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LOGIC AND EQUATIONS FOR THE REAL-TIME COMPUTATION OF THE LUNAR MODULE LAUNCH WINDOW AND RECOMMENDED LIFT-OFF TIME

By R. K. McDonough and W. A. Sullivan

Rendezvous Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER

HOUSTON, TEXAS

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PROJECT APOLLO

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LOGIC AND EQUATIONS FOR THE REAL-TIME COMPUTATION OF THE LUNAR MODULE LAUNCH WINDOW AND RECOMMENDED LIFT-OFF TIME

By R. K. McDonough and W. A. Sullivan

SUMMARY AND INTRODUCTION

This Internal Note presents the logic and mathematics of the Lunar Launch Window Processor (LLWP). The enclosed functional and detailed flow charts define the processor for the AS-504 real-time computer systems. The LLWP computes the lunar module (LM) recommended time of lift-off from the lunar surface and the lunar launch window. The output will be used for mission planning prior to AS-504 and will be used in real-time to compute the Lunar Launch Window Display for the launch time planning.

LUNAR LAUNCH WINDOW PROCESSOR

The LLWP computes lift-off times as a function of the height difference (ΔH) in the coelliptic orbits phase of the lunar concentric rendezvous plan (ref. 1). The recommended LM time of lift-off from the lunar surface is that launch time during a given command and service modules (CSM) revolution for which the required ΔH is the nominal mission value. The lunar launch window is defined as the total interval of time in the CSM revolution during which the LM can lift-off and rendezvous with the CSM within the limits of maneuver-ΔV budgets, LM ascent stage power lifetime, and safe orbital altitudes.

The lift-off time computation involves simulation of the mission from LM launch through rendezvous. The lift-off time which satisfies phase convergence for the given coelliptic ΔH at terminal phase initiation is the required time. The LLWP output for each ΔH includes the lift-off time, maneuver times, and maneuver-ΔV values.

The LLWP times may be computed based on either LM or CSM execution of the rendezvous maneuvers. In either case, ΔH is positive when the maneuvering vehicle is below the target vehicle, and is negative otherwise. The positive ΔH values are limited by the minimum allowable pericynthion altitude. The negative ΔH values are limited by the rendezvous ΔV budgeted for the maneuvering vehicle; however, a theoretical limit exists above which the vehicle cannot acquire the target along the input elevation angle.

The launch window boundary times are computed for these ΔH maxima with terminal phase delayed in time to the limit of LM ascent stage power lifetime.

The LLWP logic is divided into three blocks. The main, or control, block is called the LLWM and calls for HMALIT and TILL. The HMALIT (Lunar Height Maneuver Iterator) block computes the lunar concentric rendezvous sequence to maneuver from the input CSI position into an orbit coelliptic to the target and with the input ΔH. The TILL (Time Iterator for Lunar Lighting) block computes the time of arrival of the target vehicle at an angle from the earth-moon line and is used to fix terminal phase initiation at a point with acceptable lighting conditions. Functional and detailed flow charts for LLWM, HMALIT, and TILL are presented in Appendices A, B, and C, respectively.

The processor uses the Lunar Satellite Analytic Ephemeris Generator (LSAEG of ref. 2) for vehicle ephemeris prediction. The symbols used for LSAEG are given in Appendix D. Several special purpose trajectory subroutines are called in addition to the LSAEG. These are COEDH, ENSERT (ref. 3); STAP, STLO (ref. 4); TIMA, TIMFA, THETR (ref 5); PERHAP (ref 6); and, the two-impulse maneuver routines (ref 7).

APPENDIX A

FUNCTIONAL AND DETAILED FLOW CHARTS FOR LLWM

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SYMBOLS

Constant Input:

π	3.141592 . . .
μ	lunar gravitational potential
R_L	mean lunar radius
δ_θ	angular iteration tolerance
δ_H	height iteration tolerance
δ_T	time iteration tolerance
f_{nm}	international feet per nautical mile

Variable Input:

I_{BURN}	flag that controls at what time CSI is done
	$I_{BURN} = 0$, CSI is done 90° from insertion
	$I_{BURN} = 1$, CSI is done at an input elapsed time from insertion
I_{TPI}	flag that controls at what position TPI is done
	$I_{TPI} = 0$, TPI is done at an input angle away from the earth-moon line
	$I_{TPI} = 1$, TPI is done over an input longitude
	$I_{TPI} = 2$, TPI is at an input time

I_{SRCH}	flag that controls the search option for the absolute opening and closing of the launch window I_{SRCH} = 0, compute the launch window for only the input ΔH table I_{SRCH} = 1, compute the complete window
I_{OS}	flag that controls position for final maneuver I_{OS} = 0, compute final maneuver for a rendezvous solution I_{OS} = 1, compute final maneuver for an offset in height and phase
M	number of maneuvering vehicle M = 1, CSM is maneuvering vehicle M = 2, LM is maneuvering vehicle
P	number of non-maneuvering vehicle P = 1, CSM is non-maneuvering vehicle P = 2, LM is non-maneuvering vehicle
N_{CURV}	number of points used in the curve fit
$L_{\Delta H}$	number of entries in the ΔH table
t_{max}	maximum in-orbit lifetime of the LM ascent stage power systems
H_S	minimum safe height of an orbiting vehicle
$\Delta V_{MAX\ i}$ (i=1,2)	rendezvous ΔV budget for both vehicles

ΔH_i $(i=1,L_{\Delta H})$	input table of coelliptic altitude differences
θ_{BO}	powered flight arc of LM
H_{BO}	height of insertion of LM
t_{pf}	powered flight time of LM
V_{BO}	insertion velocity of LM
ϕ_{TPI}	angle from TPI to the earth-moon line
Y_S	yaw steer capability of LM
Δt_B	time to travel from insertion to CSI
ΔH_{SRCH}	height difference to begin curve fit with
ΔH_{STEP}	height difference to increment curve fit with
ωt	transfer angle for terminal phase
ϕ_{LA}	elevation angle to initiate terminal phase on
ΔH_{OFF}	offset height difference
$\Delta\theta_{OFF}$	phase angle offset
t_{hole}	threshold time to determine which launch window is obtained
t_{TPI}	time of TPI
R_{LS}, λ_{LS}, ϕ_{LS}	radius, longitude and latitude of landing site

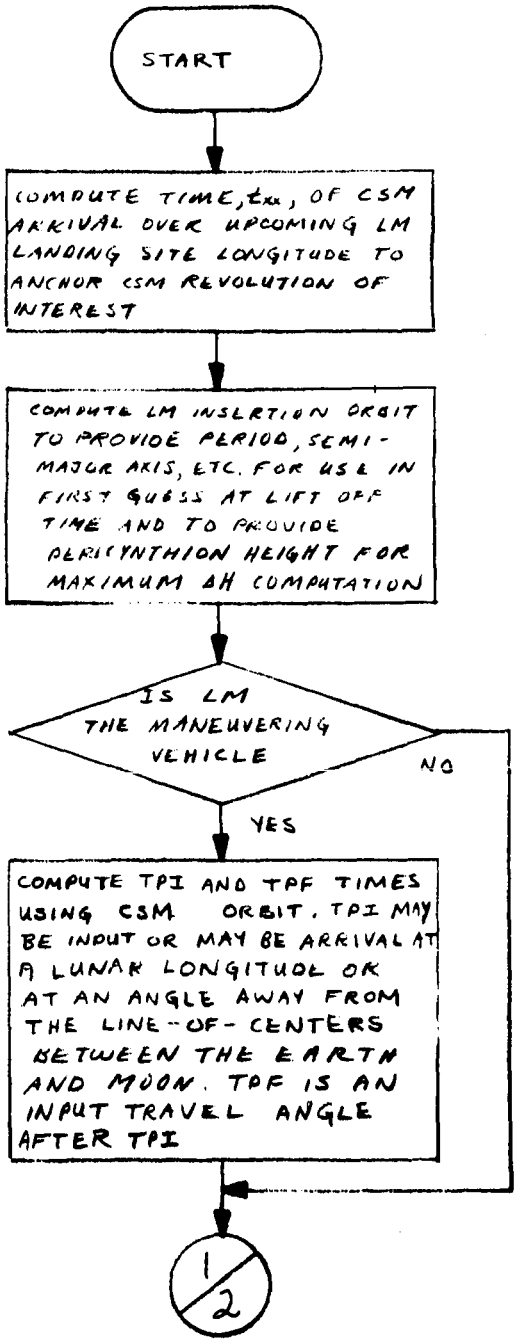
t_{ls}	time of landing site vector
a_1, e_1, i_1, g_1, h_1, l_1	CSM vector in classical coordinates
t_1	time of CSM vector
λ_{TPI}	longitude at which TPI is to be scheduled

Output

$T_{LD\ i}$ $(i = 1, I_{LOOP})$	table of lift-off times
ΔH_i $(i = 1, I_{SELET})$	table of coelliptic height differences
$T_{CSI\ i}$ $(i = 1, I_{LOOP})$	table of CSI times
$T_{CDH\ i}$ $(i = 1, I_{LOOP})$	table of CDH times
$T_{TPI\ i}$ $(i = 1, I_{LOOP})$	table of TPI times
$T_{TPF\ i}$ $(i = 1, I_{LOOP})$	table of TPF times
$DV_{CSI\ i}$ $(i = 1, I_{SELET})$	table of CSI maneuver costs
$DV_{CDH\ i}$ $(i = 1, I_{SELET})$	table of CDH maneuver costs
$DV_{TPI\ i}$ $(i = 1, I_{SELET})$	table of TPI maneuver costs
$DV_{TPF\ i}$ $(i = 1, I_{SELET})$	table of TPF maneuver costs
$DV_{T\ i}$ $(i = 1, I_{SELET})$	table of total maneuver costs in plan
N_i $(i = 1, I_{LOOP})$	table of rendezvous orbit numbers

FUNCTIONAL LLWM FLOW CHART

1



2

1

COMPUTE MAXIMUM POSITIVE ΔH BASED ON TARGET VEHICLE PERICYNTHION HEIGHT AND INPUT MINIMUM SAFE PERICYNTHION HEIGHT

COMPUTE MAXIMUM NEGATIVE ΔH AS THAT VALUE ABOVE WHICH THE TARGET CAN NO LONGER BE SEEN AT THE DESIRED ELEVATION ANGLE.

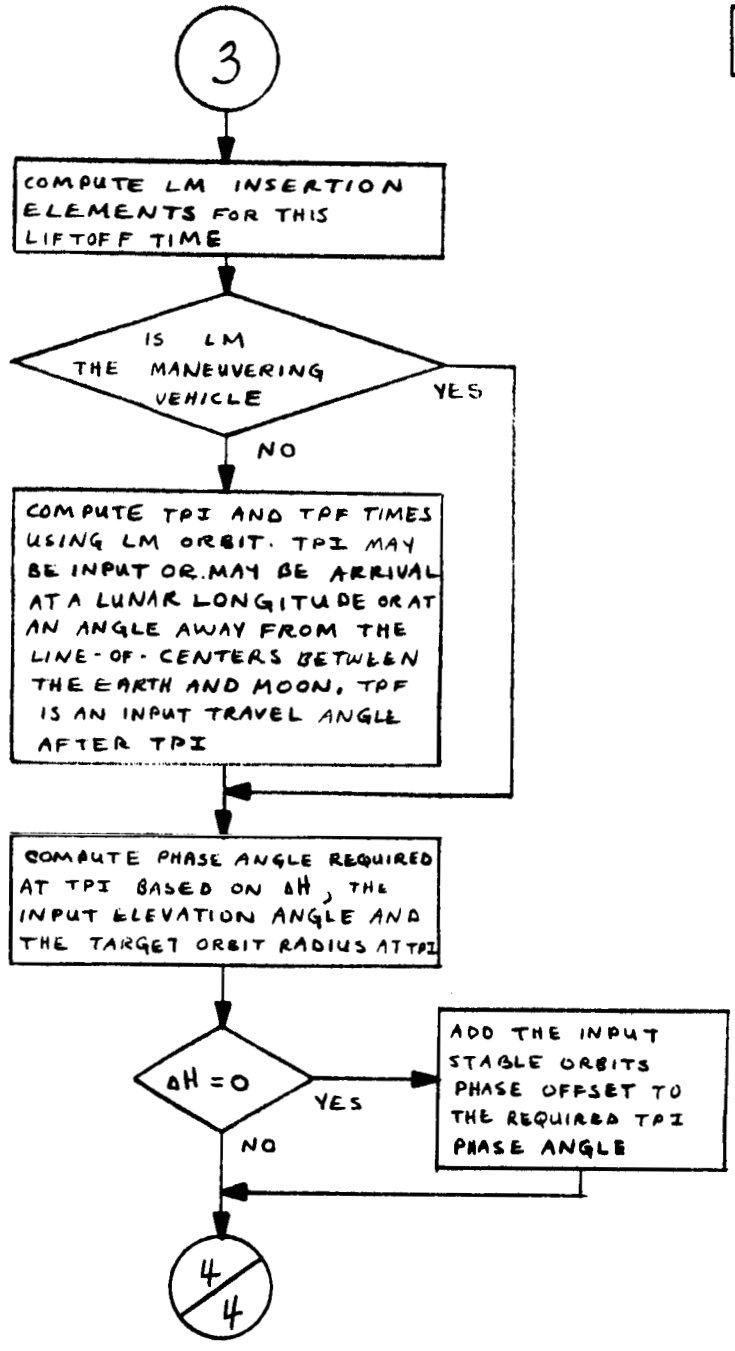
SET UP ΔH TABLE. DELETE ANY INPUT VALUES WHICH EXCEED THE COMPUTED MAXIMA. IF REQUESTED, INCLUDE MAXIMUM POSITIVE ΔH AS THE FIRST TABLE ENTRY AND MAXIMUM NEGATIVE ΔH AS A TENTATIVE FINAL ENTRY. A CURVE FIT WILL BE DONE LATER TO DETERMINE THE MAXIMUM NEGATIVE ΔH WITHIN ΔV BUDGET. CHOOSE FIRST ΔH ENTRY FOR COMPUTATION OF INITIAL LIFT-OFF TIME

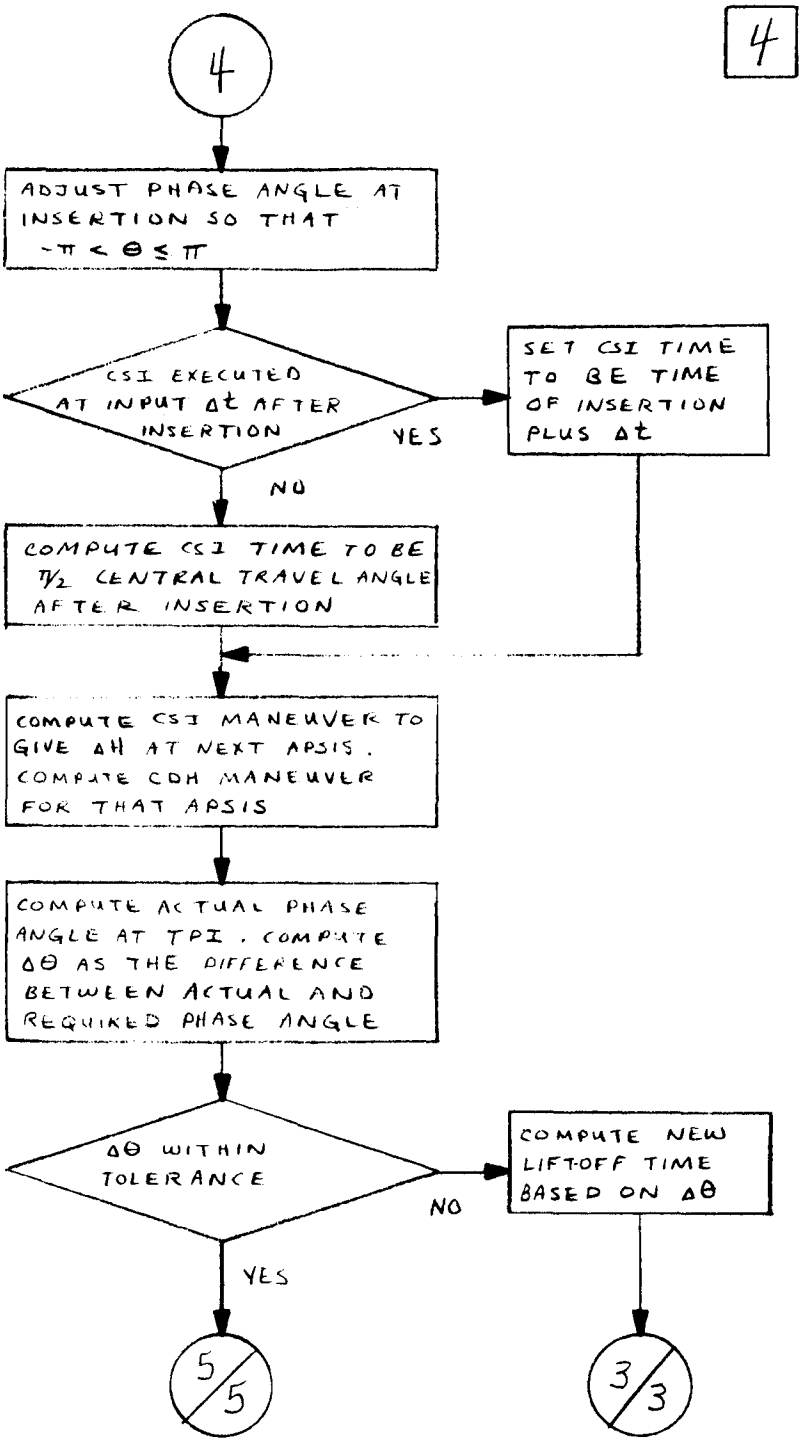
2

COMPUTE FIRST GUESS AT LM LIFTOFF TIME BY BIASING $\dot{E}_{xx}$ AS A FUNCTION OF THE CATCHUP DURING EACH ORBIT PHASE FROM LAUNCH TO TPF

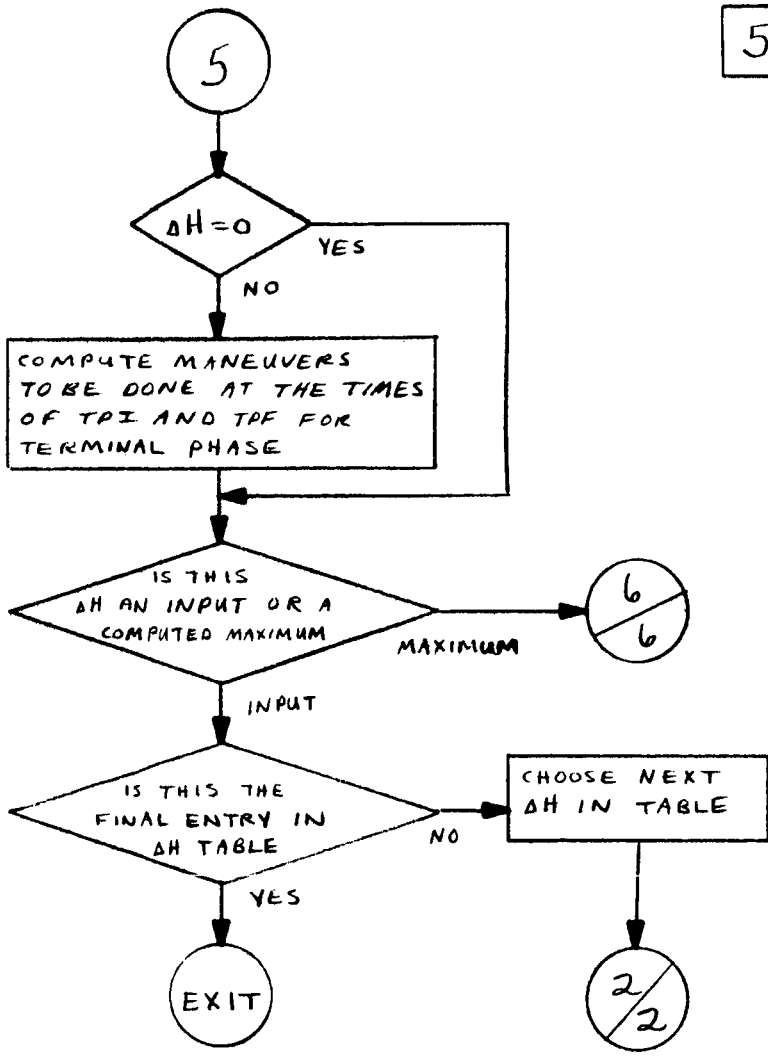
3/3

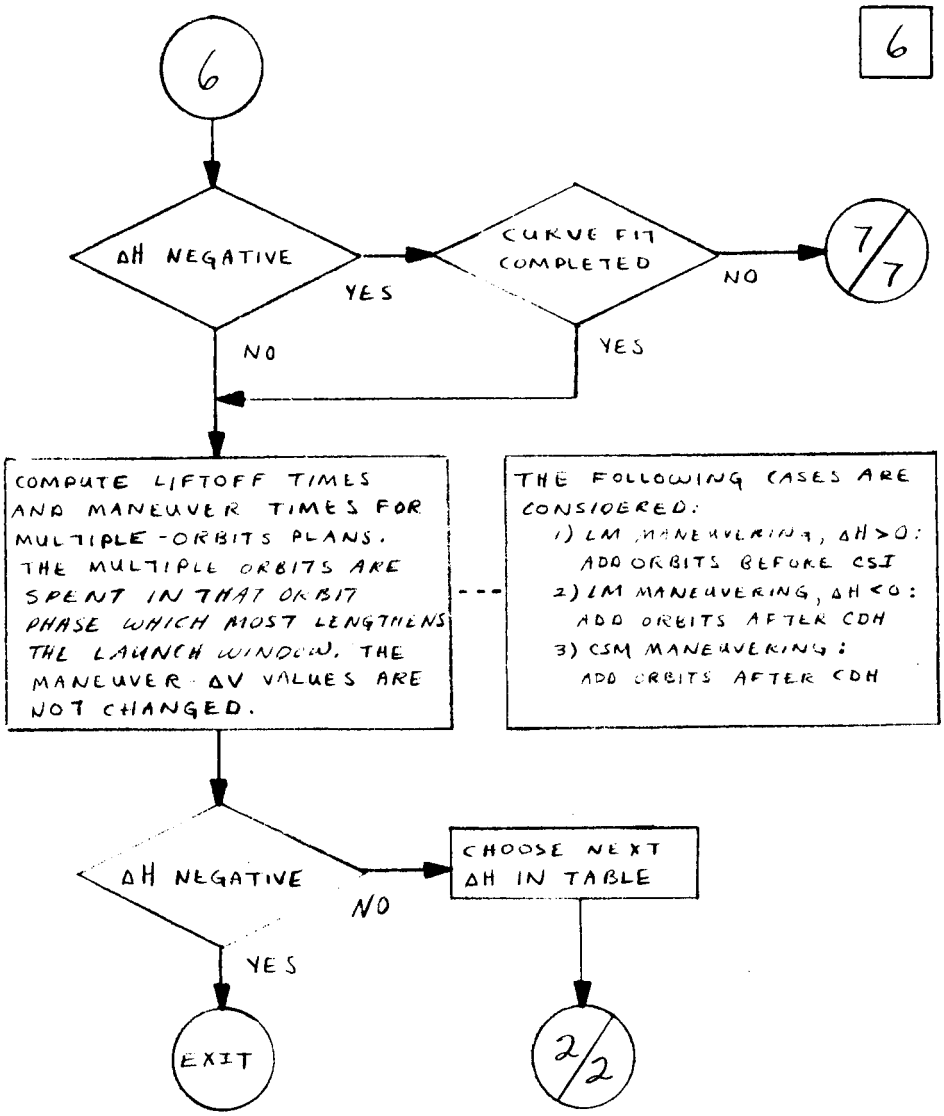
3

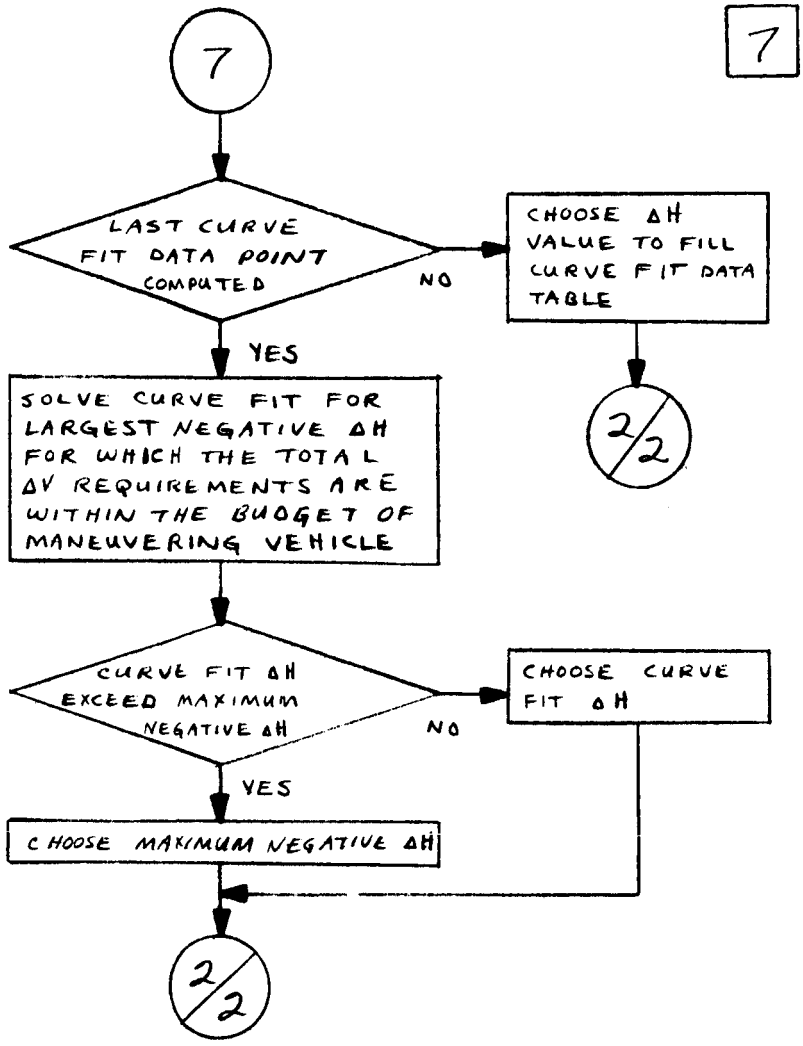

3
COMPUTE LM INSERTION ELEMENTS FOR THIS LIFTOFF TIME
IS LM THE MANEUVERING VEHICLE
YES
NO
COMPUTE TPI AND TPF TIMES USING LM ORBIT. TPI MAY BE INPUT OR MAY BE ARRIVAL AT A LUNAR LONGITUDE OR AT AN ANGLE AWAY FROM THE LINE-OF-CENTERS BETWEEN THE EARTH AND MOON, TPF IS AN INPUT TRAVEL ANGLE AFTER TPI
COMPUTE PHASE ANGLE REQUIRED AT TPI BASED ON ΔH, THE INPUT ELEVATION ANGLE AND THE TARGET ORBIT RADIUS AT TPI
ΔH = 0
YES
NO
ADD THE INPUT STABLE ORBITS PHASE OFFSET TO THE REQUIRED TPI PHASE ANGLE
4/4


4
4
ADJUST PHASE ANGLE AT INSERTION SO THAT $-\pi < \theta \leq \pi$
CSI EXECUTED AT INPUT Δt AFTER INSERTION
YES
SET CSI TIME TO BE TIME OF INSERTION PLUS Δt
NO
COMPUTE CSI TIME TO BE $\pi/2$ CENTRAL TRAVEL ANGLE AFTER INSERTION
COMPUTE CSI MANEUVER TO GIVE ΔH AT NEXT APSIS. COMPUTE CDH MANEUVER FOR THAT APSIS
COMPUTE ACTUAL PHASE ANGLE AT TPI. COMPUTE $\Delta\theta$ AS THE DIFFERENCE BETWEEN ACTUAL AND REQUIRED PHASE ANGLE
$\Delta\theta$ WITHIN TOLERANCE
NO
COMPUTE NEW LIFTOFF TIME BASED ON $\Delta\theta$
YES
5/5
3/3

5

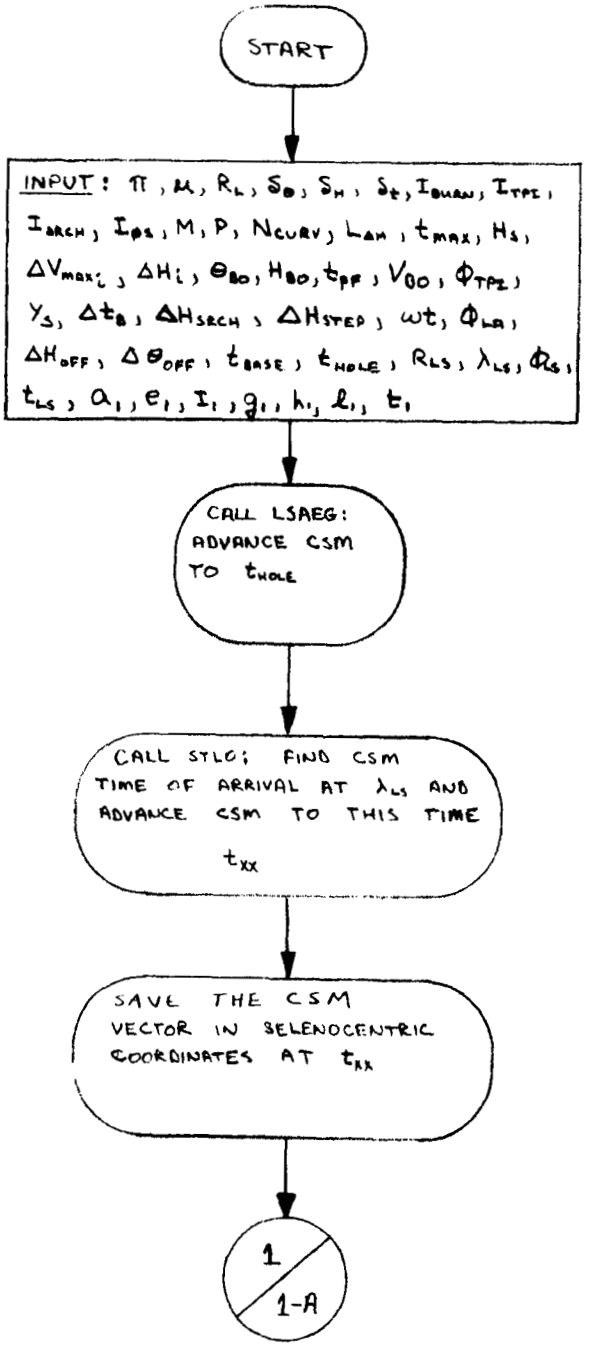

5
ΔH = 0
YES
NO
COMPUTE MANEUVERS TO BE DONE AT THE TIMES OF TPI AND TPF FOR TERMINAL PHASE
IS THIS ΔH AN INPUT OR A COMPUTED MAXIMUM
MAXIMUM
6/6
INPUT
IS THIS THE FINAL ENTRY IN ΔH TABLE
NO
CHOOSE NEXT ΔH IN TABLE
YES
EXIT
2/2


6
6
ΔH NEGATIVE
YES
CURVE FIT COMPLETED
NO
7/7
NO
YES
COMPUTE LIFTOFF TIMES AND MANEUVER TIMES FOR MULTIPLE-ORBITS PLANS. THE MULTIPLE ORBITS ARE SPENT IN THAT ORBIT PHASE WHICH MOST LENGTHENS THE LAUNCH WINDOW. THE MANEUVER ΔV VALUES ARE NOT CHANGED.
THE FOLLOWING CASES ARE CONSIDERED:
1) LM MANEUVERING, ΔH > 0: ADD ORBITS BEFORE CSI
2) LM MANEUVERING, ΔH < 0: ADD ORBITS AFTER CDH
3) CSM MANEUVERING: ADD ORBITS AFTER CDH
ΔH NEGATIVE
NO
CHOOSE NEXT ΔH IN TABLE
YES
EXIT
2/2

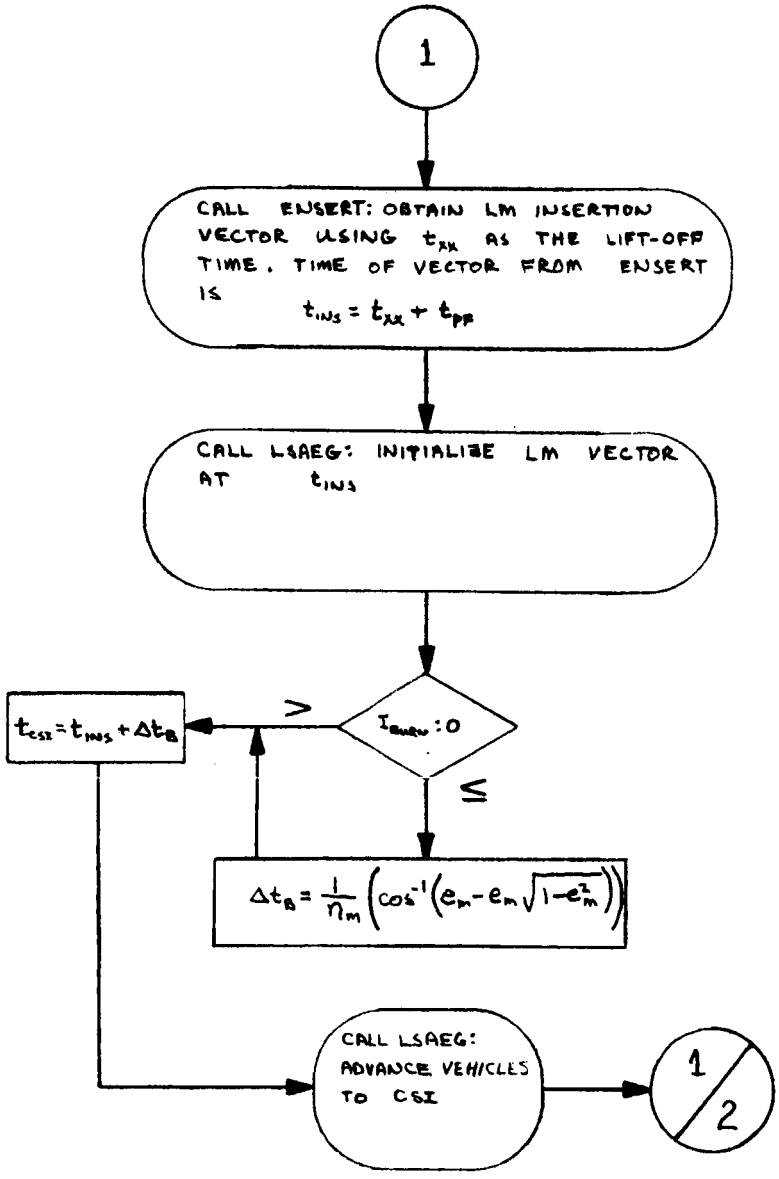

7
7
LAST CURVE FIT DATA POINT COMPUTED
NO
CHOOSE ΔH VALUE TO FILL CURVE FIT DATA TABLE
2/2
YES
SOLVE CURVE FIT FOR LARGEST NEGATIVE ΔH FOR WHICH THE TOTAL ΔV REQUIREMENTS ARE WITHIN THE BUDGET OF MANEUVERING VEHICLE
CURVE FIT ΔH EXCEED MAXIMUM NEGATIVE ΔH
NO
CHOOSE CURVE FIT ΔH
YES
CHOOSE MAXIMUM NEGATIVE ΔH
2/2

DETAILED LLWM FLOW CHART

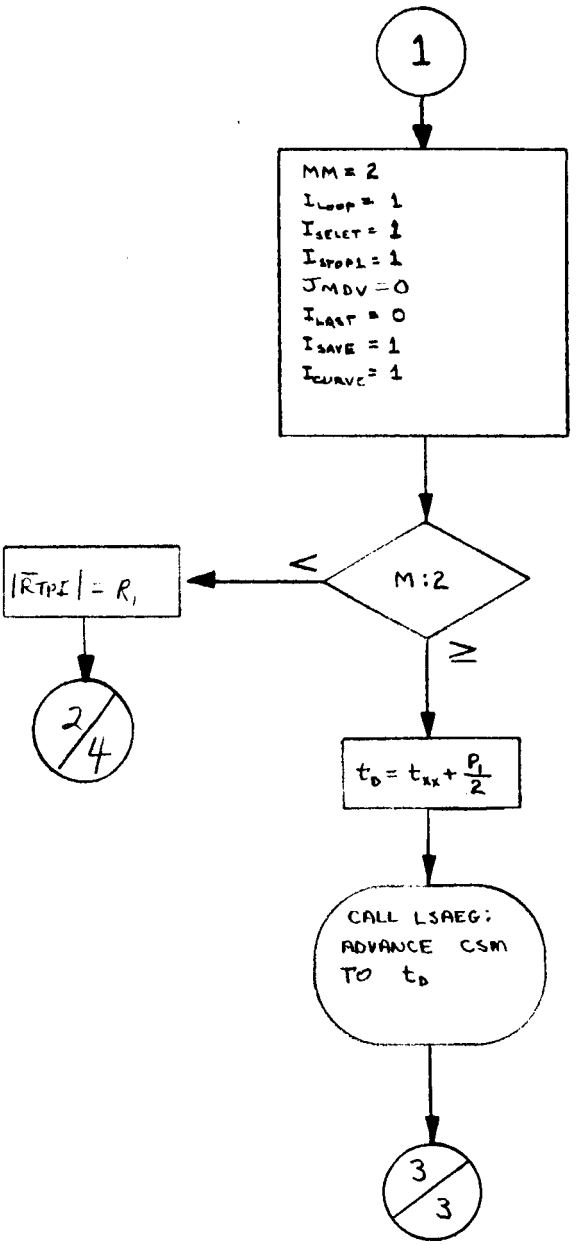
1



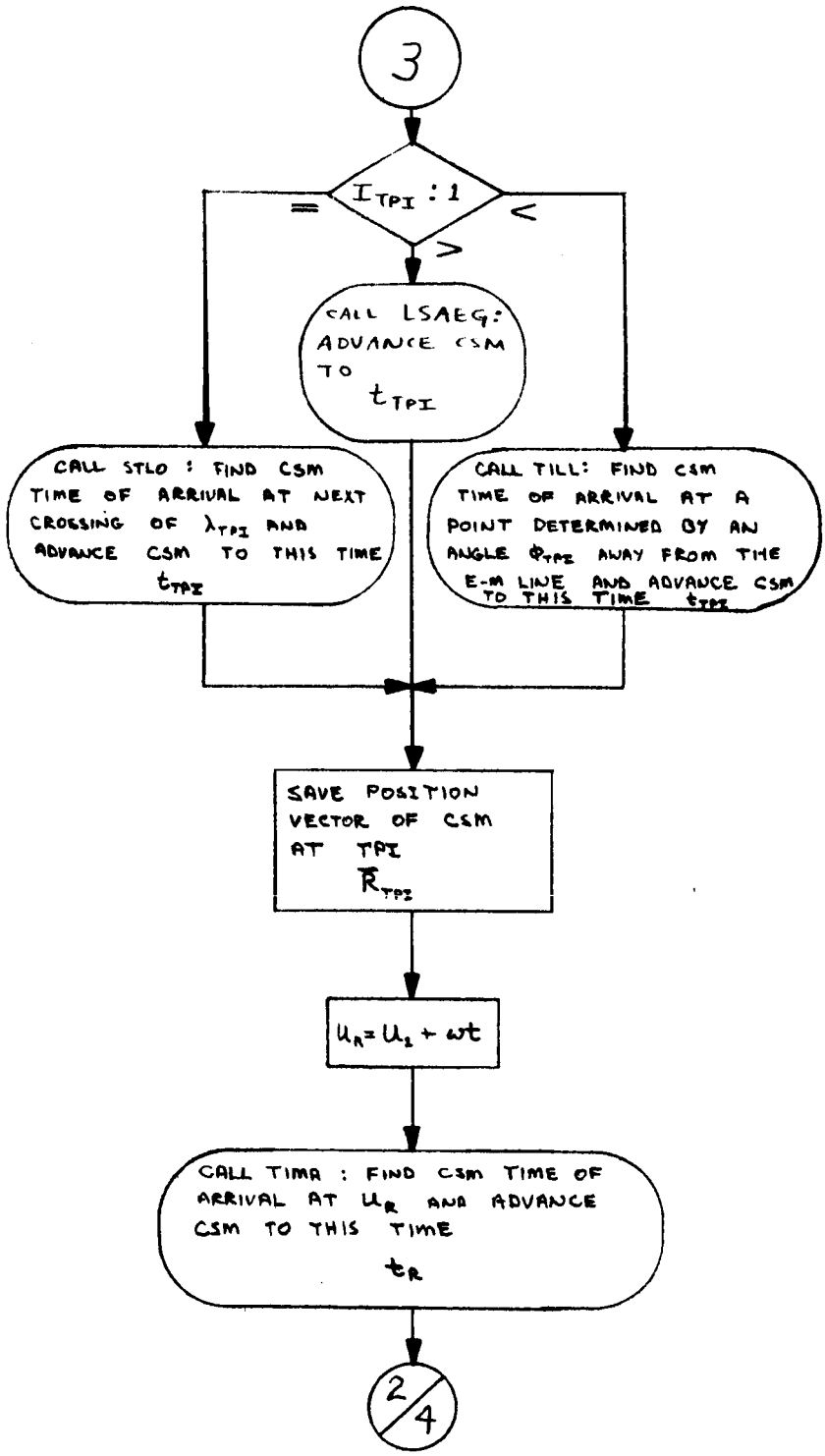
1A


1
CALL ENSERT: OBTAIN LM INSERTION VECTOR USING t_{XX} AS THE LIFT-OFF TIME. TIME OF VECTOR FROM ENSERT IS
$t_{INS} = t_{XX} + t_{PP}$
CALL LSAEG: INITIALIZE LM VECTOR AT t_{INS}
$I_{BURN} : 0$
>
$t_{CSI} = t_{INS} + \Delta t_B$
≤
$\Delta t_B = \frac{1}{n_m}\left(\cos^{-1}\left(e_m - e_m\sqrt{1-e_m^2}\right)\right)$
CALL LSAEG: ADVANCE VEHICLES TO CSI
1/2

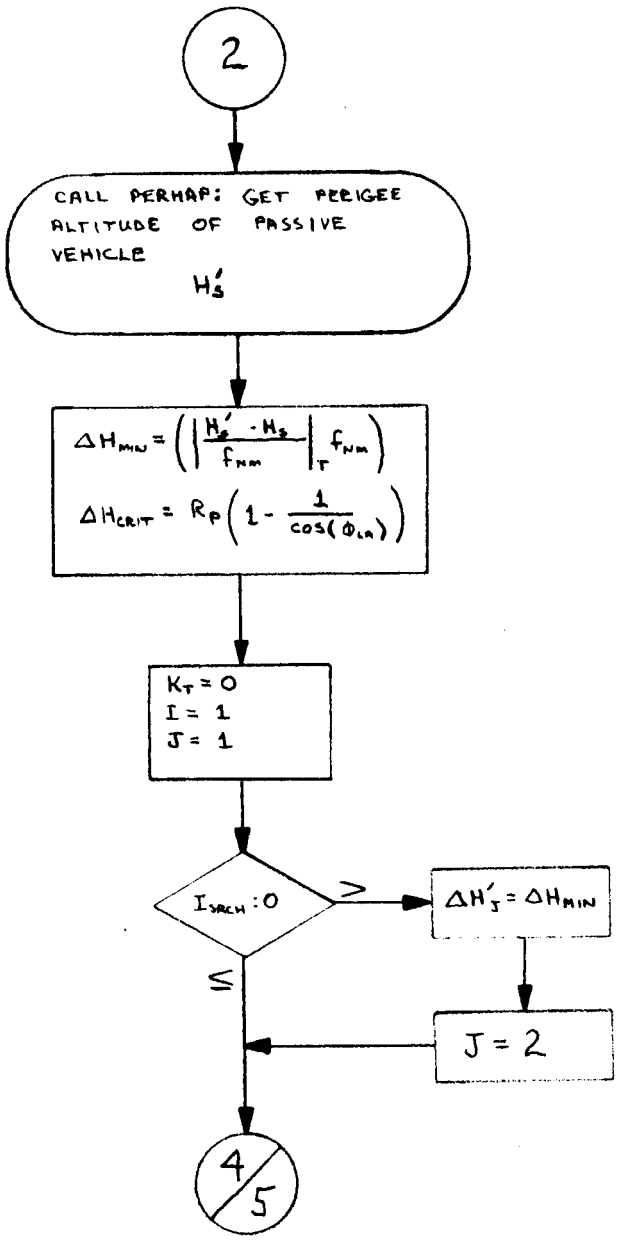
2


1
MM = 2
I_{LOOP} = 1
I_{SELET} = 1
I_{STOPL} = 1
JMDV = 0
I_{LAST} = 0
I_{SAVE} = 1
I_{CURVE} = 1
M:2
<
≥
$|\bar{R}_{TPI}| = R_1$
2/4
$t_D = t_{xx} + \frac{P_1}{2}$
CALL LSAEG;
ADVANCE CSM
TO t_D
3/3

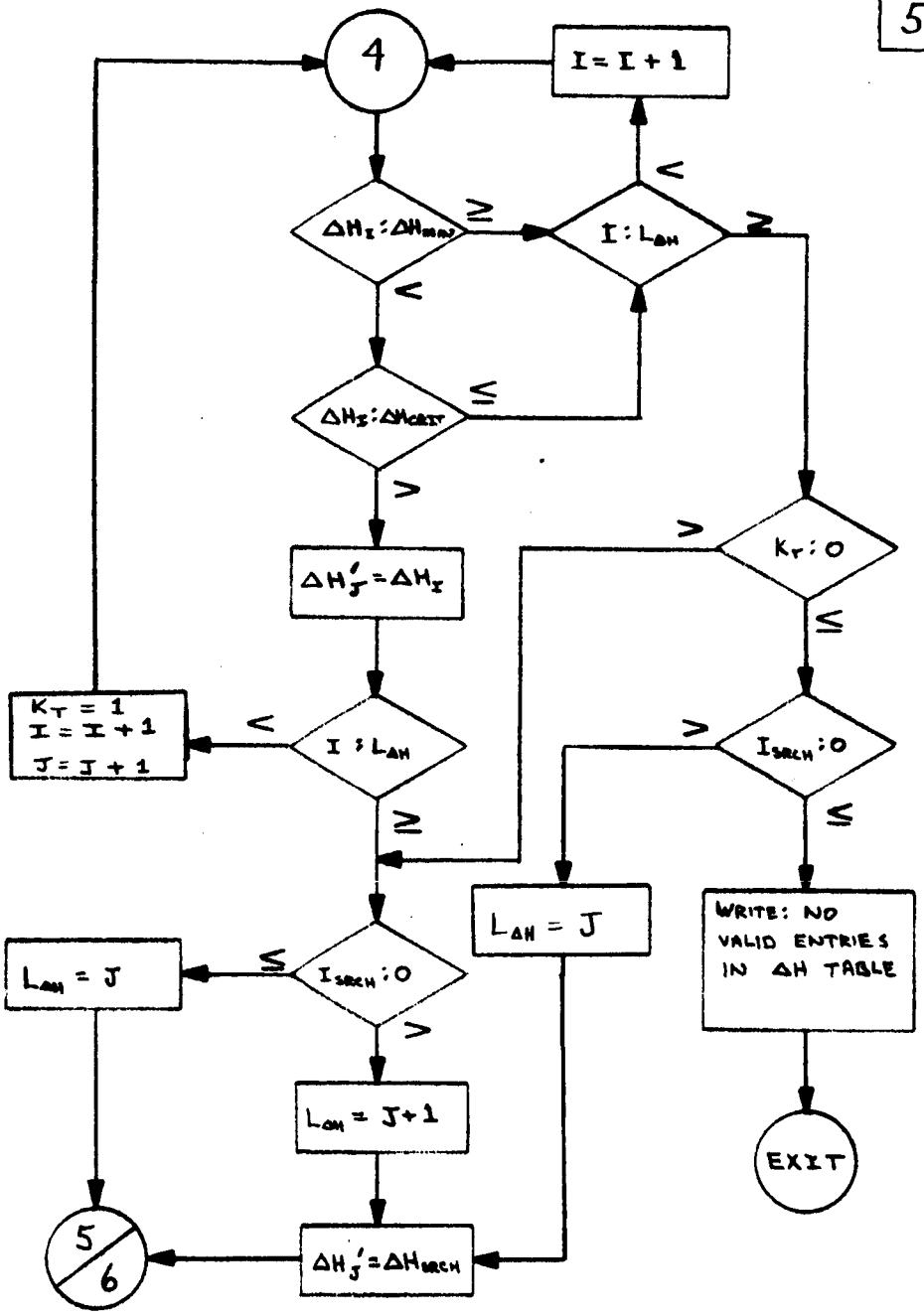
3


3
$I_{TPI} : 1$
=
<
>
CALL LSAEG: ADVANCE CSM TO t_{TPI}
CALL STLO : FIND CSM TIME OF ARRIVAL AT NEXT CROSSING OF λ_{TPI} AND ADVANCE CSM TO THIS TIME t_{TPI}
CALL TILL: FIND CSM TIME OF ARRIVAL AT A POINT DETERMINED BY AN ANGLE ϕ_{TPI} AWAY FROM THE E-M LINE AND ADVANCE CSM TO THIS TIME t_{TPI}
SAVE POSITION VECTOR OF CSM AT TPI $\bar{R}_{TPI}$
$u_R = u_1 + \omega t$
CALL TIMA : FIND CSM TIME OF ARRIVAL AT u_R AND ADVANCE CSM TO THIS TIME t_R
2/4

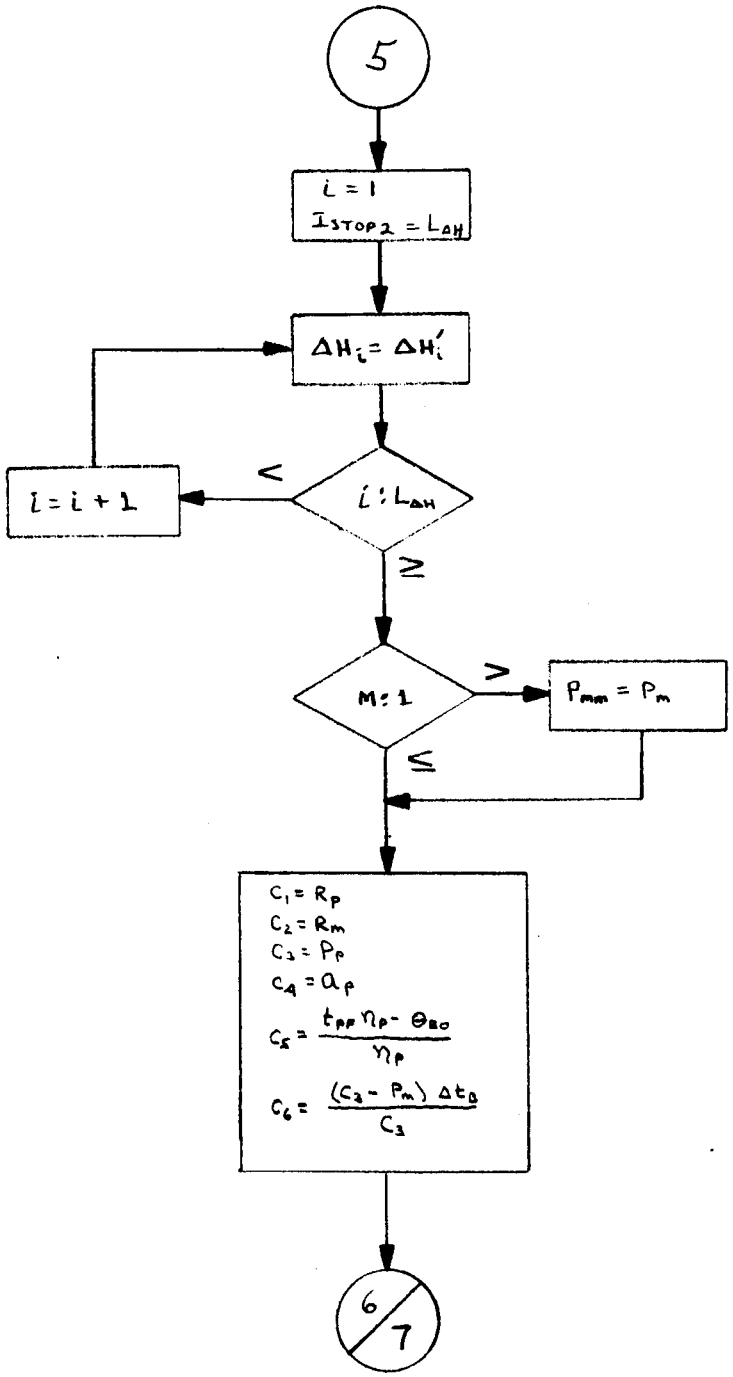
4


2
CALL PERMAP: GET PERIGEE ALTITUDE OF PASSIVE VEHICLE
H_s'
$\Delta H_{MIN} = \left(\left| \frac{H_s' - H_s}{f_{NM}} \right|_T f_{NM} \right)$
$\Delta H_{CRIT} = R_P \left(1 - \frac{1}{\cos(\Phi_{LN})} \right)$
$K_T = 0$
$I = 1$
$J = 1$
$I_{SRCH} : 0$
>
$\Delta H_J' = \Delta H_{MIN}$
$J = 2$
≤
4/5

5


4
I = I + 1
ΔH_I : ΔH_max
I : L_ΔH
ΔH_I : ΔH_CRIT
ΔH'_J = ΔH_I
K_T : 0
K_T = 1
I = I + 1
J = J + 1
I : L_ΔH
I_SRCH : 0
L_ΔH = J
WRITE: NO VALID ENTRIES IN ΔH TABLE
L_ΔH = J
I_SRCH : 0
L_ΔH = J+1
EXIT
5/6
ΔH'_J = ΔH_SRCH

6


5
i = 1
ISTOP2 = LΔH
ΔHi = ΔH'i
i : LΔH
<
i = i + 1
≥
M : 1
>
Pmm = Pm
≤
C1 = Rp
C2 = Rm
C3 = Pp
C4 = ap
C5 = (tpp ηp - θ80) / ηp
C6 = (C3 - Pm) Δt0 / C3
6/7

7

6

$$\Delta H_u = \Delta H_{ISELET}$$

7

$$\Theta_w = \frac{\pi}{2} - \Phi_{LA} - \sin^{-1}\left[\frac{(|\bar{R}_{TDZ}| - \Delta H_u)\cos(\Phi_{LA})}{|\bar{R}_{TDZ}|}\right]$$

$$C_7 = \frac{C_2 + C_1 - \Delta H_u}{2}$$

$$C_8 = \frac{1}{C_7}\sqrt{\frac{\mu}{C_7}}$$

$$C_9 = \frac{\pi}{C_8}$$

$$C_{10} = \frac{(C_3 - 2C_9)C_9}{C_3}$$

$$C_{11} = \frac{\Theta_w}{\eta_p}$$

$$C_{12} = C_4 - \Delta H_u$$

$$C_{13} = \frac{1}{C_{12}}\sqrt{\frac{\mu}{C_{12}}}$$

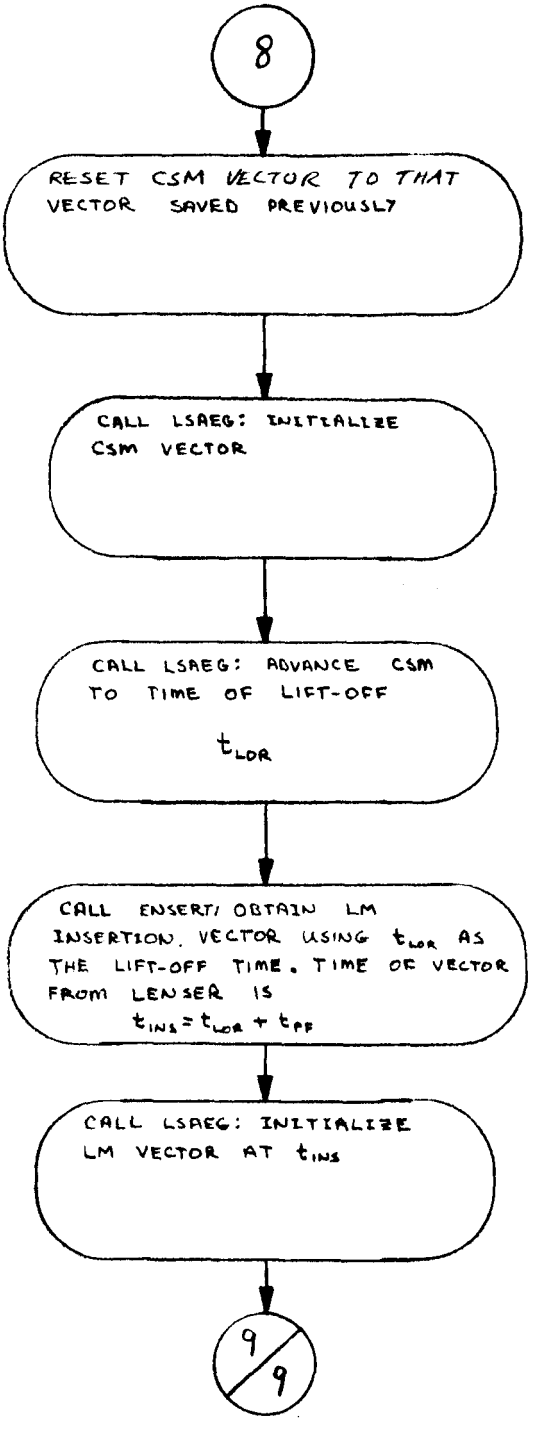
$$C_{14} = \frac{2\pi}{C_{13}}$$

$$C_{15} = \frac{(C_3 - C_{14})C_{14}}{4C_3}$$

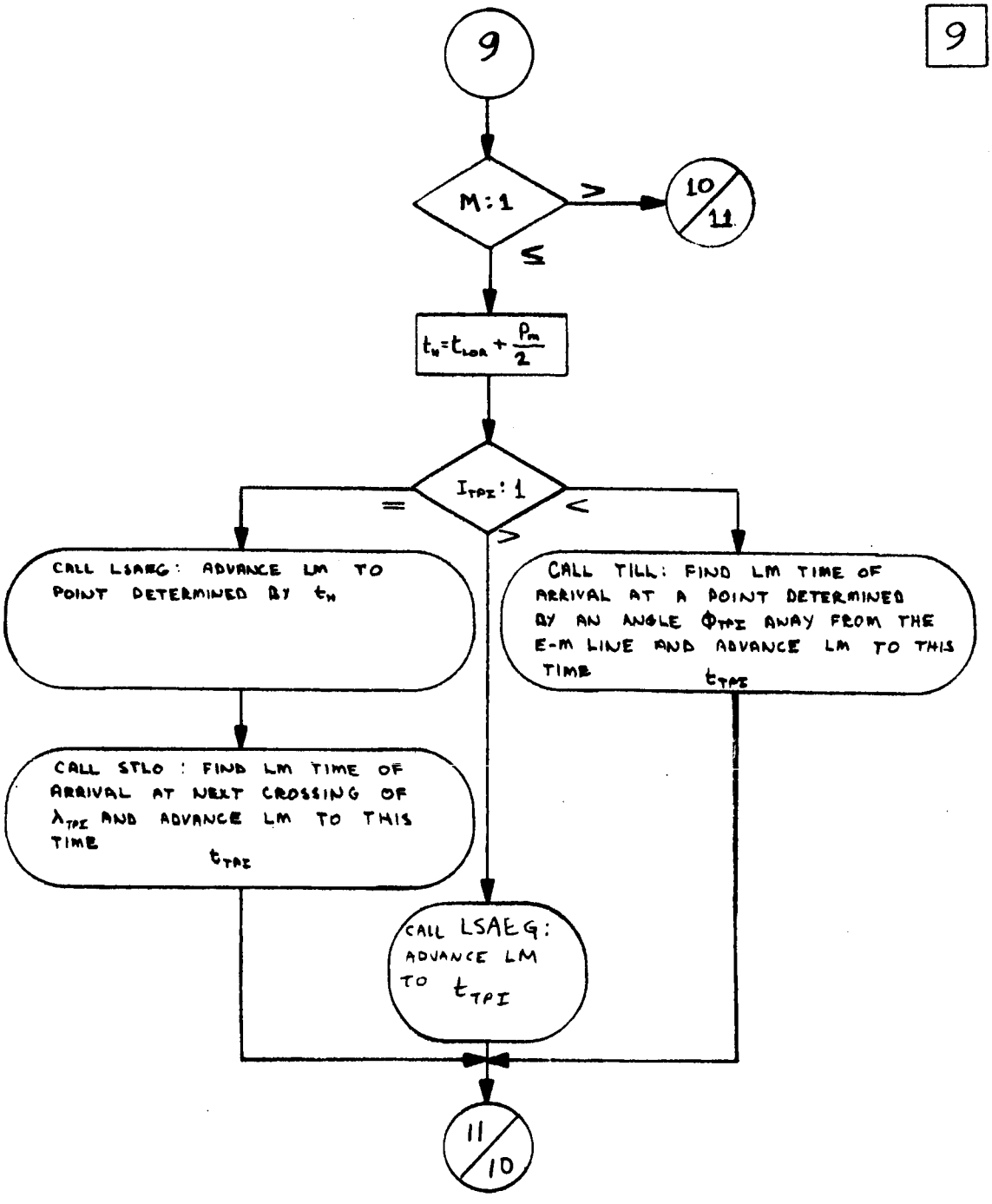
$$t_{LOR} = t_{XA} - C_5 + |C_6| + |C_{10}| + C_{15} - C_{11}$$

8/8

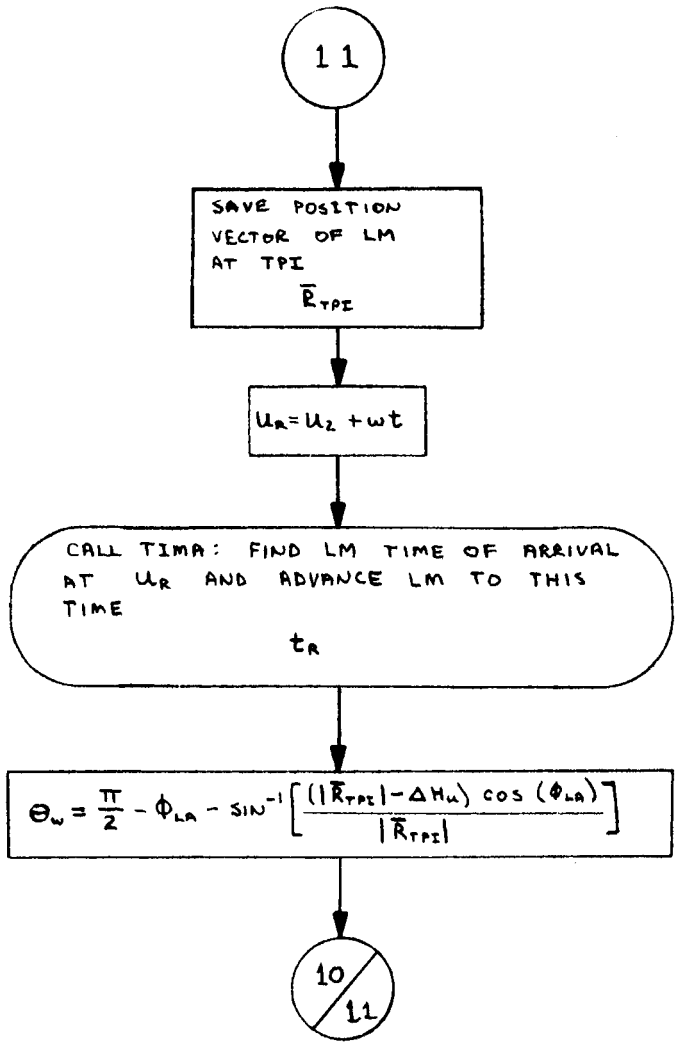
8


8
RESET CSM VECTOR TO THAT VECTOR SAVED PREVIOUSLY
CALL LSAEG: INITIALIZE CSM VECTOR
CALL LSAEG: ADVANCE CSM TO TIME OF LIFT-OFF
t_{LOR}
CALL ENSERT/ OBTAIN LM INSERTION VECTOR USING t_{LOR} AS THE LIFT-OFF TIME. TIME OF VECTOR FROM LENSER IS
$t_{INS} = t_{LOR} + t_{PF}$
CALL LSAEG: INITIALIZE LM VECTOR AT t_{INS}
9/9

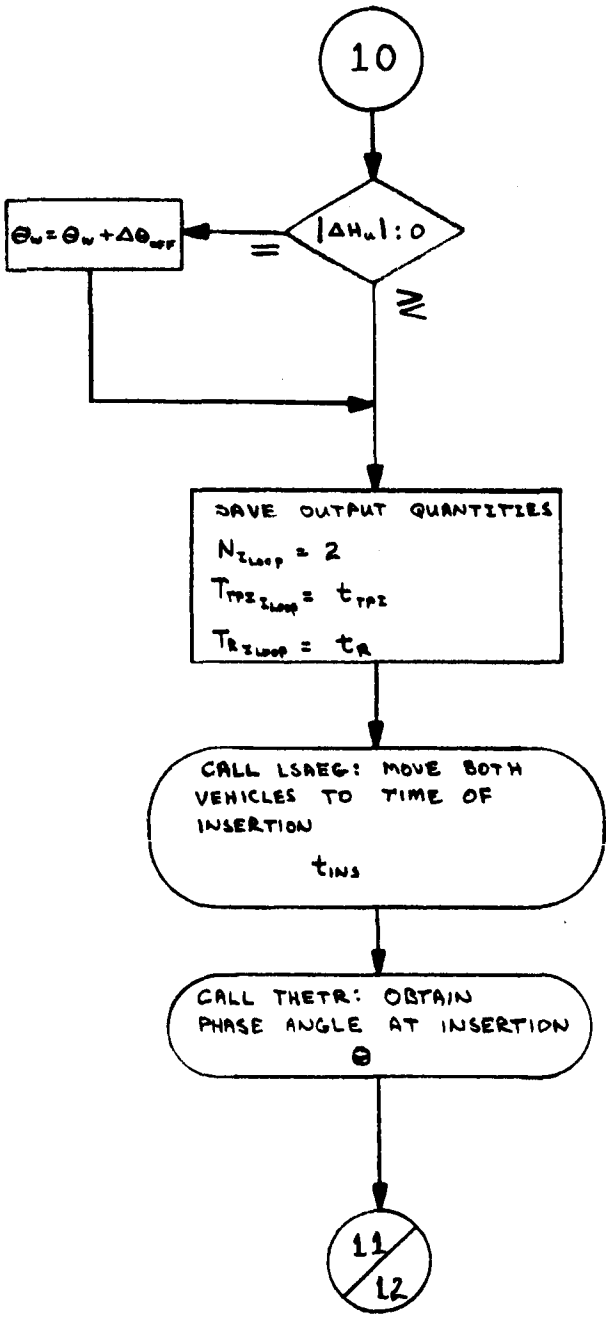
9

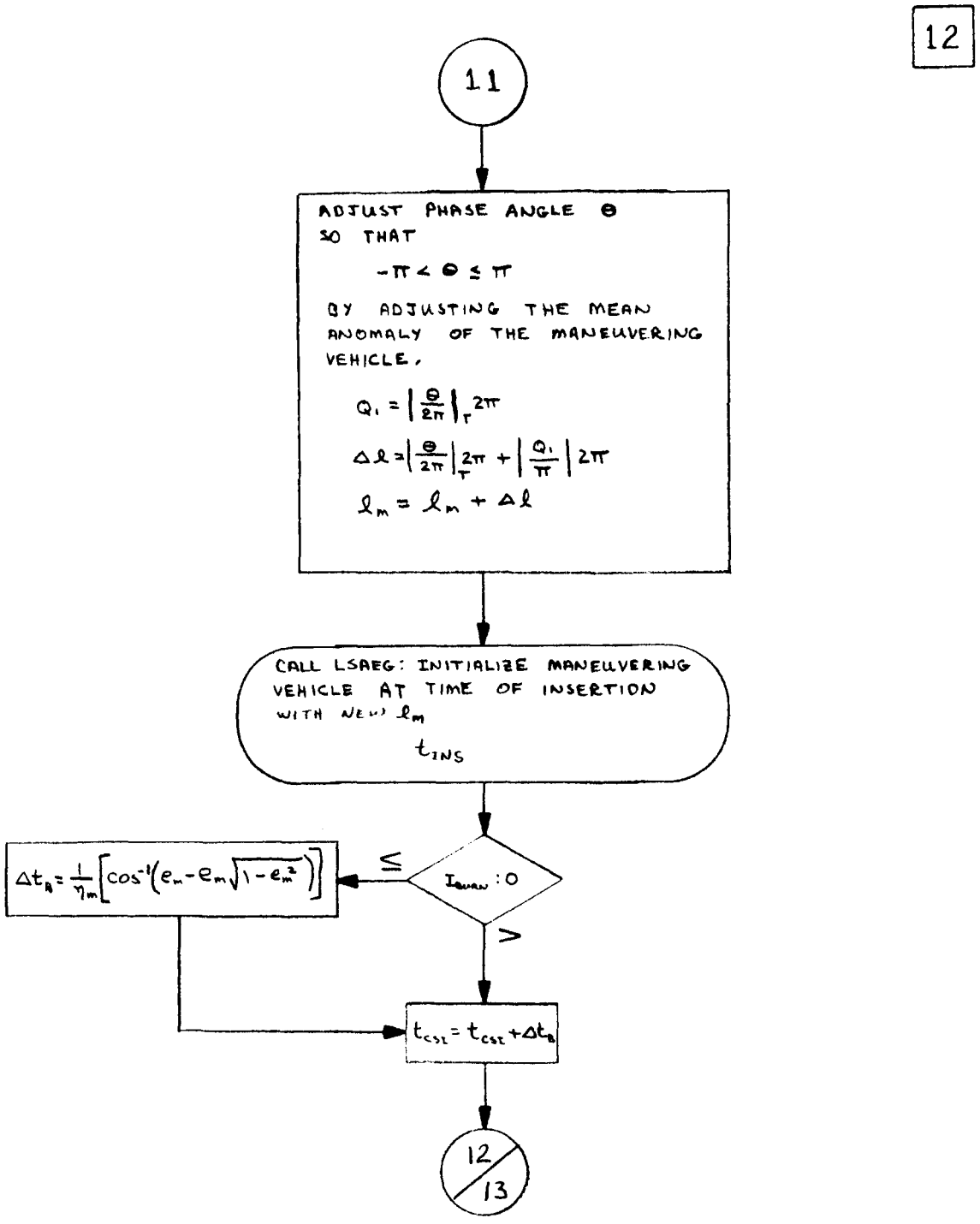

9
M : 1
>
10/11
≤
$t_H = t_{LOA} + \frac{P_m}{2}$
I_{TPI} : 1
=
<
>
CALL LSAEG: ADVANCE LM TO POINT DETERMINED BY t_H
CALL TILL: FIND LM TIME OF ARRIVAL AT A POINT DETERMINED BY AN ANGLE Φ_{TPI} AWAY FROM THE E-M LINE AND ADVANCE LM TO THIS TIME t_{TPI}
CALL STLO : FIND LM TIME OF ARRIVAL AT NEXT CROSSING OF λ_{TPI} AND ADVANCE LM TO THIS TIME t_{TPI}
CALL LSAEG: ADVANCE LM TO t_{TPI}
11/10

10

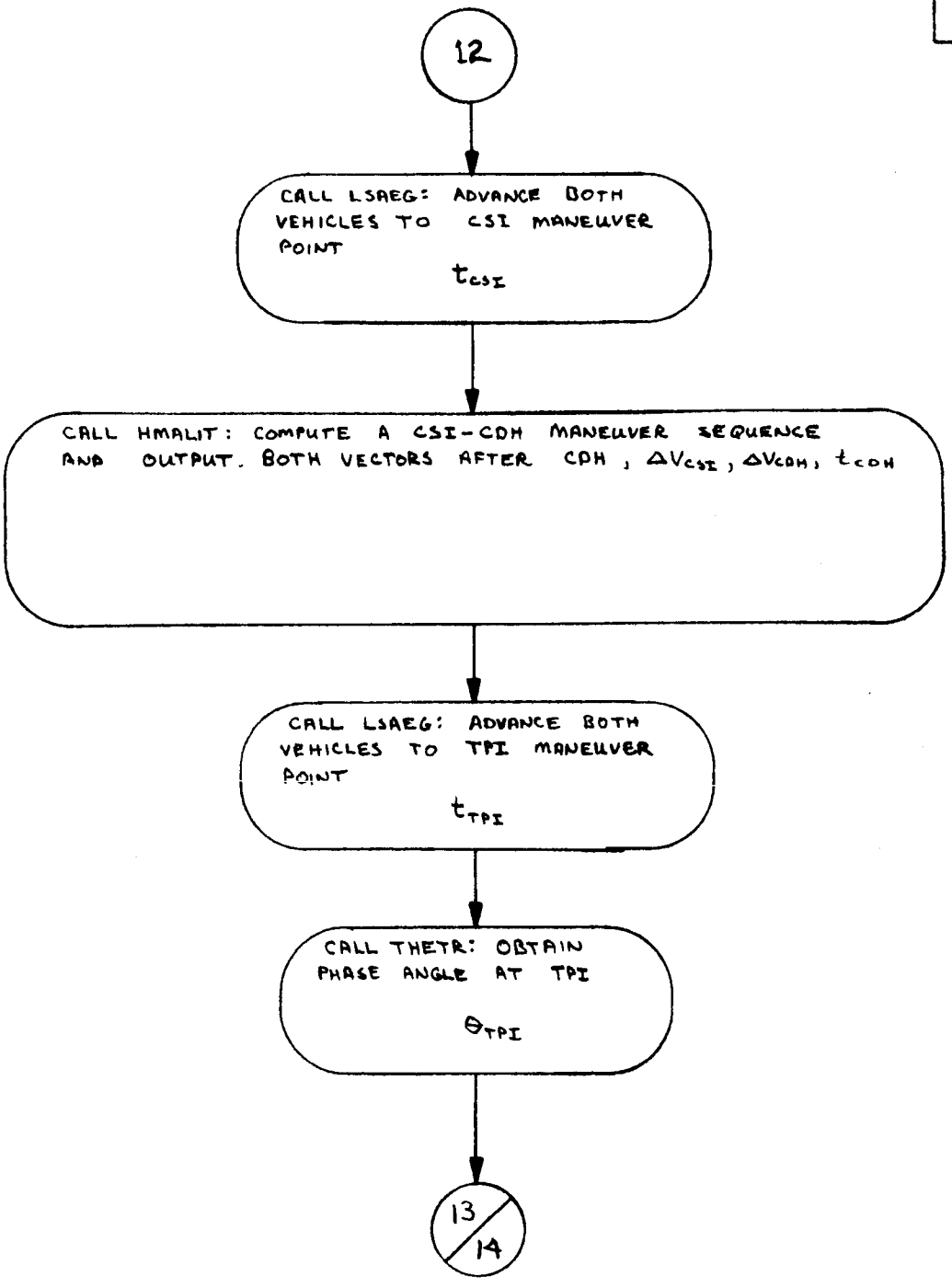

11
SAVE POSITION VECTOR OF LM AT TPI
$\bar{R}_{TPI}$
$u_R = u_2 + \omega t$
CALL TIMA: FIND LM TIME OF ARRIVAL AT u_R AND ADVANCE LM TO THIS TIME
t_R
$\theta_w = \frac{\pi}{2} - \phi_{LA} - \sin^{-1}\left[\frac{(|\bar{R}_{TPI}| - \Delta H_w)\cos(\phi_{LA})}{|\bar{R}_{TPI}|}\right]$
10/11

11

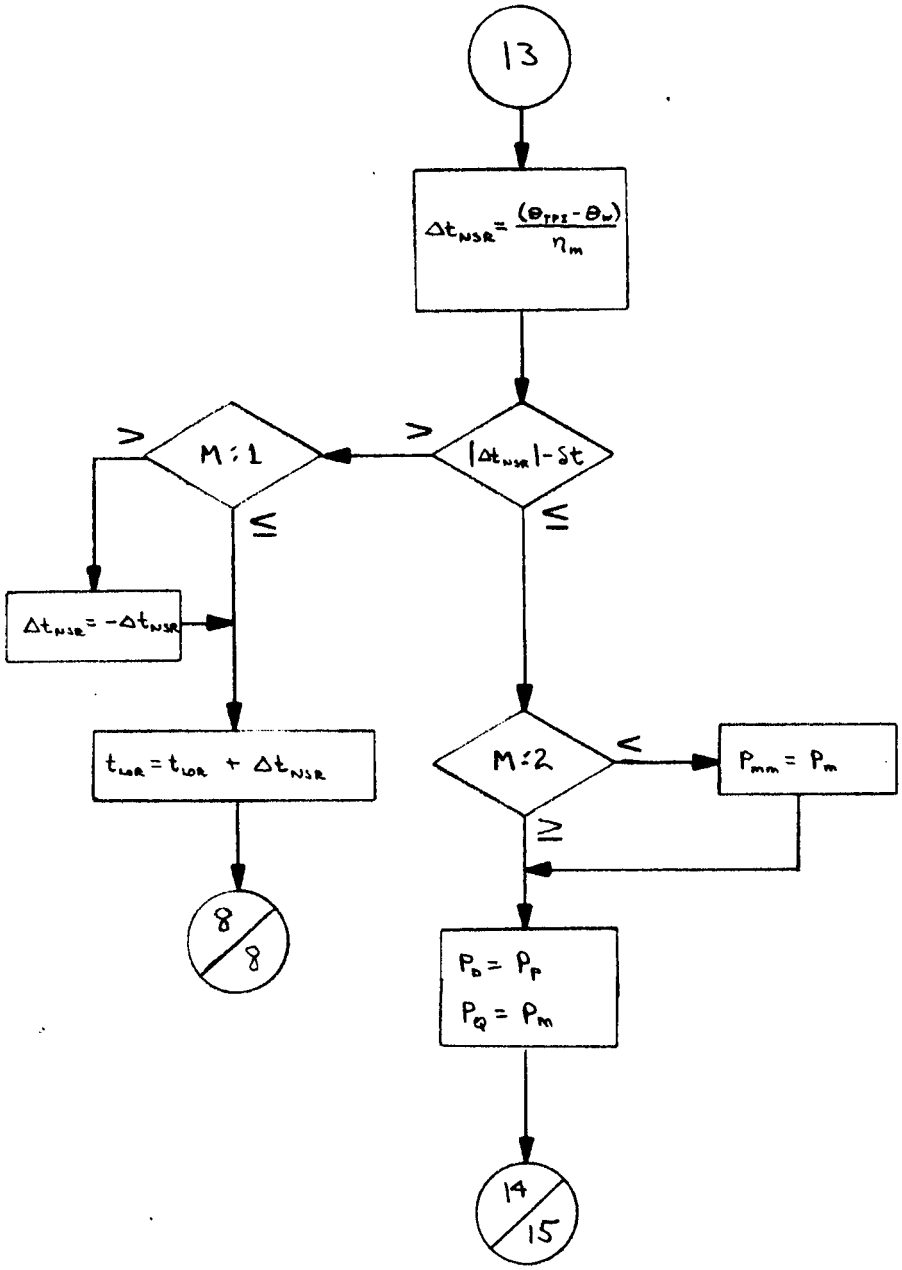

10
$|\Delta H_u| : 0$
=
$\geq$
$\theta_u = \theta_u + \Delta\theta_{off}$
SAVE OUTPUT QUANTITIES
$N_{I_{LOOP}} = 2$
$T_{TPI_{I_{LOOP}}} = t_{TPI}$
$T_{R_{I_{LOOP}}} = t_R$
CALL LSAEG: MOVE BOTH VEHICLES TO TIME OF INSERTION
t_{INS}
CALL THETR: OBTAIN PHASE ANGLE AT INSERTION
θ
11/12


12
11
ADJUST PHASE ANGLE Θ
SO THAT
$-\pi < \Theta \leq \pi$
BY ADJUSTING THE MEAN
ANOMALY OF THE MANEUVERING
VEHICLE,
$Q_1 = \left|\frac{\Theta}{2\pi}\right|_T 2\pi$
$\Delta l = \left|\frac{\Theta}{2\pi}\right|_T 2\pi + \left|\frac{Q_1}{\pi}\right| 2\pi$
$l_m = l_m + \Delta l$
CALL LSAEG: INITIALIZE MANEUVERING
VEHICLE AT TIME OF INSERTION
WITH NEW l_m
t_{INS}
$I_{avail} : 0$
≤
>
$\Delta t_a = \frac{1}{\eta_m}\left[\cos^{-1}\left(e_m - e_m\sqrt{1-e_m^2}\right)\right]$
$t_{csl} = t_{csl} + \Delta t_a$
12/13

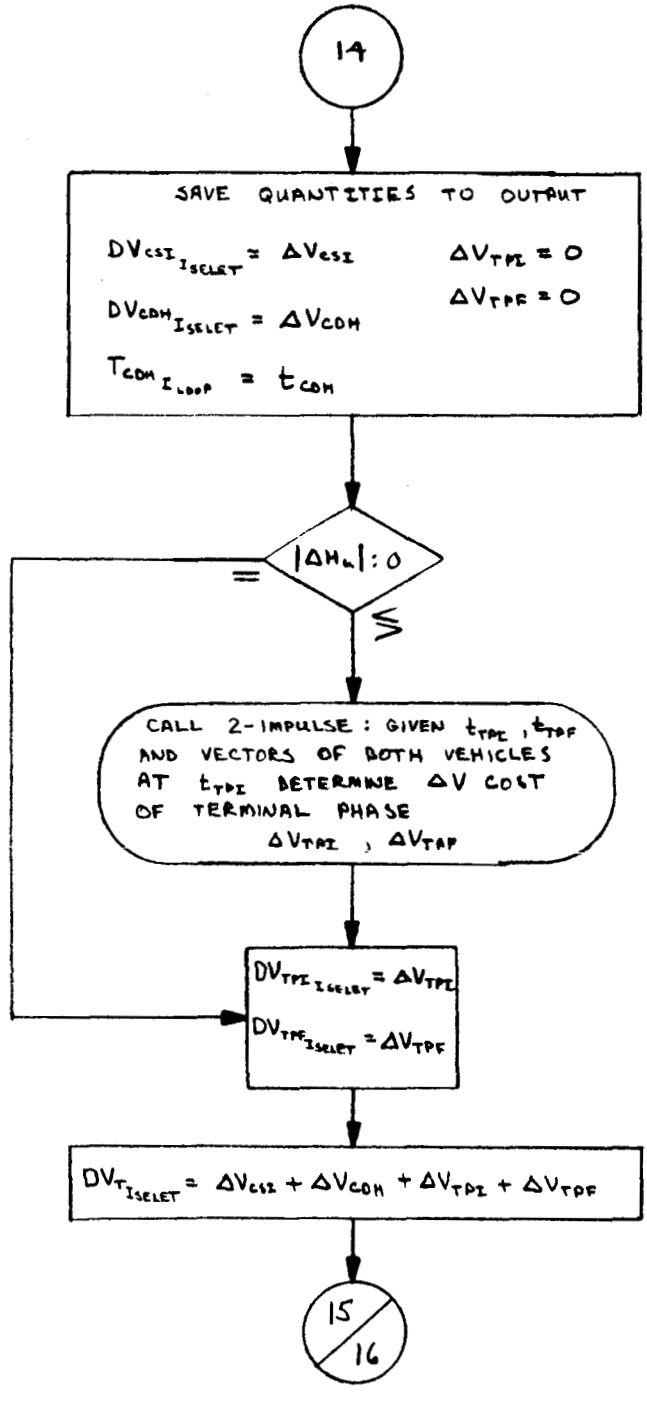
13


12
CALL LSAEG: ADVANCE BOTH VEHICLES TO CSI MANEUVER POINT
t_{CSI}
CALL HMALIT: COMPUTE A CSI-CDH MANEUVER SEQUENCE AND OUTPUT. BOTH VECTORS AFTER CDH, ΔV_{CSI}, ΔV_{CDH}, t_{CDH}
CALL LSAEG: ADVANCE BOTH VEHICLES TO TPI MANEUVER POINT
t_{TPI}
CALL THETR: OBTAIN PHASE ANGLE AT TPI
θ_{TPI}
13/14

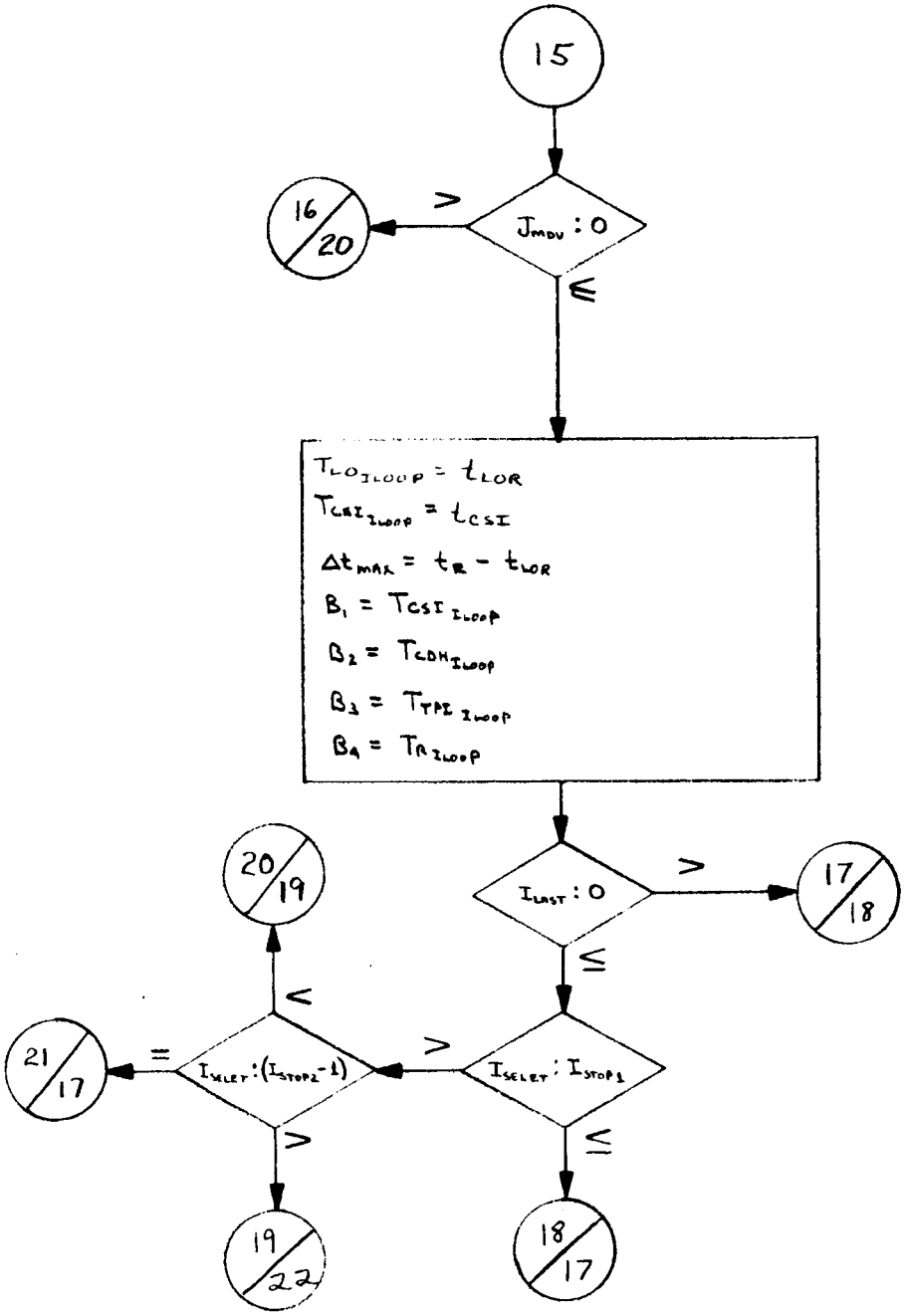
14


13
$\Delta t_{NSR} = \frac{(\theta_{TPI} - \theta_w)}{\eta_m}$
$|\Delta t_{NSR}| - \delta t$
>
≤
M : 1
>
≤
$\Delta t_{NSR} = -\Delta t_{NSR}$
$t_{LOR} = t_{LOR} + \Delta t_{NSR}$
8/8
M : 2
<
$P_{mm} = P_m$
≥
$P_D = P_P$
$P_Q = P_m$
14/15

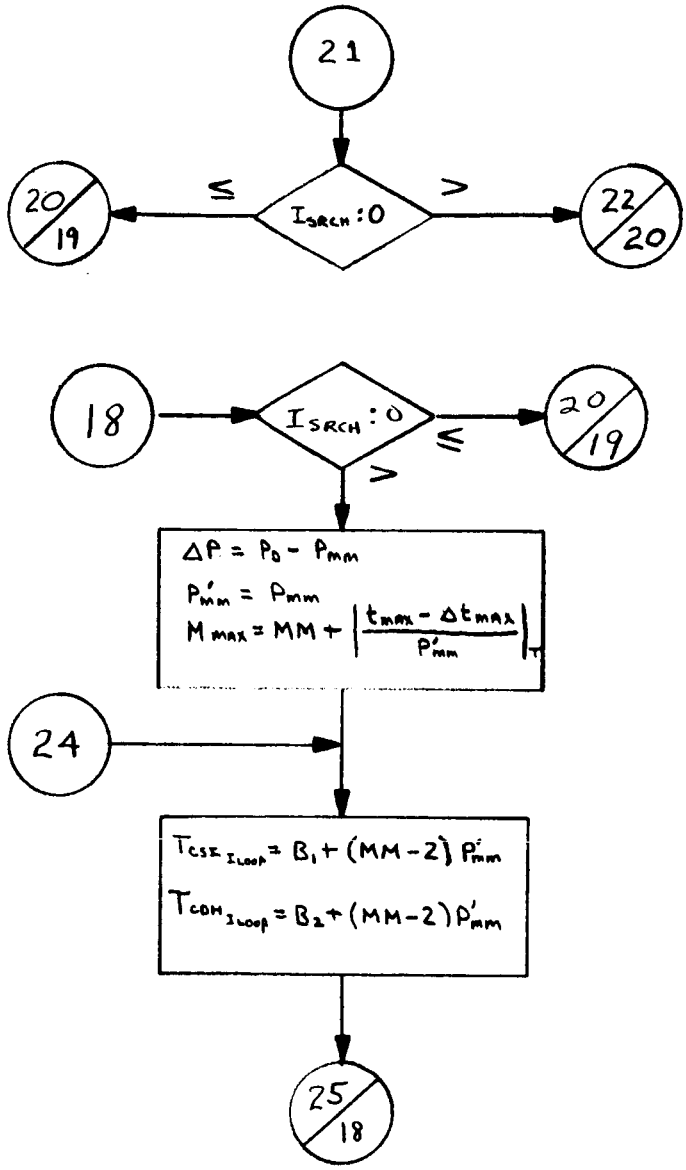
15

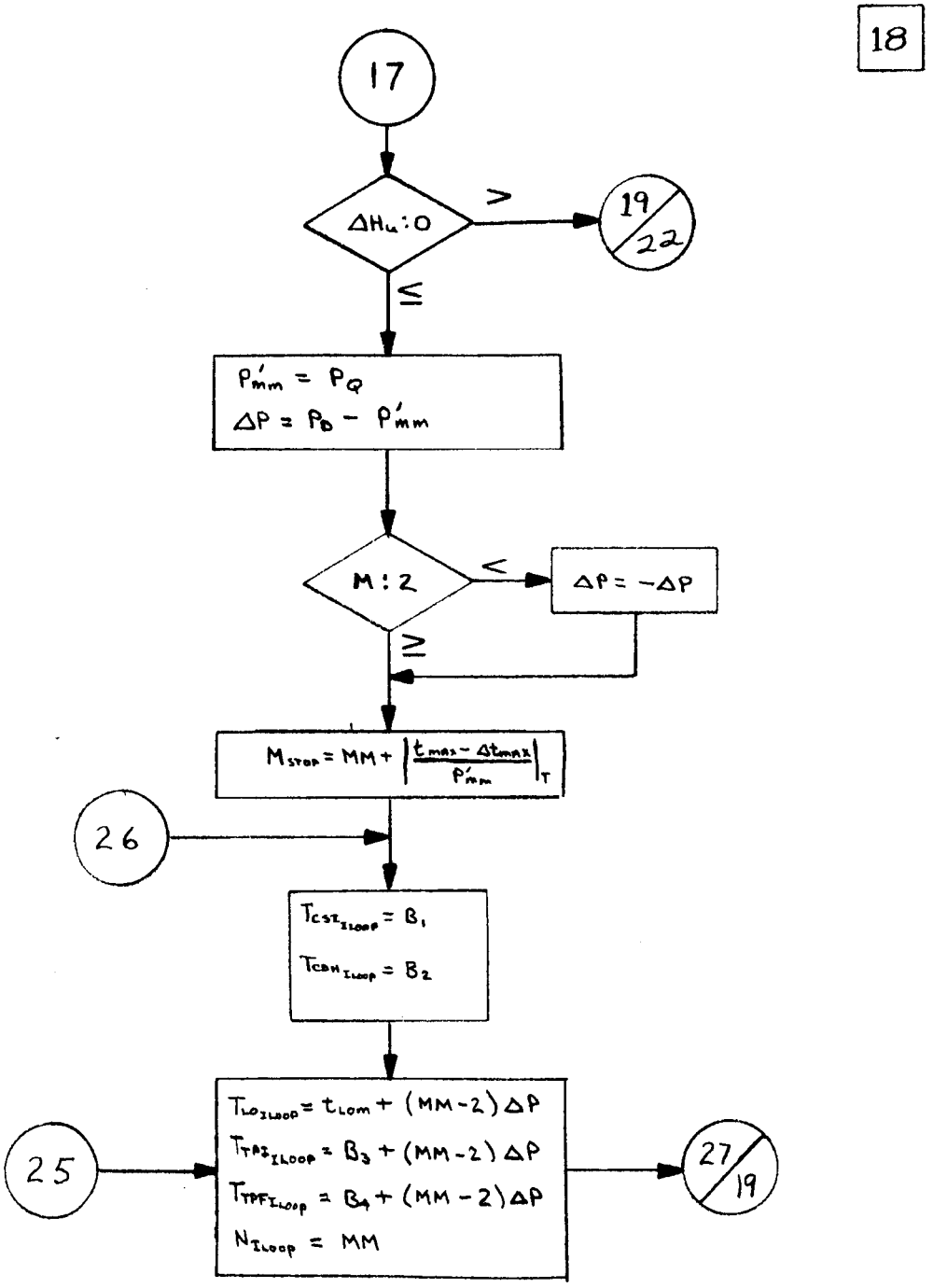

14
SAVE QUANTITIES TO OUTPUT
$DV_{CSI_{ISELET}} = \Delta V_{CSI}$
$\Delta V_{TPI} = 0$
$\Delta V_{TPF} = 0$
$DV_{COH_{ISELET}} = \Delta V_{COH}$
$T_{COH_{I_{LOOP}}} = t_{COH}$
$|\Delta H_u| : 0$
=
≤
CALL 2-IMPULSE : GIVEN t_{TPI}, t_{TPF} AND VECTORS OF BOTH VEHICLES AT t_{TPI} DETERMINE ΔV COST OF TERMINAL PHASE
ΔV_{TPI} , ΔV_{TPF}
$DV_{TPI_{ISELET}} = \Delta V_{TPI}$
$DV_{TPF_{ISELET}} = \Delta V_{TPF}$
$DV_{T_{ISELET}} = \Delta V_{CSI} + \Delta V_{COH} + \Delta V_{TPI} + \Delta V_{TPF}$
15/16

16

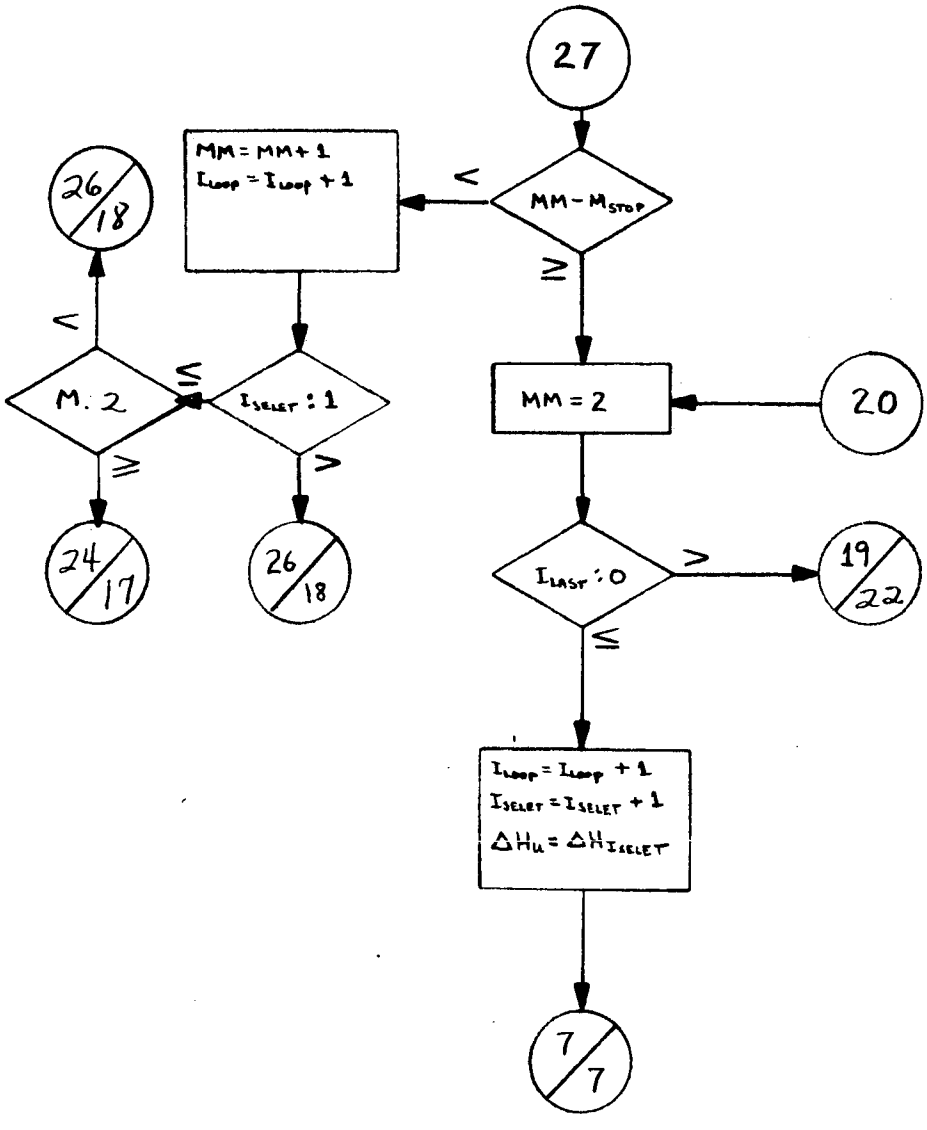

15
$J_{MOV} : 0$
>
16/20
≤
$T_{LO_{ILOOP}} = t_{LOR}$
$T_{CSI_{ILOOP}} = t_{CSI}$
$\Delta t_{MAX} = t_R - t_{LOR}$
$B_1 = T_{CSI_{ILOOP}}$
$B_2 = T_{CDH_{ILOOP}}$
$B_3 = T_{TPI_{ILOOP}}$
$B_4 = T_{R_{ILOOP}}$
$I_{LAST} : 0$
>
17/18
≤
$I_{SELET} : I_{STOP1}$
>
$I_{SELET} : (I_{STOP2} - 1)$
=
21/17
<
20/19
>
19/22
≤
18/17

17

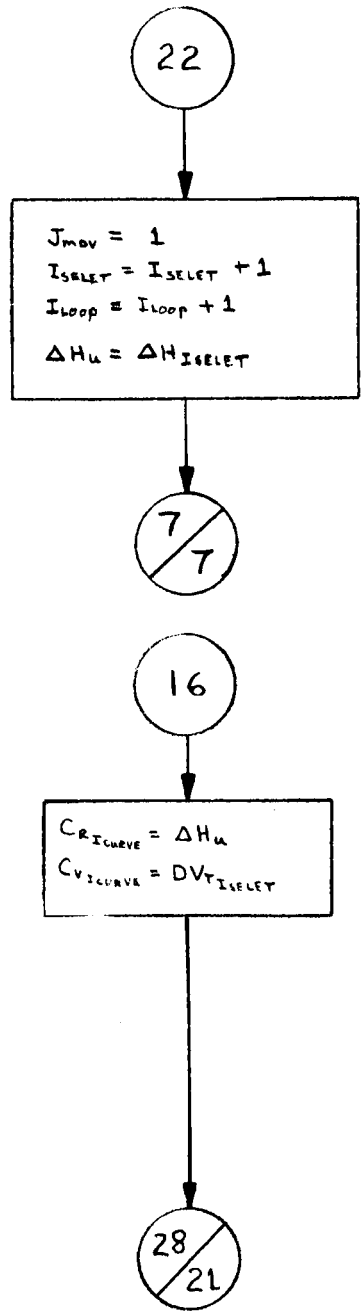

21
$I_{SRCH}:0$
≤
>
20/19
22/20
18
$I_{SRCH}:0$
≤
>
20/19
$\Delta P = P_0 - P_{mm}$
$P'_{mm} = P_{mm}$
$M_{max} = MM + \left| \frac{t_{max} - \Delta t_{max}}{P'_{mm}} \right|_T$
24
$T_{CSE_{ILOOP}} = B_1 + (MM-2)\,P'_{mm}$
$T_{COM_{ILOOP}} = B_2 + (MM-2)\,P'_{mm}$
25/18


18
17
ΔHu : 0
>
19/22
≤
P'mm = PQ
ΔP = PD − P'mm
M : 2
<
ΔP = −ΔP
≥
Mstop = MM + |(tmax − Δtmax)/P'mm|T
26
TCSTILOOP = B1
TCBNILOOP = B2
25
TLOILOOP = tLOm + (MM − 2) ΔP
TPBILOOP = B3 + (MM − 2) ΔP
TPPFILOOP = B4 + (MM − 2) ΔP
NILOOP = MM
27/19

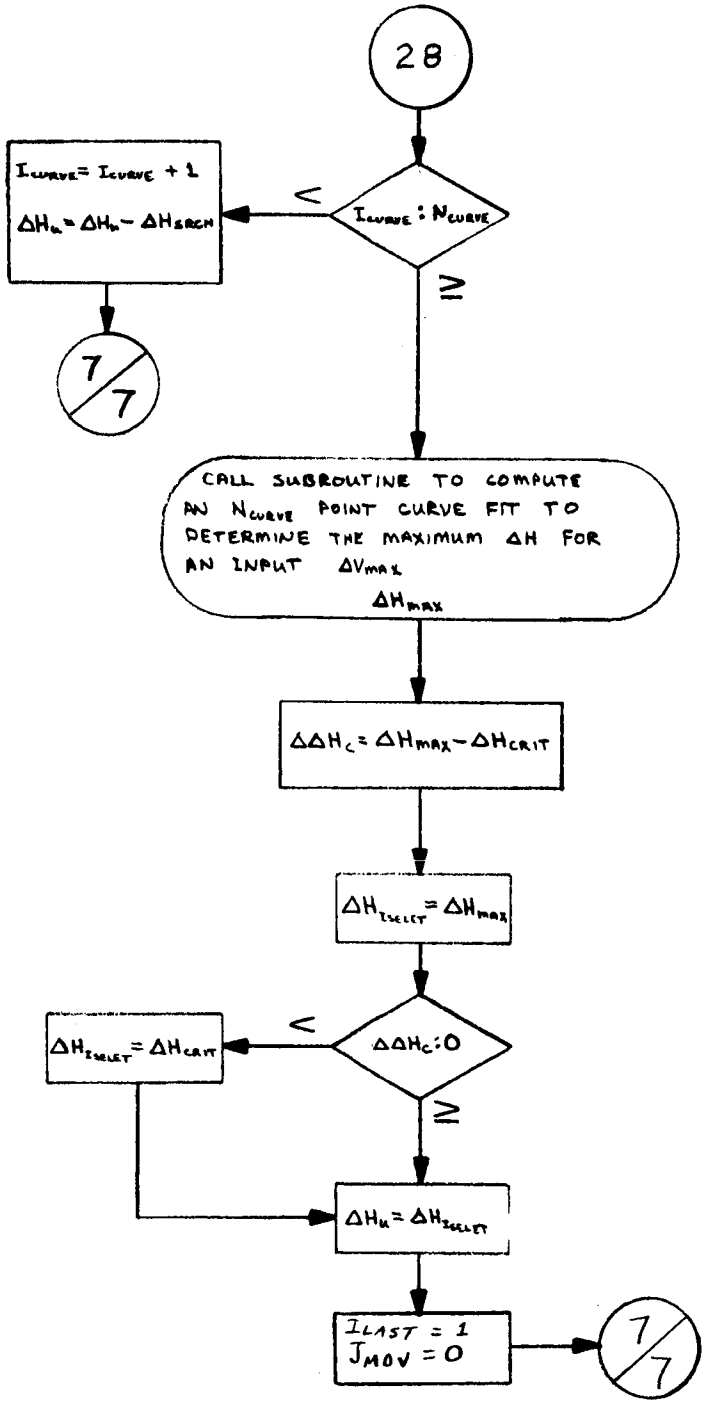
19


27
MM - M_STOP
<
≥
MM = MM + 1
I_LOOP = I_LOOP + 1
26/18
<
M : 2
≤
I_SELET : 1
≥
>
24/17
26/18
MM = 2
20
I_LAST : 0
>
19/22
≤
I_LOOP = I_LOOP + 1
I_SELET = I_SELET + 1
ΔH_u = ΔH_I_SELET
7/7

20


22
$J_{mov} = 1$
$I_{SELET} = I_{SELET} + 1$
$I_{LOOP} = I_{LOOP} + 1$
$\Delta H_u = \Delta H_{ISELET}$
7/7
16
$C_{R_{ICURVE}} = \Delta H_u$
$C_{V_{ICURVE}} = DV_{T_{ISELET}}$
28/21

21


28
$I_{CURVE} = I_{CURVE} + 1$
$\Delta H_{LL} = \Delta H_{LL} - \Delta H_{SRCH}$
<
$I_{CURVE} : N_{CURVE}$
≥
7/7
CALL SUBROUTINE TO COMPUTE AN N_{CURVE} POINT CURVE FIT TO DETERMINE THE MAXIMUM ΔH FOR AN INPUT ΔV_{MAX}
ΔH_{MAX}
$\Delta\Delta H_C = \Delta H_{MAX} - \Delta H_{CRIT}$
$\Delta H_{ISELECT} = \Delta H_{MAX}$
<
$\Delta\Delta H_C : 0$
$\Delta H_{ISELECT} = \Delta H_{CRIT}$
≥
$\Delta H_{LL} = \Delta H_{ISELECT}$
$I_{LAST} = 1$
$J_{MOV} = 0$
7/7

22

19

DISPLAY TABLE OF

LIFT OFF TIMES	T_{LO_i}
DELTA H's	ΔH_i
MANEUVER TIMES	T_{CSI_i}
	T_{CDH_i}
	T_{TPI_i}
	T_{TPF_i}
MANEUVER DELTA V COST	DV_{CSI_i}
	DV_{CDH_i}
	DV_{TPI_i}
	DV_{TPF_i}
TOTAL DELTA V COST	DV_{T_i}

EXIT

APPENDIX B

FUNCTIONAL AND DETAILED FLOW CHARTS FOR HMALIT

CONTENTS

Section Page

SYMBOLS 41

FUNCTIONAL HMALIT FLOW CHART 42

DETAILED HMALIT FLOW CHART 44

SYMBOLS

Constant Input:

π	3,141592 . . .
μ	moon gravitational constant
δh	iteration tolerance on height

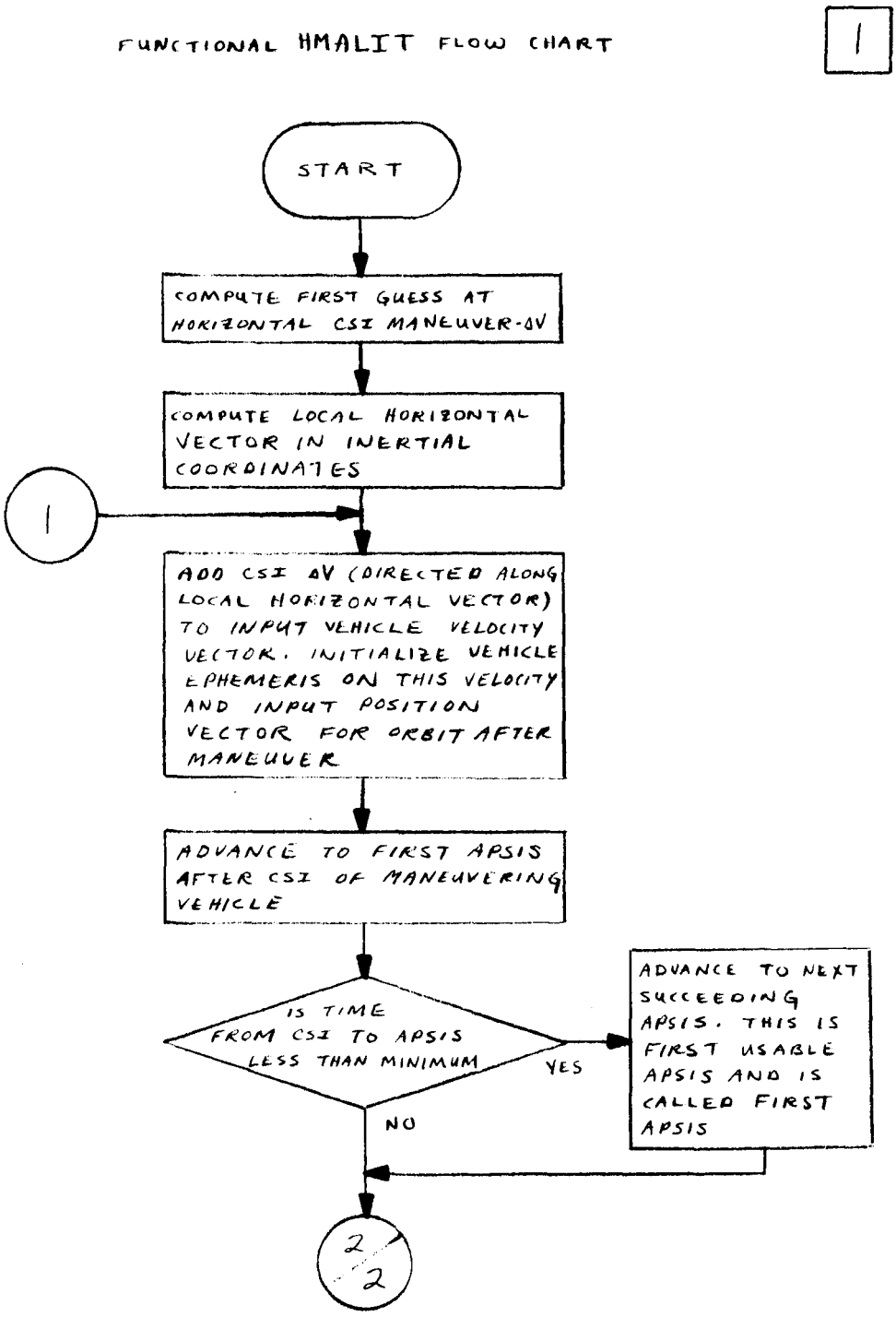
Variable Input:

t	time of CSI
LSAEG	input for both vehicles at time t
M	number of maneuvering vehicle
	M = 1 - CSM is maneuvering vehicle
	M = 2 - LM is maneuvering vehicle
P	number of passive vehicle
	P = 1 - CSM is passive vehicle
	P = 2 - LM is passive vehicle

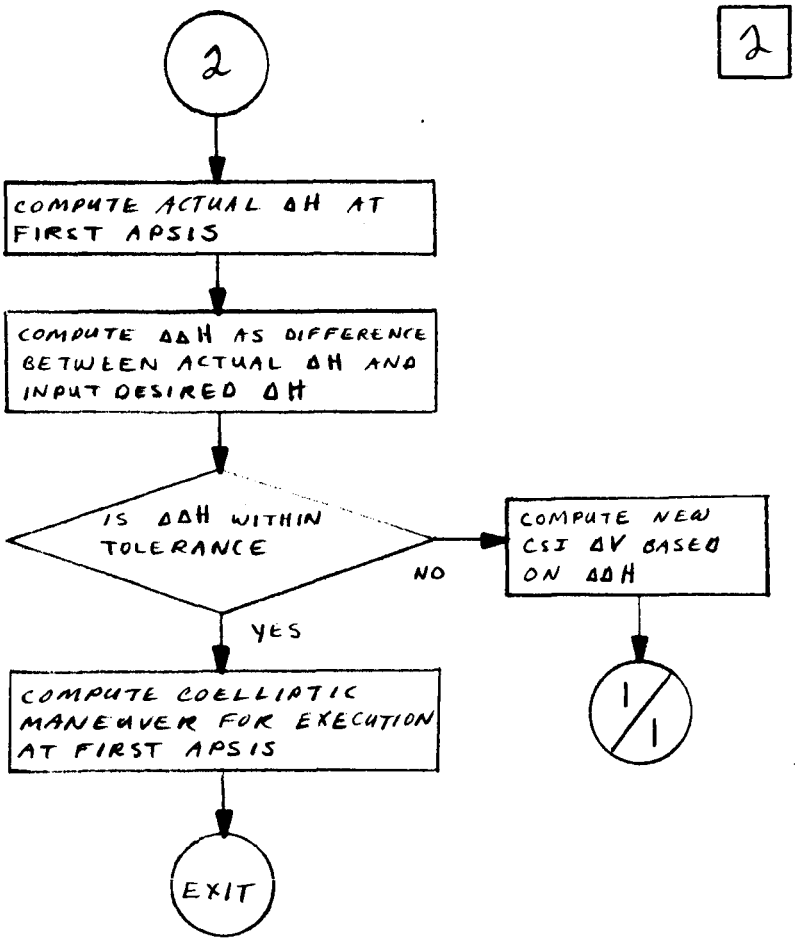
Output:

ΔV_{CSI}	CSI maneuver costs
ΔV_{CDH}	CDH maneuver costs
t_{CDH}	time of CDH maneuver

FUNCTIONAL HMALIT FLOW CHART

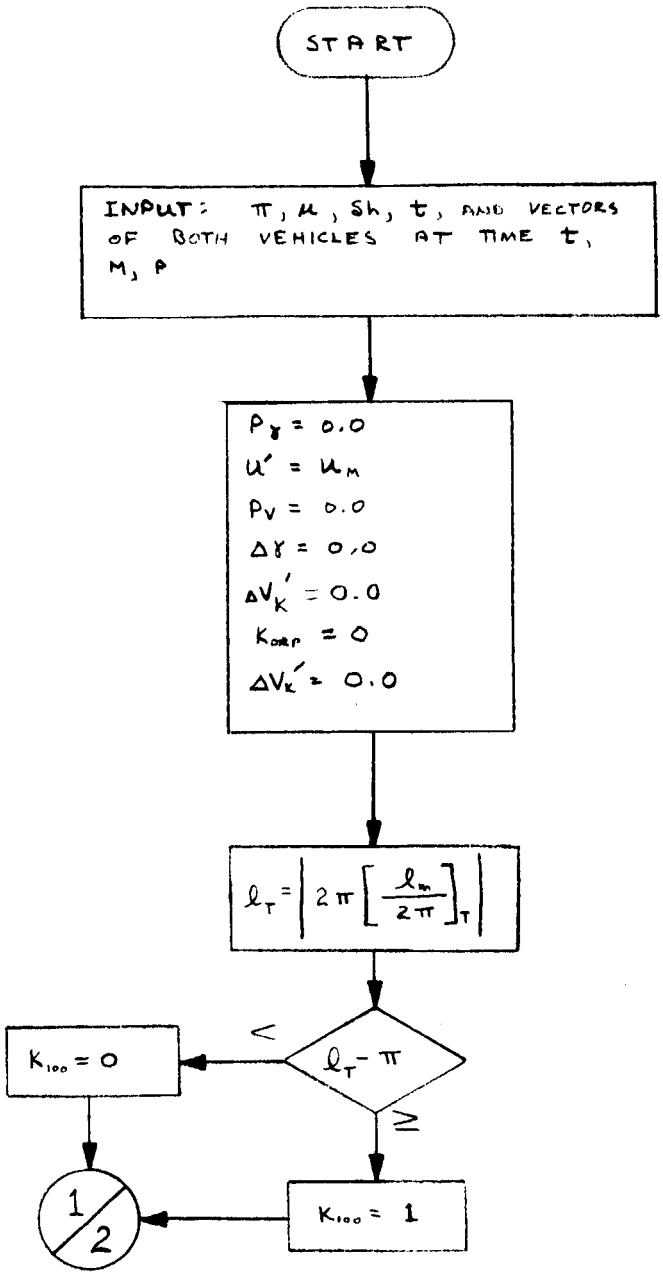


2

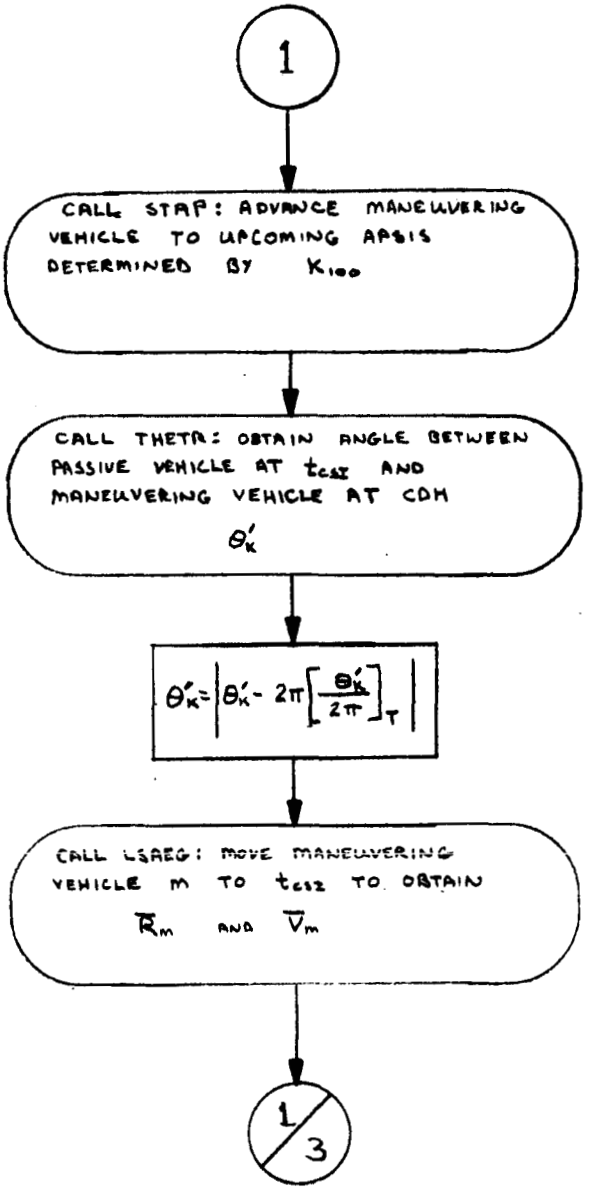

2
COMPUTE ACTUAL ΔH AT FIRST APSIS
COMPUTE ΔΔH AS DIFFERENCE BETWEEN ACTUAL ΔH AND INPUT DESIRED ΔH
IS ΔΔH WITHIN TOLERANCE
NO
COMPUTE NEW CSI ΔV BASED ON ΔΔH
1/1
YES
COMPUTE COELLIPTIC MANEUVER FOR EXECUTION AT FIRST APSIS
EXIT

DETAILED HMALIT FLOW CHART

1



2


1
CALL STAP: ADVANCE MANEUVERING VEHICLE TO UPCOMING APSIS DETERMINED BY K_{100}
CALL THETA: OBTAIN ANGLE BETWEEN PASSIVE VEHICLE AT t_{CSI} AND MANEUVERING VEHICLE AT CDH
θ'_K
$\theta'_K = \left| \theta'_K - 2\pi \left[\frac{\theta'_K}{2\pi} \right]_T \right|$
CALL LSAEG: MOVE MANEUVERING VEHICLE m TO t_{CSI} TO OBTAIN
$\bar{R}_m$ AND $\bar{V}_m$
1/3

3

1

$$\hat{k} = \frac{\bar{R}_m}{|\bar{R}_m|}$$

$$\hat{L} = \frac{\bar{V}_m}{|V_m|}$$

$$\hat{h} = \frac{\hat{k} \times \hat{L}}{|\hat{k} \times \hat{L}|}$$

$$\hat{j} = \frac{\hat{k} \times \hat{h}}{|\hat{k} \times \hat{h}|}$$

$$\dot{R}' = \dot{R}_m \qquad R' = R_m$$

$$V_H = |\bar{V}_m| \cos \gamma_m$$

$$P = a_p (1 - e_m^2)$$

$$V = \sqrt{\mu \left(\frac{2}{R_p} - \frac{1}{a_p} \right)}$$

$$G_s = \frac{\dot{R}_p}{V}$$

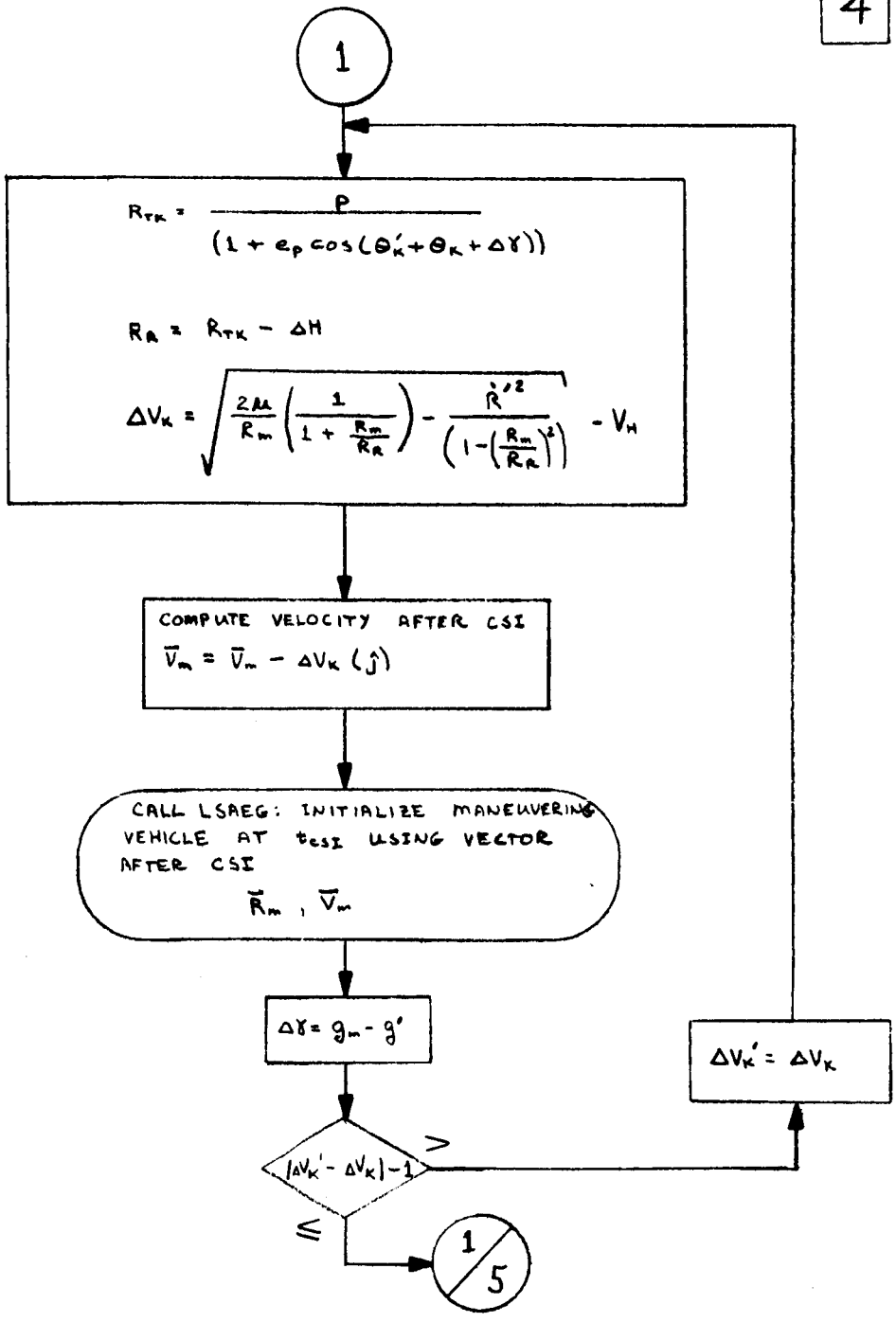
$$G_c = \sqrt{1 - G_s^2}$$

$$\theta_k = \tan^{-1} \left[\frac{P \left(\frac{G_s}{G_c} \right)}{P - R_p} \right]$$

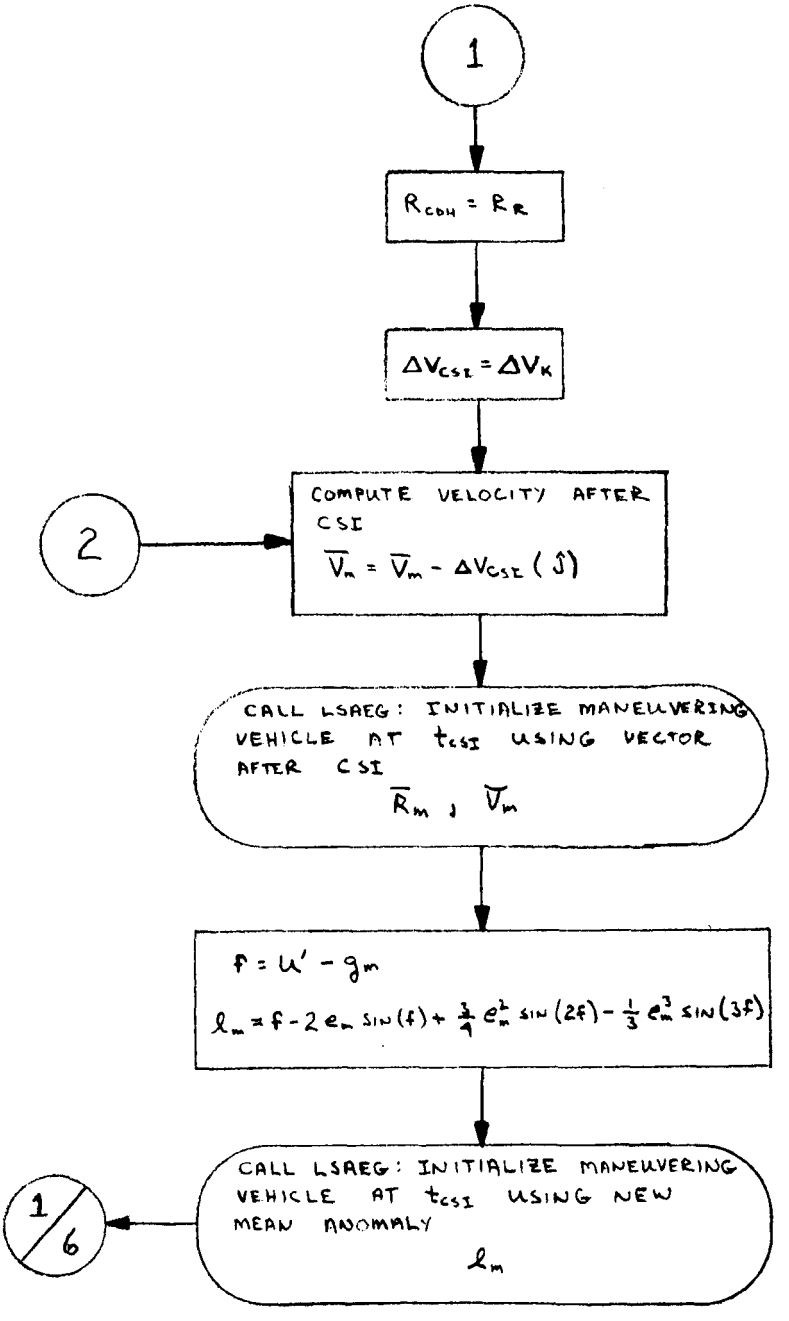
$$g' = g_m$$

1/4

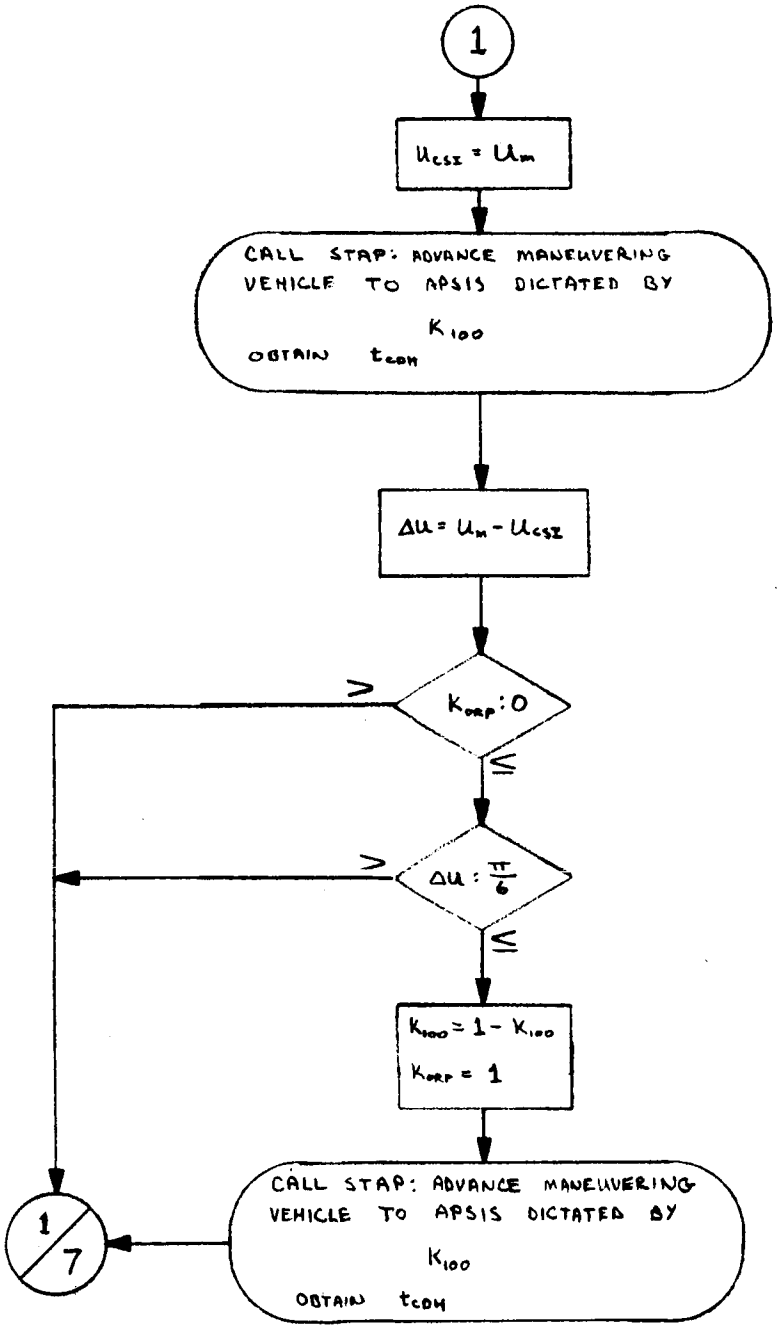
4


1
$R_{TK} = \dfrac{P}{(1 + e_p \cos(\theta_K' + \theta_K + \Delta\gamma))}$
$R_R = R_{TK} - \Delta H$
$\Delta V_K = \sqrt{\dfrac{2\mu}{R_m}\left(\dfrac{1}{1+\frac{R_m}{R_R}}\right) - \dfrac{\dot{R}'^2}{\left(1-\left(\frac{R_m}{R_R}\right)^2\right)}} - V_H$
COMPUTE VELOCITY AFTER CSI
$\bar{V}_m = \bar{V}_m - \Delta V_K (\hat{j})$
CALL LSAEG: INITIALIZE MANEUVERING VEHICLE AT t_{CSI} USING VECTOR AFTER CSI
$\bar{R}_m$, $\bar{V}_m$
$\Delta\gamma = g_m - g'$
$|\Delta V_K' - \Delta V_K| - 1$
>
$\Delta V_K' = \Delta V_K$
≤
1/5

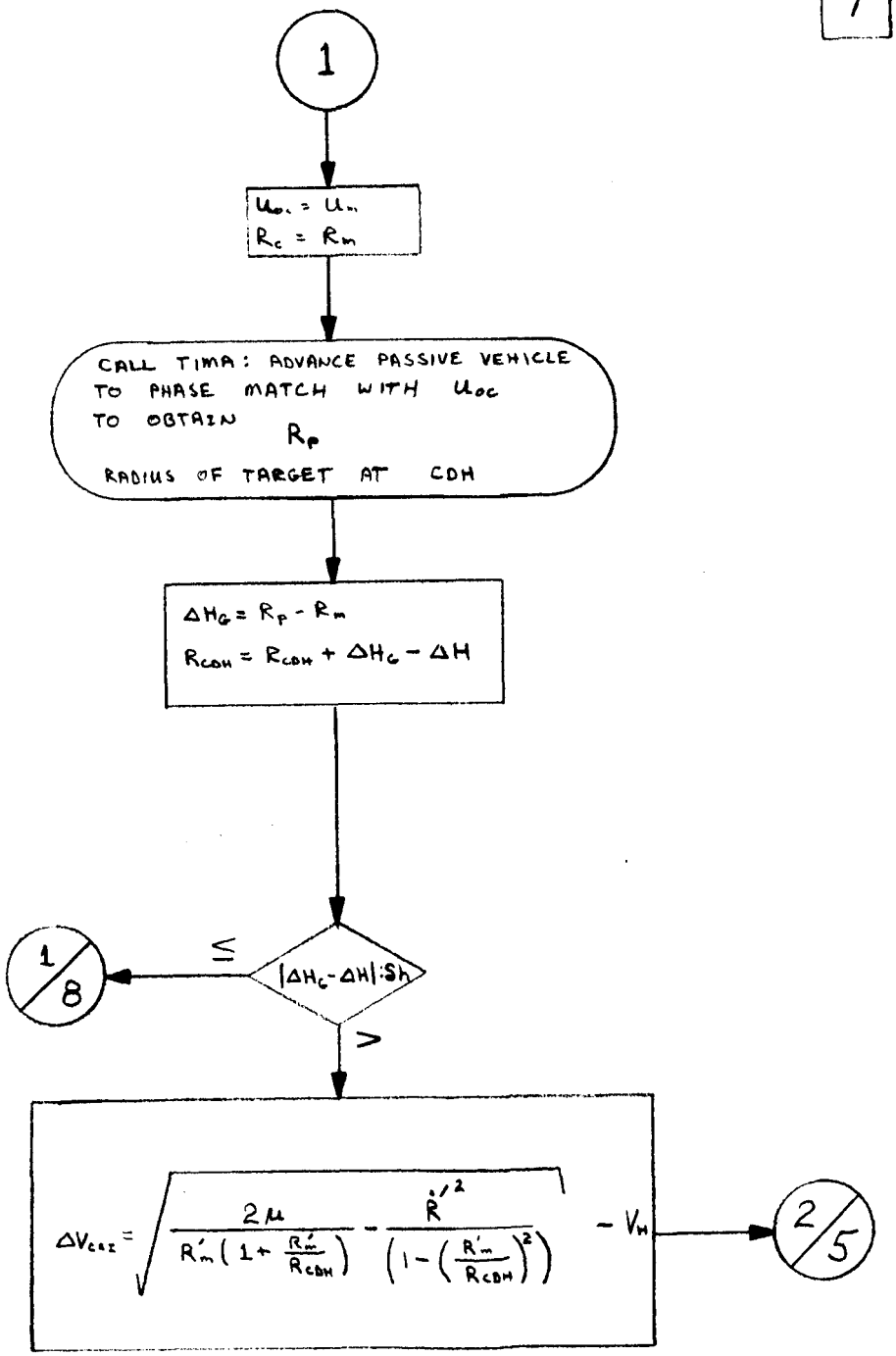
5


1
$R_{COH} = R_R$
$\Delta V_{CSI} = \Delta V_K$
2
COMPUTE VELOCITY AFTER CSI
$\bar{V}_n = \bar{V}_m - \Delta V_{CSI}(\hat{S})$
CALL LSAEG: INITIALIZE MANEUVERING VEHICLE AT t_{CSI} USING VECTOR AFTER CSI
$\bar{R}_m, \bar{V}_m$
$f = u' - g_m$
$\ell_m = f - 2e_m \sin(f) + \frac{3}{4} e_m^2 \sin(2f) - \frac{1}{3} e_m^3 \sin(3f)$
CALL LSAEG: INITIALIZE MANEUVERING VEHICLE AT t_{CSI} USING NEW MEAN ANOMALY
ℓ_m
1/6

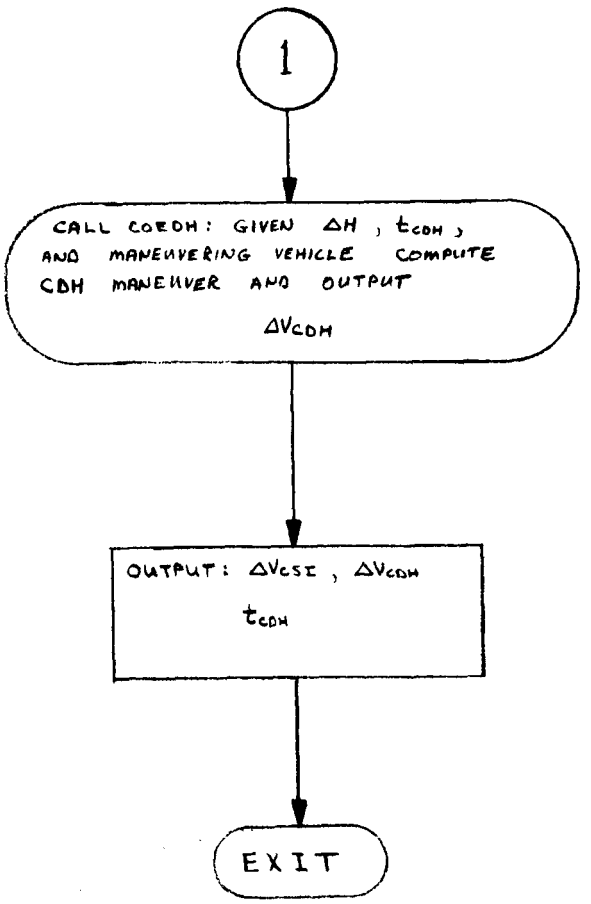
6


1
$u_{CSI} = u_m$
CALL STAP: ADVANCE MANEUVERING VEHICLE TO APSIS DICTATED BY K_{100}
OBTAIN t_{COM}
$\Delta u = u_m - u_{CSI}$
$K_{ORP} : 0$
>
≤
$\Delta u : \frac{\pi}{6}$
>
≤
$K_{100} = 1 - K_{100}$
$K_{ORP} = 1$
CALL STAP: ADVANCE MANEUVERING VEHICLE TO APSIS DICTATED BY K_{100}
OBTAIN t_{COM}
1/7

7


1
$U_{oc} = U_m$
$R_c = R_m$
CALL TIMA: ADVANCE PASSIVE VEHICLE TO PHASE MATCH WITH U_{oc} TO OBTAIN R_p RADIUS OF TARGET AT CDH
$\Delta H_G = R_p - R_m$
$R_{CDH} = R_{CDH} + \Delta H_G - \Delta H$
$|\Delta H_G - \Delta H| : \delta h$
$\leq$
1/8
$>$
$\Delta V_{CRI} = \sqrt{\frac{2\mu}{R'_m\left(1+\frac{R'_m}{R_{CDH}}\right)} - \frac{\dot{R}'^2}{\left(1-\left(\frac{R'_m}{R_{CDH}}\right)^2\right)}} - V_H$
2/5

8


1
CALL COEDH: GIVEN ΔH , t_{CDH} ,
AND MANEUVERING VEHICLE COMPUTE
CDH MANEUVER AND OUTPUT
ΔV_{CDH}
OUTPUT: ΔV_{CSI} , ΔV_{CDH}
t_{CDH}
EXIT

APPENDIX C

FUNCTIONAL AND DETAILED FLOW CHARTS FOR TILL

CONTENTS

Section Page

SYMBOLS 55

FIGURE 1 - ILLUSTRATION OF TILL COMPUTATIONS 57

FUNCTIONAL TILL FLOW CHART 58

DETAILED TILL FLOW CHART 60

SYMBOLS

Constant input:

π	3.141592 . . .
δt	iteration tolerance on time

Variable input:

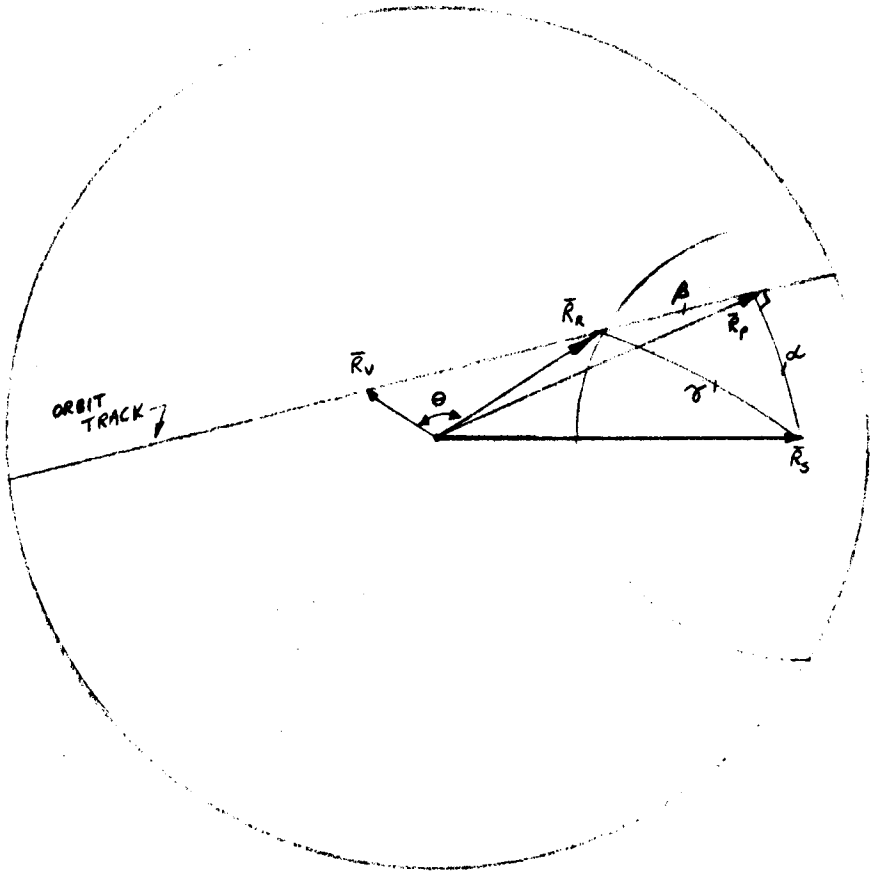
I_S	routing flag for lighting source I_S = -1 - for MSFN site I_S = 0 - for earth lighting I_S = 1 - for sun lighting
t	threshold time to begin search
$\bar{R}_S$	vector from MSFN site to moon at time t
Φ	angle from moon-source line-of-centers to entry or exit of darkness (to ACQ or LOS for MSFN site)
I_E	routing flag I_E = -1 find entry (or LOS) I_E = 1 find exit (or ACQ)
I_L	loop flag I_L = 0 advance forward on Δt I_L = 1 advance forward on computed Δt
I	vehicle number

LSAEG input for vehicle I

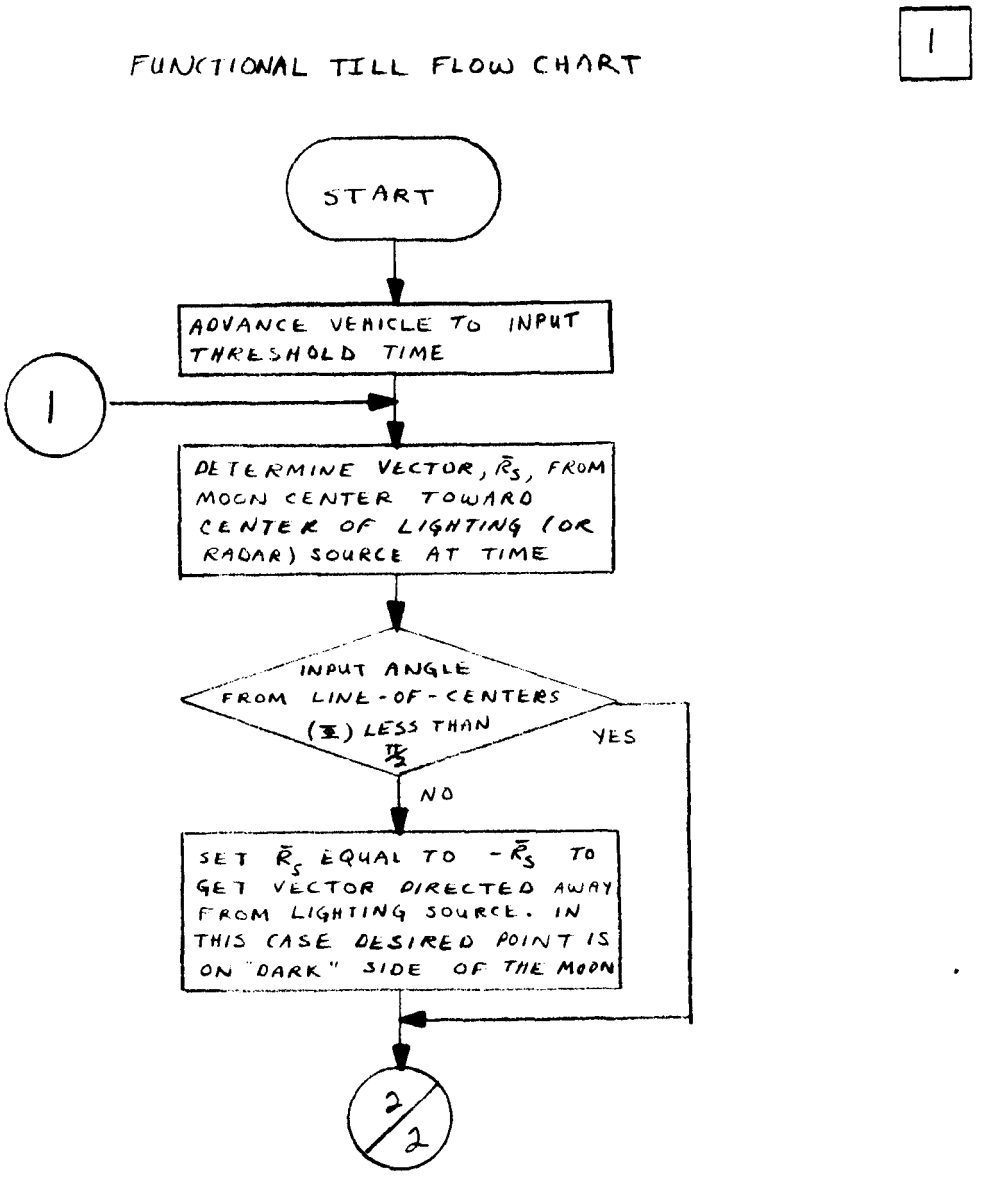
Output:

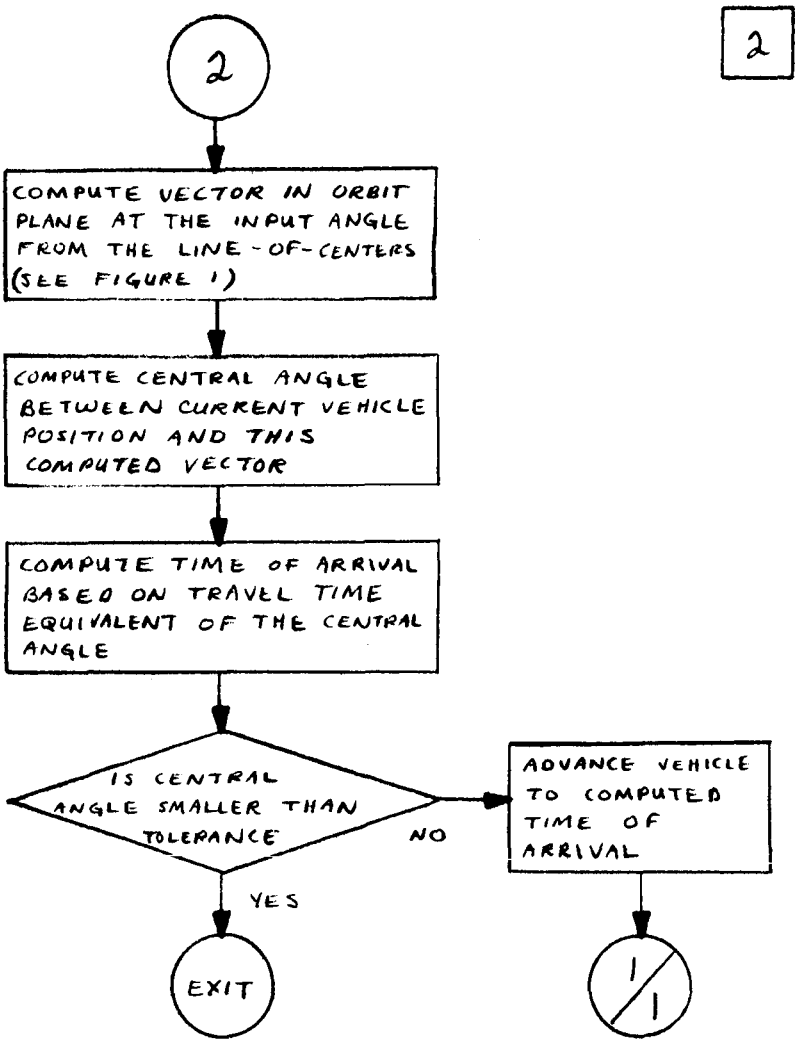
t	time of arrival at desired condition
t_G	guess time at alternate lighting conditions

FIGURE 1. ILLUSTRATION OF TILL COMPUTATIONS



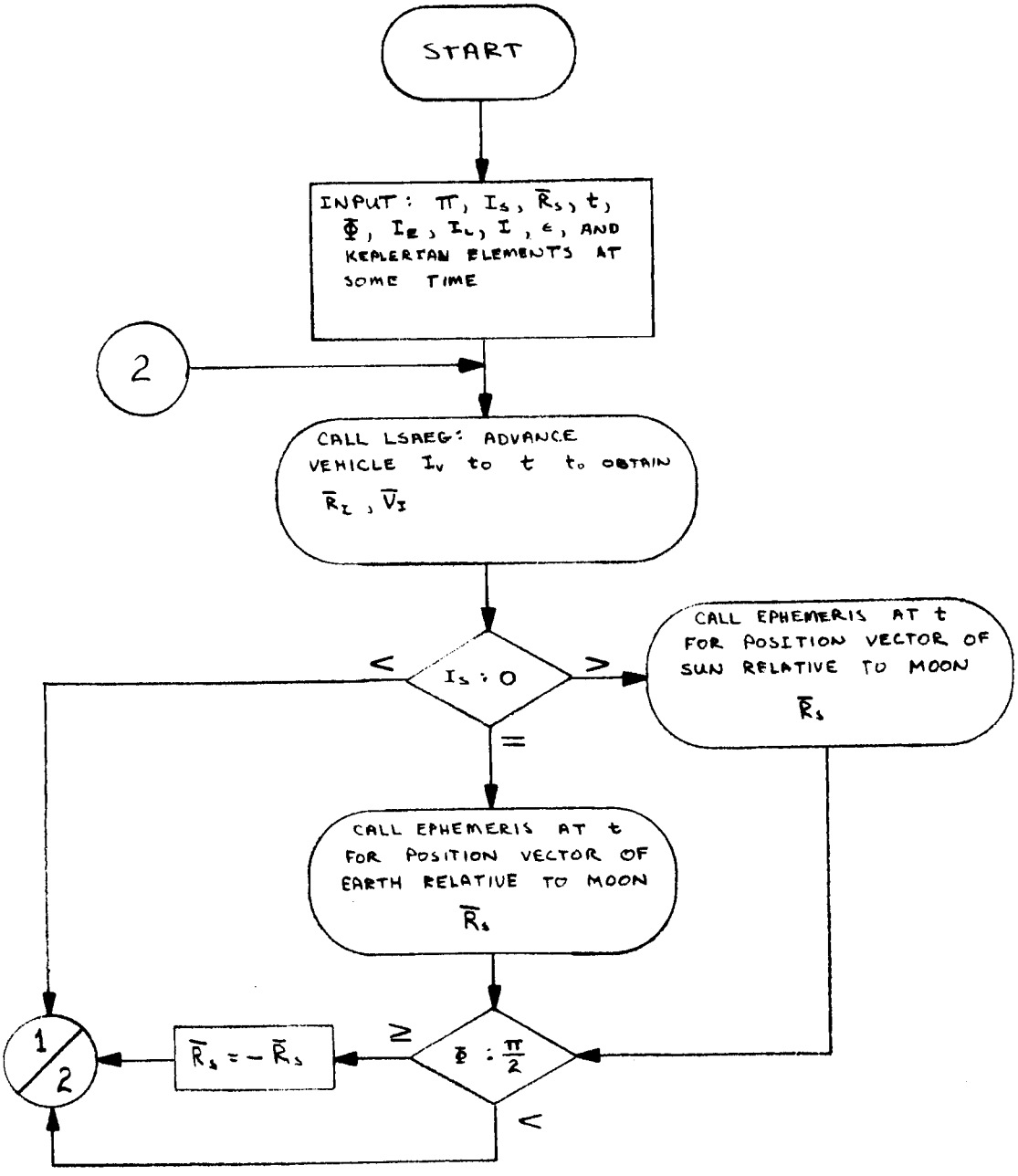
FUNCTIONAL TILL FLOW CHART



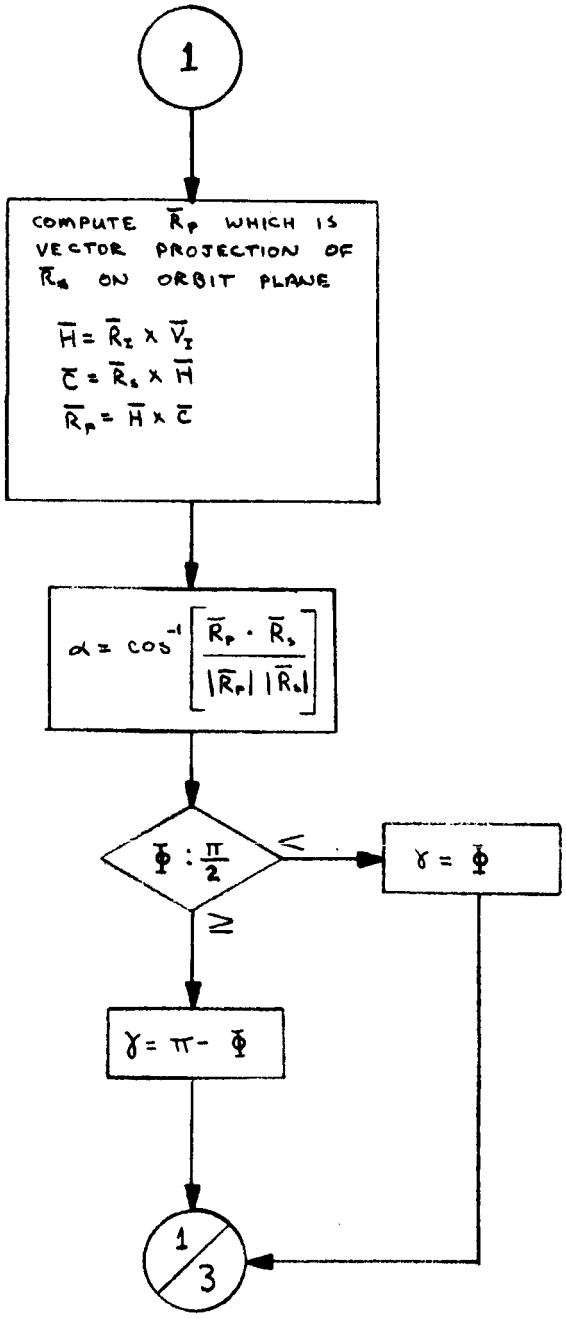

2
2
COMPUTE VECTOR IN ORBIT PLANE AT THE INPUT ANGLE FROM THE LINE-OF-CENTERS (SEE FIGURE 1)
COMPUTE CENTRAL ANGLE BETWEEN CURRENT VEHICLE POSITION AND THIS COMPUTED VECTOR
COMPUTE TIME OF ARRIVAL BASED ON TRAVEL TIME EQUIVALENT OF THE CENTRAL ANGLE
IS CENTRAL ANGLE SMALLER THAN TOLERANCE
NO
ADVANCE VEHICLE TO COMPUTED TIME OF ARRIVAL
YES
EXIT
1/1

DETAILED TILL FLOW CHART

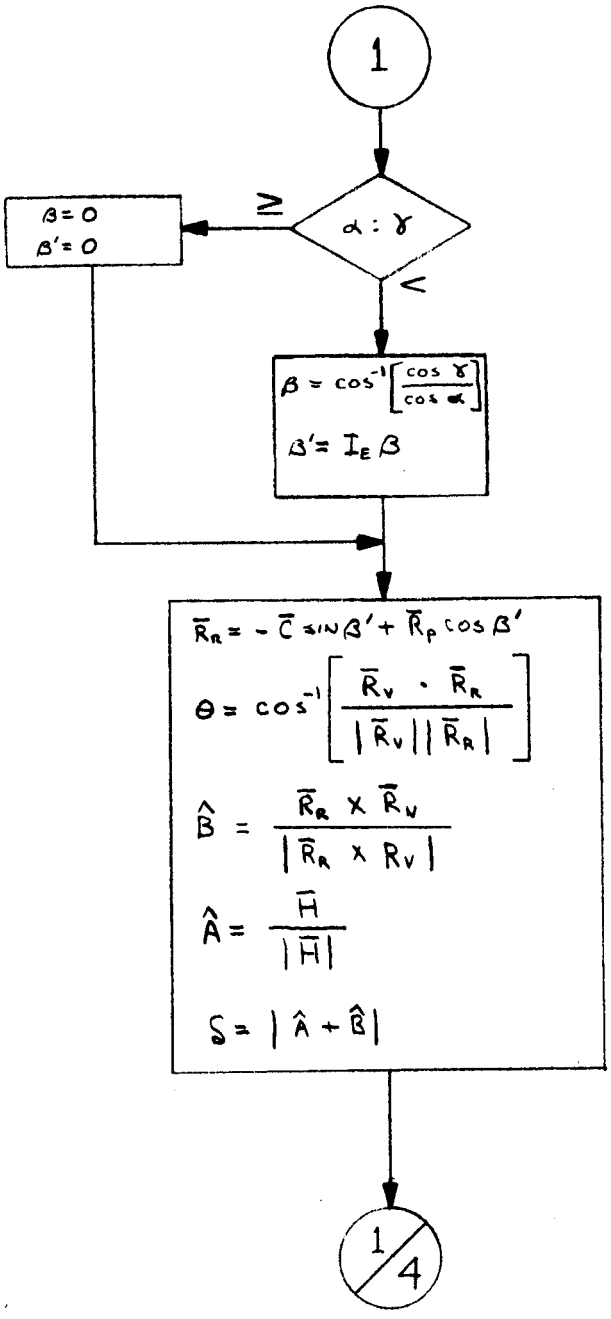
1



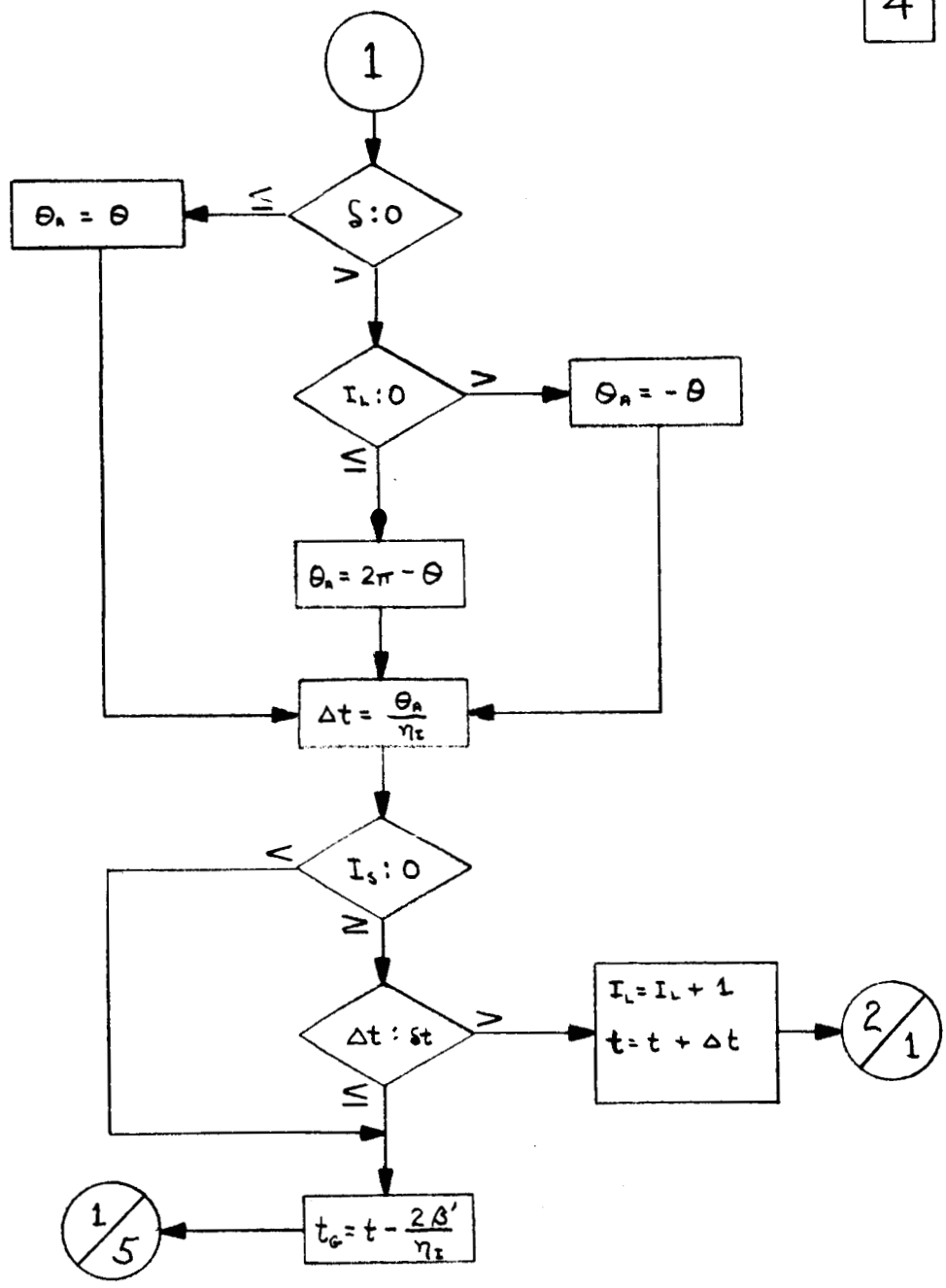
2


1
COMPUTE $\bar{R}_p$ WHICH IS VECTOR PROJECTION OF $\bar{R}_s$ ON ORBIT PLANE
$\bar{H} = \bar{R}_I \times \bar{V}_I$
$\bar{C} = \bar{R}_s \times \bar{H}$
$\bar{R}_p = \bar{H} \times \bar{C}$
$\alpha = \cos^{-1}\left[\frac{\bar{R}_p \cdot \bar{R}_s}{|\bar{R}_p|\,|\bar{R}_s|}\right]$
$\Phi : \frac{\pi}{2}$
$<$
$\gamma = \Phi$
$\geq$
$\gamma = \pi - \Phi$
1/3

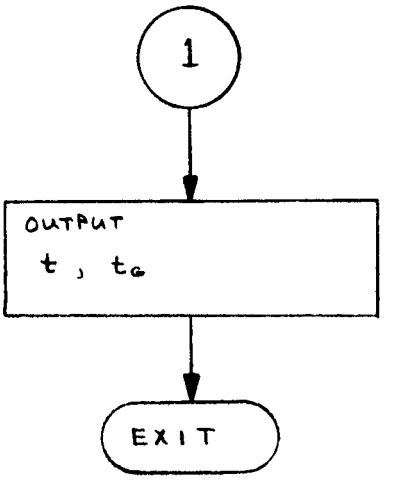
3


1
$\alpha : \gamma$
$\geq$
$<$
$\beta = 0$
$\beta' = 0$
$\beta = \cos^{-1}\left[\frac{\cos\gamma}{\cos\alpha}\right]$
$\beta' = I_E \beta$
$\bar{R}_R = -\bar{C}\sin\beta' + \bar{R}_p\cos\beta'$
$\theta = \cos^{-1}\left[\frac{\bar{R}_V \cdot \bar{R}_R}{|\bar{R}_V||\bar{R}_R|}\right]$
$\hat{B} = \frac{\bar{R}_R \times \bar{R}_V}{|\bar{R}_R \times R_V|}$
$\hat{A} = \frac{\bar{H}}{|\bar{H}|}$
$S = |\hat{A} + \hat{B}|$
1/4

4


1
δ : 0
≤
>
θA = θ
IL : 0
>
≤
θA = - θ
θA = 2π - θ
Δt = θA / ηI
Is : 0
<
≥
Δt : δt
>
≤
IL = IL + 1
t = t + Δt
2/1
tG = t - 2β' / ηI
1/5

5



APPENDIX D

LSAEG SYMBOL DEFINITION

SYMBOLS

i	vehicle number subscript
a, e, i, g, h, l	vector for vehicle in classical coordinates
$x, y, z, \dot{x}, \dot{y}, \dot{z}$	vector for vehicle in rectangular coordinates
$V, \gamma, \psi, R, \lambda, \phi$	vector for vehicle in spherical coordaintes
η	mean motion
$\dot{g}$	rate of change of argument of perigee
$\dot{h}$	rate of change of the longitude of ascending node
U	argument of latitude
$\dot{R}$	rate of change of vehicle radius
h''	mean longitude of ascending node
I''	mean inclination
P	vehicle orbital period

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