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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-17

ABORT-ONCE-AROUND ENTRY CORRIDOR ANALYSIS PROGRAM DOCUMENT

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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1.0 SUMMARY

This design note documents the Abort-Once-Around Entry Target Corridor Analysis Program (ABECAP). This program determines the allowable range of flight path angles at entry interface for acceptable entry trajectories from a Shuttle abort-once-around (AOA) situation. The solutions thus determined may be shown as corridor plots of entry interface flight path angle versus range from entry interface (EI) to the target.

2.0 INTRODUCTION

The Shuttle abort-once-around concept is based on a maneuver sequence after the abort decision which provides conditions at entry interface (400,000 feet altitude) as near as possible to those for nominal entry. For abort situations which occur early in the flight, use of maximum delta-V available for the AOA results in entry ranges of up to 6,000 miles from entry interface (EI) to the landing site. These extended ranges produce conditions during the entry phase which approach the vehicle structural and trajectory design limits. Among the vehicle constraints which must be considered are thermal protection system (TPS) surface and back-face temperatures. Trajectory considerations include maximum bank angle required to insure convergence to the reference drag-velocity profile, and minimum bank angle during the equilibrium glide phase to assure adequate crossrange capability. Based on these limiting parameters, an entry dispersion corridor can be defined depicting the allowable range-velocity-flight path angle (R-V-γ) conditions at entry interface. The manual determination of this type of corridor is described in Reference 1. A digital computer program to automate this corridor definition is described in this report.

3.0 DISCUSSION

The general method used in finding the shallowest allowable flight path angle is as follows: Position coordinates corresponding to entry ranges of interest are input. For a given entry interface position, a first guess flight path angle is used and the trajectory is integrated to TAEM interface. From this trajectory the maximum bank angle and surface control point temperatures are obtained and saved. The flight path angle is then incremented by a constant value and the trajectory again integrated from the same entry interface position. This second set of bank angle and temperature maximums is compared to the first to predict a subsequent flight path angle. A linear Reguli-Falsi scheme is used in the predictor using the previous two trajectory results. The predicted delta-gammas for each constraint are compared, and the constraint which is the most restrictive, i.e., that predicts the most negative flight path angle to produce the individual constraint limit, is used for the subsequent iteration. For example, if the gamma predicted for the limiting bank angle is -1.3°, and that predicted for the limiting temperature is -1.5°, then -1.5° is used as the next guess. This prediction method is continued until either the maximum bank angle or one surface temperature point is at the limit set and all others are less than their respective limits. This defines the shallowest flight path angle allowable for that range. This also provides an initial guess for the steepest allowable flight path angle at the same range.

In determining the steepest allowable gamma, the above method is repeated using limiting values for minimum equilibrium glide bank angle, and backface overtemperature for any two vehicle TPS panels. After both shallow and steep flight path angle solutions are found, the range is incremented by reading in the next position coordinate set.

The program is set up to determine either the shallow or steep gamma solution or both. Also, the corridor as determined by only one pair of constraints, such as minimum and maximum bank angles, may be found by setting the remaining constraint limits to specific values outside the normal range of consideration. The final outputs for each position include shallowest and steepest flight path angles, corresponding initial entry velocity, and resulting trajectory values for each parameter of interest.

The entry interface velocity corresponding to the given flight path angle under consideration is used by ABECAP. This data is input in tabular form giving EI velocity as a function of EI range and flight path angle. To date, this table was derived from data obtained by using the MLTBRN computer program discussed in Reference 2.

Several of the subroutines in this program are standard Space Vehicle Dynamic Simulation (SVDS) subroutines. Also, several are modified from the Entry Targeting Analysis Program (ETAP), which is described in Reference 3. Several subroutines, including SHALST and STEEP, were written for this program. These are the two routines which are used to predict the shallowest and steepest allowable flight path angles respectively. The program subroutines are described in detail in Section 6.

4.0 INPUT DESCRIPTION

The input data consists of data from the SVDS base data tape (described in Reference 4) for an entry run. Table 4.0-I identifies the required additional input variables, their symbols and units. These are also input using the standard SVDS input format.

Since the SVDS guidance routine (CONGID) is used to compute roll commands in the program, the associated eraseable memory load must be input for the trajectory under consideration. This is described in Reference 5.

TABLE 4.0-I

PROGRAM INPUTS

Variable	Definition	Units
HD	Initial altitude	feet
LATD	EI geodetic latitude	degrees
LONG	EI longitude	degrees
VI	EI inertial velocity	ft/sec
GAMI	EI inertial flight path angle	degrees
AZI	EI inertial azimuth	degrees
TLATD	Target geodetic latitude	degrees
TLONG	Target longitude	degrees
ALPHA	Angle of attack at EI	degrees
IETG	Flag = 1 for SVDS to call ETGX	non-dim.
BNKMAX	Desired maximum bank angle for trajectory	degrees
BNKLIN	Desired minimum bank angle for equilibrium glide	degrees
TCP1	Nose surface temperature limit	°F
TCP2	Body flap surface temperature limit	°F
TCP3	Wing leading edge surface temperature limit	°F
TCP4	Elevon surface temperature limit	°F
BFOTA	Backface overtemperature limit (panel IPANA)	°F
BFOTB	Backface overtemperature limit (panel IPANB)	°F
IPANA	Panel number to be checked for backface overtemperature (first panel)	non-dim.
IPANB	Panel number to be checked for backface overtemperature (second panel)	non-dim.
MAXCNT	Number of range points input	non-dim

5.0 OUTPUT DESCRIPTION

Output at the completion of each trajectory simulation is given in Table 5.0-I.

TABLE 5.0-I

PROGRAM OUTPUT

Maximum bank angle during trajectory	degrees
Minimum bank angle during trajectory	degrees
Temperatures for Control Points 1-4	°F
Total heat load	BTU/ft^2
Maximum heat rate	$BTU/ft^2/sec$
Backface overtemperatures (all panels)	°F
(After each flight path angle solution)	
Range from EI to target	n.m.
Steep or shallow solution	
Solution inertial flight path angle	degrees
Solution inertial velocity	ft/sec

6.0 SUBROUTINE DOCUMENTATION

The following sections describe program subroutines. Several subroutines are currently in SVDS and are not documented in this note. These were modified only as required to match common variables, and include the following subroutines:

ATMOS
AR140C
CONGID
GIDNAV
GIDOUT
GIDRTE
HTRATE
TPS

In addition, several subroutines are unchanged in form and serve the same function as in the ETAP program. These are documented in Reference 3, and are not duplicated in this note. These include the following:

ALTADJ
CONST
DELV
GEOD
NAVETG
SPHECI
TRAJ
TRANGE
TRMAT
UNITX
VISC

Those subroutines which are unique to ABECAP are described below.

6.1 Subroutine TERMIN

6.1.1 Purpose

Subroutine TERMIN is the SVDS routine which calls ETGX.

6.1.2 Input

IETG flag determining if ETGX is to be called

= 0 does not call ETGX

= 1 calls ETGX

6.1.3 Output

None applicable to ABECAP

6.1.4 Calling Sequence

Call TERMIN

6.1.5 Constants Required

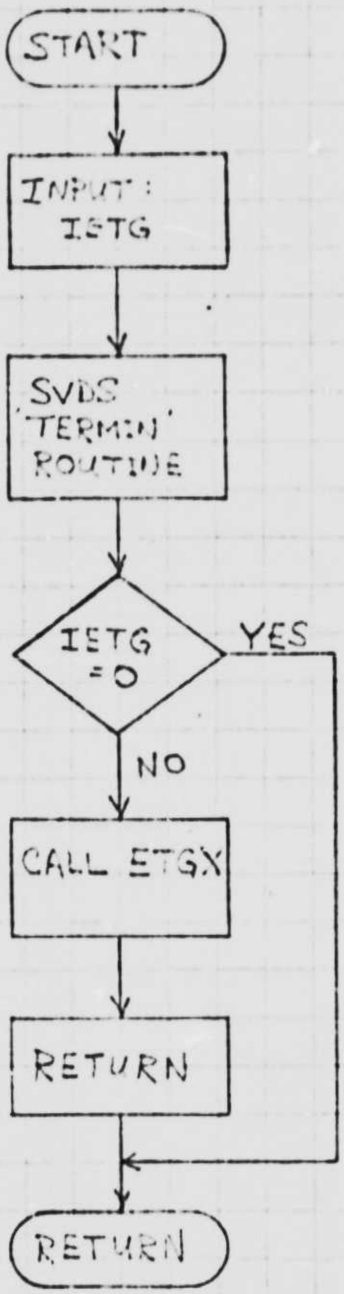
None

6.1.6 Subroutine Required

ETGX, other routines not applicable to ABECAP

6.1.7 Flowchart

(Only that portion of TERMIN applicable to ABECAP is documented in this design note.)



Subroutine TERMIN flowchart

6.2 ETGX

6.2.1 Purpose

ETGX is the routine used to initialize required parameters and adjust initial conditions for each range solution.

6.2.2 Input

STATE (I,1)	EI geodetic latitude for Ith range input	(deg)
STATE (I,2)	EI longitude	(deg)
STATE (I,3)	EI inertial azimuth	(deg)
STATE (I,4)	EI inertial velocity	(ft/sec)
STATE (I,5)	EI inertial flight path angle	(deg)
I	Range data set number	(non-dim)
MAXCNT	Number of ranges input	

6.2.3 Output

XR	Initial state vector	(ft)
RK2ROL	Roll direction indicator	(non-dim)
GAMI	Initial EI flight path angle	(deg)
ICONFL	Flag to indicate whether shallow or steep flight path angle to be determined	(non-dim)

6.2.4 Calling Sequence

Call ETGX

6.2.5 Constants Required

None

6.2.6 Subroutines Required

GEOD

SPHECI

CROSS

UNITX

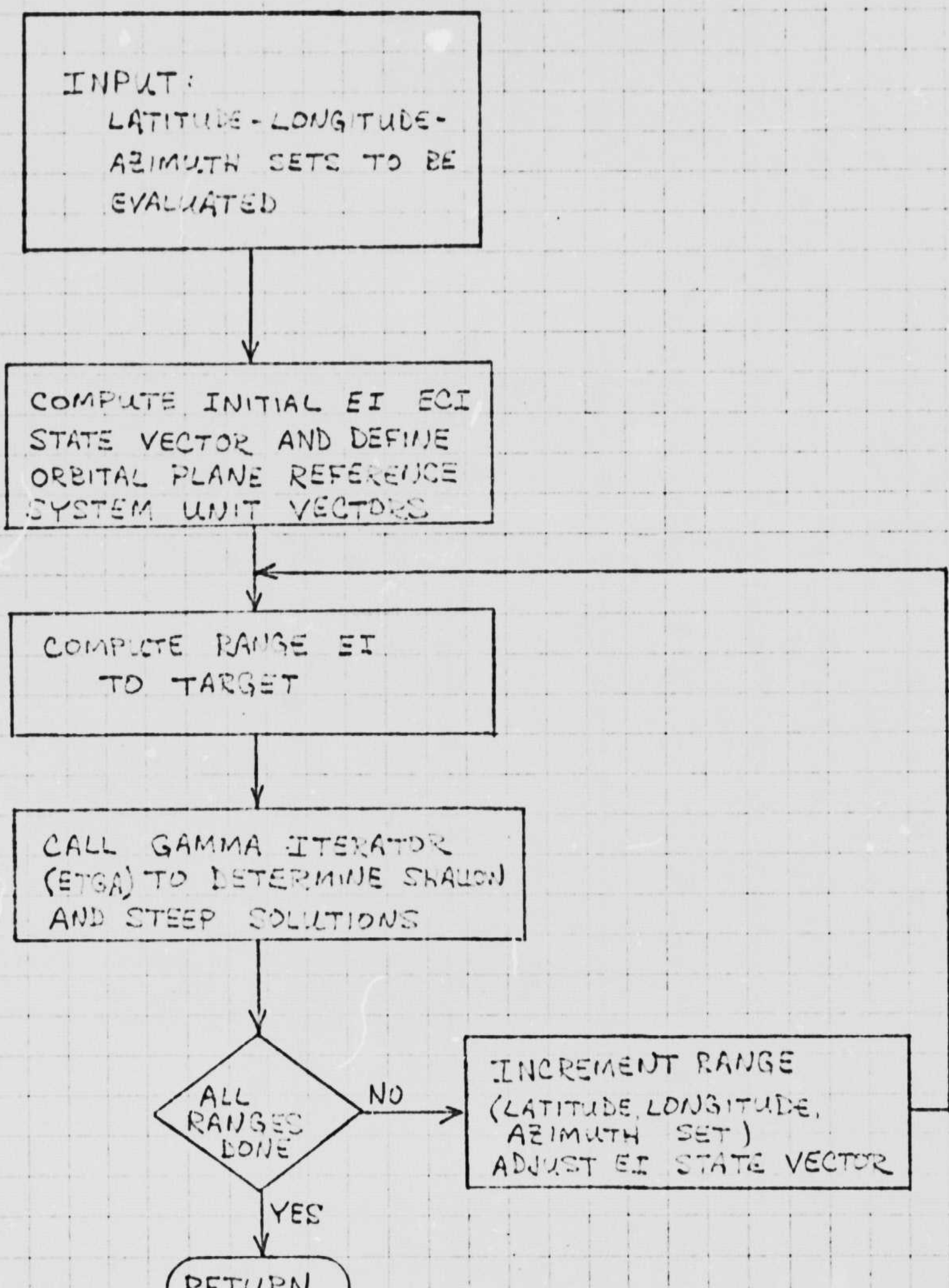
ALTADJ

ETGA

6.2.7 Flowchart

A functional flowchart for subroutine ETGX is shown below. This is essentially the same routine as is in the ETAP program. Detailed discussion of this subroutine is presented in Reference 3.

6.2.7 Flowchart: ETGX



Subroutine ETGX flowchart

6.3 ETGA

6.3.1 Purpose

Subroutine ETGA is the flight path angle iteration driver. It is modelled after the ETG subroutine in the ETAP (Reference 3).

6.3.2 Input

ROLANG	Initial bank angle	(rad)
T	Time from EI	(sec)
XR	Initial state vector	(ft)
RK2ROL	Roll direction indicator (±1)	(non-dim)
PHIDT	Target latitude	(rad)
LAMBT	Target longitude	(rad)
WT	Vehicle weight	(pounds)
ALP	Initial angle of attack	(deg)
GAMEI	Initial flight path angle	(deg)
ICONFL	Flag to indicate whether shallow (=1) or steep (=2) gamma being determined	(non-dim)
RT	Range to target	(n.mi.)

6.3.3 Output

GAMEI	Flight path angle shallow or steep solution	(deg)

6.3.4 Calling Sequence

CALL ETGA (XR, RK2ROL, PHIDT, LAMBT, WT, ALP, GAMEI)

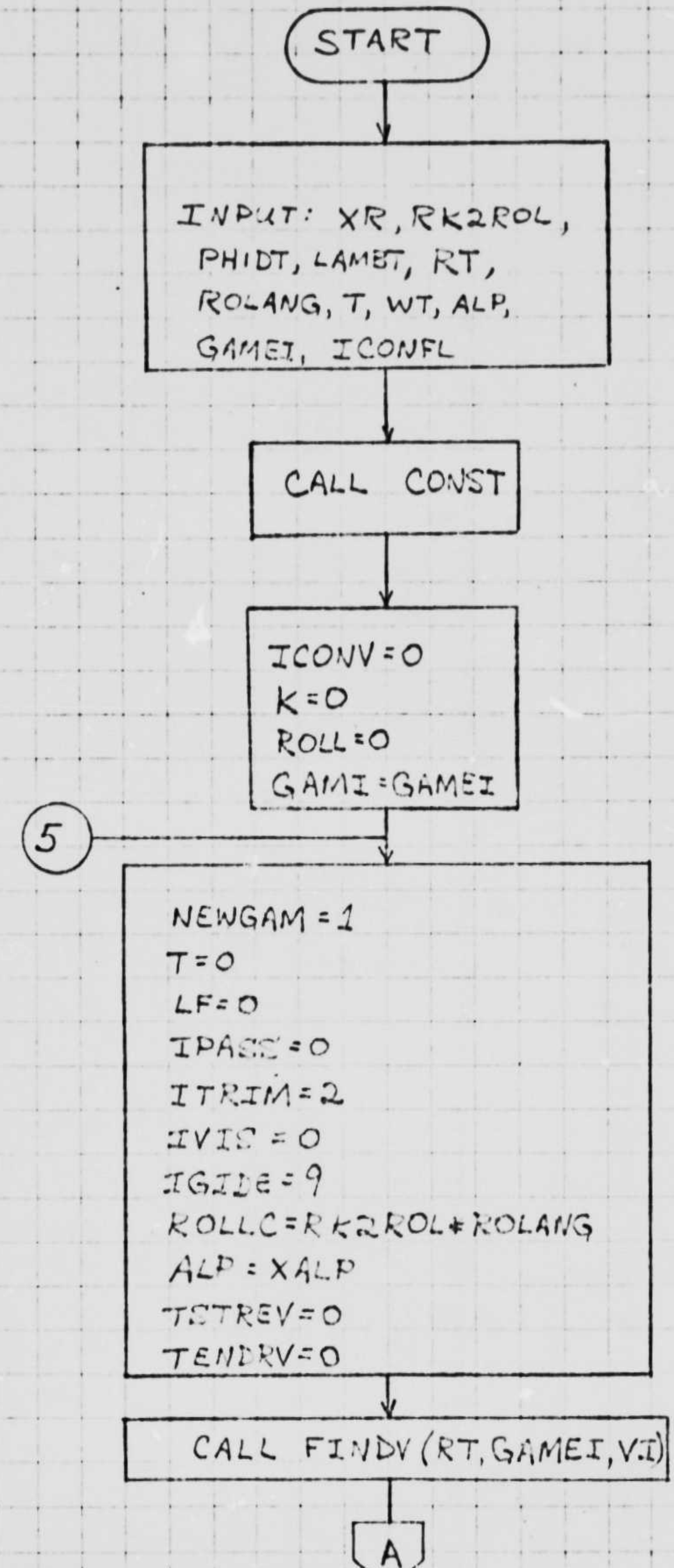
6.3.5 Constants Required

Obtained from subroutine CONST

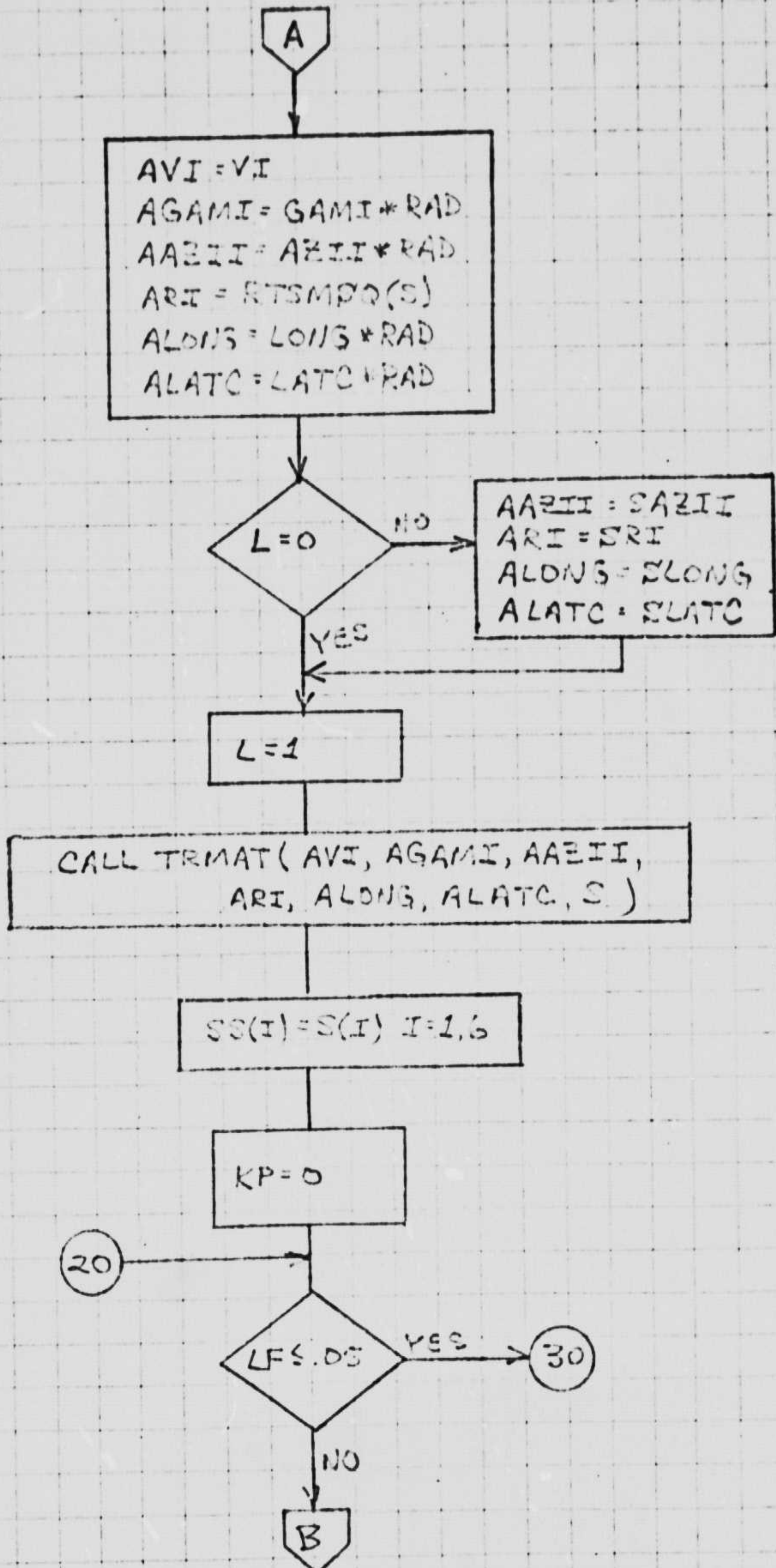
6.3.6 Subroutines Required

CONST
FINDV
TRMAT
RTSMSQ
CONGID
SHALST
STEEP
TRANGE
TRAJ
VISC
TPSDR
DELV
NAVETG
TRGGEN

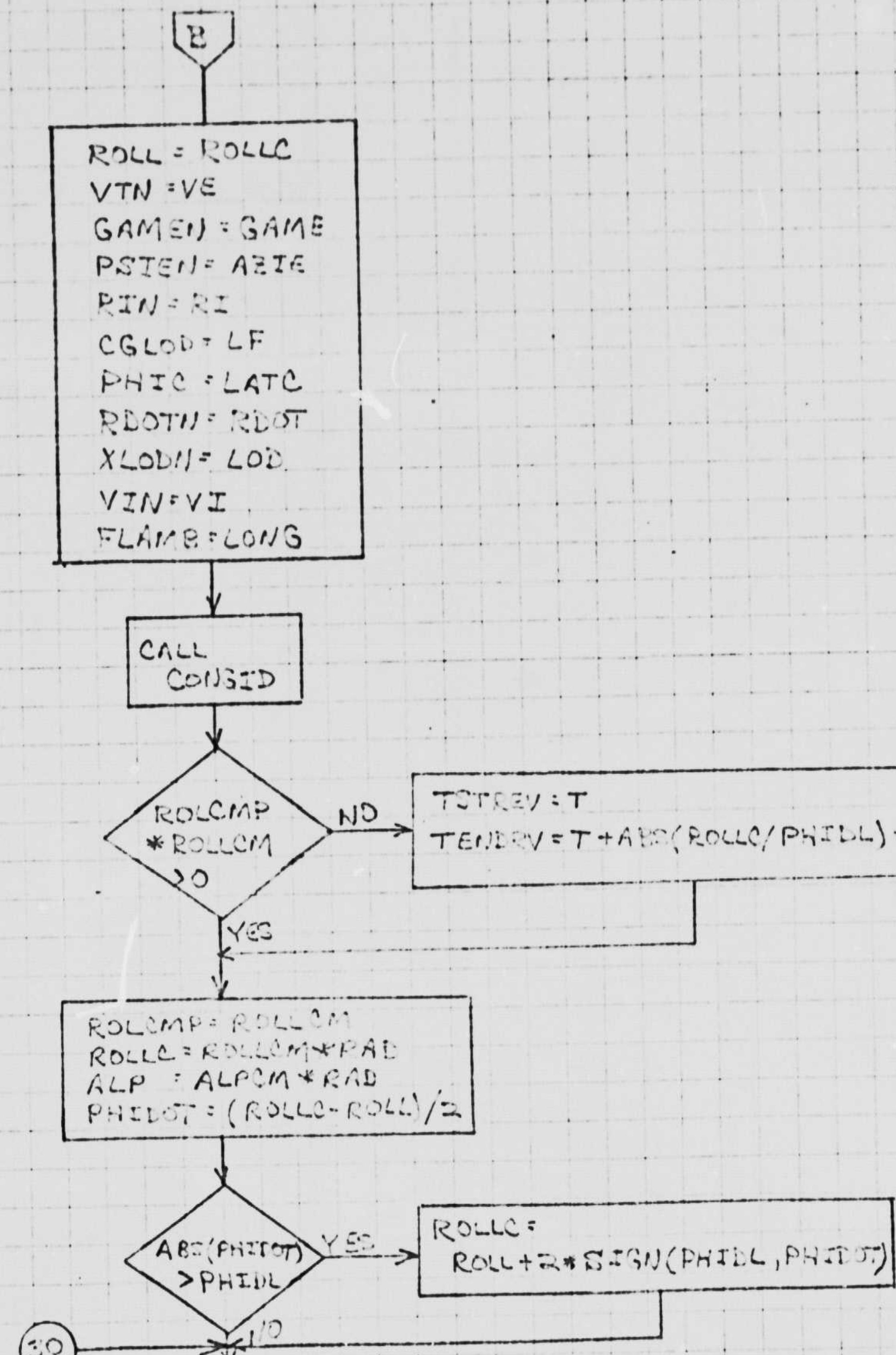
6.3.7 Flowchart



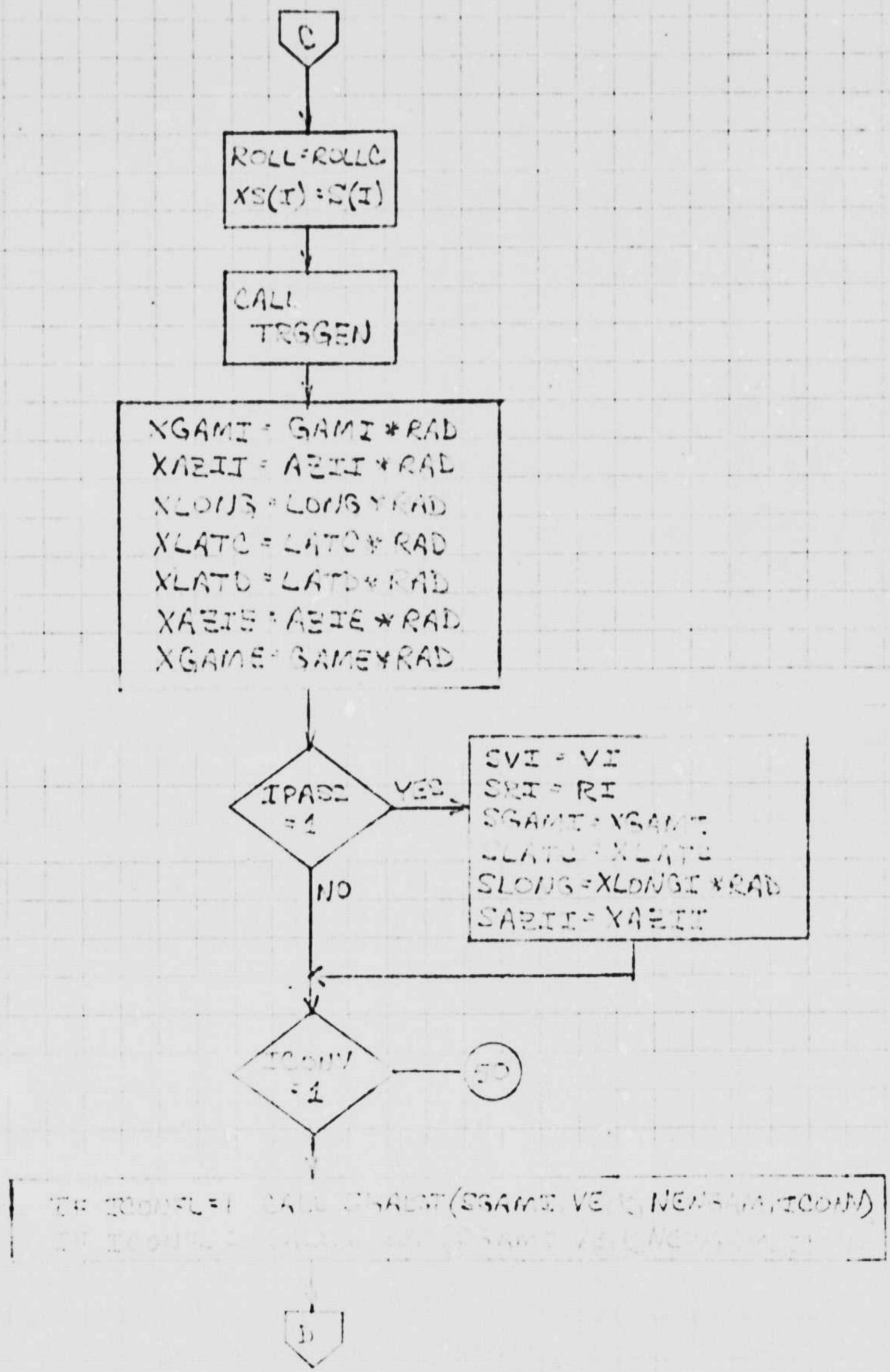
Subroutine ETGA flowchart



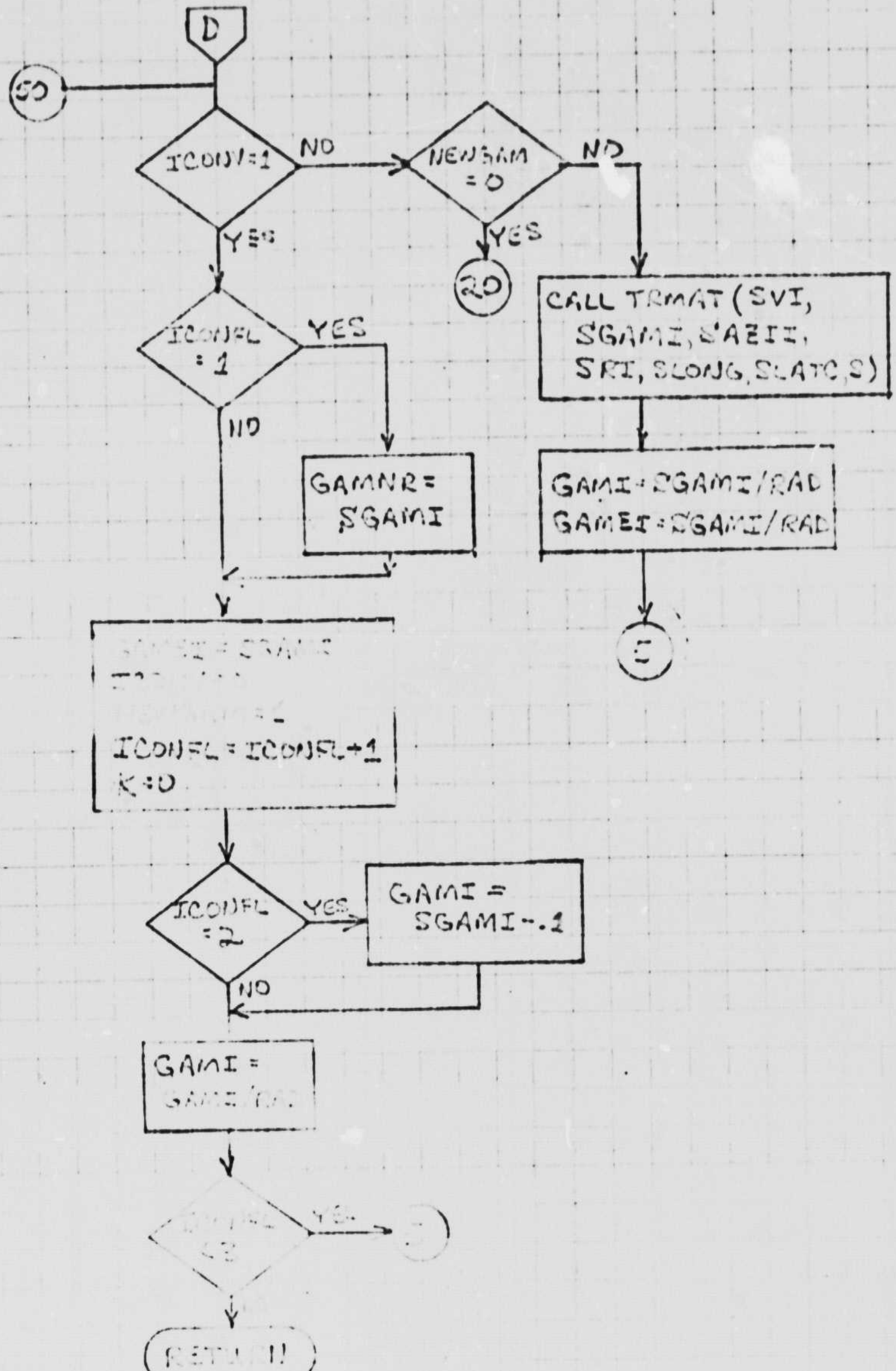
Subroutine ETGA flowchart



Subroutine ETGA flowchart



Subroutine ETGA flowchart



Subroutine ETGA flowchart concluded.

6.4 FINDV

6.4.1 Purpose

Subroutine FINDV is used to determine the velocity at entry interface corresponding to the EI range and flight path angle being used for a given trajectory.

6.4.2 Input

V(I,J) I=1,NG J=1,NR

I = 1,3,5 . . .	EI inertial velocity corresponding to range and flight path angle	(ft/sec)
I = 2,4,6 . . .	EI inertial flight path angle	(degrees)
INITRG	Initial range in table input	(n.mi.)
NG	Number of gamma-velocity points input times 2	(non-dim)
NR	Number of range points input in range, gamma → velocity table	(non-dim)
RT	Current EI range to target	(n.mi.)
GAMEI	Current EI flight path angle	(degrees)
DELR	Range increment in table	(n.mi.)

6.4.3 Output

VI	Entry interface inertial velocity	(ft/sec)

6.4.4 Calling Sequence

Call FINDV (RT, GAMEI, VI)

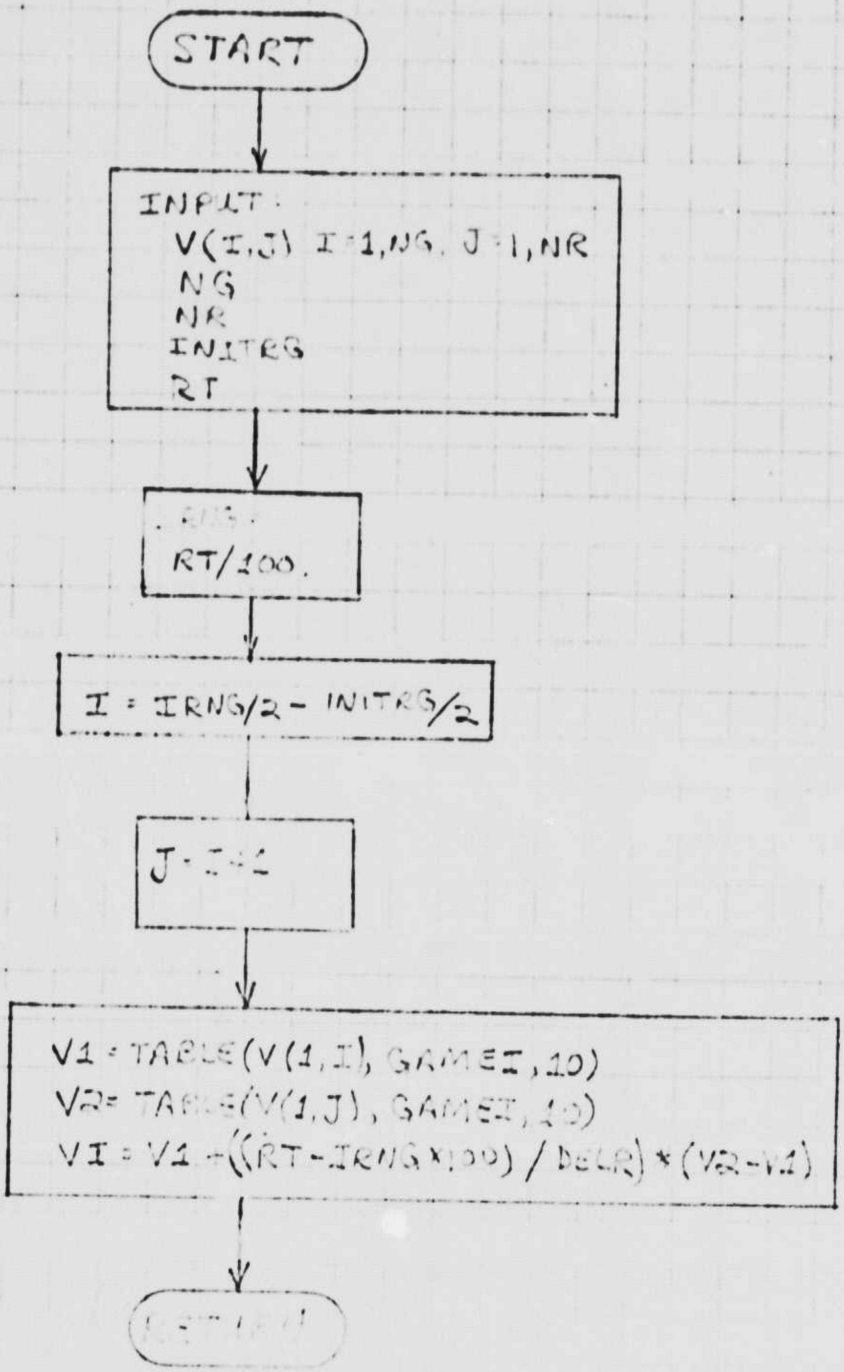
6.4.5 Constants Required

None

6.4.6 Subroutines Required

TABLE

6.4.7 Flowchart



Subroutine FINDV flowchart

6.5 TABLE

6.5.1 Purpose

The function TABLE is a table lookup routine designed for use in FINDV to determine entry interface velocity. TABLE uses a linear interpolation scheme.

6.5.2 Input

GAMEI	Entry interface flight path angle	(deg)
N	Number of gamma-velocities in input table for each range.	(non-dim)

6.5.3 Output

VI	Entry interface velocity	(ft/sec)

6.5.4 Calling Sequence

CALL TABLE (V, GAMEI, N)

6.5.5 Constants Required

None

6.5.6 Subroutines Required

None

6.5.7 Flowchart

This is a simple table lookup function with linear interpolation and is not flowcharted in this report.

6.6 TPSDR

6.6.1 Purpose

Subroutine TPSDR is the driver routine to determine the vehicle surface temperatures, heat rate, and backface overtemperatures.

6.6.2 Input

QC	Total heat load	(BTU/ft^2)
TARY(26-29)	Surface temperatures, control points 1-4	

6.6.3 Output

TMAX(1)	Maximum temperature, control point 1 (nose)	(°F)
TMAX(2)	Maximum temperature, control point 2 (body flap)	(°F)
TMAX(3)	Maximum temperature, control point 3 (wing leading edge)	(°F)
TMAX(4)	Maximum temperature, control point 4 (elevon)	(°F)
QCMAX	Maximum heat load	(BTU/ft^2)
QDTMAX	Maximum heat rate	(BTU/ft^2/sec)
TMABF	Individual panel backface over-temperatures	(°F)

6.6.4 Calling Sequence

CALL TPSDR

6.6.5 Constants Required

Reference heat rates and time in TPS (in SVDS).

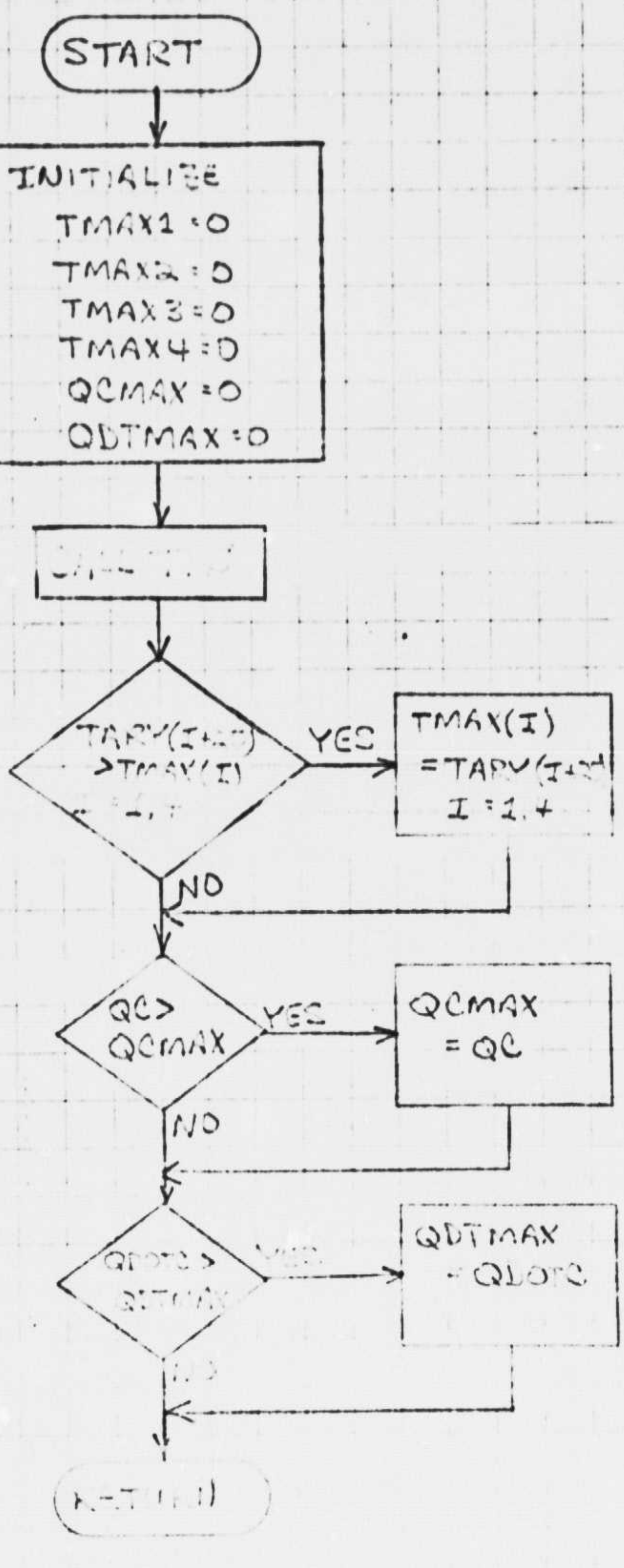
6.6.6 Subroutine Required

TPS

HTRATE

TI

6.6.7 Flowchart



Subroutine TPSDR flowchart

6.7 SHALST

6.7.1 Purpose

Subroutine SHALST is used to predict the shallowest gamma allowable at a given range, based on maximum bank angle and surface temperature constraints.

6.7.2 Input

SGAMI	Entry interface flight path angle	(deg)
VE	Relative velocity	(ft/sec)
K	Flag set (=1) to show that a workable flight path angle has been found for a given range. (=0 initial value set in ETG)	(non-dim)
T	Time from entry interface	(sec)
BNKLIM	Maximum bank angle desired during entry pullup	(deg)
TLIM(I), I=1,4	Maximum surface temperatures desired on control points 1-4	(°F)
LF	Current vehicle load factor	(g)
EPS	Flight path angle solution tolerance	(deg)
NEWGAM	Flag set (=1) to indicate that new flight path angle predicted	(non-dim)
BANK	Current bank angle	(deg)
TM(I), I=1,4	Maximum surface temperature in current trajectory CP (1-4)	(°F)

6.7.3 Output

SGAMI	Predicted flight path angle for subsequent trajectory iteration.
NEWGAM	Flag set =1 to show that new flight path angle has been determined and reset trajectory time to zero. = 0 otherwise.
ICONV	Flag set =1 if shallow gamma solution has been determined, otherwise = 0.

6.7.4 Calling Sequence

CALL SHALST (SGAMI, VE, K, NEWGAM, ICONV)

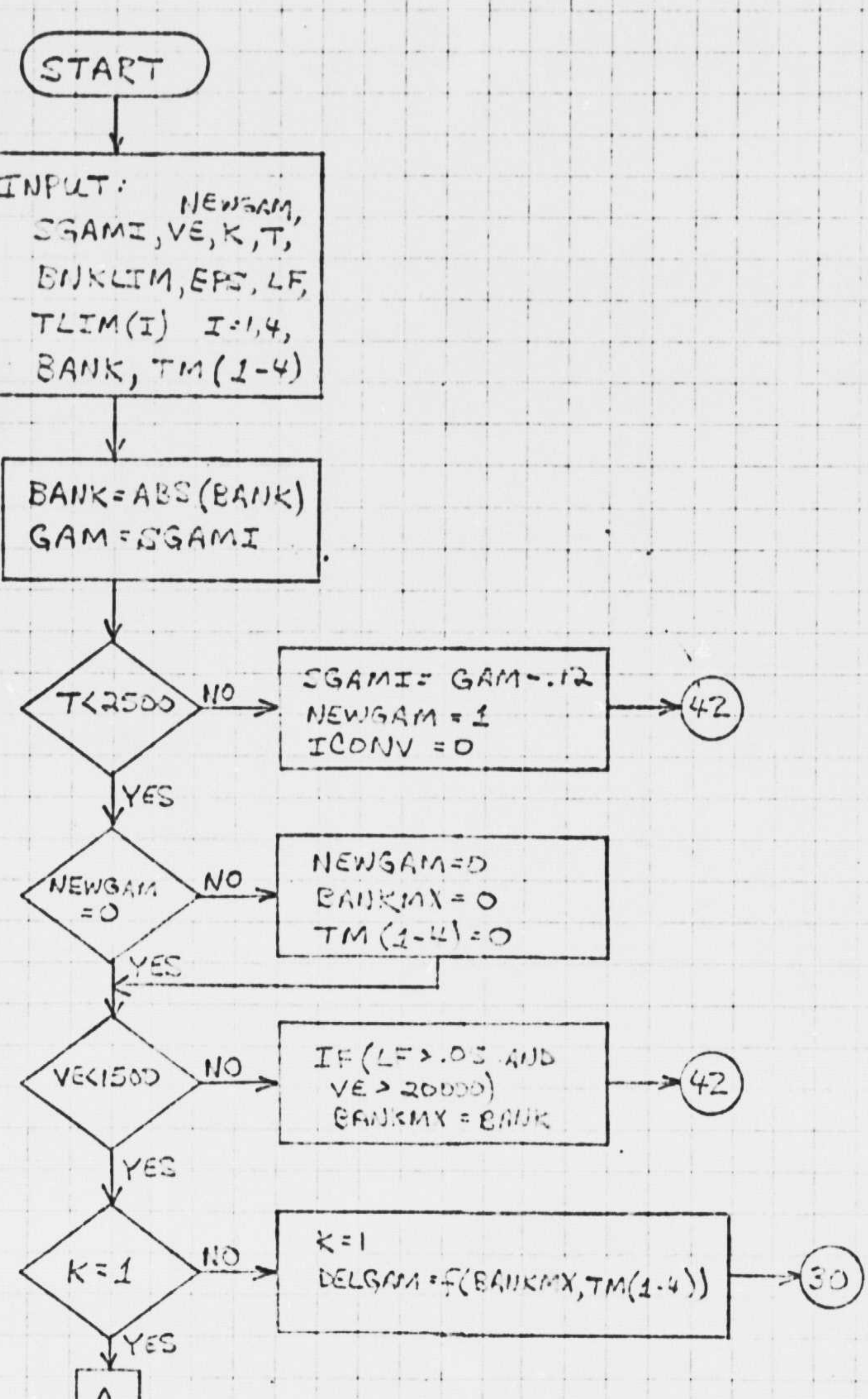
6.7.5 Constants Required

None

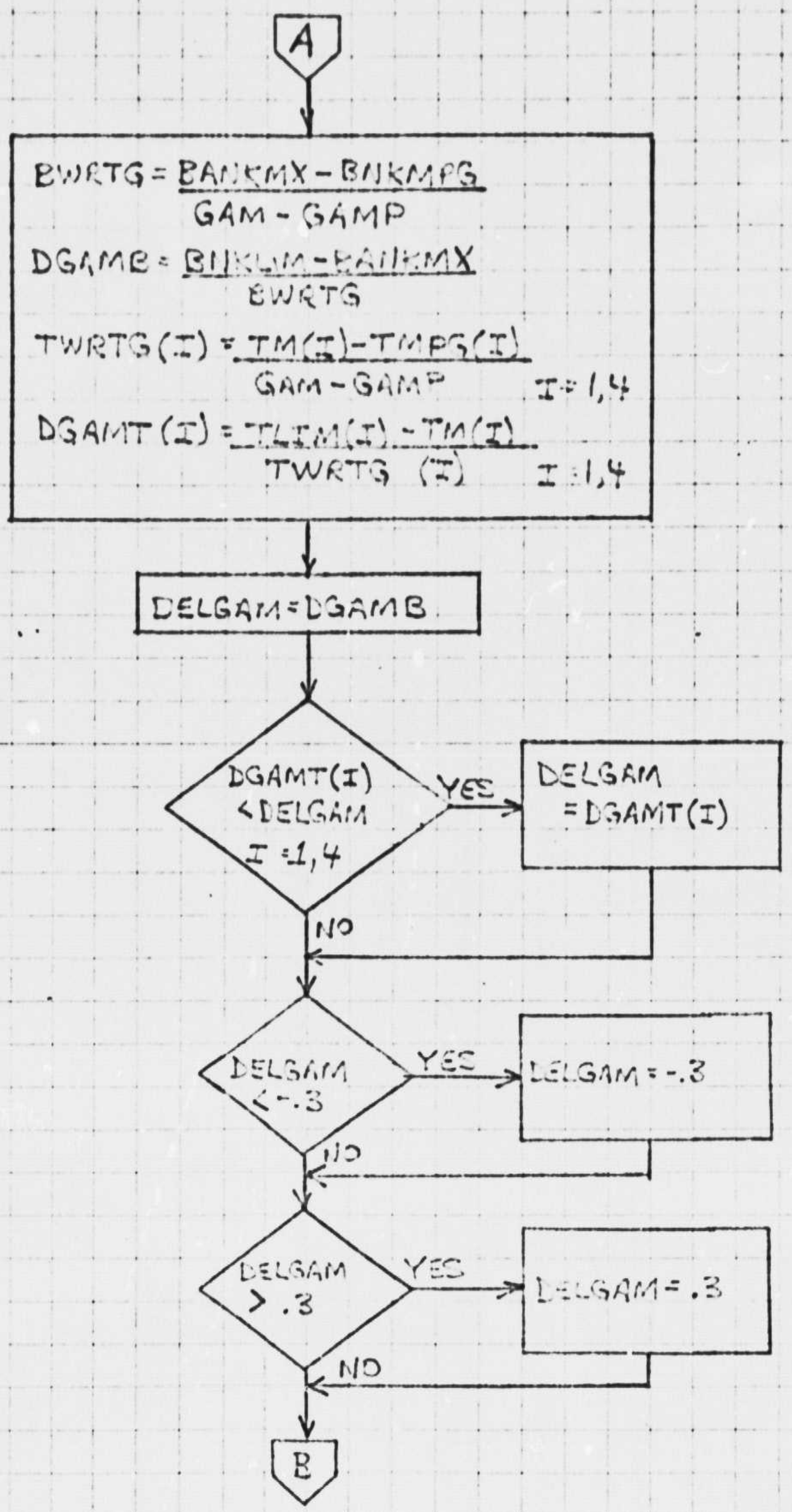
6.7.6 Subroutines Required

PROUT - print format subroutine

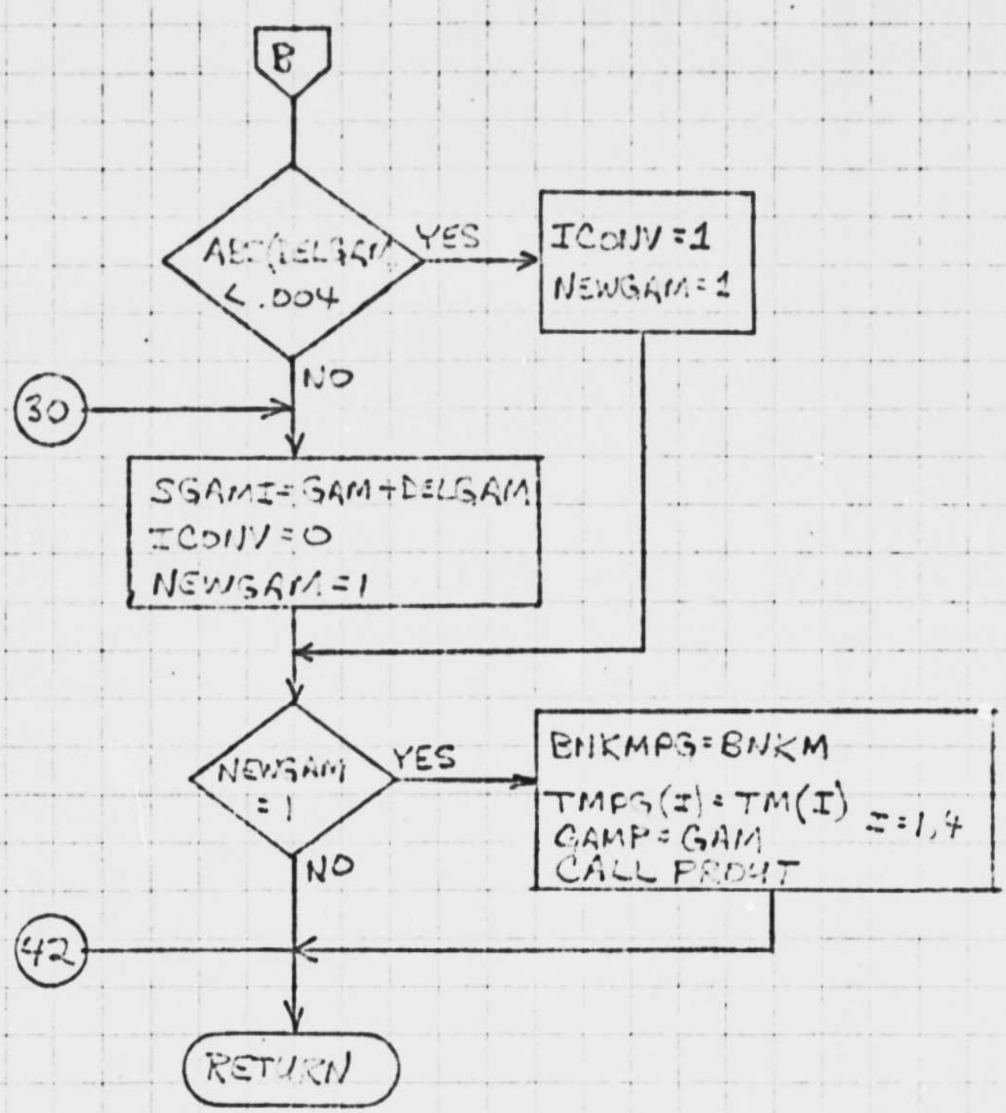
6.7.7 Flowchart



Subroutine SHALST flowchart



Subroutine SHALST flowchart



Subroutine SHALST flowchart concluded.

6.8 STEEP

6.8.1 Purpose

Subroutine STEEP is used to predict the steepest gamma allowable at a given range based on constraints of maximum TPS panel back-face overtemperature, and minimum bank angle during the equilibrium glide phase.

6.8.2 Input

SGAMI	Entry interface flight path angle	(deg)
VE	Relative velocity	(ft/sec)
K	Flag set =1 if a usable flight path angle has been found for subsequent iteration, = 0 initial value set in ETG	(non-dim)
T	Time from entry interface	(sec)
EPS	Flight path angle solution convergence tolerance	(deg)
LF	Load factor	(g's)
BANK	Current bank angle	(deg)
BNKLIN	Minimum bank angle desired during equilibrium glide	(deg)
IPANA	First panel number for which backface overtemperature is limited	(non-dim)
IPANB	Second panel number for which backface overtemperature is limited	(non-dim)
TMABF(I)	Backface overtemperature for each TPS panel	(°F)
BFLIMA	Backface overtemperature limit for panel (IPANA)	(°F)
BFLIMB	Backface overtemperature limit for panel (IPANB)	(°F)

6.8.3 Output

SGAMI	Predicted flight path angle for subsequent trajectory iteration	(deg)
NEWGAM	Flag set =1 to show that new flight path angle has been determined, and reset trajectory time to zero. = 0 if new FPA not determined	(non-dim)
ICONV	Flag set =1 if steep gamma solution is determined, else = 0	(non-dim)

6.8.4 Calling Sequence

CALL STEEP (SGAMI, VE, K, NEWGAM, ICONV)

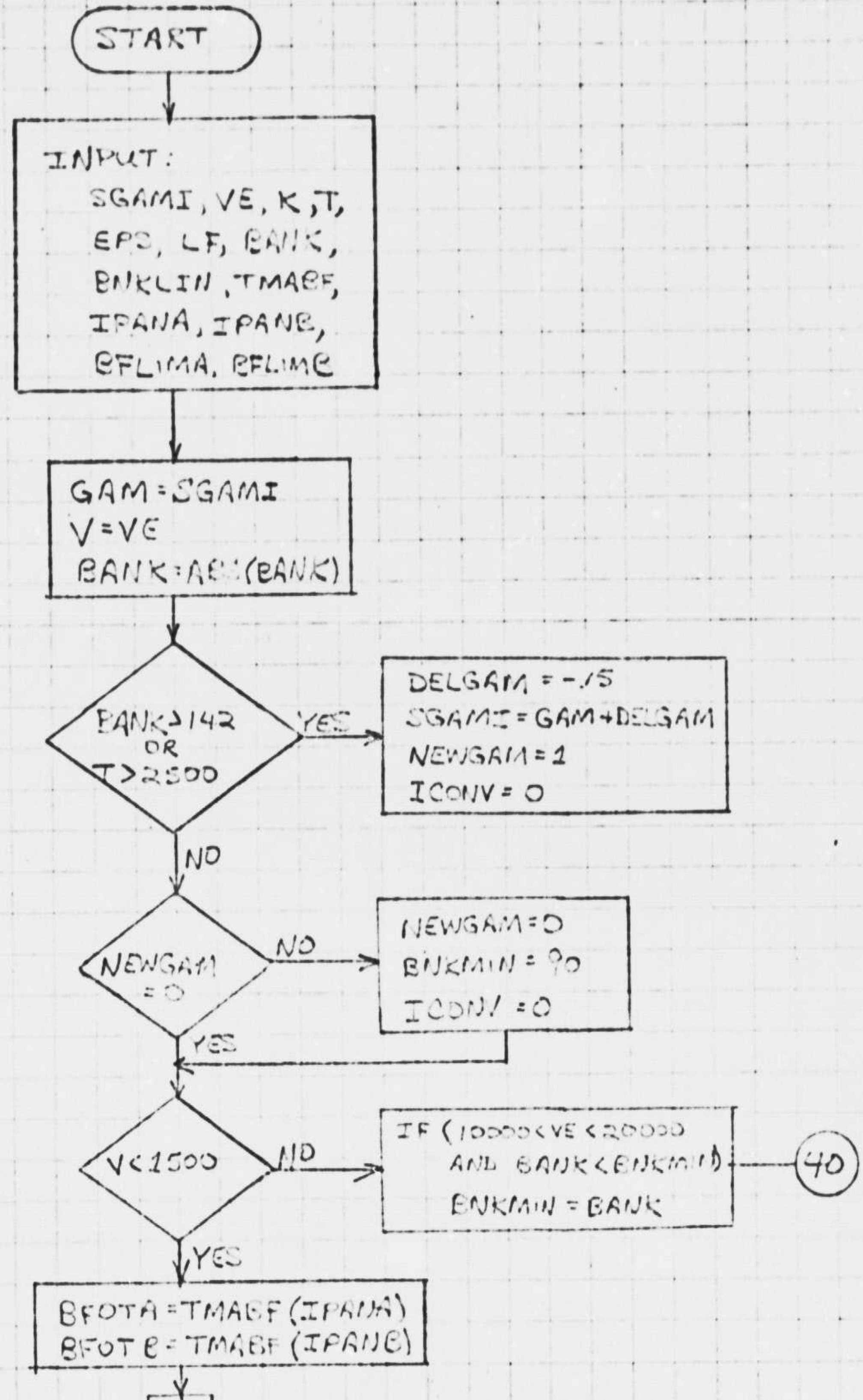
6.8.5 Constants Required

None

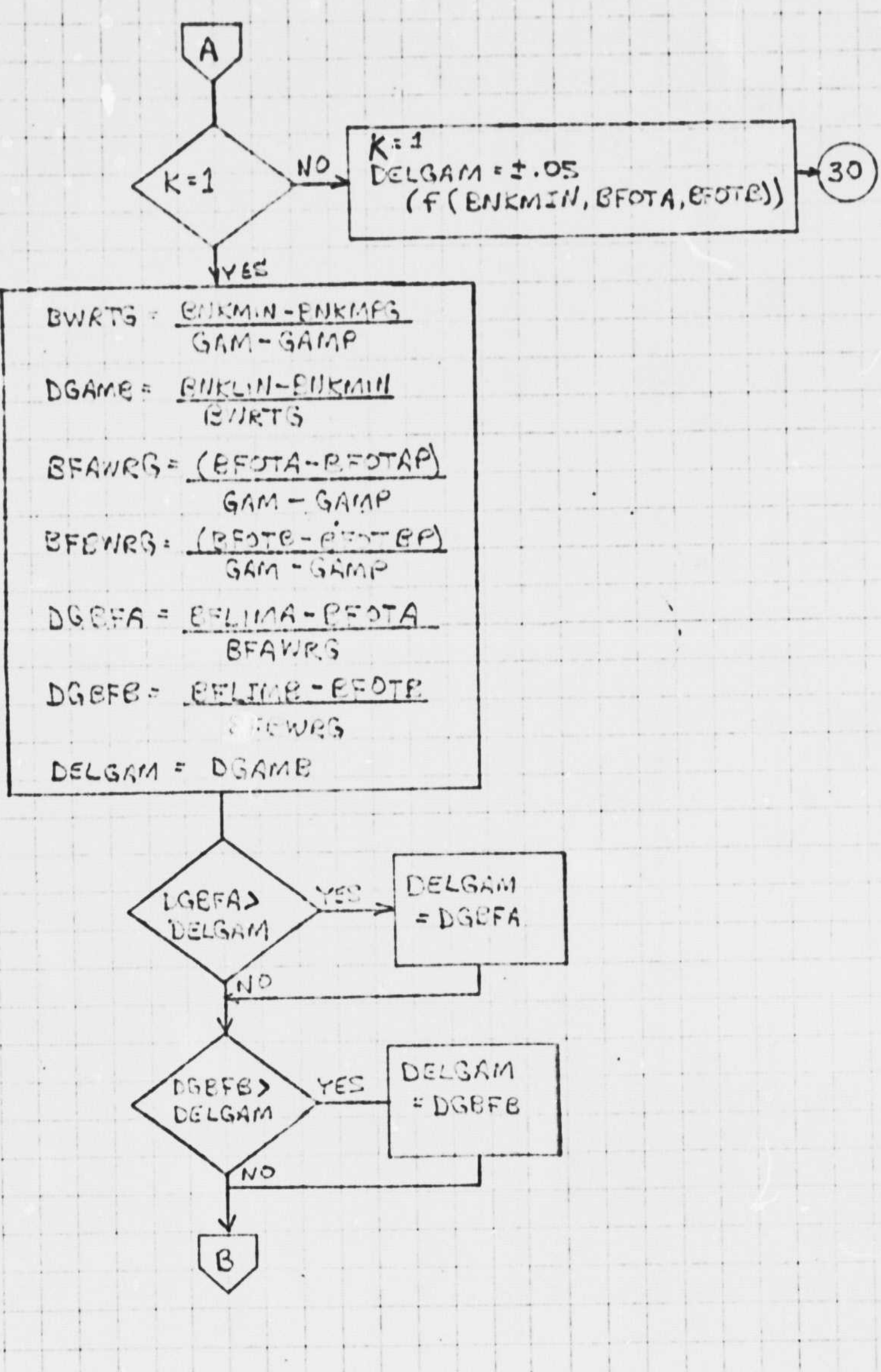
6.8.6 Subroutines Required

PROUT - print format subroutine

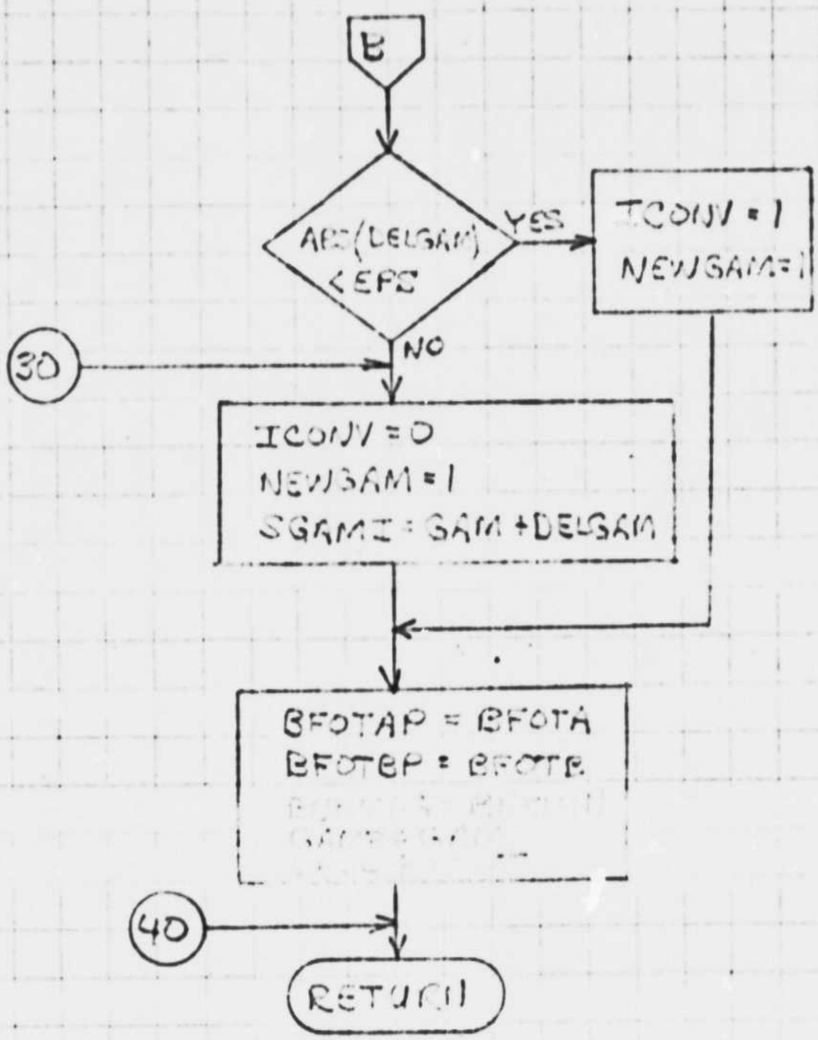
6.8.7 Flowchart



Subroutine STEEP flowchart



Subroutine STEEP flowchart



Subroutine STEEP flowchart concluded.

7.0 REFERENCES

1. Kyle, H. C. Jr.: "Abort-Once-Around Entry Dispersion Corridor Analysis." McDonnell Douglas Technical Services Company, Inc. Space Shuttle Engineering and Operations Support Design Note No. 1.4-4-12, 31 July 1975.

2. Hoch, H. R. and Hull, D. J.: "Documentation of MLTBRN (Multiple Burn) Program for AOA Targeting." McDonnell Douglas Technical Services Company, Inc. Space Shuttle Engineering and Operations Support Design Note No. 1.4-4-2, 30 August 1974.

3. Crull, T. J., Kyle, H. C. and Hiott, J. M.: "Entry Targeting Analysis Program Description." McDonnell Douglas Technical Services Company, Inc. Space Shuttle Engineering and Operations Support Design Note No. 1.4-4-4, 7 February 1975.

4. Software Development Branch, "Space Vehicle Dynamics Simulation (SVDS) Program Description Revision 2." Johnson Space Center Internal Note No. 73-FM-85, 22 December 1975.

5. Harpold, Jon C.: "Analytic Drag Control Entry Guidance System" Revision 1, Johnson Space Center Internal Note No. 74-FM-25, 21 January 1975.