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LOGIC AND EQUATIONS FOR THE REAL-TIME COMPUTATION OF THE LUNAR MODULE DESCENT PLANNING TABLE

By William A. Sullivan,
Orbital Mission Analysis Branch

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MISSION PLANNING AND ANALYSIS DIVISION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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PROJECT APOLLO

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CONTENTS

LOGIC AND EQUATIONS FOR THE REAL-TIME COMPUTATION OF THE LUNAR MODULE DESCENT PLANNING TABLE

By William A. Sullivan

SUMMARY AND INTRODUCTION

This internal note presents the revised logic and equations for the lunar module (LM) descent planning processor (LDPP) which replaces that in reference 1. The enclosed flow charts define the processor for the lunar landing mission real-time computer system. The LDPP computes maneuver sequences to be executed by the command and service modules (CSM) and the LM to yield a set of desired orbital conditions at the point of LM descent ignition or a desired CSM orbital plane at the time of LM lift-off. The output of the LDPP will be used to compute the LM descent planning table for real-time mission planning.

ABBREVIATIONS

APPLY	subroutine that computes and applies maneuvers based on input platform ΔV components
ASP	apside shift, altitude adjustment, and plane-change maneuver
ASH	apside shift and altitude adjustment maneuver
CHAPLA	subroutine that computes plane-change maneuver
CIA	circularization at an apsis maneuver
CIR	circularization maneuver
CNODE	subroutine that searches for a common node between two orbits
CSM	command and service modules
DOI	descent orbit injection maneuver
HO1	first maneuver in a double Hohmann sequence
HO2	second maneuver in a double Hohmann sequence
LATLON	subroutine that computes selenocentric position from selenographic position

LDPP	lunar module descent planning processor
LDPT	lunar module descent planning table
LLTPR	subroutine that predicts the time of lunar landing
LM	lunar module
PC	plane-change maneuver
PCC	plane change and circularization maneuver
PPC	prelaunch plane-change maneuver
SAC	subroutine that computes apsis and circularization maneuvers
STAP	subroutine that iterates to find an upcoming apsis point
STCIR	subroutine that iterates to find a specified radius in a given orbit
STLO	subroutine that iterates to find a vehicle time of arrival at an input longitude
TIMA	subroutine that iterates to find a vehicle time of arrival at an argument of latitude

LUNAR MODULE DESCENT PLANNING PROCESSOR

The LDPP computes maneuver sequences based on flight controller decisions. There are seven modes of operations from which to choose. Each of these modes may contain more than one sequence. Each sequence may or may not have more than one maneuver. The following table presents a list of maneuver sequences in each mode.

Mode	Maneuver	Sequence		
		1	2	3
1	1	PC	PCC	ASP
	2	DOI	DOI	CIA
	3	--	--	DOI
2	1	ASH	CIR	--
	2	DOI	DOI	--
3	1	ASH	--	--
	2	CIA	--	--
	3	DOI	--	--
4	1	DOI	--	--
5	1	PC	HO1	HO1
	2	HO1	PC	HO2
	3	HO2	HO2	PC
	4	DOI	DOI	DOI
6		Go to powered descent		
7	1	PPC		

These maneuver sequences are designed to give the flight controller the ability to correct a non-nominal CSM orbit after lunar orbit insertion and to place the CSM orbital plane over the LM landing site before LM lift-off. The LDPP has the capability to compute maneuvers to change the apocynthion and percynthion heights, shift the line-of-apsides and place the CSM orbital plane over a desired landing site using an input azimuth. The processor also computes a LM DOI maneuver based on a desired landing site position. To compute these maneuvers the LDPP assumes that the vehicles are docked for all maneuvers prior to DOI and are undocked for DOI and all following maneuvers.

When computing in modes 1 through 5, the flight controller is given the option of simulating powered descent; in mode 6, however, only a powered descent simulation is available. Mode 7 is used to compute a maneuver to place the CSM orbital plane over the LM landing site at the time of LM lift-off. To compute these maneuvers, the LDPP calls three specialized subroutines. The subroutines are SAC (spacecraft apsis and circularization), CHAPLA (change spacecraft plane), and LLTPR (lunar landing time prediction routine). Flow charts for the LDPP, SAC, CHAPLA, and LLTPR are presented in appendices A, B, C, and D, respectively. After all computation is completed in the LDPP, the LM descent planning table (LDPT) is then displayed. The LDPT displays maneuvers and descent trajectory parameters. From these displayed quantities the flight controller can decide whether or not the total maneuver plan is acceptable. If the plan is acceptable, the flight controller can transfer it to the mission plan table where it becomes an integral part of the over-all mission plan.

Subroutine SAC computes a maneuver to shift the line-of-apsides and change apocynthion and pericynthion height or circularize the CSM orbit.

Subroutine CHAPLA computes a maneuver to place the CSM orbital track over a desired landing site with or without a specified azimuth.

Subroutine LLTPR (ref. 2) computes the time of the DOI maneuver based on a desired landing site and a CSM vector before the maneuver.

The LDPP uses the lunar satellite analytic ephemeris generator, LSAEG, (ref. 3) for vehicle ephemeris prediction and LM descent guidance equations of reference 3 for powered descent simulation. Several other special purpose trajectory subroutines are called. These are APPLY (ref. 4), CNODE (ref. 5), STAP, STLO, STCIR (ref. 6), TLMA (ref. 7), and LATLON (ref. 8).

APPENDIX A

LDPP FLOW CHART

SYMBOLS FOR LDPP FLOW CHART

Input Constants

π	3.141592...
μ	lunar gravitational potential
R_{moon}	mean lunar radius
$\zeta\theta$	angular iteration tolerance
ζt	time iteration tolerance
$\bar{g}$	average acceleration of gravity

Input Variables

MODE — maneuver routine flag; if

- MODE = 1, compute CSM phase change sequence
- MODE = 2, compute single CSM maneuver sequence
- MODE = 3, compute double CSM maneuver sequence
- MODE = 4, compute LM maneuver sequence
- MODE = 5, compute double Hohmann plane change CSM maneuver sequence
- MODE = 6, compute LM powered-descent trajectory
- MODE = 7, compute CSM prelaunch plane-change maneuver sequence

IDO — maneuver sequence flag; when

MODE = 1 and

- IDO = -1, compute plane-change maneuver only
- IDO = 0, compute plane change and circularization maneuver
- IDO = 1, compute plane-change maneuver combined with the first maneuver of a CSM two-maneuver sequence to circularize the CSM orbit at an input altitude.

MODE = 2 and

- IDO = 0, compute CSM maneuver to establish an apsis and an input altitude at the DOI maneuver point

IDO = 1, compute CSM maneuver to circularize orbit at an input altitude

MODE = 3 and

IDO = -1, compute CSM two-maneuver sequence with the first maneuver performed at an input time and the second maneuver performed at an input altitude to circularize the orbit

IDO = 1, compute CSM two-maneuver sequence with the first maneuver performed at an apsis and the second maneuver performed at an input altitude to circularize the orbit

MODE = 5 and

IDO = -1, compute CSM three-maneuver sequence so that the first maneuver is a plane change and the following pair is a double Hohmann to a circular orbit at an input altitude

IDO = 0, compute CSM three-maneuver sequence so that the first maneuver initiates a double Hohmann, the second is a plane change, and the third completes the double Hohmann to a circular orbit at an input altitude.

IDO = 1, compute CSM three-maneuver sequence so that the first two maneuvers constitute a double Hohmann to a circular orbit at an input altitude and the third is a plane change.

I_{PD} powered-descent simulation flag

IPD = 0, simulate powered descent

IPD = 1, do not simulate powered descent

I_{AZ} descent azimuth flag

$I_{AZ} = 0$, descent azimuth is not specified

$I_{AZ} = 1$, descent azimuth is specified

I_{TPD} powered-descent time flag

$I_{TPD} = 0$, let powered descent compute time to ignite

$I_{TPD} = 1$, input time for powered-descent ignition

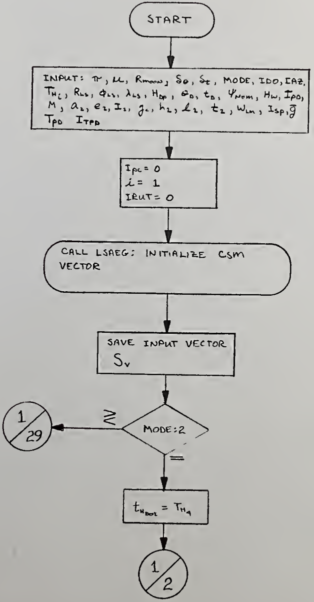
T_{PD}	time for powered descent ignition
TH	table of threshold times
M	number of dwell orbits desired between DOI and powered-descent ignition
R_{LS}, ϕ_{LS}, λ_{LS}	radius, latitude, and longitude of the desired landing site
H_{DP}	altitude of point of descent ignition
θ_D	powered-flight arc of descent
t_D	powered-flight time of descent
ψ_{nom}	descent azimuth desired
H_W	altitude wanted at apsis
I_{SP}	average specific impulse of LM descent engine
W_{LM}	initial weight of LM
a_2, e_2, I_2, g_2, h_2, ℓ_2, t_2	CSM state vector and time

Output Variables

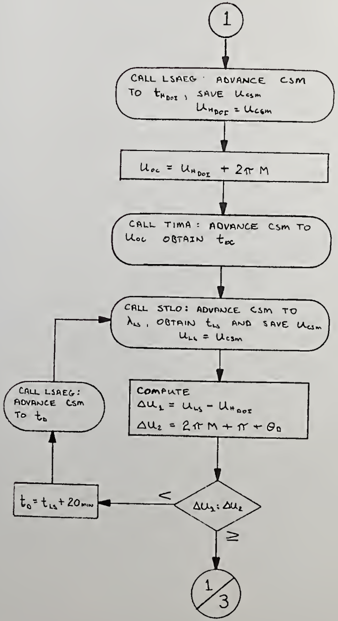
i	number of maneuver computed
ΔV_i	delta V costs of each maneuver
Y_i	yaw angle of each maneuver
P_i	pitch angle of each maneuver
T_{Mi}	time of each maneuver

LDPP FLOW CHART

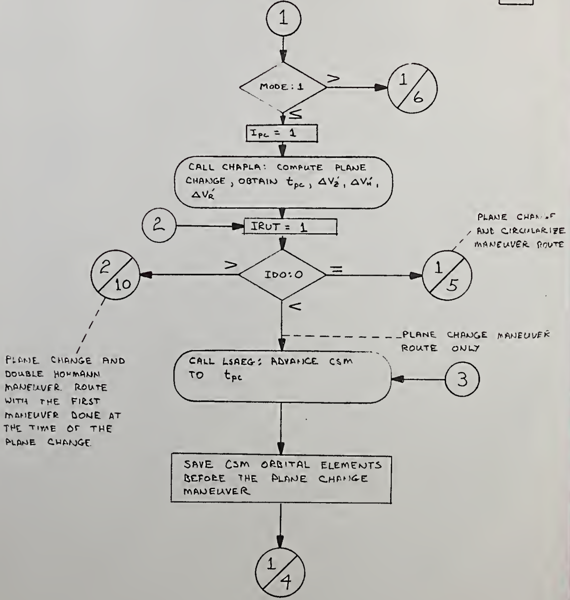
1



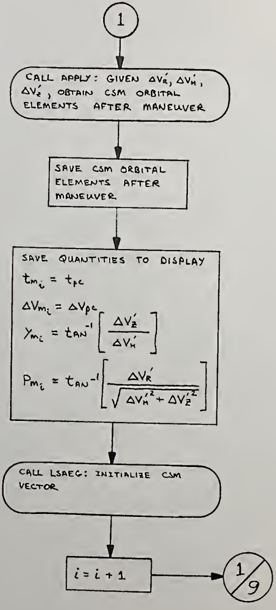
2


1
CALL LSAEG: ADVANCE CSM TO t_{HDOI}, SAVE u_{csm}
$u_{HDOI} = u_{csm}$
$u_{oc} = u_{HDOI} + 2\pi M$
CALL TIMA: ADVANCE CSM TO u_{oc} OBTAIN t_{oc}
CALL STLO: ADVANCE CSM TO λ_{LS}, OBTAIN t_{LS} AND SAVE u_{csm}
$u_{LS} = u_{csm}$
COMPUTE
$\Delta u_1 = u_{LS} - u_{HDOI}$
$\Delta u_2 = 2\pi M + \pi + \theta_D$
$\Delta u_1 : \Delta u_2$
<
$\geq$
$t_D = t_{LS} + 20_{min}$
CALL LSAEG: ADVANCE CSM TO t_D
1/3

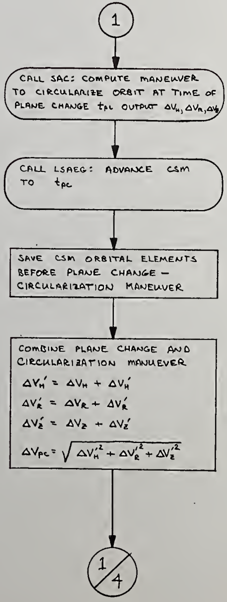
3


1
MODE : 1
>
1/6
≤
I_{pc} = 1
CALL CHAPLA: COMPUTE PLANE CHANGE, OBTAIN t_{pc}, $\Delta V_Z'$, $\Delta V_H'$, $\Delta V_R'$
2
IRUT = 1
PLANE CHANGE AND CIRCULARIZE MANEUVER ROUTE
>
IDO : 0
=
2/10
1/5
<
PLANE CHANGE MANEUVER ROUTE ONLY
PLANE CHANGE AND DOUBLE HOHMANN MANEUVER ROUTE WITH THE FIRST MANEUVER DONE AT THE TIME OF THE PLANE CHANGE
CALL LSAEG: ADVANCE CSM TO t_{pc}
3
SAVE CSM ORBITAL ELEMENTS BEFORE THE PLANE CHANGE MANEUVER
1/4

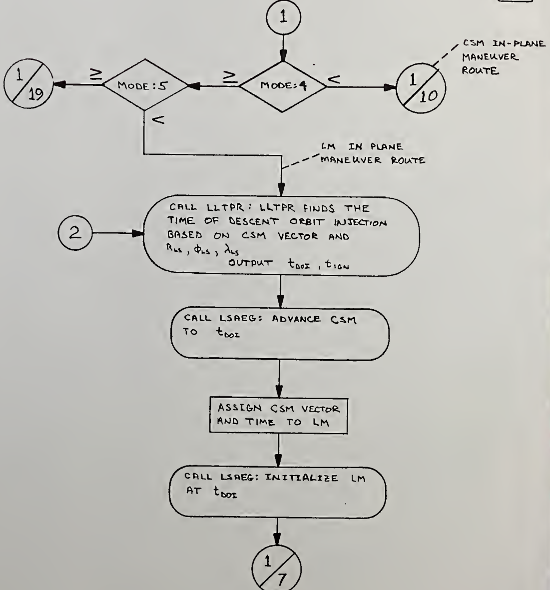
4

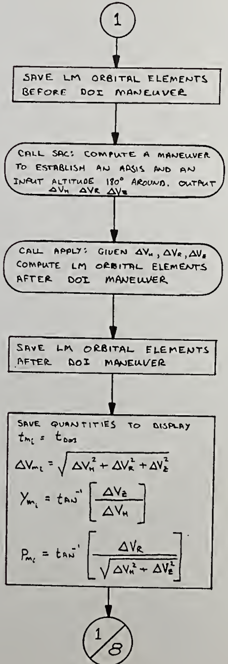

1
CALL APPLY: GIVEN $\Delta V_R'$, $\Delta V_H'$, $\Delta V_Z'$, OBTAIN CSM ORBITAL ELEMENTS AFTER MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
SAVE QUANTITIES TO DISPLAY
$t_{m_i} = t_{pc}$
$\Delta V_{m_i} = \Delta V_{pc}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z'}{\Delta V_H'}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R'}{\sqrt{\Delta V_H'^2 + \Delta V_Z'^2}}\right]$
CALL LSAEG: INITIALIZE CSM VECTOR
$i = i + 1$
1/9

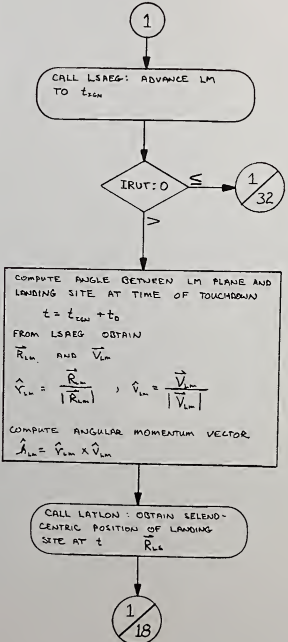
5


1
CALL SAC: COMPUTE MANEUVER TO CIRCULARIZE ORBIT AT TIME OF PLANE CHANGE t_{pc} OUTPUT $\Delta V_H, \Delta V_R, \Delta V_Z$
CALL LSAEG: ADVANCE CSM TO t_{pc}
SAVE CSM ORBITAL ELEMENTS BEFORE PLANE CHANGE — CIRCULARIZATION MANEUVER
COMBINE PLANE CHANGE AND CIRCULARIZATION MANUEVER
$\Delta V_H' = \Delta V_H + \Delta V_H'$
$\Delta V_R' = \Delta V_R + \Delta V_R'$
$\Delta V_Z' = \Delta V_Z + \Delta V_Z'$
$\Delta V_{pc} = \sqrt{\Delta V_H'^2 + \Delta V_R'^2 + \Delta V_Z'^2}$
1/4

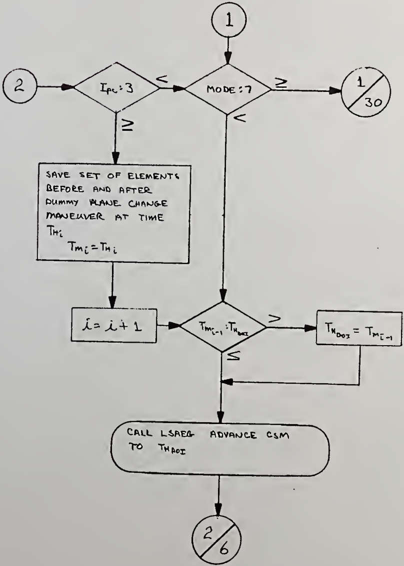
6


1
MODE:4
≥
<
1/10
CSM IN-PLANE MANEUVER ROUTE
MODE:5
≥
1/19
<
LM IN PLANE MANEUVER ROUTE
2
CALL LLTPR: LLTPR FINDS THE TIME OF DESCENT ORBIT INJECTION BASED ON CSM VECTOR AND R_{LS}, ϕ_{LS}, λ_{LS}
OUTPUT t_{DOI}, t_{IGN}
CALL LSAEG: ADVANCE CSM TO t_{DOI}
ASSIGN CSM VECTOR AND TIME TO LM
CALL LSAEG: INITIALIZE LM AT t_{DOI}
1/7

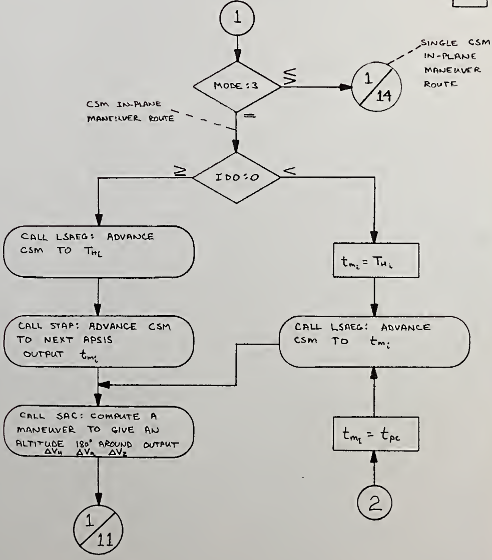

1
SAVE LM ORBITAL ELEMENTS BEFORE DOI MANEUVER
CALL SAC: COMPUTE A MANEUVER TO ESTABLISH AN APSIS AND AN INPUT ALTITUDE 180° AROUND. OUTPUT ΔV_H ΔV_R ΔV_Z
CALL APPLY: GIVEN $\Delta V_H, \Delta V_R, \Delta V_Z$ COMPUTE LM ORBITAL ELEMENTS AFTER DOI MANEUVER
SAVE LM ORBITAL ELEMENTS AFTER DOI MANEUVER
SAVE QUANTITIES TO DISPLAY
$t_{m_i} = t_{DOI}$
$\Delta V_{m_i} = \sqrt{\Delta V_H^2 + \Delta V_R^2 + \Delta V_Z^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z}{\Delta V_H}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R}{\sqrt{\Delta V_H^2 + \Delta V_Z^2}}\right]$
1/8

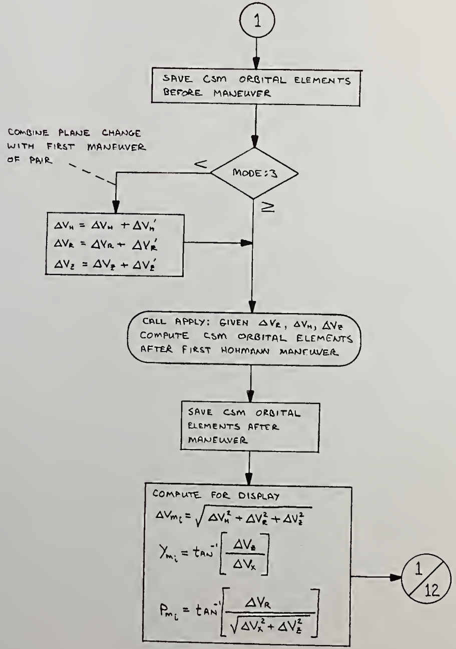

1
CALL LSAEG: ADVANCE LM TO t_{IGN}
IRUT: 0
≤
1/32
>
COMPUTE ANGLE BETWEEN LM PLANE AND LANDING SITE AT TIME OF TOUCHDOWN
$t = t_{IGN} + t_0$
FROM LSAEG OBTAIN
$\vec{R}_{LM}$ AND $\vec{V}_{LM}$
$\hat{r}_{LM} = \frac{\vec{R}_{LM}}{|\vec{R}_{LM}|}$, $\hat{v}_{LM} = \frac{\vec{V}_{LM}}{|\vec{V}_{LM}|}$
COMPUTE ANGULAR MOMENTUM VECTOR
$\hat{h}_{LM} = \hat{r}_{LM} \times \hat{v}_{LM}$
CALL LATLON: OBTAIN SELENOCENTRIC POSITION OF LANDING SITE AT t $\vec{R}_{LS}$
1/18

9

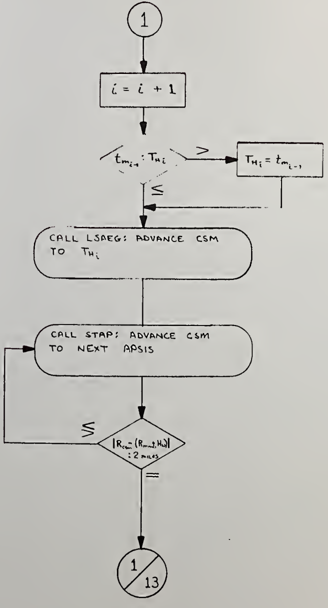

1
2
I_pc : 3
<
MODE : 7
≥
1/30
≥
<
SAVE SET OF ELEMENTS BEFORE AND AFTER DUMMY PLANE CHANGE MANEUVER AT TIME TH_i
Tm_i = TH_i
i = i + 1
Tm_{i-1} : TH_DOI
>
TH_DOI = Tm_{i-1}
≤
CALL LSAEG ADVANCE CSM TO TH_DOI
2/6

10

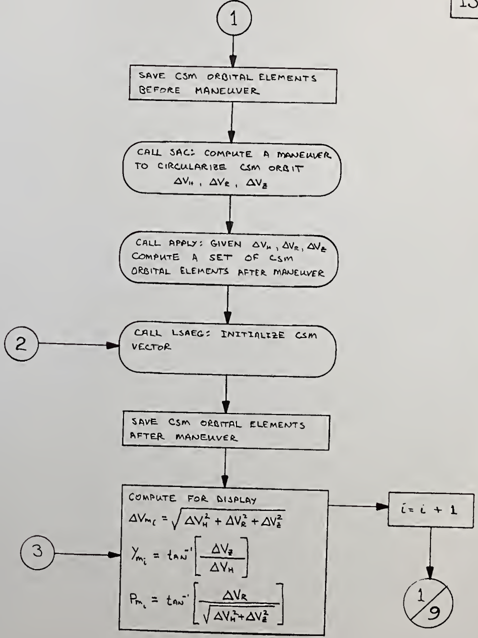

1
MODE:3
≤
1/14
SINGLE CSM IN-PLANE MANEUVER ROUTE
CSM IN-PLANE MANEUVER ROUTE
=
IDO:0
≥
<
CALL LSAEG: ADVANCE CSM TO T_{H_i}
$t_{m_i} = T_{H_i}$
CALL STAP: ADVANCE CSM TO NEXT APSIS OUTPUT t_{m_i}
CALL LSAEG: ADVANCE CSM TO t_{m_i}
CALL SAC: COMPUTE A MANEUVER TO GIVE AN ALTITUDE 180° AROUND OUTPUT ΔV_H ΔV_R ΔV_Z
$t_{m_i} = t_{pc}$
2
1/11


1
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
COMBINE PLANE CHANGE WITH FIRST MANEUVER OF PAIR
MODE:3
<
≥
$\Delta V_H = \Delta V_H + \Delta V_H'$
$\Delta V_R = \Delta V_R + \Delta V_R'$
$\Delta V_Z = \Delta V_Z + \Delta V_Z'$
CALL APPLY: GIVEN ΔV_R, ΔV_H, ΔV_Z COMPUTE CSM ORBITAL ELEMENTS AFTER FIRST HOHMANN MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
COMPUTE FOR DISPLAY
$\Delta V_{m_i} = \sqrt{\Delta V_H^2 + \Delta V_R^2 + \Delta V_Z^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z}{\Delta V_X}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R}{\sqrt{\Delta V_X^2 + \Delta V_Z^2}}\right]$
1/12

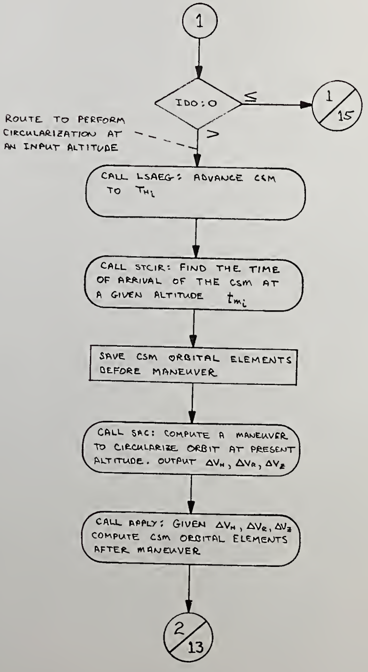
12

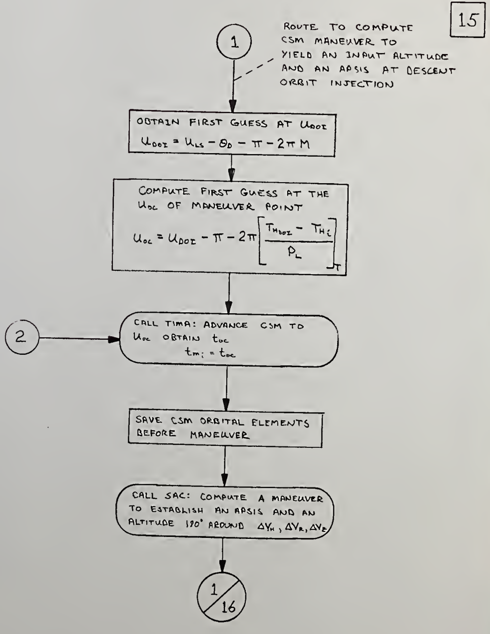

1
i = i + 1
$t_{m_{i-1}} : T_{H_i}$
>
$T_{H_i} = t_{m_{i-1}}$
≤
CALL LSAEG: ADVANCE CSM TO T_{H_i}
CALL STAP: ADVANCE CSM TO NEXT APSIS
≶
$|R_{csm} - (R_{moon}, H_w)| : 2$ miles
=
1/13

13

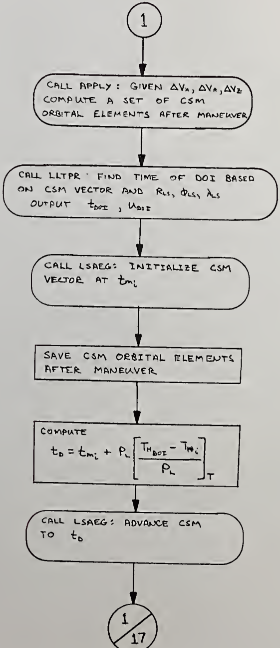

1
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL SAC: COMPUTE A MANEUVER TO CIRCULARIZE CSM ORBIT ΔV_H, ΔV_R, ΔV_Z
CALL APPLY: GIVEN ΔV_H, ΔV_R, ΔV_Z COMPUTE A SET OF CSM ORBITAL ELEMENTS AFTER MANEUVER
2
CALL LSAEG: INITIALIZE CSM VECTOR
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
3
COMPUTE FOR DISPLAY
$\Delta V_{m_i} = \sqrt{\Delta V_H^2 + \Delta V_R^2 + \Delta V_Z^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z}{\Delta V_H}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R}{\sqrt{\Delta V_H^2 + \Delta V_Z^2}}\right]$
$i = i + 1$
1/9

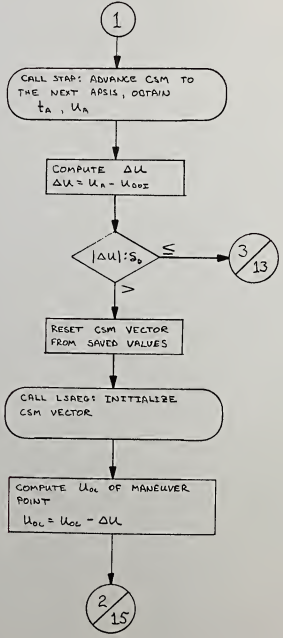
14

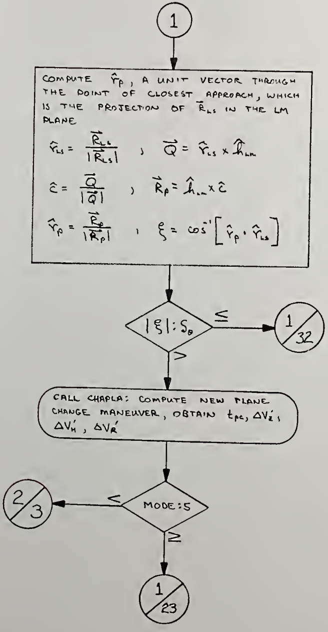

1
IDO:O
≤
1/15
>
ROUTE TO PERFORM CIRCULARIZATION AT AN INPUT ALTITUDE
CALL LSAEG: ADVANCE CSM TO T_{H_i}
CALL STCIR: FIND THE TIME OF ARRIVAL OF THE CSM AT A GIVEN ALTITUDE t_{m_i}
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL SAC: COMPUTE A MANEUVER TO CIRCULARIZE ORBIT AT PRESENT ALTITUDE. OUTPUT ΔV_H, ΔV_R, ΔV_Z
CALL APPLY: GIVEN ΔV_H, ΔV_R, ΔV_Z COMPUTE CSM ORBITAL ELEMENTS AFTER MANEUVER
2/13


15
1
ROUTE TO COMPUTE CSM MANEUVER TO YIELD AN INPUT ALTITUDE AND AN APSIS AT DESCENT ORBIT INJECTION
OBTAIN FIRST GUESS AT U_{DOI}
$U_{DOI} = U_{LS} - \theta_D - \pi - 2\pi M$
COMPUTE FIRST GUESS AT THE U_{oc} OF MANEUVER POINT
$U_{oc} = U_{DOI} - \pi - 2\pi \left[\frac{T_{H_{DOI}} - T_{H_i}}{P_L} \right]_T$
2
CALL TIMA: ADVANCE CSM TO U_{oc} OBTAIN t_{oc}
$t_{m_i} = t_{oc}$
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL SAC: COMPUTE A MANEUVER TO ESTABLISH AN APSIS AND AN ALTITUDE 180° AROUND ΔV_H, ΔV_R, ΔV_E
1/16

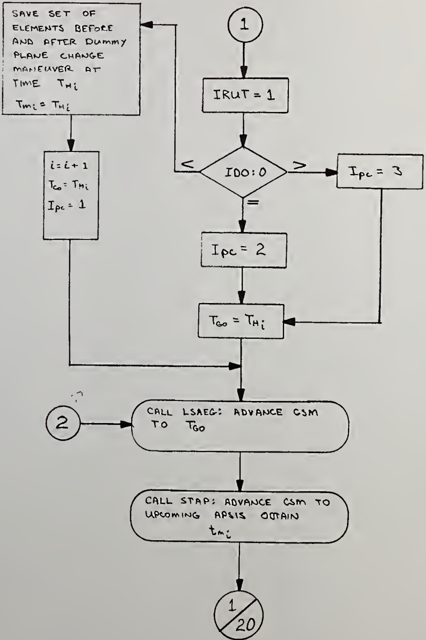
16


1
CALL APPLY: GIVEN ΔVx, ΔVR, ΔVZ COMPUTE A SET OF CSM ORBITAL ELEMENTS AFTER MANEUVER
CALL LLTPR: FIND TIME OF DOI BASED ON CSM VECTOR AND RLS, ΦLS, λLS OUTPUT tDOI, uDOI
CALL LSAEG: INITIALIZE CSM VECTOR AT tmi
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
COMPUTE
$t_D = t_{m_i} + P_L \left[\frac{T_{H_{DOI}} - T_{H_i}}{P_L} \right]_T$
CALL LSAEG: ADVANCE CSM TO tD
1/17

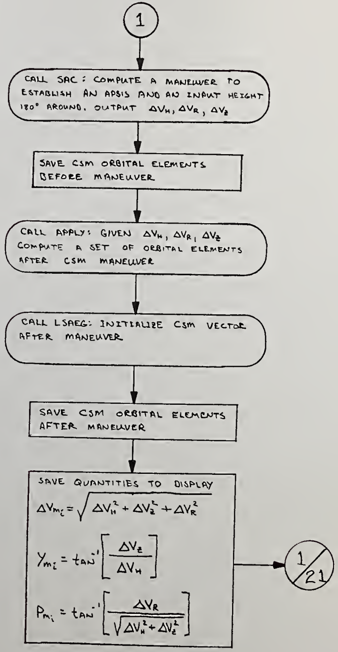

1
CALL STAP: ADVANCE CSM TO THE NEXT APSIS, OBTAIN t_A , u_A
COMPUTE Δu
$\Delta u = u_A - u_{OOI}$
$|\Delta u| : S_0$
≤
3/13
>
RESET CSM VECTOR FROM SAVED VALUES
CALL LSAEG: INITIALIZE CSM VECTOR
COMPUTE u_{oc} OF MANEUVER POINT
$u_{oc} = u_{oc} - \Delta u$
2/15

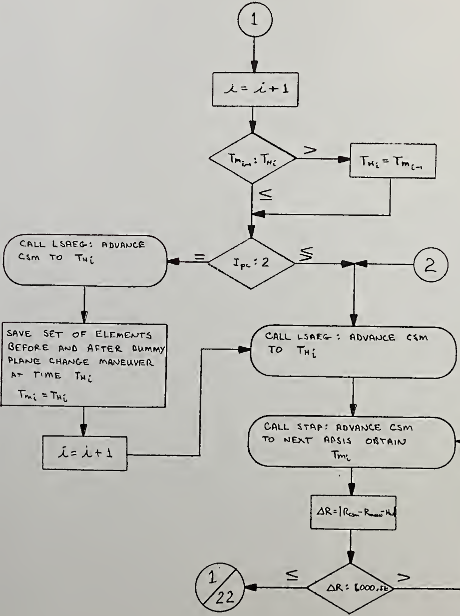

1
COMPUTE $\hat{r}_p$, A UNIT VECTOR THROUGH THE POINT OF CLOSEST APPROACH, WHICH IS THE PROJECTION OF $\vec{R}_{LS}$ IN THE LM PLANE
$\hat{r}_{LS} = \frac{\vec{R}_{LS}}{|\vec{R}_{LS}|}$, $\vec{Q} = \hat{r}_{LS} \times \hat{h}_{LM}$
$\hat{c} = \frac{\vec{Q}}{|\vec{Q}|}$, $\vec{R}_p = \hat{h}_{LM} \times \hat{c}$
$\hat{r}_p = \frac{\vec{R}_p}{|\vec{R}_p|}$, $\xi = \cos^{-1}\left[\hat{r}_p \cdot \hat{r}_{LS}\right]$
$|\xi| : S_\theta$
$\leq$
1/32
$>$
CALL CHAPLA: COMPUTE NEW PLANE CHANGE MANEUVER, OBTAIN t_{pc}, $\Delta V_z'$, $\Delta V_H'$, $\Delta V_R'$
MODE : 5
$<$
2/3
$\geq$
1/23

19

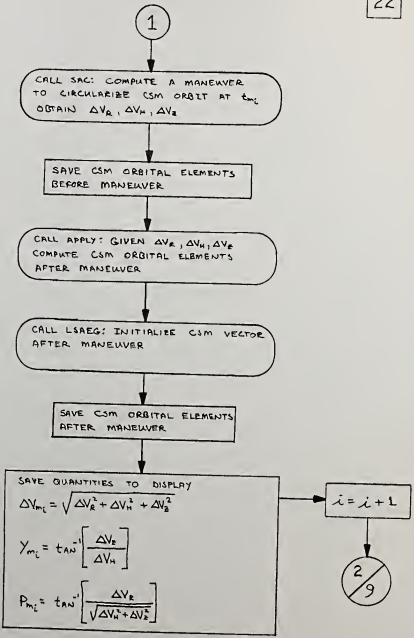

1
IRUT = 1
IDO : 0
<
>
=
Ipc = 3
Ipc = 2
TGO = THi
SAVE SET OF ELEMENTS BEFORE AND AFTER DUMMY PLANE CHANGE MANEUVER AT TIME THi
Tmi = THi
i = i + 1
TGO = TMi
Ipc = 1
2
CALL LSAEG: ADVANCE CSM TO TGO
CALL STAP: ADVANCE CSM TO UPCOMING APSIS OBTAIN tmi
1/20

20

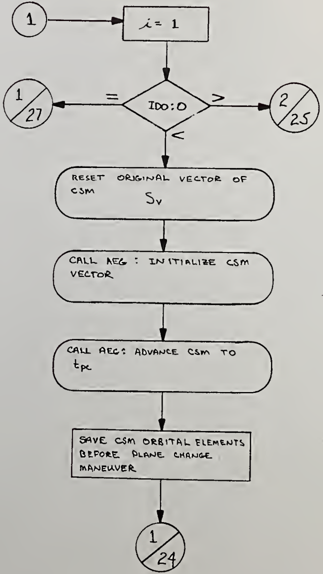

1
CALL SAC: COMPUTE A MANEUVER TO ESTABLISH AN APSIS AND AN INPUT HEIGHT 180° AROUND. OUTPUT ΔV_H, ΔV_R, ΔV_Z
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL APPLY: GIVEN ΔV_H, ΔV_R, ΔV_Z COMPUTE A SET OF ORBITAL ELEMENTS AFTER CSM MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR AFTER MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
SAVE QUANTITIES TO DISPLAY
$\Delta V_{m_i} = \sqrt{\Delta V_H^2 + \Delta V_Z^2 + \Delta V_R^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z}{\Delta V_H}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R}{\sqrt{\Delta V_H^2 + \Delta V_Z^2}}\right]$
1/21


1
i = i + 1
Tm_{i-1} : TH_i
>
TH_i = Tm_{i-1}
≤
CALL LSAEG: ADVANCE CSM TO TH_i
=
I_pc : 2
≤
2
SAVE SET OF ELEMENTS BEFORE AND AFTER DUMMY PLANE CHANGE MANEUVER AT TIME TH_i
Tm_i = TH_i
CALL LSAEG: ADVANCE CSM TO TH_i
i = i + 1
CALL STAP: ADVANCE CSM TO NEXT APSIS OBTAIN Tm_i
ΔR = |R_csm − R_moon − H_d|
≤
ΔR : 6000. ft
>
1/22

22


1
CALL SAC: COMPUTE A MANEUVER TO CIRCULARIZE CSM ORBIT AT t_{m_i} OBTAIN ΔV_R, ΔV_H, ΔV_Z
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL APPLY: GIVEN ΔV_R, ΔV_H, ΔV_Z COMPUTE CSM ORBITAL ELEMENTS AFTER MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR AFTER MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
SAVE QUANTITIES TO DISPLAY
$\Delta V_{m_i} = \sqrt{\Delta V_R^2 + \Delta V_H^2 + \Delta V_Z^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z}{\Delta V_H}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R}{\sqrt{\Delta V_H^2 + \Delta V_Z^2}}\right]$
$i = i + 1$
2/9

23


1
i = 1
=
IDO:O
>
1/27
2/25
<
RESET ORIGINAL VECTOR OF CSM
Sv
CALL AEG : INITIALIZE CSM VECTOR
CALL AEG: ADVANCE CSM TO tpc
SAVE CSM ORBITAL ELEMENTS BEFORE PLANE CHANGE MANEUVER
1/24

24

(1)

CALL APPLY: GIVEN $\Delta V_R'$, $\Delta V_H'$, $\Delta V_Z'$ COMPUTE CSM ORBITAL ELEMENTS AFTER MANEUVER

↓

CALL AEG: INITIALIZE CSM VECTOR AFTER MANEUVER

↓

SAVE QUANTITIES FOR DISPLAY

$$t_{m_i} = t_{pc}$$

$$\Delta V_{pc} = \sqrt{\Delta V_H'^2 + \Delta V_R'^2 + \Delta V_Z'^2}$$

$$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z'}{\Delta V_H'}\right]$$

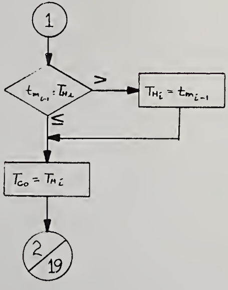
$$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R'}{\sqrt{\Delta V_H'^2 + \Delta V_Z'^2}}\right]$$

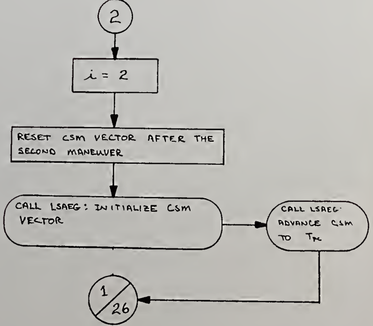
↓

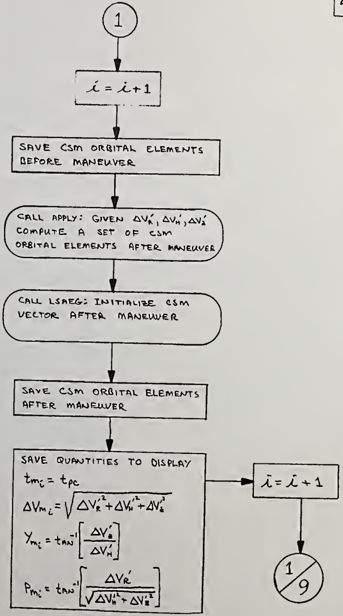
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER

↓

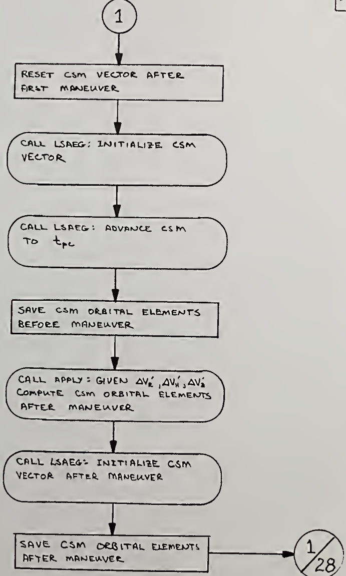
$i = i + 1$ → 1/25


1
$t_{m_{i-1}} : T_{H_i}$
>
$T_{H_i} = t_{m_{i-1}}$
≤
$T_{C0} = T_{H_i}$
2/19

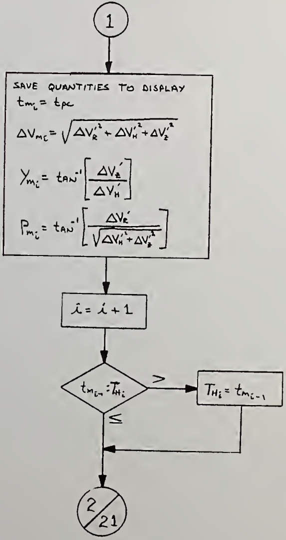

2
$i = 2$
RESET CSM VECTOR AFTER THE SECOND MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR
CALL LSAEG: ADVANCE CSM TO T_{PC}
1/26

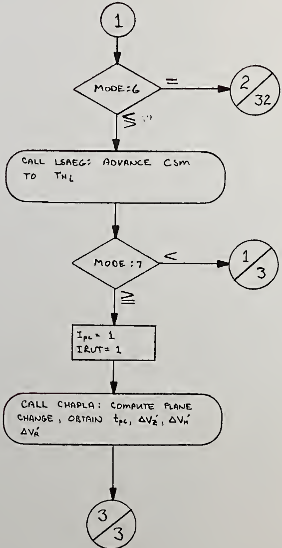

1
$i = i + 1$
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL APPLY: GIVEN $\Delta V_R'$, $\Delta V_H'$, $\Delta V_Z'$ COMPUTE A SET OF CSM ORBITAL ELEMENTS AFTER MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR AFTER MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
SAVE QUANTITIES TO DISPLAY
$t_{m_i} = t_{pc}$
$\Delta V_{m_i} = \sqrt{\Delta V_R'^2 + \Delta V_H'^2 + \Delta V_Z'^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z'}{\Delta V_H'}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R'}{\sqrt{\Delta V_H'^2 + \Delta V_Z'^2}}\right]$
$i = i + 1$
1/9

27

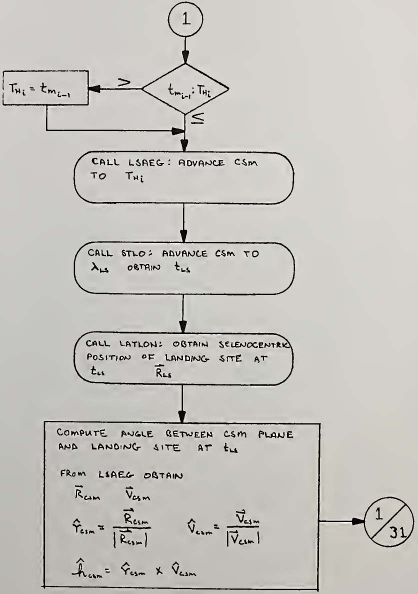

1
RESET CSM VECTOR AFTER FIRST MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR
CALL LSAEG: ADVANCE CSM TO t_{pc}
SAVE CSM ORBITAL ELEMENTS BEFORE MANEUVER
CALL APPLY: GIVEN $\Delta V_R'$, $\Delta V_H'$, $\Delta V_Z'$ COMPUTE CSM ORBITAL ELEMENTS AFTER MANEUVER
CALL LSAEG: INITIALIZE CSM VECTOR AFTER MANEUVER
SAVE CSM ORBITAL ELEMENTS AFTER MANEUVER
1/28

28

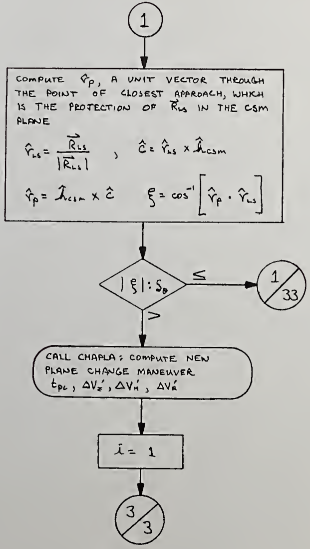

1
SAVE QUANTITIES TO DISPLAY
$t_{m_i} = t_{pc}$
$\Delta V_{mc} = \sqrt{\Delta V_R'^2 + \Delta V_H'^2 + \Delta V_Z'^2}$
$Y_{m_i} = \tan^{-1}\left[\frac{\Delta V_Z'}{\Delta V_H'}\right]$
$P_{m_i} = \tan^{-1}\left[\frac{\Delta V_R'}{\sqrt{\Delta V_H'^2 + \Delta V_Z'^2}}\right]$
$i = i + 1$
$t_{m_{i-1}} : T_{H_i}$
$>$
$T_{H_i} = t_{m_{i-1}}$
$\leq$
2/21


1
MODE:6
=
2
32
≤
CALL LSAEG: ADVANCE CSM TO THL
MODE:7
<
1
3
≧
Ipc= 1
IRUT= 1
CALL CHAPLA: COMPUTE PLANE CHANGE, OBTAIN tpc, ΔVz', ΔVH', ΔVR'
3
3

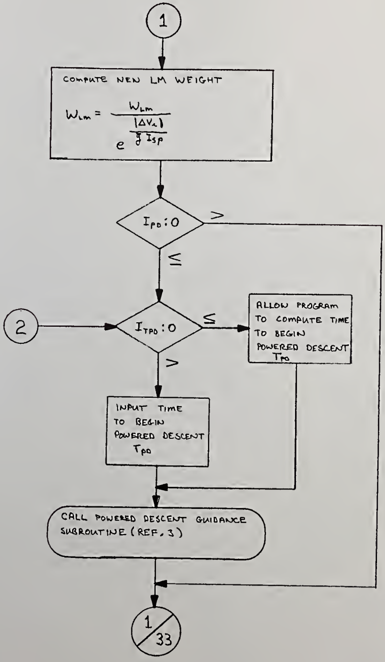
30


1
$t_{m_{i-1}} : T_{H_i}$
>
$T_{H_i} = t_{m_{i-1}}$
≤
CALL LSAEG: ADVANCE CSM TO T_{H_i}
CALL STLO: ADVANCE CSM TO λ_{LS} OBTAIN t_{LS}
CALL LATLON: OBTAIN SELENOCENTRIC POSITION OF LANDING SITE AT t_{LS} $\vec{R}_{LS}$
COMPUTE ANGLE BETWEEN CSM PLANE AND LANDING SITE AT t_{LS}
FROM LSAEG OBTAIN
$\vec{R}_{csm}$ $\vec{V}_{csm}$
$\hat{r}_{csm} = \frac{\vec{R}_{csm}}{|\vec{R}_{csm}|}$ $\hat{v}_{csm} = \frac{\vec{V}_{csm}}{|\vec{V}_{csm}|}$
$\hat{h}_{csm} = \hat{r}_{csm} \times \hat{v}_{csm}$
1/31

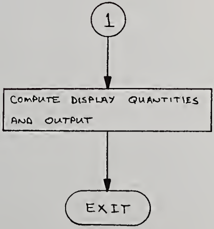
31


1
COMPUTE $\hat{r}_p$, A UNIT VECTOR THROUGH THE POINT OF CLOSEST APPROACH, WHICH IS THE PROJECTION OF $\vec{R}_{LS}$ IN THE CSM PLANE
$\hat{r}_{LS} = \frac{\vec{R}_{LS}}{|\vec{R}_{LS}|}$, $\hat{c} = \hat{r}_{LS} \times \hat{h}_{csm}$
$\hat{r}_p = \hat{h}_{csm} \times \hat{c}$ $\xi = \cos^{-1}\left[\hat{r}_p \cdot \hat{r}_{LS}\right]$
$|\xi| : S_\theta$
$\leq$
1/33
>
CALL CHAPLA; COMPUTE NEW PLANE CHANGE MANEUVER
t_{pc}, $\Delta V_z'$, $\Delta V_H'$, $\Delta V_R'$
$i = 1$
3/3

32


1
COMPUTE NEW LM WEIGHT
$W_{LM} = \frac{W_{LM}}{e^{\frac{|\Delta V_L|}{g\, I_{sp}}}}$
$I_{PD} : 0$
>
≤
2
$I_{TPD} : 0$
≤
ALLOW PROGRAM TO COMPUTE TIME TO BEGIN POWERED DESCENT T_{PD}
>
INPUT TIME TO BEGIN POWERED DESCENT T_{PD}
CALL POWERED DESCENT GUIDANCE SUBROUTINE (REF. 3)
1/33

33



APPENDIX B

SAC FLOW CHART

SYMBOLS FOR SAC FLOW CHART

Input Constants

π	3.141592...
μ	lunar gravitational potential
R_{moon}	mean lunar radius

Input Variables

L — vehicle number; if

- L = 1, the LM is maneuvering
- L = 2, the CSM is maneuvering

H_W — height wanted at an apsis, or circular altitude wanted

J — routine flag; if

- J = 0, compute maneuver to yield H_W at an apsis 180° away from maneuver
- J = 1, compute maneuver to circularize at input altitude

t — time of maneuver

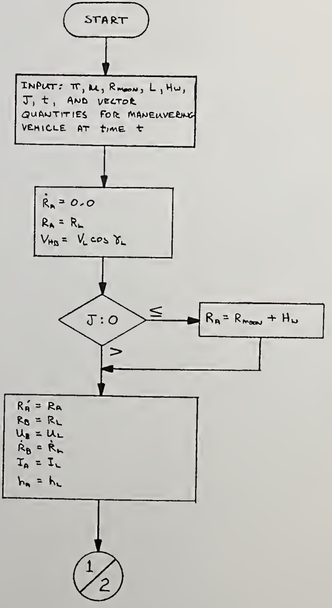
LSAEG — vector input for maneuvering vehicle at time t

Output Variables

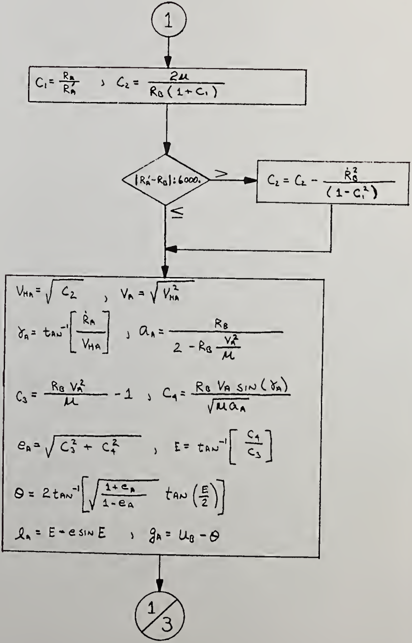
ΔV_H, ΔV_R, ΔV_Z — delta V costs in platform coordinate systems

1

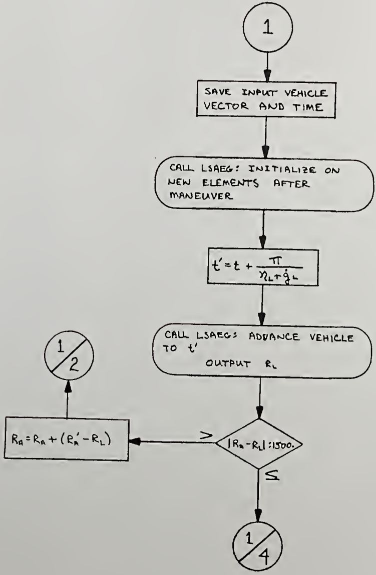
SAC FLOW CHART



2

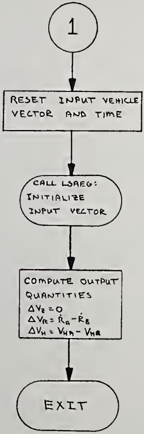

1
$C_1 = \frac{R_A}{R'_A}$, $C_2 = \frac{2\mu}{R_B(1 + C_1)}$
$|R'_A - R_B| : 6000.$
>
≤
$C_2 = C_2 - \frac{\dot{R}_B^2}{(1 - C_1^2)}$
$V_{HA} = \sqrt{C_2}$, $V_A = \sqrt{V_{HA}^2}$
$\gamma_A = \tan^{-1}\left[\frac{\dot{R}_A}{V_{HA}}\right]$, $a_A = \frac{R_B}{2 - R_B \frac{V_A^2}{\mu}}$
$C_3 = \frac{R_B V_A^2}{\mu} - 1$, $C_4 = \frac{R_B V_A \sin(\gamma_A)}{\sqrt{\mu a_A}}$
$e_A = \sqrt{C_3^2 + C_4^2}$, $E = \tan^{-1}\left[\frac{C_4}{C_3}\right]$
$\theta = 2\tan^{-1}\left[\sqrt{\frac{1 + e_A}{1 - e_A}} \tan\left(\frac{E}{2}\right)\right]$
$l_A = E - e \sin E$, $g_A = u_B - \theta$
1/3

3



1
SAVE INPUT VEHICLE VECTOR AND TIME
CALL LSAEG: INITIALIZE ON NEW ELEMENTS AFTER MANEUVER
$t' = t + \frac{\pi}{n_L + \dot{g}_L}$
CALL LSAEG: ADVANCE VEHICLE TO t'
OUTPUT R_L
$|R_A - R_L| : 1500.$
>
≤
$R_A = R_A + (R_A' - R_L)$
1/2
1/4

4


1
RESET INPUT VEHICLE VECTOR AND TIME
CALL LSAEG: INITIALIZE INPUT VECTOR
COMPUTE OUTPUT QUANTITIES
$\Delta V_Z = 0$
$\Delta V_R = \dot{R}_A - \dot{R}_B$
$\Delta V_H = V_{HA} - V_{HB}$
EXIT

APPENDIX C

CHAPLA FLOW CHART

SYMBOLS FOR CHAPLA FLOW CHART

Input Constants

π	3.141592...
ζ_t	iteration tolerance or time

Input Variables

L	vehicle number, if
	L = 1, LM is maneuvering
	L = 2, CSM is maneuvering
IWA	flag that determines azimuth; if
	IWA = 0, the azimuth is not specified
	IWA = 1, the azimuth is specified
I	number of maneuvers in sequence
I_{PC}	number of the plane-change maneuver
I_{GO}	input flag
	IGO = 0, compute plane change as if it were only maneuver being done
	IGO = 1, compute plane change as part of maneuver sequence
ψ_{nom}	descent azimuth desired
R_{LS}, ϕ_{LS}, λ_S	radius, latitude, and longitude of desired landing site
E_i, k, j	table of elements before and after all maneuvers in sequence
	i = number of maneuver
	k = before or after index (k = 1, elements before; k = 2, elements after)
	j = element counter
T_{M_i} (i = 1,I)	table of maneuver times

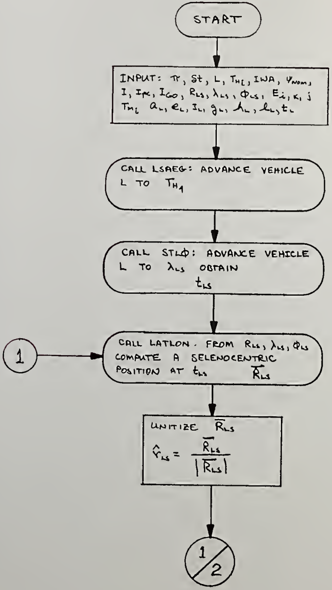
T_{H_i} (k = 1,I)	table of threshold times
a_L, e_L, I_L, g_L, h_L, ℓ_L, t_L	maneuvering vehicle state vector and time

Output Variables

ΔV_H, ΔV_R, ΔV_Z	maneuver delta V costs in platform coordinate system
t_m	maneuver time

CHAPLA FLOW CHART

1



(1)

FROM AEG OBTAIN

$\bar{R}_L = (X_L, Y_L, Z_L)$

$\bar{V}_L = (\dot{X}_L, \dot{Y}_L, \dot{Z}_L)$

UNITIZE $\bar{R}_L$ AND $\bar{V}_L$

$\hat{r}_L = \frac{\bar{R}_L}{|\bar{R}_L|}$, $\hat{v}_L = \frac{\bar{V}_L}{|\bar{V}_L|}$

COMPUTE ANGULAR MOMENTUM VECTOR

$\bar{H}_L = \hat{r}_L \times \hat{v}_L$, $\hat{h}_L = \frac{\bar{H}_L}{|\bar{H}_L|}$

COMPUTE $\hat{r}_p$, A UNIT VECTOR THROUGH THE POINT OF CLOSEST APPROACH, WHICH IS THE PROJECTION OF $\bar{R}_{LS}$ IN THE CSM PLANE

$Q = \hat{r}_{LS} \times \hat{h}_L$, $\hat{c} = \frac{\bar{Q}}{|\bar{Q}|}$

$\bar{R}_p = \hat{h}_L \times \hat{c}$, $\hat{r}_p = \frac{\bar{R}_p}{|\bar{R}_p|}$

(1/3)

1

COMPUTE ANGULAR DISTANCE VEHICLE IS AWAY FROM THE POINT OF CLOSEST APPROACH

θ

$$\theta = \cos^{-1}\left[\hat{r}_P \cdot \hat{r}_L \right]$$

TO DETERMINE THE SIGN ON θ,

$$\vec{H}_D = \hat{r}_L \times \hat{r}_P \quad , \quad \hat{h}_D = \frac{\vec{H}_D}{|\vec{H}_D|}$$

OBTAIN THE SIGN ON THE Z COMPONENT OF $\hat{h}_D$ AND $\hat{h}_L$

$$S_1 = \frac{h_{D_z}}{|h_{D_z}|} \qquad S_2 = \frac{h_{L_z}}{|h_{L_z}|}$$

SO THAT

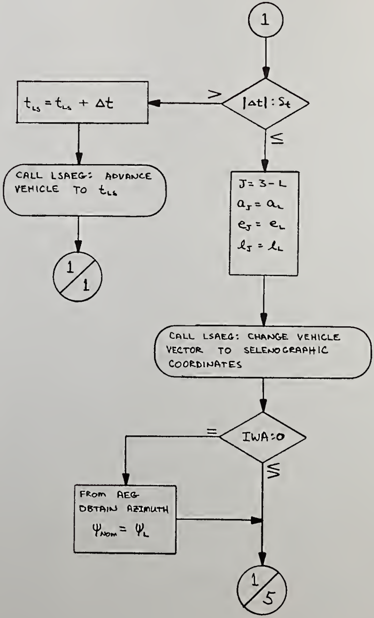
$$\theta = \theta \left[\frac{S_1}{S_2} \right]$$

NOW COMPUTE Δt

$$\Delta t = \frac{\theta}{n_L}$$

1/4

4


1
|Δt| : St
>
tLS = tLS + Δt
CALL LSAEG: ADVANCE VEHICLE TO tLS
1/1
≤
J = 3 − L
aJ = aL
eJ = eL
lJ = lL
CALL LSAEG: CHANGE VEHICLE VECTOR TO SELENOGRAPHIC COORDINATES
IWA:0
=
FROM AEG OBTAIN AZIMUTH
ΨNOM = ΨL
≤
1/5

5

1

COMPUTE INCLINATION, NODE, AND ARGUMENT OF PERIGEE FOR DUMMY ORBIT

$$I_J = \cos^{-1}\left(\sin \psi_{NOM} \cos \phi_{LS}\right)$$

$$u_W = \tan^{-1}\left[\frac{\sin \phi_{LS} \sin \psi_{NOM}}{-\cos I_J \cos \psi_{NOM}}\right]$$

MAKE $u_W > 0$

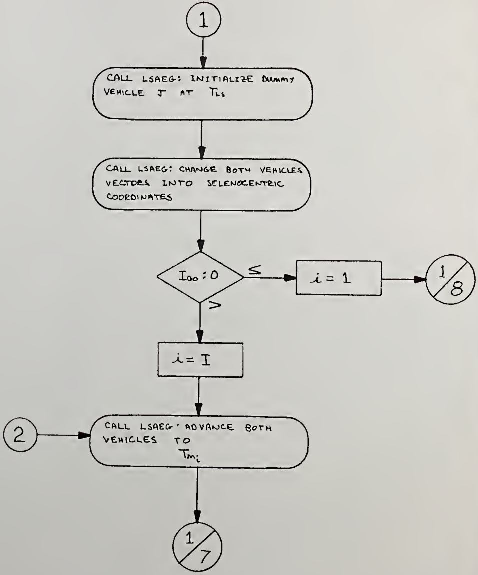
$u_W < 2\pi$

$$h_J = \lambda_{LS} - u_W + 2\tan^{-1}\left[\tan\frac{\phi_{LS}}{2}\left\{\frac{\sin\left(\frac{1}{2}\left(\psi_{NOM} - \frac{\pi}{2}\right)\right)}{\sin\left(\frac{1}{2}\left(\psi_{NOM} + \frac{\pi}{2}\right)\right)}\right\}\right]$$

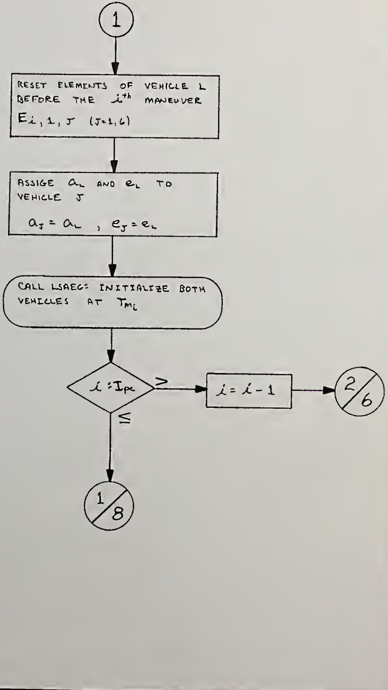
$$g_J = g_L - 2\tan^{-1}\left[\tan\left(\frac{h_J - h_L}{2}\right)\left\{\frac{\sin\left(\frac{1}{2}\left(\pi - I_J - I_L\right)\right)}{\sin\left(\frac{1}{2}\left(\pi - I_J + I_L\right)\right)}\right\}\right]$$

1/6

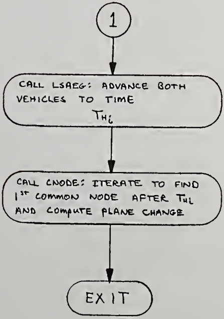
6


1
CALL LSAEG: INITIALIZE DUMMY VEHICLE J AT TLS
CALL LSAEG: CHANGE BOTH VEHICLES VECTORS INTO SELENOCENTRIC COORDINATES
IGO : 0
≤
i = 1
1/8
>
i = I
2
CALL LSAEG: ADVANCE BOTH VEHICLES TO Tmi
1/7

7


1
RESET ELEMENTS OF VEHICLE L BEFORE THE i^th MANEUVER
E i, 1, J (J=1,6)
ASSIGE a_L AND e_L TO VEHICLE J
a_J = a_L , e_J = e_L
CALL LSAEC: INITIALIZE BOTH VEHICLES AT T_mi
i : I_pe
>
≤
i = i - 1
2/6
1/8

8


1
CALL LSAEG: ADVANCE BOTH VEHICLES TO TIME
THi
CALL CNODE: ITERATE TO FIND 1ST COMMON NODE AFTER THL AND COMPUTE PLANE CHANGE
EXIT

APPENDIX D

LLTPR FLOW CHART

SYMBOLS FOR LLTPR FLOW CHART

Input Constants

π	3.141592...
μ	lunar gravitational potential
R_{moon}	mean lunar radius
$\delta\theta$	angular iteration tolerance

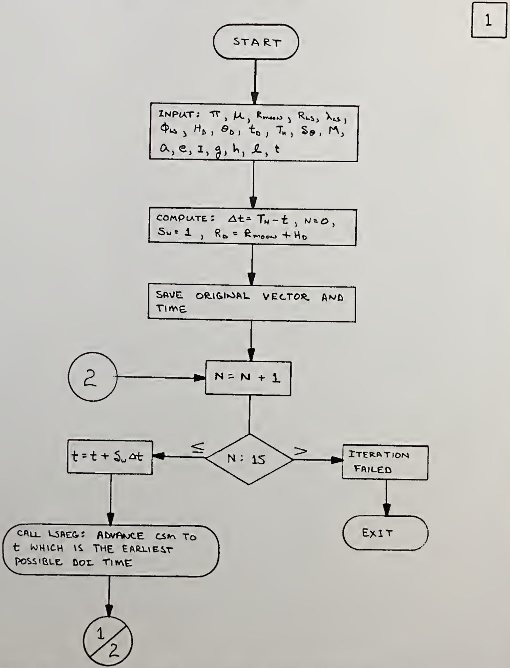
Input Variables

R_{LS}, λ_{LS}, ϕ_{LS}	position of desired landing site
H_D	height of descent ignition
θ_D	powered-flight arc of descent
t_D	powered-flight time of descent
T_H	threshold time for descent
a, e, I, g, h, ℓ, t	CSM state vector and time
M	number of dwell orbits desired between DOI and descent ignition

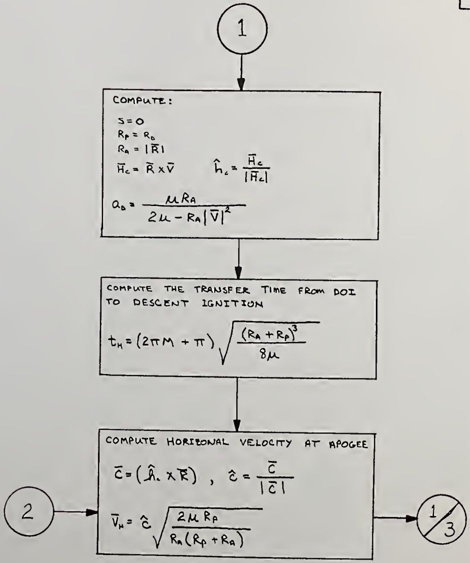
Output Variable

t_{DOI}	time of descent orbit injection

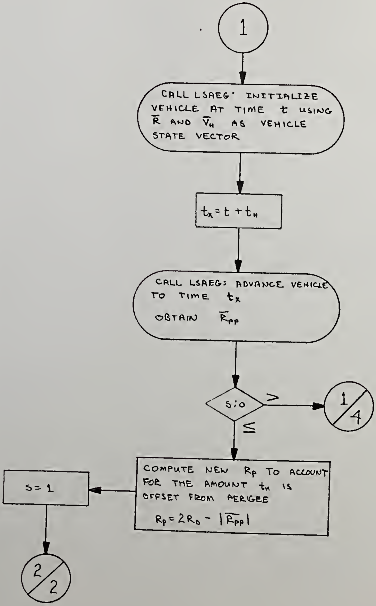
FLOW CHART OF LLTPR



2


1
COMPUTE:
$S = 0$
$R_P = R_D$
$R_A = |\bar{R}|$
$\bar{H}_c = \bar{R} \times \bar{V}$
$\hat{h}_c = \frac{\bar{H}_c}{|\bar{H}_c|}$
$a_D = \frac{\mu R_A}{2\mu - R_A |\bar{V}|^2}$
COMPUTE THE TRANSFER TIME FROM DOI TO DESCENT IGNITION
$t_H = (2\pi M + \pi)\sqrt{\frac{(R_A + R_P)^3}{8\mu}}$
COMPUTE HORIZONAL VELOCITY AT APOGEE
$\bar{C} = (\hat{h}_c \times \bar{R})$, $\hat{c} = \frac{\bar{C}}{|\bar{C}|}$
$\bar{V}_H = \hat{c}\sqrt{\frac{2\mu R_P}{R_A(R_P + R_A)}}$
2
1/3

3


1
CALL LSAEG' INITIALIZE VEHICLE AT TIME t USING R̄ AND V̄H AS VEHICLE STATE VECTOR
tx = t + tH
CALL LSAEG: ADVANCE VEHICLE TO TIME tx
OBTAIN R̄PP
S:0
>
1/4
≤
COMPUTE NEW RP TO ACCOUNT FOR THE AMOUNT tH IS OFFSET FROM PERIGEE
RP = 2R0 − |R̄PP|
S = 1
2/2

4

(1)

COMPUTE LM LANDING TIME

$$t_L = t + t_n + t_D$$

COMPUTE RADIUS OF LM AT LANDING POINT

$$\hat{r}_{pp} = \frac{\bar{R}_{pp}}{|\bar{R}_{pp}|} \qquad \hat{d} = \frac{\hat{h}_c \times \hat{r}_{pp}}{|\hat{h}_c \times \hat{r}_{pp}|}$$

$$\bar{D}_L = \cos\Theta_D \, \hat{r}_{pp} + \sin\Theta_D \, \hat{d}$$

↓

CONVERT R_{LS}, λ_{LS}, ϕ_{LS} TO A VECTOR $\bar{R}_{LS}$ AT TIME t_L

↓

PROJECT LANDING SITE VECTOR INTO CSM PLANE

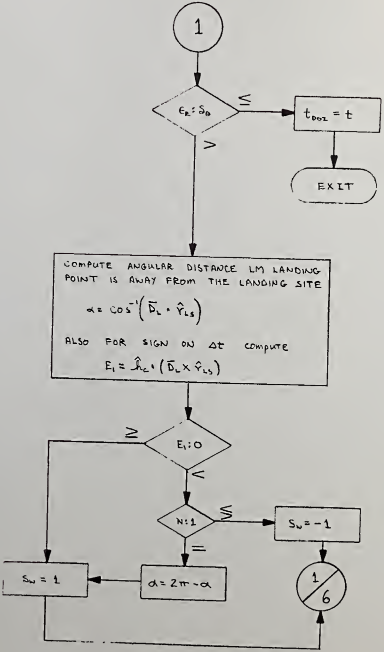
$$C = \hat{h}_c \cdot \bar{R}_{LS} \quad , \quad \bar{R}_{LS} = \bar{R}_{LS} - C\hat{h}_c$$

$$\hat{r}_{LS} = \frac{\bar{R}_{LS}}{|\bar{R}_{LS}|}$$

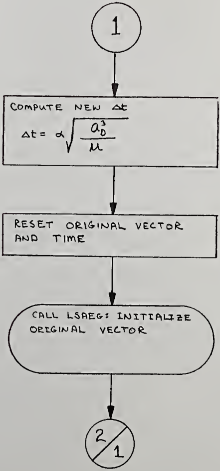
$$\epsilon_R = |\bar{D}_L - \hat{r}_{LS}|$$

↓

(1/5)



1
$E_R : S_\theta$
≤
>
$t_{DOZ} = t$
EXIT
COMPUTE ANGULAR DISTANCE LM LANDING POINT IS AWAY FROM THE LANDING SITE
$\alpha = \cos^{-1}(\bar{D}_L \cdot \hat{r}_{LS})$
ALSO FOR SIGN ON Δt COMPUTE
$E_1 = \hat{h}_c \cdot (\bar{D}_L \times \hat{r}_{LS})$
≥
$E_1 : 0$
<
N:1
≶
=
$S_w = -1$
$S_w = 1$
$\alpha = 2\pi - \alpha$
1/6


1
COMPUTE NEW Δt
$\Delta t = \alpha \sqrt{\frac{a_D^3}{\mu}}$
RESET ORIGINAL VECTOR AND TIME
CALL LSAEG: INITIALIZE ORIGINAL VECTOR
2/1

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