\underline{u}_P \cdot \underline{u} \times \underline{r}_L)\right] \end{aligned} \qquad (6.7.3)$$

$$\text{If } \underline{u}_Z \cdot \underline{r}_L < 0;\ \theta = 2\pi - \theta$$

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 Final Attitude Display

Routine R-63 may be used to compute and display the FDAI angles required to point either the LM Z-axis or LM X-axis at the CSM. The choice of axis is made by the astronaut at the beginning of the routine as described in Section 4.

After initiation of this routine the state vectors of both vehicles are extrapolated to the present time plus one minute using the Conic Kepler Subroutine (Section 5.5.5). Based on these new state vectors the required gimbal angles are computed. These angles are converted to FDAI angles using the transformation described in Section 5.6.12 and the result is displayed.

There is no automatic display update; however, R-63 may easily be recycled manually.

5.6.7.3 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. Three quantities(Y, $\dot{Y}$, and ψ) are computed for a given time. (The present time of ignition is automatically selected in the absence of a time determined by the astronaut.) The first two, Y and $\dot{Y}$, represent the out-of-plane position and and velocity in some sense. The third display, ψ is the angle between the

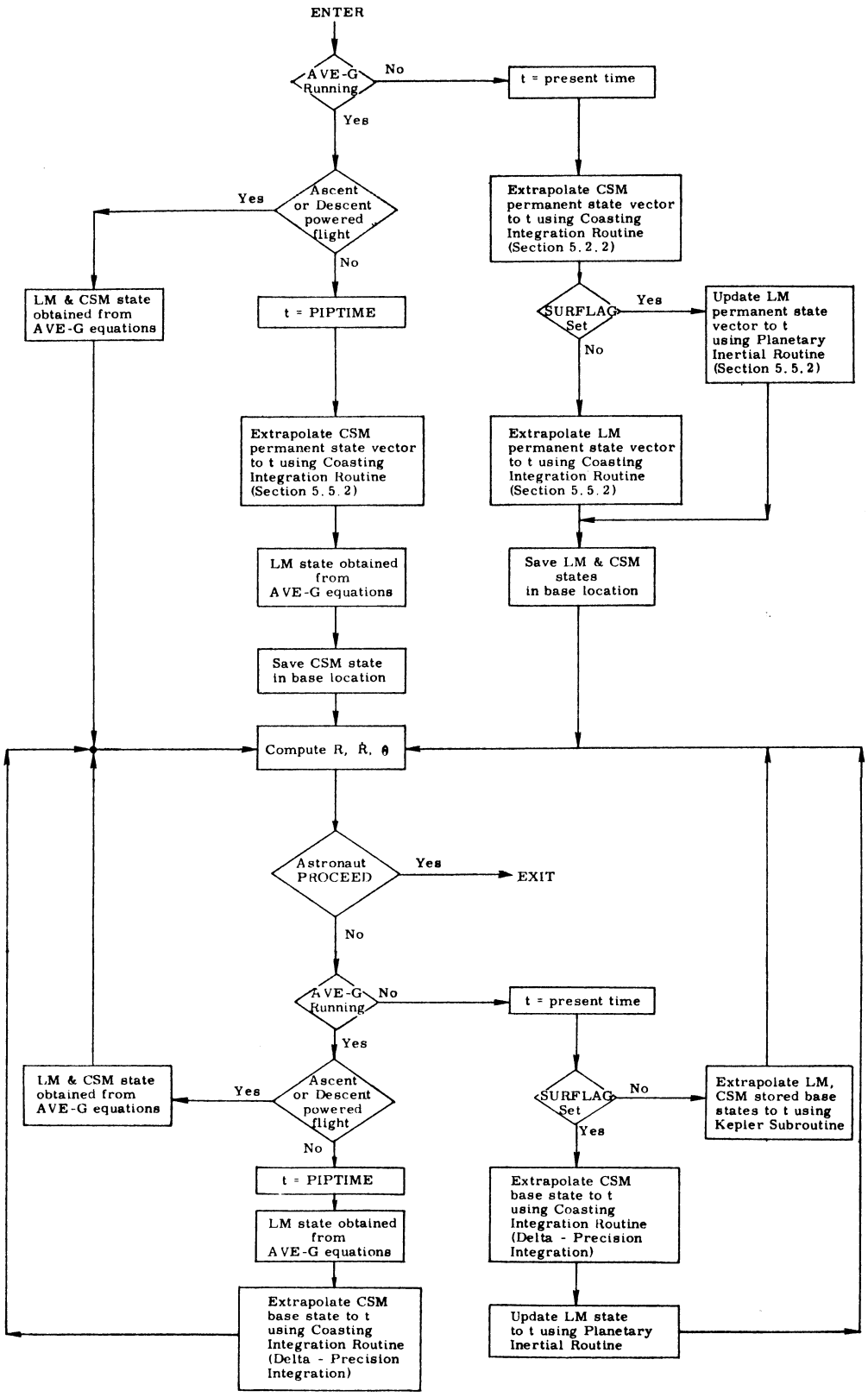


Figure 6.7-2 Range, Range Rate, θ

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 such that the Z-axis were pointed along the line of sight.

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

$$\underline{u} = \text{UNIT}\,(\underline{v}_C \times \underline{r}_C) \tag{6.7.4}$$

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

$$\begin{aligned} Y &= \underline{r}_L \cdot \underline{u} \\ \dot{Y} &= \underline{v}_L \cdot \underline{u} \end{aligned} \tag{6.7.5}$$

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

$$\begin{aligned} \underline{u}_F &= \text{UNIT}\left[(\underline{r}_L \times \underline{v}_L) \times \underline{r}_L\right] \\ \underline{u}_R &= \text{UNIT}\,(\underline{r}_L) \\ \underline{LOS} &= \underline{r}_C - \underline{r}_L \end{aligned} \tag{6.7.6}$$

$$\begin{aligned} \underline{u}_{LOS} &= \text{UNIT}\left[\underline{LOS} - (\underline{LOS} \cdot \underline{u}_R)\,\underline{u}_R\right] \\ \psi &= \cos^{-1}(\underline{u}_{LOS} \cdot \underline{u}_F) \\ \underline{N} &= \underline{u}_{LOS} \times \underline{u}_F \end{aligned} \tag{6.7.7}$$

$$\text{If } \underline{N} \cdot \underline{r}_L < 0;\ \psi = 2\pi - \psi$$

5.6.8 AGS INITIALIZATION ROUTINE

The Abort Guidance System (AGS) initialization involves a separate routine R-47 in the LGC that prepares a special telemetry downlink list with the required AGS initialization parameters. The AGS-LGC initialization interface is through the telemetry subsystem. At a desired GET, the astronaut may simultaneously make an "ENTER" in both LGC and AEA (Abort Electronic Assembly). The LGC stores the GET at this ENTER and subtracts this time from all state vector reference times used in the AGS initialization. There is also the option of loading an AGS initialization time obtained from an external source.

The AGS Initialization Routine next integrates the CSM and LM state vectors to the current GET. This state vector integration (Sec. 5.2.2) is based on the determination of the earth or lunar orbit condition by examining the CSM primary body indicator P_C of Section 5.2.2.6. In the earth orbital condition, the CSM and LM state vectors are divided by a factor of four and these modified state vectors are put on the special down-link telemetry list together with the difference between the state vector time and the AGS reference GET. In the lunar orbit condition the CSM and LM state vectors are modified by only the subtraction of the AGS reference GET from the state vector time before being put on the down-link list. This special telemetry down-link list is then sent 10 consecutive times before the normal down-link format is resumed.

Subsequent AGS initializations do not normally require a new AGS time referencing operation involving the simultaneous LGC and AEA ENTER inputs. During AGS initializations following the first, the AEA clock initialization may be omitted. In that case, the special initialization down-link is prepared by modifying the state vector times by subtracting the initial GET reference time determined in the first initialization.

The final operation is to zero the IMU CDU's for the AGS alignment procedure as described in Section 4 provided CDU zeroing is permissible in the LGC at that time.

5.6.9 LGC INITIALIZATION

The LGC initialization procedure prior to LM separation is a manual operation which does not involve a numbered LGC 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, 1969 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.

The estimated CSM and LM state vectors (as defined in Eq. (2.2.28) of Section 5.2.2.6), the estimated landing site state vector, and the reference time t_0 are then initialized as follows:

$$\underline{r}_{C0} = \underline{r}_C$$

$$\underline{v}_{C0} = \underline{v}_C$$

$$\underline{r}_{Ccon} = \underline{r}_C$$

$$\underline{v}_{Ccon} = \underline{v}_C$$

$$^*\underline{\delta}_C = \underline{0}$$

$$^*\underline{\nu}_C = \underline{0}$$

$$t_C = t_C$$

$$^*\tau_C = 0$$

$$^*x_C = 0$$

$$P_C = \begin{cases} 0 \text{ for earth orbit} \\ 1 \text{ for lunar orbit} \end{cases}$$

$$\underline{r}_{L0} = \underline{r}_C$$

$$\underline{v}_{L0} = \underline{v}_C$$

$$\underline{r}_{Lcon} = \underline{r}_C$$

$$\underline{v}_{Lcon} = \underline{v}_C$$

$$^*\underline{\delta}_L = \underline{0}$$

$$
\begin{aligned}
{}^{*}\underline{\nu}_L &= \underline{0} \\
t_L &= t_C \\
{}^{*}\tau_L &= 0 \\
{}^{*}x_L &= 0 \\
P_L &= \begin{cases} 0 \text{ for earth orbit} \\ 1 \text{ for lunar orbit} \end{cases} \\
{}^{*}\underline{r}_{LS} &= \underline{r}_{LS} \\
t_0 &= t_0
\end{aligned}
$$

where the items on the left-hand side of the above equations are LGC variables, and the items on the right-hand side are the uplinked or voice-linked parameters. The subscripts C and L refer to CSM and LM, respectively. The variables marked with an asterisk (*) are initialized during the prelaunch erasable load and do not have to be reset unless the values have been changed during the mission.

5.6.11 LGC IDLING PROGRAM

This program is used to maintain the LGC 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.

This periodic state vector extrapolation is valid for near-earth or near-moon orbits only since the capability for accurate cislunar-midcourse integration does not exist in the LGC.

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. 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

$$t_1 > t_C + 4\,\Delta t_{max} \qquad (6.11.1)$$

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.

The error transition matrix W (See Section 5.2.2.4) is extrapolated with the estimated LM or CSM state vector if RENDWFLG indicates that the W matrix is valid. RENDWFLG is defined in Sections 5.2.4.2.2 and 5.2.5.4. The selection of which state vector to extrapolate the W matrix with depends upon whether the LM is in flight or on the moon.

The logic for the periodic state vector extrapolation is illustrated in Fig. 6.11-1. The variables D and V are indicators which control the Coasting Integration Routine. The quantities $\underline{x}_L$ and $\underline{x}_C$ are the estimated LM and CSM 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) when 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 LGC Idling Program (P-00) is activated.
4. The P-00 state vector test is bypassed so that no state vector integration test occurs until reselection of P-00.

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

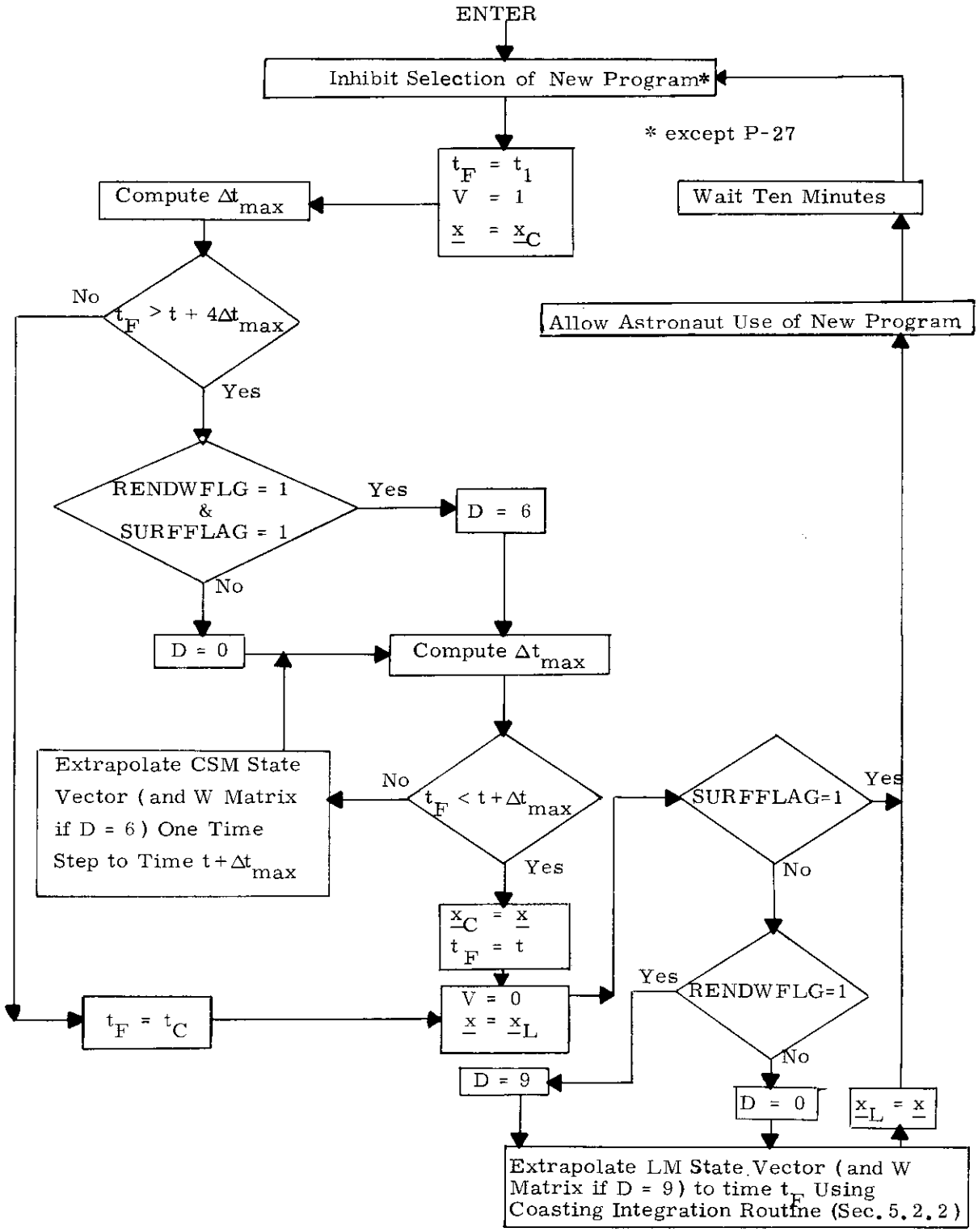


Figure 6.11-1 LGC Idling Program State Vector Extrapolation Logic Diagram

5.6.12 FDAI-IMU TRANSFORMATIONS

The following transformations are used to convert IMU gimbal angles to angular readings on the LM FDAI Ball.

YAW

$$Y = \sin^{-1}\left[-\cos(MGA)\sin(OGA)\right]$$

where the display is such that

$$90^{\circ} \geq Y \geq 0^{\circ}$$

or

$$360^{\circ} > Y \geq 270^{\circ}$$

PITCH

$$(\text{If } |\sin Y| \neq 1.0)$$

$$P = \sin^{-1}\left[\frac{\sin(IGA)\cos(OGA) + \cos(IGA)\sin(MGA)\sin(OGA)}{\cos Y}\right]$$

$$= \cos^{-1}\left[\frac{\cos(IGA)\cos(OGA) - \sin(IGA)\sin(MGA)\sin(OGA)}{\cos Y}\right]$$

ROLL

(If $|\sin Y| \neq 1.0$)

$$R = \sin^{-1}\left[\frac{\sin(MGA)}{\cos Y}\right] = \cos^{-1}\left[\frac{\cos(MGA)\cos(OGA)}{\cos Y}\right]$$

where the displays for both P and R are always positive angles less than 360°.

For $Y = 90^{\circ}$ or 270° the preceding equations are indeterminate and the pitch and roll readings become meaningless since they are not uniquely defined in terms of IMU gimbal angles because the FDAI outer and inner gimbal angles are likewise not unique. However, the following equations give the relationships between the IMU gimbal angles and the sum or differences of P and R.

If

1. $Y = 90^{\circ}$, then either

   a. $MGA = 0^{\circ}$ and $OGA = -\frac{\pi}{2}$ whence $P + R = IGA$

   or

   b. $MGA = \pi$ and $OGA = +\frac{\pi}{2}$ whence $P + R = IGA + 180^{\circ}$

2. $Y = 270^{\circ}$, then either

   a. $MGA = 0^{\circ}$ and $OGA = +\frac{\pi}{2}$ whence $P - R = IGA$

   or

   b. $MGA = \pi$ and $OGA = -\frac{\pi}{2}$ whence $P - R = IGA + 180^{\circ}$

where

IGA = inner IMU gimbal angle

MGA = middle IMU gimbal angle

OGA = outer IMU gimbal angle

The IMU gimbal angles are defined to be zero when the axes of rotation of the gimbals are mutually orthogonal. Each gimbal angle is defined as that angle through which the designated gimbal must be rotated, in the conventional right hand sense, with respect to its outer neighbor to make the X, Y, Z Coordinate Systems of both gimbals coincident.

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

$$PIPA_C = (1 + SFE_I)\, PIPA_I - BIAS_I\, \Delta t$$

where

$PIPA_C$ is the compensated data for the Ith PIPA denoted $PIPAX_C$, $PIPAY_C$, $PIPAZ_C$

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

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

$BIAS_I$ is the bias for the Ith 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

$$XIRIG = -ADIAX\ PIPAX_C + ADSRAX\ PIPAY_C - NBDX\ \Delta t$$

$$YIRIG = -ADIAY\ PIPAY_C + ADSRAY\ PIPAZ_C - NBDY\ \Delta t$$

$$ZIRIG = -ADIAZ\ PIPAZ_C - ADSRAZ\ PIPAY_C + NBDZ\ \Delta t$$

*The term "erasable load" refers to data entered in LGC erasable memory just prior to launch.

where

XIRIG, YIRIG, ZIRIG are gyro drift compensations

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 RR / LR SELF TEST ROUTINE

The purpose of the RR / LR Self Test Routine (R-04 in Section 4) is to provide suitable DSKY displays and LGC down-link information to support the self tests of the Rendezvous Radar (RR) and the Landing Radar (LR). In doing this the routine also provides a check on the data transmission interface between the LGC and the two radar systems.

The self test of either radar system is accomplished by the astronaut through use of a radar test switch at the LM console. When this switch is in the RR or LR position, artificial target signals are generated within the associated radar system. These signals when acquired by the tracking networks of the radar correspond to certain known values in the measurement parameters (range, etc).

The self tests of the RR and LR can be conducted with or without the assistance of the LGC. Since these tests can interfere with the normal RR and LR data read and update functions of the LGC, it is essential that the astronaut not have the radar test switch in one of its test positions (RR or LR) when either radar is being used for update purposes.

If the astronaut wishes to have the radar self test parameters displayed on the DSKY and placed on the LGC down-link, he calls the RR / LR Self Test Routine. At the beginning of the routine he indicates which radar is being self tested. If he selects the LR, the routine will start reading continuously the four LR data parameters ($\underline{v}_X$, $\underline{v}_Y$, $\underline{v}_Z$, and range) once per second. Each parameter is sampled by a single 80.001 millisecond gate. These are placed on the LGC down-link and are displayed to him in two separate DSKY displays.

One display contains the range and the present position of the LR antenna. The other display contains the three LR velocity components (v_X, v_Y, and v_Z). The LGC will transfer, display, and downlink the contents of the LR output register regardless of the status of the Range and Velocity Data Good discretes. In the absence of either of these discretes, the corresponding parameter indication may be zero because of the implementation of the LR which inhibits filling the LR output register in the absence of the particular Data Good discrete. However, whenever a given parameter is obtained from the LR, the associated data good discrete is checked and the associated DSKY light (LR Altitude Fail or LR Velocity Fail) is turned on if the discrete is missing.

If the RR test mode is selected, a check is made to see if the RR Auto Mode discrete is being received from the RR. If it is present, the RR Track Enable discrete is issued to allow the radar to lock-on the self test signals and subsequently generate the RR Data Good discrete during the data reading process. The purpose of checking the RR Auto Mode discrete is to insure that the mode control switch of the RR is in the LGC position during the data read operation. This insures that the phase of the RR resolver excitation is within tolerance for normal angle measurements by the RR CDU's. If the RR mode control switch is in either of its other two positions, this phase tolerance is not insured. If the RR Auto Mode is absent, a request is issued to the astronaut to place the RR mode control switch in the LGC position. Once this has been accomplished, the routine starts reading the RR CDU angles (shaft and trunnion) every second and the range and range rate on alternate seconds. These quantities are displayed on the DSKY in two separate displays, and thus normally will be down-linked. One display contains the RR CDU angles. It should be noted that the polarity of the displayed RR trunnion angle is opposite that defined in Fig. 6.15-1. The other display contains the range and range rate. The four RR data parameters are displayed and placed on the down-link regardless of the status of the RR Data Good discrete. However, whenever a range or range rate measurement is obtained from the RR, the RR Data Good discrete is checked and the Tracker Fail Alarm is turned on if the discrete is missing. Each range and range rate parameter obtained by this routine is the result of a single 80 millisecond gating interval.

It should be noted that the RR or LR data initially displayed by this routine may not be meaningful since the radar tracking loops may still be in the process of locking onto the internally generated target signals of the radar. In addition, the CDU data displayed at the beginning of the RR self test may be that associated with the process of zeroing the RR CDU's. Whenever the RR Auto Mode discrete is first detected by the RR Monitor Routine (R-25) of Section 5. 2. 4. 3, the RR CDU's are zeroed.

5.6.15 RR ANGLE TRANSFORMATIONS

5.6.15.1 Determination of RR Antenna Direction in Navigation Base Coordinates

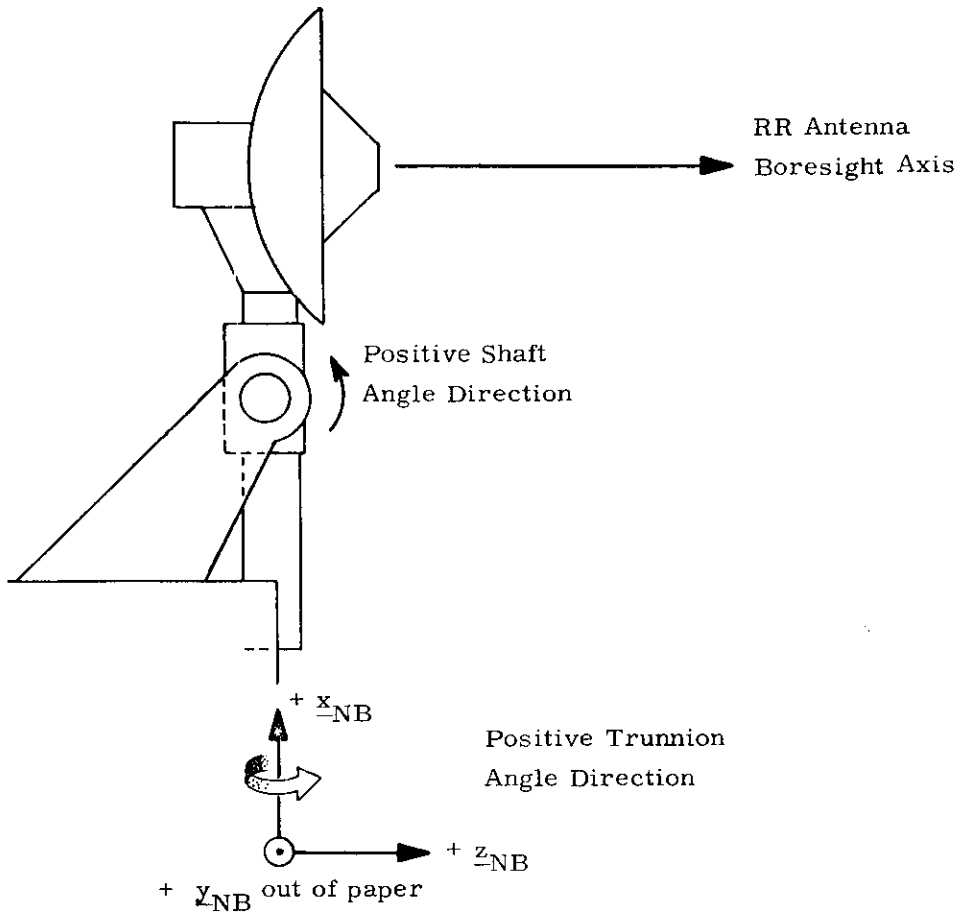
To obtain a unit vector $\underline{u}_{RR}$ specifying the present direction of the boresight axis of the RR antenna in navigation base coordinates use is made of the following:

$$\underline{u}_{RR} = \begin{bmatrix} \sin S \ \cos T \\ -\sin T \\ \cos S \ \cos T \end{bmatrix} \qquad (6.15.1)$$

where S and T are the shaft and trunnion angles of the RR antenna as indicated by the RR CDU's. The positive sense of these angles is shown in Fig. 6.15-1.

5.6.15.2 Equivalent RR Angles for a Desired Pointing Direction

Let $\underline{u}_D$ be a unit vector defining a desired pointing direction in navigation base coordinates. This direction may be a desired direction for RR designation for which the corresponding RR shaft and trunnion angles must be computed in order to see if they are within the angular coverage modes of the antenna. The corresponding shaft and trunnion angles for this direction are determined as follows:



1. $+\underline{x}_{NB}$, $+\underline{y}_{NB}$, and $+\underline{z}_{NB}$ are positive axes of Navigation Base Coordinate System.
2. Zero shaft and trunnion angles place the RR electrical boresight axis parallel to $+\underline{z}_{NB}$.
3. The antenna shaft axis is the outer gimbal axis and is parallel to $+\underline{y}_{NB}$.
4. The antenna trunnion axis is the inner gimbal axis and is orthogonal to the shaft axis and the RR electrical boresight axis.
5. Positive shaft rotation is clockwise motion of antenna as viewed along $+\underline{y}_{NB}$.
6. Positive trunnion rotation is clockwise motion of antenna as viewed along $+\underline{x}_{NB}$ when shaft angle is zero.

Figure 6.15-1 RR Shaft and Trunnion Angles

$$
\begin{aligned}
\underline{u}_D &= (x,\ y,\ z) \\
T(1) &= -\sin^{-1}(y) \\
T(2) &= 180^{\circ} - T(1) \\
\underline{u}_P &= (x',\ 0,\ z') = \mathrm{UNIT}(x,\ 0,\ z) \\
\cos\left[S(1)\right] &= z' \\
\sin\left[S(1)\right] &= x' \\
S(1) &= \mathrm{ARCTRIG}\left\{\sin\left[S(1)\right],\ \cos\left[S(1)\right]\right\} \\
S(2) &= 180^{\circ} + S(1)
\end{aligned}
\tag{6.15.2}
$$

where T (1) and S (1) are the shaft and trunnion angles for Mode 1 of the RR antenna, T (2) and S (2) are the corresponding angles for Mode 2, and ARCTRIG implies computing the angle, choosing either $\sin^{-1}$ or $\cos^{-1}$ so as to yield maximum accuracy.

5.6.15.3 Determination of RR Gyro Commands during RR Target Designation

When the RR is being designated towards the CSM, the commands issued to the RR CDU's for digital to analog conversion before being sent to the RR gyros are computed approximately every 0.5 seconds as follows: Let $C_S(1)$ and $C_T(1)$ be the shaft (S) and trunnion (T) commands to the RR CDU's for the antenna in Mode 1, and $C_S(2)$ and $C_T(2)$ be the corresponding commands for the antenna in Mode 2. Initially, the unit vector $\underline{u}_D$ defining the desired direction of designate in navigation base coordinates is obtained from stable member coordinates as follows:

$$\underline{u}_D = [SMNB]\ \mathrm{UNIT}\ (\underline{r}'_{LOS}) \tag{6.15.3}$$

where [SMNB] is defined in Section 5.6.3.2.1 and $\underline{r}'_{LOS}$ is the lag compensated range vector in Section 5.2.4.1. The commands are then computed as follows:

$$C_S(1) = K \left[\underline{u}_D \cdot \begin{pmatrix} \cos S \\ 0 \\ -\sin S \end{pmatrix} \right] \tag{6.15.4}$$

$$C_S(2) = -C_S(1) \tag{6.15.5}$$

$$C_T(1) = C_T(2) = -K \left[\underline{u}_D \cdot \begin{pmatrix} \sin T & \sin S \\ & \cos T \\ \sin T & \cos S \end{pmatrix} \right] \tag{6.15.6}$$

where S and T are the present shaft and trunnion angles and K is a scale factor to establish the proper number of bits in the RR CDU's. A limit check is made to insure that no more than 384 bits are sent to an RR CDU.

5.6.16 TARGET ΔV PROGRAM

The purpose of the Target ΔV Program is to update the estimated CSM state vector in accordance with the maneuver $\Delta \underline{V}$ which is voice-linked to the LM from the CSM and then entered into the LGC as described in Sections 5.2.1 and 5.2.4.2. The logic for the program is shown in Fig. 6.16-1. In the figure, $\Delta \underline{V}$ is the maneuver velocity change expressed in a CSM local vertical coordinate system, and $t_{\Delta V}$ is the time of the maneuver.

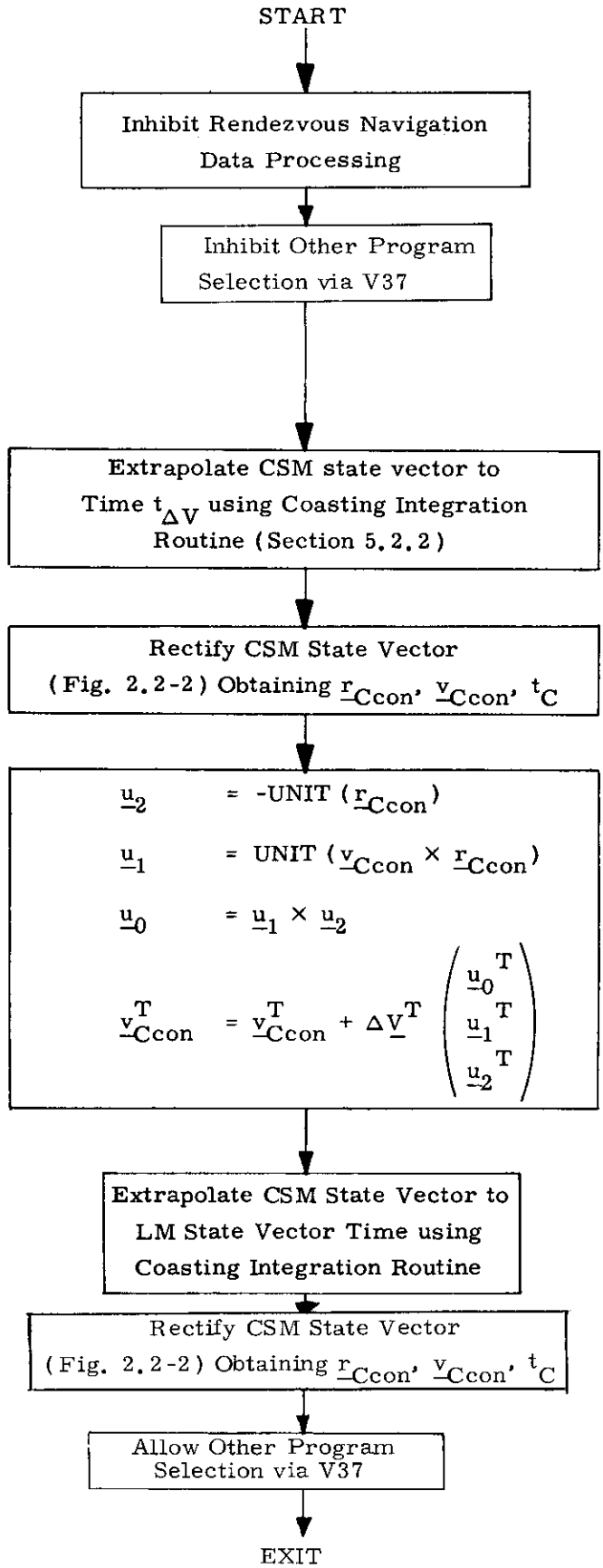


Figure 6.16-1 TargetΔV Program

5.6.17 ORBIT PARAMETER DISPLAY ROUTINE

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 contained in Figs. 6.17-1 through 6.17-3. The following is a list of important parameter definitions which apply to these figures.

$\left.\begin{matrix}\underline{r}\\ \underline{v}\end{matrix}\right\}$: State vector of the selected vehicle

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

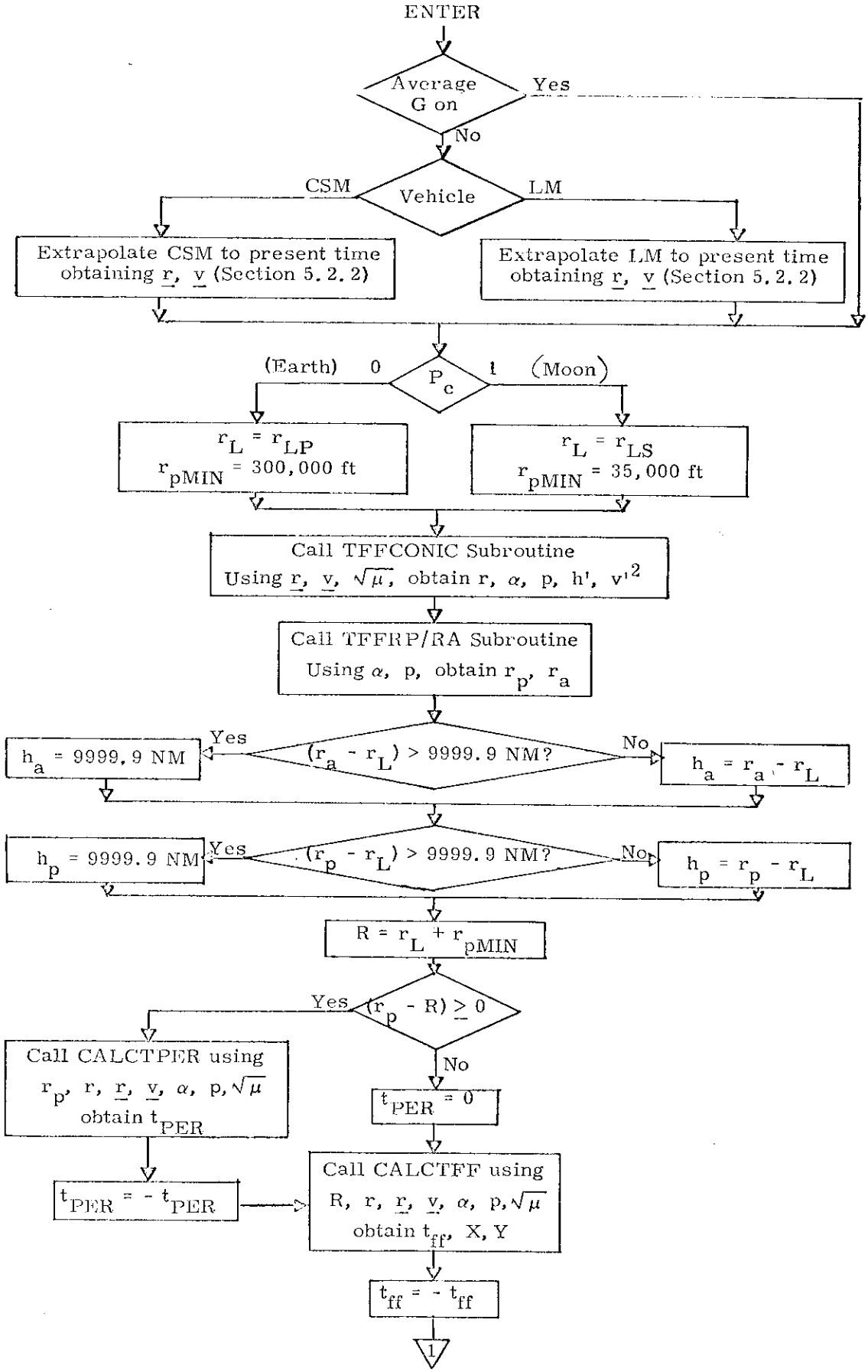


Figure 6.17-1 Orbital Parameter Display Routine (page 1 of 2)

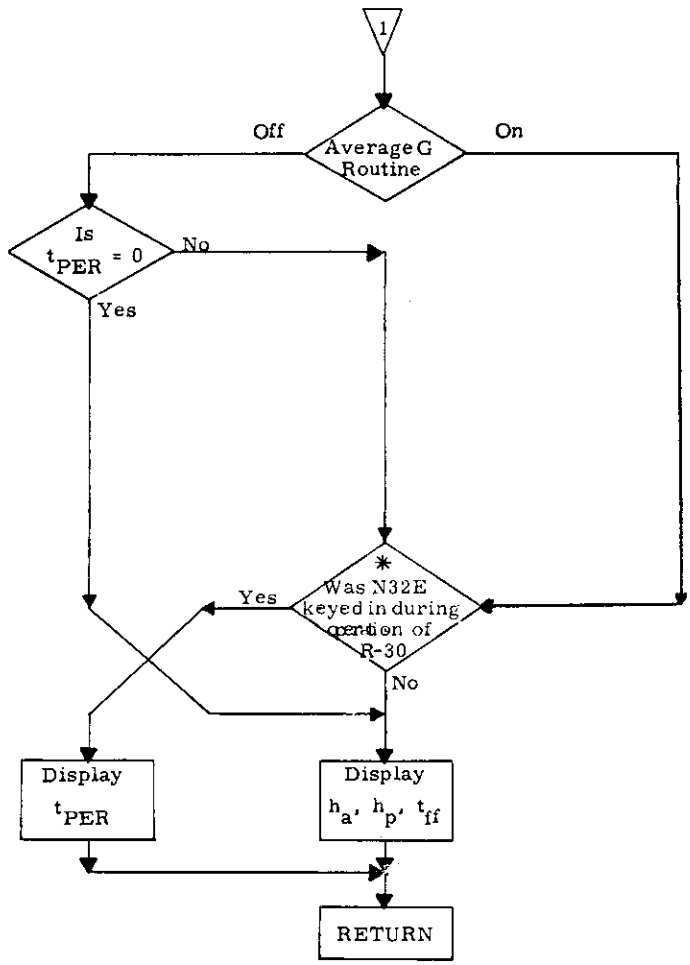


Figure 6.17-1 Orbital Parameter Display Routine
(page 2 of 2)

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, if and only if AVERAGE-G is off, although this is not shown explicitly in the above Figure.

* For full explanation of displays and DSKY options, see R30 description in Section 4 GSOP.

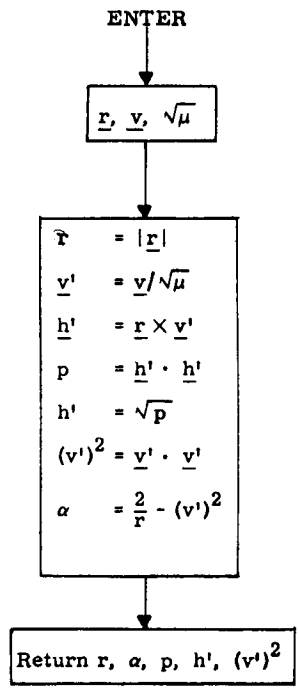


Figure 6.17-2a TFFCONIC Subroutine

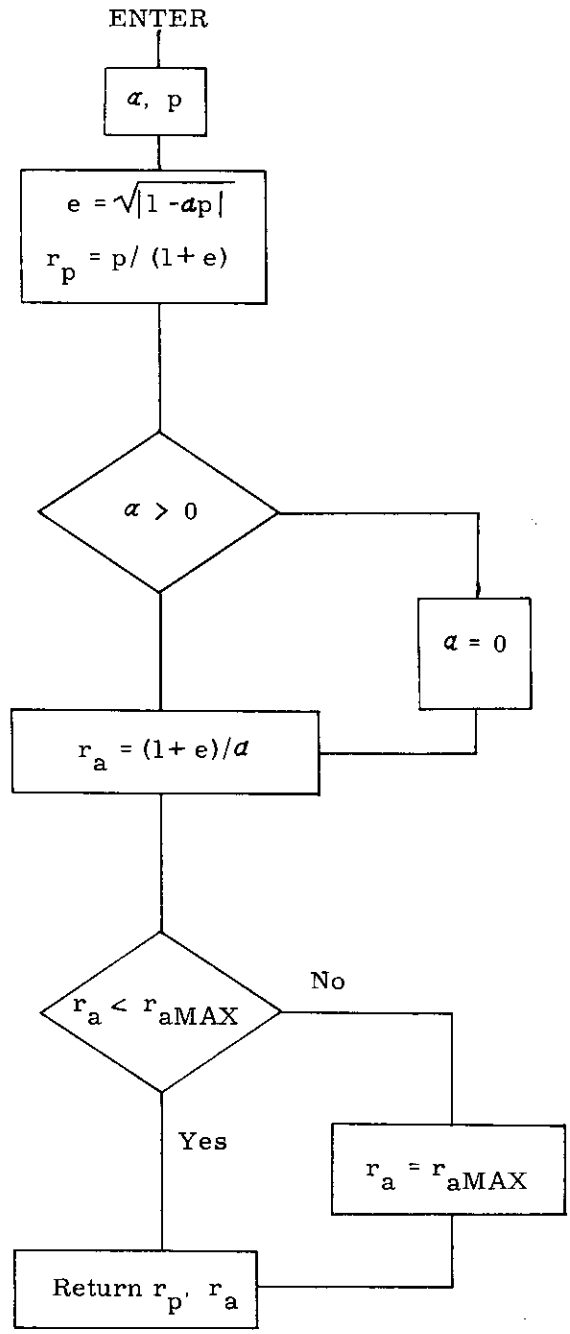
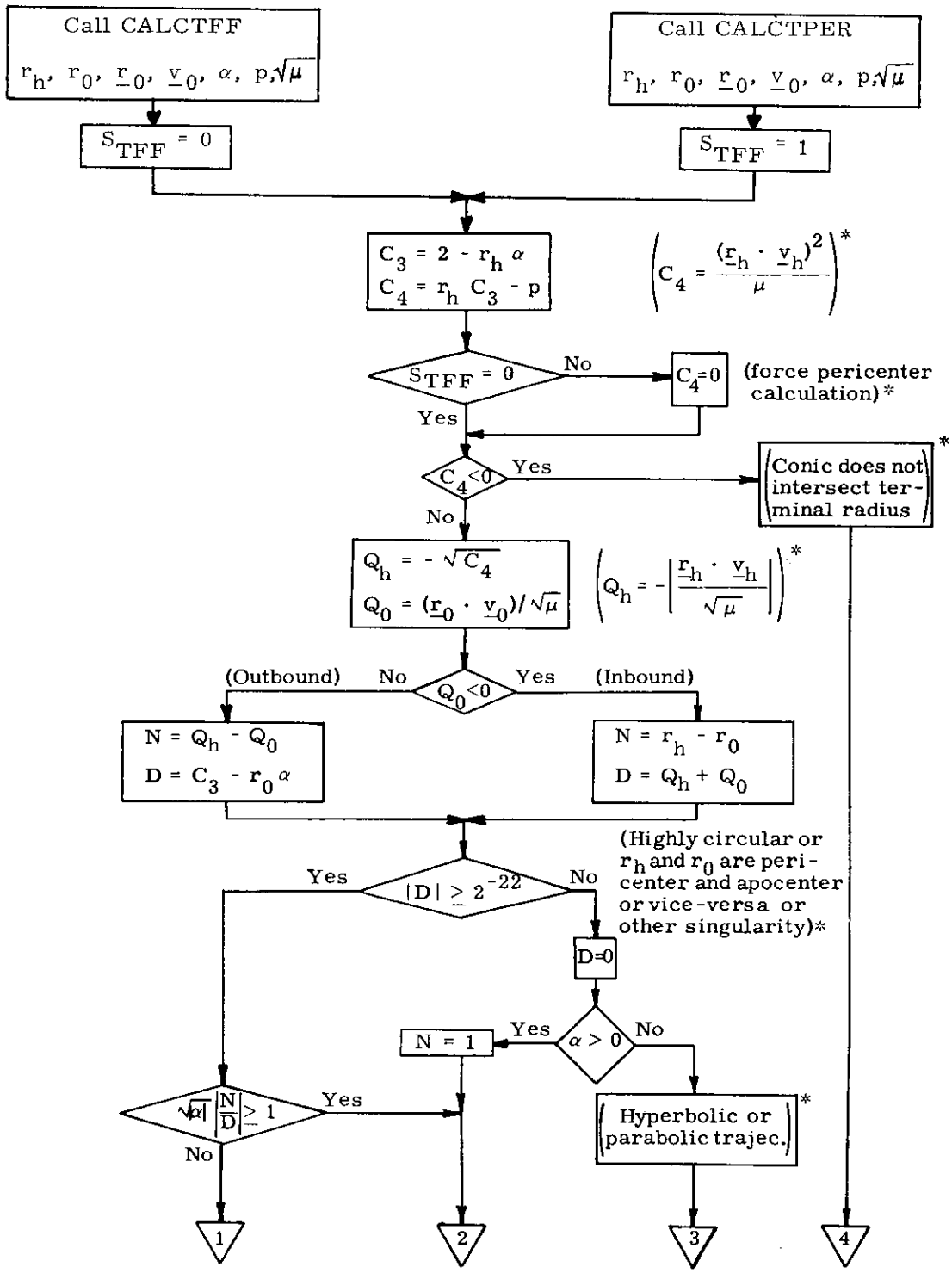


Figure 6.17-2b TFFRP/RA Subroutine



* Supplementary Information

Fig. 6.17-3 CALCTFF/CALCTPER Subroutine
(page 1 of 2)

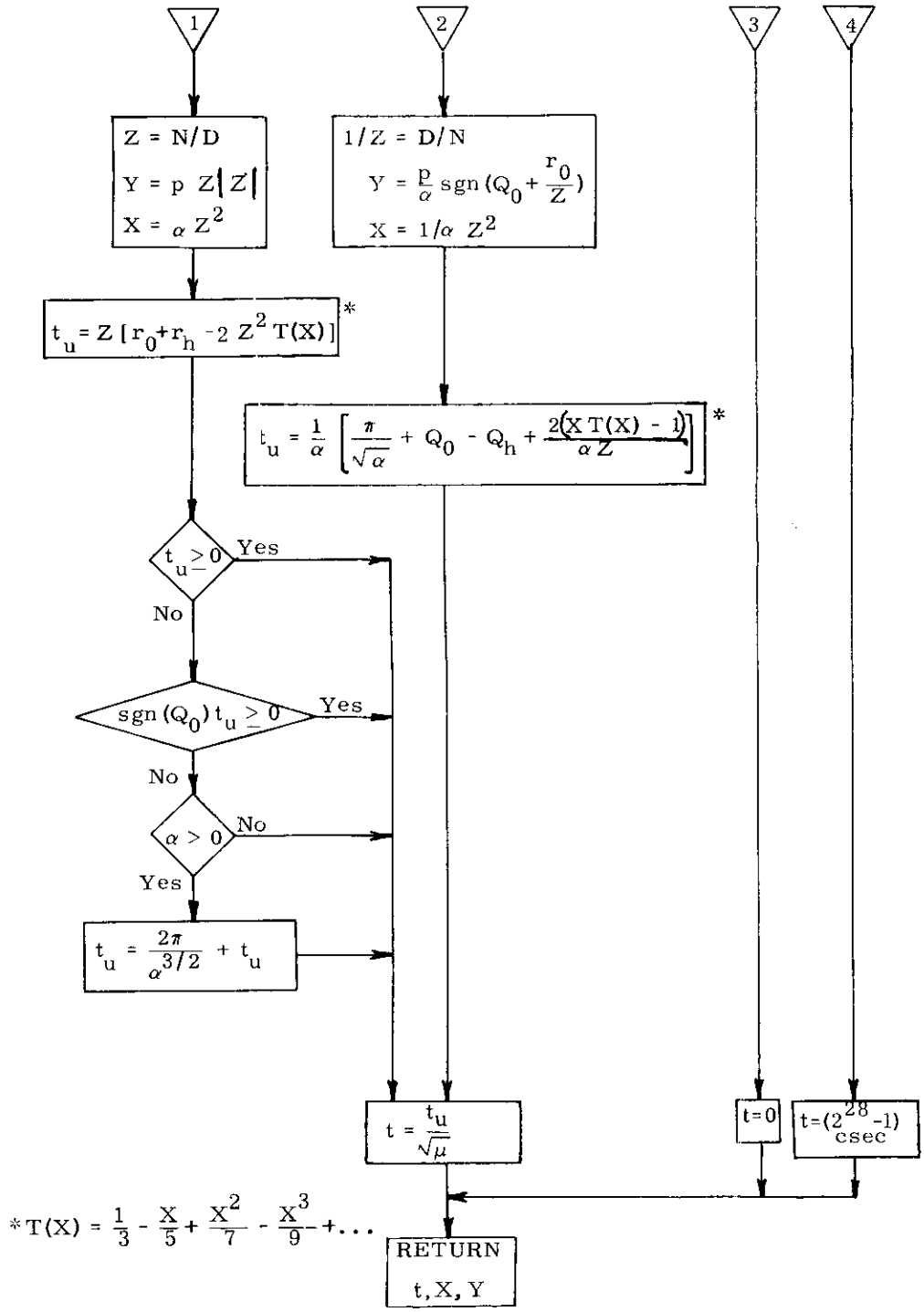


Figure 6.17-3 CALCTFF/CALCTPER Subroutine
(page 2 of 2)

5.6.18 POWERED FLIGHT RR DESIGNATE ROUTINE

The purpose of the Powered Flight RR Designate Routine (R-29 of Section 4) is to establish lock-on of the LM Rendezvous Radar (RR) with the transponder on the CSM and to read the RR data for downlink transmission during the lunar powered ascent phase. This routine will operate only when the Average-G Routine (Section 5.3.2) is being used. The routine is automatically enabled when the NOR29 flag is reset by P-12 at pitch-over in the powered ascent.

The routine is automatically terminated when the NOR29 flag is set at the end of program P-12. The astronaut can also terminate this routine by taking the RR mode control switch out of the LGC position which causes the RR to remove the RR Auto Mode discrete from the LGC. The routine designates the RR towards the CSM only when the line-of-sight (LOS) to the CSM is within the antenna angular tracking region of Mode 2 shown in Fig. 2.4-3.

The logic associated with routine R-29 and its associated subroutines is shown in Figs. 6.18-1 through 6.18-3. This routine is called every 2 seconds whenever the Average-G Routine is being used. When the NOR29 flag is not set it is seen in Fig. 6.18-1 that the status of various flags and discretes are checked before designating the RR. The indications provided by some of the flags and discretes are given in Section 5.2.4. The

[X] Revised LUMINARY
[ ] Added GSOP # 567 PCR # 845 Rev. 7 Date 11/69

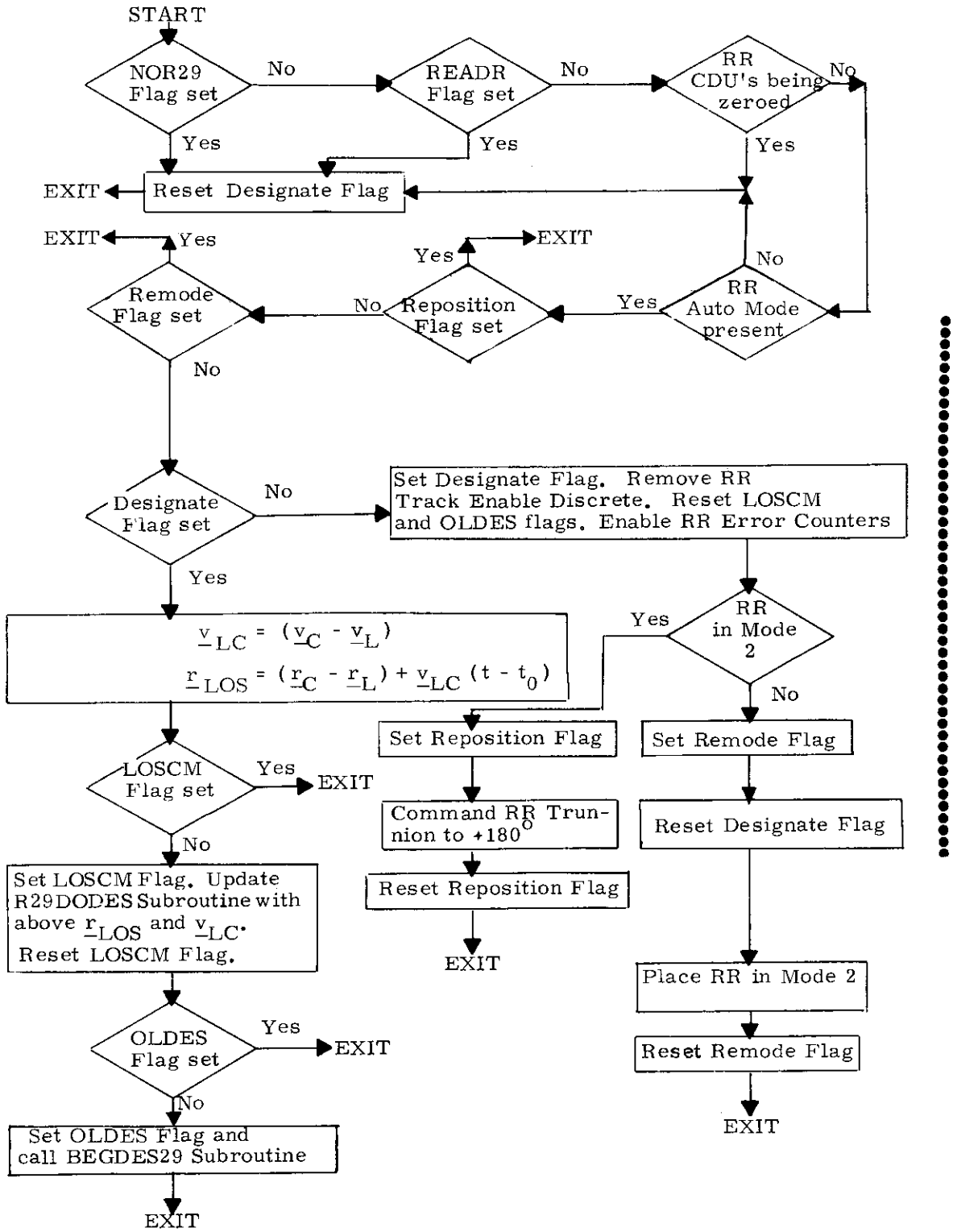


Figure 6.18-1 Powered Flight RR Designate Routine

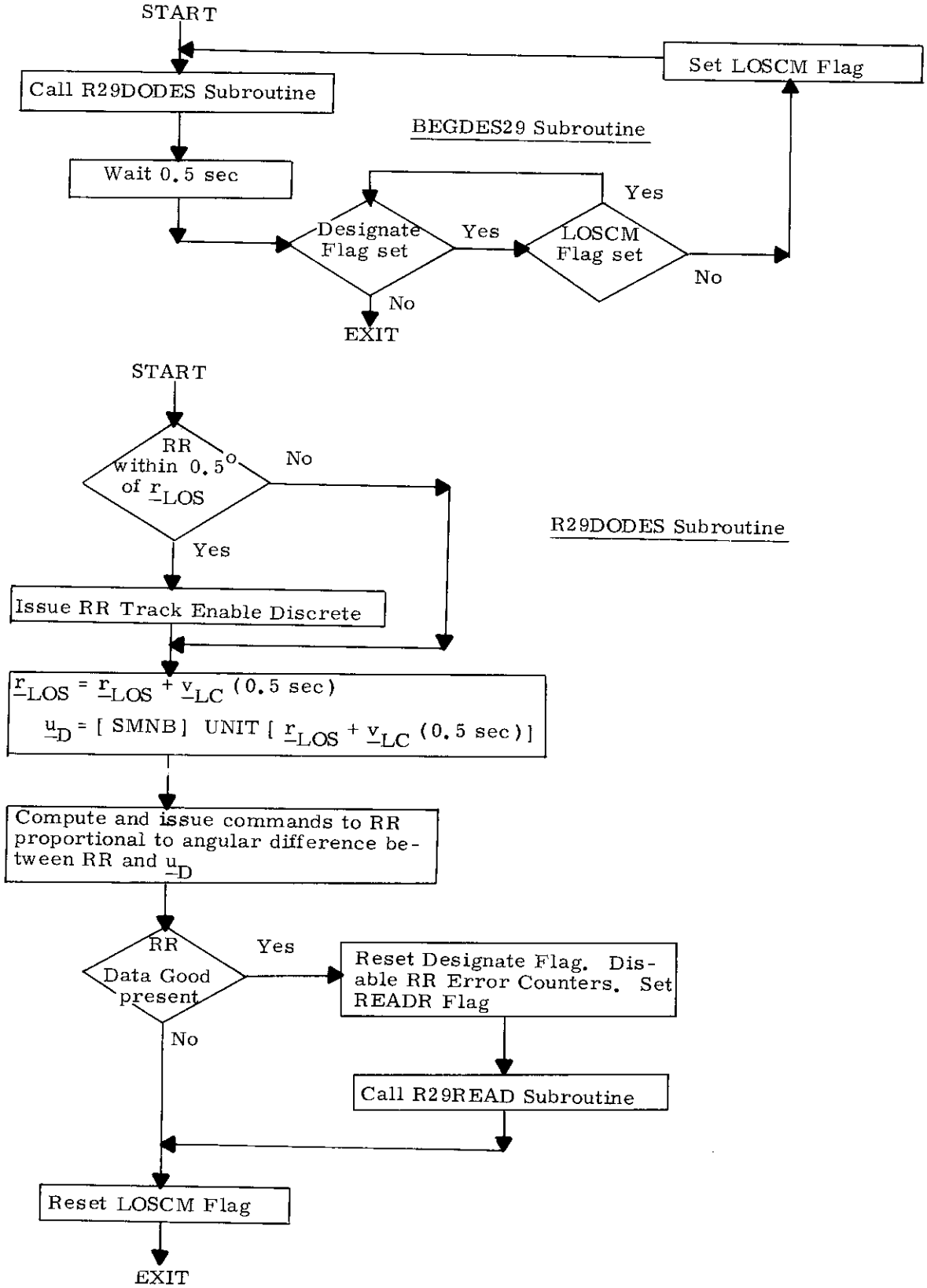


Figure 6.18-2 BEGDES29 and R29DODES Subroutines

READR flag is set when the RR achieves lock-on. It remains set during the RR data read operation until the RR loses lock-on or the routine is terminated. The Designate flag is set by this routine when it is designating the RR towards the CSM.

At the beginning of RR designation it is seen in the middle of Fig. 6.18-1 that the Designate flag is set, the RR Track Enable discrete is removed from the RR, the LOSCM and OLDES flags are reset, the RR CDU Error Counters are enabled, and steps are taken to insure that the RR antenna is in Mode 2 and the RR trunnion angle is $+180^{\circ}$. It should be noted that whenever the antenna is transferred from Mode 1 to 2, (i.e. a remode) the resulting trunnion angle is $+180^{\circ}$ (see Section 5.2.4.1.1). After establishing the RR antenna in the desired position, the routine computes the LOS range vector $\underline{r}_{LOS}$ to the CSM and the relative velocity $\underline{v}_{LC}$ of the CSM with respect to the LM as follows:

$$\underline{v}_{LC} = (\underline{v}_C - \underline{v}_L)$$

$$\underline{r}_{LOS} = (\underline{r}_C - \underline{r}_L) + \underline{v}_{LC}(t - t_0)$$

where $\underline{r}_C$, $\underline{v}_C$, $\underline{r}_L$, and $\underline{v}_L$ are respectively the position and velocity vectors of the CSM and LM in IMU stable member coordinates for the last piptime (t_0) used by the Average-G Routine. The term "piptime" refers to the time when the accelerometers are read. It should be noted that $\underline{r}_{LOS}$ is updated to the present time (t) by use of the approximate correction $\underline{v}_{LC}(t - t_0)$. This correction eliminates any staleness in time associated with t_0.

If this is the first time $\underline{r}_{LOS}$ and $\underline{v}_{LC}$ have been computed for RR designation, it is seen in Fig. 6.18-1 that the R29DODES subroutine will be updated with these vectors and the BEGDES29 subroutine will be called due to the fact that the LOSCM and OLDES flags were reset at the beginning of Routine R-29. However, note in Fig. 6.18-1 that the LOSCM flag is set during the update of R29DODES so as to prevent the BEGDES29 subroutine in Fig. 6.18-2 from calling the R29DODES subroutine until after the update. In addition, it is seen in Fig. 6.18-2 that the LOSCM flag is also set by the BEGDES29 subroutine prior to calling the R29DODES subroutine, and reset at the end of R29DODES, so as to prevent an update during the operation of R29DODES. In Fig. 6.18-1 it is seen that the OLDES flag is only used to place the BEGDES29 subroutine into operation at the start of RR designation.

In Fig. 6.18-2 it is seen that the purpose of the R29DODES subroutine is to compute and issue commands to the RR. When the RR antenna is within 0.5 degrees of $\underline{r}_{LOS}$ the RR Track Enable discrete is issued to the RR, enabling its angle tracking servos to track the target if its range-rate tracking network has already acquired the target. The 0.5 degree check is made in the same manner as described in Section 5.2.4.1.1. Note in Fig. 6.18-2 that the R29DODES subroutine, in addition to receiving periodically (usually every 2 seconds) an updated $\underline{r}_{LOS}$ from Fig. 6.18-1, also performs its own update of $\underline{r}_{LOS}$ for use the next time R29DODES is called (approximately 0.5 seconds later):

$$\underline{r}_{LOS} = \underline{r}_{LOS} + \underline{v}_{LC}\,(0.5 \text{ sec.})$$

Also note that the vector $\underline{u}_D$ used to compute the commands to the RR is the present $\underline{r}_{LOS}$ advanced one second into the future. This correction to $\underline{r}_{LOS}$ for RR designation essentially compensates for the lag error associated with the type of control system existing between the RR and the LGC. The method used to compute the commands for the RR is given in Section 5.6.15.3. When the RR Data Good discrete is received from the RR, signifying that the RR has locked-on in range and range-rate and has received the RR Track Enable discrete, the R29DODES subroutine terminates the RR designation process and calls the R29READ subroutine.

In Fig. 6.18-3 it is seen that R29READ subroutine calls the R29RDJOB subroutine every 2 seconds to obtain a complete set of RR data for downlink transmission where each set consists of the following:

1) Range rate - one 80 millisecond sample of raw range rate data
2) Range - one 80 millisecond sample of raw range data
3) A complete set of RR and IMU CDU angle readings
4) The time recorded for the midpoint of the 80 millisecond range rate sampling interval

Note that the logic associated with the R29RDJOB subroutine is somewhat similar to that described for the data read portion of the RR Data Read Routine in Section 5.2.4.2.1. If the RR Data Good discrete is removed from the LGC by the RR due to the loss of lock-on, the Tracker Fail Light is turned on and the READR flag is reset, causing termination of the data read process and re-initiation of RR designation.

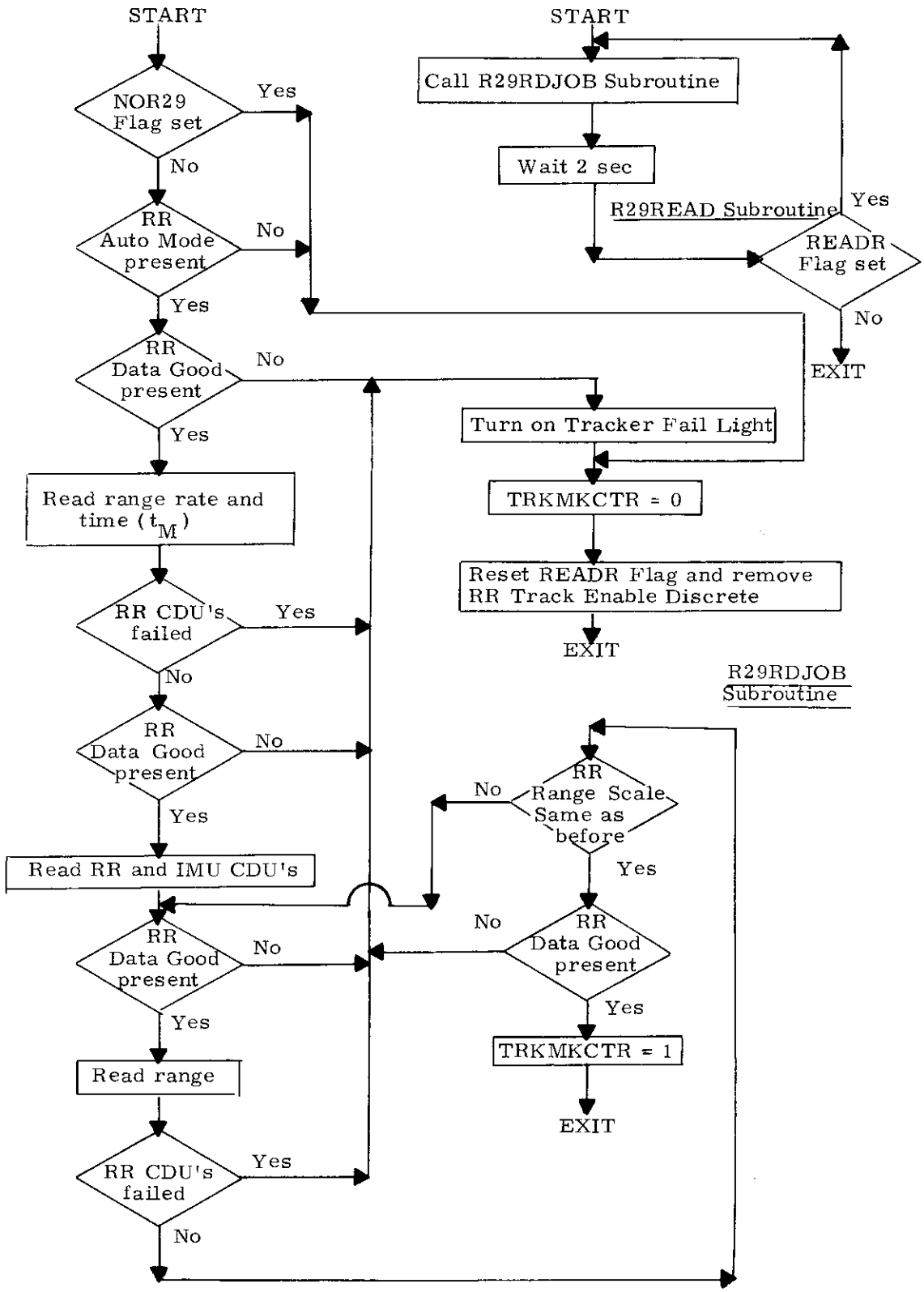


Figure 6.18-3 R29READ and R29RDJOB Subroutines

It should be noted that the RR Monitor Routine of Section 5.2.4.3 does not monitor the RR antenna gimbal angles during the operation of routine R-29 since the No Angle Monitor flag is set in program P-12 prior to initiating routine R-29.

5.6.19 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, velocity and bias 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 and RMS Bias error Δb_{RMS} is illustrated in Fig. 6.19-1. The vectors $\underline{w}_i$ are partitions of the W matrix as defined in Eq. (2.2.19) of Section 5.2.2.4. The variables w_{rr}, w_{rv}, $w_{\ell r}$ and $w_{\ell v}$ are W matrix initialization parameters, and RENDWFLG is the W matrix validity flag. See Sections 5.2.4.2.2 and 5.2.5.4 for further definitions and usage of these terms.

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[ ] Added GSOP # 567 PCR # 732 Rev. 7 Date 11/69

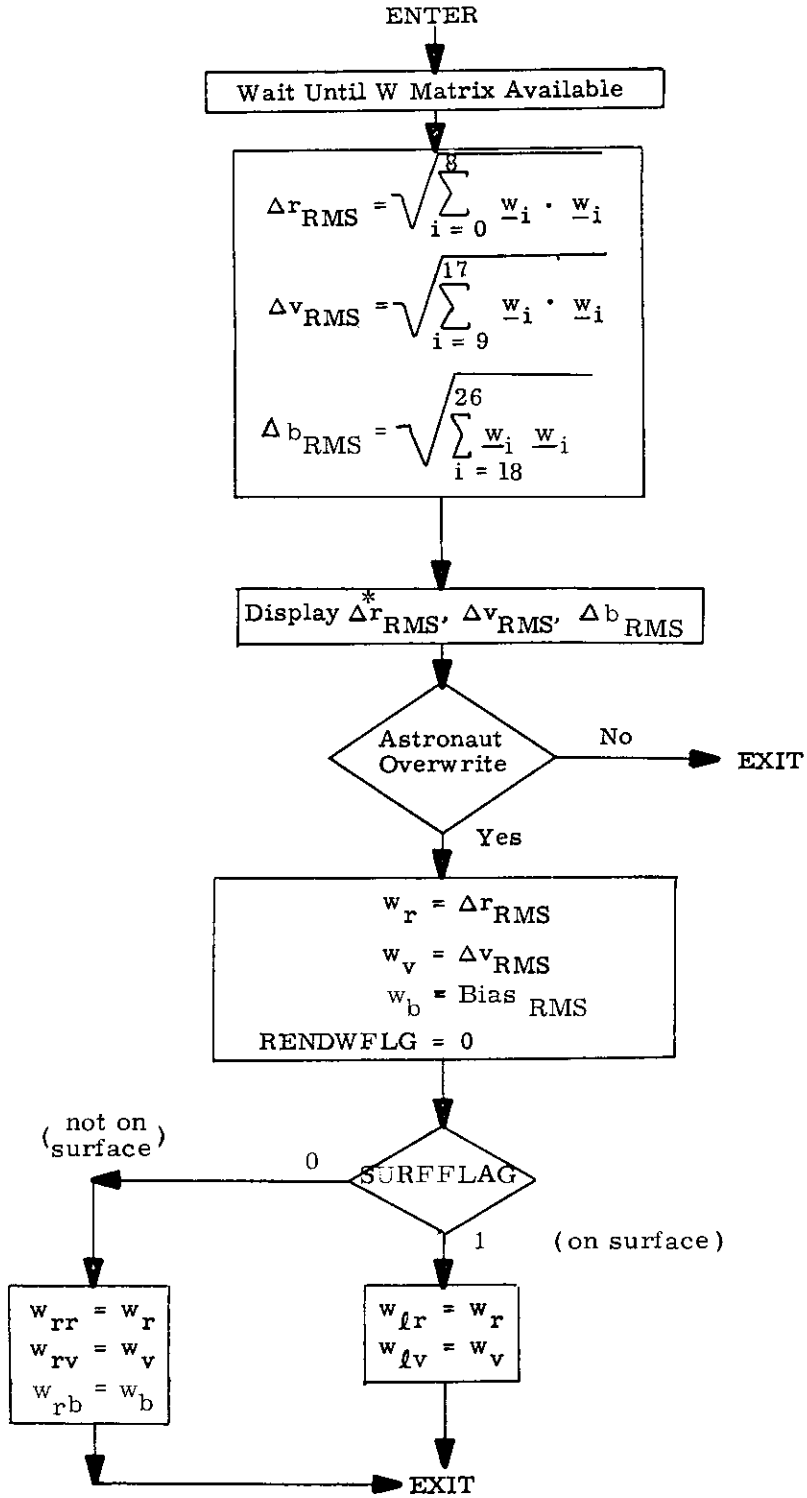

Figure 6.19-1 RMS Position and Velocity Error Display Logic Diagram

* Largest value displayed will be 99997 ft. for $\Delta r_{RMS} > 30479$ meters

5.6.20 LR SPURIOUS TEST ROUTINE

The purpose of the LR Spurious Test Routine (R-77 of Section 4) is to read out the range and velocity data of the landing radar and place it on the LGC down-link during the landing radar spurious return flight tests. This is a special routine for earth orbital tests of the LR. The routine sequentially obtains individual data samples (80 milliseconds duration each) from each of the three velocity beams and the range beam once per second. This data is placed on the down-link regardless of the status of the LR Range Data Good and LR Velocity Data Good discretes. This routine is instigated and terminated by the astronaut and is capable of performing the above data readout prior to, during, and after a DPS maneuver.

Before performing the flight test it assumed that the astronaut will place the LR antenna in either of its two positions by use of the LR manual controls provided for this purpose.

It should be noted that the status of all LR discretes (Range Data Good, Velocity Data Good, Range Low Scale, Antenna Position One, and Antenna Position Two) is already indicated at least once every two seconds on the down-link list.

5.6.21 RR LOS AZIMUTH AND ELEVATION DISPLAY

To permit the astronaut to monitor the LOS of the RR in either antenna mode, there exists a special DSKY verb which converts the RR shaft and trunnion CDU angles to more meaningful angles (azimuth and elevation) for display on the DSKY.

The azimuth and elevation angles are shown in Fig. 6.21-1 where the azimuth angle (AZ) is defined as the angle between the RR antenna LOS and the X-Z navigation base plane. The azimuth angle changes from 0 to +90 degrees as the LOS moves from the X-Z plane toward the $+Y_{NB}$ axis and changes

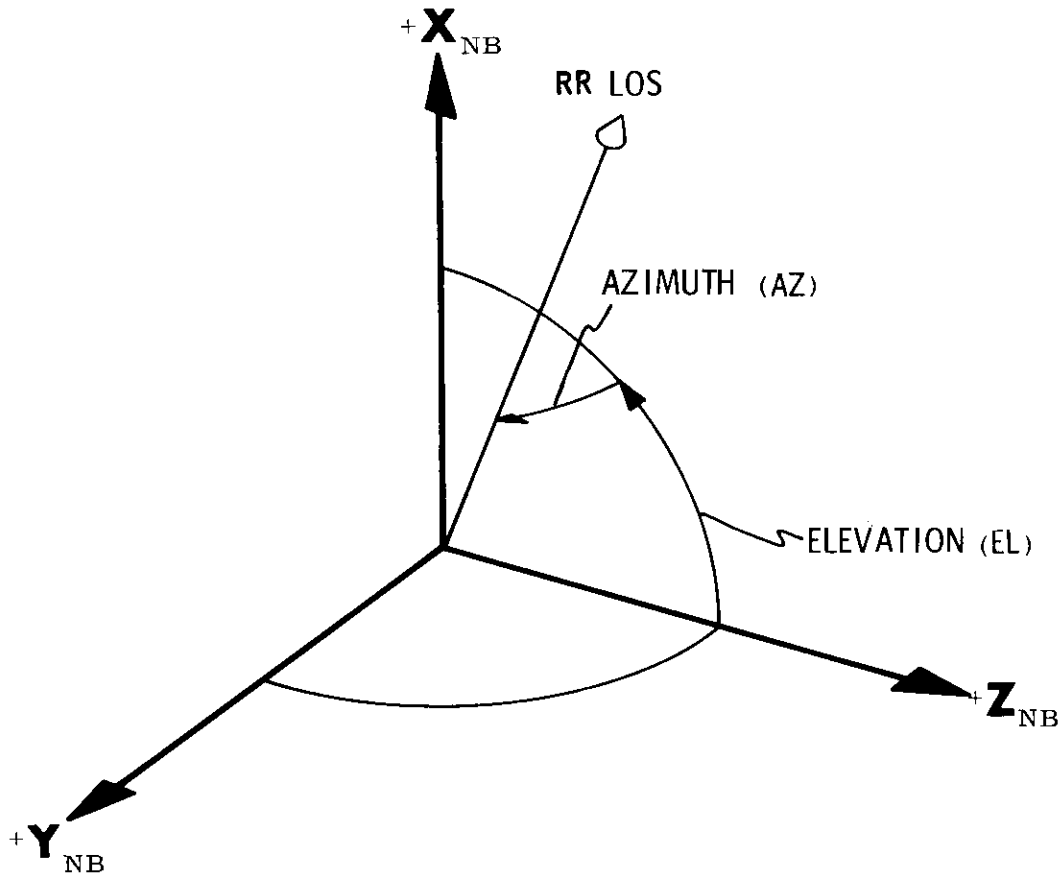

Figure 6.21-1 RR LOS Azimuth and Elevation Angles.

from 0 (360) to +270 deg as the LOS moves from the X-Z plane toward the $-Y_{NB}$ axis.

The elevation angle (EL) is defined as the angle between the $+Z_{NB}$ axis and the projection of the LOS in the X-Z plane. The elevation angle changes from 0 to +360 deg as the LOS projection rotates positively (right hand rule) about the $+Y_{NB}$ axis. The value of the elevation angle is indeterminate when the LOS is coincident with either the $+Y_{NB}$ or $-Y_{NB}$ axis. Only the $+Y_{NB}$ orientation is physically possible with the RR, and there the elevation angle displayed is +90 deg.

When the RR antenna is in Mode 1, the angles computed and displayed by this verb are equivalent to the trunnion and shaft angles displayed in the RR/LR Self Test Routine of Section 5.6.14.

The method used to compute the azimuth and elevation angles is given in Fig. 6.21-2.

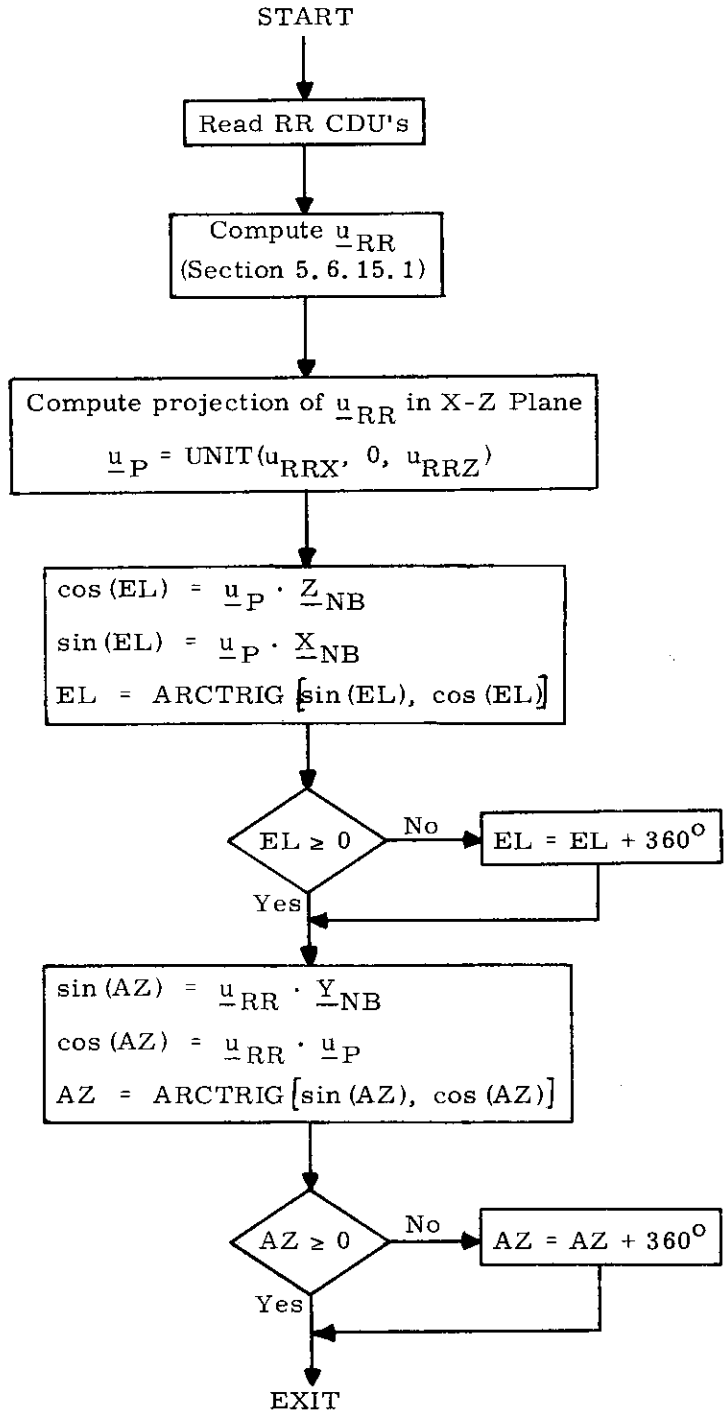

Figure 6.21-2 Computation of RR LOS Azimuth and Elevation Angles.

5.7 ERASABLE MEMORY PARAMETER LIST

This section presents a list of selected parameters required for various program operations. It should be noted that this is a very limited LGC erasable parameter list. The objective of this selected list is to identify those parameters that should be stored in erasable memory and are required primarily to initialize the operation of programs and routines. In most cases these parameters cannot be originated within the LGC and must be stored prior to the mission. Some parameters then 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 LGC program.

Section No.	GSOP Name	LGC Name
5.2.2.3	J_{22}	
	C_{31}	
5.2.2.6	$\underline{r}_{C0}$, $\underline{r}_{L0}$	
	$\underline{v}_{C0}$, $\underline{v}_{L0}$	
	$\underline{r}_{C\ con}$, $\underline{r}_{L\ con}$	
	$\underline{v}_{C\ con}$, $\underline{v}_{L\ con}$	
	$\underline{\delta}_C$, $\underline{\delta}_L$	
	$\underline{\nu}_C$, $\underline{\nu}_L$	
	t_C, t_L	
	τ_C, τ_L	
	x_C, x_L	
	P_C, P_L	

Section No.	GSOP Name	LGC Name
5.2.4.2.2	$\delta\beta$	
	$\delta\theta$	
	0	
	var_R	
	var_{Rmin}	
	var_V	
	var_{Vmin}	
	var_β	
	var_θ	
	δr_{MAX}	
	δv_{MAX}	
	w_{rr}	
	w_{rv}	
	w_β	
	w_θ	
5.2.5.4	$w_{\ell r}$	
	$w_{\ell v}$	
5.3.2	$\Delta\underline{v}(\Delta t)$	
5.3.3.3.1	$\Delta\underline{V}_{LV}$	
	t_{IG}	
	m	
	S_E	
5.3.3.3.2	SR	
	UT	
5.3.3.3.3	$\Delta t_{Tail\text{-}off}$	

Section No.	GSOP Name	LGC Name
5.3.4.3	h_m	
	k_h	
	k_{VX}	
	k_{VY}	
	k_{VZ}	
	LRVF	
	LRVMAX	
	LRWVFF	
	LRWVFX	
	LRWVFY	
	LRWVFZ	
5.3.4.4	α_1	
	β_1	
	α_2	
	β_2	
	t_{SW}	
	q_{SW}	
5.3.4.5	DELQFIX	
	VELBIAS	

Section No.	GSOP Name	LGC Name
5.3.4.6 (Note 1)	m	MASS
	t_{LAND}	TLAND
	$\underline{D}LAND$	DLAND
	$\underline{r}_{LSL}$	RLS
	r_{IGZG}	RIGNZ
	r_{IGXG}	RIGNX
	v_{IGG}	VIGN
	K_X	KIGNX/B4
	K_Y	KIGNY/B8
	K_V	KIGNV/B4
	DELTTRIM	ZOOMTIME
	TTT^*_{CGPI} (BRAK)	TCGIBRAK
	TTT^*_{CGPF} (BRAK)	TCGFBRAK
	TTT^*_{END} (BRAK)	TENDBRAK
	$GAIN^*$ (BRAK)	GAINBRAK
	$\underline{r}^*_{TG}$ (BRAK)	RBRFG
	$\underline{v}^*_{TG}$ (BRAK)	VBRFG
	$\underline{a}^*_{TG}$ (BRAK)	ABRFG
	j^*_{TZG} (BRAK)	JBRFG* (Note 2)

(1) The landing maneuver PADLOADS share erasable locations with the Rendezvous Navigation Program P20. This places operating restrictions on P20 prior to lunar landing as described in Section 4.

(2) The LGC erasable JBRFG* is loaded with eight times the target jerk (in the units used by the descent guidance). Therefore, JBRFG* is equivalent to 8 j^*_{TZG} (BRAK), and likewise JAPFG* is equivalent to 8 j^*_{TZG} (APPR).

Section No.	GSOP Name	LGC Name
	DELTTTAP	DELTTFAP
	TTT^*_{CGPI} (APPR)	TCGIAPPR
	TTT^*_{CGPF} (APPR)	TCGFAPPR
	TTT^*_{END} (APPR)	TENDAPPR
	$GAIN^*$ (APPR)	GAINAPPR
	$\underline{r}^*_{TG}$ (APPR)	RAPFG
	$\underline{v}^*_{TG}$ (APPR)	VAPFG
	$\underline{a}^*_{TG}$ (APPR)	AAPFG
	j^*_{TZG} (APPR)	JAPFG* (Note 2)
	TAUVERT	TAUVERT
	$\underline{v}$VERTG	V2FG
	LEADTIME	LEADTIME
	AZBIAS ELBIAS OGABIAS	AZBIAS ELBIAS OGABIAS
	LAG	LAG/TAU
	MAXFORCE	MAXFORCE
	MINFORCE	MINFORCE
	RODSCALE	RODSCALE
	TAUROD	TAUROD
	ξ	
5.3.4.7	FLO	LOWCRIT
	FHI	HIGHCRIT

☒ Revised
☐ Added GSOP # 567 PCR # 968 Rev. 7 Date 11/69

Section No.	GSOP Name	LGC Name
5.3.5.3	t_{IG}	
	R_D	
	Y_D	
	$\dot{R}_D$	
	$\dot{Y}_D$	
	$\dot{Z}_D$	
5.3.5.9	R_{AMIN}	RAMIN

Section No.	GSOP Name	LGC Name
5.4.2.2	N	
	t_3	

Section No.	GSOP Name	LGC Name
5.4.2.4	t	
	ωt	
	$\Delta \underline{V}_{TPI}$ (LV)	
5.4.2.5	$\delta\tau_3$	
	$\delta\tau_7$	
	$\Delta \underline{V}$ (LV)	
5.4.3.1.3	J_1	J1PARM
	J_2	J2PARM
	K_1	K1PARM
	K_2	K2PARM
	θ_C	THETCRIT
5.5.2	A_X	
	A_Y	
	A_{Z0}	
	t_0	
	$\underline{\ell}_M$	
5.6.3	AZ_1 thru AZ_6	
	EL_1 thru EL_6	
	AZ	
	EL	

Section No.	GSOP Name	LGC Name
5.6.13	SFE_1, SFE_2, SFE_3	
	$BIAS_1$, $BIAS_2$, $BIAS_3$	
	ADIAX, ADIAY, ADIAZ	
	ADSRAX, ADSRAY, ADSRAZ	
	NBDX, NBDY, NBDZ	

5.8 FIXED MEMORY CONSTANTS

Section 5.8.1 contains a list and the numerical values of those fixed memory constants in Sections 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 5.8.2. Explanatory comments are noted in Section 5.8.1 where applicable and listed in Section 5.8.3. It should be noted that only one section number is given for a constant in the list of Section 5.8.1, 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 5.8.1.

5.8.1 Fixed Constants

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.2.2.1	$\mu_P \begin{cases} \mu_E \\ \mu_M \end{cases}$		m^3/s^2	0.3986032×10^{15}	2,3,4	
			m^3/s^2	0.4902778×10^{13}	2,3,4	
5.2.2.3	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	
	J_{2M}		–	0.207108×10^{-3}	2,3,4	
	J_{3M}		–	$-2.1(10)^{-5}$	2,3,4	
	J_{4M}		–	0	2,3,4	
	r_M		m	1,738,090	2,3,4	
5.2.2.6	ϵ_t		csec	3.0	–	1
5.2.4.2.1	f_{BRR}		cps	212,500	14	
	$f_{BRR}\tau_{RR}$		–	17,000	5	
	k_{RR}		fps/bit	-0.6278	5,14,15	
	k_{R1}		ft/bit	75.04	5,14,15	
	k_{R2}		ft/bit	9.38	5,14,15	

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.2.4.2.2	var_{IMU}		$(mr)^2$	1.0	6	
5.2.5.3	ω_M		rad/sec	$2.66169948 \times 10^{-6}$	2,3,4	
5.3.3.3.1	F_{DPS}		pounds	9817.5	29,30	24
	F_{APS}		pounds	3500	5,17	
	F_{RCS}		pounds	400 or 200	5,17	
5.3.3.3.3	ΔV_K(DPS) LM only		cm/sec	36	19	2
	ΔV_K(DPS) CSM docked		cm/sec	12	19	2
	ΔV_K(APS)		cm/sec	308	19	2
	$\dot{m}$(APS)		lb/sec	11.32	30	
	K_1		kg-m/cs	124.55	18	
	K_2		kg-m/cs	31.138	18	
	K_3		$kg\text{-}m/cs^2$	1.5569	18	
	K_4		pounds	1050	5, 17	
	V_e(DPS)	DPSVEX	m/sec	2955.889	29, 30	24
	V_e(APS)	APSVEX	fps	9942	30	25
	F_L		pounds	200	17	

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.3.3.4	$\Delta t_{Tail\text{-}off}$(DPS)		csec	-38	19, 26	
	$\Delta t_{Tail\text{-}off}$(APS)		csec	-17.65	31	
	$\Delta t_{Tail\text{-}off}$(P70)		csec	-23.68	32	
5.3.4.3	VUP		ft/sec	6,000	24	
	Δt		sec	2		8
5.3.4.4	ξ		deg	20.380	20	
	τ_{VMES}		csec	17		15
	f_B		cps	153,600	14,16	
	$f_B \tau_{LR}$		–	12,288.2	14,16	
	k_{XA}		fps/bit	-0.6440	14,16	
	k_{YA}		fps/bit	1.212	14,16	
	k_{ZA}		fps/bit	0.8668	14,16	
	k_{LR1}		ft/bit	5.395	14,16	
	k_{LR2}		ft/bit	1.079	14,16	

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.3.4.6	GUIDDURN	GUIDDURN	sec	664.40		23
	AF_{TRIM}	TRIMACCL	m/sec^2	.350133		14
	$\Delta\Delta T_{REDES}$	N/A	sec	4		Note (11,1) of the Guidance-and-Control Routine
	k_a	AZEACH	rad	.03490	21,22,23	9
	k_e	ELEACH	rad	.008726	21,22,23	9
	u_{XCRIT}	DEPRCRIT	rad	-.02		22
	FRAC	HIGHESTF	newtons	43,455		17
	qmax	PROJMAX	–	.4226	23	10
	qmin	PROJMIN	–	.2588	23	10
5.3.4.7	BITPERF	SCALEFAC	bits/newton	.079796		17
	FMAX	FMAXPOS	newtons	43,455		17
	FSAT	FMAXODD	newtons	48,145		17
	FEXT	FEXTRA	newtons	51,331		19
	FRATE	N/A	newtons/sec	40,102		17
	τ_{th}	THROTLAG	sec	0.2		18
5.3.5.4	a_T(APS)		m/sec^2	3.2883		12
	τ (APS)		sec	919.02		12
	$1/\Delta V$		sec/m	.152		13

Section No.	GSOP Name	AGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.3.5.9	ΔV_{min}		m/sec	3.56		26
	A_T (RCS)		m/sec^2	0.785		16
5.4.3.1.2	$\dot{m}$ (DPS)		lb/sec	32.62	29, 30	24
5.5.1.2	(Kepler) ϵ_t		–	2^{-22}	12	
	(Lambert) ϵ_t		–	2^{-19}	12	
	ϵ_x (earth)		$m^{1/2}$	2^{-12}	12	
	ϵ_x (moon)		$m^{1/2}$	2^{-13}	12	
	ϵ_c		–	2^{-23}	12	
	k_1		–	2^{-17}	12	
5.5.2	ω_E		rad/U-sec	$7.292115147 \times 10^{-5}$	8	
	B_0		rad	$4.091619030 \times 10^{-1}$	7, 8	3
	Ω_{I0}		rad	6.196536640	7, 8	3
	F_0		rad	5.209327056	7, 8	3
	$\dot{B}$		rad/U-sec	$-7.197573418 \times 10^{-14}$	7, 8	3
	$\dot{\Omega}_I$		rad/U-sec	$-1.070470170 \times 10^{-8}$	7, 8	3

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.5.2	$\dot{F}$		rad/U-sec	$2.672404256 \times 10^{-6}$	7, 8	3
	C_I		–	$9.996417320 \times 10^{-1}$	7, 8	3
	S_I		–	$2.676579050 \times 10^{-2}$	7, 8	3
5.5.3	a		m	6,378,166	2, 3, 4	
	b		m	6,356,784	2, 3, 4	
	r_{LP}		m	6,373,338	11	
5.5.4	K_1		–	0.917455029	9, 10	4
	K_2		–	0.035711455	9, 10	4
	K_3		–	0.397839501	9, 10	4
	K_4		–	0.082353949	9, 10	4
	LOM_O		rad	5.122570	9, 10	4
	LOM_R		rad/sec	2.661699×10^{-6}	9, 10	4
	A		deg	6.2160	9, 10	4
	B		deg	1.2619	9, 10	4
	$OMEGA_A$		rad/sec	2.6392078×10^{-6}	9, 10	4
	$OMEGA_B$		rad/sec	2.2725641×10^{-6}	9, 10	4
	$PHASE_A$		rad	3.3350170	9, 10	4
	$PHASE_B$		rad	3.6779607	9, 10	4

Section No.	GSOP Name	LGC Name	Units	Value	Reference (Sec. 5.8.2)	Comments (Sec. 5.8.3)
5.5.4	LON_O		rad	6.19653704	9,10	4
	LON_R		rad/sec	$-1.07037037 \times 10^{-8}$	9,10	4
	LOS_O		rad	1.7258333	9,10	4
	LOS_R		rad/sec	1.9909838×10^{-7}	9,10	4
	C		deg	1.9171	9,10	4
	$OMEGA_C$		rad/sec	1.991076×10^{-7}	9,10	4
	$PHASE_C$		rad	-0.06951346	9,10	4
⋮ 5.5.13	T_{SS}		sec	360	–	5
5.6.15.3	K		bits/rad	2200.16	–	6
5.8.1	Star Table			See Fig. 8-1	–	7

Catalog No. (Octal)		Star Name	Vis. Mag.	X Coordinate	Y Coordinate	Z Coordinate
1	α	Andromedae (Alpheratz)	2.1	+.8748658918	+.0260879174	+.4836621670
2	β	Ceti (Diphda)	2.2	+.9342640400	+.1735073142	-.3115219339
3	γ	Cassiopeiae (Navi)	2.2	+.4775639450	+.1166004340	+.8708254803
4	α	Eridani (Achernar)	0.6	+.4917678276	+.2204887125	-.8423473935
5	α	Ursae Minoris (Polaris)	2.1	+.0130968840	+.0078062795	+.9998837600
6	θ	Eridani (Acamar)	3.4	+.5450107404	+.5314955466	-.6484410356
7	α	Ceti (Menkar)	2.8	+.7032235469	+.7075846047	+.0692868685
10	α	Persei (Mirfak)	1.9	+.4105636020	+.4988110001	+.7632988371
11	α	Tauri (Aldebaran)	1.1	+.3507315038	+.8926333307	+.2831839492
12	β	Orionis (Rigel)	0.3	+.2011399589	+.9690337941	-.1432348512
13	α	Aurigae (Capella)	0.2	+.1371725575	+.6813721061	+.7189685267
14	α	Carinae (Canopus)	-0.9	-.0614937230	+.6031563286	-.7952489957
15	α	Canis Majoris (Sirius)	-1.6	-.1820751783	+.9404899869	-.2869271926
16	α_2	Canis Minoris (Procyon)	0.5	-.4118589524	+.9065485360	+.0924226975
17	γ	Velorum (Regor)	1.9	-.3612508532	+.5747270840	-.7342932655
20	ι	Ursae Majoris (Dnoces)	3.1	-.4657947941	+.4774785033	+.7450164351
21	α	Hydrae (Alphard)	2.2	-.7742591356	+.6152504197	-.1482892839
22	α	Leonis (Regulus)	1.3	-.8608205219	+.4636213989	+.2098647835
23	β	Leonis (Denebola)	2.2	-.9656605484	+.0525933156	+.2544280809
24	γ	Corvi (Gienah)	2.8	-.9525211695	-.0593434796	-.2986331746
25	α	Crucis (Acrux)	1.0	-.4523440203	-.0493710140	-.8904759346
26	α	Virginis (Spica)	1.2	-.9170097662	-.3502146628	-.1908999176
27	η	Ursae Majoris (Alkaid)	1.9	-.5812035376	-.2909171294	+.7599800468
30	θ	Centauri (Menkent)	2.3	-.6898393233	-.4182330640	-.5909338474
31	α	Bootis (Arcturus)	0.2	-.7861763936	-.5217996305	+.3311371675
32	α	Coronae Borealis (Alphecca)	2.3	-.5326876930	-.7160644554	+.4511047742
33	α	Scorpii (Antares)	1.2	-.3516499609	-.8240752703	-.4441196390
34	α	Triangui Austr. (Atria)	1.9	-.1146237858	-.3399692557	-.9334250333
35	α	Ophiuchi (Rasalhague)	2.1	-.1124304773	-.9694934200	+.2178116072
36	α	Lyrae (Vega)	0.1	+.1217293692	-.7702732847	+.6259880410
37	σ	Sagittarii (Nunki)	2.1	+.2069525789	-.8719885748	-.4436288486
40	α	Aquilae (Altair)	0.9	+.4537196908	-.8779508801	+.1527766153
41	β	Capricorni (Dabih)	3.2	+.5520184464	-.7933187400	-.2567508745
42	α	Pavonis (Peacock)	2.1	+.3201817378	-.4436021946	-.8370786986
43	α	Cygni (Deneb)	1.3	+.4541086270	-.5392368197	+.7092312789
44	ϵ	Pegasi (Enif)	2.5	+.8139832631	-.5557243189	+.1691204557
45	α	Piscis Austr. (Fomalhaut)	1.3	+.8342971408	-.2392481515	-.4966976975

Figure 8-1 Unit Vectors of the Navigational Stars

5.8.2 References for Fixed Constants

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4. Apollo Missions and Navigation Systems Characteristics, Apollo Navigation Working Group Technical Report No. AN-1.3, December 15, 1967.

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26. Oral communication with Harry Byington as directed by 25th Meeting of the Apollo Software Control Board.

27. DPS Models Evaluation, R. K. M. Seto, TRW Interoffice Correspondence, 68.4711.8-187, August 22, 1968.

28. Mathematical Model for the LM Lunar Descent Hybrid Simulator, Willis M. Bolt, et. al., MSC Internal Note 68-FM-79, April 12, 1968.

29. CSM/LM Spacecraft Operational Data Book (Volume II), LED-540-54, Grumman Aircraft Engineering Corporation, June 1968.

30. Oral communication with Harry Byington of MSC on October 25, 1968.

31. GAEC TWX No. LTX-500-141, October 2, 1969.

32. PCR 846 Rev 1, More Accurate $\Delta t_{Tail-off}$ for P70, Oct. 30, 1969.

[x] Revised LUMINARY
[ ] Added GSOP # 567 PCR # 846 Rev 1 Rev. 7 Date 11/69
PCN 971*

5.8.3 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 ΔV_K (DPS) values and ΔV_K (APS) value are given in Reference 19. Two values are given for ΔV_K (DPS), depending on spacecraft configuration. The values were selected to be between the maximum possible ullage acceleration and minimum anticipated main engine acceleration.

3. 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.

4. The Lunar and Solar Ephemerides (Section 5.5.4) are based upon the technique given in Reference 10. The fixed constants were determined from various data points on the JPL Ephemeris Tape E-9511 (Reference 9).

5. The quantity T_{SS} is a rough estimate of the time between the initiation of the Star Selection Routine in the Fine Alignment Routine (R-51) and the midpoint of the optical sightings on the two celestial bodies.

6. The quantity K is the scale factor used to determine the number of bits to be sent to the RR CDU's during RR target designation. This scaling is applied to the angular difference between the present and desired pointing directions of the RR. No more than 384 bits are sent to an RR CDU because of saturation conditions.

7. The direction of each of the 37 navigation stars in Fig. 8-1 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. Due to the need at M. I. T. for these star directions prior to the availability of The American Ephemeris and Nautical Almanac for 1970, the star directions were computed by M. I. T. using essentially the same technique employed by the Nautical Almanac Office.

8. The quantity Δt is the period between successive updates of the LM state vector and the guidance equations during the lunar powered descent and ascent. A value of 2 seconds was selected in order to allow the LGC sufficient time to perform all of its functions.

9. The quantities k_a and k_e are respectively the LPD azimuth and elevation increment values chosen arbitrarily from simulations at MIT and confirmed by simulations at MSC.

10. The quantities q_{min} and q_{max} are respectively the quantities PROJMAX and PROJMIN in Ref. 23.

12. The quantities a_t (APS) and τ (APS) are the engine performance initialization parameters estimated from LM mass and off loaded by descent RCS fuel consumption. These will be replaced by the output of the Thrust Magnitude Filter after its first pass.

13. The quantity $1/\Delta V$ is the initial value of $1/\Delta V_1$, $1/\Delta V_2$, and $1/\Delta V_3$ used in the thrust filter computations and is equal to $1/2\ a_T$ (APS) where a_t (APS) is given in Section 5.8.1.

14. AF_{TRIM} is the expected acceleration during the trim phase. It is computed as the thrust corresponding to the throttle setting of the trim phase divided by the mass expected at that time.

15. The quantity τ_{VMES} is the time when the PIPA's are read after initiation of the LR Velocity Data Read Subroutine. This value is equal to 25 centiseconds (approximately one half of the LR velocity sampling period) minus 8 centiseconds to compensate for lag of the LR velocity tracking networks.

16. A_T(RCS) is the maximum possible acceleration available with 4 RCS jets on and the LM dry.

17. FRAC, BITPERF, FMAX, FSAT, and FRATE are non-critical constants computed in terms of the tables of the Victory VII Hybrid Propulsion System model described in References 27 and 28. Although all these constants are non-critical, they will be updated when improved tables are available.

18. τ_{th} is the empirically determined time interval used for providing minimum overshoot in throttle response at throttle recovery time.

19. FEXT is the non-critical bias added to throttle commands to assure setting throttle against mechanical stop.

22. u_{XCRIT} is the arbitrary limit on the pointing of the unit line-of-sight to the landing site to assure landing site redesignations to not produce a site behind the current LM position. This constant allows a maximum forward landing site range of 50 times the current altitude.

23. GUIDDURN is the non-critical estimate of the duration from start of FTP thrust in the braking phase to touchdown.

24. The quantities F_{DPS}, V_e(DPS), and $\dot{m}$ (DPS) are the average values determined from data in References 29 and 30.

25. The quantity V_e (APS) was determined from data in Reference 30. It has been rounded in the coding to about 3030 m/sec. This will not affect its use in the program.

26. The quantity ΔV_{min} is equivalent to 2 seconds of an acceleration 10 percent larger than lunar gravity.

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