RN-8

SPECIAL-PURPOSE INTERPLANETARY TRAJECTORY COMPUTATION PROGRAM FOR GUIDANCE AND NAVIGATION STUDIES

User's Manual

by

William T. McDonald

NASA Grant NsG 254-62

July 1965

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Aeronautics and Astronautics
Experimental Astronomy Laboratory
Cambridge, Massachusetts, 02139

RN-8

SPECIAL-PURPOSE INTERPLANETARY TRAJECTORY COMPUTATION PROGRAM FOR GUIDANCE AND NAVIGATION STUDIES

User's Manual

30986

ABSTRACT

This manual provides the necessary information for use and modification of the interplanetary trajectory computation program. It has been prepared as a supplement to Ref. (1), which gives a technical description of the program. This manual describes input and output data formats and contains detailed functional flow charts for the program. An example of a typical trajectory computation is given also.

William T. McDonald

July 1965

1. Introduction

This manual has been prepared as a supplementary document to Ref.(1). The reference is a technical description of the program, while this manual provides basic information necessary for use and modification of the program. Sections 2 and 3 describe the input and output data formats, respectively, and Section 4 contains detailed functional flow charts for the program.

Reference is made throughout this manual to a set of numbers which identify the Sun and planets in the program. They are listed below for convenient reference, and they also appear in each output data listing (see, example, Fig. 3-1):

Number	Body
1	Earth
2	Mars
3	Venus
4	Jupiter
5	Saturn
6	Sun

2. Description of Input Data Card Format and Use

Data input to the program is by means of punched cards. The total number of input data cards varies from 22 to 42, with allowance for from 0 to 20 cards specifying times of required data printouts. The data are punched according to FORTRAN standard word formats. Cols. 1 through 72 contain the data words. Cols. 73 through 80 are not used (except that Cols. 79 and 80 may conveniently be used for card numbering). The first data word of each card begins in Col. 1, and all data words are right-justified. The card formats and data words are described below. Refer to Fig. 2-1, which is a sample coding form for the input data.

SPACE TRAJECTCRY INTEGRATION I RCGRAM

Input Data Card Format

Form&Type (1)	Equation (7–72)				Comment	Identification (75–80)
TSTART DAY (I9)	TSTART HR (I9)	TSTART MIN (I9)	TSTART SEC F9.6	TEND DAY (I9)	TEND HR (I9) | TEND MIN (I9) | TEND SEC (F9.6	1
(I3) NSTART	USTART (1) (E15.8)	USTART (2) (E15.8)	USTART (3) (E15.8)			2
VSTART(1)	(E15.8)	VSTART (2) (E15.8)	VSTART (3) (E15.8)			3
VSTART(1)	(0.12)	VSTART (2) (0.12)	VSTART (3) (0.12)		Alternate #3 card -octal format	3
(I3) NEND	UEND (1) (E15.8)	UEND (2) (E15.8)	UEND (3) (E15.8)	TCL (E15.8)		4
(I3) NPRINT | (I3) MODE	(I3) NOSC | (I3) MAX | (I3) NCYCLE | (I3) EPHINV	(I5) LNCHMO	LNCHDY (I5) | LNCHYR (I5) | HMULT (F5.3)			5
DAY	(I9)	HR (I9)	MIN (I9)	SEC (F9.6)	Printout Time Cards (20 max, actual no. set by NPRINT on card #5) (Cne time point per card) (Time from TSTART)	6 – 25
EPOCH DAY (I9)	EPCCH HR (I9)	EPOCH MIN (I9)	EPCCH SEC F9.6		Epochs of planetary ephemerides	26 – 30
UPC(1, 1) ... UPO(1, 5)	(E15.8) " "	UPC(2, 1) ... UPO(2, 5) (E15.8) " "	UPC(3, 1) ... UPO(3, 5) (E15.8) " "		Planet position ephemerides (5 cards, 1 card per planet)	31 – 35
VPC(1, 1) ... VPO(1, 5)	(E15.8) " "	VPC(2, 1) ... VPC(2, 5) (E15.8) " "	VPC(3, 1) ... VPO(3, 5) (E15.8) " "		Planet velocity ephemerides (5 cards, 1 card per planet)	36 – 40
SMU(1)	(E15.8)	SMU(2) (E15.8)	SMU(3) (E15.8)		Planet gravitational constants	41
SMU(4)	(E15.8)	SMU(5) (E15.8)	SMU(6) (E15.8)			42

Fig. 2.1

Card No.	Description
1	Julian dates of start time (TSTART) and end time (TEND) of the trajectory. The difference of these two times is the duration of the trip. If the trajectory integration is forward in time, TSTART is the injection time and TEND is the arrival time. If the integration is backward in time, TSTART is the arrival time and TEND is the injection time. Julian date measured from an arbitrary epoch should be used, and it is convenient to use the last three or four digits of the whole Julian day number.

Day numbers larger than 131, 172 (2^{17}) cannot be read in the integer word format used, so whole number Julian data cannot be used.

Word Format

TSTART (DAY)	-	I9
TSTART (HR)	-	I9
TSTART (MIN)	-	I9
TSTART (SEC)	-	F9.6
TEND (DAY)	-	I9
TEND (HR)	-	I9
TEND (MIN)	-	I9
TEND (SEC)	-	F9.6

2	The number of the primary body from which the integration starts (NSTART) and the position vector (USTART) of the trajectory starting point. If the integration is forward, NSTART is the number of the primary body at injection and USTART is the position at injection. If the integration is backward, NSTART is the number of the target body and

Card No.	Description
(cont.) 2	USTART is the position at arrival. Position components are in starting body-centered coordinates (usually ecliptic of 1950.0) and units are kilometers. Components 1, 2, 3 correspond to x, y, z.
	NSTART may be either positive or negative. If it is positive, Card No. 3 (VSTART) will be read in decimal format. If NSTART is negative, Card No. 3 will read in octal format.

Format

NSTART	-	I3
USTART (1)	-	E15.8
USTART (2)	-	E15.8
USTART (3)	-	E15.8

Card No.	Description
3	Estimated velocity at the starting point (VSTART) required to cause the trajectory to ready the end point. VSTART will usually be simply an initial guess, and the program will search to find the correct starting velocity. The velocity components are in starting body-centered coordinates (usually ecliptic of 1950.0) and the units are km/sec. Components 1, 2, 3 correspond to x, y, z. If NSTART is positive, VSTART will be read by the program in decimal format; if NSTART is negative, VSTART will be read in octal format. There are thus two different formats for this card. The octal readin option is to allow precise duplication of initial conditions in separate runs.

Card No.		Description		
(cont.)	3	Format:	Decimal	Octal
		VSTART (1)	E15.8	012
		VSTART (2)	E15.8	012
		VSTART (3)	E15.8	012

4

The number of the primary body at which the trajectory integration ends (NEND), the position vector (UEND) of the trajectory endpoint, and the trajectory endpoint tolerance (TOL). If the trajectory integration is forward, NEND is the number of the target body and UEND is the position vector at arrival. If the trajectory integration is backward. NEND is the number of the primary body at injection and UEND is the position vector at injection. The position components are in end body-centered coordinates, and the units are km. Components 1, 2, 3 correspond to x, y, z.

The trajectory endpoint tolerance TOL is an amount (vector magnitude) by which the actual trajectory endpoint can differ from the specified UEND. The trajectory search terminates when the magnitude of the vector difference between the computed endpoint and UEND is less than TOL. Units are km.

Format:

NEND	-	I3
UEND (1)	-	E15.8
UEND (2)	-	E15.8
UEND (3)	-	E15.8
TOL	-	E15.8

Card No.	Description
(cont.) 5	Program control constants and the calendar date of launch.

Format and Function:

NPRINT - I3:
Specifies the number of time points along the trajectory at which special data printouts are required. The upper limit on NPRINT is 20; no more than 20 time points can be specified for any one run. $0 \leq NPRINT \leq 20$.

MODE - I3
Program operating mode, 1, 2, or 3.

NOSC - I3
Flag which causes the osculating conic routine (OSCON), to compute and print out osculating conic data at each printout point.
NOSC = 0 for no osculating conic data,
NOSC = 1 for osculating conic data.

MAX - I3
Maximum number of trajectory search iterations allowed. $MAX \geq 1$.

NCYCLE - I3
Flag which causes printout at all specified times and at the beginning, end, and phase change points during every cycle of the trajectory search. NCYCLE = 0: print out only during last cycle (after search convergence); NCYCLE = 1: print out every cycle during search.

KPHINV - I3
Flag which causes the product of the state transition matrix and its inverse to be

Card No.	Description
(cont.) 5	computed and printed out in all normal print-out records in which the state transition matrix is printed. KPHINV = 0: product is not computed and not printed; KPHINV = 1: product is computed and printed. LNCHMO - I5 Launch date - month. LNCHDY - I5 Launch date - day. LNCHYR - I5 Launch date - year. Calendar date of launch, month, day, and year only. HMULT - F5.3 Scaling factor for the time step computation. Value is usually about .100.
6 through 25	Time points along trajectory at which data printouts are required. The times are <u>always positive and measured from TSTART regardless of the direction of the integration</u> (forward from injection to target, or backward from target to injection). Each card specifies one time point in days, hours, minutes, and seconds from TSTART. A maximum of 20 time points are allowed; any number from 0 to 20 is permitted, the number of time points (cards) must correspond to NPRINT on Card No. 5. <u>Format</u> (each card) DAYS - I9 HRS - I9 MIN - I9 SEC - F9.6

Card No.	Description
26 through 30	Epochs (Julian dates) of the reference plant ephemerides in the following data cards 31 through 40. TSTART, TEND, and these epochs must all be measured from the same zero time reference. Crdinarily, the reference ephemerides are chosen as follows: Launch planet - on or near launch date Target planet - on or near arrival date Other planets - date abouve midway between launch and arrival dates. These choices provide the best approximation to actual planet ephemerides in all phases of the flight. Format: EPCCH DAY - I9 EPOCH HR - I9 EPCCH MIN - I9 EPOCH SEC - F9.6
31 through 40	Reference ephemerides of the 5 planets, Earth, Mars, Venus, Jupiter, and Saturn, in order (planet numbers 1 through 5, respectively, in the program). Corresponding to the 5 epochs in cards 26 through 30. Cards 31 through 35 contain components of the planet positions (3 x, y, x components per card, 1 card per planet). Cards 36 through 40 contain components of the planet velocities (3 x, y, z components per card, 1 card per planet). The ephemerides are in heliocentric coordinates (usually ecliptic of 1950.0) and units are a.u. and a.u. / day. These units are convenient

Card No.		Description
(cont.) 31 through 40		because they are used in the sources of the reference ephemerides; conversion to km and km/sec takes place in the program.
		Format:
	each position card	UPO(1, N) (x position component, planet N)-E15. UPO(2, N) (y position component, planet N)-E15. UPC(3, N) (z position component, planet N)-E15.
	each velocity card	VPO(1, N) (x velocity component, planet N)-E15. VPO(2, N) (y velocity component, planet N)-E15. VPO(3, N) (z velocity component, planet N)-E15.
41 and 42		Gravitational constants (mu = G x mass) of the 5 planets, Earth, Mars, Venus, Jupiter, and Saturn, and the Sun, in order. Units are km^3/sec^2. Suggested values have been computer using 1.49599×10^8 km per astronomical unit and the Sun/planet mass ratios given in Ref. (2):
		SMU (1) (Earth) 3.986032×10^5 km^3/sec^2 SMU (2) (Mars) $4,296455 \times 10^4$ SMU (3) (Venus) $3,2576185 \times 10^5$ SMU (4) (Jupiter) 1.2690142×10^8 SMU (5) (Saturn) 3.7957172×10^7 SMU (6) (Sun) 1.3291083×10^{11}
		The influence of any or all of the solar bodies may be deleted by setting the appropriate mu's to zero. For conic analysis, for example, 5 of the mu's are set to zero, and only the one for the primary body of conic problem is non-zero.
		Format:
		3 words per card, each word is E15.8.

3. Description of Output Data Formats

The program puts out printed data only, and this section describes the formats of the printed records. There are five basic types of printed records to be described:

1. A record of the input data as read from the input data cards.
2. An identification record.
3. The basic data record.
4. An end of cycle record.
5. Csculating conic data record.

The program operations and options which determine the sequence of these records are explained in Ref. (1). The subsections below describe these basic record types and indicate the modifications caused by different program modes and options.

In addition to the normal data records, the program prints special messages, most of which are intended to indicate an error condition in the computations. Most of these special messages are self-exaplanatory, but some of the more commonly appearing ones are illustrated in the last subsection.

3.1 Record of Input Data as Read From Input Data Cards

This record begins the printed listing for each execution of the program. The purpose is to list the input data cards in an unmodified format for convenient reference if the need arises. Fig. 3-1 shows a typical illustration of this record together with other records to be described below. The card identification is noted in the figure, and the formats may be compared directly with the card formats shown in Fig. 2-1.

3.2 Identification Record

Fig. 3-1 shows a typical identification record which appears with each execution of the program. The information in the record is self-explanatory. Only a few comments are necessary about interpretation of some quantities.

```
      EXECUTION
INPUT DATA FROM INPUT DATA CARDS

   5730        0         0 0.             585C        0         0 0.        1
 1 -.68000000E 04  .00000000E 00  .000CCCCOE CO                              2
.56849790E 00 -.13103690E 02  .10164334E 01                                  3
 3 -.10000000E 05  .10000000E 05  .CC000000E CO  .COCCC000E CO               4
 0  2  0 15  1  0    9    9 1965 .100                                        5
   5810        0         0 0.                                                26
   5810        0         0 0.                                                27
   5810        0         0 0.                                                28
   5810        0         0 0.                                                29
   5810        0         0 0.                                                30
.41773626E 00  .89647618E 00 -.31601531E-04                                  31
.78236605E 00 -.11587573E 01 -.43564776E-01                                  32
.62639174E 00  .36222346E 00 -.30946557E-01                                  33
.51008352E 00  .50845224E 01 -.31536461E-01                                  34
.93715779E 01 -.22863206E 01 -.33521876E C0                                  35
-.15915706E-01  .71204049E-02 -.21688101E-06                                 36
.11975715E-01  .92664052E-02 -.96584368E-04                                  37
-.10189571E-01  .17422294E-01  .83353691E-C3                                 38
-.76002648E-02  .10869224E-02  .16643811E-05                                 39
.10028476E-02  .54149091E-02 -.13293204E-03                                  40
.39860320E 06  .42977799E 05  .32476950E 06                                  41
.12671060E 09  .37902839E 08  .13271544E 12                                  42
```

INPUT DATA RECORD

DATA CARD NUMBERS — COMPARE WITH FIGURE 2-1.

NOTE THAT CARDS 6 THROUGH 25 ARE OPTIONAL.

NOTE THAT CARD 3 MAY APPEAR IN OCTAL FORMAT.

IDENTIFICATION RECORD

```
* * * * * * * * * * * * * * * * * * * * * INTERPLANETARY TRAJECTORY INTEGRATION * * * * * * * * * * * * * * * * * * * * *

LAUNCH PLANET NO. 1                                                          ** SUN-PLANET IDENTIFICATION TABLE **
TARGET PLANET NO. 3
LAUNCH DATE (JULIAN)      5730 D    0 HR    0 MIN  0.     SEC                    1          EARTH
        (CALENDAR)    9/ 9/1965                                                  2          MARS
ARRIVAL TIME (FROM LAUNCH)    120 D    0 HR    C MIN -0.    SEC                  3          VENUS
EPOCHS OF PLANET EPHEMERIDES                                                     4          JUPITER
      PLANET 1  5810 D   0 HR    0 MIN  0.    SEC    (JULIAN DATE)               5          SATURN
                  80 D   0 HR    0 MIN -0.    SEC    (FROM LAUNCH)               6          SUN
               2  5810 D   0 HR    0 MIN  0.    SEC
                  80 D   0 HR    0 MIN -0.    SEC
               3  5810 D   0 HR    0 MIN  0.    SEC
                  80 D   0 HR    0 MIN -0.    SEC
               4  5810 D   0 HR    0 MIN  0.    SEC
                  80 D   0 HR    0 MIN -0.    SEC
               5  5810 D   0 HR    0 MIN  0.    SEC
                  80 D   0 HR    0 MIN -0.    SEC
PROGRAM MODE  2
LAUNCH POSITION VECTOR (LAUNCH PLANET-CENTERED ECLIPTIC COORDINATES)
                        -.68000000E 04      .CCCCOCCOE 00      .00000000E 00
ARRIVAL POSITION VECTOR (TARGET PLANET-CENTERED ECLIPTIC COORDINATES)
                        -.1C000000E 05      .1CCC00COE 05      .C0000000E 00
IN THIS RUN THE INTEGRATION IS FORWARD ALONG THE TRAJECTORY.  STARTING PLANET IS THE LAUNCH PLANET.
INITIAL GUESS FOR STARTING VELOCITY (PLANET-CENTERED ECLIPTIC COORDINATES)
                         .55849790E 00     -.13103650E 02      .10164334E 01
TRAJECTORY TOLERANCE  .0000C000E 00 KM                MAXIMUM NUMBER OF TRAJECTORY SEARCH ITERATIONS ALLOWED 15
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

SPECIAL MESSAGE

```
ENCKE RECTIFICATION.  PRIMARY BODY NO. 1
ENCKE CONIC IS AN HYPERBOLA
TIME FROM START      0 D    0 HR    0 MIN -0.    SEC
```

FIGURE 3-1

1573

The body number identification table is shown for convenient reference. "Launch" and "target" designations generally refer to the primary bodies at the injection and arrival points on the trajectory. Thus the "launch planet", for example, might very well be the Sun if the program is used to determine the effect of a midcourse correction.

The time conversions done in the program suffer two types of errors. The first is the error in binary-to-decimal conversion of the numbers in the computer during the printing. The second error arises from the limited 8-decimal figure word length in the computer. Time quantities in which the number of significant digits exceed this limitation suffer round-off errors. Generally speaking, dates and durations exceeding 100 days should be rounded to the nearest whole second for both input and interpretation of output data. For smaller times, fractional seconds are handled accurately in the program to within the 8 decimal figure precision limitation.

Reference to ecliptic coordinates appears in the Identification Record because these are the coordinates most often used. In the event the equatorial or other coordinates are used, this reference will of course be in error.

3.3 Data Record

Fig. 3-2 shows the basic data for Mode 1 of the program. This record is modified for different time points in the trajectory integration and print options. The basic record shown is explained in the following paragraphs and the modifications are pointed out.

At key time points in the trajectory integration the record will have an identifying title at the top. The title and time point correspondences are listed below:

Starting point	*** TRAJECTORY STARTING POINT
Phase change point	
Before phase change	*** PHASE CHANGE POINT-DATA REFERENCED TO OLD PRIMARY BODY

FIGURE 3-2 - BASIC DATA RECORD

```
TIME FROM START  .13925365E 03 SEC (   0 D   0 HR   2 MIN 19.254 SEC)
PRIMARY BODY NUMBER  1
TRUE POS      .49883199E 04  .17770561E 04 -.41404317E 04    TRUE VEL    -.35970882E 01  .10380283E 02 -.27565638E 01
                                                             (OCTAL)      602714332614   204514126440   602540656126
ENCKE POS     .49883199E 04  .17770561E 04 -.41404318E 04    ENCKE VEL   -.35970882E 01  .10380283E 02 -.27565639E 01
DELTA POS     .43889377E-07  .98143099E-07  .46532705E-07    DELTA VEL    .37840394E-08  .83469652E-08  .39640116E-08
GRAV FORCE    .16774135E-09  .35557475E-09  .16967126E-09
G(PRIMARY) MATRIX
                                    .85582175E-06      .77240524E-06     -.17996569E-05
                                    .77240524E-06     -.10372091E-05     -.64111590E-06
                                   -.17996569E-05     -.64111590E-06      .18138734E-06
G(PERTURBATION) MATRIX
                                    .11912662E-13      .60924681E-13     -.63254680E-17
                                    .60924681E-13      .29106217E-13     -.72776254E-17
                                   -.63254680E-17     -.72776254E-17     -.41018878E-13
STATE TRANSITION MATRIX
      .26380694E 03    .29385728E 02   -.34907972E 03    .13978776E 03    .22746099E 00   -.86451766E 00
      .30287670E 02   -.24565935E 03   -.20660080E 02    .22791018E 00    .13868830E 03   -.17386288E 00
     -.34952384E 03   -.20069658E 02   -.86675365E 01   -.86473884E 00   -.17356883E 00    .13928973E 03
      .19308456E 01    .20677252E 00   -.25231501E 01    .10105116E 01    .58293305E-02   -.18314472E-01
      .23217492E 00   -.17567560E 01   -.15754386E 00    .58482935E-02    .98848608E 00   -.46000486E-02
     -.25356583E 01   -.14091518E 00   -.38790627E-01   -.18323809E-01   -.45876350E-02    .10011728E 01
PRODUCT OF STATE TRANSITION MATRIX AND ITS INVERSE
      .10075680E 01    .41695908E-02   -.53620231E-02    .45013428E-03   -.44440532E 00    .21821308E 00
     -.32792687E-02    .10025238E 01    .21461404E-02    .44459772E 00   -.75256824E-03   -.29098029E 00
     -.16860962E-02   -.27296543E-02    .10049741E 01   -.21972656E 00    .29086304E 00   -.15258789E-04
     -.13038516E-07    .30441006E-04   -.14992911E-04    .10075755E 01   -.32787360E-02   -.16969051E-02
     -.30444935E-04    .23450411E-07    .19927353E-04    .41708648E-02    .10025195E 01   -.27302583E-02
      .15079975E-04   -.19922853E-04    .00000000E 00   -.53710938E-02    .21455288E-02    .10049741E 01
RMS MATRIX
      .26555326E-02    .95600929E-04   -.10771466E-04    .86309219E-08   -.75610703E-04    .31656728E-05
     -.78129304E-04    .29144114E-02    .75329013E-04    .75643438E-04   -.15619162E-07   -.72659551E-04
     -.33839352E-05   -.92046327E-04    .81965049E-01   -.31876293E-05    .72630271E-04   -.86693867E-08
     -.47239190E-08    .97641665E-04   -.41666389E-05    .26555524E-02   -.78116612E-04   -.34056283E-05
     -.97654267E-04    .95488987E-08    .94375928E-04    .95630141E-04    .29143988E-02   -.92066692E-04
      .41908346E-05   -.94354615E-04    .00000000E 00   -.10789688E-04    .75307544E-04    .81965048E-01
PLANET POSITIONS (HELIOCENTRIC ECLIPTIC COORDINATES)
           PLANET NO. 1                 .96998232E 08    .11165005E 09   -.74071819E 04
           PLANET NO. 2                -.10859953E 09    .21806380E 09    .72570433E 07
           PLANET NO. 3                -.82126611E 08    .69096455E 08    .57094743E 07
           PLANET NO. 4                 .47353249E 09    .57852885E 09   -.10546613E 08
           PLANET NO. 5                 .13117923E 10   -.64052638E 09   -.13597130E 06
```

After phase change	***	PHASE CHANGE POINT-DATA REFERENCED TO NEW PRIMARY BODY
Endpoint	***	TRAJECTORY ENDPOINT
Special printout point	***	REQUIRED PRINTOUT POINT N

In Modes 2 and 3 each data record will have one of the titles listed above followed by the information appearing in Fig. 3-2. In Mode 1, the majority of data records have no title.

TIME FROM START appears both as whole number of seconds and days, hours, minutes, and seconds with starting time as the zero reference. For integration backward along a trajectory, the whole number of seconds will be preceded by a negative sign, but the days, hours, minutes, and seconds quantity does not have a negative sign within the parentheses.

The primary body may be identified from PRIMARY BODY NUMBER N by reference to the identification table in the Identification Record.

The positions and velocities are given in primary-body centered coordinates (usually ecliptic) and in units of km and km/sec. The true velocity is given in octal as well as decimal format to facilitate initialization of other trajectory computations without suffering a decimal-to-binary conversion error in reading in this sensitive parameter. ENCKE POS and ENCKE VEL are the conic state variables in the Encke method (Ref. 1). DELTA POS and DELTA VEL as the numerically integrated corrections to the conic state in the Encke method. In all cases the listed components are in x, y, z order.

GRAV FORCE is the many-body perturbation gravitational force per unit mass (acceleration) used in the Encke method (see Eq. 3.4, Ref. (1)). Units are km/sec^2 and components are in x, y, z order.

G(PRIMARY) and G(PERTURBATION) are the gravity gradient matrices of the primary body attraction and the vector sum of the perturbing body effects, respectively. Units are km/sec^3 (See Section 3.2, Ref. (1)).

STATE TRANSITION MATRIX is defined in Section 3.2 of Ref. (1). The matrix relates state perturbations at the present time point to small variations in the initial state. The units are as follows:

upper left 3 x 3 submatrix - km/km
upper right 3 x 3 submatrix - km/km/sec
lower left 3 x 3 submatrix - km/sec/km
lower right 3 x 3 submatrix - km/sec/km/sec

The two matrices following the state transition matrix are described in some detail in Section 2.2.2.2 of Ref. (1). They are accuracy checks on the state transition matrix computations, and are optional, depending on the value of KPHINV in the program input data (see Section 2, and Card No. 5, of this manual).

The planet position data are printed only in Mode 1. The units are km, and the components are in x, y, z order. The reference to ecliptic coordinates appears because those are most often used. If equatorial or other coordinates are used, the position data will be in the correct coordinates, and the ecliptic reference will be in error.

The modifications of this record format which normally occur are listed below:

Option or Mode	Modification
Modes 2, 3	Planet position data do not appear.
KPHINV = 0	PRODUCT OF STATE TRANSITION MATRIX AND ITS INVERSE and RMS MATRIX do not appear (both Modes 1 and 2).
Mode 3	STATE TRANSITION MATRIX and all following data do not appear.
Phase change point	Normal data record occurs before phase is changed; after phase is changed a shortened record is printed with state transition matrix and subsequent data deleted.

3.4 End of Cycle Record

The end of cycle record appears after the end point of a full trajectory computation. It appears in Mode 1 automatically, and in Modes 2 and 3 it appears either at the end of each search cycle or only at the end of the last cycle, depending on the input data control NCYCLE (see Section 2, Card No. 5).

The basic record format as it appears in Mode 1 is shown in Fig. 3-3. The updated starting velocity appears in both decimal and octal formats; units are km /sec. The matrix product is an error check on the inversion of the upper right 3 x 3 submatrix N of the state transition matrix. The inversion is done in the computation of the updated velocity. The miss vector is the computed endpoint position vector minus the target position vector. The x, y, z components and the magnitude of the miss are listed; units are km.

In Modes 2 and 3 only the miss vector appears in the end of the cycle record. The other two printed quantitites are deleted in these search modes.

3.5 Osculating Conic Data Record

Osculating conic data are computed and printed only when the NOSC input data control is specifically set (see Section 2, Card No. 5). Then the osculating conic data record follows each normal data record and lists parameters of the osculating conic of the actual orbit at that time point.

Fig. 3-4 shows an osculating conic data record. The type of conic is identified initially, and the data following are referred to the primary coordinates of the program, that is, planetocentric or heliocentric coordinates, depending on the primary body. UXI, UETA, and UZETA are unit vectors locating the principle axes of the osculating conic.

END OF CYCLE RECORD

```
MISS VECTCR        -.43252832E 03      -.8C66C62CE C3      .26720509E 02         MAGNITUDE       .51564637E C3


UPDATED STARTING VELCCITY                                     .23924965E 01        -.13694C71E 02        -.26C18C18E 01
                   (OCTAL)                                    202462172517         604666153526          6C2515C17534
MATRIX PRODUCT N*N-INVERSE
                                  .99999999E CC       .51222742E-08       -.18626451E-08
                                  .59662852E-09       .99999999E 00       -.0CCCC000E 00
                                 -.58207661E-1C       .46566129E-09        .99999999E 00
```

FIGURE 3-3

OSCULATING CONIC DATA RECORD

```
*** CSCULATING CCNIC DATA


OSC CONIC IS HYPERBOLA
     UXI           -.997863546        -.065136496        .CC5C52537
     UETA           .065332160        -.994874999        .C77170938
     UZETA         -.C00000CC1         .077336164        .99700C5C68
     ULN          -1.000000000        -.0C0000018       0.
     UM             .000000018        -.997005068        .C77336164
     UR            -.151124328        -.985554233        .076447940
     US             .988514744        -.150671719        .011687377
     UP            -.882867627        -.468215436        .036318757
     UQ             .469621923        -.880223520        .C68277598
     FLT PATH ANGLE GAMMA=     .93022826    ANGLE G=     .42348374
  LCNGITUDE OF NODE    -3.14159259ARGUMENT OF PERIPOINT      .06537871     INCLINATION ANGLE        .07741346
     SEMI-MAJOR AXIS -.71400017E 04          ECCENTRICITY     1.95103553                   TAU  .33762100E 02
        TRUE ANOMALY      1.35371201   HYPERBOLIC ANOMALY      .98481308     HYP MEAN ANOMALY       1.26258706
```

FIGURE 3-4

0354

UXI - in plane of conic in the direction of periapse.

UZETA - perpendicular to the plane of the orbit in the direction of the angular momentum vector.

UETA - completes right-handed coordinate set XI, ETA, ZETA ULN; UM, and UZETA are unit vectors, locating another set of osculating conic coordinates:

ULN - along the line of ascending nodes.

UZETA - as above.

UM - completes right hand coordinate set LN, M, ZETA UR, US, and UZETA are unit vectors locating the R, S, Z coordinate system:

UR - along the radius vector from primary body to the current point on the orbit at which the osculating conic is defined.

UZETA - as above.

US - completes right-handed coordinate set R, S, ZETA UP, UQ, and UZETA are unit vectors locating the P, Q, Z coordinates (Ref. (3)):

UQ - along the velocity vector at the current point on the orbit at which the osculating conic is defined.

UZETA as above.

UP - completes right-handed coordinate set P, Q, ZETA FLIGHT PATH ANGLE GAMMA AND ANGLE G have the special definitions givin in Ref. (3) and are associated with the P, Q, Z coordinate system. Units are radians.

The three angle parameters of the osculating conic all have standard definitions with respect to the primary x, y, z coordinate system. Units of these angle are radians.

The following osculating conic parameters listed depend upon whether the conic is an ellipse or hyperbola. For an hyperbola the semi-major axis (km), eccentricity, time of pericenter passage (seconds), true anomaly (radians), hyperbolic anomaly, and "hyperbolic mean anomaly" are listed. The latter three quantities are all referenced to pericenter, and the last quantity is defined as

$$\text{hyperbolic mean anomaly} = \sqrt{\frac{\mu}{|a|^3}}\,(t - \tau)\ .$$

For an ellipse the semi-major axis (km), eccentricity, time of pericenter passage (seconds), true anomaly (radians), eccentric anomaly (radians), and mean anomaly are listed. All anomalies are referenced to pericenter.

3.6 Special Messages

At a number of points in the program special messages are printed to indicate either error conditions in the computations or changes in the operating sequence. An example of the latter type appears in Fig. 3-1. This message is specifically chosen for illustration because it appears regularly in data listings. It indicates rectification of the Encke conic in the ENCON subroutine, the number of the primary body for the new conic, and the time of rectification referenced to start time.

Error messages which appear are always self-explanatory. They emanate from a number of points in the program, and reference to the flow charts in the next section shows these error message sources.

4. Program Flow Charts

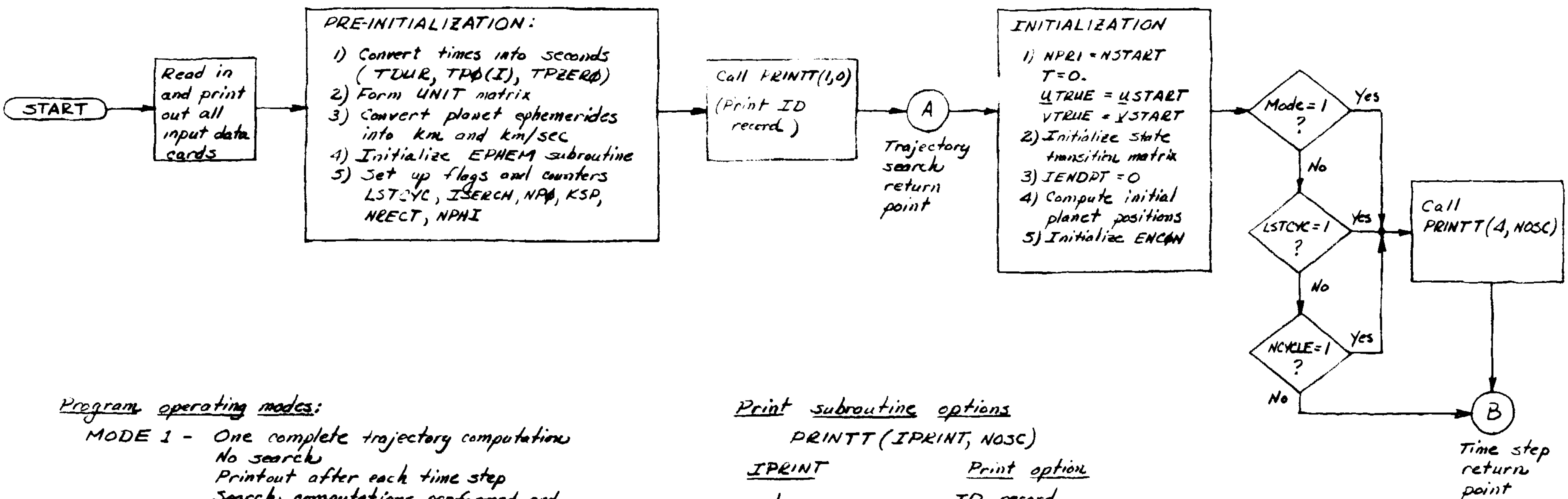
The following pages show the flow charts of the main program and each of the subroutines and function subprograms. Section 4 of Ref. (1) briefly explains the purpose of each subprogram. The charts show detailed functional flow; detailed computational procedures are shown. They are intended to make the program listings easily understandable.

REFERENCES

1. McDonald, W.T., "Special-Purpose Interplanetary Trajectory Computation Program for Guidance and Navigation Studies–Technical Report," RE-19, Dept. of Aeronautics and Astronautics, M.I.T., Experimental Astronomy Laboratory, July 1965.

2. Peabody, P.R., Scott, J.F., Orozeo, E.G., "JPL Ephemeris Tapes E9510, E9511, and E9512," Technical Memorandum No. 33-167, Jet Propulsion Laboratory, California Inst. of Tech., 1964.

3. Stern, R.G., "Interplanetary Midcourse Guidance Analysis," Vols. 1 and 2, Thesis (Sc.D.) TE-5, Dept. Aeronautics and Astronautics, M.I.T., Experimental Astronomy Laboratory, June 1963.



<u>Program operating modes:</u>

- MODE 1 - One complete trajectory computation
  No search
  Printout after each time step
  Search computations performed and results printed
- MODE 2 - Search mode
  Printout at beginning, end, and phase change points
- MODE 3 - Same as MODE 2, except state transition matrix not computed.

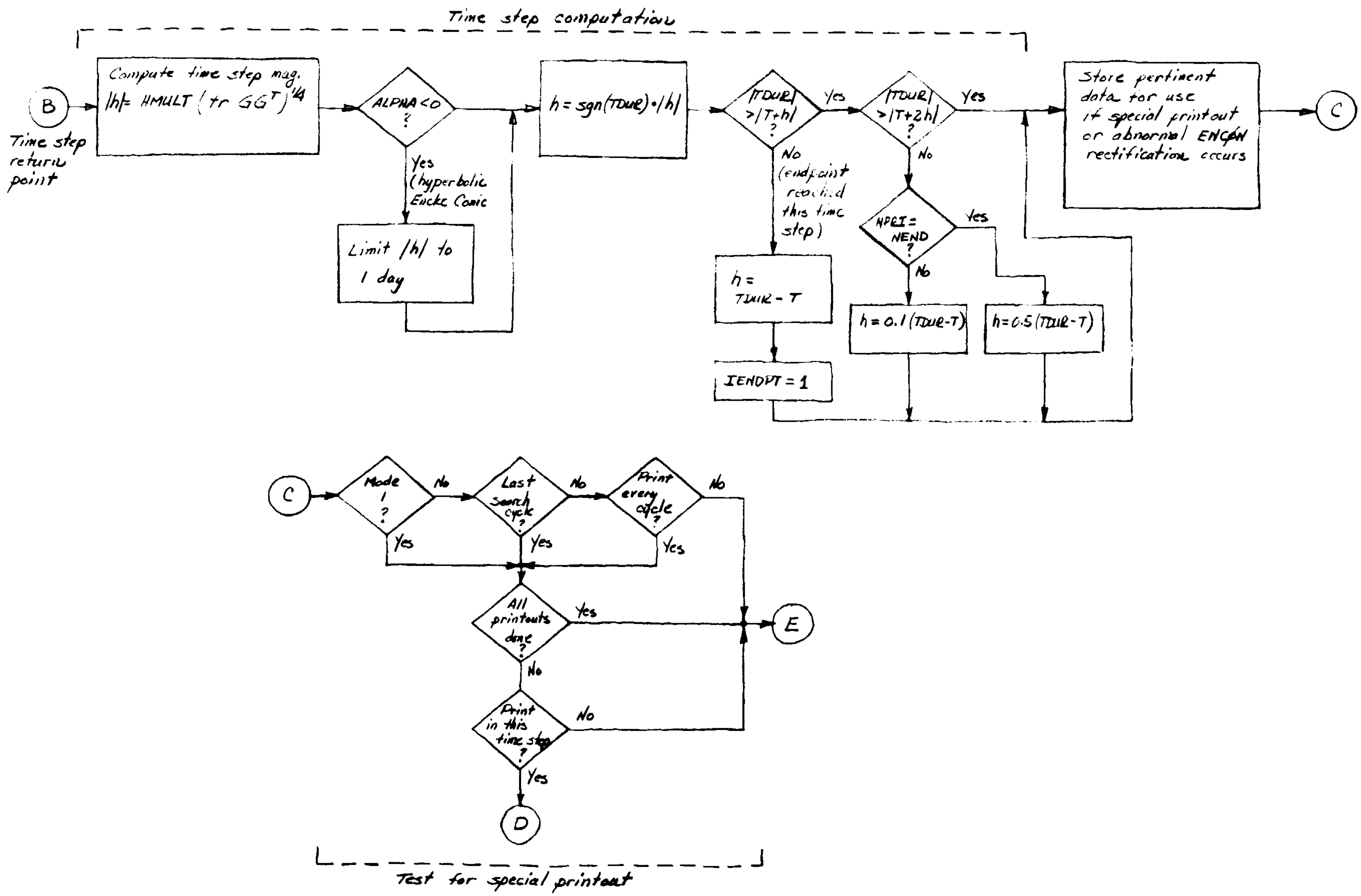
<u>Print subroutine options</u>

PRINTT (IPRINT, NOSC)

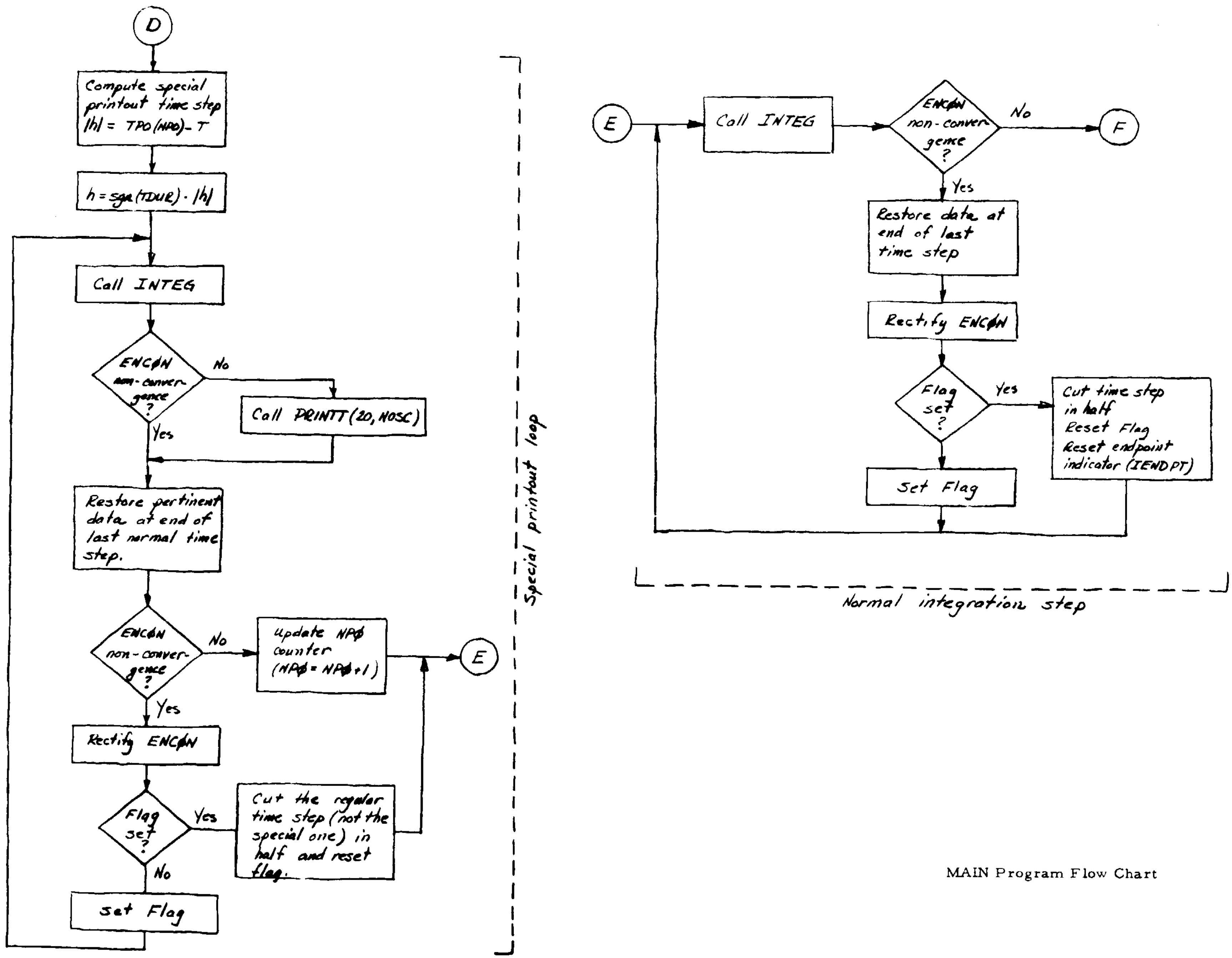
IPRINT	Print option
1	ID record
2	Normal data record, MODE 1
3 (30)	Phase change data record, two parts.
4	Starting point data record
5	Endpoint data record
6	Special search computation data record, MODE 1 only.

NOSC	Option
1	Calls ØSCØN, which computes and prints osculating conic data
0	ØSCØN not called.

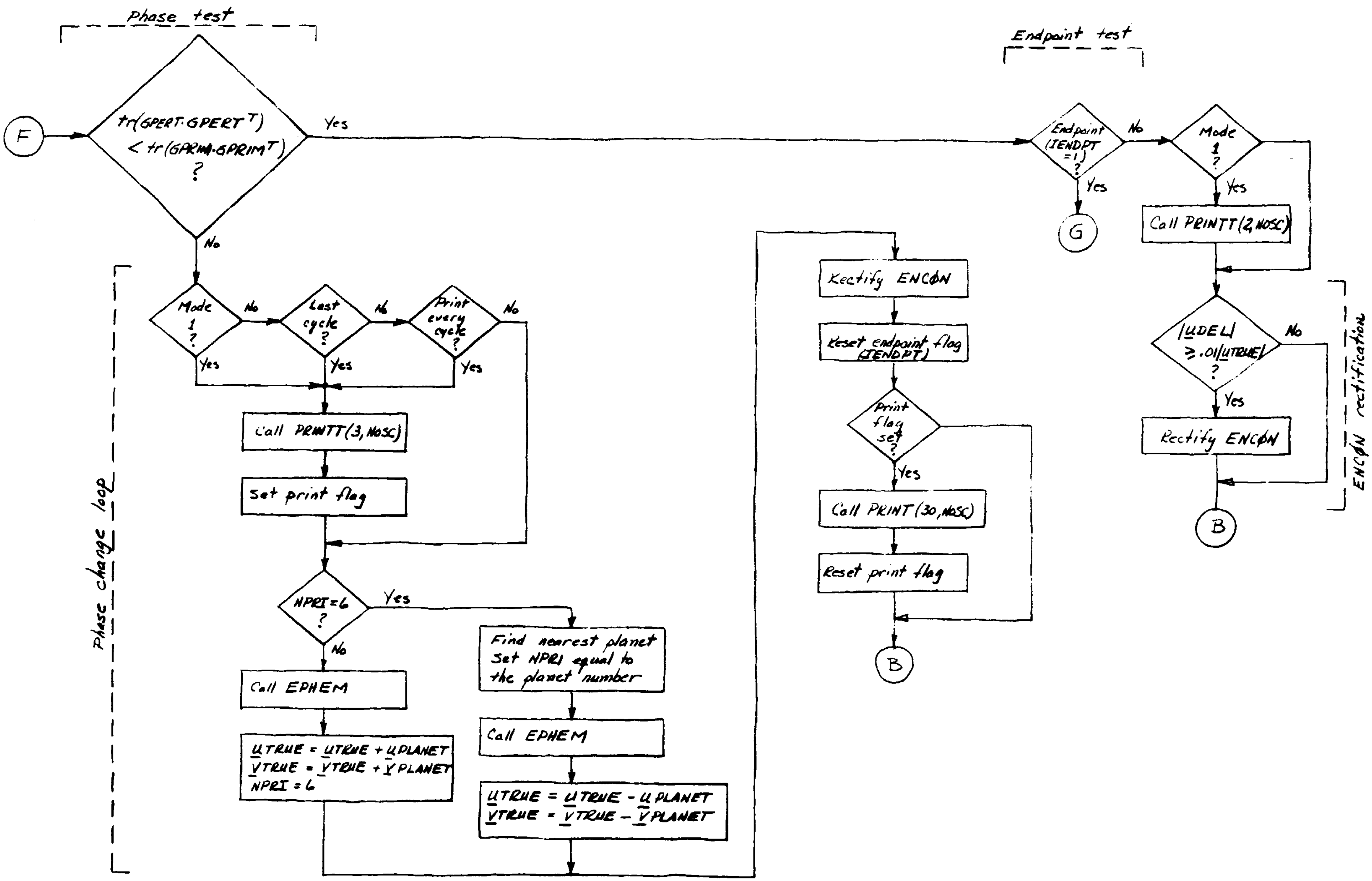
MAIN Program Flow Chart



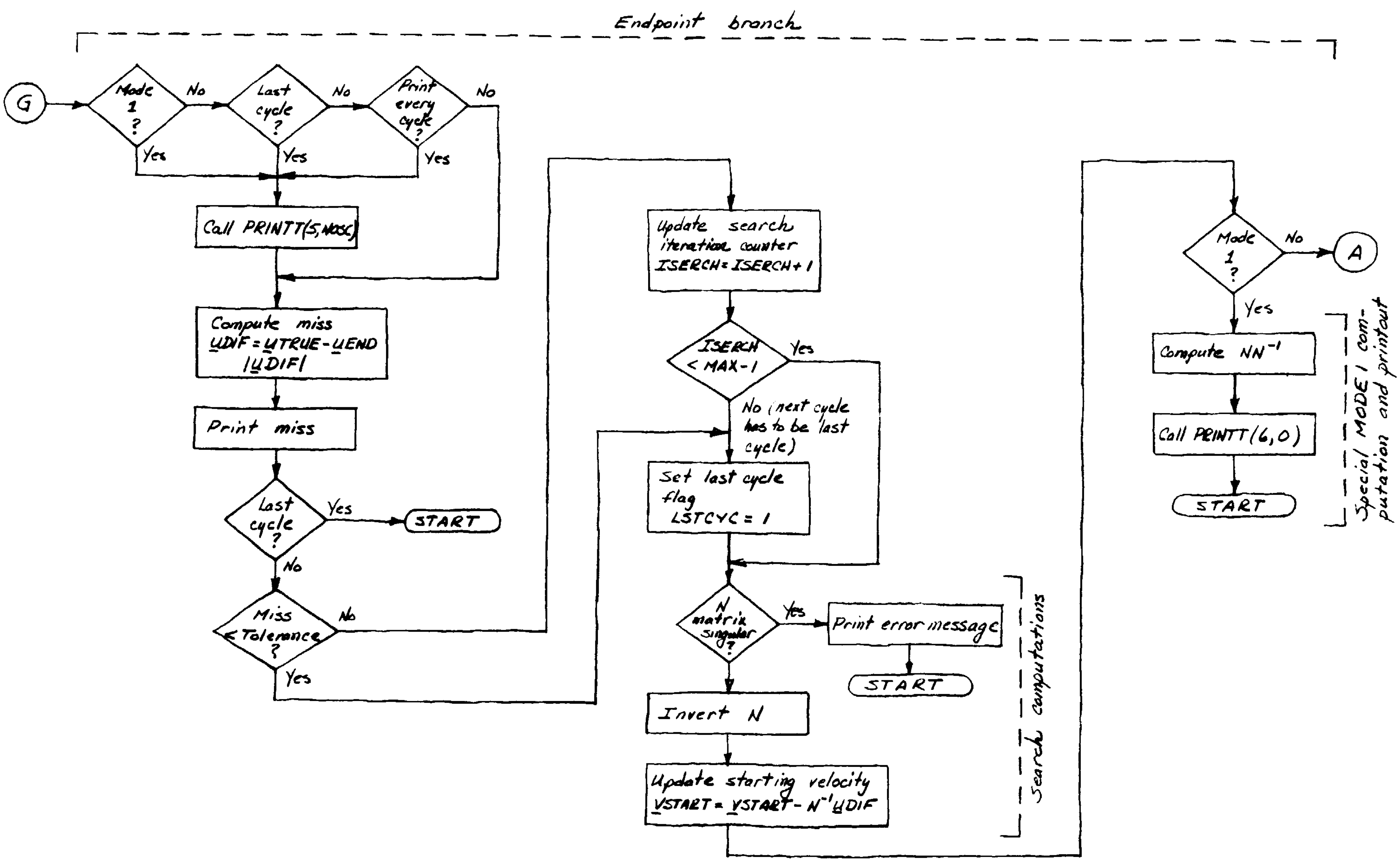
MAIN Program Flow Chart



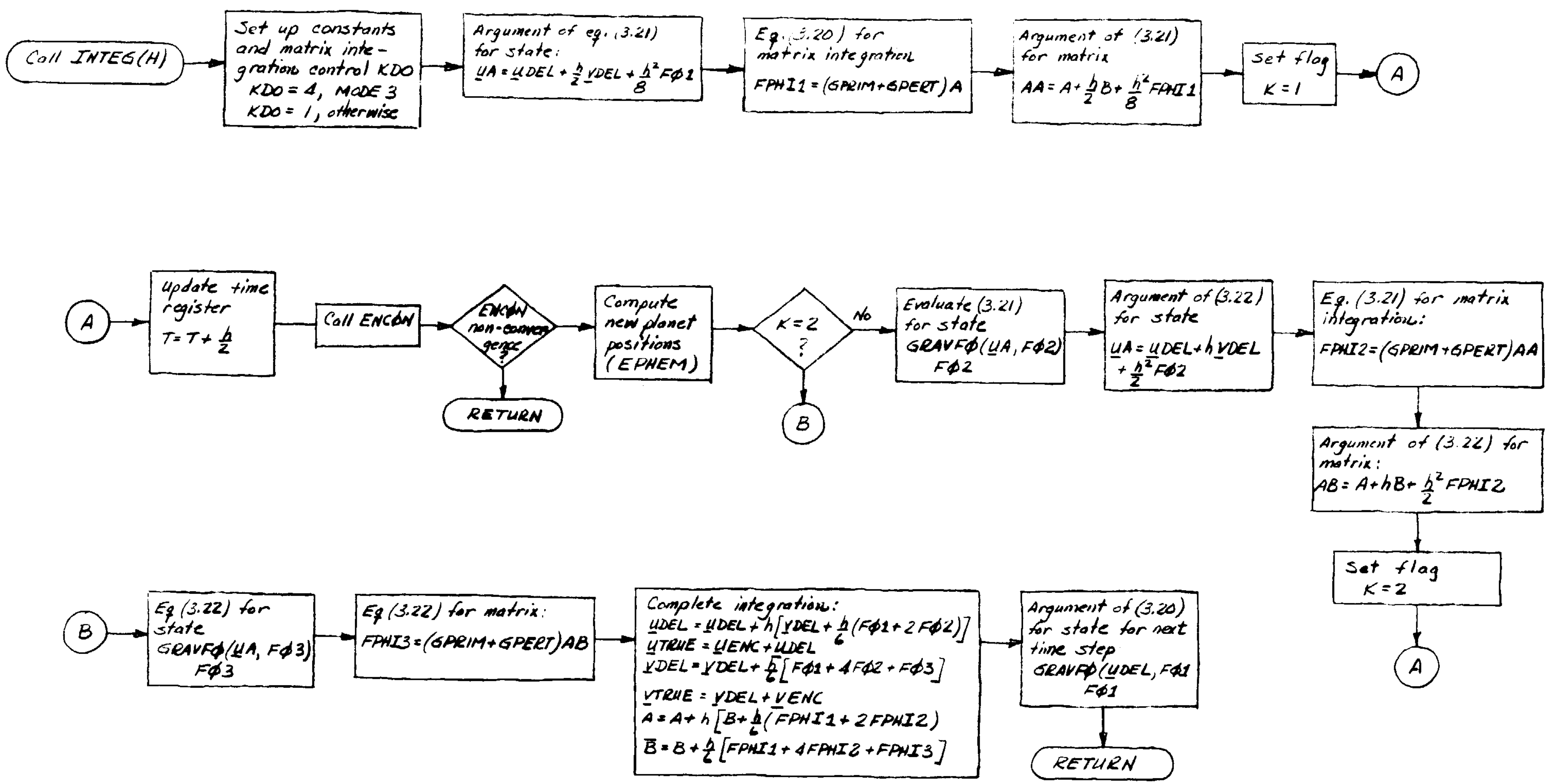
MAIN Program Flow Chart



MAIN Program Flow Chart

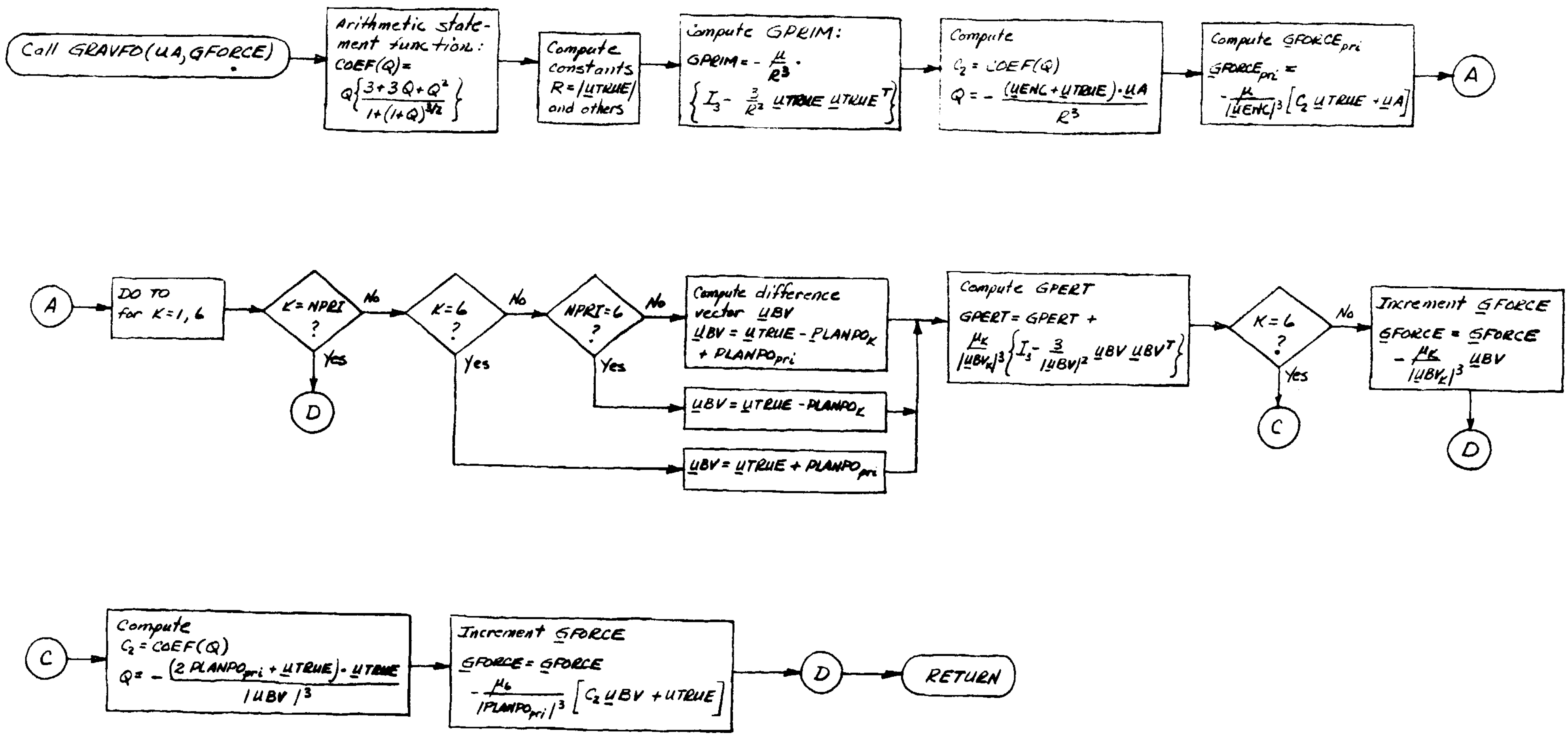


MAIN Program Flow Chart

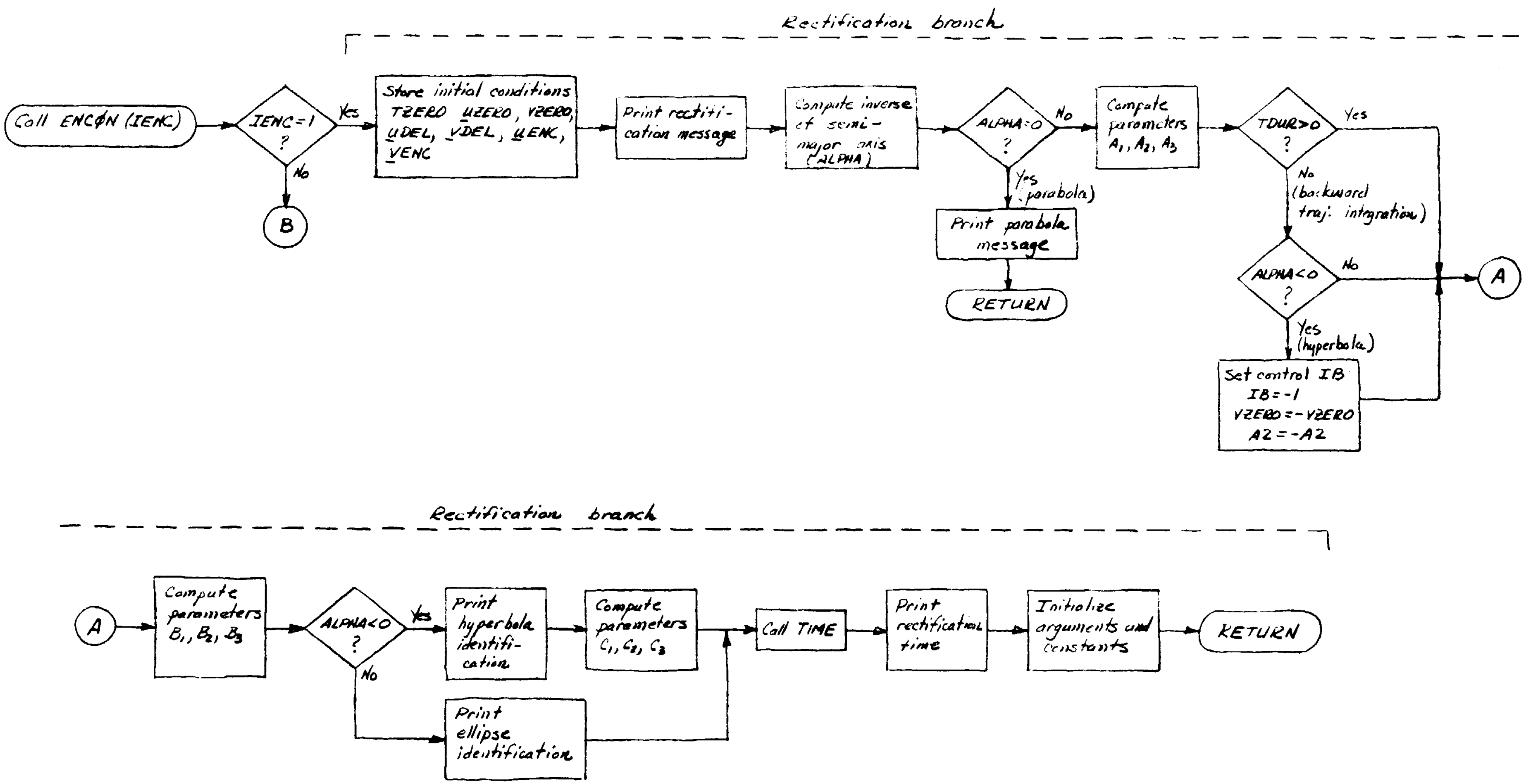


NOTE: Equation numbers refer to Section 3.3 of reference 1

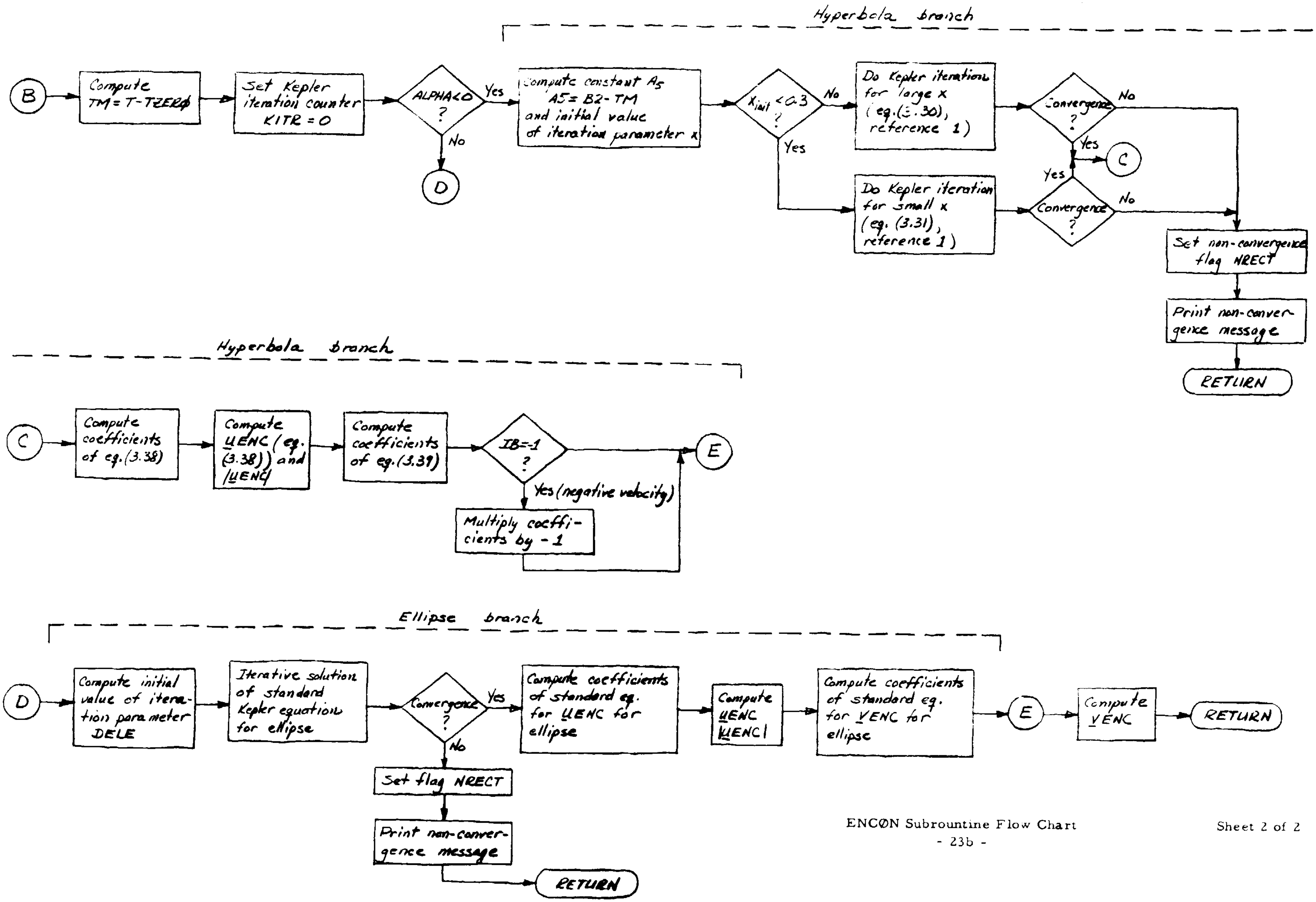
INTEG Subroutine Flow Chart



GRAVFØ Subroutine Flow Chart

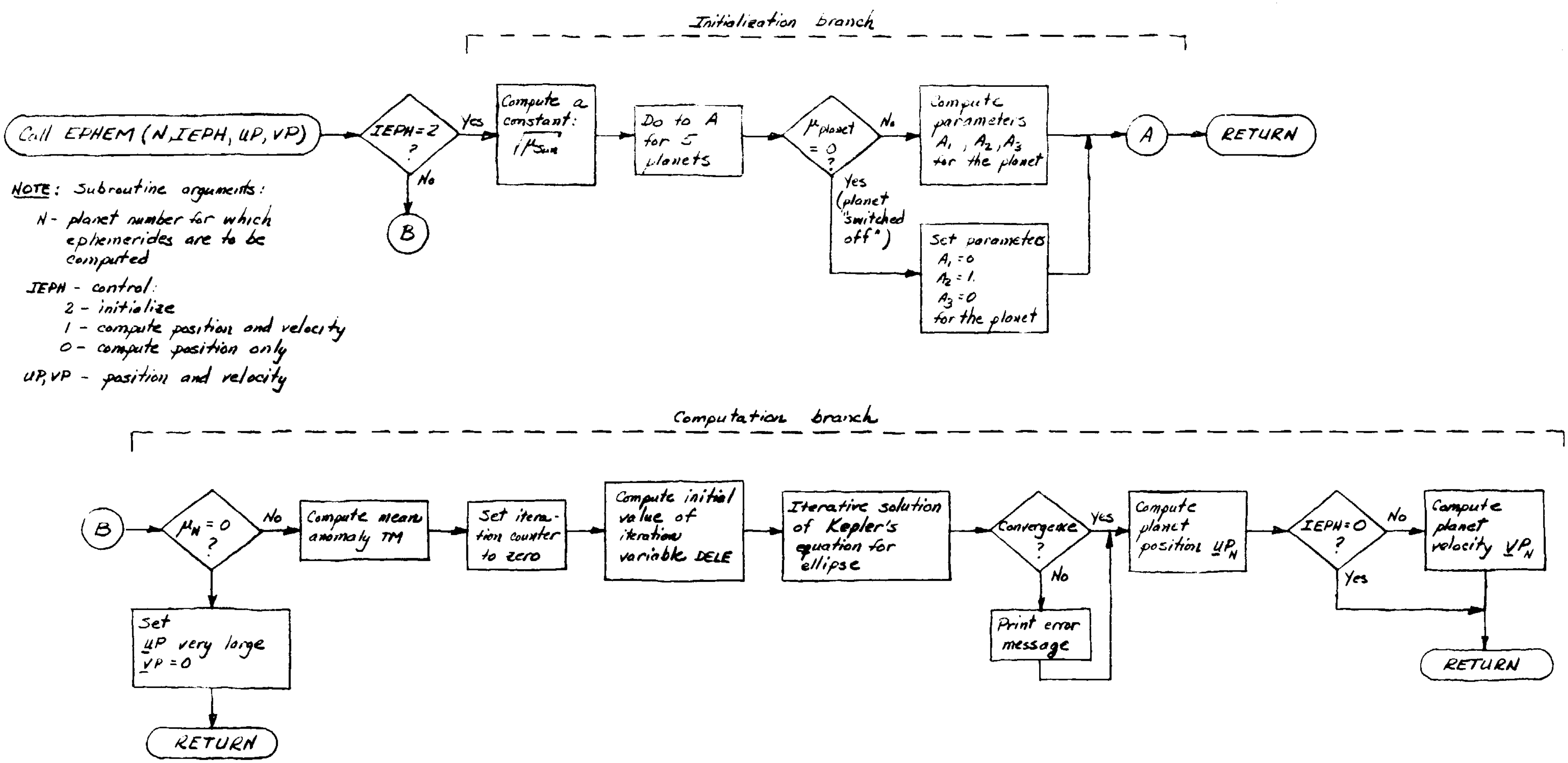


ENCØN Subroutine Flow Chart

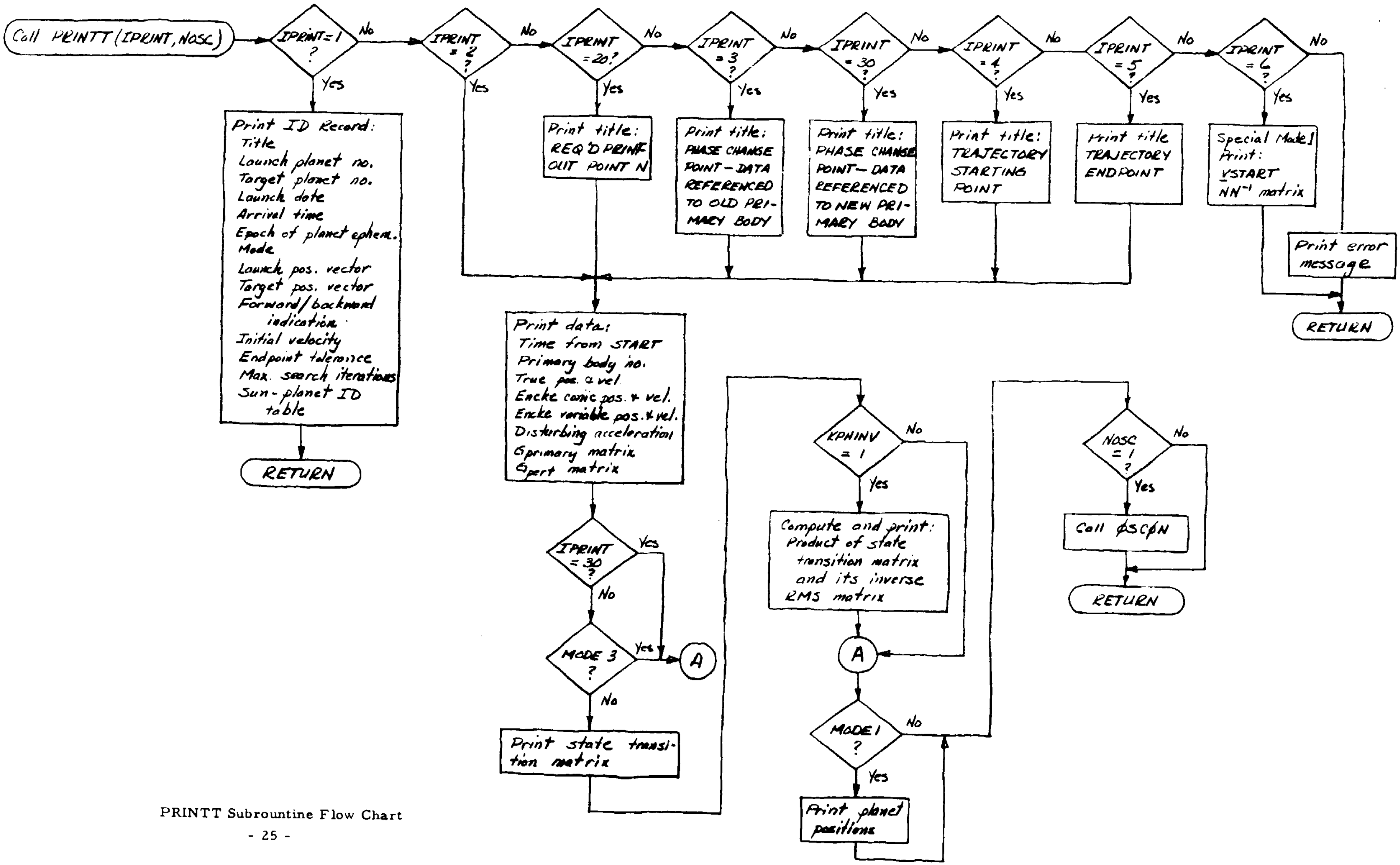


ENCØN Subrountine Flow Chart

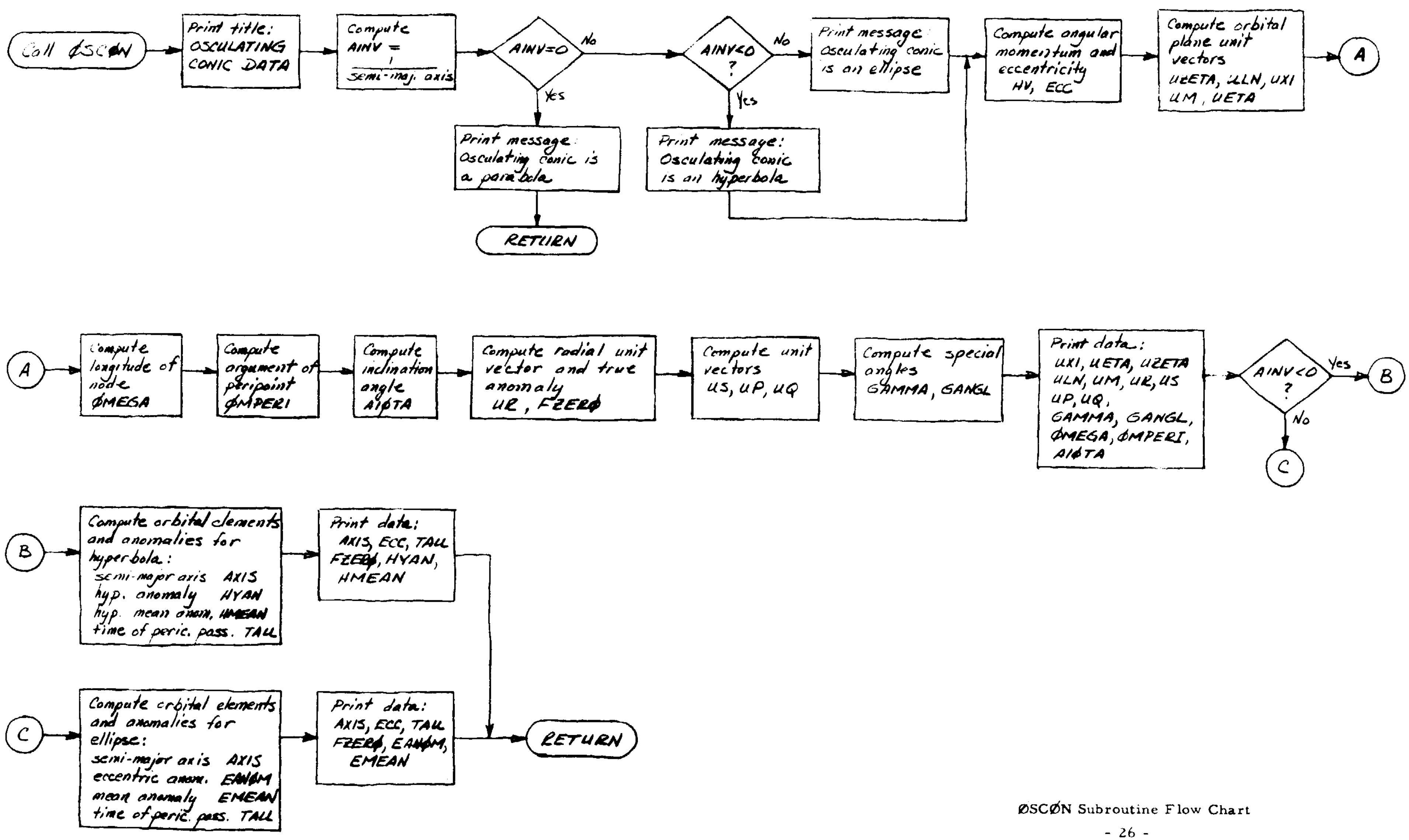
Sheet 2 of 2



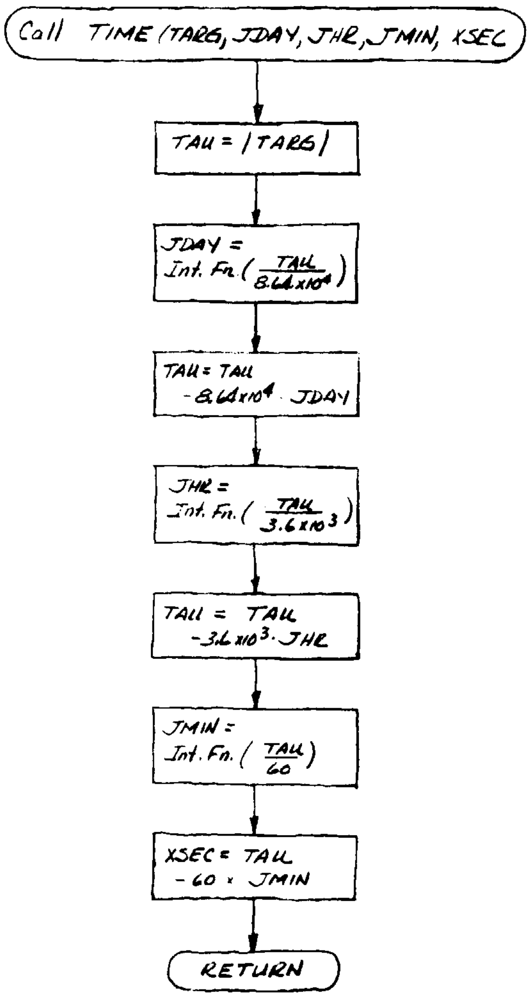
EPHEM Subroutine Flow Chart



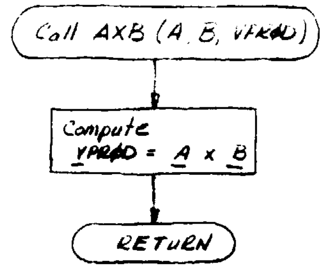
PRINTT Subrountine Flow Chart



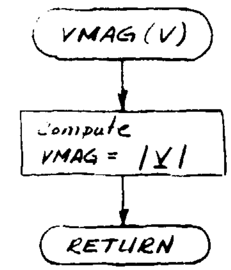
ØSCØN Subroutine Flow Chart



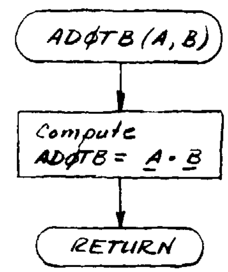
TIME Subroutine Flow Chart



AXB Subroutine Flow Chart



YMAG Function Subprogram Flow Chart



ADOTB Function Subprogram Flow Chart