MSC-01567

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 70-FM-23

March 23, 1970

RTCC REQUIREMENTS FOR APOLLO 14 (H-3) MISSION: EARTH-CENTERED RETURN-TO-EARTH CONIC SUBPROCESSOR

Lunar Mission Analysis Branch
MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

MSC-01567

MSC INTERNAL NOTE NO. 70-FM-23

PROJECT APOLLO

RTCC REQUIREMENTS FOR APOLLO 14 (H-3) MISSION: EARTH-CENTERED RETURN-TO-EARTH CONIC SUBPROCESSOR

By D. R. Davis and T. P. Garrison
TRW Systems Group

March 23, 1970

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

MSC Task Monitor: R. S. Davis

Approved: Ronald L. Berry
Ronald L. Berry, Chief
Lunar Mission Analysis Branch

Approved:
for John P. Mayer, Chief
Mission Planning and Analysis Division

CONTENTS

Section Page

RTCC REQUIREMENTS FOR APOLLO 14 (H-3) MISSION:
EARTH-CENTERED RETURN-TO-EARTH CONIC SUBPROCESSOR

By D. R. Davis and T. P. Garrison
TRW Systems

1.0 SUMMARY AND INTRODUCTION

This documentation of the earth-centered return-to-earth conic subprocessor completes the logic specification, corrects errors found in reference 1, and incorporates several changes that have been made since the previous documentation. New subroutines added are the analytic calibration subroutine and the entry simulation subroutine. This document completely defines the earth-centered conic subprocessor with the exception of the state vector advance subroutine. Some of the control logic has been restructured to correspond more closely with the current RTCC formulation or to present a more logical flow sequence. Modifications to the program which eliminate the polynomial curve fits in subroutine ETAARF are included in this document and are indicated by bars in the margin of the affected pages. Symbol definitions are presented in appendix A for the logic defined in appendix B, which is the specification for the earth-centered return-to-earth conic subprocessor for Apollo 14 and subsequent missions and supersedes that defined in reference 1.

Detailed logic of the moon-centered return-to-earth conic subprocessor is presented in reference 2. The supervisory and precision computation logic which completes the RTCC requirements for the return-to-earth processor (RTEAP) for Apollo 14 and subsequent missions is presented in reference 3.

2.0 ABBREVIATIONS

ATP	alternate target point
DV	change in velocity
DVM	maximum allowable DV

EFCUA	extreme fuel critical unspecified area
FCUA	fuel critical unspecified area
MD	miss distance to a PTP
MDM	maximum allowable miss distance to a PTP
MSI	moon's sphere of influence
PTP	primary target point, that is, a point on the earth's surface
RTCC	Real-Time Computer Complex
RTEAP	Return-to-Earth Abort Processor
TCUA	time critical unspecified area

3.0 EARTH-CENTERED SUBPROCESSOR MODES

The following subsections describe the manner in which solutions are generated in this subprocessor, the input required to operate the different modes, and the output parameters for each mode. In addition to the required input, each subprocessor mode is initialized with a premaneuver state vector(s) $X(j)$, where J_m is the total number of state vectors, and a reference epoch time from the abort processor's supervisory logic.

3.1 Time Critical Unspecified Area

The TCUA mode generates the trajectories that return to a specified reentry target line with the smallest transit time without regard to landing point. This solution will be characterized by either maximum allowable DV at abort or by the maximum allowable reentry speed. The solution plane coincides with the preabort plane of motion if the preabort inclination is not greater than the maximum allowable inclination; otherwise, the maneuver plane is rotated to the plane characterized by maximum inclination (the rotation being through the smaller angle because there are generally two planes that have a specified inclination passing through the abort position).

The solution generated in this mode is user determined in the sense that it is characterized by either maximum reentry speed or maximum DV for the maneuver. The solution is generated in subroutine TMIN and the inclination constraints are checked in subroutine INITAL.

The input quantities for the TCUA mode are the following.

DVM	Maximum DV to be used for the abort maneuver
T_o	Time at which the maneuver is to be computed
ICRNGG	Flag that defines the reentry mode which is to be simulated
I_{rmax}	Maximum inclination computed at reentry
U_{rmax}	Maximum reentry speed
RRBI	Constant reentry relative range (down range) which will be substituted for the relative range value obtained from the reentry curve fits
IMSFN	Flag that selects the reentry target line

The output quantities to the abort processor supervisory logic (ref. 3) are as follows.

$\overline{DV}$	Maneuver velocity vector increment (calibrated)
DVC	Conic DV magnitude (uncalibrated)
$\overline{RR}$	Reentry radius vector
$\overline{U}_r$	Reentry velocity vector
T_r	Time of reentry
λ_z and δ_z	Longitude and geocentric latitude of landing site
η_{rz}	Down-range angle from reentry to landing
θ_{cr}	Cross-range angle from reentry to landing
T_{rz}	Time from reentry to landing
NOSOLN	Error flag indicating whether a valid solution was found in the conic program

3.2 Fuel Critical Unspecified Area

The FCUA mode generates the minimum fuel maneuver required to return to acceptable reentry conditions ignoring landing point constraints. The earth reference logic first analytically determines the fuel critical inplane solution that returns to the specified reentry target line. If the preabort inclination is acceptable, the solution is determined in the preabort plane. Otherwise, a plane change is made to the maximum inclination plane that is selected in the same manner as the TCUA mode, and the solution is found in this plane.

If sufficient DV is allowed for an abort, the return is computed to the selected reentry target line. However, if the DVM constraint is violated, the logic attempts to generate a trajectory using DVM to minimize the deviation from the desired reentry target line. The program uses flight-path angle at reentry as the independent variable to drive DV to DVM. If this solution is available, it becomes the solution returned by the FCUA mode and is called the extreme fuel critical unspecified area (EFCUA) solution. If the DVM cannot be satisfied by varying the reentry path angle between 90° and 110°, the logic returns no solution.

The input quantities for this option are identical to those given for the TCUA mode.

The output quantities to the abort processor supervisory logic (ref. 3) are as follows.

$\overline{DV}$	Maneuver velocity vector increment (uncalibrated)
$\overline{RR}$	Reentry radius vector
$\overline{U}_r$	Reentry velocity vector
T_r	Time of reentry
λ_z and δ_z	Longitude and geocentric latitude of landing site
η_{rz}	Down-range angle from reentry to landing
θ_{cr}	Cross-range angle from reentry to landing
T_{rz}	Time from reentry to landing
NOSOLN	Error flag that indicates whether a valid solution was found in the conic program

3.3 Primary Target Point Mode

This mode generates, for the maneuver time considered, the DV and trip time required to return to a specified PTP. Whenever the PTP is accessible within the constraints, the minimum fuel solution for the specified miss distance is generated.

3.3.1 PTP tradeoff.- Two formats are available for the PTP tradeoff mode, namely the near-earth tradeoff and the remote-earth tradeoff. The basic logic for generating solutions is identical; however, the near-earth format will consider up to five different values for MDM, while the remote-earth format is limited to the zero miss distance solution. Each tradeoff display consists of all the solutions for up to forty state vectors within the allowed range of maneuver times.

The logic presented is the current RTCC logic known as the fuel-critical PTP logic. The initial presentation of the PTP mode (ref. 4) considered the reentry maneuver as a planar profile. Because this approximation has proved invalid, the logic discussed here considers a reentry profile which has a cross-range component and whose characteristics are determined by the geocentric position as well as by the velocity magnitude and direction at reentry. The PTP solution generation logic is not an exact simulation, but this logic is the first iteration of a procedure which can generate a more precise PTP solution. The procedure is described here and is the same as that defined for the PTP discrete mode, except that for the PTP discrete mode only a single maneuver time and a single miss distance are considered.

The first computation is the determination of the minimum trip time solution (subroutine TMIN). For this transit time, the azimuth of a plane which contains the PTP is computed. This azimuth is tested against the pair of azimuths which were chosen as the most constraining planes based on the inclination and DVM constraints. If the azimuth or the plane which contains the site is acceptable, then the plane through the desired landing site is chosen to be the maneuver plane; otherwise, the constraint plane that has an azimuth closest to the azimuth of the site plane is selected. Note that this choice of azimuth minimizes the miss distance, where the miss distance may be defined (as a function of azimuth) as the minimum great circle distance between the desired landing site and the actual impact point. The reentry point is defined for the trajectory with the specified transit time and with the defined azimuth. The reentry trajectory and the associated impact point are computed for this reentry point. The coordinates of the PTP are offset by the negative of the difference between the impact point defined by this out-of-plane reentry profile and the one defined by the corresponding planar reentry profile. (This offset is defined such that, if the planar reentry trajectory passes through the offset landing point, the out-of-plane reentry profile would pass through the PTP.) For this new impact point, the miss distance is computed with the azimuth re-defined for the offset reentry to minimize the miss distance. The miss distance is computed in subroutine MSDS. Transit time is now increased by a small amount, and the miss distance is recomputed by the above procedure. The logic next goes to subroutine TCOMP which computes the next value of transit time based on the present and past values of miss distance and the desired direction of motion of the impact point. At this point, the logic is attempting to minimize the miss distance; therefore, if the present value of miss distance is smaller than the past value, TCOMP continues to increase the transit time. This procedure continues until the maximum allowable miss distance is achieved or until a minimum in the MD is found. If a minimum is found, a flag is set based on the direction of motion of the impact point. If motion of the impact point is easterly, the miss distance should be maximized before the next minimum is sought. If motion of the impact point is westerly, the transit time is incremented by 24 hours and a new minimum immediately sought. When the miss distance is equal to the maximum allowable miss distance (MDM), a scan is performed by incrementing transit time. During this scan, the azimuth is varied for each trip time to generate the set of trajectories which miss by the specified miss distances. The miss distance is used in each case to minimize the required plane change and therefore DV. This procedure is repeated until the miss distance is larger than the maximum distance allowed. When the maximum distance is exceeded, the search is re-initiated to determine the next time interval of PTP accessibility within the framework of problem constraints. The entire process is repeated for each state vector.

The PTP tradeoff near-earth option produces a graph that presents time at abort along the abcissa and two other parameters, DV required for the abort and time at landing, along the ordinate. Both latter parameters are given for several fixed values of miss distance.

The PTP remote-earth option of the tradeoff display is designed to display abort solutions for those flight regions in which the DV difference between miss distance contours is very small. The interval between landing times of these solutions is approximately 24 hours. For this option, the abort time is plotted along the abcissa, and the required DV is plotted along the ordinate. Only the zero miss distance contour is presented in this option. The multiple curves which will appear on the display are identified by their time at landing, rather than with a separate curve. For aborts outside the MSI, only solutions which return directly to the earth (posigrade) are generated and displayed.

All solutions are computed to the specified reentry target line and include the selected reentry profile. All appropriate constraints are considered.

The input quantities for both PTP modes are as follows.

T_{omin}	Earliest abort time to be considered
T_{omax}	Latest abort time to be considered
DVM	Maximum DV to be used for the abort maneuver
λ_z and δ_z	Longitude and geocentric latitude of the desired PTP landing site
T_{zmin}	Minimum time at landing
T_{zmax}	Maximum time at landing
ICRNGG	Flag that selects one of the reentry modes
I_{rmax}	Maximum inclination at reentry
U_{rmax}	Maximum reentry speed
RRBI	Constant reentry relative range (down range) which will be substituted for the relative range value obtained from the reentry curve fit
IMSFN	Flag that selects the reentry target line

The abort time range indicated ($T_{omax} - T_{omin}$) will be limited by the RTEAP logic to a maximum of either 24 hours on the trajectory of the input state vector or the period associated with the initial abort state vector, whichever is smaller.

The output of the PTP tradeoff option to the abort processor supervisory logic (ref. 3) is as follows.

DV	Change in velocity at abort (calibrated)

as a function of

T_o	Time at which abort solution is generated
T_z	Time of landing

MD	Miss distance to the PTP
NOSOLN	Error flag that indicates whether a valid solution was found for any state vector in the conic program

The output is displayed as a set of curves of constant miss distance with the DV required at abort and time at landing given as a function of abort time.

3.3.2 PTP discrete.- These computations are exactly those of the PTP tradeoff mode, except that a single miss distance, a single approximate landing time, and single time of maneuver are considered.

The following quantities are supplied to the PTP discrete option.

T_o	Time at which an abort solution will be generated
T_{zmin}, T_{zmax}	Minimum and maximum landing times that bracket the approximate landing time of the abort solution
λ_z and δ_z	Longitude and geocentric latitude of the desired PTP landing site
ICRNGG	Flag that selects the reentry mode
MDM	Maximum miss distance to a PTP
I_{rmax}	Maximum inclination measured at reentry
U_{rmax}	Maximum reentry speed
RRBI	Constant reentry relative range (down range) which will be substituted for the relative range value obtained from the reentry curve fit
IMSFN	Flag that selects the reentry target line

The output quantities to the abort processor supervisory logic (ref. 3) are as follows.

$\overline{DV}$	Maneuver velocity vector increment (calibrated)
$\overline{RR}$	Reentry radius vector
$\overline{U}_r$	Reentry velocity vector

T_r	Time of reentry
λ_z and δ_z	Longitude and geocentric latitude of landing site
η_{rz}	Down-range angle from reentry to landing
θ_{cr}	Cross-range angle from reentry to landing
T_{rz}	Time from reentry to landing
NOSOLN	Error flag that indicates whether a valid solution was found in the conic program

3.4 Alternate Target Point Mode

The ATP generates solutions which return to lines defined on the earth's surface by successive pairs of latitude and longitude. The trajectories return in the plane of original motion if this plane satisfies the inclination constraint. If the plane of preabort motion is not acceptable, the return is computed in the plane with an acceptable inclination which requires minimum fuel for plane change. This logic operates in a manner quite similar to the PTP logic. The minimum trip time solution is generated (subroutine TMIN), and the miss distance for this trajectory is computed (subroutine MSDS). For the ATP mode, only the zero miss distance solution is an acceptable solution. The miss distance for the ATP is defined as the longitude difference between the impact point and the ATP measured at the latitude of the impact point. The logic then attempts to drive the miss distance to zero. If it succeeds, the solution is stored if no constraints are violated. After storing a solution or finding a non-zero minimum, the logic increments transit time to search for the next possible solution. If motion is easterly, the miss distance must first be maximized prior to seeking the next minimum. If motion is westerly, the transit time is increased by 24 hours and a new solution sought if the maximum trip time constraint is not violated. The logic is limited to ATP definitions which have a variation in latitude; that is, constant latitude ATP's are unacceptable.

3.4.1 <u>ATP tradeoff</u>.- The ATP procedure is applied sequentially to each state vector within the allowed range of maneuver times. The two formats for the tradeoff display are the same as that for PTP tradeoffs, except that for the near-earth format only the zero miss distance is computed and, in addition, the latitude of the landing point is displayed as an ordinate. The ATP tradeoff input are as follows.

T_{omin}	Earliest abort time to be considered
T_{omax}	Latest abort time to be considered
DVM	Maximum DV to be used for the abort maneuver
$\lambda'(j)$ $\delta'(j)$	j longitude-latitude pairs that define the ATP line
mm	Maximum value for j; that is, the number of points that defines the ATP line
T_{zmin}	Minimum time at landing
T_{zmax}	Maximum time at landing
ICRNGG	Flag that selects one of the reentry modes
I_{rmax}	Maximum inclination at reentry
U_{rmax}	Maximum reentry speed
RRBI	Constant reentry relative range (down range) which will be substituted for the relative range value obtained from the reentry curve fit
IMSFN	Flag that selects the reentry target line

The abort time range indicated ($T_{omax} - T_{omin}$) will be limited by the RTEAP logic to a maximum of either 24 hours on the trajectory of the input state vector or the period associated with the initial abort state vector, whichever is smaller.

The output of the ATP tradeoff option to the abort processor supervisory logic (ref. 3) is as follows.

The conic program returns

DV	change in velocity at abort (calibrated)

as a function of

T_o	Time at which abort solution is generated

T_z	Time of landing
δ_z	Geocentric latitude of the landing site
NOSOLN	Error flag that indicates whether a valid solution was found for any of the state vectors in the conic program

The ATP format gives DV required at abort, time of landing, and, only in the near-earth option, latitude of landing as a function of abort time, but only for the zero miss distance condition.

3.4.2 ATP discrete.- The ATP discrete mode generates the ATP solution for a single maneuver time and a single approximate landing time. The following quantities are entered as input to the ATP discrete option.

T_o	Time at which an abort solution will be generated
T_{zmin}, T_{zmax}	Minimum and maximum landing times that bracket the approximate landing time of the abort solution
$\lambda'(j)$ $\delta'(j)$	j longitude-latitude pairs that define the ATP line
mm	Maximum value for j, that is, the number of points that defines the ATP line
ICRNGG	Flag that selects the reentry mode
I_{rmax}	Maximum inclination measured at reentry
U_{rmax}	Maximum reentry speed
RRBI	Constant reentry relative range (down range) which will be substituted for the relative range value obtained from the reentry curve fit
IMSFN	Flag that selects the reentry target line

The output quantities to the abort processor supervisory logic (ref. 3) are as follows.

$\overline{DV}$	Maneuver velocity vector increment (calibrated)

$\overline{RR}$	Reentry radius vector
$\overline{U}_r$	Reentry speed vector
T_r	Time of reentry
λ_z and δ_z	Longitude and geocentric latitude of landing site
η_{rz}	Down-range angle from reentry to landing
θ_{cr}	Cross-range angle from reentry to landing
T_{rz}	Time from reentry to landing
NOSOLN	Error flag that indicates whether a valid solution was found in the conic program

APPENDIX A

DEFINITION OF SYMBOLS USED IN FLOW CHARTS

APPENDIX A

DEFINITION OF SYMBOLS USED IN FLOW CHARTS

A,B,C,D,E	Coefficients of quartic equation giving normals to locus of acceptable abort velocity from preabort velocity
a	Semimajor axis
AFG	Flag used in subroutine MSDS in PTP mode. A nonzero value indicates that the preabort motion is retrograde and that the return plane is to be determined by computing the miss distance in two different planes and selecting the one that yields the smaller miss distance.
CE	Cosine of eccentric anomaly
CNT	Number of steps taken across the landing site
DDT	Fraction of the step size to be taken in trip time
DFDA	Conic partial derivative $\partial f/\partial a$
DL	Longitude difference between successive ATP points
DT	Step size in trip time
DTDA	Conic partial derivative $\partial T/\partial a$
DV, DVS	Maneuver velocity change
DVC	Conic DV magnitude (uncalibrated)
DVM	Maximum allowable DV
DVSP	Total DV for minimum DV solution previously found
DVSSP	Past value of DVSP
DVT, DVN, DVR	Tangential, normal, and radial components of the DV vector

E	Eccentric anomaly
e	Eccentricity
ERR	Difference in transfer angle between impact point and PTP
f	True anomaly
I	Inclination
J_m	Number of state vectors to be considered
k	Indicator that gives number of roots
L	Longitude on ATP measured at latitude of impact point
MD1	Miss distance which is first found to satisfy the desired conditions
MDMM	Minimum possible miss distance for the present trip time
mm	Number of ATP latitude, longitude pairs
NOSOLN	Flag that indicates whether solution has been found. If NOSOLN = 0, TCUA or FCUA solution found = 1, no solution found = 2, PTP or ATP solution found
P_{ar}	Function that the PTP mode attempts to drive to zero to generate acceptable solutions
Q	Step size in trip time for scanning across the maximum allowable miss distance contour
$\bar{R}_a$	Preabort position vector
RR	Reentry radius
$\bar{R}_z$	Unit vector through impact point
SE	Sine of eccentric anomaly
SEEK	Indicates whether a zero miss distance is possible

SF	Sine of true anomaly
SOL	Indicates whether a solution has been found
SW	Flag used in TMIN. SW = 0 initially, SW = 1 during the iteration for the minimum time solution, and SW = 0 if the upper bound on the iteration exceeds T_{max}
SW2	Control flag used in the PTP, ATP, and FCUA modes. For the PTP mode, flag is used to generate PTP solutions within a maximum miss contour. When SW2 = 0, the logic is searching for the maximum miss boundary; when SW2 = 1, the direction for the optimizing scan is being determined; and when SW2 = 2 the logic is performing the optimizing scan across the maximum miss contour. When SW2 is used in the ATP logic, it changes from 0 to 1 when the ATP line has been bracketed and a linear partial is to be used to generate the solution. For the FCUA mode, SW2 indicates the type of computation being performed. When SW2 = 0, a solution is sought to the entry target line = 1, a solution is sought with DV < DVM = 2, a solution is sought with DV = DVM
SW6	Indicates whether the impact point moves easterly or westerly with increasing trip time = 0, indicates easterly motion = 1, indicates westerly motion
SW7	Indicates whether a time step based on longitude error has been previously taken = 0, indicates no such step previously taken = 1, otherwise
T	Trip time
T_1, T_2, T_3	Limits on transit time for iteration
T_{apo}	Flight time from abort to reentry when the abort occurs at apogee on the post maneuver trajectory
TARSP	Transit time that corresponds to MD1

TEST	Indicates whether the possibility of a zero has been detected in the function being minimized
TP	Past value of trip time
T_{max}	Maximum allowable trip time
T_{min}	Minimum allowable trip time
T_{mt}	Minimum possible trip time, computed in subroutine TMIN
$\overline{U}_o$	Preabort velocity vector
U_r	Reentry speed
$\overline{V}_a$	Preabort velocity vector
VT_a, VN_a, VR_a	Tangential, normal, and radial components of the postabort velocity vector
X, X(j)	Seven-dimension array that defines the preabort state vector (i.e., position vector, velocity vector, and time)
$\hat{X}$, $\hat{Y}$, $\hat{Z}$	Unit vectors along geocentric Cartesian coordinate axes
$\overline{X}_1,\overline{X}_2,\overline{X}_3,\overline{X}_4$	Values for nonradial component of speed
XK	Indicates whether the function is being minimized or maximized
$\overline{Y}_1,\overline{Y}_2,\overline{Y}_3,\overline{Y}_4$	Values for radial component of speed
α	Right ascension of impact point
β_a	Postabort flight-path angle
β_o	Preabort flight-path angle
β_r	Reentry flight-path angle

$\Delta\theta$	Maximum change in azimuth with allowable miss distance
δ'	Latitude of one ATP point
δ_z	Geocentric latitude of the desired PTP
η	True anomaly
θ	Difference in azimuth from preabort plane to transfer plane
θ_z	Difference in azimuth from preabort plane to plane that contains the desired landing point
λ'	Longitude of one ATP point
λ_z	Longitude of the desired PTP
μ_e	Earth's gravitational parameter
ϕ	Angle inplane from abort to impact point
ϕ_z	Angle inplane from abort to desired landing point
ω_e	Earth's rotational rate

APPENDIX B

LOGIC FLOW OF THE EARTH-CENTERED RETURN-TO-EARTH CONIC SUBPROCESSOR

APPENDIX B

LOGIC FLOW OF THE EARTH-CENTERED RETURN-TO-EARTH CONIC SUBPROCESSOR

SUBROUTINE DVMINQ

Purpose

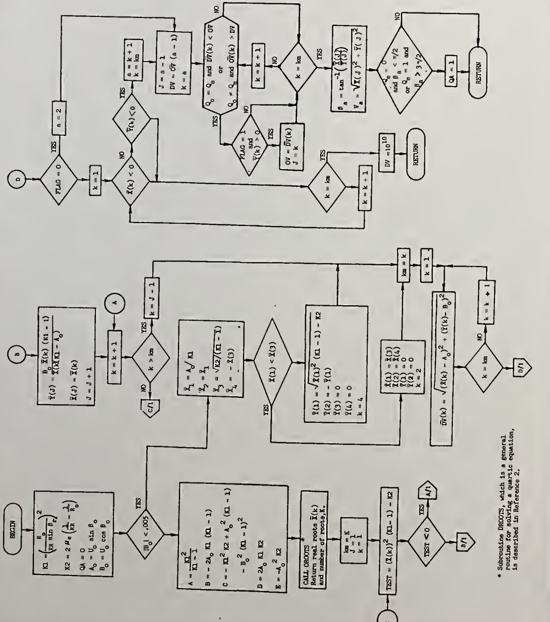
This subroutine, called from FCUA, is used to establish the minimum fuel required to obtain safe reentry conditions with specified initial position, velocity, flight-path angle, reentry radius, and reentry flight-path angle. The input flag, FLAG, is used to specify whether apogee passage is desired on the postabort trajectory.

Input

FLAG	Input flag = 1, solution trajectory has a negative radial rate = -1, solution trajectory has a positive radial rate
Q_e	Postabort direction of motion = 0, direct = 1, retrograde
Q_o	Preabort direction of motion = 0, direct = 1, retrograde
RR	Radial distance at reentry
R_o	Radial distance at abort
U_o	Preabort velocity
β_o	Preabort flight-path angle
β_r	Path angle at reentry

Output

DV	Minimum change in velocity required at abort
QA	Apogee passage flag = 0, no apogee passage = 1, apogee passage
V_a	Postabort velocity magnitude
β_a	Postabort flight-path angle



* Subroutine DROOTS, which is a general routine for solving a quartic equation, is described in Reference 2.

SUBROUTINE FCUA

Purpose

This subroutine computes the fuel critical unspecified area solution which has a reentry velocity and flight-path angle satisfying the reentry target line conditions and with DV less than DVM. This solution is generated through subroutine DVMINQ. DVMINQ generates the minimum DV solutions for a given preabort state, reentry radius, and reentry flight-path angle. The reentry speed for this solution is then computed, and the flight-path angle corresponding to this reentry speed is generated from the target line. If this reentry path angle is equal to the value supplied to DVMINQ, the solution is accepted; otherwise, the most recent value of path angle is supplied to DVMINQ, and the solution is repeated until convergence is achieved. The input constraints are then checked. If no solution is found that satisfies these constraints, the logic attempts to find an extreme fuel-critical solution with a reentry flight-path angle between 90° and 110° that satisfies the available fuel and maximum velocity at reentry constraints.

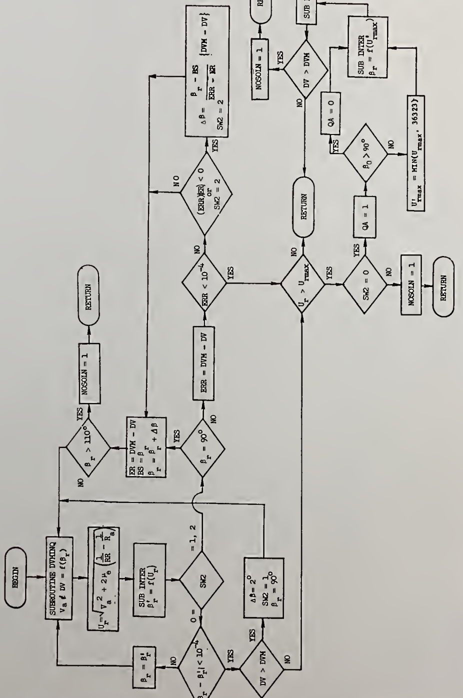
Input

DVM	DV allowed for abort (may include rotation to acceptable inclination)
RR	Reentry radius
$\overline{R}_a$, R_a	Position vector at abort and its magnitude
SW2	Control flag = 0, when generating the normal FCUA solution that satisfies the reentry target line = 1 or 2, when generating the EFCUA solution, depending on the state of the search
β_o	Preabort flight-path angle
β_r	Reentry flight-path angle
μ_e	Earth's gravitational parameter

Output

DV	Change in velocity
U_r	Reentry speed
β_r	Reentry flight-path angle

FCUA
Logic Flow
Page 1



SUBROUTINE INITAL

Purpose

This routine initializes the program at the beginning of each new state vector.

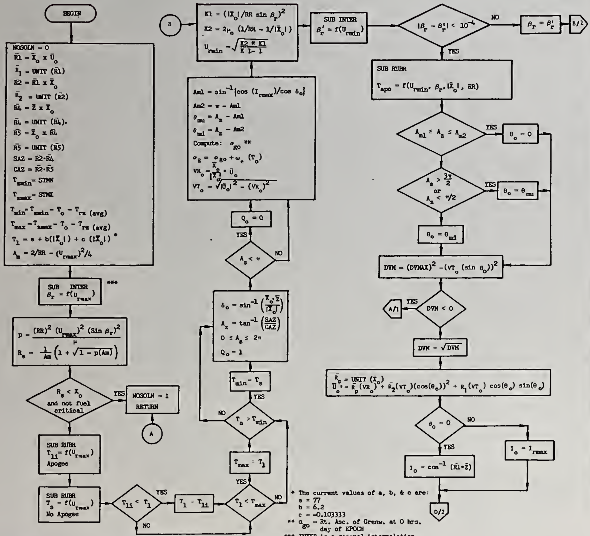
Input

DVM	Maximum allowable change in velocity
I_{rmax}	Maximum inclination of postabort orbit
RR	Reentry radius
$\overline{R}_p$	Unit vector in direction of abort position vector
T_o	Time of abort
T_{rz} (avg)	Average time from reentry to landing
T_{zmax} or STMX	Maximum time of landing
T_{zmin} or STMN	Minimum time of landing
$\overline{U}_o$	Preabort velocity vector
U_{rmax}	Maximum allowable reentry velocity
$\overline{X}_o$	Preabort position vector
δ_z	Latitude of desired landing site

Output

Am1	Constraint that limits the inclination of the postabort orbit north of the equator
Am2	Constraint that limits the inclination of the postabort orbit south of the equator

A_z	Azimuth of premaneuver velocity vector
DDT	Fraction of trip time increment to be taken during the search for PTP and ATP solutions
DT	Trip time increment used in searching for PTP and ATP solutions
p	Semi-latus rectum for preabort orbit
Q_o	Preabort motion direction flag
$\overline{R}_1$	Unit vector in direction of premaneuver angular momentum
$\overline{R}_2$	Unit vector in preabort plane of motion which is orthogonal to abort position vector
TSW6	Trip time for which motion of the impact point switches from easterly to westerly
T_{max}	Maximum allowable trip time
T_{min}	Minimum trip time
$\lvert\overline{U}_o\rvert$	Magnitude of preabort velocity
VR_o	Radial component of preabort velocity
VT_o	Tangential component of preabort velocity
$\lvert\overline{X}_o\rvert$	Magnitude of abort position
α_g	Right ascension at Greenwich at abort time
α_{go}	Right ascension of Greenwich at 0^h on day of abort
β_o	Preabort flight-path angle
η_{dr}	Average down-range distance
θ_{md}	Azimuth change to south inclination constraint
θ_{mu}	Azimuth change to north inclination constraint
θ_o	Azimuth change to nearest inclination constraint

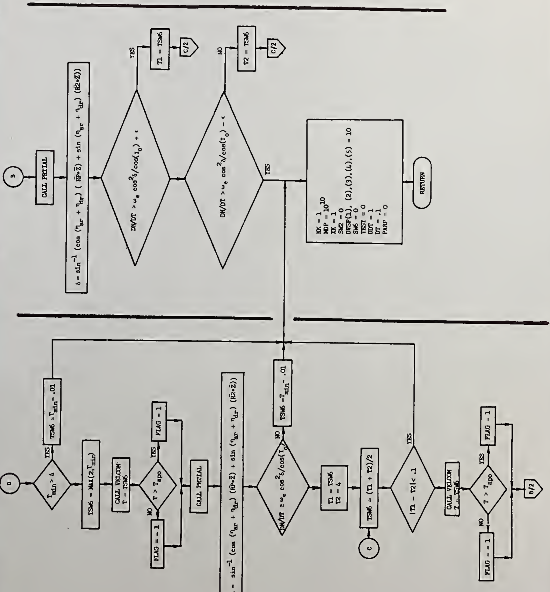


* The current values of a, b, & c are:
a = 77
b = 6.2
c = -0.103333

** α_{go} = Rt. Asc. of Grenw. at 0 hrs. day of EPOCH

*** INTER is a general interpolation scheme

INITAL
Logic Flow
Page 2



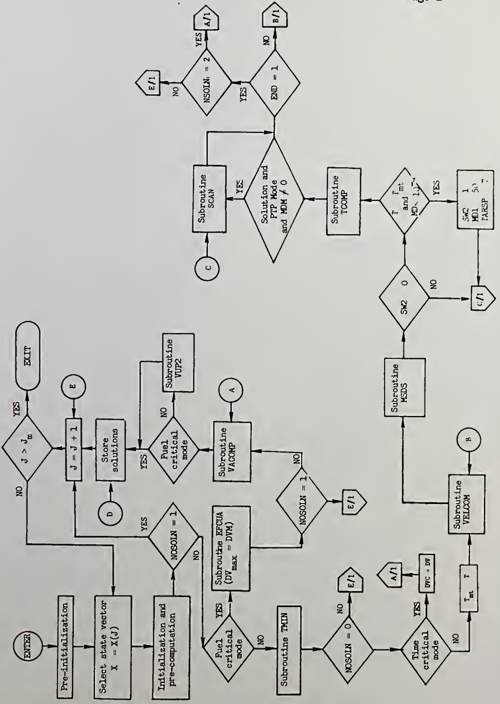
SUBROUTINE MAIN

Purpose

This subroutine is the main control routine and the entry point for the conic program. In the flow chart are shown the logic flow for the overall program and the sequence in which subroutines are used to generate solutions.

Input

See section 3 for the mode specified input and appendix A.


ENTER
Pre-initialization
Select state vector X = X(J)
Initialization and pre-computation
NOSOLN = 1
YES
NO
J = J + 1
J > J_m
YES
NO
EXIT
E
D
Store solutions
Fuel critical mode
YES
NO
Subroutine VUP2
Subroutine VACOMP
A
Subroutine EFCUA (DV_{max} = DVM)
NOSOLN = 1
NO
E/1
Subroutine TMIN
NOSOLN = 0
NO
E/1
Time critical mode
YES
DVC = DV
A/1
NO
T_{mt} T
Subroutine VELCOM
B
Subroutine MSDS
SW2 0
NO
C/1
T T_{mt} and MD 10^{-4}
YES
SW2 1
MD1 50
TARSP
Subroutine TCOMP
Solution and PTP Mode and MDM ≠ 0
YES
Subroutine SCAN
C
END = 1
YES
NO
B/1
NSOLN = 2
YES
A/1
NO
E/1

SUBROUTINE MSDS

Purpose

This subroutine computes the miss distance (i.e., the distance between the current impact point and the desired landing site) for the ATP and the PTP modes. If an ATP solution is being generated, the impact point may be computed immediately because the plane of the postmaneuver conic is known. From the impact point, the miss distance is computed as the longitude difference between the impact point and the desired landing line, measured at the latitude of the impact point.

For PTP modes, the return plane must first be determined. The return plane is chosen to be that which minimizes the miss distance from the site without violating either the inclination or ΔV constraints. The miss distance in this mode is the smallest distance between the impact point and the desired landing site. To determine the return plane, the subroutine first generates the azimuths of trajectory planes determined by the inclination and ΔV constraints and retains the most constraining set as limits on the azimuth of the postabort velocity vector. Next, the azimuth of a plane passing through the desired landing site (at the current transit time) is computed. If this azimuth is between the limiting values, then the plane through the site is determined to be the postabort plane of motion. Otherwise, the constraint plane nearest the plane passing through the site is selected. When the return plane is known, the impact point and corresponding miss distance may be determined. This subroutine was formulated using logic from subroutines PHICOM, THZCOM, and the ATP computations found in reference 1.

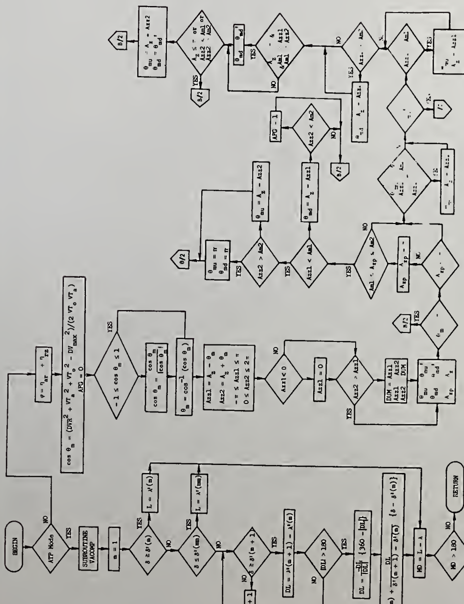
Input

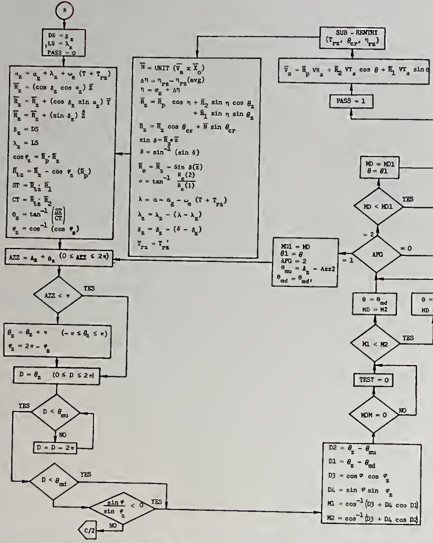
A_z	Preabort azimuth
DVM	Maximum allowable DV
DVR	Radial component of the ΔV vector
$\bar{R}_p$	Unit vector in direction of abort point
$\bar{R}_1$	Unit vector in direction of preabort angular momentum
$\bar{R}_2$	Unit vector in direction of $(\bar{R}_1 \times \bar{R}_p)$

VT_a	Tangential component of the postabort velocity vector
VT_o	Tangential component of the preabort velocity vector
α_g	Right ascension of Greenwich at the abort time
δ_z	Latitude of the desired landing site
δ' (mm) λ' (mm)	mm latitude-longitude pairs defining the ATP line
λ_z	Longitude of the desired landing site
η_{ar}	Transfer angle from abort to reentry
θ'_{md}	Azimuth change to maximum inclination plane with an azimuth > 90°
θ'_{mu}	Azimuth change to maximum inclination plane with an azimuth < 90°

Output

MD	Miss distance
δ	Latitude of the impact point
ϕ	Total transfer angle to the impact point
ϕ_z	Total transfer angle from abort to desired landing site
λ	Longitude of the impact point
θ_z	Azimuth change to desired landing site


BEGIN
ATP Mode
NO
YES
SUBROUTINE VACOMP
m = 1
δ ≥ δ'(m)
L = λ'(m)
δ ≤ δ'(mm)
L = λ'(mm)
δ ≥ δ'(m + 1)
m = m + 1
DL = λ'(m + 1) - λ'(m)
|DL| > 180
DL = -DL/|DL| {360 - |DL|}
L = λ'(m) + DL/(δ'(m + 1) - δ'(m)) {δ - δ'(m)}
MD = L - λ
MD > 180
RETURN
MD = -MD/|MD| {360 - |MD|}
RETURN
φ = η_ar + η_rz
cos θ_m = (DVR² + VT_a² + VT_o² - DV_max²)/(2 VT_o VT_a)
APG = 0
-1 ≤ cos θ_m ≤ 1
cos θ_m = cos θ_m/|cos θ_m|
θ_m = cos⁻¹ (cos θ_m)
Azz1 = A_z - θ_m
Azz2 = A_z + θ_m
-π ≤ Azz1 ≤ π
0 ≤ Azz2 ≤ 2π
Azz1 < 0
Azz1 = 0
Azz2 > Azz1
DUM = Azz1
Azz1 = Azz2
Azz2 = DUM
θ_mu θ_mu'
θ_md θ_md'
A_zp A_z
θ_m
B/2
A_zp
Aml ≤ A_zp ≤ Am2
Azz1 < Aml
Azz2 > Am2
θ_mu = π
θ_md = π
θ/2
θ_mu = A_z - Azz2
θ_md = A_z - Azz1
Azz2 < Am2
APG - 1
B/2
A_z - Azz1
θ_md θ_md'
A_z ≤ π or Azz2 < Aml or Azz2 > Am2
θ_mu = A_z - Azz2
θ_md = θ_md'
B/2
A_z - Azz1


B
$DS = \delta_z$
$LS = \lambda_z$
PASS = 0
$\alpha_z = \alpha_g + \lambda_z + \omega_e (T + T_{rz})$
$\bar{R}_z = (\cos \delta_z \cos \alpha_z) \bar{X}$
$\bar{R}_z = \bar{R}_z + (\cos \delta_z \sin \alpha_z) \bar{Y}$
$\bar{R}_z = \bar{R}_z + (\sin \delta_z) \hat{Z}$
$\delta_z = DS$
$\lambda_z = LS$
$\cos \varphi_z = \bar{R}_p \cdot \bar{R}_z$
$\bar{R}_{tz} = \bar{R}_z - \cos \varphi_z (\bar{R}_p)$
$ST = \bar{R}_{tz} \cdot \bar{R}_1$
$CT = \bar{R}_{tz} \cdot \bar{R}_2$
$\theta_z = \tan^{-1} \left(\frac{ST}{CT}\right)$
$\varphi_z = \cos^{-1} (\cos \varphi_z)$
$AZZ = A_z + \theta_z \quad (0 \le AZZ \le 2\pi)$
$AZZ < \pi$
YES
$\theta_z = \theta_z + \pi \quad (-\pi \le \theta_z \le \pi)$
$\varphi_z = 2\pi - \varphi_z$
$D = \theta_z \quad (0 \le D \le 2\pi)$
$D < \theta_{mu}$
YES
NO
$D = D - 2\pi$
$D < \theta_{md}$
YES
$\frac{\sin \varphi}{\sin \varphi_z} < 0$
YES
NO
C/2
$\bar{N} = UNIT (\bar{V}_a \times \bar{X}_o)$
$\Delta\eta = \eta_{rz} - \eta_{rz}(avg)$
$\eta = \varphi_z + \Delta\eta$
$\bar{R}_z = \bar{R}_p \cos \eta + \bar{R}_2 \sin \eta \cos \theta_z + \bar{R}_1 \sin \eta \sin \theta_z$
$R_z = \bar{R}_z \cos \theta_{cr} + \bar{N} \sin \theta_{cr}$
$\sin \delta = \bar{R}_z \cdot \bar{z}$
$\delta = \sin^{-1} (\sin \delta)$
$\bar{R}_e = \bar{R}_z - \sin \delta(\bar{z})$
$\alpha = \tan^{-1} \frac{R_e(2)}{R_e(1)}$
$\lambda = \alpha - \alpha_g - \omega_e (T + T_{rz})$
$\lambda_z = \lambda_z - (\lambda - \lambda_z)$
$\delta_z = \delta_z - (\delta - \delta_z)$
$T_{rz} = T'_{rz}$
SUB - RENTRY
$(T_{rz}, \theta_{cr}, \eta_{rz})$
$\bar{V}_a = \bar{R}_p VR_a + \bar{R}_2 VT_a \cos \theta + \bar{R}_1 VT_a \sin \theta$
PASS = 1
C
$\theta = D$
$MD = \varphi_z - \varphi$
$MD < \pi$
YES
$MD = 2\pi - MD$
PASS = 1
YES
$MD = MD \sqrt{MDM}$
RETURN
AFG = 0
$MD = MD1$
$\theta = \theta 1$
$MD < MD1$
YES
AFG
= 2
= 0
= 1
$MD1 = MD$
$\theta 1 = \theta$
AFG = 2
$\theta_{mu} = A_z - Azz2$
$\theta_{md} = \theta_{md}'$
$\theta = \theta_{md}$
$MD = M2$
$\theta = \theta_{mu}$
$MD = M1$
$M1 < M2$
YES
TEST = 0
MDM = 0
NO
$D2 = \theta_z - \theta_{mu}$
$D1 = \theta_z - \theta_{md}$
$D3 = \cos \varphi \cos \varphi_z$
$D4 = \sin \varphi \sin \varphi_z$
$M1 = \cos^{-1} (D3 + D4 \cos D1)$
$M2 = \cos^{-1} (D3 + D4 \cos D2)$

SUBROUTINE PRTIAL

Purpose

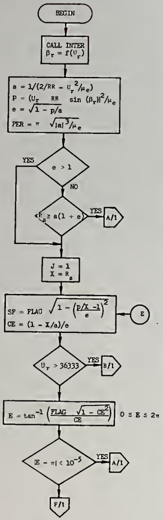
The purpose of this subroutine is to compute the partial derivative $\frac{\partial \eta_{ar}}{\partial T_{ar}}$ from the conic equations of motion. The partial is computed by using the chain rule to write $\frac{\partial \eta_{ar}}{\partial T_{ar}} = \frac{\partial \eta_{ar}}{\partial a} \frac{\partial a}{\partial T_{ar}} = \left(\frac{\partial fa}{\partial a} - \frac{\partial fr}{\partial a} \right) \frac{\partial a}{\partial T_{ar}}$. The derivatives may then be calculated from Kepler's equations, and the polar equation of the orbit. Also from the fact that the perigee radius is nearly constant along the target line (it varies from 3091 n. mi. to 3465 n. mi. as the entry speed varies from 25 000 fps to 38 000 fps), the approximation that perigee radius is constant is made.

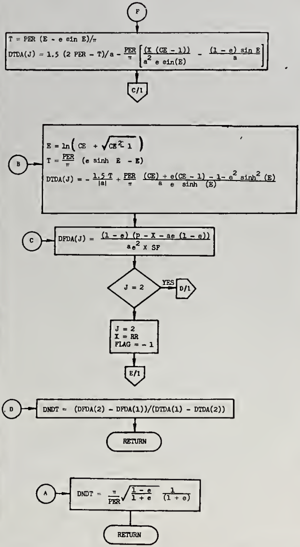
Input

FLAG	= 1, preapogee on conic trajectory = -1, postapogee on conic trajectory
RR	Reentry radius magnitude
R_a	Abort radius magnitude
U_r	Reentry speed

Output

DNDT	Conic partial derivative $\partial \eta_{ar}/\partial T_{ar}$


BEGIN
CALL INTER
$\beta_r = f(U_r)$
$a = 1/(2/RR - U_r^2/\mu_e)$
$P = (U_r \quad RR \quad \sin(\beta_r))^2/\mu_e$
$e = \sqrt{1 - p/a}$
$PER = \pi \quad \sqrt{|a|^3/\mu_e}$
$e > 1$
YES
NO
$R_a \geq a(1 + e)$
YES
A/1
$J = 1$
$X = R_a$
$SF = FLAG \sqrt{1 - \left(\frac{p/X - 1}{e}\right)^2}$
$CE = (1 - X/a)/e$
E
$U_r > 36333$
YES
B/1
$E = \tan^{-1}\left(\frac{FLAG \quad \sqrt{1 - CE^2}}{CE}\right) \quad 0 \leq E \leq 2\pi$
$|E - \pi| < 10^{-5}$
YES
A/1
F/1


F
$T = PER\ (E - e \sin E)/\pi$
$DTDA(J) = 1.5\ (2\ PER - T)/a - \frac{PER}{\pi}\left[\frac{(X\ (CE - 1))}{a^2\ e \sin(E)} - \frac{(1 - e) \sin E}{a}\right]$
C/1
B
$E = \ln\left(CE + \sqrt{CE^2 - 1}\right)$
$T = \frac{PER}{\pi}\ (e \sinh E - E)$
$DTDA(J) = -\frac{1.5\ T}{|a|} + \frac{PER}{\pi}\ \frac{(CE) + e(CE - 1) - 1 - e^2 \sinh^2(E)}{a\ e\ \sinh(E)}$
C
$DFDA(J) = \frac{(1 - e)\ (p - X - ae\ (1 - e))}{a e^2\ X\ SF}$
$J = 2$
YES
D/1
$J = 2$
$X = RR$
$FLAG = -1$
E/1
D
$DNDT = (DFDA(2) - DFDA(1))/(DTDA(1) - DTDA(2))$
RETURN
A
$DNDT = \frac{\pi}{PER}\sqrt{\frac{1 - e}{1 + e}}\ \frac{1}{(1 + e)}$
RETURN

SUBROUTINE RENTRY

Purpose

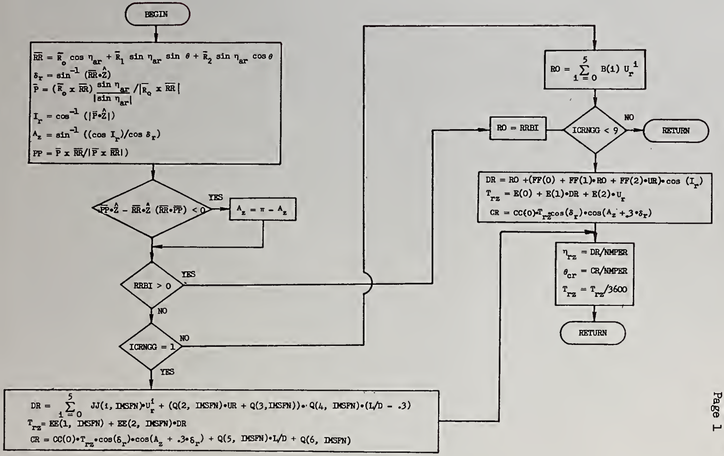
The function of this subroutine is to compute down-range distance, cross-range distance, and time from reentry to landing when the state vector at reentry is given.

Input

ICRNGG	= 1, constant G reentry = 2, G&N reentry = 10, compute RO only; RO is that portion of the down-range distance that depends on reentry speed only
IMSFN	= 1, use shallow reentry target line = 2, use steep reentry target line
L/D	Lift over drag
RRBI	Constant relative range (down range)
$\bar{R}_o$	Unit vector in direction of abort point
$\bar{R}_1$	Unit vector in direction of preabort angular momentum
$\bar{R}_2$	Unit vector in direction of $(\bar{R}_1 \times \bar{R}_o)$
U_r	Reentry speed
η_{ar}	Transfer angle from abort to reentry
θ	Azimuth change

Output

T_{rz}	Time from reentry to landing
η_{rz}	Down-range angle
θ_{cr}	Cross-range angle.


BEGIN
$\overline{RR} = \bar{R}_o \cos \eta_{ar} + \bar{R}_1 \sin \eta_{ar} \sin \theta + \bar{R}_2 \sin \eta_{ar} \cos \theta$
$\delta_r = \sin^{-1} (\overline{RR} \cdot \hat{Z})$
$\bar{P} = (\bar{R}_o \times \overline{RR}) \frac{\sin \eta_{ar}}{|\sin \eta_{ar}|} / |\bar{R}_o \times \overline{RR}|$
$I_r = \cos^{-1} (|\bar{P} \cdot \hat{Z}|)$
$A_z = \sin^{-1} ((\cos I_r)/\cos \delta_r)$
$PP = \bar{P} \times \overline{RR} / |\bar{P} \times \overline{RR}|$
$\overline{PP} \cdot \hat{Z} - \overline{RR} \cdot \hat{Z} (\overline{RR} \cdot \overline{PP}) < 0$
YES
$A_z = \pi - A_z$
RRBI > 0
YES
NO
ICRNGG = 1
NO
YES
$DR = \sum_{i=0}^{5} JJ(i, IMSFN) \cdot U_r^i + (Q(2, IMSFN) \cdot UR + Q(3, IMSFN)) \cdot Q(4, IMSFN) \cdot (L/D - .3)$
$T_{rz} = EE(1, IMSFN) + EE(2, IMSFN) \cdot DR$
$CR = CC(0) \cdot T_{rz} \cdot \cos(\delta_r) \cdot \cos(A_z + .3 \cdot \delta_r) + Q(5, IMSFN) \cdot L/D + Q(6, IMSFN)$
$RO = \sum_{i=0}^{5} B(i)\, U_r^i$
RO = RRBI
ICRNGG < 9
NO
RETURN
$DR = RO + (FF(0) + FF(1) \cdot RO + FF(2) \cdot UR) \cdot \cos (I_r)$
$T_{rz} = E(0) + E(1) \cdot DR + E(2) \cdot U_r$
$CR = CC(0) \cdot T_{rz} \cdot \cos(\delta_r) \cdot \cos(A_z + .3 \cdot \delta_r)$
$\eta_{rz} = DR/NMPER$
$\theta_{cr} = CR/NMPER$
$T_{rz} = T_{rz}/3600$
RETURN

SUBROUTINE RUBR

Purpose

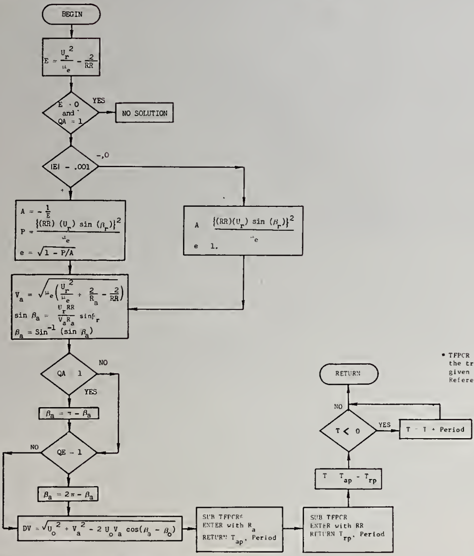
This subroutine constructs a trajectory between the radial distance at abort and the radial distance at reentry when the speed and path angle at the reentry altitude are given.

Input

QA	Apogee passage flag
QE	Postabort motion flag
RR	Reentry radius magnitude
R_a	Radial distance at abort
U_o	Preabort speed
U_r	Reentry speed
β_o	Preabort flight-path angle
β_r	Reentry flight-path angle

Output

A	Semimajor axis
DV	Change in velocity required for an inplane maneuver
e	Eccentricity
T	Trip time from abort to reentry
V_a	Postabort speed
β_a	Postabort flight-path angle



* TFPCR is a conic utility subroutine which computes the transit time from the input position to perigee; given the conic elements. TFPCR is described in Reference 2.

SUBROUTINE SCAN

Purpose

This subroutine is used only for non-zero maximum miss cases in the PTP mode. It determines the plane change permissable within the maximum miss constraint which minimizes ΔV required, and it controls the optimization scan across the maximum miss circle to produce the minimum ΔV solution. At the completion of a scan, it re-initializes the problem to begin the search for the next solution region. This subroutine was formulated from part of the T = f(MD) logic found in reference 1.

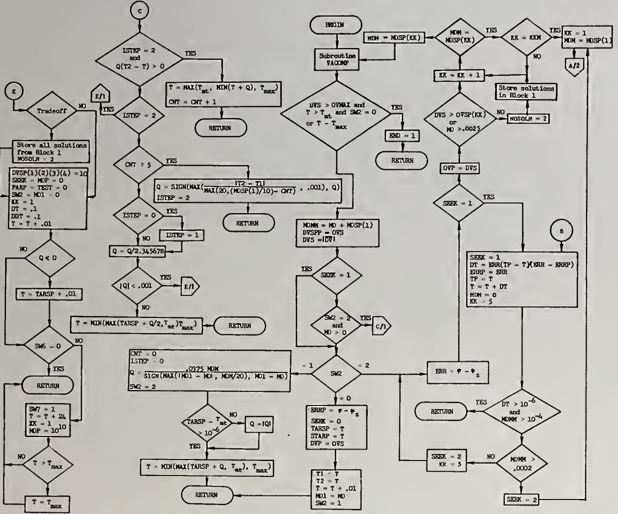
Input

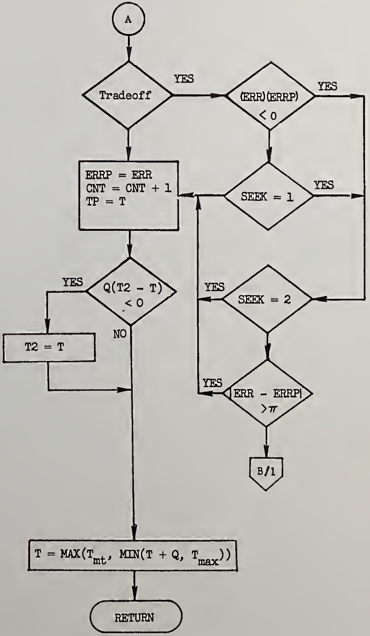
DVS	Saved value of DV
MD	Miss distance
MDSP(KK)	KK values of maximum allowable miss distance. Up to five values may be run during a single tradeoff case
SW6	East - west motion flag
T	Trip time
ϕ	Total transfer angle to impact point
ϕ_z	Total transfer angle from abort to desired landing site

Output

T	Trip time
XK	Indicates whether the function is being minimized or maximized

SCAN
Logic Flow
Page 1




A
Tradeoff
YES
(ERR)(ERRP) < 0
YES
ERRP = ERR
CNT = CNT + 1
TP = T
SEEK = 1
YES
Q(T2 - T) < 0
YES
NO
T2 = T
YES
SEEK = 2
YES
|ERR - ERRP| > π
B/1
T = MAX(T_mt, MIN(T + Q, T_max))
RETURN

SUBROUTINE TCOMP

Purpose

This subroutine computes the new transit time based on the miss distance determined from the current transit time and the way that the miss distance is changing. This computation is done for both the ATP and PTP modes. This subroutine encompasses part of the ATP and T = f(MD) logic found in reference 1.

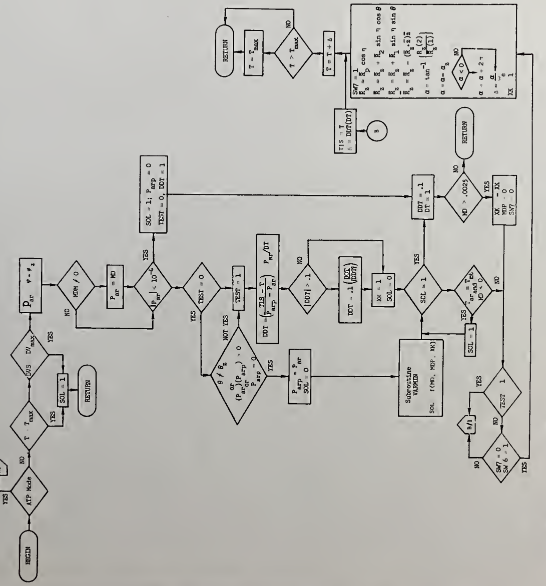
Input

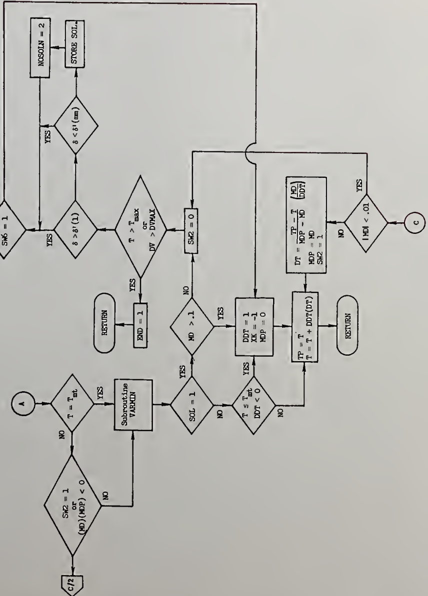
DVMAX	Maximum allowable DV
MD	Miss distance
MDM	Maximum miss distance
$\overline{R}_p$	Unit vector in direction of abort point
$\overline{R}_1$	Unit vector in direction of preabort angular momentum
$\overline{R}_2$	Unit vector in direction of $(\overline{R}_1 \times \overline{R}_p)$
T	Current value of trip time
T_{max}	Maximum allowable trip time
T_{mt}	Minimum possible trip time
XK	Indicates whether the function is being minimized or maximized
α_z	Right ascension of desired landing site
$\delta'(1)$, $\delta'(mm)$	Latitudes of end points on the ATP line
ϕ	Total transfer angle to the impact point

ϕ_z	Total transfer angle from abort to desired landing site
θ	Azimuth change between the preabort and postabort planes
θ_z	Azimuth change to desired landing site

Output

T	Trip time for next iteration
XK	Indicates whether the function is being minimized or maximized


BEGIN
ATP Mode
YES
A/2
NO
T T_{max}
YES
SOL = 1
RETURN
DVS DV_{max}
YES
P_{ar} $\varphi \cdot \varphi_2$
NO
MDM / 0
P_{ar} = MD
$|P_{ar}| < 10^{-4}$
YES
SOL = 1; P_{arp} = 0
TEST = 0, DDT = 1
TEST = 0
YES
$\theta \neq \theta_2$ or $(P_{ar})(P_{arp}) > 0$ or $P_{arp} = 0$
NOT YES
TEST = 1
$DDT = \left(\frac{TIS - T}{P_{arp} - P_{ar}}\right) P_{ar}/DT$
NO
|DDT| > .1
$DDT = .1\left(\frac{DDT}{|DDT|}\right)$
XK = 1
SOL = 0
YES
$P_{arp} = P_{ar}$
SOL = 0
Subroutine VARMIN
SOL f(MD, MDP, XK)
SOL = 1
YES
SOL = 1
YES
T_{ar} and T_{mt}
MD < 0
NO
DDT = .1
DT = 1
MD > .0025
NO
RETURN
YES
XK - XK
MDP - 0
SW7 - 0
TEST 1
YES
B/1
NO
SW7 = 0
SW 6 = 1
NO
YES
TIS = T
Δ = DDT(DT)
B
SW7 = 1
$\bar{R}_z = \bar{R}_p \cos \eta$
$\bar{R}_z = \bar{R}_z + \bar{R}_2 \sin \eta \cos \theta$
$\bar{R}_z = \bar{R}_z + \bar{R}_1 \sin \eta \sin \theta$
$\bar{R}_z = \bar{R}_z - (\bar{R}_z \cdot \bar{z})\bar{z}$
$\alpha = \tan^{-1}\left(\frac{R_z(2)}{R_z(1)}\right)$
$\alpha = \alpha - \alpha_z$
$\alpha < 0$
NO
$\alpha = \alpha + 2\pi$
$\Delta = \frac{\alpha}{\omega_e}$
XK 1
T = T + Δ
T > T_{max}
NO
T = T_{max}
RETURN


A
T = T_{mt}
YES
NO
SW2 = 1 or (MD)(MDP) < 0
NO
C/2
Subroutine VARMIN
SOL = 1
YES
NO
MD > .1
YES
NO
T ≤ T_{mt} DDT < 0
YES
NO
DDT = 1 XK = -1 MDP = 0
SW2 = 0
T > T_{max} or DV > DVMAX
YES
END = 1
RETURN
δ > δ'(1)
YES
δ < δ'(nn)
YES
STORE SOL.
NOSOLN = 2
SW6 = 1
YES
NO
T = T + 24 MDP = 10^{10} XK = 1
RETURN
TP = T T = T + DDT(DT)
RETURN
DT = $\frac{TP - T}{MDP - MD}$ $\left(\frac{MD}{DDT}\right)$ MDP = MD SW2 = 1
|MD| < .01
YES
NO
C

SUBROUTINE TMIN

Purpose

This subroutine computes the minimum trip time solution which returns to the reentry target line and satisfies the following constraints: maximum fuel, maximum reentry velocity, maximum inclination, and minimum landing time. The logic first generates the solution that has the maximum allowable reentry speed; and, if this trajectory satisfies all constraints, it is accepted and the subroutine is exited. Otherwise, an attempt is made to generate a solution using all the available DV to minimize the flight time. The procedure is to iteratively drive DV to DVM using transit time as the independent variable. The maximum entry speed solution is used as a lower bound on trip time; an upper bound is generated from the minimum fuel unspecified area solution. A new trip time is selected by averaging the upper and lower bounds, and the DV is computed for this flight time. If DV ≈ DVM, the solution is accepted; otherwise, the upper or lower bound on transit time is reset with the current transit time depending on whether DV is greater than DVM or less than DVM. The iteration continues until an acceptable solution is generated or until the upper and lower bounds become equal.

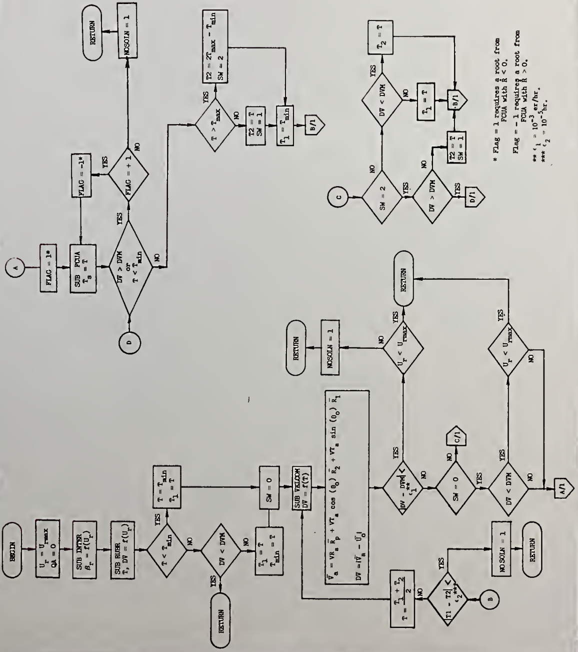
Input

DVM	Maximum allowable DV at abort (with acceptable inclination)
T_{min}	Minimum allowable transit time
U_{rmax}	Maximum allowable entry speed
θ_o	Azimuth change necessary to satisfy inclination constraint

Output

DV	Change in velocity
FLAG	Used to force a solution with a negative radial rate from FCUA

T	Transit time
U_r	Reentry speed
VT_a	Tangential component of postabort velocity
VT_r	Radial component of postabort velocity



* Flag = 1 requires a root from FCUA with $\dot{R} < 0$.

Flag = − 1 requires a root from FCUA with $\dot{R} > 0$.

** $\epsilon_1 = 10^{-3}$ er/hr.

*** $\epsilon_2 = 10^{-5}$ hr.

SUBROUTINE VACOMP

Purpose

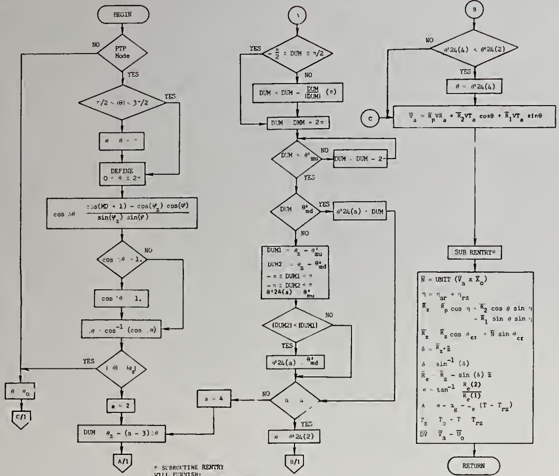
This subroutine computes the vector to the conic impact point, the latitude and longitude of the impact point, the postabort velocity vector, and the time of landing. In the case of a PTP solution, if a solution has been found within the maximum allowable miss distance, this subroutine tries to minimize fuel consumption by increasing the miss distance to the maximum allowable before it computes the impact point.

Input

$\overline{R}_p$	Unit vector in direction of abort point
$\overline{R}_1$	Unit vector in direction of preabort angular momentum
$\overline{R}_2$	Unit vector in direction of $(\overline{R}_1 \times \overline{R}_p)$
VR_a	Radial component of postabort velocity
VT_a	Tangential component of postabort velocity
θ	Change in azimuth to minimize the miss distance
θ_o	Change in azimuth to nearest acceptable plane
θ'_{mu}, θ'_{md}	Maximum changes in azimuth from preabort azimuth based on inclination constraints

Output

$\overline{DV}$	Change in velocity vector
T_z	Time of landing
$\overline{V}_a$	Postabort velocity vector
α	Right ascension of the impact point
δ	Latitude of impact point
λ	Longitude of impact point



* SUBROUTINE RENTRY
WILL FURNISH:
$\overline{RR}$ - POSITION VECTOR AT ENTRY
η_{rz} - DOWNRANGE MAN. ANGLE
θ_{cr} - CROSSRANGE
T_{rz} - RENTRY MAN. TIME
GIVEN:
$\overline{X}_o$, $\overline{V}_a$, T_o

SUBROUTINE VARMIN

Purpose

This subroutine determines the direction of the scan for the required landing site by deciding whether the difference between the past and present values of the miss distance is small enough to be considered an extremum and if so, sets the time increment, direction, and scan flag to the proper values.

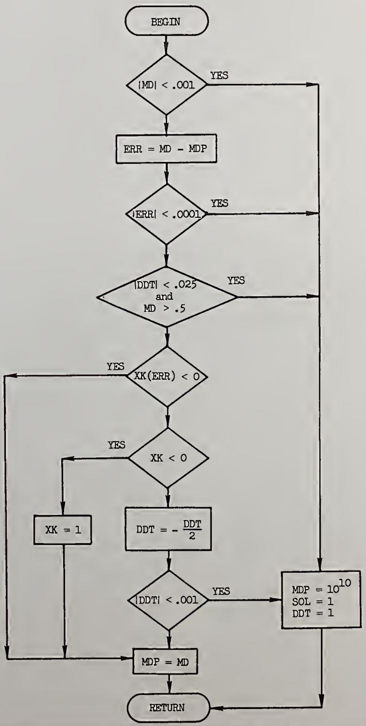
Input

DDT	Independent variable
MD	Function to be minimized (miss distance)
MDP	Past value of MD
XK[a]	Flag that indicates whether a minimization or maximization is to be performed

Output

DDT	Independent variable
MDP	Present value of miss distance stored for the next pass
SOL	Flag that indicates a zero or an extremum
XK[a]	Flag that indicates whether a minimization or maximization is to be performed

[a] If XK = -1, then a maximization is performed until an extremum is reached; then XK is set to 1 and the minimization is continued.


BEGIN
|MD| < .001
YES
ERR = MD - MDP
|ERR| < .0001
YES
|DDT| < .025
and
MD > .5
YES
XK(ERR) < 0
YES
XK < 0
YES
XK = 1
DDT = - DDT/2
|DDT| < .001
YES
MDP = 10^10
SOL = 1
DDT = 1
MDP = MD
RETURN

SUBROUTINE VELCOM

Purpose

This subroutine is used to generate trajectories which return to the reentry target line with a specified transit time.

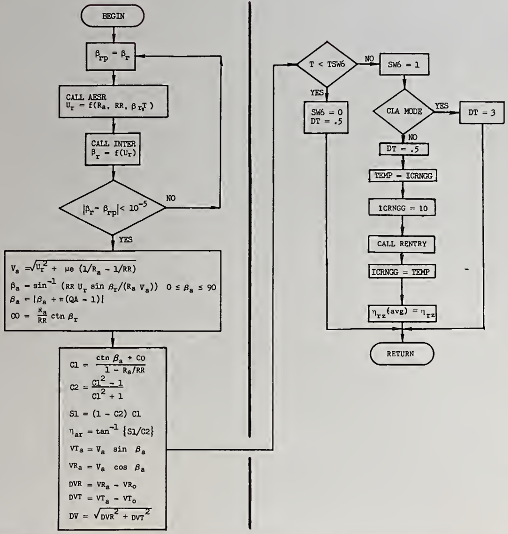
Input

T	Desired transit time
RR	Radial distance at reentry
R_a	Abort radial distance
β_r	Current value of the flight-path angle at reentry
β_{rp}	Past value of the flight-path angle at reentry

Output

DT	Time increment
p	Semilatus rectum
QA	Apogee passage flag = 1, apogee passage = 0, no apogee passage
SW6	Direction of motion flag at impact point
U_r	Reentry speed
VR_a	Radial component of required velocity
VT_a	Tangential component of required velocity
β_a	Flight-path angle at abort
β_r	Flight-path angle at reentry
η_{ar}	Transfer angle from abort to reentry
$\eta_{rz}(\text{ave})$	Down-range angle based on reentry speed only; that is, geometry effects are neglected

Subroutine INTER, which is frequently used but not specified is a general interpolation subroutine. In this program, it is used to determine the reentry flight-path angle given the reentry speed and the data point for the specified reentry target line. Subroutines INTER and AESR, which are conic trajectory utility subroutines, are specified in reference 2.


BEGIN
$\beta_{rp} = \beta_r$
CALL AESR
$U_r = f(R_a, RR, \beta_r, T)$
CALL INTER
$\beta_r = f(U_r)$
$|\beta_r - \beta_{rp}| < 10^{-5}$
NO
YES
$V_a = \sqrt{U_r^2 + \mu e\,(1/R_a - 1/RR)}$
$\beta_a = \sin^{-1}(RR\,U_r \sin\beta_r/(R_a V_a))\quad 0 \le \beta_a \le 90$
$\beta_a = |\beta_a + \pi(QA - 1)|$
$CO = \frac{R_a}{RR}\operatorname{ctn}\beta_r$
$C1 = \frac{\operatorname{ctn}\beta_a + CO}{1 - R_a/RR}$
$C2 = \frac{C1^2 - 1}{C1^2 + 1}$
$S1 = (1 - C2)\,C1$
$\eta_{ar} = \tan^{-1}\{S1/C2\}$
$VT_a = V_a \sin\beta_a$
$VR_a = V_a \cos\beta_a$
$DVR = VR_a - VR_o$
$DVT = VT_a - VT_o$
$DV = \sqrt{DVR^2 + DVT^2}$
T < TSW6
NO
YES
SW6 = 1
SW6 = 0
DT = .5
CLA MODE
YES
NO
DT = 3
DT = .5
TEMP = ICRNGG
ICRNGG = 10
CALL RENTRY
ICRNGG = TEMP
$\eta_{rz}(avg) = \eta_{rz}$
RETURN

SUBROUTINE VUP2

Purpose

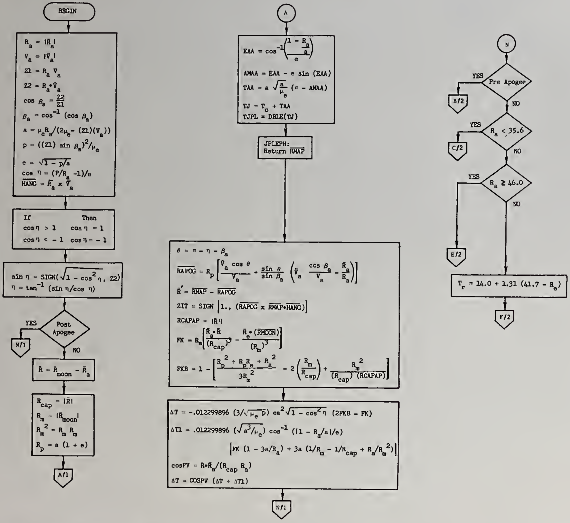
This subroutine is used to calibrate the postabort velocity by accounting for the lunar third-body effects.

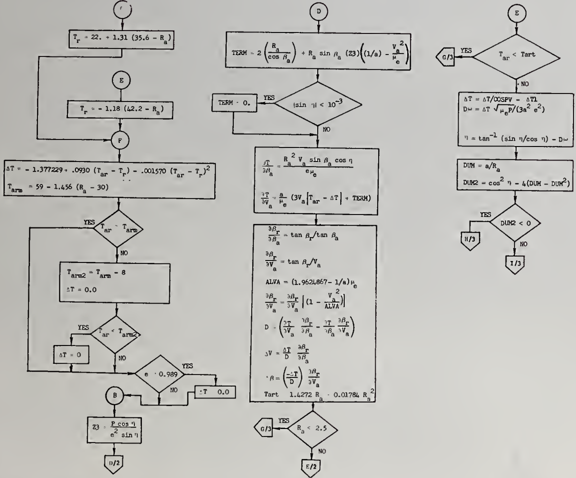
Input

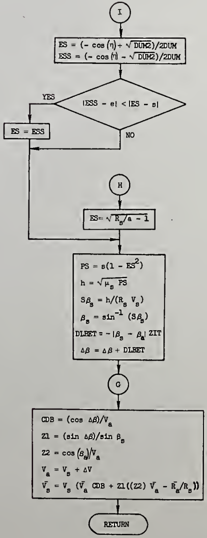
$\bar{R}_a$	Position vector at abort
$\bar{R}_{moon}$	Position of the moon with respect to the earth
T_{ar}	Trip time from abort to reentry
$\bar{V}_a$	Postabort velocity vector
β_r	Reentry flight-path angle

Output

$\bar{V}_a$	Postabort velocity calibrated to include the lunar third-body effects


BEGIN
$R_a = |\bar{R}_a|$
$V_a = |\bar{V}_a|$
$Z1 = R_a V_a$
$Z2 = R_a \bullet \hat{V}_a$
$\cos \beta_a = \frac{Z2}{Z1}$
$\beta_a = \cos^{-1} (\cos \beta_a)$
$a = \mu_e R_a/(2\mu_e - (Z1)(V_a))$
$p = ((Z1) \sin \beta_a)^2/\mu_e$
$e = \sqrt{1 - p/a}$
$\cos \eta = (P/R_a - 1)/a$
$\overline{HANG} = \tilde{R}_a \times \bar{V}_a$
If
Then
$\cos \eta > 1$
$\cos \eta = 1$
$\cos \eta < -1$
$\cos \eta = -1$
$\sin \eta = SIGN(\sqrt{1 - \cos^2 \eta}, Z2)$
$\eta = \tan^{-1} (\sin \eta/\cos \eta)$
Post Apogee
YES
N/1
NO
$\bar{R} = \bar{R}_{moon} - \bar{R}_a$
$R_{cap} = |\bar{R}|$
$R_m = |\bar{R}_{moon}|$
$R_m^2 = R_m R_m$
$R_p = a (1 + e)$
A/1
A
$EAA = \cos^{-1}\left(\frac{1 - \frac{R_a}{a}}{e}\right)$
$AMAA = EAA - e \sin (EAA)$
$TAA = a \sqrt{\frac{a}{\mu_e}} (\pi - AMAA)$
$TJ = T_o + TAA$
$TJPL = DBLE(TJ)$
JPLEPH:
Return $\overline{RMAP}$
$\theta = \pi - \eta - \beta_a$
$\overline{RAPOG} = R_p \left[\frac{\bar{V}_a \cos \theta}{V_a} + \frac{\sin \theta}{\sin \beta_a} \left(\bar{V}_a \frac{\cos \beta_a}{V_a} - \frac{\bar{R}_a}{R_a}\right)\right]$
$\bar{R}' = \overline{RMAP} - \overline{RAPOG}$
$ZIT = SIGN \left[1., (\overline{RAPOG} \times \overline{RMAP} \bullet \overline{HANG})\right]$
$RCAPAP = |\bar{R}'|$
$FK = R_a \left[\frac{\bar{R}_a \bullet \bar{R}}{(R_{cap})^3} - \frac{\bar{R}_e \bullet (\overline{RMOON})}{(R_m)^3}\right]$
$FKB = 1 - \left[\frac{R_p^2 + R_p R_e + R_a^2}{3R_m^2} - 2\left(\frac{R_m}{R_{cap}}\right) + \frac{R_m^2}{(R_{cap})(RCAPAP)}\right]$
$\Delta T = -.012299896 (3/\sqrt{\mu_e p}) ea^2 \sqrt{1 - \cos^2 \eta} (2FKB - FK)$
$\Delta T1 = .012299896 (\sqrt{a^3/\mu_e}) \cos^{-1} (|1 - R_a/a|/e)$
$\left[FK (1 - 3a/R_a) + 3a (1/R_m - 1/R_{cap} + R_a/R_m^2)\right]$
$\cos PV = \bar{R} \bullet \bar{R}_a/(R_{cap} R_a)$
$\Delta T = COSPV (\Delta T + \Delta T1)$
N/1
N
Pre Apogee
YES
B/2
NO
$R_a < 35.6$
YES
C/2
NO
$R_a \geq 46.0$
YES
E/2
NO
$T_r = 14.0 + 1.31 (41.7 - R_e)$
F/2


C
$T_r = 22. + 1.31 (35.6 - R_a)$
E
$T_r = - 1.18 (42.2 - R_a)$
F
$\Delta T = - 1.377229 + .0930 (T_{ar} - T_r) - .001570 (T_{ar} - T_r)^2$
$T_{arm} = 59 - 1.456 (R_a - 30)$
$T_{ar} \cdot T_{arm}$
YES
NO
$T_{arm2} = T_{arm} - 8$
$\Delta T = 0.0$
$T_{ar} < T_{arm2}$
YES
$\Delta T = 0$
NO
$e \cdot 0.989$
YES
NO
$\Delta T \quad 0.0$
B
$Z3 = \frac{P \cos \eta}{e^2 \sin \eta}$
D/2
D
$\text{TERM} = 2 \left(\frac{R_a}{\cos \beta_a}\right) + R_a \sin \beta_a (Z3)\left((1/a) - \frac{V_a^2}{\mu_e}\right)$
$|\sin \eta| < 10^{-3}$
YES
$\text{TERM} \cdot 0.$
NO
$\frac{\partial T}{\partial \beta_a} = \frac{R_a^2 V_a \sin \beta_a \cos \eta}{e \mu_e}$
$\frac{\partial T}{\partial V_a} = \frac{a}{\mu_e} (3V_a \left|T_{ar} - \Delta T\right| + \text{TERM})$
$\frac{\partial \beta_r}{\partial \beta_a} = \tan \beta_r / \tan \beta_a$
$\frac{\partial \beta_r}{\partial V_a} = \tan \beta_r / V_a$
$\text{ALVA} = (1.9624867 - 1/a)\mu_e$
$\frac{\partial \beta_r}{\partial V_a} = \frac{\partial \beta_r}{\partial V_a} \left|(1 - \frac{V_a^2}{\text{ALVA}})\right|$
$D \cdot \left(\frac{\partial T}{\partial V_a} \frac{\partial \beta_r}{\partial \beta_a} - \frac{\partial T}{\partial \beta_a} \frac{\partial \beta_r}{\partial V_a}\right)$
$\Delta V = \frac{\Delta T}{D} \frac{\partial \beta_r}{\partial \beta_a}$
$\Delta \beta = \left(\frac{-\Delta T}{D}\right) \frac{\partial \beta_r}{\partial V_a}$
$\text{Tart} \quad 1.4272 R_a \cdot 0.01784 R_a^2$
$R_a < 2.5$
YES
G/3
NO
E/2
E
$T_{ar} < \text{Tart}$
YES
G/3
NO
$\Delta T = \Delta T/\text{COSPV} - \Delta T1$
$D\omega = \Delta T \sqrt{\mu_e P}/(3a^2 e^2)$
$\eta = \tan^{-1} (\sin \eta/\cos \eta) - D\omega$
$\text{DUM} = a/R_a$
$\text{DUM2} = \cos^2 \eta - 4(\text{DUM} - \text{DUM}^2)$
$\text{DUM2} < 0$
YES
H/3
NO
I/3


I
ES = (- cos (η) + √DUM2)/2DUM
ESS = (- cos (η) - √DUM2)/2DUM
YES
|ESS - e| < |ES - e|
NO
ES = ESS
H
ES = √(R_s/a - 1)
PS = s(1 - ES²)
h = √(μ_s PS)
Sβ_s = h/(R_s V_s)
β_s = sin⁻¹ (Sβ_s)
DLBET = - |β_s - β_a| ZIT
Δβ = Δβ + DLBET
G
CDB = (cos Δβ)/V_a
Z1 = (sin Δβ)/sin β_s
Z2 = cos (β_s)/V_a
V_a = V_s + ΔV
V̄_s = V_s (V̄_a CDB + Z1((Z2) V̄_a - R̄_a/R_s))
RETURN

REFERENCES

1. Lee, W. R.: AS-503A Requirements for the RTCC: Return-to-Earth Abort Conic Subprocessor, Revision 1. MSC IN 67-FM-56, Dec. 12, 1967.

2. Northcutt, F. M.: RTCC Requirements for Apollo 14 (H-3) Mission: Moon-Centered Return-to-Earth Conic Subprocessor. MSC IN 70-FM-19, Jan. 30, 1970.

3. Davis, R. S.: RTCC Requirements for Apollo 14 (H-3) Mission: Return-to-Earth Processor Supervisory and Precision Computation Logic. MSC IN to be published.

4. Berry, R. L.; and Lee, W. R.: AS-503A Requirements for the RTCC: Return-to-Earth Abort Conic Subprocessor. MSC IN 66-FM-117, Oct. 19, 1966.

NASA — MSC — Coml., Houston, Texas