AFAL-TR-76-247

PROFGEN - A COMPUTER PROGRAM FOR GENERATING FLIGHT PROFILES

REFERENCE SYSTEMS BRANCH
RECONNAISSANCE AND WEAPON DELIVERY DIVISION

NOVEMBER 1976

TECHNICAL REPORT AFAL-TR-76-247
FINAL REPORT FOR PERIOD JUNE 1975 - FEBRUARY 1976

AIR FORCE AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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AIR FORCE - 22 DECEMBER 76 - 100

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

[redacted]

AFAL-TR-76-247

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

PROFGEN - A Computer Program for Generating Flight Profiles.

5. TYPE OF REPORT & PERIOD COVERED

Final Rept.

Jun [redacted]75 - Feb [redacted]76

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

Stanton H. Musick

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Reference Systems Branch
Reconnaissance and Weapon Delivery Division
Air Force Avionics Laboratory, WPAFB, OH 45433

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

6095 0501

11. CONTROLLING OFFICE NAME AND ADDRESS

Same as 9

12. REPORT DATE

Nov[redacted]r [redacted]76

13. NUMBER OF PAGES

200

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Trajectory driver	Numerical integration
Profile generator	Navigation
Computer simulation	Flight path
Six degree-of-freedom	Wander azimuth

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a computer program that calculates flight path data for an aircraft moving over the earth. The program is called PROFGEN, is written in FORTRAN, and is intended to support simulations that require a six degree-of-freedom trajectory driver.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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PROFGEN computes the position, velocity, acceleration, attitude and attitude rate of an aircraft flying over an ellipsoidal earth and responding to maneuver commands specified by the program user. Four types of maneuver commands are available: vertical turn, horizontal turn, sinusoidal heading change and straight flight. In addition, a speed change may be superimposed on any maneuver. Extended flight paths are created by stringing together a sequence of maneuvers.

PROFGEN uses a fifth-order numerical integrator to solve the kinematic equations of motion. This high-order integrator can operate in a self-analysis mode to produce a highly consistent set of values for position, velocity, acceleration, etc. In addition to using such an integrator, PROFGEN insures self-consistent and accurate results by (1) adjusting the step size to suit the problem's dynamics, (2) using the exact non-linear differential equations of motion, (3) avoiding integrations that span abrupt rate changes and (4) stopping the integration process to make output only when required by the user.

PROFGEN was developed on a CDC CYBER-74 computer where it compiles in about six seconds and uses less than 60,000 words of memory. The program includes a plotting capability that increases the memory requirement to 137,000 when installed.

FOREWORD

This technical report was prepared by Stanton H. Musick of the Reference Systems Branch, Reconnaissance and Weapon Delivery Division, Air Force Avionics Laboratory, Wright-Patterson AFB, Ohio.

This work was initiated under Project Work Unit Number 60930501 and spanned the period from June 1975 through February 1976. The final manuscript was typed by Mrs. Shirley Suttman and was originally released in March 1976 as AFAL-TM-76-3.

Since the initial release in March 1976, one minor sign correction has been made in the PROFGEN program (see Subroutine GRAVITY in the listing) while numerous revisions have been made in this manuscript to correct mistakes and improve its readability.

ACKNOWLEDGEMENTS

The author would like to recognize two people for their substantial contributions to the development of PROFGEN: Jay Burns for developing and documenting the equations necessary to maintain flight in a great circle plane, and for doing the analysis that lead to a companion program named HEADING (see page 35); and Dave Kaiser for the writing, debugging and testing of HEADING and of all the code that produces plotted output in PROFGEN.

The author would also like to thank Shirley Suttman for her patience and skill in typing this report.

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NOTATION

Subscripts, Superscripts, Prefixes

$\triangleq$	Equals by definition
$\cong$	Equals approximately
$(\underline{\ })$	Physical vector
$(\underline{\ })^j$	Math vector with components in j frame
$(\ )^T$	Matrix or vector transpose
$(\dot{\ })$	Time derivative
$\Delta(\ )$	The change over time of the variable ( )
$(\bar{\ })$	Average value
C_j^k	Transformation matrix, frame j to frame k

Coordinate Frames

Frame	Symbol	Components
Inertial	i	X_i, Y_i, Z_i
Earth	e	X_e, Y_e, Z_e
Navigation	n	x, y, z
Cardinal navigation	-	N, W, U
Path	p	x_p, y_p, z_p

I. INTRODUCTION

This report describes a computer program that calculates flight path data for an aircraft moving over the earth. The program is called PROFGEN and was written in FORTRAN. Its primary intended use is to support simulations that require a six degree-of-freedom trajectory driver.

This version of PROFGEN evolved from one written in 1973 that became obsolete because it lacked a wander-azimuth capability and employed an unrealistic roll control mechanization. These shortcomings are corrected in the revised version and several new features are added including output at user-determined times, the computation of attitude rates, an improved gravity model and the ability to turn through a precise angle without overshoot. In addition the revised version is coded in a modular fashion for ease of understanding and change.

This report will document PROFGEN in full. Section II is a general description of PROFGEN's capabilities and limitations that should allow the reader to determine the program's applicability to his problem. Section III is a user's guide that tells how to construct a flight profile with the available input parameters. Section IV develops the equations that PROFGEN solves. Section V describes the program itself. Appendix A presents an example problem and Appendix B gives a listing of the program source deck.

II. GENERAL CHARACTERIZATION

PROFGEN computes position, velocity, acceleration, attitude and attitude rate for an aircraft moving over the earth. Position is given as (geographic) latitude, longitude and altitude (see Figure 1). Velocity with respect to earth is componentized and presented in a local-vertical frame (x-y-z in Figure 1) that will be called the navigation frame. Acceleration consists of velocity rates-of-change summed with Coriolis effects and gravity. Attitude consists of roll, pitch and yaw, the Euler angles between the path frame and the navigation frame. These quantities will be defined precisely in Section IV.

Although the descriptions herein always refer to "aircraft" flight paths, PROFGEN has applicability to path generation for land and sea craft as well. In general PROFGEN is suited for simulation of any craft under continuous control. It is not well suited to describing bodies in free fall or earth orbit where mass attraction is the primary forcing function.

PROFGEN models a point mass responding to maneuver commands specified by the user. These maneuvers are available:

- vertical turns (pitch up or down)
- horizontal turns (yaw left or right)
- sinusoidal heading changes (oscillates left and right)
- straight flights (great circle or rhumb line path)

N-W-U ~ Geographic Coordinates
x-y-z ~ Navigation Coordinates
λ ~ Longitude
ϕ ~ Latitude (geographic)
h ~ Altitude

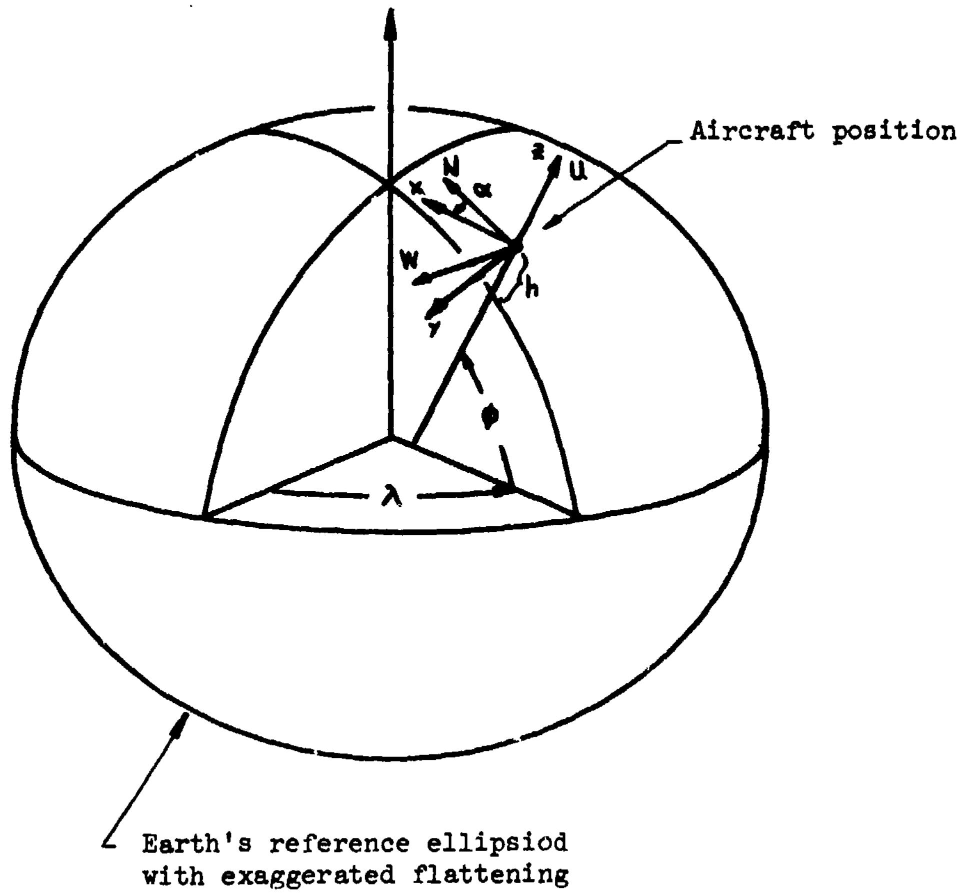


Figure 1 - Coordinate Frame Geometry

All horizontal-plane maneuvers are executed in a coordinated fashion. This simply means that the aircraft is rolled to an angle where the vector sum of the centrifugal turning force and the force of "gravity" (32.2 ft/sec^2) acts perpendicular to the wings. Only one type of maneuver may be executing at any given time but it can commence from any aircraft attitude. For example, the aircraft may go into a left turn while in a dive.

In addition to the four basic maneuvers, the user also has control of path acceleration by which the aircraft can be forced to change speeds. Path acceleration may be superimposed over any maneuver. This would allow, for example, an accelerated diving turn.

PROFGEN is used to create an extended flight profile by stringing together a sequence of maneuvers chosen from the basic four. The user specifies how long each maneuver shall last and thereby divides the profile into flight segments. Up to fifty flight segments may be strung together to produce a varied total profile. The final values of the variables in each segment are passed along as the initial values for the start of the next segment thereby creating uninterrupted time histories for all output variables.

The program allows step changes to occur in displacement acceleration and in rotational velocity. This produces continuous time histories for displacement velocity and rotational position (roll, pitch, yaw) but results in infinite jerk (rate-of-change of displacement acceleration) and infinite rotational acceleration.

Acceleration, velocity and position are related instantaneously by integration and differentiation to within the accuracy of the Kutta-Merson numerical integrator. Every effort has been made to configure this integrator to produce an accurate result so that the output variables form a self-consistent set. Thus the integrator is fifth order and can adjust its step size automatically to control the growth of errors. To illustrate, a great circle path from Dayton to Moscow accumulated less than 15 feet of error over its 5000 mile distance.

PROFGEN is limited in its capability to simulate intricate fighter maneuvers. This arises in part because PROFGEN forces the aircraft body and path frames to be coincident and thereby loses the ability to simulate slipping or crabbing motion. Thus, for example, one could not simulate a fighter aircraft doing a barrel roll or an Immelmann. On the other hand, one could simulate a complete loop of arbitrary radius since severity of maneuver is not restricted. In general, PROFGEN can simulate any maneuver possible with a bomber or cargo aircraft.

The earth is modeled as a perfect ellipsoid having values for eccentricity, semimajor axis length, spin velocity and gravitational constant equal to those of the DOD World Geodetic System 1972 (Ref. 1). Earth's gravity is modeled as a function of latitude and altitude, having both radial and level components. This model is not overly precise (probably no better than 25 micro gees) and may need revision for some applications.

PROFGEN compiles and executes in less than 60,000 words of CDC CYBER-74 memory. It uses only single precision variables and all source code is FORTRAN. The program takes six seconds of central processor time to compile. The ratio of simulated time to execution time improves as problem dynamics become less severe, reaching 20267 : 1 for straight flight segments but falling to 4 : 1 for a 10 gee horizontal turn.

III. USER'S GUIDE

This section defines the input data that the user supplies to run PROFGEN. The input data specifies

- initial conditions
- maneuver characteristics
- integrator control
- output control

All data is entered under a NAMELIST format that permits the entry of character strings. A character string is a parameter name followed by its values written in the user's choice of format specification. The use of NAMELIST on the CDC CYBER-74 will be illustrated in Figures 2 and 3.

Two NAMELIST input data lists are used, PRDATA and PASDATA. The PRDATA (Problem Data) list contains 15 parameters that remain fixed for the entire run. These parameters specify all initial conditions and control output.

The PASDATA (Path Segment Data) list contains 13 parameters that remain fixed only for the length of a segment. These parameters specify and describe each maneuver, control the numerical integrator, and control the output frequency.

3.1 PRDATA Input

Fifteen parameters are entered through the PRDATA list. Failure to specify any one of these results in program termination. All parameters are single precision and all must be entered in units of feet, seconds and/or degrees. The following format will be used to describe input parameters throughout this section and the next.

Parameter	(Type)	Units (If Any)
IPROB	(Integer)	

The problem identification number. It is set by the user for identification purposes only.

NSEGT (Integer)

The total number of path segments required to complete the entire problem. This number may not exceed 50 as the program is now configured.

LLMECH (Integer)

The local-level azimuth angle mechanization index. See Section 4 and Table 2.

LLMECH	Azimuth Mechanization
1	Alpha Wander
2	Constant Alpha
3	Unipolar
4	Free Azimuth

TSTART (Real) seconds

The initial time. It is used to begin the problem at any desired point. It may be negative.

VTO (Real) feet per second

The initial magnitude of total velocity with-respect-to the earth. VTO must be non-negative.

PHEADO (Real) degrees

The initial heading angle of the path coordinate frame. It is specified as positive clockwise from North. Its range is the closed interval [-180., +180.].

PPITCHO (Real) degrees

The initial pitch angle of the path coordinate frame. It is specified as positive in the upward direction. The path frame is level when the pitch angle is zero. Its range is [-90., +90.].

ALFAO (Real) degrees

The initial alpha angle. Alpha is the navigation frame heading angle and is specified positive counterclockwise from North. Its range is [-180., +180.].

LATO (Real) degrees

The initial geographic latitude. Its range is the open interval (-90., +90.). Since the program falters when trying to compute at exactly 90 degrees, these two extreme points must be avoided.

LONO (Real) degrees

The initial longitude. It has no effect on the problem's dynamics but is necessary to establish a reference point for the calculation of current position. Its range is [-180., +180.].

ALTO (Real) feet

The initial altitude above the reference ellipsoid. ALTO may be negative.

IPRNT (Integer)

Print control index having control, in part, over what is written on TAPE6. This tape is considered to be printed output. All TAPE6 output is formatted.

IPRNT	Action
1	Output on TAPE6 at time-intervals specified by DTO (a PASDATA parameter)
≠1	Output at DTO intervals is turned off.

Regardless of the state of IPRNT, the following output also appears on TAPE6:

- date and time
- input data from PRDATA and PASDATA lists
- variable values at start of each segment and at t-final
- error messages
- post-run assessment of numerical integrator performance

IRITE (Integer)

Write control index. This output is written on TAPE3 and is designed for compact storage of data for subsequent use by another program. All TAPE3 output is unformatted.

IRITE	Action
1	Output on TAPE3 consisting of date, time, input data and variable values beginning at TSTART and continuing at DTO intervals.
≠1	No output on TAPE3.

IPLOT (Integer)

Plot control index. This output is on PLFILE for post-run graphing using DISSPLA, a CALCOMP plot library.

IPLOT	Action
1	Program plots five graphs, latitude vs. longitude and time histories of altitude, roll, pitch and yaw. Up to 501 points are plotted in each graph, the first being at TSTART and all thereafter at DTO intervals.
≠1	No plotted output.

ROLRATE (Real) degrees per second

Nominal aircraft roll rate. When the aircraft must bank to execute a coordinated horizontal turn, it rolls to the proper bank angle at a rate of ROLRATE. In sine-heading-change maneuvers, ROLRATE serves as the limiting value for the derivative of roll. ROLRATE must be positive.

Figure 2 is a sample of a PRDATA card input set. Note that the data items may be listed in any order so long as they all appear between the beginning identifier, $ PRDATA, and the ending identifier, $.

3.2 PASDATA Input

Thirteen parameters having up to 50 values each are entered through the PASDATA list. Each parameter is dimensioned in the program as a 50 element array, the number 50 corresponding to the maximum number of segments allowed. Each parameter value must be assigned to the array element corresponding to its segment number; for example, if the output spacing in the sixth segment is to be 25 seconds, one would input DTO(6) = 25. Each parameter name in the list that follows has the argument i appended to it to indicate its dependence on segment i, $1 \leq i \leq 50$.

Six of the PASDATA parameters (TURN, NPATH, PACC, TACC, HEAD, PITCH) describe the maneuver and four (MODE, ERROR, HMAX, HMIN) are associated with numerical integration. The other three control output frequency (DTO), set segment length (SEGLNT), and control initial conditions (RESTART). Each parameter has a default option that is invoked in lieu of input data. The default saves the user the trouble of specifying values that often recur. All parameters are single precision and all must be entered in units of feet, seconds, gees (1 gee $\triangleq$ 32.2 ft/sec.^{2}) and/or degrees.

```
$PRDATA IPROB=650,
NSEGT=17,
LLMECH=2,
TSTART=0.,
VTO=1000.,
PHEADO=180.,
PPITCHO=0.,
ALFAO=45.,
ALTO=30000.,
LATO=39.,
LONO=-84.,
ROLRATE=250.,
IPRNT=1,
IRITE=0,
IPLOT=1$
```

Figure 2 - Sample of PRDATA Input

Parameter	(Type)	Units (If Any)
SEGLNT(i)	(Real)	seconds

The time interval of the i^{th} segment. SEGLNT(i) can be any non-negative number, including zero. The program remains in segment i until exactly SEGLNT(i) seconds have been simulated. The default value is zero seconds.

RESTART(i) (Integer)

The index number for control of the initial conditions at the beginning of each segment.

RESTRART(i)	Action
1	All variables in the state vector are reset to the conditions that existed at TSTART, namely those in PRDATA. RESTART = 1 is useful when one wishes to produce a reference flight, and a variation of that flight, all in one run.
≠1	The variable values at the beginning of segment i equal those at the end of segment i-1.

The default value is zero, no reset performed.

TURN(i)

The index number for the type of maneuver to be used.

TURN(i)	Action
1	vertical turn
2	horizontal turn
3	sinusoidal heading change
4	straight flight

All maneuvers begin at the start of a segment. Vertical and horizontal turns are complete when a specified turn angle is reached. If specified angle is reached and time remains in the segment, PROFGEN reverts to a straight flight mode (TURN = 4) for the remaining seconds of the segment. If TURN(i) is 3, a "sinusoidal" path (oscillatory yawing motion in the horizontal plane) is flown for SEGLNT(i) seconds. For sine maneuvers, the user must select a segment length that is a multiple of Tp/4 where Tp is the period of the sinusoid. If TURN(i) is 4, a straight-flight segment will be flown over a nominal path determined by the value of NPATH(i) for SEGLNT(i) seconds. Section 3.4 discusses these maneuver characteristics more fully. The default value is 4, straight flight.

NPATH(i) (Integer)

The index number for the nominal path.

NPATH(i)	Action
1	Great cricle path
2	Rhumb line path

When a rhumb line path is chosen, the aircraft maintains a constant heading angle during straight flight periods. When a great circle path is chosen, the aircraft flies in a fixed plane during straight flight periods. The aircraft maintains this fixed-plane flight over the ellipsoidal earth, even when altitude changes, by correcting heading continuously. When not in straight flight (i.e. TURN = 1, 2 or 3), the rhumb line or great circle actions are superimposed on the chosen maneuver. The default value is 2, rhumb line path.

PACC(i) (Real) gees

The signed value of the constant acceleration along the velocity vector, i.e. along the path x-axis. The program converts PACC(i) in gees to path acceleration in feet/second^2 by multiplying by 32.2. PACC(i) may be assigned any real value; it remains that value for the entire segment regardless of maneuver specification. Positive (negative) values cause the aircraft to gain (lose) total speed. Since all active maneuvers (TURN = 1, 2 or 3) require a division by total speed (VT) to compute acceleration, the user must assign PACC(i) so VT is never zero during the actual turning portion of such maneuvers. PACC(i) may force VT to zero anytime during a straight flight segment. The default is zero gees.

TACC(i) (Real) gees

The magnitude of the maximum centrifugal acceleration during either a vertical or horizontal turn. The program converts TACC(i) in gees to acceleration in feet/second^2 by multiplying by 32.2. TACC(i) must be positive for vertical and horizontal turns. The default value is zero gees.

HEAD(i) (Real) degrees

HEAD(i) has two uses.

For horizontal turns, HEAD(i) is the desired change in heading angle. Other factors permitting (SEGLNT, TACC, ROLRATE, PACC, VT) this turn angle will be executed accurately. The magnitude of HEAD(i) may be greater than 360 degrees. A positive (negative) HEAD(i) forces a right (left) turn.

For sine maneuvers HEAD(i) is the maximum variation of the heading angle and its absolute value must be less than 90 degrees. A positive (negative) HEAD(i) forces the sine maneuver's ground track to lie right (left) of the initial ground track. The default value is zero degrees.

PITCH(i) (Real) degrees or deg/sec

PITCH(i) has two uses.

For vertical turns PITCH(i) is the desired change in pitch angle in degrees. Other factors permitting (SEGLNT, TACC, PACC, V_T), this value will be achieved precisely. PITCH(i) may exceed 90 degrees. A positive (negative) PITCH(i) forces the pitch angle to increase (decrease).

For sine maneuvers, PITCH(i) is the frequency of the sinusoidal rate of change of heading in degrees per second. It must be non-zero. The sign of PITCH(i) has no effect on the sine maneuver. The default value is zero in degrees or degrees per second, as the case may be.

DTO(i) (Real) seconds

The time interval between required output times. DTO(i) is referenced to zero seconds; e.g., if DTO(i) = 6, output would be available at T = (···, -12, -6, 0, 6, 12,···). DTO(i) must be positive. DTO(i) controls output frequency for printing, writing and plotting (see IPRNT, IRITE, IPLOT). Careful sizing of DTO(i) is a necessity, especially when two or three output modes are used simultaneously. The default value is 100 million seconds corresponding to no output at all.

MODE(i) (Integer)

The index for control of step size in the numerical integration routine.

MODE(i)	Action
0	Fixed step-size integration.
1	Variable step-size integration.

The step size is HMIN(i) when fixed step-size integration is used. A fifth order numerical integration is performed.

With the variable step-size mode, the program begins the integration with a step size of HMIN(i). The numerical integrator adjusts the step size upwards from there while keeping the within-step error below the value specified in ERROR(i). If problem dynamics are mild, the step size can grow very large, limited finally by HMAX(i). If problem dynamics are severe, the minimum step size may not be adequately small to satisfy the error criterion in which case an error message is printed.

In summary both integration modes perform fifth order numerical integrations but MODE = 1 adjusts step size automatically to conform to an error criterion. The default value is variable step-size integration.

ERROR(i) (Real)

The allowable within-step integration error. It must be positive. The default value is 10^{-6}, a value that has proven satisfactory during program development.

HMAX(i) (Real) seconds

The maximum step size when variable step-size integration is used. It must be positive. The default value is 10,000 seconds.

HMIN(i) (Real) seconds

The minimum step size when variable step-size integration is used. With fixed step-size integration, HMIN(i) is the size of each step. It must be positive. The default value is one second.

Table 1 shows the relationship of TURN, TACC, HEAD and PITCH. Figure 3 is a sample of a PASDATA card input set. Note that some parameters are not specified because the desired values agreed with the default option. Also note the capability to specify repeated values using a repetition factor.

```
$PASDATA

SEGLNT(1)=20.,30.,10.,30.,30.,40.,10.,10.,50.,10.,10.,10.,50.,10.,40.5,
50.,40.,

TURN(1)=4,3,4,3,2,2,1,2,4,2,1,4,2,4,2,4,2,

NPATH(1)=17*1,

TACC(5)=1.,1.,0.5,5.,0.,5.,0.5,0.,4.,0.,2.,0.,2.,

PACC(7)=-.1,

PACC(11)=.1,

P  C(17)=1.,

HEAD(1)=0.,20.,0.,-20.,-30.,30.,0.,-90.,0.,-90.,0.,0.,365.,0.,-135.,0.,
135.,

PITCH(1)=0.,36.,0.,36.,0.,0.,5.,3*0.,-5.,

MODE(1)=17*1,

HMIN(1)=17*.0001,

DTO(1)=17*1.$
```

Figure 3 - Sample of PASDATA Input

TABLE 1 DEFINITION OF TURN PARAMETERS+

	Vertical Turn	Horizontal Turn	Sinusoidal Heading Change	Straight Flight
TURN(i)	1	2	3	4
TACC(i)	Magnitude of vertical turn centrifugal acceleration.	Magnitude of horizontal turn centrifugal acceleration.	Not used.	Not used.
HEAD(i)	Not used. Heading will change slowly if great circle path selected.	Change in heading angle (+~CW).	Amplitude off nominal of sinusoidal flight path.	Not used. Heading will change slowly if great circle path selected.
PITCH(i)	Change in pitch angle (+~up).	Not used. Pitch remains unchanged.	Frequency of heading rate of change.	Not used. Pitch remain unchanged.

+See text for units

3.3 Program Limitations (What Happens If ...)

PROFGEN will not begin profile generation until each parameter lies within its permitted range as specified in 3.1 and 3.2. Subroutine VALDATA range-checks NSEGT, LLMECH, VTO, PHEADO, PPITCHO, ALFAO, LATO, LONO, ROLRATE, SEGLNT, TURN, NPATH, TACC, HEAD, PITCH, DTO, MODE, ERROR, HMAX and HMIN. A message is printed for each range-check that fails and the program is terminated.

Error messages can also occur during profile generation (i.e. after TSTART). One such mid-run message occurs if and when the integrator reduces step size to HMIN and is still not able to satisfy the error criterion (ERROR). In such cases this message is printed:

THE INTEGRATION ERROR EXCEEDS ITS ALLOWED VALUE

When this occurs PROFGEN is designed to continue to run, doing the best it can with HMIN. The value of the result is questionable, however, and the best advice is to scrap the output, reduce HMIN by at least a factor of ten, and rerun the program.

Another mid-run error message occurs if and when the product of computed roll rate and minimum step size would produce a roll bank angle in excess of 90 degrees. Since the aircraft must bank to execute either a horizontal turn or a sine maneuver, excessive roll angles could occur in either type of maneuver. PROFGEN avoids this problem in a horizontal turn but succumbs to it in a sine maneuver; prior to each sine maneuver the program checks for the problem and, if it exists, prints the following warning message and then terminates execution.

CHKSHC MESSAGE - THE PRODUCT OF COMPUTED
ROLL RATE AND MINIMUM STEP SIZE EXCEEDS
90 DEGREES. BANK ANGLES IN EXCESS OF
90 DEGREES ARE NOT ALLOWED. PROGRAM
TERMINATED.

Again the solution is to reduce HMIN for that segment.

Another mid-run message occurs if and when the cosine of pitch is exactly zero. This would happen, of course, if pitch magnitude were exactly $\Pi/2$ radians (90 degrees). At 90 degrees, the algorithm for computing yaw rate and roll rate would make both of these quantities infinite. PROFGEN recognizes the situation and prints the following warning message from subroutine ETADOT.

ROLL AND YAW RATES ARE UNDEFINED
WHEN PITCH IS 90 DEGREES. THUS
ALL RATES HAVE BEEN TEMPORARILY
ZEROED.

No divisions by zero are attempted so the program continues to execute. In short PROFGEN handles a pitch angle of $\pm$ 90 degrees by avoiding the fatal rate computations.

If latitude becomes $\pm$ 90 degrees, PROFGEN attempts a division by zero in LAMDOT and suffers a fatal error in which the CDC operating system kicks the program off the machine. Similar zero-division failures occur when one attempts a horizontal plane maneuver (horizontal turn or sine maneuver) with horizontal velocity equal zero, or when a vertical turn is attempted with total velocity equal zero, or when the aircraft is flown into the earth's center. Other zero-division situations would be even rarer than these and are not worth mentioning.

3.4 What to Expect from Each Maneuver

This section describes each maneuver in depth to see what it does and how it does it. These descriptions form the basis for the development of the control equations in Section 4.3.

3.4.1 Vertical Turn

A vertical turn is a pitch-up or pitch-down maneuver that takes place in a vertical plane. As with all maneuvers, vertical turns begin executing at the start of a segment (TI). Pitch angle advances, at a rate controlled by TACC and aircraft speed, until the time in the segment runs out at TF or until the change-in-pitch reaches PITCH degrees at TDONE, whichever time comes first. Altitude, pitch and acceleration curves for two vertical turns are shown in Figure 4.

Let a_n represent turn acceleration normal to the flight path. PROFGEN holds a_n (=TACC fps^2) constant while pitch advances. Since

$$a_n = \frac{V^2}{r} = V\dot{\theta} \qquad (1)$$

the turn's radius of curvature, r, and its advancement rate, $\dot{\theta}$, are also constant as long as total speed, V, remains fixed.

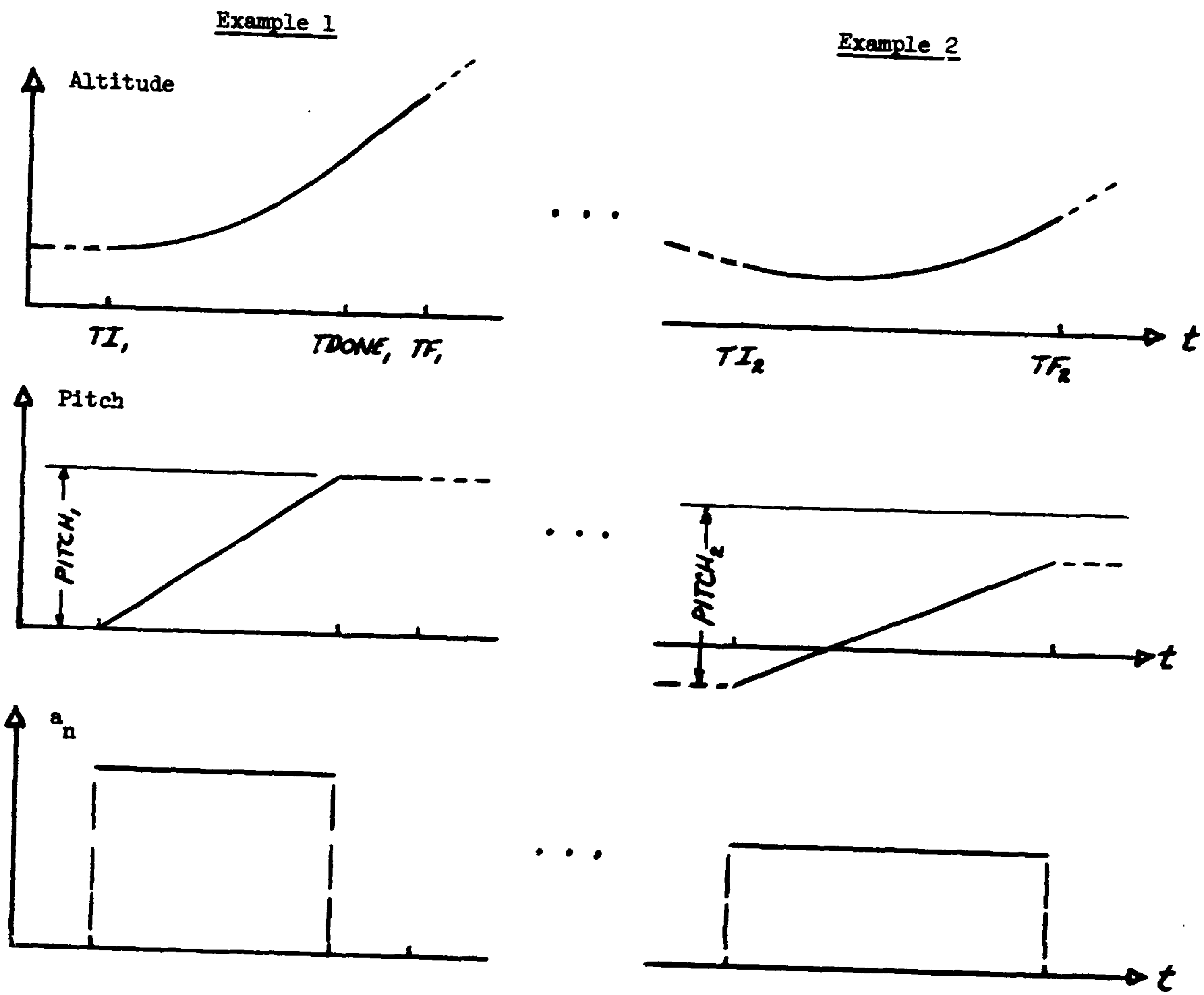


Figure 4 - Two Examples of Constant-Speed Vertical Turns

Turning action is enabled by switching $\dot{\theta}$ on at TI and then off at min (TF, TDONE). This produces a pitch-rate discontinuity at min (TF, TDONE) that the numerical integrator, KUTMER, cannot handle. PROFGEN solves the problem by splitting the segment into two pieces, one from TI to TDONE and the other from TDONE to TF. (If TDONE > TF, only one piece is necessary, viz. TI to TF.) KUTMER integrates the two disjoint pieces separately and thereby avoids a time step that would span the pitch-rate discontinuity.

The switching action on $\dot{\theta}$ may be observed in the program's pitch-rate output which is a non-zero constant while pitch is advancing and zero thereafter. Vertical plane maneuvers induce no rolling or yawing motion.

TDONE is computed in subroutine TSETUP1 before segment integration begins. The computation for TDONE assumes two things:

- turn acceleration is constant
- total speed does not drop to zero

The first assumption is guaranteed by the program's construction. The user must guarantee the second assumption by choosing PACC so total speed will remain positive. When these assumptions hold the aircraft's PITCH angle will advance exactly PITCH degrees in the interval TI to TDONE as illustrated in Example 1 of Figure 4. If TDONE exceeds TI, the change-in-pitch will fall short of PITCH as illustrated in Example 2 of Figure 4.

The minimum time required to complete a vertical turn through an arbitrary pitch angle $\Delta\theta$ is as follows:

$$\Delta t = \begin{cases} \dfrac{V_0 \, \Delta\theta}{a_n} , & \dot{V}_0 = 0 \\ \dfrac{V_0}{\dot{V}_0}\left(\exp\left(\dfrac{\dot{V}_0}{a_n}\Delta\theta\right) - 1\right) , & \dot{V}_0 \neq 0 \end{cases} \qquad (2)$$

where Δt = time required to pitch through $\Delta\theta$ radians (>0)

V_o = total speed at TI (>o)

$\Delta\theta$ = turn angle = |PITCH| (>o)

a_n = normal turning acceleration = TACC (>o)

$\dot{V}_o$ = tangential acceleration = PACC

A derivation of this result is given in Section 4.3.2. Equation (2) is useful for computing flight time in a pitch maneuver.

3.4.2 Horizontal Turn

In a horizontal turn the aircraft heading swings left or right to force the aircraft to follow a pseudo-circular path over the ground. Such a turn can be performed in any pitch attitude except ± 90 degrees. Horizontal turns are always performed in coordinated fashion. (Coordinated turns are also termed symmetric.) A coordinated turn is one in which the aircraft roll (bank) angle is controlled so that the vector sum of the horizontal turning force and the vertical force of "gravity" (defined for this purpose as 32.2 ft/sec^2) acts perpendicular to the wings. For example, in a level one-gee turn to the pilot's right, the aircraft rolls about its long axis to a bank angle of 45 degrees, right wing down. Because heading and roll must both be controlled, the software implementation for the horizontal turn is more complex than that for the vertical turn.

As was true with pitch in the vertical turn, heading advances in the horizontal turn until the time in the segment runs out at TF or until the change-in-heading reaches HEAD degrees at TDONE, whichever time comes first. Another way to say this is that the aircraft turns in the time interval between TI and min (TF, TDONE). During this turning interval, while heading advances continuously, roll also goes through its own set of gyrations in order to implement a coordinated turn. Representative roll curves are shown in Figure 5.

Note that roll always begins and ends at zero and remains in the interval $(-90^\circ, +90^\circ)$. Also note that when roll changes, it does so at the constant rate, ROLRATE.

In contrast to the vertical turn where a_n was constant, a_n for the horizontal turn follows a curve similar in shape to the roll curves from Figure 5. a_n is given by

$$a_n(t) = 32.2 \cos(\eta_y) \tan(\eta_x(t)) \qquad (3)$$

where η_y is (constant) pitch and η_x is roll. Note that, since η_x varies with time, a_n does also thereby producing a path with a variable radius of curvature. (The radius of curvature is infinite at the two ends of the turn and reaches a minimum when bank angle peaks.) Lat-long, yaw, roll and acceleration curves for two horizontal turns are shown in Figure 6.

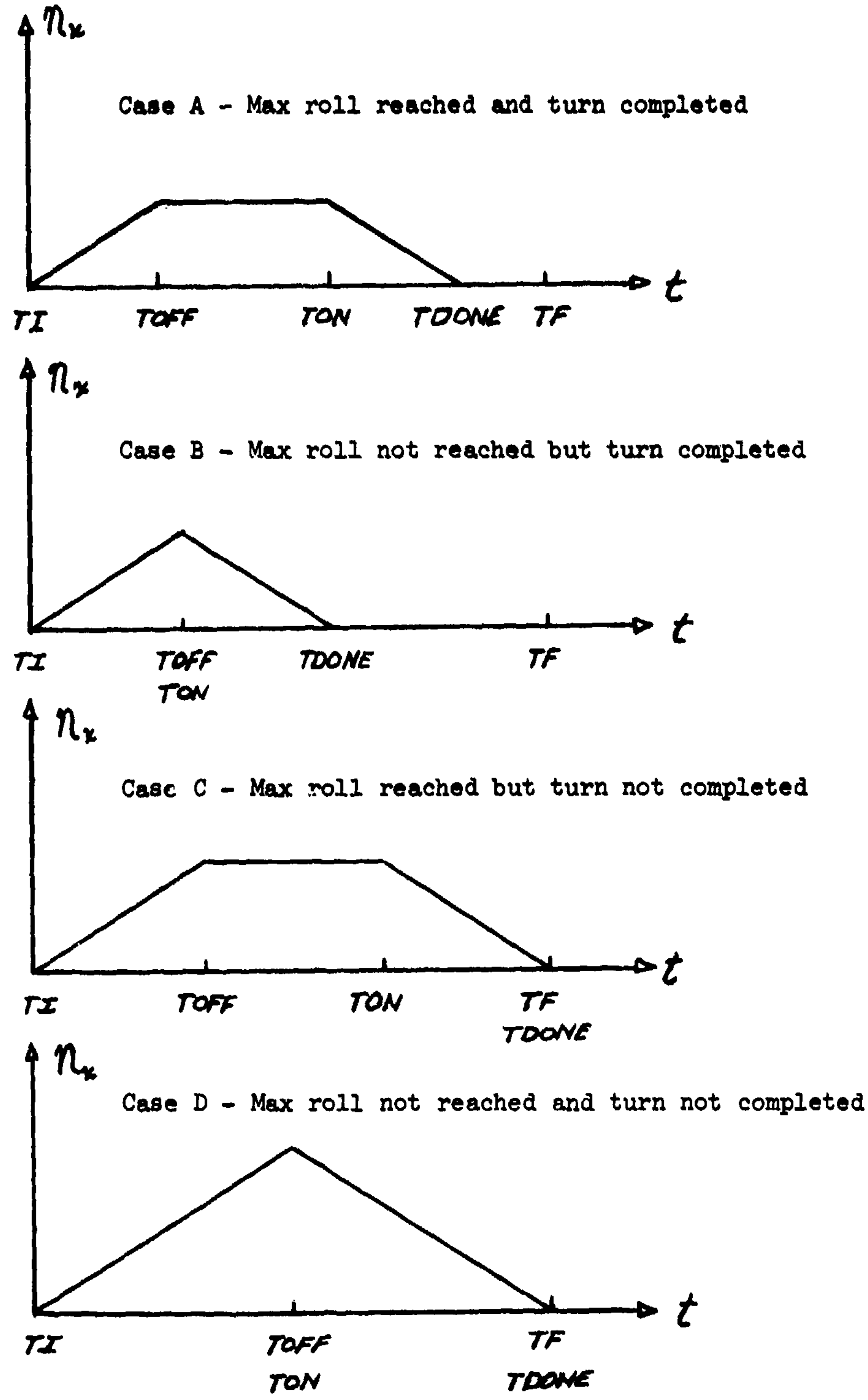


Figure 5 - Roll Angle Behavior in a Horizontal Turn

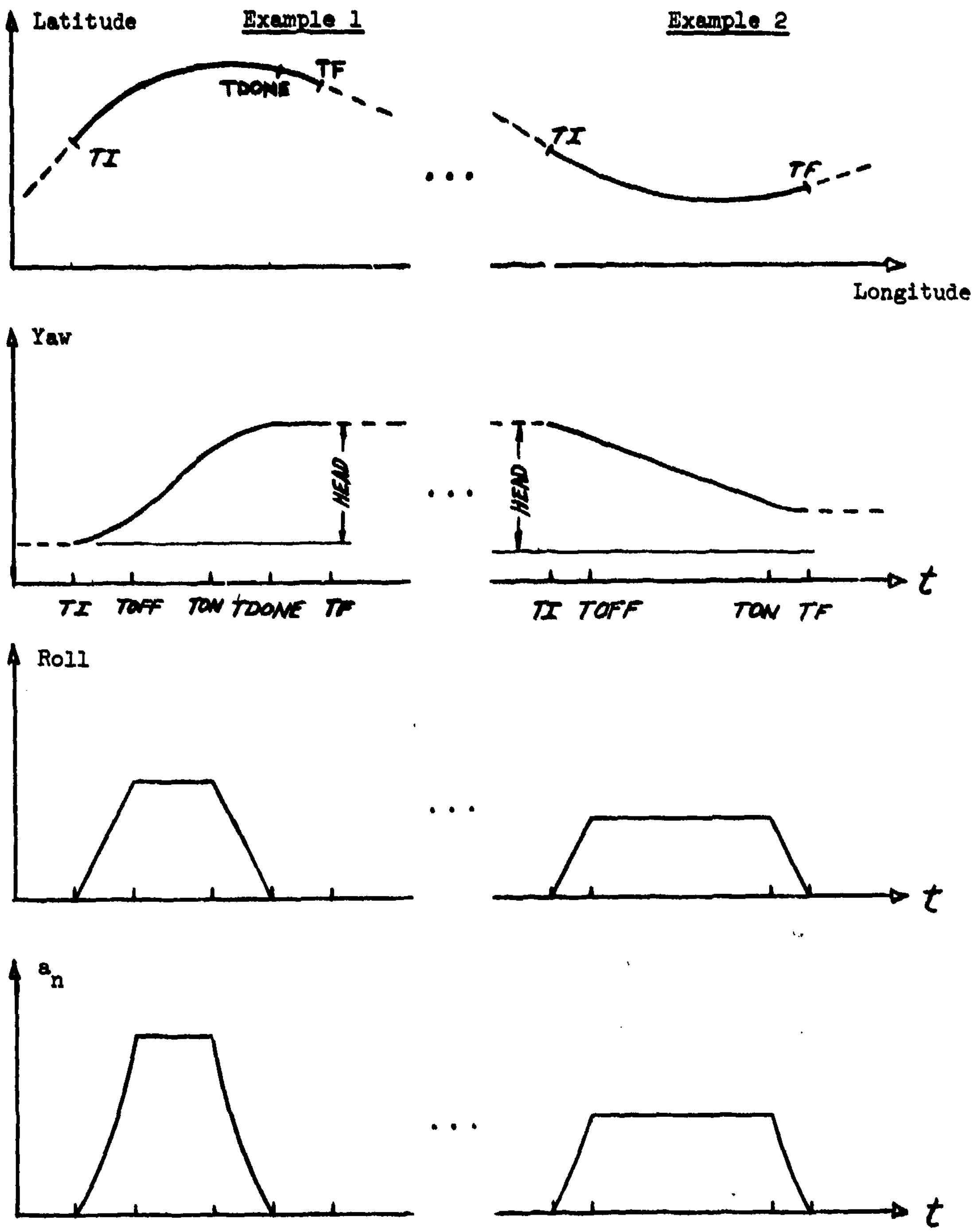


Figure 6 - Two Examples of Constant-Speed Horizontal Turns

It is apparent from Figure 5 that roll rate has from one to three points of discontinuity within the segment - one in Case D, two in B and C and three in A. Again, the numerical integration problem that this presents is handled by piecewise integration as explained in Section 3.4.1.

Before integration begins, time points TOFF, TON and TDONE (defined in Fig. 5) are computed in subroutine TSETUP2. The condition on TDONE is that heading at TDONE should be different from heading at TI by HEAD degrees. To compute TDONE, TSETUP2 must account for variations in both acceleration ($a_n(t)$) and speed. The exact equations for doing this are very non-linear and have been approximated in PROFGEN as quadratics in TDONE. If TSETUP2 finds TDONE is larger than TF it makes TDONE equal to TF to keep the turn within the time limit of the segment. Once TDONE is known, TOFF and TON are easily computed based on max roll angle and ROLRATE. As in the vertical turn, PROFGEN assumes that speed remains positive throughout the turn segment, a condition that the user must guarantee.

The following equation is an approximate expression for the time required to complete a turn through $\Delta\psi$ radians.

$$\Delta t = \begin{cases} \dfrac{V_0 \, \Delta\psi}{a_n} \cos \eta_y + 2\,(TOFF - TI) & , \dot{V}_0 = 0 \\ \dfrac{V_0}{\dot{V}_0}\left(\exp\left(\dfrac{\dot{V}_0 \, \Delta\psi}{a_n} \cos \eta_y\right) - 1\right) + 2\,(TOFF - TI) & , \dot{V}_0 \neq 0 \end{cases} \qquad (4)$$

where

Δt = time required to turn $\Delta\psi$ radians (>o)

V_o = total speed at TI (>o)

$\Delta\psi$ = turn angle = |HEAD| (>o)

a_n = normal turning acceleration = TACC (>o)

$\dot{V}_o$ = tangential acceleration = PACC

2(TOFF-TI) = time required to roll into and out of turn

$$= 2 \tan^{-1} \left\{ \frac{a_n}{32.2 \cos(n_y)} \right\} \Big/ \text{ROLRATE}$$

This equation is approximately correct for a turn that rolls quickly to its maximum bank angle, holds that angle for awhile and then rolls quickly back to zero (Case A in Figure 5). The error in this equation grows large as $\Delta\psi$ and ROLRATE grow smaller and as PACC and TACC grow larger.

3.4.3 Sine Maneuver

In a sine maneuver the aircraft follows a ground path like that of Figure 7a. This path results when ground heading, $\psi(t)$, is controlled by the equation

$$\psi(t) = \begin{cases} +A \sin^2 \omega t & , \quad 0 \le t < T_p/2 \\ -A \sin^2 \omega t & , \quad T_p/2 \le t < T_p = 2\pi/\omega \end{cases} \qquad (5)$$

where A is maximum heading variation (HEAD) and w is oscillation frequency (PITCH).

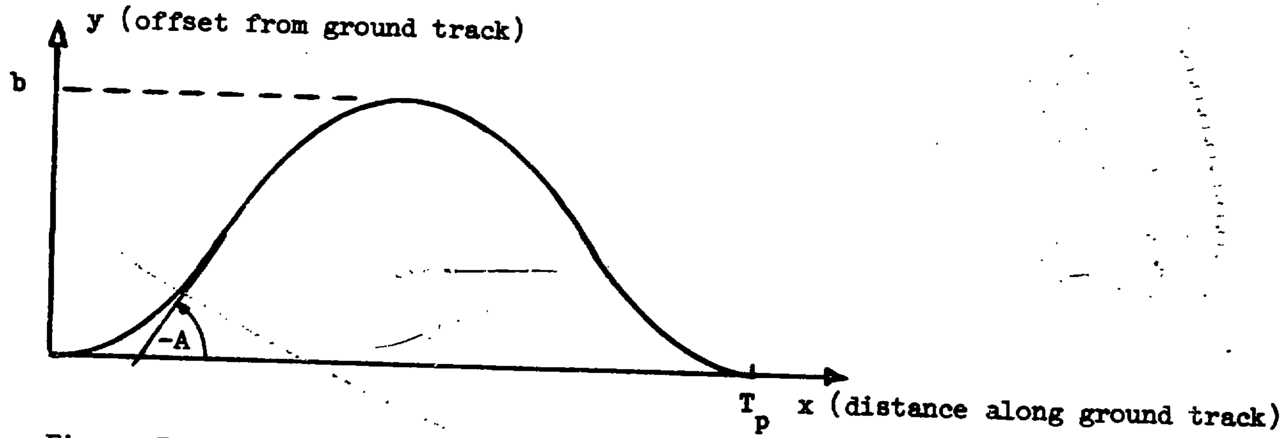


Figure 7a

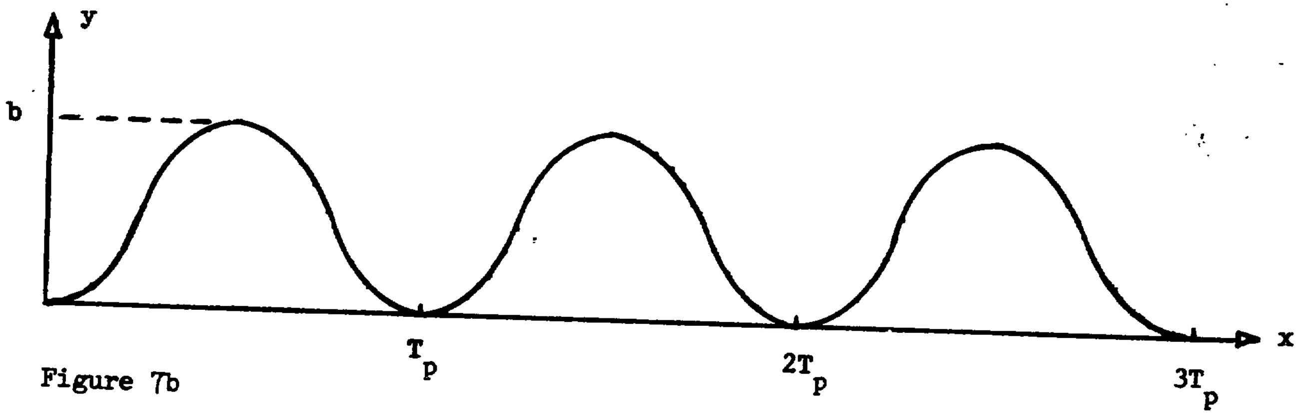


Figure 7b

Figure 7 - Sine Maneuver Ground Tracks

Repeated cyles of 7a are shown in 7b and are produced by simply iterating the above equation to yield a longer maneuver similar to jinking. Note that neither 7a or 7b are properly scaled.

A sine maneuver may execute in any pitch attitude except ±90 degrees and is always performed in coordinated fashion. Again, heading and roll must both be controlled but the governing equation is the one for heading given above. The companion equation for roll that produces coordinated maneuvers is

$$\eta_x = \tan^{-1}\left\{ \frac{VA\omega}{32.2} \sin(2\omega t) \right\} \qquad (6)$$

where V is total speed. Since $\dot{\eta}_x$ has no discontinuities, the numerical integration can proceed uninterrupted and the sine maneuver thereby avoids complex event-time calculations like those for a horizontal turn.

Figure 8 shows ground track, roll and heading curves (to scale) for a sine maneuver where A is -20°, T_p is 10 seconds, V is 1000 fps and SEGLNT is 12.5 seconds. Note that roll passes through zero at multiples of $T_p/4$ seconds so that the aircrafts wings are level when the segment is finished at 12.5 seconds.

3.4.4 Straight Flight

Complete straight-flight segments occur when TURN is 4 and partial segments occur anytime a vertical or horizontal turn has reached its max turn angle with time remaining in the segment. Neither roll nor

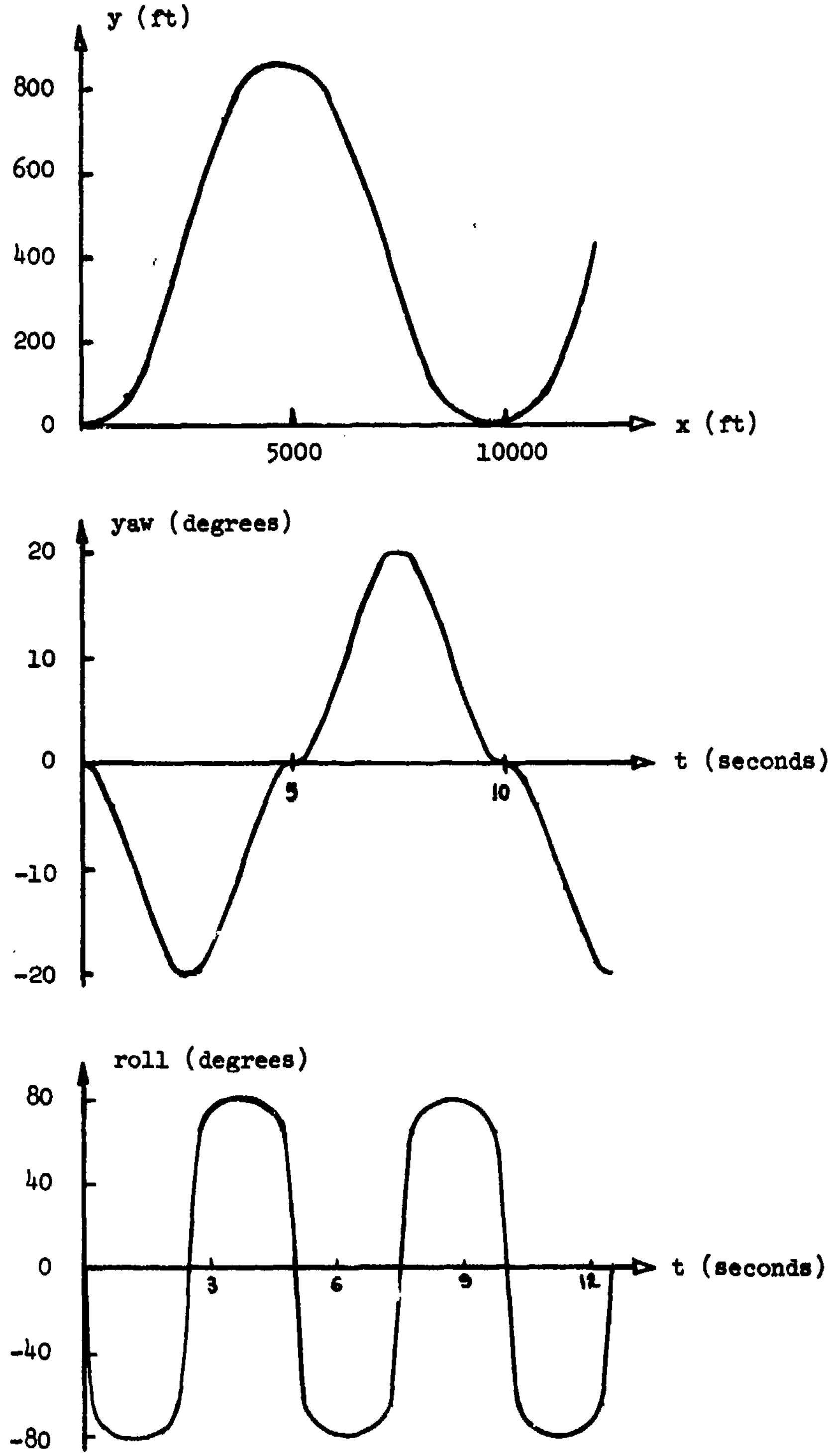


Figure 8 - Example of Sine Maneuver

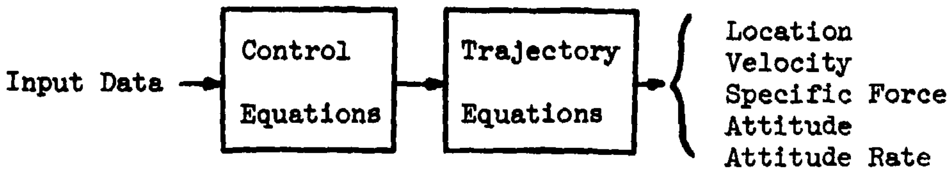
pitch vary in straight flight segments and heading is governed by the users choice of nominal path (NPATH). Heading is constant over a rhumb line path whereas, for a great circle path, heading must vary to keep the aircraft in the great circle plane. Rhumb line flights that continue long enough spiral in on one of the earth's poles and end up causing a division-by-zero failure.

Total speed, which had to remain positive during turning maneuvers, may be zero in straight flight segments. At such times, aircraft position is fixed and attitude is that which existed just prior to speed becoming zero.

To aid the user in constructing straight flight segments between locations over the earth, a program called HEADING has been written. In response to user inputs of lat, lon and altitude at origin and destination, HEADING computes the heading angle at origin needed to reach destination over a great circle path. HEADING also computes the great circle distance from origin to destination. HEADING is a double precision FORTRAN program that can be made available to interested users.

IV. ANALYTICAL DEVELOPMENT

This section develops the equations that govern the trajectory of an aircraft under continuous control in the earth's gravity field. These equations can be conveniently divided into two groups, control equations and trajectory equations, which are related schematically as follows:



The control equations are the relationships that specify turn rates according to the user's input data.

The trajectory equations are a collection of differential and algebraic equations that produce position, velocity, specific force, attitude and attitude rate in response to the imposed control. They are, in short, the equations of motion for a body free to move in six directions in inertial space.

The trajectory equations are kinematic relationships, i.e. they deal with motion in the abstract without reference to force or mass. Since force/mass concepts are immaterial, PROFGEN avoids all aircraft-specific considerations such as moment of inertia, aerodynamic force and thrust force. It follows that the aircraft modeled here is a weightless body that can be displaced and rotated, without restriction, to suit the users demands.

In the following development those equations that became part of the actual code in PROFGEN have stars (*) beside their numbers.

4.1 Coordinate System Descriptions and Relationships

The coordinate systems of particular interest in this report are the inertial, earth, navigation and path systems. These four systems, or frames, will be defined shortly as right-handed orthogonal frames. The relationship of the earth and navigation frames will determine aircraft location (longitude, latitude, alpha) while that of the navigation and path frames will determine attitude (roll, pitch, yaw). Location and attitude data will be carried in two direction cosine matrices (C_e^n and C_p^n) that describe the rotations between pairs of coordinate frames. The subsequent portions of this section describe the four frames, define the two direction cosine matrices and delineate the extraction of location and attitude angles from each of these matrices.

4.1.1 Frame Descriptions

- Inertial frame (i frame: X_i, Y_i, Z_i axes)

  The inertial frame has its origin at the earth's center of mass and is non-rotating relative to the stars. This frame is important mainly as it applies to the computation of specific force. Its relationship to the earth frame is portrayed in Figure 9.

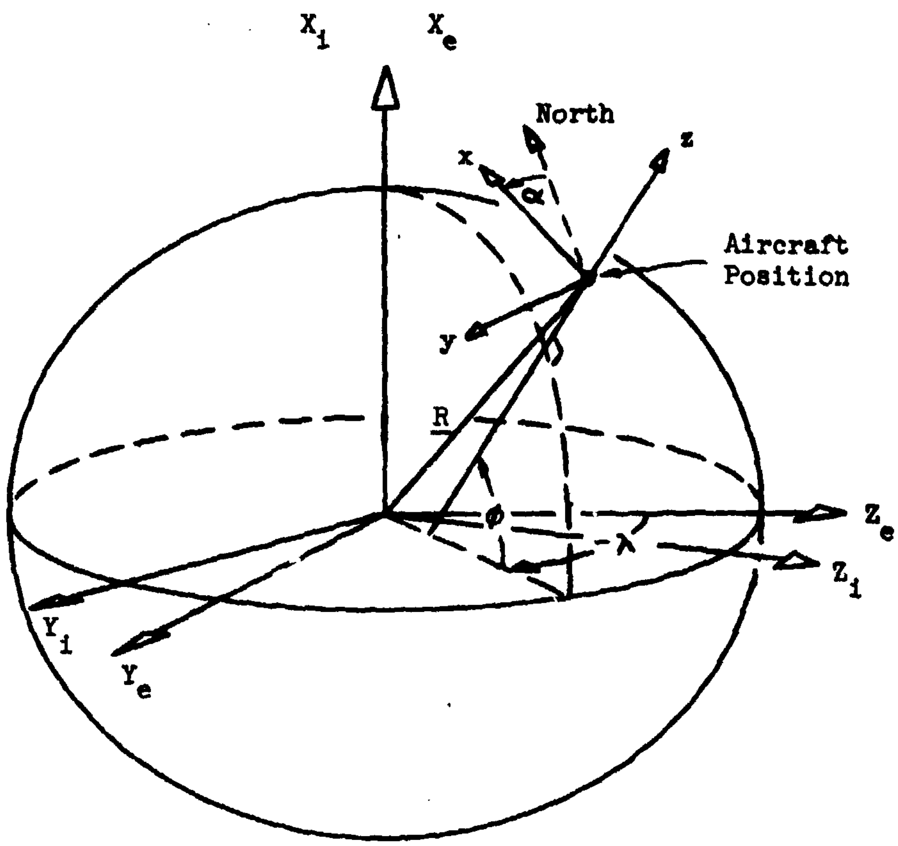


Figure 9 - Earth, Inertial and Navigation Coordinate Frames

- Earth frame (e frame: X_e, Y_e, Z_e axes)

  The earth frame has its origin at the earth's center of mass and has axes fixed in the earth, Figure 9. Axes Y_e, Y_i, Z_e and Z_i all lie in the earth's equatorial plane while axes X_e and X_i are coincident, passing through both poles. The rate of rotation between these two frames is the earth sidereal rate, designated Ω. WGS-72 (Reference 1) gives this value for Ω which is denoted WEI in PROFGEN:

$$\Omega = 0.7292115147 \times 10^{-4} \text{ rad/sec}$$

- Navigation frame (n frame: x, y, z axes)

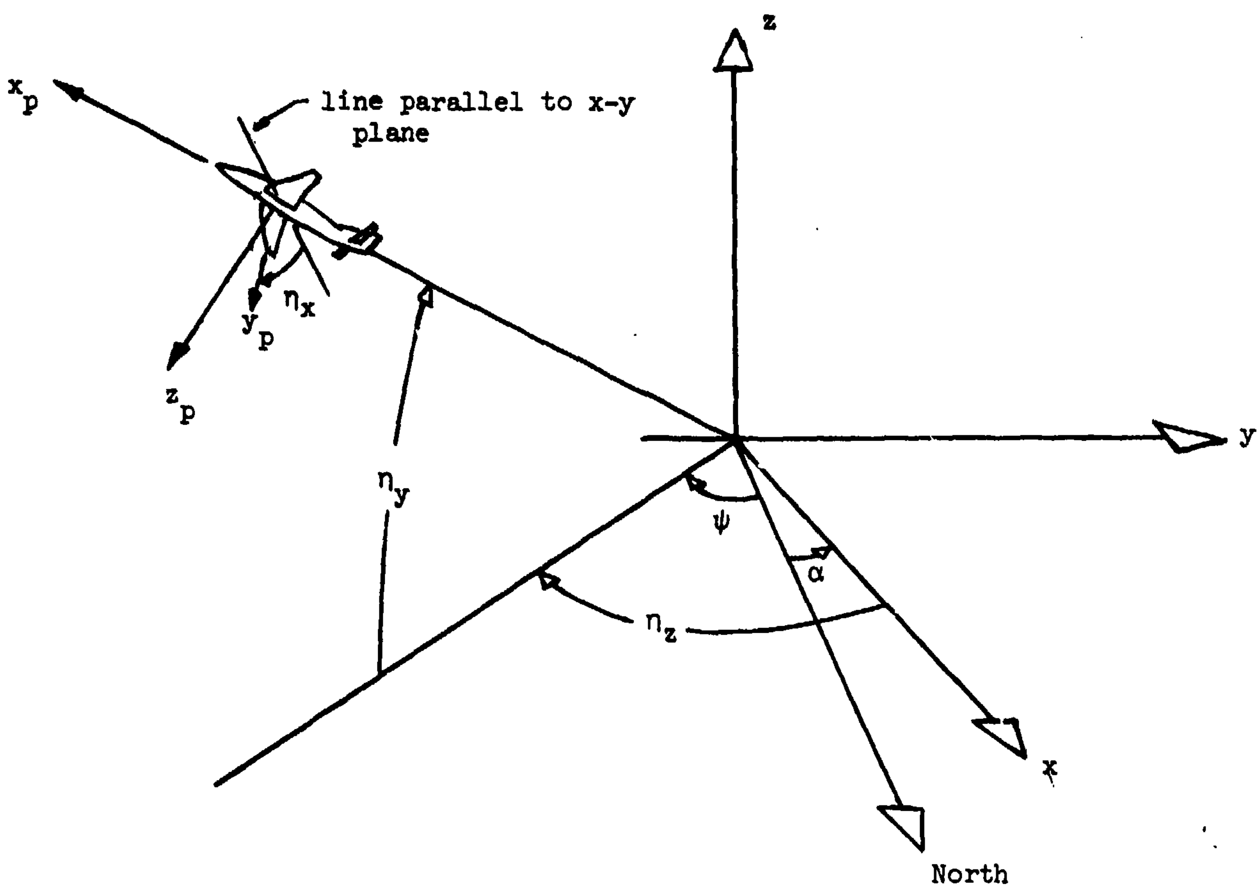
  This locally-level frame has its origin at the aircraft center of mass with x and y in a plane tangent to the reference ellipsoid and z perpendicular to the ellipsoid, Figure 9. (Center of mass and center of rotation are coincident in this development). PROFGEN solves the trajectory equations in the navigation frame. Aircraft location is specified relative to the earth frame by the three-tuple (λ, ϕ, α) where λ is longitude, ϕ is geographic latitude and α is the navigation frame heading angle, referred to variously as alpha, wander angle or wander azimuth angle. Figure 9 shows that ϕ is geographic latitude, not geocentric latitude. Thus z is normal to the elliptical surface of the earth rather than in the direction of the earth center. The values for λ, ϕ, and α will be computed from the direction cosine matrix C_e^n.

- Path frame (p frame: x_p, y_p, z_p axes)

The path frame, depicted in Figure 10, has its origin at the aircraft center of mass. It takes its name from the fact that the x_p-axis follows the aircraft path by staying aligned with the total velocity vector, $\underline{V}$. ($\underline{V}$, velocity with respect to the earth, will be defined precisely in Section 4.2.3)

In general $\underline{V}$ is misaligned from the aircraft's longitudinal axis by an angle of attack and a crab angle. In this development we assume these angles are zero. The effect of this assumption is to weld the path frame to the aircraft's body thus causing x_p to pass through the aircraft nose and y_p to point out the right wing. z_p points down in level flight but rotates about x_p during coordinated turns so there is never any maneuver acceleration along y_p.

Since path and body are coincident, the familiar body frame terms of roll, pitch and yaw will be borrowed to describe the Euler angles between the path and navigation frames. Roll, pitch and yaw are denoted η_x, η_y and η_z and are



Note: Origin of path frame displaced from that of nav frame only for clarity of diagram; they are actually coincident at aircraft center of mass.

<u>Figure 10</u> - <u>Navigation and Path Coordinate Frames</u>

measured around x_p, y_p and z_p respectively. A right turn produces a positive yaw rotation, a pitch up is a positive pitch rotation, and a clockwise roll (as viewed from behind the aircraft) is a positive roll rotation. The values of η_x, η_y and η_z will be computed from the direction cosine matrix C_p^n.

4.1.2 Frame Relationships: Direction Cosines and Euler Angles

- Earth and Navigation Frames

Figure 9 presents the relationship between the earth and navigation frames. When λ, ϕ and α are zero, the navigation frame is directionally aligned with the earth frame. Beginning at the aligned position, the rotations necessary to go from earth to nav coordinates form the direction cosine matrix C_e^n. This matrix is the ordered product of three individual matrices describing these rotations: an x rotation of λ degrees, a y rotation of ϕ degrees and a z rotation of α degrees. Using an "s" prefix for the trigonometric sine and a "c" prefix for the cosine, C_e^n is

$$C_e^n = \begin{bmatrix} c\alpha & s\alpha & 0 \\ -s\alpha & c\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\phi & 0 & -s\phi \\ 0 & 1 & 0 \\ s\phi & 0 & c\phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\lambda & s\lambda \\ 0 & -s\lambda & c\lambda \end{bmatrix} \qquad (7)$$

Now if the elements of C_e^n are identified as

$$C_e^n = \begin{bmatrix} CEN_{11} & CEN_{12} & CEN_{13} \\ CEN_{21} & CEN_{22} & CEN_{23} \\ CEN_{31} & CEN_{32} & CEN_{33} \end{bmatrix}$$

then the individual elements are

$$\begin{aligned}
CEN_{11} &= \cos\alpha \cos\phi \\
CEN_{21} &= -\sin\alpha \cos\phi \\
CEN_{31} &= \sin\phi \\
CEN_{12} &= \sin\alpha \cos\lambda + \cos\alpha \sin\phi \sin\lambda \\
CEN_{22} &= \cos\alpha \cos\lambda - \sin\alpha \sin\phi \sin\lambda \\
CEN_{32} &= -\cos\phi \sin\lambda \\
CEN_{13} &= \sin\alpha \sin\lambda - \cos\alpha \sin\phi \cos\lambda \\
CEN_{23} &= \cos\alpha \sin\lambda + \sin\alpha \sin\phi \cos\lambda \\
CEN_{33} &= \cos\phi \cos\lambda
\end{aligned} \qquad (9)^*$$

* Coded for implementation in PROFGEN.

To extract latitude, longitude and alpha from the elements of C_e^n, the following calculations are made

$$\phi = \sin^{-1}(CEN_{31}) \qquad , \phi \in [-\pi/2, +\pi/2] \qquad (10)^*$$

$$\lambda = \tan^{-1}(-CEN_{32}/CEN_{33}) , \lambda \in [-\pi, +\pi] \qquad (11)^*$$

$$\alpha = \tan^{-1}(-CEN_{21}/CEN_{11}) , \alpha \in [-\pi, +\pi] \qquad (12)^*$$

where the initial values for ϕ, λ and α are

ϕ = LATO

λ = LONO

α = ALFAO

The FORTRAN functions SIN (·) and ATAN2 (· , ·) were used to implement (10), (11) and (12) because their range agrees with that desired for ϕ, λ and α. An important aspect of the computation for λ in Equation (11) is that $\phi \in [-\pi/2, \pi/2]$, which means cos (ϕ) is always positive, which in turn makes the sign of CEN_{32} and CEN_{33} depend solely on λ, which removes any doubt as to the quadrant where λ lies. A similar statement applies to α as computed in (12).

● Path and Navigation Frames

Figure 10 presents the relationship between the path and navigation frames. Beginning at the nonaligned position shown there, the ordered sequence of rotations necessary to form the C_p^n matrix is as follows: a roll about x_p of η_x degrees to get the wings level; a pitch about y_p of η_y degrees to get the nose level; a yaw about z_p of η_z degrees to align the x_p and x axes; finally, a flip about x_p of 180° to align z_p, which is nominally down, with z which is always up. Thus

$$C_p^n = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} c\eta_z & -s\eta_z & 0 \\ s\eta_z & c\eta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\eta_y & 0 & s\eta_y \\ 0 & 1 & 0 \\ -s\eta_y & 0 & c\eta_y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\eta_x & -s\eta_x \\ 0 & s\eta_x & c\eta_x \end{bmatrix}$$

Now if the elements of C_p^n are identified as

$$C_p^n = \begin{bmatrix} CPN_{11} & CPN_{12} & CPN_{13} \\ CPN_{21} & CPN_{22} & CPN_{23} \\ CPN_{31} & CPN_{32} & CPN_{33} \end{bmatrix} \qquad (14)$$

then the individual elements are

$$CPN_{11} = \cos\eta_z \cdot \cos\eta_y$$

$$CPN_{21} = -\sin\eta_z \cdot \cos\eta_y$$

$$CPN_{31} = \sin\eta_y$$

$$CPN_{12} = \cos\eta_z \cdot \sin\eta_y \cdot \sin\eta_x - \sin\eta_z \cdot \cos\eta_x$$

$$CPN_{22} = -\sin\eta_z \cdot \sin\eta_y \cdot \sin\eta_x - \cos\eta_z \cdot \cos\eta_x \qquad (15)^*$$

$$CPN_{32} = -\cos\eta_y \cdot \sin\eta_x$$

$$CPN_{13} = \cos\eta_z \cdot \sin\eta_y \cdot \cos\eta_x + \sin\eta_z \cdot \sin\eta_x$$

$$CPN_{23} = \cos\eta_z \cdot \sin\eta_x - \sin\eta_z \cdot \sin\eta_y \cdot \cos\eta_x$$

$$CPN_{33} = -\cos\eta_y \cdot \cos\eta_x$$

Roll, pitch and yaw are extracted from the elements of C_p^n as follows:

$$\eta_x = \tan^{-1}(-CPN_{32} / -CPN_{33}) \quad , \eta_x \in [-\pi, +\pi] \qquad (16)^*$$

$$\eta_y = \sin^{-1}(CPN_{31}) \quad , \eta_y \in [-\pi/2, +\pi/2] \qquad (17)^*$$

$$\eta_z = \tan^{-1}(-CPN_{21} / CPN_{11}) \quad , \eta_z \in [-\pi, +\pi] \qquad (18)^*$$

where the initial values are

$$\eta_x = 0$$

$$\eta_y = \text{PPITCHO}$$

$$\eta_z = \text{ALFAO} + \text{PHEADO}$$

Again SIN (·) and ATAN2 (· , ·) were used to implement (16), (17) and (18). As with λ and α, the key to the computations in (16) and (18) lies in the fact that η_y has a restricted range which makes its cosine always positive. The relationship between α, η_z and ψ (heading) is illustrated in Figure 11.

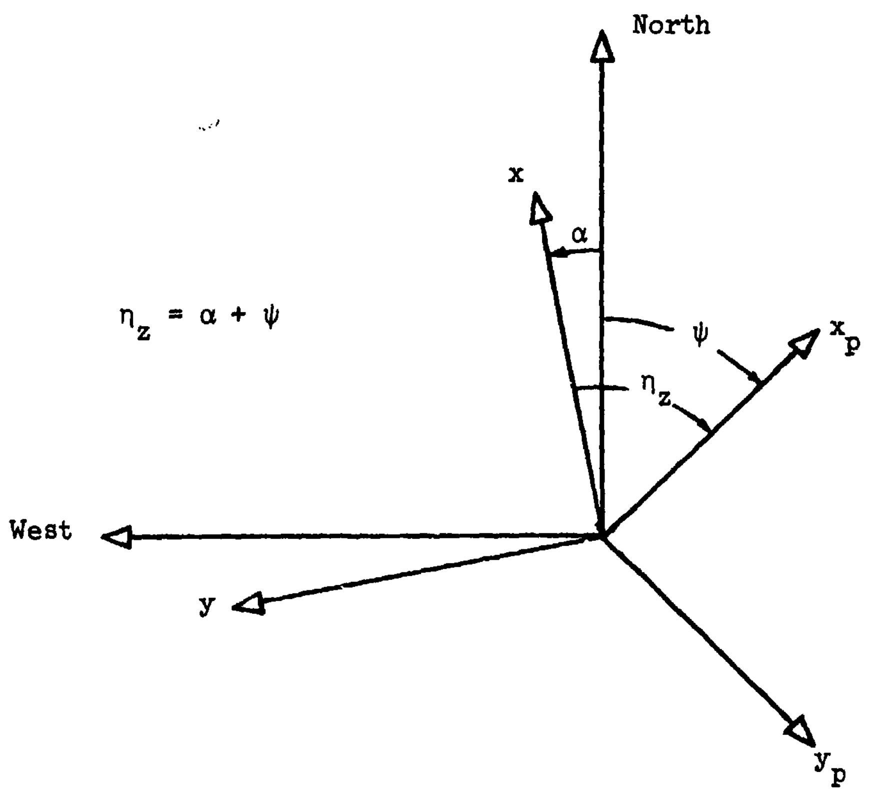


Figure 11 - Relationship of η_z, α and ψ

4.2 Trajectory Equations

Sections 4.2.1, 4.2.2 and 4.2.3 will develop first order differential equations to describe the motion of a body in six degrees of freedom. Section 4.2.4 defines the states of the state vector, $\underline{x}$. The companion algebraic relationships for specific force, attitude rates and plumb-bob gravity will be developed in Section 4.2.5.

4.2.1 Direction Cosine Rates: Location and Attitude

At least three methods are available for keeping track of the rotation angles between frames, including direct integration of the Euler angle rates, propagation of four quaterion parameters representing a complete direction cosine matrix (Reference 5), and propagation of the direction cosine matrix. The last approach was chosen for PROFGEN because of its simplicity and versatility. This section derives a general expression for the direction cosine rate and then displays the result in notation appropriate to C_e^n and C_p^n.

For any two frames, a and b, the Theorm of Coriolis can be written for any vector $\underline{u}$ as

$$\left.\frac{d\underline{u}}{dt}\right|_a = \left.\frac{d\underline{u}}{dt}\right|_b + \underline{\beta}_{ba} \times \underline{u} \qquad (1)$$

This equation is in "physical vector" form. It states that the time rate of change of $\underline{u}$, as observed in the a frame (i.e. with respect to the a frame), equals the time rate of change of $\underline{u}$, as observed in the b frame, plus the angular rate of change of frame b with respect to frame a crossed onto $\underline{u}$. The addition and multiplication in (19) are physical-vector addition and physical-vector cross multiplication. When (19) is coordinatized in the a frame, these "math vector" relationships follow:

$$\left(\frac{d\underline{u}}{dt}\Big|_a\right)^a = \left(\frac{d\underline{u}}{dt}\Big|_b + \underline{\beta}_{ba} \times \underline{u}\right)^a$$

$$= \left(\frac{d\underline{u}}{dt}\Big|_b\right)^a + B_{ba}^a \underline{u}^a$$

$$= C_b^a \left(\frac{d\underline{u}}{dt}\Big|_b\right)^b + B_{ba}^a C_b^a \underline{u}^b$$

or

$$\dot{\underline{u}}^a = C_b^a \dot{\underline{u}}^b + B_{ba}^a C_b^a \underline{u}^b \qquad (20)$$

where B^a_{ba} is a "cross-matrix" that produces a result on a math vector identical to that of cross multiplication on a physical vector. B^a_{ab} is defined below. Continuing

$$\underline{\underline{u}}^a = C^a_b \underline{\underline{u}}^b$$

$$\dot{\underline{\underline{u}}}^a \triangleq \frac{d}{dt} \underline{\underline{u}}^a = \frac{d}{dt}\left(C^a_b \underline{\underline{u}}^b\right)$$

$$= C^a_b \dot{\underline{\underline{u}}}^b + \dot{C}^a_b \underline{\underline{u}}^b \qquad (21)$$

Equating (20) and (21) yields

$$\dot{C}^a_b \underline{\underline{u}}^b = B^a_{ba} C^a_b \underline{\underline{u}}^b$$

and, since $\underline{u}$ is any vector, it follows that

$$\dot{C}^a_b = B^a_{ba} C^a_b \qquad (22)$$

where

$$B_{ba}^{a} = \begin{bmatrix} 0 & -\beta_z & \beta_y \\ \beta_z & 0 & -\beta_x \\ -\beta_y & \beta_x & 0 \end{bmatrix} \qquad (23)$$

$$\begin{pmatrix} \beta_x \\ \beta_y \\ \beta_z \end{pmatrix} = \underset{\sim}{\beta}_{ba}^{a} \qquad (24)$$

The specific notation chosen to implement (22) and (24) for C_e^n and C_p^n is shown below:

$$\dot{C}_e^n = -\begin{bmatrix} 0 & -\rho_z & \rho_y \\ \rho_z & 0 & -\rho_x \\ -\rho_y & \rho_x & 0 \end{bmatrix} C_e^n \qquad (25)^*$$

where

$$\begin{pmatrix} \rho_x \\ \rho_y \\ \rho_z \end{pmatrix} \triangleq \underset{\sim}{\rho}_{ne}^{n} = -\underset{\sim}{\rho}_{en}^{n} \qquad (26)^*$$

Also

$$\dot{C}_p^n = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} C_p^n \qquad (27)^*$$

where

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \triangleq \underline{\omega}_{pn}^n \qquad (28)^*$$

For writing convenience, $\underline{\rho}_{ne}^n$ and $\underline{\omega}_{pn}^n$ will be referred to hereafter as $\underline{\rho}$ and $\underline{\omega}$. In (25) and (27) we have expressions for keeping track of location and attitude provided $\underline{\rho}$ and $\underline{\omega}$ can be computed. Sections 4.2.2 and 4.2.3 deal with $\underline{\rho}$. The computation for $\underline{\omega}$ will be given in Section 4.3 where turning rates are discussed.

4.2.2 Angular Rate - Nav Frame w.r.t. Earth Frame

$\underline{\rho}$ is the angular rate of the nav frame with respect to the earth frame. The fact that the x and y axes of the nav frame remain tangent to the earth will be used to derive expressions for ρ_x and ρ_y. ρ_z will be determined by the users choice of azimuth-angle mechanization.

Consider the geometry of Figure 12, a section of the earth ellipsoid, where V_N and V_W denote North and West velocity components. The North-West-Up (N-W-U) frame differs from the nav frame only by the rotation α. If $\underline{V}$ is earth frame velocity, its navigation frame components are denoted

$$\underline{V}^n \triangleq \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \tag{29}$$

Then from Figure 11, V_N, V_W, V_{UP} are given by

$$\begin{pmatrix} V_N \\ V_W \\ V_{UP} \end{pmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \qquad (30)^*$$

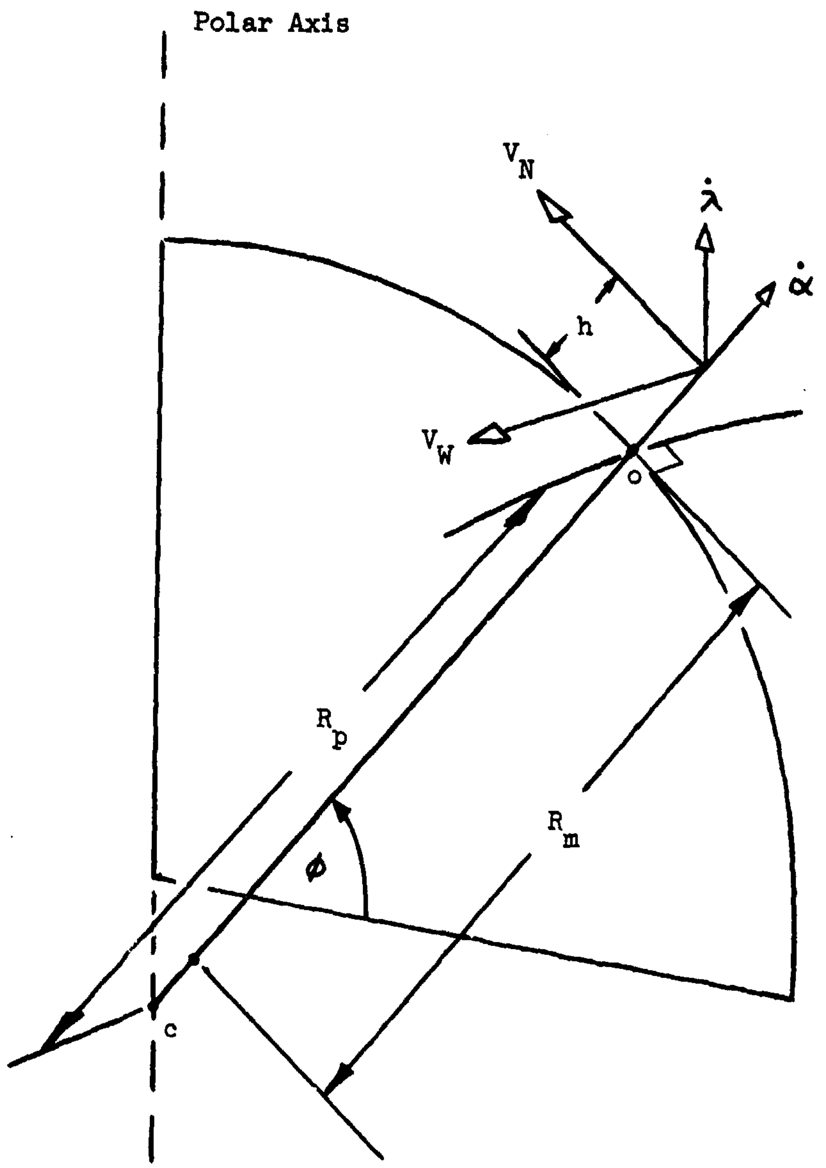


Figure 12 - Geometry for Deriving ρ

The angular rates required to keep the N-W-U frame level over the earth ellipsoid are deduced from Figure 12 as

$$\rho_N = \frac{-V_W}{R_p + h} \qquad (31)^*$$

$$\rho_W = \frac{V_N}{R_m + h} \qquad (32)^*$$

where h is altitude above the ellipsoid, R_m is the radius of curvature of an ellipsoid meridian line and R_p is the radius of curvature of the ellipsoid in a plane through the normal and at right angles to the meridian. (It can be shown that R_p is the distance $\overline{oc}$ where c lies on the polar axis.) R_m and R_p vary with ϕ according to the following equations (Ref. 2, pp 168-170):

$$R_m = \frac{R_e (1 - e^2)}{(1 - e^2 \sin^2 \phi)^{3/2}} \qquad (33)^*$$

$$R_p = \frac{R_e}{(1 - e^2 \sin^2 \phi)^{1/2}} \qquad (34)^*$$

where

$$e^2 = \text{eccentricity}^2 = \frac{R_e^2 - b^2}{R_e^2} = 0.006694317778 \text{ (WGS-72 data)}$$

$$R_e = \text{semimajor earth axis} = 20925640 \text{ feet (WGS-72)}$$

$$b = \text{semiminar earth axis} = 20855481 \text{ feet (WGS-72)}$$

ρ_N and ρ_W lie in the x-y plane of the nav frame and can be resolved into components along x and y as follows:

$$\begin{aligned} \rho_x &= \rho_N \cos\alpha + \rho_W \sin\alpha \\ \rho_y &= -\rho_N \sin\alpha + \rho_W \cos\alpha \\ \rho_z &= \rho_{UP} \end{aligned} \qquad (35)^*$$

The general relationship between ρ_z and α can be deduced from the geometry of Figure 12 as

$$\rho_z = \dot{\lambda} \sin\phi + \dot{\alpha} \qquad (36)^*$$

The value for $\dot{\alpha}$ depends on the azimuth angle mechanization (LLMECH) desired by the user. The various choices and the resulting ρ_z values are tabulated in Table 2.

LLMECH	Name	$\dot{\alpha}$	ρ_z
1	Alpha Wander	$-\dot{\lambda} \sin \phi$	0
2	Constant Alpha	0	$\dot{\lambda} \sin \phi$
3	Unipolar	$-J \dot{\lambda}$ †	$\dot{\lambda} (\sin \phi - J)$
4	Free Azimuth	$-(\Omega + \dot{\lambda}) \sin \phi$ ††	$-\Omega \sin \phi$

† $J \triangleq \text{sign} (\phi)$ †† $\Omega = 0.7292115147 \times 10^{-4}$ rad/sec

Table 2 - Azimuth Angle Mechanization Schemes

Figure 13, a section of the earth, is drawn so V_W is perpendicular to the paper at the indicated point. (Note again that R_p terminates on the polar axis.) Examination of this figure shows that the equation for $\dot{\lambda}$ is

$$\dot{\lambda} = \frac{-V_W}{(R_p + h) \cos \phi} \qquad (37)^*$$

ρ_x, ρ_y and ρ_z, as derived in this section, depend on α, ϕ, V_x, V_y and V_z. α and ϕ can be obtained from C_e^n using Equations (10) and (12) while expressions for V_x, V_y and V_z will be derived in the next section.

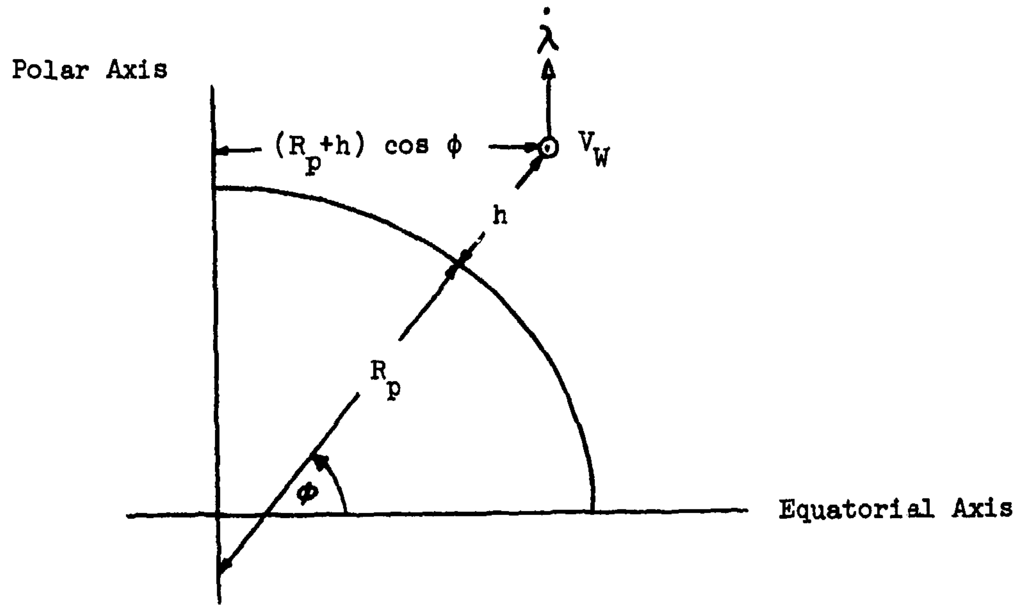


Figure 13 - Geometry for Deriving $\dot{\lambda}$

4.2.3 Velocity w.r.t. Earth

Referring now to Figure 9, the vector $\underline{R}$ connects the earth's center with the aircraft location at all times. By definition of $\underline{V}$ and by Coriolis' Law

$$\underline{V} \triangleq \left.\frac{d\underline{R}}{dt}\right|_e \tag{38}$$

$$\left.\frac{d\underline{V}}{dt}\right|_n = \left.\frac{d\underline{V}}{dt}\right|_p + \underline{\omega}_{pn} \times \underline{V} \tag{39}$$

Coordinatize (39) in the nav frame and use (22) and (28) to produce the following equivalent expressions in math-vector form:

$$\left(\frac{d\underline{V}}{dt}\bigg|_n\right)^n = \left(\frac{d\underline{V}}{dt}\bigg|_p\right)^n + \Omega^n_{pn}\ \underline{V}^n$$

$$\triangleq \left(\frac{d\underline{V}}{dt}\bigg|_p\right)^n + \begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix}\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix}$$

$$= C^n_p\left(\frac{d\underline{V}}{dt}\bigg|_p\right)^p + \begin{pmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{pmatrix}\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} \qquad (40)$$

Since velocity in the path frame lies entirely along the x_p axis

$$\underline{V}_p = \begin{pmatrix} \sqrt{V_x^2 + V_y^2 + V_z^2} \\ 0 \\ 0 \end{pmatrix} \triangleq \begin{pmatrix} V_T \\ 0 \\ 0 \end{pmatrix} \qquad (41)$$

$$\left(\frac{d\underline{V}}{dt}\bigg|_p\right)^p = \begin{pmatrix} \dot{V}_T \\ 0 \\ 0 \end{pmatrix} \qquad (42)$$

Substituting (42) in (40) and writing out the individual equations yields

$$\dot{V}_x = CPN_{11}\,\dot{V}_T - \omega_z V_y + \omega_y V_z$$

$$\dot{V}_y = CPN_{21}\,\dot{V}_T + \omega_z V_x - \omega_x V_z \qquad (43)^*$$

$$\dot{V}_z = CPN_{31}\,\dot{V}_T - \omega_y V_x + \omega_x V_y$$

$\dot{V}_T$ will be recognized as PACC, the path acceleration needed to alter the magnitude of $\underline{V}$.

$$\dot{V}_T = PACC \quad ft/sec^2 \qquad (44)^*$$

In (43) we have a differential equation for earth frame velocity that depends only on factors already specified save for $\underline{\omega} = (\omega_x\ \omega_y\ \omega_z)^T$. To repeat, $\underline{\omega}$ will be derived in Section 4.3

4.2.4 State Vector

PROFGEN carries a state vector, $\underline{x}$, containing 23 states in a 23 element, labled-common array named STATE:

$$\underline{x} = (V_x\ V_y\ V_z\ V_T\ h\ CPN_{11}\ CPN_{21} \cdots CPN_{33}\ CEN_{11}\ CEN_{21} \cdots CEN_{33})^T_{23\times1}$$

The appropriate differential equations for the elements of $\underline{x}$ are Equation (43) for the velocity components V_x, V_y, V_z; Equation (44) for the total velocity V_T; Equation (25) for attitude data in C_p^n; Equation (27) for the location data in C_e^n and this differential equation for altitude, h;

$$\dot{h} = V_z \qquad (45)^*$$

4.2.5 Other Trajectory Relationships

The following three topics are discussed now to conclude the derivation of the trajectory equations:

a. Specific Force

b. Attitude Rates

c. Gravity Model

Topic c supports topic a. Topics a and b are important only insofar as they provide a way to compute specific force and attitude rate for PROFGEN output. Specific force and attitude rate are algebraic expressions not required during state vector propagation; therefore, in some sense, these equations lie outside the mainstream of PROFGEN's calculations.

a. Specific Force

Specific force, $\underline{F}$, is the acceleration that a velocity meter (accelerometer) aboard the aircraft would detect. Specific force is the total inertial acceleration minus the mass-attraction gravitational acceleration; i.e. specific force is the second rate of change of $\underline{R}$ as viewed by an observer fixed in inertial space, minus mass-attraction gravity, $\underline{G}_m$. The physical vector equation for this (see Reference 3, p. 121), where + and - are physical vector operations, is

$$\underline{F} = \left.\frac{d^2\underline{R}}{dt^2}\right|_i - \underline{G}_m \qquad (46)$$

Recall from (38) that

$$\underline{V} \triangleq \left.\frac{d\underline{R}}{dt}\right|_e \qquad (38)$$

The e frame rotates at rate $\underline{\Omega}$ ($\underline{\Omega}^e = (\Omega\ 0\ 0)^T$) with respect to the inertial frame so we can write

$$\left.\frac{d\underline{R}}{dt}\right|_i = \left.\frac{d\underline{R}}{dt}\right|_e + \underline{\Omega} \times \underline{R}$$

$$= \underline{V} + \underline{\Omega} \times \underline{R} \qquad (47)$$

The navigation frame rotates at rate $\underline{T}$ ($\underline{T} \triangleq \underline{\rho} + \underline{\Omega}$) with respect to the inertial frame. Differentiating (47), substituting the result in (46), and continuing with the expansion gives

$$
\begin{aligned}
\underline{F} &= \frac{d}{dt}\left(\underline{V} + \underline{\Omega}\times\underline{R}\right)\Big|_i - \underline{G}_m \\
&= \frac{d\underline{V}}{dt}\Big|_i + \frac{d}{dt}\left(\underline{\Omega}\times\underline{R}\right)\Big|_i - \underline{G}_m \\
&= \frac{d\underline{V}}{dt}\Big|_n + \underline{T}\times\underline{V} + \frac{d}{dt}\left(\underline{\Omega}\times\underline{R}\right)\Big|_i - \underline{G}_m \\
&= \frac{d\underline{V}}{dt}\Big|_n + \underline{T}\times\underline{V} + \frac{d}{dt}\left(\underline{\Omega}\times\underline{R}\right)\Big|_e + \underline{\Omega}\times(\underline{\Omega}\times\underline{R}) - \underline{G}_m \\
&= \frac{d\underline{V}}{dt}\Big|_n + (\underline{\rho}+\underline{\Omega})\times\underline{V} + \underline{\Omega}\times\underline{V} + \underline{\Omega}\times(\underline{\Omega}\times\underline{R}) - \underline{G}_m \\
&= \frac{d\underline{V}}{dt}\Big|_n + (\underline{\rho}+2\underline{\Omega})\times\underline{V} - \underline{g} \qquad (48)
\end{aligned}
$$

where we have used the fact $d\underline{\Omega}/dt|_e = \underline{0}$ and where

$$\underline{g} \triangleq \underline{G}_m - \underline{\Omega} \times (\underline{\Omega} \times \underline{R}) \tag{49}$$

The vector $\underline{g}$ is the usual plumb-bob gravity composed of both mass attraction and earth rotation components. The vector $\underline{g}$ points downward. Recalling from Section 4.2.3 that

$$\left(\frac{d\underline{V}}{dt}\Big|_n\right)^n = \dot{\underline{V}}^n = (\dot{V}_x \ \dot{V}_y \ \dot{V}_z)^T$$

we can componentize (48) in the nav frame (subscripts x, y, z) as follows

$$F_x = \dot{V}_x + (\rho_y + 2\Omega_y)V_z - (\rho_z + 2\Omega_z)V_y - g_x$$

$$F_y = \dot{V}_y + (\rho_z + 2\Omega_z)V_x - (\rho_x + 2\Omega_x)V_z - g_y \tag{50}^*$$

$$F_z = \dot{V}_z + (\rho_x + 2\Omega_x)V_y - (\rho_y + 2\Omega_y)V_x - g_z$$

where

$$\begin{pmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{pmatrix} = C_e^n \begin{pmatrix} \Omega \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} CEN_{11} \\ CEN_{21} \\ CEN_{31} \end{pmatrix} \Omega \qquad (51)^*$$

$$\Omega = 0.7292115147 \cdot 10^{-4} \text{ rad/sec}$$

Gravity (g_x, g_y, g_z) will be discussed presently. Ω_x, Ω_y and Ω_z are the projections onto the nav frame of the angular velocity between the earth and inertial frames; these quantities are not related to ω_x, ω_y and ω_z except that both share the greek letter "omega", upper and lower case. All other quantities needed for computing (50) have already been discussed.

b. Attitude Rates

This section derives an expression for each Euler angle rate ($\dot{\eta}_x$, $\dot{\eta}_y$, $\dot{\eta}_z$) as a function of the commanded turning rates, ω_x ω_y and ω_z. Recall these formulas from (15) and (27):

$$CPN_{11} = \cos\eta_z \cos\eta_y \qquad (52a)$$

$$CPN_{21} = -\sin\eta_z \cos\eta_y \qquad (52b)$$

$$CPN_{31} = \sin\eta_y \qquad (52c)$$

$$CPN_{33} = -\cos \eta_y \cos \eta_x \qquad (52d)$$

$$\dot{CPN}_{11} = -\omega_z \, CPN_{21} + \omega_y \, CPN_{31} \qquad (52e)$$

$$\dot{CPN}_{31} = -\omega_y \, CPN_{11} + \omega_x \, CPN_{21} \qquad (52f)$$

$$\dot{CPN}_{33} = -\omega_y \, CPN_{13} + \omega_x \, CPN_{23} \qquad (52g)$$

Differentiate (52c) to get

$$\dot{CPN}_{31} = (\cos \eta_y) \, \dot{\eta}_y$$

and equate this to (52f) to get

$$-\omega_y \, CPN_{11} + \omega_x \, CPN_{21} = (\cos \eta_y) \, \dot{\eta}_y$$

$$-\omega_y \, (\cos \eta_z \cos \eta_y) + \omega_x \, (-\sin \eta_z \cos \eta_y) = (\cos \eta_y) \, \dot{\eta}_y$$

Assume now that pitch is not $\pm 90^{\circ}$ and cancel $\cos \eta_y$ to yield

$$\dot{\eta}_y = -\omega_y \cos \eta_z - \omega_x \sin \eta_z \qquad (53)^{*}$$

$$(\cos \eta_y \neq 0)$$

which is the desired expression for $\dot{\eta}_y$. Similar manipulations of (52) produced the following expressions for $\dot{\eta}_x$ and $\dot{\eta}_z$:

$$\dot{\eta}_x = (\omega_x \cos\eta_z - \omega_y \sin\eta_z)/\cos\eta_y \qquad (54)^*$$

$$(\cos\eta_y \neq 0)$$

$$\dot{\eta}_z = -\omega_z + \tan\eta_y(\omega_x \cos\eta_z - \omega_y \sin\eta_z) \qquad (55)^*$$

$$(\cos\eta_y \neq 0)$$

PROFGEN does not attempt to make attitude rate calculations when $\cos \eta_y = 0$. It simply prints a warning message and goes on (see Section 3.3).

c. Gravity Model

Throughout this report the ellipticity of the earth has been accounted for while higher order effects and local geoid perturbations have been neglected. The purpose here is to derive equations for g_x, g_y and g_z that are consistent with this philosophy for modeling the earth. The normal component g_z will be tackled first following the approach beginning on page 78 of Reference 4.

■ Derivation for Normal Gravity, g_z

Define γ as gravity normal to the ellipsoid at altitude zero. Then for an altitude h above the ellipsoid, g_z at this altitude can be expanded in a MacLaurin series of terms in h:

$$g_\delta = g_\delta(\phi, h)$$

$$= g_\delta(\phi, 0) + \left.\frac{\partial g_\delta}{\partial h}\right|_{h=0} \cdot h + \frac{1}{2} \left.\frac{\partial^2 g_\delta}{\partial h^2}\right|_{h=0} \cdot h^2 + \cdots$$

$$\triangleq \gamma + \frac{\partial \gamma}{\partial h} h + \frac{\partial^2 \gamma}{\partial h^2} h^2 + \cdots \tag{56}$$

The first partial is given by Brun's formula (Reference 4, Equation 2-79) which is based on an ellipsoidal earth model:

$$\frac{\partial \gamma}{\partial h} = -\gamma\left(\frac{1}{R_m} + \frac{1}{R_p}\right) - 2\Omega^2 \tag{57}$$

where R_m and R_p are the principle radii of curvature defined by (33) and (34). Taking reciprocals and expanding in a binomial series gives

$$\frac{1}{R_m} = \frac{(1 - e^2 \sin^2\phi)^{3/2}}{R_e(1 - e^2)} = \frac{1}{R_e(1-e^2)}\left(1 - \frac{3}{2} e^2 \sin^2\phi - \cdots\right)$$

$$\frac{1}{R_p} = \frac{(1 - e^2 \sin^2\phi)^{1/2}}{R_e} = \frac{1}{R_e}\left(1 - \frac{1}{2} e^2 \sin^2\phi - \cdots\right)$$

Truncating these equations, adding them, and dropping higher order terms, produces the following result

$$\frac{1}{R_m} + \frac{1}{R_p} \cong \frac{1}{R_e}\left(2 + e^2 - 2e^2 \sin^2\phi\right) \tag{58}$$

If γ_e is the value of γ at the equator at h=o, the first order relationship between γ_e and Ω^2 is $\Omega^2 = m\gamma_e/R_e$ where m is 0.003449783. Substituting this and (58) in (57), and simplifying, yields

$$\frac{\partial \gamma}{\partial h} = -\frac{\gamma}{R_e}\left(2 + e^2 + m - 2e^2 \sin^2 \phi\right) \qquad (59)$$

The second ... tive $\partial^2\gamma/\partial h^2$ may be taken from the spherical approximation obtained when earth flattening is neglected entirely. Then according to Newton's law of mass attraction

$$\gamma = kM/R_e^2$$

where M is earth's mass and k is the universal gravitational constant.

$$\frac{\partial \gamma}{\partial h} = \frac{\partial \gamma}{\partial R_e} = -\frac{2kM}{R_e^3}$$

$$\frac{\partial^2 \gamma}{\partial h^2} = \frac{\partial^2 \gamma}{\partial R_e^2} = \frac{6kM}{R_e^4}$$

so that

$$\frac{\partial^2 \gamma}{\partial h^2} = \frac{6\gamma}{R_e^2} \qquad (60)$$

Combining (59) and (60) with (56) produces the desired approximate equation for normal gravity.

$$g_z = \gamma\left[1 - \frac{1}{R_e}\left(2 + e^2 + m - 2e^2\sin^2\phi\right)h + \frac{3}{R_e^2}h^2\right] \quad (61)$$

where γ is gravity at the ellipsoid surface which is given in Reference 1, page 22, as

$$\gamma = \gamma_e\left(1 + 0.005278994\sin^2\phi + 0.000023461\sin^4\phi\right) \quad (62)$$

$$\gamma_e = -32.0877057 \quad ft/sec^2 \quad (63)$$

Combining (62) and (63) with (61), and evaluating all constants, produced this final expression for g_z:

$$g_z = -\left[32.0877057 + 0.16939081\sin^2\phi + 0.000752810\sin^4\phi\right]\times$$

$$\times\left[1.0 - (9.6227E\text{-}8 - 6.4089E\text{-}10\sin^2\phi)h + 6.8512E\text{-}15\,h^2\right] \quad (64)^*$$

■ Derivation for Level Gravity, g_x and g_y

At first it is somewhat surprising to realize that plumb-bob gravity has a level component. Such component arises because level surfaces at different altitudes (but same latitude) are not parallel. This fact is evident when one considers these two extremes: at h=o the level surface is the ellipsoid and gravity points along ϕ; at the same latitude but elevated to $h=\infty$, gravity points at earths center of mass. Between these extremes the difference in slope of the two gravity vectors is the difference between geographic and geocentric latitude.

Another way to view the level gravity phenomenon is through the curvature of the normal plumb line as illustrated in Figure 14. Curvature is zero in the east-west direction owing to the rotational symmetry of the ellipsoid of revolution. Thus level gravity is entirely a north-south acceleration.

From Figure 14, observe the following relationship

$$dh = r\, d\beta \qquad (65)$$

The plumb line's radius of curvature, r, is given by (2-22a) in Reference 4:

$$r = \frac{1}{\frac{1}{g_z} \cdot \frac{\partial g_z}{\partial d}} \qquad (66)$$

where d is distance along a north-south direction. Combining (66) with (65) and rearranging

$$d\beta = \frac{1}{g_z} \cdot \frac{\partial g_z}{\partial d}\, dh \qquad (67)$$

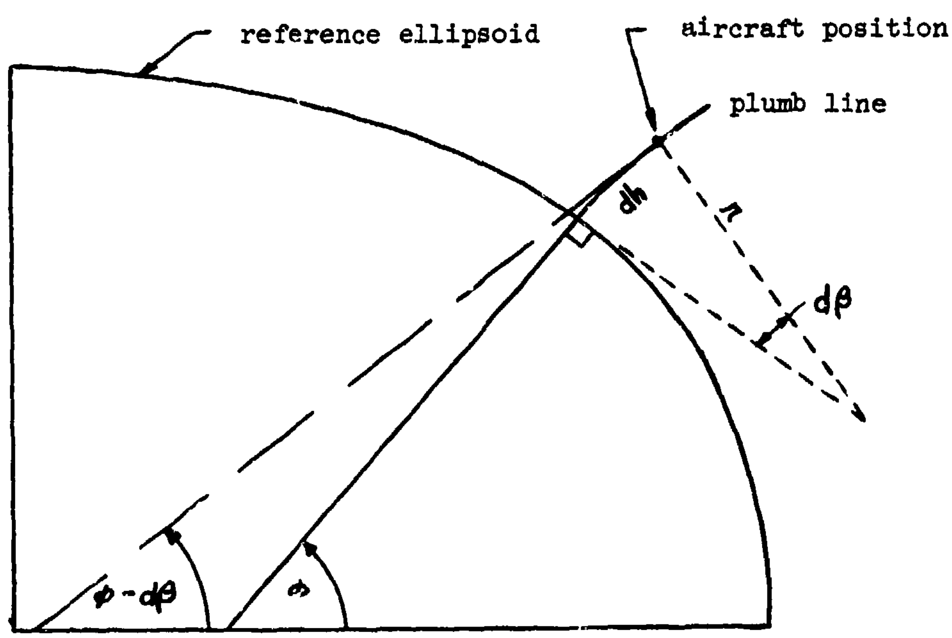


Figure 14 - Geometry for Deriving Level Gravity

The change in plumb line direction, β, between h=o and h=h is

$$\beta = \int_0^h \frac{1}{g_z} \cdot \frac{\partial g_z}{\partial d} \, dh \qquad (68)$$

An approximate relationship for d is $d = R_e \phi$. Then

$$\frac{\partial g_z}{\partial d} = \frac{\partial g_z}{\partial \phi} \cdot \frac{\partial \phi}{\partial d} = \frac{\partial g_z}{\partial \phi} \cdot \frac{1}{R_e}$$

Thus (68) becomes'

$$\beta = \frac{1}{R_e} \int_0^h \frac{1}{g_z} \cdot \frac{\partial g_z}{\partial \phi} \, dh \qquad (69)$$

To obtain a closed form expression for (69), simplify g_z as follows:

$$g_z = \gamma \left[1 - \frac{1}{R_e}(2 + e^2 + m - 2e^2 \sin^2\phi)h + \frac{3}{R_e^2}h^2 \right] \qquad (61)$$

$$\cong \gamma \left[1 - 2h/R_e \right]$$

$$\triangleq \gamma_e \left(1 + f_1 \sin^2\phi + f_2 \sin^4\phi\right) \left[1 - 2h/R_e\right] \text{ using (62)}$$

$$\cong \gamma_e \left(1 + f_1 \sin^2\phi - 2h/R_e\right)$$

Then

$$\frac{1}{g_3}\frac{\partial g_3}{\partial \phi} \cong \frac{1}{\gamma_e}\left(\gamma_e 2f_1 \sin\phi \cos\phi\right) = 2f_1 \sin\phi \cos\phi$$

Substitute this in (69) and integrate

$$\beta = \frac{1}{R_e}\int_0^h 2f_1 \sin\phi \cos\phi \, dh$$

$$= \frac{2f_1 \sin\phi \cos\phi}{R_e} h \qquad (70)$$

β is the tilt angle through which the gravity vector tips over as altitude increases. Projecting the magnitude of gravity (approximated here as $|\gamma_e|$) through β and onto the level surface gives for g_n (g north)

$$g_n = -|\gamma_e|\beta$$

$$= -1.63 \times 10^{-8}(h \sin\phi \cos\phi) \qquad (71)$$

Now rotate g_n through α to obtain g_x and g_y

$$g_x = g_n \cos\alpha = -1.63 \times 10^{-8} h \sin\phi \cos\phi \cos\alpha \qquad (72)$$

$$g_y = -g_n \sin\alpha = 1.63 \times 10^{-8} h \sin\phi \cos\phi \sin\alpha \qquad (73)$$

which may be stated in terms of the elements of C_e^n as

$$g_x = -1.63 \times 10^{-8}\, h\, CEN_{31}\, CEN_{11} \qquad (74)^*$$

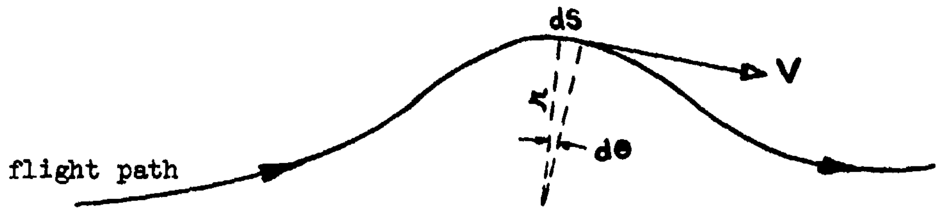
$$g_y = -1.63 \times 10^{-8}\, h\, CEN_{31}\, CEN_{21} \qquad (75)^*$$

This derivation of level gravity was based on material in Section 5-6 of Reference 4 where it is pointed out that the effect of topographic irregularities on the curvature of the plumb line often overwhelms the value from equation (71). In high mountains the actual deflection could be 10 times greater so the limitations of (71) are apparent.

4.3 Path to Nav Rotation Rates and Control Equations

The relationships derived here for $\underline{\omega}$ will produce turning rates commensurate with the input data and with the restriction that level-plane turns be coordinated. In addition, equations for controlling the application of $\underline{\omega}$ will be derived. This control will usually take the form of a switch to turn $\underline{\omega}$ on or off at a critical event time. The control equation will compute the event time; e.g. the time at which $\dot{\eta}_y$ should be disabled in a vertical turn to make $\Delta\eta_y$ = PITCH This section evolved from the work in Section 3 of Reference 6.

As a preface, we list some basic kinematic equations for the illustration below where S is arc length, V is speed tangent to the path, r is radius of curvature and a_n is acceleration normal to the curved path:



$$V = \frac{dS}{dt} \qquad dS = r \cdot d\theta \qquad a_n = \frac{V^2}{r} \tag{76}$$

Combining these equations produces this relation for angular rate

$$\frac{d\theta}{dt} = \frac{a_n}{V} \tag{77}$$

4.3.1 A General Expression for $\underline{\omega}$

Now recall equations (13) and (28) defining C_p^n and $\underline{\omega}$:

$$C_p^n = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} c\psi_z & -s\psi_z & 0 \\ s\psi_z & c\psi_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c\psi_y & 0 & s\psi_y \\ 0 & 1 & 0 \\ -s\psi_y & 0 & c\psi_y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\psi_x & -s\psi_x \\ 0 & s\psi_x & c\psi_x \end{bmatrix} \tag{13}$$

$$\triangleq T_{180} \cdot T_z \cdot T_y \cdot T_x \tag{78}$$

$$\underline{\omega} \triangleq \underline{\omega}_{pn}^{n} \triangleq \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \qquad (28)$$

where T_{180}, T_z, T_y and T_x are introduced here for reasons that will be apparent shortly.

Each Euler angle, η_x, η_y and η_z, has an associated rate, $\dot{\eta}_x$, $\dot{\eta}_y$ and $\dot{\eta}_z$. For a given path to nav orientation, the vector associated with $\dot{\eta}_x$ is directed along x_p. If the given path frame is rotated so that roll is zero (η_x=o), the vector associated with $\dot{\eta}_y$ is directed along the new (unrolled) y_p axis. When the new path frame is rotated again to remove pitch (η_y=o), the vector associated with $\dot{\eta}_z$ is directed along the new (unrolled and unpitched) z_p axis. Note that these three vectors <u>are not</u> mutually orthogonal. When transformed into the nav frame and added vectorially, they give the entire path to nav rotation velocity. Thus

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = T_{180} T_z T_y T_x \begin{pmatrix} \dot{\eta}_x \\ 0 \\ 0 \end{pmatrix} + T_{180} T_z T_y \begin{pmatrix} 0 \\ \dot{\eta}_y \\ 0 \end{pmatrix} + T_{180} T_z \begin{pmatrix} 0 \\ 0 \\ \dot{\eta}_z \end{pmatrix} \qquad (79)$$

This may be simplified using $\eta_z = \alpha + \psi$ (Figure 11) and the definitions of T_{180}, T_z and C_p^n in (78):

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = C_p^n \begin{pmatrix} \dot{\eta}_x \\ 0 \\ 0 \end{pmatrix} + T_{180} T_z T_y \begin{pmatrix} 0 \\ \dot{\eta}_y \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -\dot{\alpha} - \dot{\psi} \end{pmatrix} \quad (80)$$

Equation (80) is the most general relation for angular rate between the path and nav frames. It will simplify considerably depending on (1) the type of maneuver (2) the nominal path (great circle or rhumb line) over which that maneuver is superimposed, and (3) $\dot{\alpha}$ which is given in Table 2 as a function of the nav frame mechanization choice. In the following four subsections it is assumed that the reader is familiar with Section 3.4.

4.3.2 Vertical Turn

a. $\underline{\omega}$ Equation

Since the aircraft's wings remain level in a vertical turn, $T_x = I$ and $\dot{\eta}_x = 0$. Thus (80) becomes

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = T_{180} T_z T_y I \begin{pmatrix} 0 \\ \dot{\eta}_y \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -\dot{\alpha} - \dot{\psi} \end{pmatrix}$$

or

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = C_p^n \begin{pmatrix} 0 \\ \dot{\eta}_y \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -\dot{\alpha} - \dot{\psi} \end{pmatrix} \qquad (81)^*$$

where $\dot{\eta}_y$ is given by (77) as

$$\dot{\eta}_y = \frac{a_n}{V_T(t)} \qquad (82)^*$$

and

$$V_T(t) = V_T(t_i) + (t - t_i)\,\dot{V}_T \qquad (83)$$

$$a_n = TACC \cdot sign\,(PITCH) \qquad (84)^*$$

Note that TACC is positive and in units of ft/sec^2. A vertical turn will have a slight heading rate if the aircraft is following a great circle path so

$$\dot{\psi} = \dot{\psi}_N \triangleq \begin{cases} 0 & \text{, rhumb line} \\ \dot{\psi}_G & \text{, great circle (Section 4.3.6)} \end{cases} \qquad (85)^*$$

b. Control Derivation

Equation (82) can be integrated to yield change in η_y over the interval (t_i, t). In the case where V_T varies linearly with time ($\dot{V}_T$ = PACC $\neq 0$),

$$\Delta \eta_y(t) = \int_{t_i}^{t} \dot{\eta}_y(\tau)\, d\tau = \int_{t_i}^{t} \frac{a_n}{V_T(\tau)}\, d\tau$$

$$= \int_{t_i}^{t} \frac{a_n}{V_T(t_i) + (\tau - t_i)\dot{V}_T}\, d\tau$$

$$= \frac{a_n}{\dot{V}_T} \ln\left[1 + \frac{\dot{V}_T}{V_T(t_i)}(t - t_i)\right], \quad \dot{V}_T \neq 0 \qquad (86)$$

In the case where V_T is constant

$$\Delta \eta_y(t) = \int_{t_i}^{t} \frac{a_n}{V_T}\, d\tau = \frac{a_n}{V_T}(t - t_i), \quad \dot{V}_T = 0 \qquad (87)$$

Equations (86) and (87) may be inverted to compute a time, t = TDONE, when $\Delta\eta_y$ (TDONE) = |PITCH|:

$$TDONE = \begin{cases} t_i + \dfrac{V_T(t_i)}{\dot{V}_T}\left[\exp\left(\dfrac{\dot{V}_T \cdot PITCH}{a_n}\right) - 1\right], & \dot{V}_T \neq 0 \\[2ex] t_i + \dfrac{PITCH}{a_n} V_T, & \dot{V}_T = 0 \end{cases} \qquad (88)^*$$

4.3.3 Horizontal Turn

a. $\underline{\omega}$ Equation

Since the aircraft does not pitch in a horizontal turn, $\dot{\eta}_y$ is zero and (80) becomes

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = C_p^n \begin{pmatrix} \dot{\eta}_x \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ -\dot{\alpha} - \dot{\psi} \end{pmatrix} \qquad (89)^*$$

where η_x behaves as pictured in Figure 5. ($\dot{\eta}_x$ is either on or off. When on, $\dot{\eta}_x$ = ± ROLRATE.) $\dot{\psi}$ is the sum of $\dot{\psi}_N$, the nominal path contribution from (85), and $\dot{\psi}_M$, the maneuver contribution due to TACC:

$$\dot{\psi} \triangleq \dot{\psi}_M + \dot{\psi}_N \qquad (90)$$

$$= \begin{cases} \dot{\psi}_M & \text{, rhumb line} \\ \dot{\psi}_M + \dot{\psi}_G & \text{, great circle} \end{cases} \qquad (91)^*$$

- Coordinated Turn Requirement

During the turn the normal acceleration, $a_n(t)$, progresses from zero to a peak - a flat peak has a magnitude of TACC ft/sec^2 - and back to zero (see Figure 6). This progression occurs because $a_n(t)$

must "follow" $\eta_x(t)$ to satisfy the requirement for coordinated turns. This requirement manifests itself in this way:

$$a_n(t) = 32.2 \cos \eta_y \tan[\eta_x(t)] \qquad (92)$$

Equation (92) shows the aircraft will turn only if its wings are banked. The genesis for (92) is provided in Figure 15, a nose-on view of the aircraft in a right turn with pitch zero ($\eta_y = 0$).

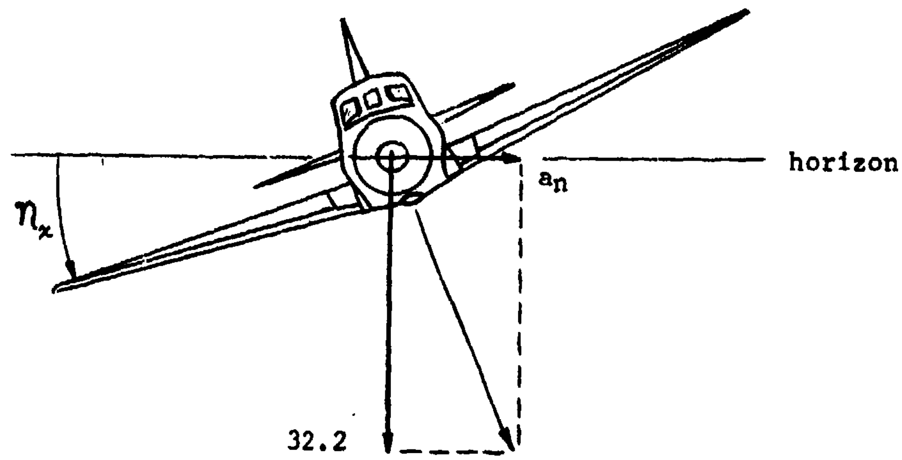


Figure 15 - Balancing Accelerations in a Coordinated Turn

The vector sum of 32.2 and a_n must act perpendicular to the wings in order to implement the coordinated turn. Thus

$$a_n = 32.2 \tan \eta_x \qquad (93)$$

When pitch is nonzero, Figure 15 is altered by making the downward component of gravity $32.2 \cdot \cos \eta_y$ instead of 32.2. Equation (92) then follows immediately.

• $\dot{\psi}_M$ Equation

Defining V_L as the level-plane component of total speed ($V_L = V_T \cos \eta_y$), we may plug (92) in (77) to get the maneuver turning rate:

$$\dot{\psi}_M = \frac{32.2 \cos\eta_y \tan[\eta_x(t)]}{V_L(t)}$$

$$= \frac{32.2 \tan[\eta_x(t)]}{V_T(t)} \qquad (94)^*$$

$$= \frac{32.2 \tan[\eta_x(t)]}{V_T(t_i) + (t-t_i)\dot{V}_T} \qquad (95)$$

b. Control Derivation

Examination of (89) and (94) shows that roll and roll rate must be known before $\underline{\omega}$ can be computed. Their determination rests on choosing the appropriate roll history from Figure 5 and then on computing TOFF, TON and TDONE. The logic and calculations for accomplishing this are contained in PROFGEN subroutines TSETUP2 and YAWCHG and are outlined below.

- $\Delta\psi_M$ Computation

The most general roll history is pictured in Figure 16. (This roll history is for a right turn. A left turn would be the negative of Figure 16).

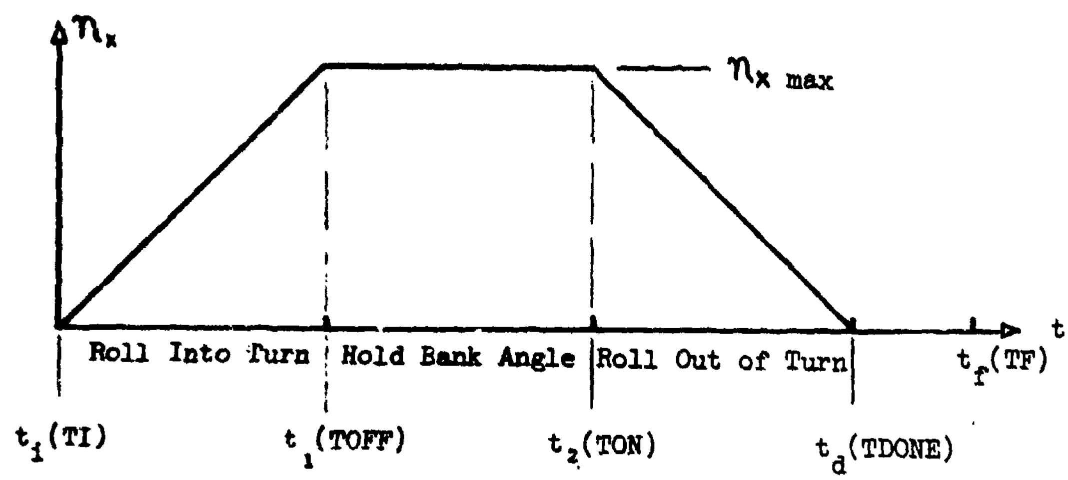


Figure 16 - Roll Angle History (Case A)

We wish to compute the change in heading, $\Delta\psi_M$, that would occur if Figure 16 was the roll history. For this purpose we may assume t_1, t_2 and t_d are time increments measured from a t_i of zero. Set up the integral of (94) as follows:

$$\Delta\psi_M = 32.2 \left\{ \int_0^{t_1} \frac{\tan[n_x(\tau)]}{V_T(\tau)} d\tau + \int_{t_1}^{t_2} \frac{\tan[n_{x_{max}}]}{V_T(\tau)} d\tau + \int_{t_2}^{t_d} \frac{\tan[n_x(\tau)]}{V_T(\tau)} d\tau \right\} \qquad (96)$$

From (92)

$$\tan \eta_{x_{max}} = \frac{|a_{n_{max}}|}{32.2 \cos \eta_y} = \frac{TACC}{32.2 \cos \eta_y} \qquad (97)$$

Recalling (83) for $V_T(t)$, the middle integral in (96) is

$$\int_{t_1}^{t_2} \frac{\tan \eta_{x_{max}}}{V_T(\tau)} d\tau = \begin{cases} \dfrac{TACC}{32.2 \cos \eta_y \, \dot{V}_T} \ln\left[1 + \dfrac{(t_2 - t_1)\dot{V}_T}{V_T(t_1)}\right], & \dot{V}_T \neq 0 \\[2ex] \dfrac{TACC}{32.2 \cos \eta_y \, V_T} (t_2 - t_1), & \dot{V}_T = 0 \end{cases} \qquad (98)$$

The first and third integrals in (96) are not closed-form integrable unless $\dot{V}_T = 0$. Satisfactory approximations have been obtained for them by substituting $\bar{V}_T$, average speed, for $V_T(t)$ as follows:

$$\int_0^{t_1} \frac{\tan \eta_x(\tau)}{V_T(\tau)} \cong \frac{1}{\bar{V}_{T1}} \int_0^{t_1} \tan \eta_x(\tau) d\tau$$

$$= \frac{1}{\bar{V}_{T1}} \int_0^{t} \tan(\dot{\eta}_x \tau) d\tau$$

$$= \frac{-\ln\left[\cos(\dot{\eta}_x t_1)\right]}{\bar{V}_{T1} \, \dot{\eta}_x} \qquad (99)$$

where $\dot{\eta}_x$ = ROLRATE and V_{T1}, average speed in (t_i, t_1), is

$$\bar{V}_{T1} = \frac{V_T(t_i) + V_T(t_1)}{2} = V_T(t_i) + \frac{t_1 \dot{V}_T}{2} \qquad (100)$$

Similarly

$$\int_{t_2}^{t_d} \frac{\tan \eta_x(\tau)}{V_T(\tau)} d\tau \cong \frac{-\ln[\cos(\dot{\eta}_x t_1)]}{\bar{V}_{Td}\, \dot{\eta}_x} \qquad (101)$$

$$\bar{V}_{Td} = \frac{V_T(t_2) + V_T(t_d)}{2} = V_T(t_i) + \left(t_2 + \frac{t_1}{2}\right)\dot{V}_T \qquad (102)$$

Inserting (98) - (101) in (96) and simplifying gives

$$\Delta\psi_M \cong \begin{cases} \dfrac{-32.2}{\dot{\eta}_x}\left\{\dfrac{\ln[\cos(\dot{\eta}_x t_1)]}{V_T(t_i) + \frac{t_1 \dot{V}_T}{2}} + \dfrac{\ln[\cos(\dot{\eta}_x t_1)]}{V_T(t_i) + \left(t_2 + \frac{t_1}{2}\right)\dot{V}_T}\right\} + \\ \quad + \dfrac{TACC\ \ln\left[1 + \dfrac{(t_3 - t_1)\dot{V}_T}{V_T(t_1)}\right]}{\cos \eta_y\ \dot{V}_T} \quad , \quad \dot{V}_T \neq 0 \\ -\dfrac{64.4 \ln[\cos(\dot{\eta}_x t_1)]}{\dot{\eta}_x V_T} + \dfrac{TACC\,(t_3 - t_1)}{\cos \eta_y\ V_T} \quad , \quad \dot{V}_T = 0 \end{cases} \qquad (103)^*$$

Since η_{xmax} and $\dot{\eta}_x$ (=ROLRATE) are known, t_1 is

$$t_1 = \frac{\eta_{x\,max}}{\dot{\eta}_x} = \frac{\tan^{-1}(TACC/32.2\cos\eta_y)}{\dot{\eta}_x} \qquad (104)^*$$

● Reasoning on $\Delta\psi_{Mmax}$

PROFGEN determines if the maneuver can be completed (HEAD reached) by seeing how far the aircraft would turn if turn acceleration was left on for the entire segment, t_i to t_f. Equation (103) is used for this purpose where t_1 is obtained from (104) and t_2 is placed t_1 seconds short of $t_d = t_f$. (If 2 t_1 exceeds SEGLNT, t_1 is set to SEGLNT ÷ 2.) PROFGEN solves for $\Delta\psi_{Mmax}$ in subroutine YAWCHG using (103).

If $\Delta\psi_{Mmax}$ exceeds |HEAD|, the turn can be completed and either Case A or B of Figure 5 is appropriate. Having decided A or B (not C or D), the problem becomes determination of t_1 and t_2 (In Case B, $t_1 = t_2$.) The following paragraphs will derive equations for t_1 and t_2 for both Case A and Case B.

If $\Delta\psi_{Mmax}$ falls short of |HEAD|, the turn cannot be completed and either Case C or D of Figure 5 is appropriate. For Cases C and D, the determination of t_1 and t_2 is trivial.

● Case A Roll History

The roll history shown in Figure 16 is identifiable as Case A from Figure 5. Setting $\Delta\psi_M$ = |HEAD| and obtaining t_1 from (104), everything is known in (103) except t_2, the time at which roll-out should begin. Unfortunately, (103) cannot be easily inverted for t_2. This difficulty was overcome by ridding (103) of its "ln" function which was accomplished by approximating the middle integral of (96) just as the first and last integrals in (96) were approximated earlier. Thus (98) becomes

$$\int_{t_1}^{t_2} \frac{\tan \eta_{x\,max}}{V_T(\tau)}\, d\tau = \frac{TACC\,(t_2 - t_1)}{32.2 \cos \eta_y \, \bar{V}_{T2}} \qquad (105)$$

where

$$\bar{V}_{T2} = V(t_i) + \frac{t_1 + t_2}{2} \dot{V}_T \qquad (106)$$

Now replace the first term in (103) with (105) - (106), set $\Delta\psi_M = |HEAD|$ and simplify to get this quadratic equation in t_2:

$$t_2^2 \left[(\tfrac{1}{2}) b_1 \dot{V}_T + (\tfrac{1}{2}) b_0 \dot{V}_T / b_2 - TACC \right] \dot{V}_T$$

$$+ t_2 \left[(\tfrac{3}{2}) b_1 b_2 \dot{V}_T + 2 b_0 \dot{V}_T - TACC\, b_2 + TACC\, t_1 \dot{V}_T \right]$$

$$+ b_2 \left[b_1 b_2 + 2 b_0 + TACC\, t_1 \right] = 0 \qquad (107)^*$$

where

$$
\left.
\begin{aligned}
b_0 &= 32.2 \cos\eta_y \ln\left[\cos(\dot{\eta}_x t_1)\right] \div \dot{\eta}_x \\
b_1 &= |HEAD| \cos\eta_y \\
b_2 &= V(t_i) + t_1 \dot{V}_T / 2
\end{aligned}
\right\} \quad (108)^*
$$

Note that (107) reduces to a linear equation in t_2 if $\dot{V}_T$ is zero.

The coefficients in (107) are computed in TSETUP2 and supplied to QUADRT where t_2 is computed. TOFF, TON and TDONE are given below. To reference them to true time instead of $t_i=0$, merely add TI to each one.

$$TOFF = t_1 = \tan^{-1}\left[TACC/(32.2 \cos\eta_y)\right]/\dot{\eta}_x \qquad (104)^*$$

$$TON = t_2 = \text{solution of } (107)$$

$$TDONE = t_d = t_2 + t_1$$

- Case B Roll History

A "Case B" type roll history is illustrated below.

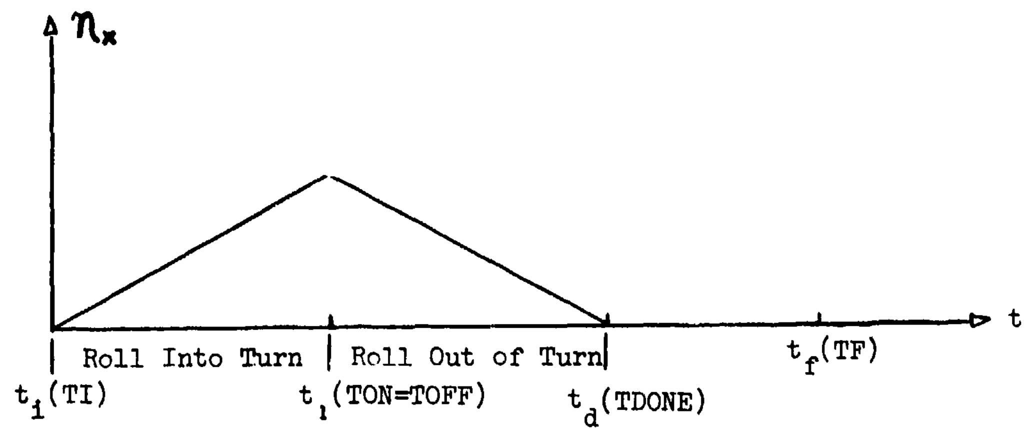


Figure 17 - Roll Angle History (Case B)

The following equation in t_1 was obtained using a procedure like that which lead to (103):

$$64.4 \ln\left[\cos(\dot{\eta}_x t_1)\right] + \dot{\eta}_x \,|HEAD|\left[\dot{V}_T t_1 + V_T(t_i)\right] = 0 \qquad (109)$$

If ln (cos x) is approximated as $-.632x^2$, (109) becomes

$$t_1^2\left[-40.7\,\dot{\eta}_x^2\right] + t_1\left[\dot{V}_T\,|HEAD|\,\dot{\eta}_x\right] + V_T(t_i)\,|HEAD|\,\dot{\eta}_x = 0 \qquad (110)^*$$

The coefficients in (110) are computed in TSETUP2 and supplied to QUADRT where t_1 is computed. TOFF, TON and TDONE follow immediately (see Figure 17) when t_1 is known.

4.3.4 Sine Maneuver

a. $\underline{\omega}$ Equation

Since the aircraft does not change pitch in a sine maneuver, η_y is zero. Hence $\underline{\omega}$ in (80) reduces to a form identical to that for a horizontal turn:

$$\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix} = C_p^n \begin{pmatrix}\dot{\eta}_x\\ 0\\ 0\end{pmatrix} + \begin{pmatrix}0\\ 0\\ -\dot{\alpha} - \dot{\psi}\end{pmatrix} \qquad (89)^*$$

$\dot{\psi}$ is the sum of ψ_N, the nominal path contribution from (85), and $\dot{\psi}_M$, the maneuver contribution due to $a_n(t)$:

$$\dot{\psi} \triangleq \dot{\psi}_M + \dot{\psi}_N \tag{90}$$

$$= \begin{cases} \dot{\psi}_M & \text{, rhumb line} \\ \dot{\psi}_M + \dot{\psi}_G & \text{, great circle} \end{cases} \tag{91}^*$$

The next two paragraphs derive expressions for $\dot{\psi}_M$ and $\dot{\eta}_x$. Expressions for $\dot{\alpha}$ and $\dot{\psi}$ are given in Table 2 and Section 4.3.6, respectively.

b. $\dot{\psi}_M$ Equation

For the aircraft to fly a sine maneuver, its heading must vary per Equation (5):

$$\dot{\psi}_M(t) = \begin{cases} +A \sin^2 wt & , t_i \le t < T_p/2 \\ -A \sin^2 wt & , T_p/2 \le t < T_p \end{cases} \tag{5}$$

where

A = max heading variation

w = heading oscillation frequency

T_p = $2\pi/w$ = period of one full oscillation

Differentiating (5) twice gives

$$\dot{\psi}_M = \begin{cases} A\omega \sin(2\omega t) \\ -A\omega \sin(2\omega t) \end{cases} \qquad (111)^*$$

$$\ddot{\psi}_M = \begin{cases} 2A\omega^2 \cos(2\omega t) \\ -2A\omega^2 \cos(2\omega t) \end{cases} \qquad (112)^*$$

c. $\dot{\eta}_x$ Equation

In the context of a sine maneuver, (77) becomes

$$\dot{\psi}_M = \frac{a_n(t)}{V_L(t)} = \frac{a_n(t)}{\cos \eta_y \; V_T(t)} \qquad (113)^*$$

where $a_n(t)$ acts in the level plane and V_L is level-plane speed. Now recall (92), the coordinated turn requirement relating $a_n(t)$ to $\eta_x(t)$.

$$a_n(t) = 32.2 \cos \eta_y \tan[\eta_x(t)] \qquad (92)$$

Plug (92) into (113) and rearrange to get

$$\eta_x(t) = \tan^{-1}\left(\frac{V_T(t)}{32.2} \dot{\psi}_M \right) \qquad (114)$$

from which it follows that

$$\dot{n}_x = \frac{32.2\ V_T}{32.2^2 + (V_T\ \dot{\psi}_M)^2}\ \ddot{\psi}_M \qquad (115)^*$$

The trouble that was experienced in establishing roll control in the horizontal turn is entirely avoided in the sine maneuver because there is no need to compute any special "event times".

4.3.5 Straight Flight

a. $\underline{\omega}$ Equation

Since aircraft attitude remains fixed in straight flight, (80) simplifies to

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -\dot{\alpha} - \dot{\psi} \end{pmatrix} \qquad (116)^*$$

where

$$\dot{\psi} = \dot{\psi}_N = \begin{cases} 0 & \text{, rhumb line} \\ \dot{\psi}_G & \text{, great circle} \end{cases} \qquad (85)^*$$

To repeat, $\dot{\alpha}$ is given in Table 2 . As with the sine maneuver, no "events" occur in straight flight so (116) tells the whole story.

4.3.6 Heading Angle Turning Rate for a Great Circle Path

Figure 18 shows the geometry associated with the problem of determining the rate of change of heading along a great circle route. (The E frame in Figure 18 is established here to facilitate this analysis). A great circle route lies in a single plane, Plane I, which passes through the center of the earth. This plane is described by λ_{eq} and ψ_{eq} where λ_{eq} is the longitude at which the great circle plane, Plane I, intersects the equatorial plane and ψ_{eq} is the heading at the aforementioned intersection.

Consider a vehicle at point P proceeding along a path lying in Plane I. The coordinates of this point are given by $\lambda-\lambda_{eq}$, ϕ_c and R where ϕ_c is the geocentric latitude and R is the length of the geocentric radius vector.

The geocentric heading, ψ_c, at point P is given as the angle between the horizontal velocity vector and a vertical plane, Plane II, erected at longitude $\lambda-\lambda_{eq}$ and containing point P. Thus ψ_c is the angle between Planes I & II. In rectangular coordinates (X_E, Y_E, Z_E) the equations for Planes I & II are respectively

$$X_E - Y_E \tan \psi_{eq} = 0 \tag{117}$$

$$X_E - Z_E \tan (\lambda - \lambda_{eq}) = 0 \tag{118}$$

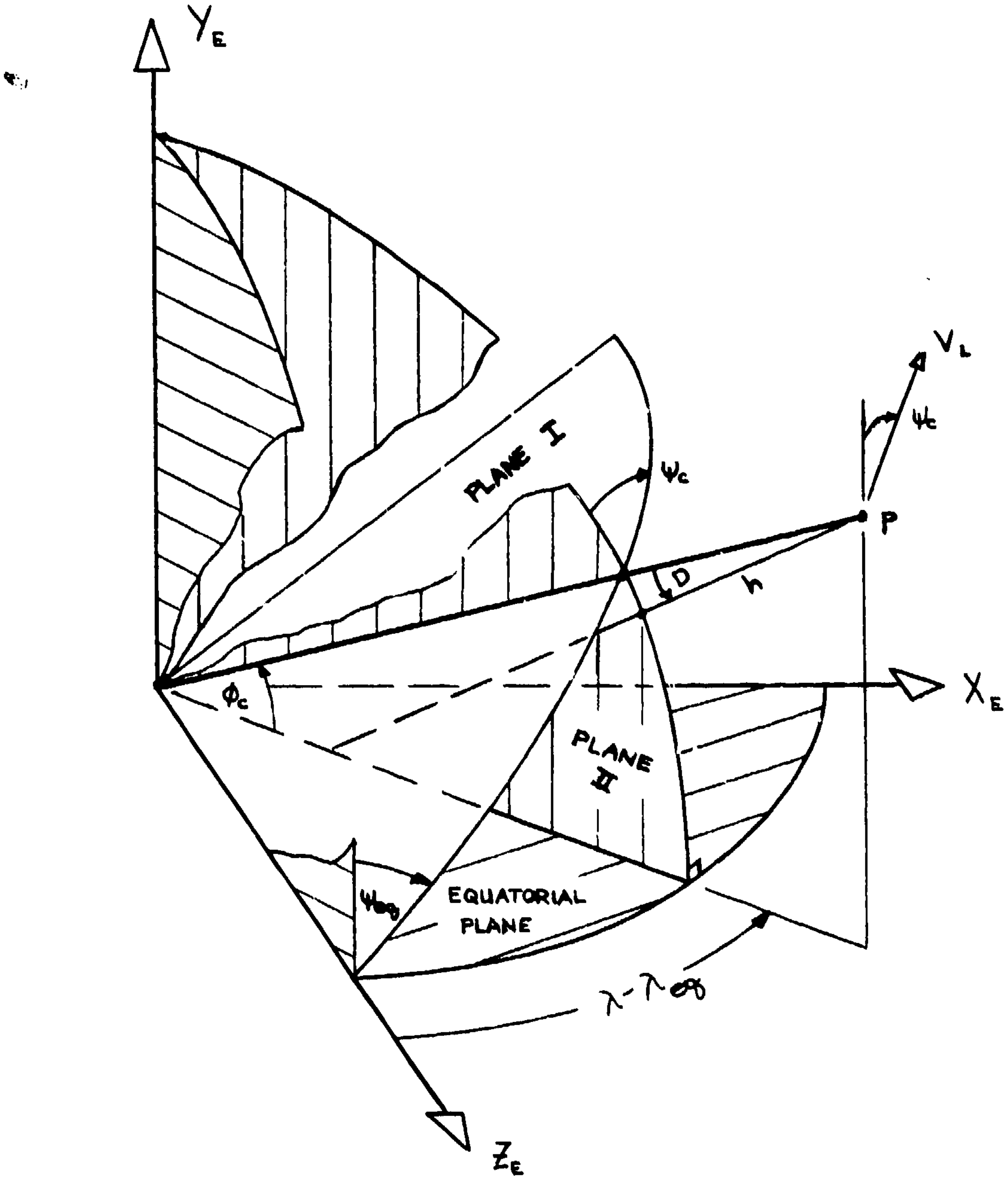


Figure 18 - Great Circle Geometry

The angle is therefore given by

$$\cos\psi_c = \cos\psi_{eq} \cos(\lambda - \lambda_{eq}) \tag{119}$$

The primary concern here is with the geographic heading angle ψ rather than the geocentric heading ψ_c. These two angles differ due to the deviation angle D between the local vertical and the geocentric position vector, see Figure 18. If ϕ denotes geographic latitude, then

$$D = \phi - \phi_c \tag{120}$$

The projection of ψ_c onto a local level coordinate system (rotation through angle D about the local east axis) yields

$$\sin\psi = \frac{\sin\psi_c}{\sqrt{1 - \cos^2\psi_c \sin^2 D}} \tag{121}$$

and

$$\cos\psi = \frac{\cos\psi_c \cos D}{\sqrt{1 - \cos^2\psi_c \sin^2 D}} \tag{122}$$

Differentiation of (121) with respect to time yields the desired quantity:

$$\dot{\psi} = \frac{\dot{\psi}_c \cos D + \dot{D} \sin\psi_c \cos\psi_c \sin D}{1 - \cos^2\psi_c \sin^2 D} \tag{123}$$

The remaining steps are concerned with determining usable expressions for the right side of (123).

The time derivative of ψ_c is obtained from equation (119) as

$$\dot{\psi}_c = \frac{\dot{\lambda}\sqrt{\cos^2\psi_{eq} - \cos^2\psi_c}}{\sin\psi_c} \tag{124}$$

From Figure 18 it is seen that

$$Y_E = R\sin\phi_c \tag{125}$$

and

$$Z_E = R\cos\phi_c\cos(\lambda - \lambda_{eq}) \tag{126}$$

Combining equations (117), (118), (119), (125) and (126) yields

$$\cos^2\psi_{eq} = \cos^2\psi_c\cos^2\phi_c + \sin^2\phi_c \tag{127}$$

which when substituted into (124) gives the simple expression

$$\dot{\psi}_c = \dot{\lambda}\sin(\phi - D) \tag{128}$$

Also required is the inverse solution of equations (121) and (122)

$$\sin\psi_c = \frac{\sin\psi\cos D}{\sqrt{\cos^2\psi\sin^2 D + \cos^2 D}} \tag{129}$$

$$\cos\psi_c = \frac{\cos\psi}{\sqrt{\cos^2\psi\sin^2 D + \cos^2 D}} \tag{130}$$

Substituting (128), (129) and (130) into (123) yields the expression for the turning rate of the heading angle

$$\dot{\psi} = \dot{\lambda} \sin(\phi - D) \cos D \left[1 + \cos^2\psi \tan^2 D \right] + \dot{D} \sin\psi \cos\psi \tan D \qquad (131)^*$$

Since this is the value of $\dot{\psi}$ required to maintain flight in the great circle plane, it is the quantity labeled previously as $\dot{\psi}_G$. Thus

$\dot{\psi}_G$ <=> Equation (131)

The angle D and its time derivative $\dot{D}$ are given for the ellipsoidal earth by the following relationships:

$$\tan D = \frac{R_e \, e^2 \sin\phi \cos\phi}{R \sqrt{1 - \left[1 + (R_e \, e \cos\phi / R)^2 \right] e^2 \sin^2\phi}} \qquad (132)^*$$

$$R = R_e \sqrt{ \frac{1 - (2 - e^2) e^2 \sin^2\phi}{1 - e^2 \sin^2\phi} + 2\sqrt{1 - e^2 \sin^2\phi} \left(\frac{h}{R_e} \right) + \left(\frac{h}{R_e} \right)^2 } \qquad (133)^*$$

$$\dot{D} = \frac{R_e \, e^2}{R \cos D \sqrt{1 - e^2 \sin^2\phi}} \left[\frac{\cos^2\phi - (1 - e^2 \sin^2\phi) \sin^2\phi}{1 - e^2 \sin^2\phi} \dot{\phi} - \frac{\dot{R}}{R} \sin\phi \cos\phi \right] \qquad (134)^*$$

$$\dot{R} = \frac{R_e}{R} \left[\dot{h} \left(\sqrt{1 - e^2 \sin^2\phi} + \frac{h}{R_e} \right) - \dot{\phi} R_e \, e^2 \sin\phi \cos\phi \left(\frac{1 - e^2}{(1 - e^2 \sin^2\phi)^2} + \frac{h/R_e}{\sqrt{1 - e^2 \sin^2\phi}} \right) \right] \qquad (135)^*$$

Equations (131) through (135) are the exact relationships for an ellipsoidal earth. If the earth had been assumed spherical, its eccentricity would have been zero and (131) through (135) would reduce to,

$$\dot{\psi}_G = \dot{\lambda} \sin \phi \tag{136}$$

$$D = 0$$

$$R = R_e + h$$

$$\dot{D} = 0$$

$$\dot{R} = \dot{h}$$

The earth model in PROFGEN may be converted from an ellipsoid to a sphere by simply setting $e^2=0$ in BLOCK DATA. However, to take full advantage of the spherical-earth simplification would require replacing (131) through (135) with (136) and revising the gravity and earth radii computations.

SECTION V

PROGRAM ORGANIZATION

Previous sections have described what PROFGEN does, explained how to use it, and derived equations for its implementation. This section assembles these equations in a sequence amenable to solution in FORTRAN code. Flow of equations and code are both presented.

Two principles will guide us now (Reference 7):

- The most reliable documentation for any program is the code itself. Therefore our purpose is not to describe the code in minute detail - such a description would be unreliable, redundant, and probably harder to read than the code itself - but merely to show how large pieces of code interact.

- Each subprogram contains comments giving a readable description of what that subprogram is supposed to do. These comments form the core of the micro-level documentation and do not need to be repeated here.

Figure 19 is a macro-level flow chart emphasizing overall computational structure, especially with regard to control of step size, h. The name(s) beside each block in Figure 19 designates the subprogram(s) where the action in that block occurs. Each of these subprograms usually calls one or more other subprograms to complete this action (see Figure 21). The main program and master executive is named PROFGEN. The subexecutive for controlling numerical integration during each maneuver is FLTPATH.

Figure 20 is an expansion of the integration block that appears in heavy outline in Figure 19. Figure 20 was included here to show how the differential equations in Section IV actually get solved.

Figure 21 is a dependency chart showing what calls what. Although timing relationships are vague, (Figures 19 and 20 deal with timing) this chart is nevertheless useful for getting a bigger picture of how PROFGEN fits together. It was kept during program development to help assess the impact of proposed changes.

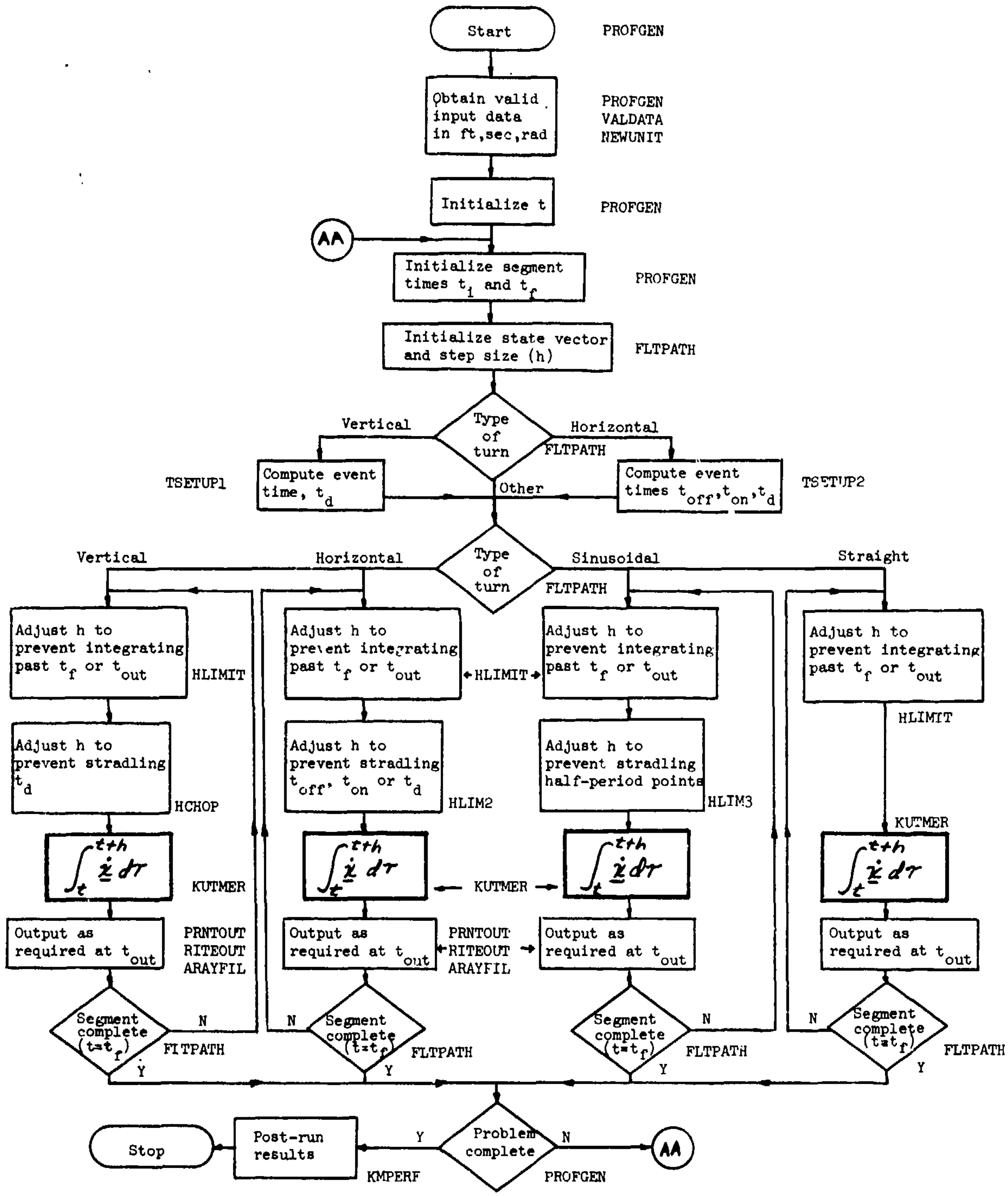


Figure 19 - Macro-Level Logic Flow Diagram

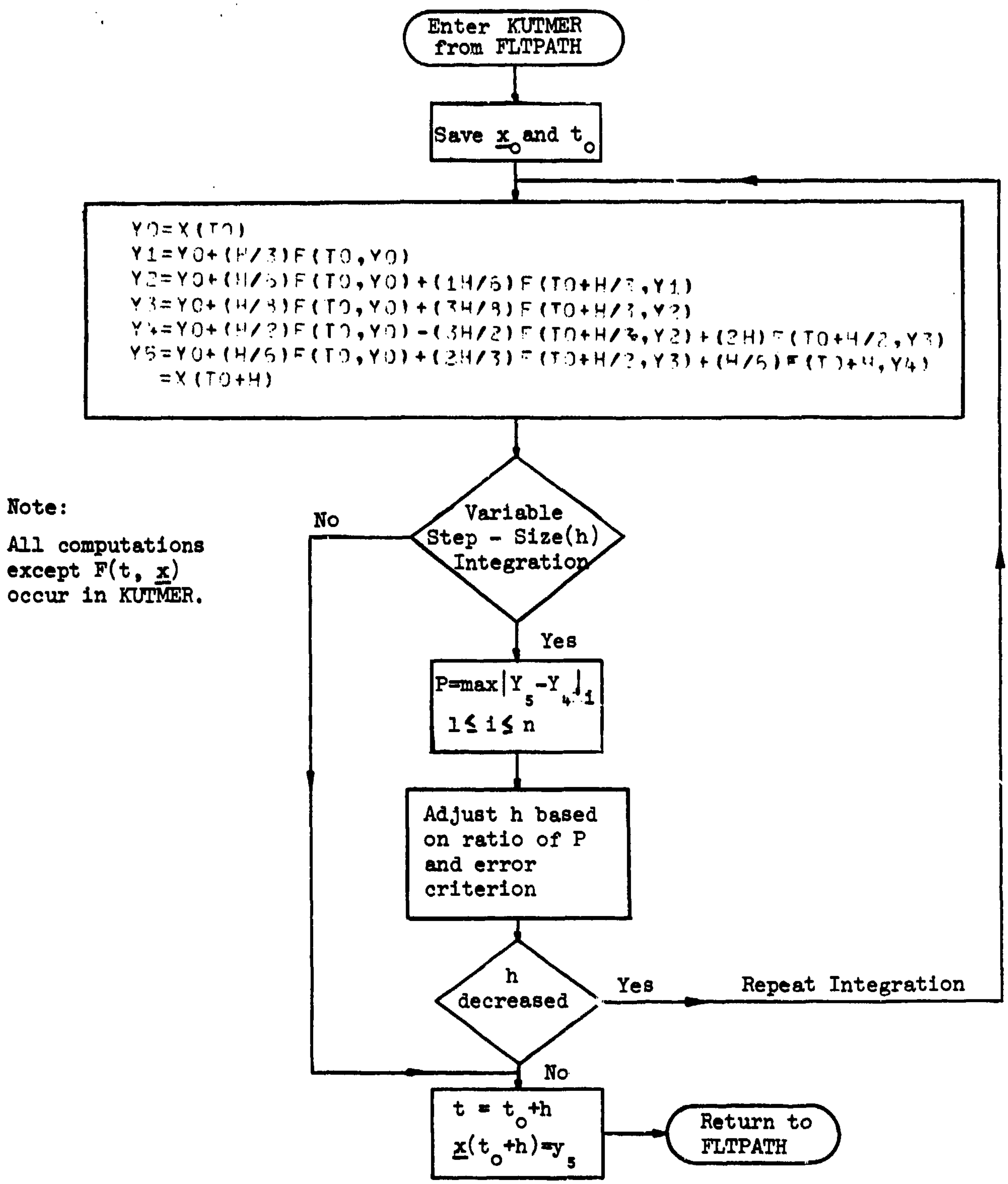


Figure 20 - Numerical Integration of $\dot{\underline{x}} = F(t, \underline{x})$ from t_o to t_o+h

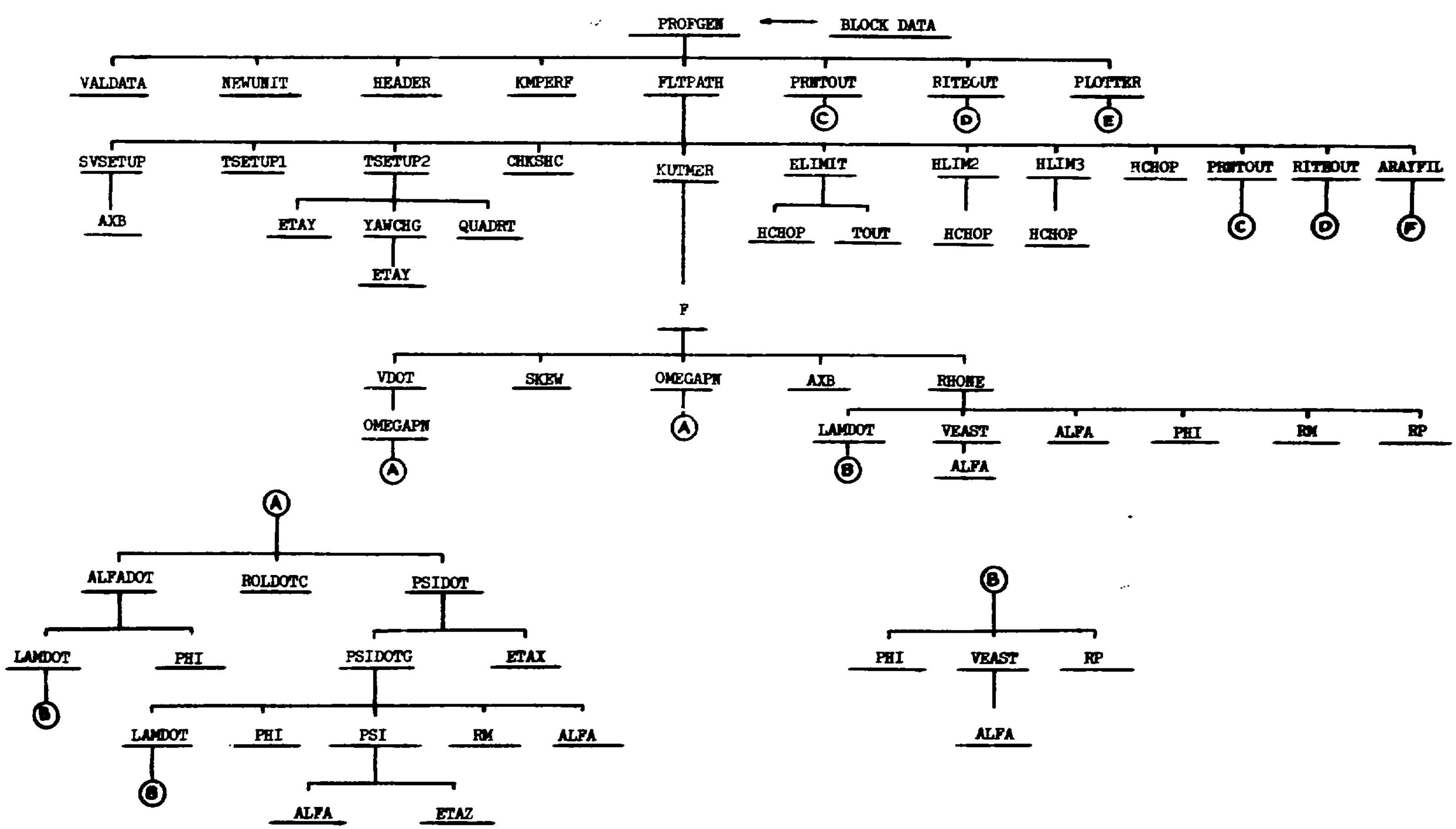
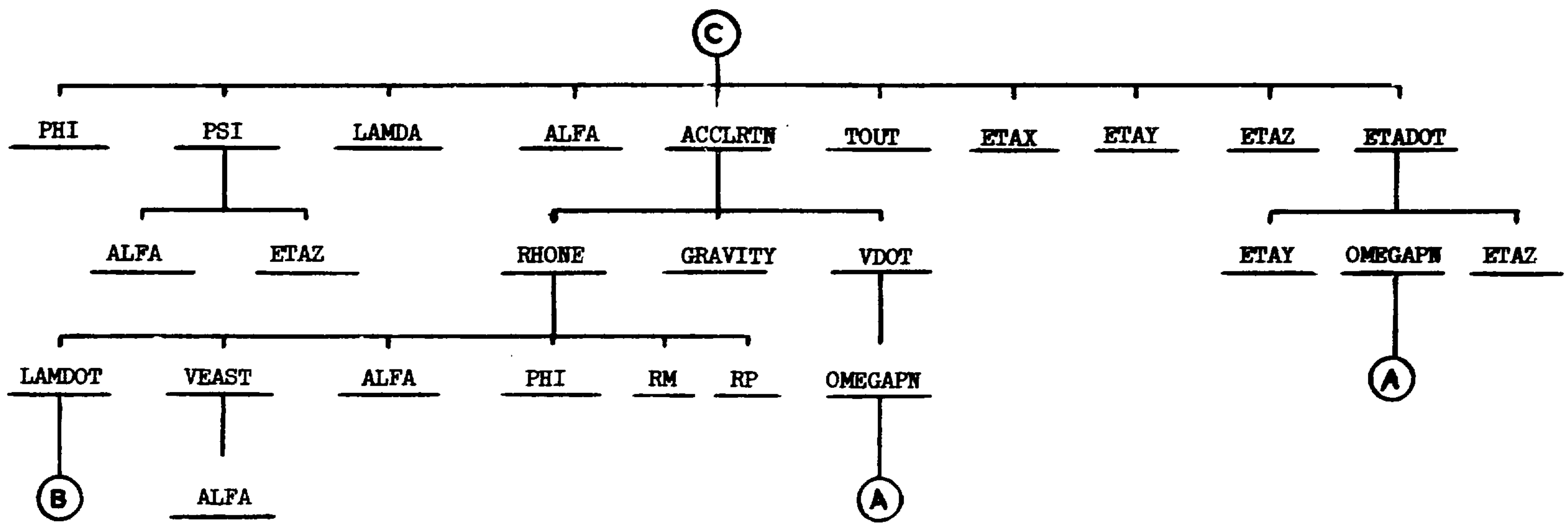


Figure 21 - Subprogram Dependency Chart



(D) ~ Same as (C) with calls to PSI and ETADOT removed.

(F) ~ Same as (C) with calls to PSI, ALFA, ACCLRTN and ETADOT removed.

Figure 21 (Continued)

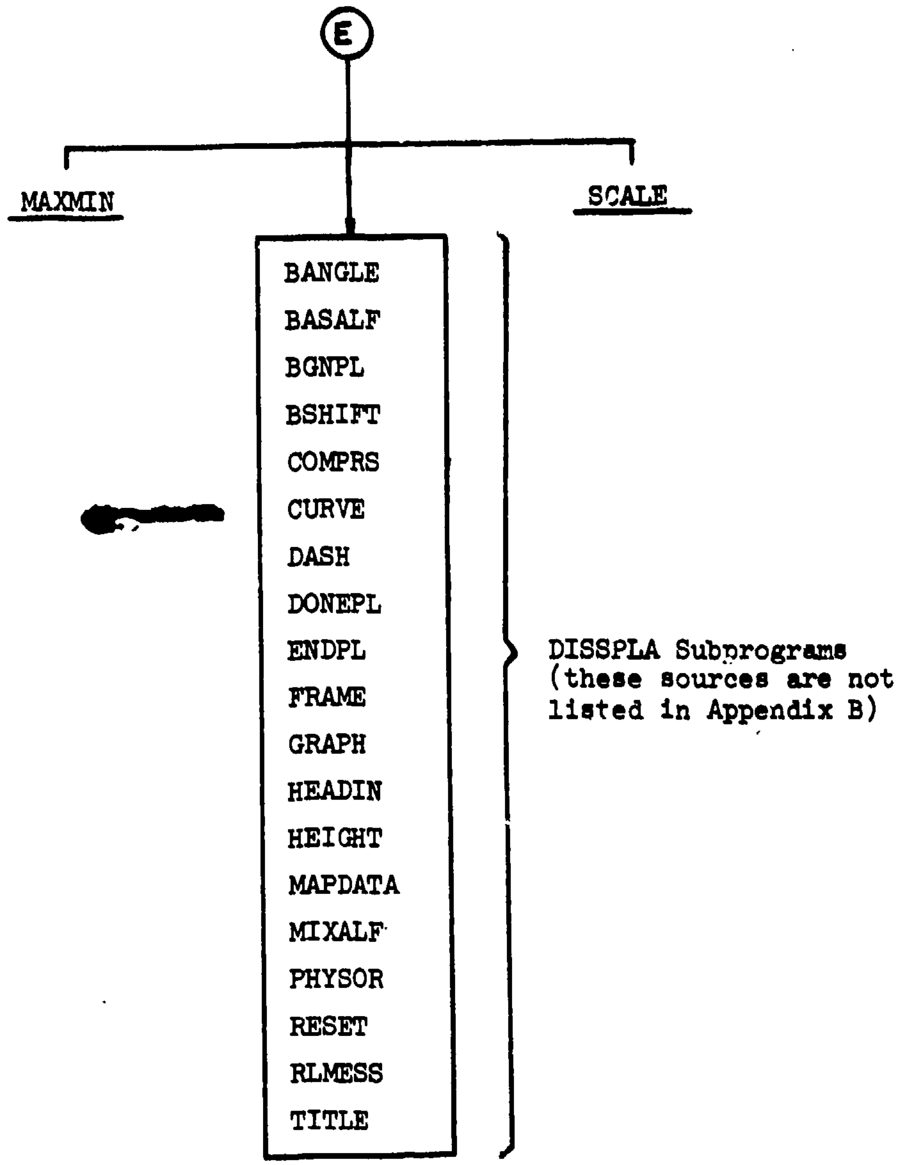


Figure 21 (Continued)

APPENDIX A

SAMPLE RUN OF PROFGEN

The sample run described here was constructed in seventeen segments to exercise most of PROFGEN's code including at least two segments of each of the four types of maneuvers. Throughout the sample run the nominal flight path is a great circle, the output interval is one second, and the integration step-size is variable. Figures 2 and 3 are the PRDATA and PASDATA lists that were used as input.

- Printed Output

Figure A-1 is a portion of the printed output from the sample run. The first page of printed output consists of a banner (automatically printed by the CYBER-74 computer) followed by the date and clock time of the run. The second and third pages are listings of the PRDATA and PASDATA lists as read from TAPE9, the local file on which the input should reside. These listings simply echo the data, including its mistakes if any.

Page 4 of Figure A-1 begins the printed output generated during the computational portion of the run with IPRNT=1. This output consists of a header and a list of variable values at the start of each segment, followed by output at DTO intervals (one second in this run) during the segment. The list of variables printed does not change and the definition for each such variable, with its units, is given in Table A-1. Pages 5, 6 and 7 of Figure A-1 show output up through the beginning of segment 2.

The last page of the sample printout contains, in addition to output spaced at DTO intervals, output at t-final (460.5 seconds in this run) plus a post-run assessment of the numerical integration burden. In this case 5393 numerical integration steps were used and F was called 34675 times.

- Plotted Output

Figures A-2 through A-6 are the plotted output for the sample run. The small numbers appearing along the curve in each figure are segment numbers designating approximately where each new segment began. The latitude - longitude plot in Figure A-2 is constructed with the latitude and longitude axes at the same scale.

- Other Output

TAPE3 output was suppressed in the sample run by setting IRITE=0. If TAPE3 output had been specified (unformatted binary records), each record would have contained the following list of variables in units of feet, seconds and/or radians: time, latitude, longitude, alpha, altitude, roll, pitch, yaw, velocity components along nav x, y, z and specific force components along nav x, y, z. Subroutine RITEOUT should be consulted if a more definitive description of TAPE3 output is needed.

Table A-1 - Output Variables

Variable	Units	Description
TIME	sec.	time (t)
LAT	deg.	geographic latitude (ϕ)
LON	deg.	longitude (λ)
ALPHA	deg.	angle between north and nav X-axis (α)
ALT	feet	altitude from ellipsoid (h)
ROLL	deg.	roll (η_x)
PITCH	deg.	pitch (η_y)
YAW	deg.	yaw (η_z)
PSI	deg.	ground heading angle measured positive cw from north (ψ)
DROLL	deg/sec	derivative of roll ($\dot{\eta}_x$)
DPITCH	deg/sec	derivative of pitch ($\dot{\eta}_y$)
DYAW	deg/sec	derivative of yaw ($\dot{\eta}_z$)
VX	ft/sec	velocity w.r.t. earth along nav x-axis (V_x)
VY	ft/sec	velocity w.r.t. earth along nav y-axis (V_y)
VZ	ft/sec	velocity w.r.t. earth along nav z-axis (V_z)
VPATH	ft/sec	magnitude of total velocity (V_T)
FX	ft/sec^2	specific force along nav X-axis (F_x)
FY	ft/sec^2	specific force along nav y-axis (F_y)
FZ	ft/sec^2	specific force along nav z-axis (F_z)
APATH	ft/sec^2	acceleration along path X-axis (i.e. along $\underline{V}$)

```
$$$$$$$$   $$$$$$   $$     $$  $       $   $$$$$$     $$$$$ $   $$$$$$$$
   $$     $$    $$  $$     $$  $$     $$  $$    $$   $$     $   $$
   $$     $$        $$     $$  $$$   $$$  $$    $$   $$    $$$  $$
   $$      $$$$$$   $$$$$$$$$  $$$$$$$$$  $$    $$   $$  $ $$   $$$$$$$
   $$           $$  $$     $$  $$ $$ $$   $$    $$   $$ $$ $$         $$
   $$           $$  $$     $$  $$     $$  $$    $$   $$ $  $$         $$
   $$           $$  $$     $$  $$     $$  $$    $$   $$$   $$         $$
   $$     $$    $$  $$     $$  $$     $$  $$    $$   $     $$   $$    $$
$$$$$$$$   $$$$$$   $$     $$  $$     $$   $$$$$$    $ $$$$$     $$$$$$
```

TODAY = 11/16/76

CLOCK = 15.51.32.

Figure A-1 Sample Output (1 of 8)

```
$PRDATA
IPRGB   = 650,
NSEGT   = 17,
LLMECH  = 2,
TSTART  = 0.0.
VTO     = .1E+04,
PHEADO  = .18F+03,
PPITCHO = 0.0,
ALFAO   = .45E+02,
LATO    = .39E+02,
LONO    = -.84E+02,
ALTO    = .3E+05,
IPRNT   = 1,
IRITE   = 0,
IPLOT   = 1,
ROLRATE = .25E+03,
$END
```

(2 of 8)

```
$PASDATA

SEGLNT  = .2E+02, .3E+02, .1E+02, .3E+02, .3E+02, .4E+02, .1E+02, .1E+02,            .6E+02, .1E+02, .1E+02, .1E+02, .5E+02,
          .1E+02, .405E+02, .5E+02, .4E+02, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,      0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     0.0, 0.0, 0.0, 0.0, 0.0,

RESTART = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,    0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
          0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,

TURN    = 4, 3, 4, 3, 2, 2, 1, 2, 4, 2, 1, 4, 2, 4, 2, 4, 2, 4, 4, 4, 4, 4, 4,    4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,
          4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4, 4,

NPATH   = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2,    2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2.
          2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,

PACC    = 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, -.1E+00, 0.0, 0.0, 0.0, .1E+00, 0.0,        0.0, 0.0, 0.0, 0.0, .1E+01, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

TACC    = 0.0, 0.0, 0.0, 0.0, .1E+01, .1E+01, .5E+00, .5E+01, 0.0, .5E+01,          .5E+00, 0.0, .4E+01, 0.0, .2E+01, 0.0,
          .2E+01, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,       0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

HEAD    = 0.0, .2E+02, 0.0, -.2E+02, -.3E+02, .3E+02, 0.0, -.9E+02, 0.0,            -.9E+02, 0.0, 0.0, .365E+03, 0.0, -.135E+03,
          0.0, .135E+03, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     0.0,

PITCH   = 0.0, .36E+02, 0.0, .36E+02, 0.0, 0.0, .5E+01, 0.0, 0.0, 0.0, -.5E+01,    0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,     0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,
          0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0,

DTO     = .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,           .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,
          .1E+01, .1E+01, .1E+01, .1E+01, .1E+09, .1E+09, .1E+09, .1E+09,           .1E+09, .1E+09, .1E+09, .1E+09, .1E+09,
          .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09,           .1E+09, .1E+09, .1E+09, .1E+09, .1E+09,
          .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09, .1E+09,           .1E+09, .1E+09, .1E+09,

MODE    = 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,    1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,
          1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,

ERROR   = .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,           .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,
          .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,           .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,
          .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,           .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,
          .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05, .1E-05,           .1E-05, .1E-05, .1E-05,

HMAX    = .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,           .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,
          .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,           .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,
          .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,           .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,
          .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05, .1E+05,           .1E+05, .1E+05, .1E+05,

HMIN    = .1E-03, .1E-03, .1E-03, .1E-03, .1E-03, .1E-03, .1E-03, .1E-03,           .1E-03, .1E-03, .1E-03, .1E-03, .1E-03,
          .1E-03, .1E-03, .1E-03, .1E-03, .1E+01, .1E+01, .1E+01, .1E+01,           .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,
          .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,           .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,
          .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01, .1E+01,           .1E+01, .1E+01, .1E+01,

$END
```

(3 of 8)

```
BEGIN SEGMENT NUMBER 1
INITIAL TIME      0.00000
FINAL TIME       20.00000
THIS FLIGHT SEGMENT IS A STRAIGHT FLIGHT.
THE NOMINAL FLIGHT PATH OVER THE EARTH IS A GREAT CIRCLE.
THE INTEGRATION STEP SIZE IS VARIABLE.
THE LOCAL LEVEL MECHANIZATION IS CONSTANT ALPHA.

TIME      0.00000
   LAT     39.00000000      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      180.0000000
   DROLL   0.               DPITCH  0.                DYAW     .1482136080E-15
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6473823627E-01 FY      -.6506845547E-01  FZ       32.01467768       APATH    0.

TIME      1.00000
   LAT     38.99725638      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      180.0000000
   DROLL   0.               DPITCH  0.                DYAW     .6408621741E-16
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6472640472E-01 FY      -.6506461703E-01  FZ       32.01466970       APATH    0.

TIME      2.00000
   LAT     38.99451675      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      -180.0000000
   DROLL   0.               DPITCH  0.                DYAW     .4005008575E-17
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6472257382E-01 FY      -.6506077845E-01  FZ       32.01466171       APATH    0.

TIME      3.00000
   LAT     38.99177513      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      -180.0000000
   DROLL   0.               DPITCH  0.                DYAW     -.4004528769E-17
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6471874117E-01 FY      -.6505693971E-01  FZ       32.01465373       APATH    0.

TIME      4.00000
   LAT     38.98903358      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      -180.0000000
   DROLL   0.               DPITCH  0.                DYAW     .4369568301E-22
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6471490917E-01 FY      -.6505310082E-01  FZ       32.01464574       APATH    0.

TIME      5.00000
   LAT     38.98629197      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      -180.0000000
   DROLL   0.               DPITCH  0.                DYAW     -.4003743884E-17
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6471107792E-01 FY      -.6504926178E-01  FZ       32.01463776       APATH    0.

TIME      6.00000
   LAT     38.98355024      LON     -84.00000000      ALPHA    45.00000000       ALT      30000.00000
   ROLL    0.               PITCH   0.                YAW      -135.0000000      PSI      -180.0000000
   DROLL   0.               DPITCH  0.                DYAW     .4003430951E-17
   VX      -707.1067812     VY      707.1067812       VZ       0.                VPATH    1000.000000
   FX      -.6470724472E-01 FY      -.6504542258E-01  FZ       32.01462978       APATH    0.
```

```
TIME     7.00000
    LAT     38.98080861          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    -.4002959119E-17
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6470341227E-01     FY      -.6504158324E-01     FZ      32.01462179          APATH   0.

TIME     8.00000
    LAT     38.97806698          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    .4376932623E-22
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6469957958E-01     FY      -.6503774374E-01     FZ      32.01461381          APATH   0.

TIME     9.00000
    LAT     38.97532535          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    -.4002174476E-17
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6469574694E-01     FY      -.6503390409E-01     FZ      32.01460582          APATH   0.

TIME     10.00000
    LAT     38.97258371          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    .4380613829E-22
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6469191494E-01     FY      -.6503006429E-01     FZ      32.01459784          APATH   0.

TIME     11.00000
    LAT     38.96984207          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    -.4001389354E-17
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6468808190E-01     FY      -.6502622433E-01     FZ      32.01458986          APATH   0.

TIME     12.00000
    LAT     38.96710044          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    .4384294397E-22
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6468424751E-01     FY      -.6502238423E-01     FZ      32.01458168          APATH   0.

TIME     13.00000
    LAT     38.96435880          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    -.4000605553E-17
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6468041448E-01     FY      -.6501854397E-01     FZ      32.01457389          APATH   0.

TIME     14.00000
    LAT     38.96161716          LON     -84.00000000         ALPHA   45.00000000          ALT     30000.00000
    ROLL    0.                   PITCH   0.                   YAW     -135.0000000         PSI     -180.0000000
    DROLL   0.                   DPITCH  0.                   DYAW    .4000301157E-17
    VX      -707.1067812         VY      707.1067812          VZ      0.                   VPATH   1000.000000
    FX      -.6467658099E-01     FY      -.6501470356E-01     FZ      32.01456591          APATH   0.
```

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```
TIME      15.00000
     LAT       38.95887552        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     -.3999821273E-17
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6467274735E-01   FY       -.6501086300E-01   FZ       32.01455793         APATH   0.

TIME      16.00000
     LAT       38.95613397        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     .4391653618E-22
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6466891357E-01   FY       -.6500702229E-01   FZ       32.01454995         APATH   0.

TIME      17.00000
     LAT       38.95339223        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     -.3999037114E-17
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6466507963E-01   FY       -.6500318142E-01   FZ       32.01454196         APATH   0.

TIME      18.00000
     LAT       38.95065059        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     .4395332278E-22
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6466124555E-01   FY       -.6499934041E-01   FZ       32.01453398         APATH   0.

TIME      19.00000
     LAT       38.94790894        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     -.7996550123E-17
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6465741132E-01   FY       -.6499549924E-01   FZ       32.01452600         APATH   0.

TIME      20.00000
     LAT       38.94516729        LON      -84.00000000       ALPHA    45.00000000         ALT     30000.00000
     ROLL      0.                 PITCH    0.                 YAW      -135.0000000        PSI     -180.0000000
     DROLL     0.                 DPITCH   0.                 DYAW     .4399010282E-22
     VX        -707.1067812       VY       707.1067812        VZ       0.                  VPATH   1000.000000
     FX        -.6465357694E-01   FY       -.6499165792E-01   FZ       32.01451802         APATH   0.
```

BEGIN SEGMENT NUMBER 2
INITIAL TIME 20.00000
FINAL TIME 50.00000
THIS FLIGHT SEGMENT IS A SINE HEADING CHANGE
THE NOMINAL FLIGHT PATH OVER THE EARTH IS A GREAT CIRCLE.
THE INTEGRATION STEP SIZE IS VARIABLE.
THE LOCAL LEVEL MECHANIZATION IS CONSTANT ALPHA.

TIME	20.00000										
	LAT	38.94516729	LON	-84.00000000	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	0.	PITCH	0.	YAW	-135.0000000	PSI	-180.0000000			
	DROLL	250.0000000	DPITCH	-.8142219985E-12	DYAW	.4399010282E-22					
	VX	-707.1067812	VY	707.1067812	VZ	0.	VPATH	1000.000000			
	FX	-.6465357694E-01	FY	-.6499165792E-01	FZ	32.01451802	APATH	0.			
TIME	21.00000										
	LAT	38.94242647	LON	-84.00006749	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	65.52537060	PITCH	-.5679838075E-15	YAW	-132.1729768	PSI	-177.1729768			
	DROLL	3.527304764	DPITCH	-.6361109363E-14	DYAW	4.052963114					
	VX	-671.3711187	VY	741.1213268	VZ	-.3846229019E-12	VPATH	1000.000000			
	FX	52.35874746	FY	47.43871184	FZ	32.02010512	APATH	0.			
TIME	22.00000										
	LAT	38.93969519	LON	-84.00036422	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	60.27669862	PITCH	.6310426594E-15	YAW	-128.2503941	PSI	-173.2503941			
	DROLL	-23.29905581	DPITCH	.5088887490E-13	DYAW	3.231183693					
	VX	-619.0993512	VY	785.3126723	VZ	-.8276927869E-12	VPATH	1000.000000			
	FX	44.21928636	FY	34.85986547	FZ	32.02783712	APATH	0.			
TIME	23.00000										
	LAT	38.93697620	LON	-84.00081429	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	-60.27636503	PITCH	-.9179019857E-14	YAW	-128.2506633	PSI	-173.2506633			
	DROLL	-23.29905581	DPITCH	.5088887490E-13	DYAW	-3.231656498					
	VX	-619.1030407	VY	785.3097638	VZ	-.2425667732E-10	VPATH	1000.000000			
	FX	-44.36211905	FY	-34.97340979	FZ	32.02782918	APATH	0.			
TIME	24.00000										
	LAT	38.93424491	LON	-84.00111106	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	-65.52503709	PITCH	-.9154993794E-14	YAW	-132.1735580	PSI	-177.1735580			
	DROLL	3.527304764	DPITCH	.1908332809E-13	DYAW	-4.053117275					
	VX	-671.3786372	VY	741.1145158	VZ	-.2168947292E-10	VPATH	1000.000000			
	FX	-52.49296791	FY	-47.55391407	FZ	32.02008080	APATH	0.			
TIME	25.00000										
	LAT	38.93150408	LON	-84.00117841	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	.1361560541E-03	PITCH	.1024889322E-13	YAW	-135.0006262	PSI	179.9993738			
	DROLL	250.0000000	DPITCH	-.1628443997E-11	DYAW	.5852232868E-05					
	VX	-707.1145088	VY	707.0990535	VZ	-.5485148183E-11	VPATH	1000.000000			
	FX	-.6457170448E-01	FY	-.6491116588E-01	FZ	32.01447700	APATH	0.			
TIME	26.00000										
	LAT	38.92876325	LON	-84.00111099	ALPHA	45.00000000	ALT	30000.00000			
	ROLL	-65.52521476	PITCH	-.1156213180E-14	YAW	-137.8276305	PSI	[illegible]7.1723695			
	DROLL	-3.527304764	DPITCH	.6361109363E-14	DYAW	-4.052933776					
	VX	-741.1284431	VY	671.3632638	VZ	-.2166464198E-10	VPATH	1000.000000			
	FX	-47.55287912	FY	-52.49472520	FZ	32.00887385	APATH	0.			

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TIME 456.00000

LAT	38.60555833	LON	-84.10503992	ALPHA	45.00000000	ALT	37596.11896
ROLL	63.43497896	PITCH	-.2995299753E-09	YAW	1.690553102	PSI	-43.38944690
DROLL	0.	DPITCH	0.	DYAW	1.718545553		
VX	2142.167190	VY	-63.22452895	VZ	-.1062224105E-07	VPATH	2143.100000
FX	30.29203974	FY	-65.12776636	FZ	31.98631233	APATH	32.20000000

TIME 457.00000

LAT	38.60992467	LON	-84.11013054	ALPHA	45.00000000	ALT	37596.11896
ROLL	63.43497896	PITCH	-.2995299753E-09	YAW	3.395319533	PSI	-41.60360047
DROLL	0.	DPITCH	0.	DYAW	1.693114726		
VX	2171.479380	VY	-128.8696668	VZ	-.1079057571E-07	VPATH	2175.300000
FX	28.34014960	FY	-65.99765320	FZ	31.97672065	APATH	32.20000000

TIME 458.00000

LAT	38.61447397	LON	-84.11512826	ALPHA	45.00000000	ALT	37596.11896
ROLL	63.43497896	PITCH	-.2995299753E-09	YAW	5.077031796	PSI	-39.92296820
DROLL	0.	DPITCH	0.	DYAW	1.668431693		
VX	2198.839140	VY	-195.3527255	VZ	-.1095891036E-07	VPATH	2207.500000
FX	26.39252992	FY	-66.79752279	FZ	31.96680459	APATH	32.20000000

TIME 459.00000

LAT	38.61920410	LON	-84.12002629	ALPHA	45.00000000	ALT	37596.11896
ROLL	63.43497896	PITCH	-.2995299753E-09	YAW	6.733421439	PSI	-38.26657856
DROLL	0.	DPITCH	0.	DYAW	1.644464277		
VX	2224.251501	VY	-262.6049317	VZ	-.1112724502E-07	VPATH	2239.700000
FX	24.45104364	FY	-67.52955813	FZ	31.95657025	APATH	32.20000000

TIME 460.00000

LAT	38.62411243	LON	-84.12481801	ALPHA	45.00000000	ALT	37596.11896
ROLL	63.43497896	PITCH	-.2995299753E-09	YAW	8.366188750	PSI	-36.63381125
DROLL	0.	DPITCH	0.	DYAW	1.621182117		
VX	2247.723274	VY	-330.5596689	VZ	-.1129557967E-07	VPATH	2271.900000
FX	22.51741198	FY	-68.19589925	FZ	31.94602370	APATH	32.20000000

TIME 460.50000

LAT	38.62663115	LON	-84.12717484	ALPHA	45.00000000	ALT	37596.11896
ROLL	.3029935759E-04	PITCH	-.2995355128E-09	YAW	8.913073484	PSI	-36.08692652
DROLL	-250.0000000	DPITCH	0.	DYAW	-.2927341102E-02		
VX	2260.371345	VY	-354.4931340	VZ	-.2009382221E-06	VPATH	2288.000000
FX	31.84358041	FY	-4.783832879	FZ	31.94159996	APATH	32.20000000

THIS FLIGHT REQUIRED 5393 PASSES THROUGH THE NUMERICAL INTEGRATOR, KUTMER.
KUTMER IN TURN MADE 34675 CALLS TO SUBROUTINE F, THE DERIVATIVE SUBPROGRAM.

*********** ISHM005 //// END OF LIST ////

(8 of 8)

Figure A-2

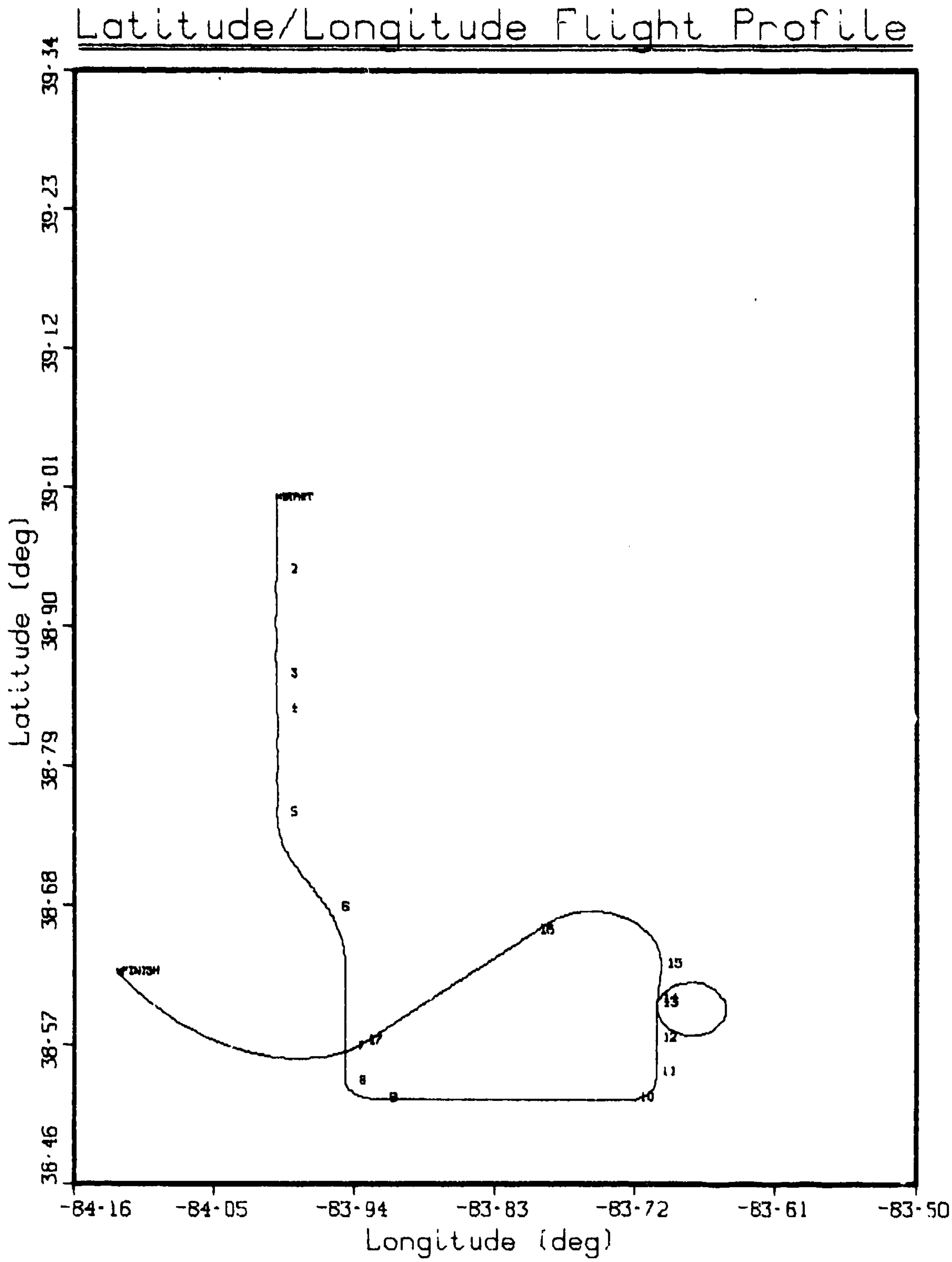
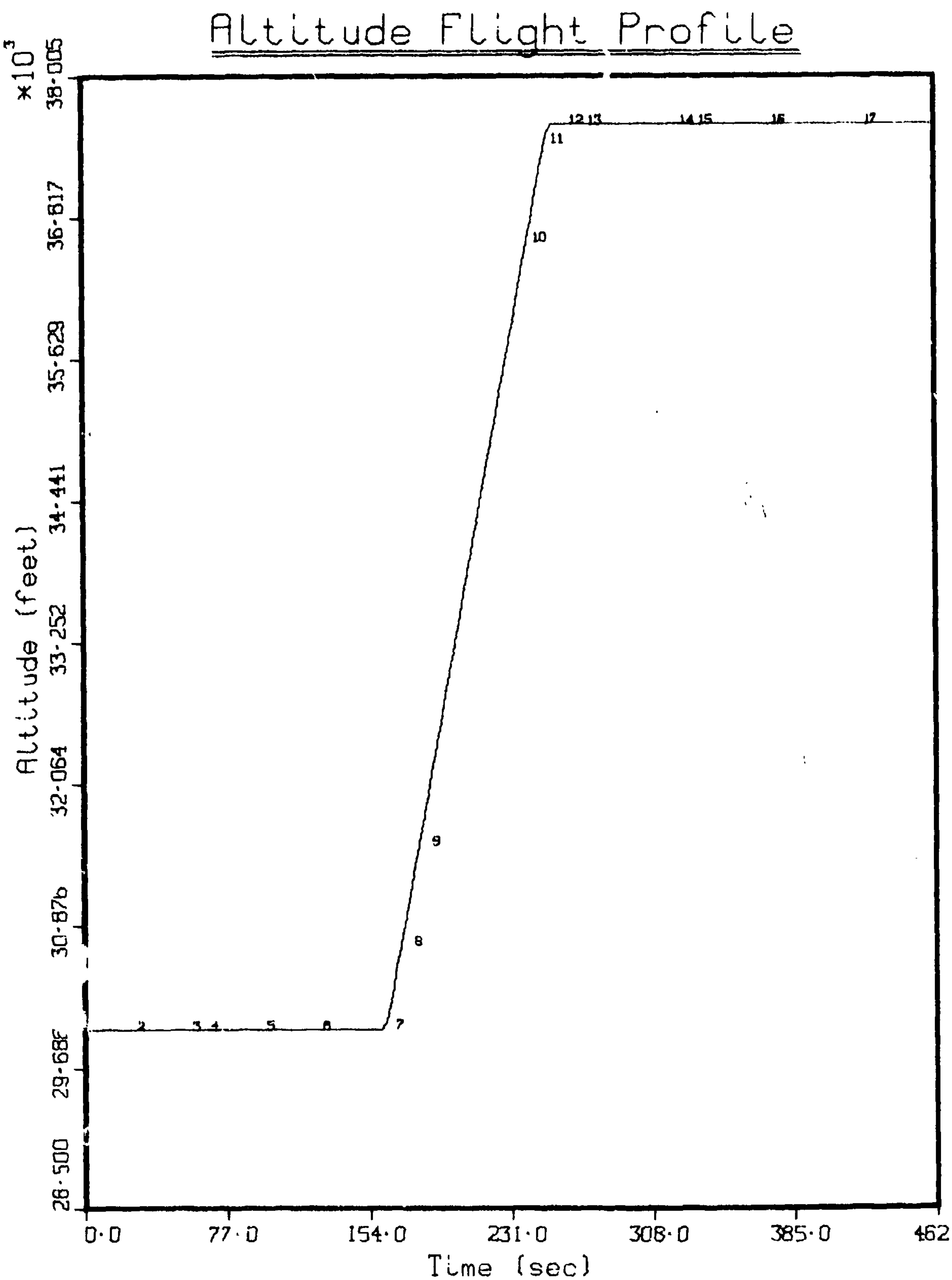

Latitude/Longitude Flight Profile
Latitude (deg)
Longitude (deg)
39.34
39.23
39.12
39.01
38.90
38.79
38.68
38.57
38.46
-84.16
-84.05
-83.94
-83.83
-83.72
-83.61
-83.50
2
3
5
6
8
10
11
12
13
15
16
17

Figure A-3



Altitude Flight Profile
*10^3
38.005
36.817
35.629
34.441
33.252
32.064
30.876
29.688
28.500
Altitude (feet)
0.0
77.0
154.0
231.0
308.0
385.0
462.
Time (sec)

Figure A-4

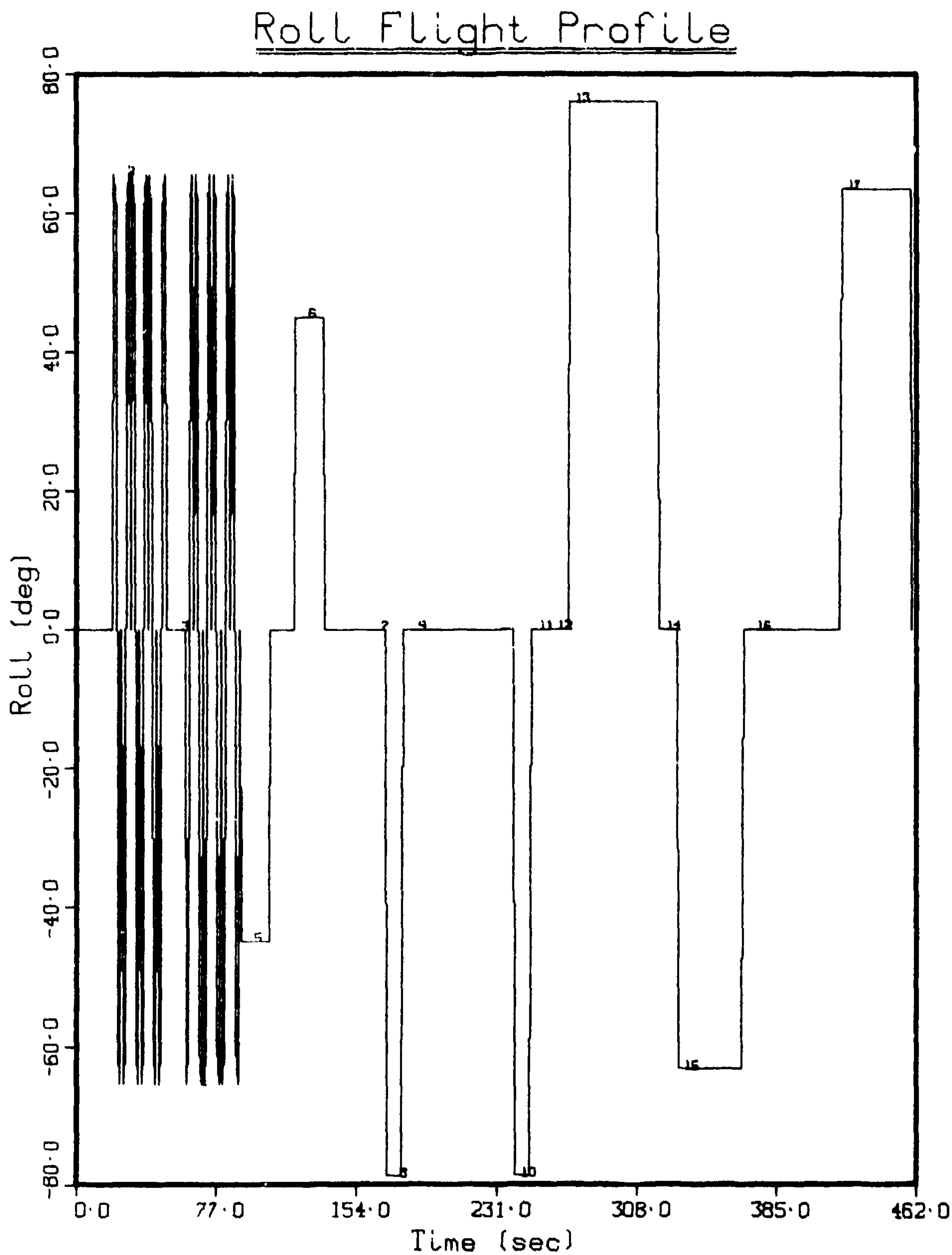

Roll Flight Profile
Roll (deg)
Time (sec)
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
0.0
77.0
154.0
231.0
308.0
385.0
462.0
3
5
6
7
8
9
10
11
12
13
14
15
16
17

Figure A-5

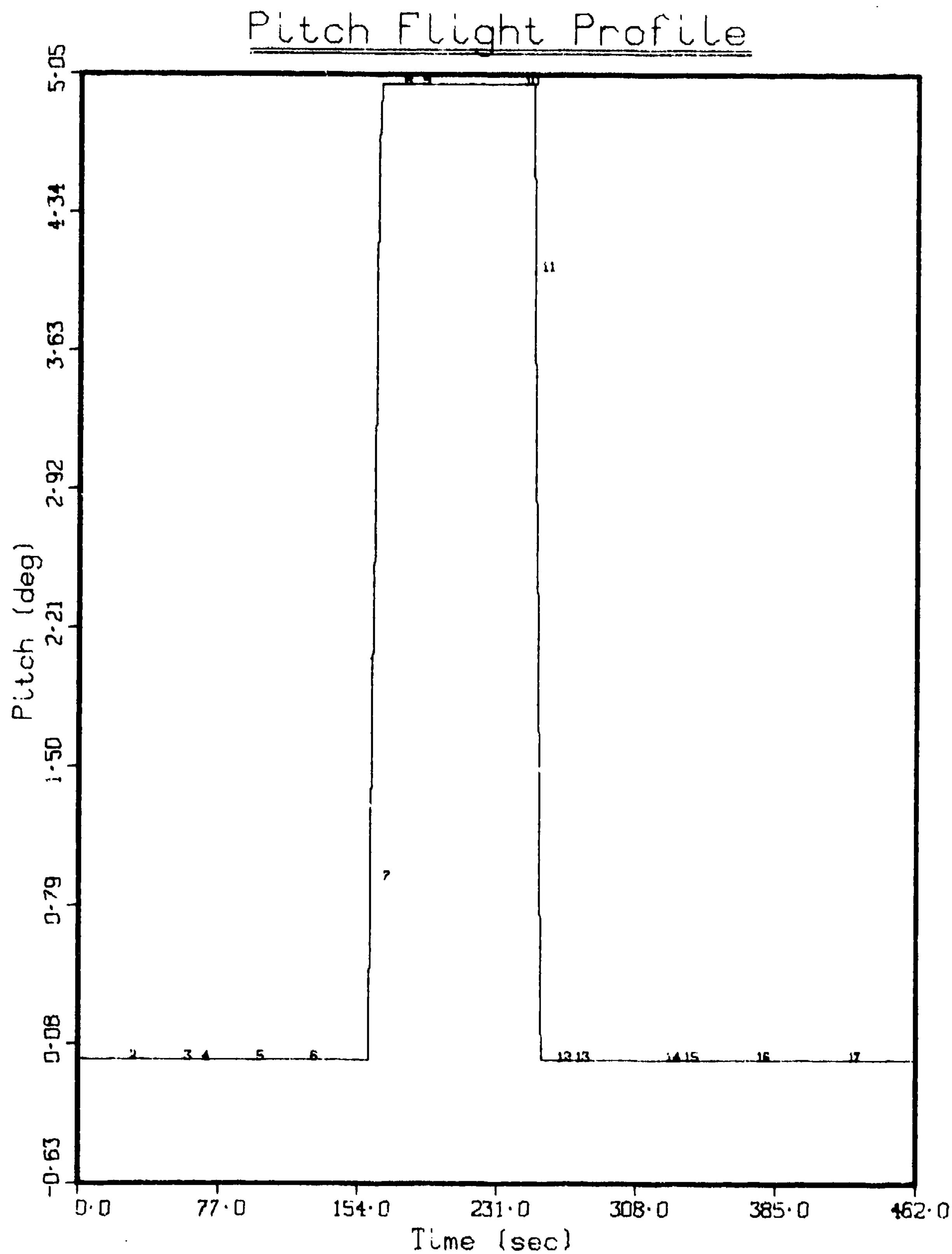
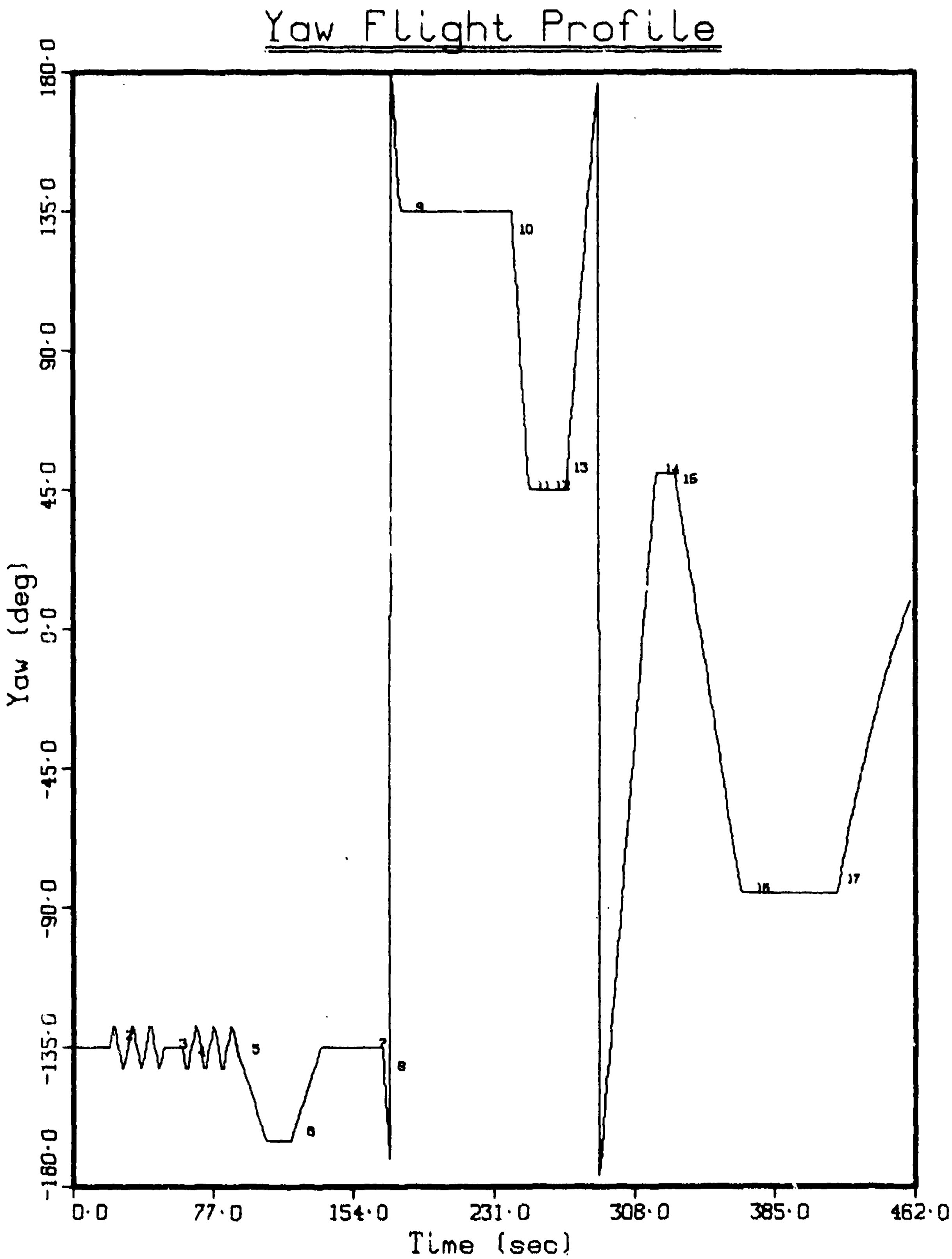

Pitch Flight Profile
5·05
4·34
3·63
2·92
2·21
1·50
0·79
0·08
-0·63
Pitch (deg)
0·0
77·0
154·0
231·0
308·0
385·0
462·0
Time (sec)
2
3 4
5
6
7
11
12 13
14 15
16
17

Figure A-6


Yaw Flight Profile
Yaw (deg)
180.0
135.0
90.0
45.0
0.0
-45.0
-90.0
-135.0
-180.0
0.0
77.0
154.0
231.0
308.0
385.0
462.0
Time (sec)
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

APPENDIX B

PROFGEN LISTING

```
            PROGRAM PROFGEN (INPUT,OUTPUT,TAPE3,TAPE6,TAPE9,                PROFGEN    2
     1 PLFILE=0,MAPDTA=0)                                                   PROFGEN    3
                                                                            PROFGEN    4
C**  THIS IS THE MAIN PROGRAM OF A SIMULATION DESIGNED TO GENERATE          PROFGEN    5
C**  FLIGHT PROFILES. A PROFILE CONSISTS OF A SEQUENCE OF UP TO 50          PROFGEN    6
C**  FLIGHT SEGMENTS, ONE FOLLOWING ANOTHER. EACH FLIGHT SEGMENT            PROFGEN    7
C**  EXECUTES ONE "MANEUVER". THESE KINDS OF MANEUVERS ARE POSSIBLE:        PROFGEN    8
C**         * VERTICAL TURNS                                                PROFGEN    9
C**         * HORIZONTAL TURNS                                              PROFGEN   10
C**         * SINUSOIDAL HEADING CHANGES                                    PROFGEN   11
C**         * STRAIGHT FLIGHTS OVER GREAT CIRCLE OR RHUMB LINE PATHS        PROFGEN   12
C**  INPUT IS MADE VIA TWO NAMELISTS, PRDATA AND PASDATA. THE AIRCRAFT      PROFGEN   13
C**  POSITION, VELOCITY, ACCELERATION AND ORIENTATION ARE COMPUTED          PROFGEN   14
C**  USING THE KINEMATIC EQUATIONS APPROPRIATE FOR AN ELLIPSOIDAL EARTH     PROFGEN   15
C**  AND A LOCAL-LEVEL, ALPHA-CONTROLLED MECHANIZATION. OUTPUT CAN BE       PROFGEN   16
C**  TAYLORED TO THE USER'S NEEDS. COMPLETE INFORMATION ABOUT PROFGEN,      PROFGEN   17
C**  ITS CAPABILITIES, ITS LIMITATIONS AND THE MEANS FOR USING IT, IS       PROFGEN   18
C**  GIVEN IN "PROFGEN - A COMPUTER PROGRAM FOR GENERATING FLIGHT           PROFGEN   19
C**  PROFILES". CONTACT RWA, AFAL, W-P AFB, OH. (513)255-6843. 2/11/76      PROFGEN   20
                                                                            PROFGEN   21
      COMMON /DTO/DTO(50)        /ERROR/ERROR(50)     /FIXED/FIXED(15)      PROFGEN   22
      COMMON /HEAD/HEAD(50)      /HMAX/HMAX(50)       /HMIN/HMIN(50)        PROFGEN   23
      COMMON /MODE/MODE(50)      /NPATH/NPATH(50)     /PACC/PACC(50)        PROFGEN   24
      COMMON /PITCH/PITCH(50)    /PRBLK/PRBLK(13)                           PROFGEN   25
      COMMON /RESTART/RESTART(50)/SEGLNT/SEGLNT(50)  /SUPLE/SUPLE(9)        PROFGEN   26
      COMMON /TACC/TACC(50)      /TURN/TURN(50)                             PROFGEN   27
                                                                            PROFGEN   28
      EQUIVALENCE (FIXED(3),TWOPI)                                          PROFGEN   29
      EQUIVALENCE (FIXED(4),PI)                                             PROFGEN   30
      EQUIVALENCE (FIXED(5),HALFPI)                                         PROFGEN   31
      EQUIVALENCE (PRBLK(1),LLMECH)                                         PROFGEN   32
      EQUIVALENCE (PRBLK(2),TSTART)                                         PROFGEN   33
      EQUIVALENCE (PRBLK(3),VTO)                                            PROFGEN   34
      EQUIVALENCE (PRBLK(4),PHEADO)                                         PROFGEN   35
      EQUIVALENCE (PRBLK(5),PPITCHO)                                        PROFGEN   36
      EQUIVALENCE (PRBLK(6),ALFAO)                                          PROFGEN   37
      EQUIVALENCE (PRBLK(7),LATO)                                           PROFGEN   38
      EQUIVALENCE (PRBLK(8),LONO)                                           PROFGEN   39
      EQUIVALENCE (PRBLK(9),ALTO)                                           PROFGEN   40
      EQUIVALENCE (PRBLK(10),IPRNT)                                         PROFGEN   41
      EQUIVALENCE (PRBLK(11),IRITE)                                         PROFGEN   42
      EQUIVALENCE (PRBLK(12),IPLOT)                                         PROFGEN   43
      EQUIVALENCE (PRBLK(13),ROLRATE)                                       PROFGEN   44
      EQUIVALENCE (SUPLE(1),T)                                              PROFGEN   45
      EQUIVALENCE (SUPLE(2),TF)                                             PROFGEN   46
      EQUIVALENCE (SUPLE(3),TI)                                             PROFGEN   47
      EQUIVALENCE (SUPLE(6),ISEG)                                           PROFGEN   48
                                                                            PROFGEN   49
      INTEGER RESTART,TURN                                                  PROFGEN   50
      REAL LATO,LONO                                                        PROFGEN   51
                                                                            PROFGEN   52
      NAMELIST /PRDATA/ IPROB,NSEGT,LLMECH,TSTART,VTO,PHEADO,PPITCHO,       PROFGEN   53
     1 ALFAO,LATO,LONO,ALTO,IPRNT,IRITE,IPLOT,ROLRATE                       PROFGEN   54
      NAMELIST /PASDATA/ SEGLNT,RESTART,TURN,NPATH,PACC,TACC,HEAD,          PROFGEN   55
     1 PITCH,DTO,MODE,ERROR,HMAX,HMIN                                       PROFGEN   56
                                                                            PROFGEN   57
C                                                                           PROFGEN   58
```

```
      C          PRINT DATE AND TIME                                  PROFGEN    59
            TODAY=DATE(DMY)                                           PROFGEN    60
            CLOCK=TIME(DMY)                                           PROFGEN    61
            WRITE (6,100) TODAY,CLOCK                                 PROFGEN    62
      C                                                               PROFGEN    63
      C          READ, PRINT AND VALIDATE INPUT DATA                  PROFGEN    64
            READ (9,PRDATA)                                           PROFGEN    65
            READ (9,PASDATA)                                          PROFGEN    66
            WRITE (6,PRDATA)                                          PROFGEN    67
            WRITE (6,PASDATA)                                         PROFGEN    68
            CALL VALDATA(NSEGT)                                       PROFGEN    69
            IF (IRITE.NE.1) GO TO 10                                  PROFGEN    70
      C                                                               PROFGEN    71
      C          WRITE INPUT DATA ON A TAPE ANNOTATED WITH DATE AND TIME PROFGEN 72
            REWIND 3                                                  PROFGEN    73
            WRITE (3) TODAY,CLOCK                                     PROFGEN    74
            WRITE (3) IPROB,NSEGT,LLMECH,TSTART,VTO,PHEADO,PPITCHO,   PROFGEN    75
           1 ALFAO,LATO,LONO,ALTO,IPRNT,IRITE,IPLOT,ROLRATE           PROFGEN    76
            WRITE (3) SEGLNT,RESTART,TURN,NPATH,PACC,TACC,HEAD,       PROFGEN    77
           1 PITCH,DTO,MODE,ERROR,HMAX,HMIN                           PROFGEN    78
      C                                                               PROFGEN    79
      C          CONVERT INPUT TO UNITS OF FEET, SECONDS AND RADIANS  PROFGEN    80
         10 CALL NEWUNIT                                              PROFGEN    81
      C                                                               PROFGEN    82
      C          COMPUTE MACHINE-CRITICAL CONSTANTS FOR               PROFGEN    83
      C          STORAGE IN COMMON BLOCK "FIXED"                      PROFGEN    84
            PI=ABS(ATAN2(0.,-1.))                                     PROFGEN    85
            HALFPI=PI/2.                                              PROFGEN    86
            TWOPI=2.*PI                                               PROFGEN    87
      C                                                               PROFGEN    88
      C          INITIALIZE TIME AND THEN ENTER LOOP                  PROFGEN    89
      C          GOVERNING PASSAGE TO EACH FLIGHT SEGMENT             PROFGEN    90
            T=TSTART                                                  PROFGEN    91
            DO 20 I=1,NSEGT                                           PROFGEN    92
               ISEG=I                                                 PROFGEN    93
               IF (RESTART(I).EQ.1) T=TSTART                          PROFGEN    94
               TI=T                                                   PROFGEN    95
               TF=T+SEGLNT(I)                                         PROFGEN    96
               CALL HEADER                                            PROFGEN    97
               CALL FLTPATH                                           PROFGEN    98
         20 CONTINUE                                                  PROFGEN    99
      C                                                               PROFGEN   100
      C          POST-FLIGHT OUTPUT                                   PROFGEN   101
            TI=T                                                      PROFGEN   102
            CALL PRNTOUT                                              PROFGEN   103
            CALL KMPERF                                               PROFGEN   104
            IF (IRITE.EQ.1) CALL RITEOUT                              PROFGEN   105
            IF (IPLOT.EQ.1)  CALL PLOTTER(NSEGT)                      PROFGEN   106
            STOP                                                      PROFGEN   107
        100 FORMAT(//////T2,*TODAY = *,A10//T2,*CLOCK = *,A10)        PROFGEN   108
            END                                                       PROFGEN   109
```

```
      SUBROUTINE FLTPATH                                                FLTPATH    2
                                                                        FLTPATH    3
C**   FLTPATH CONTROLS THE FLIGHT PATH GENERATION PROCESS DURING        FLTPATH    4
C**   EACH FLIGHT SEGMENT. THE PASSAGE FROM SEGMENT TO SEGMENT IS       FLTPATH    5
C**   GOVERNED BY PROFGEN, THE MAIN PROGRAM.                            FLTPATH    6
                                                                        FLTPATH    7
      COMMON /ERROR/ERROR(50)                                           FLTPATH    8
      COMMON /FIXED/FIXED(15)                                           FLTPATH    9
      COMMON /HMAX/HMAX(50)                                             FLTPATH   10
      COMMON /HMIN/HMIN(50)                                             FLTPATH   11
      COMMON /MODE/MODE(50)                                             FLTPATH   12
      COMMON /PRBLK/PRBLK(13)                                           FLTPATH   13
      COMMON /RESTART/RESTART(50)                                       FLTPATH   14
      COMMON /STATE/X(23)                                               FLTPATH   15
      COMMON /SUPLE/SUPLE(9)                                            FLTPATH   16
      COMMON /TURN/TURN(50)                                             FLTPATH   17
                                                                        FLTPATH   18
      EQUIVALENCE (FIXED(1),N)                                          FLTPATH   19
      EQUIVALENCE (PRBLK(2),TSTART)                                     FLTPATH   20
      EQUIVALENCE (PRBLK(10),IPRNT)                                     FLTPATH   21
      EQUIVALENCE (PRBLK(11),IRITE)                                     FLTPATH   22
      EQUIVALENCE (PRBLK(12),IPLOT)                                     FLTPATH   23
      EQUIVALENCE (SUPLE(1),T)                                          FLTPATH   24
      EQUIVALENCE (SUPLE(2),TF)                                         FLTPATH   25
      EQUIVALENCE (SUPLE(4),TRNDONE)                                    FLTPATH   26
      EQUIVALENCE (SUPLE(5),TDONE)                                      FLTPATH   27
      EQUIVALENCE (SUPLE(6),ISEG)                                       FLTPATH   28
      EQUIVALENCE (SUPLE(7),TOFF)                                       FLTPATH   29
      EQUIVALENCE (SUPLE(8),TON)                                        FLTPATH   30
      EQUIVALENCE (SUPLE(9),RRCOEF)                                     FLTPATH   31
                                                                        FLTPATH   32
      INTEGER RESTART,TURN                                              FLTPATH   33
      EXTERNAL F                                                        FLTPATH   34
                                                                        FLTPATH   35
C                                                                       FLTPATH   36
C       INITIALIZE THE STATE VECTOR PRIOR TO BEGINNING THE FIRST        FLTPATH   37
C       SEGMENT OR WHENEVER A PROBLEM RESTART IS REQUIRED.              FLTPATH   38
      IF (ISEG.EQ.1 .OR. RESTART(ISEG).EQ.1) CALL SVSETUP               FLTPATH   39
C                                                                       FLTPATH   40
C       INITIALIZE SEVERAL PARAMETERS THAT ARE FLIGHT SEGMENT DEPENDENT FLTPATH   41
      H=HMN=HMIN(ISEG)                                                  FLTPATH   42
      MDE=MODE(ISEG)                                                    FLTPATH   43
      ERR=ERROR(ISEG)                                                   FLTPATH   44
      HMX=HMAX(ISEG)                                                    FLTPATH   45
      TRNDONE=1.                                                        FLTPATH   46
      RRCOEF=0.                                                         FLTPATH   47
      IF (TURN(ISEG).EQ.1) CALL TSETUP1(TDONE)                          FLTPATH   48
      IF (TURN(ISEG).EQ.1) TRNDONE=0.                                   FLTPATH   49
      IF (TURN(ISEG).EQ.2) CALL TSETUP2(TOFF,TON,TDONE)                 FLTPATH   50
      IF (TURN(ISEG).EQ.2) TRNDONE=0.                                   FLTPATH   51
      IF (TURN(ISEG).EQ.2) RRCOEF=+1.                                   FLTPATH   52
      IF (TURN(ISEG).EQ.3) CALL CHKSHC                                  FLTPATH   53
      IF (TURN(ISEG).EQ.3) RRCOEF=+1.                                   FLTPATH   54
C                                                                       FLTPATH   55
C       PRINT THE VALUE OF EACH VARIABLE AT THE BEGINNING OF EACH       FLTPATH   56
C       SEGMENT AND THEN TRANSFER CONTROL TO THE SPECIFIED MANEUVER     FLTPATH   57
      CALL PRNTOUT                                                      FLTPATH   58
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      IF (IRITE.EQ.1 .AND. T.EQ.TSTART) CALL RITEOUT          FLTPATH    59
      IF (IPLOT.EQ.1) CALL ARAYFIL                            FLTPATH    60
      GO TO (40,50,60,70), TURN(ISEG)                         FLTPATH    61
C                                                             FLTPATH    62
C                                                             FLTPATH    63
C         ***   VERTICAL TURN   ***                           FLTPATH    64
C                                                             FLTPATH    65
C                                                             FLTPATH    66
   40 H=HLIMIT(T,TF,H,HMN)                                    FLTPATH    67
      H=HCHOP(H,T,TDONE)                                      FLTPATH    68
      CALL KUTMER(N,T,X,H,F,MDE,ERR,HMX,HMN)                  FLTPATH    69
      IF (T.GE.TDONE) TRNDONE=1.                              FLTPATH    70
      IF (IPLOT.EQ.1) CALL ARAYFIL                            FLTPATH    71
      IF (IPRNT.EQ.1) CALL PRNTOUT                            FLTPATH    72
      IF (IRITE.EQ.1) CALL RITEOUT                            FLTPATH    73
      IF (T.LT.TF) GO TO 40                                   FLTPATH    74
      RETURN                                                  FLTPATH    75
C                                                             FLTPATH    76
C                                                             FLTPATH    77
C         ***   HORIZONTAL TURN   ***                         FLTPATH    78
C                                                             FLTPATH    79
C                                                             FLTPATH    80
   50 H=HLIMIT(T,TF,H,HMN)                                    FLTPATH    81
      CALL HLIM2(H,RRCOEF)                                    FLTPATH    82
      CALL KUTMER(N,T,X,H,F,MDE,ERR,HMX,HMN)                  FLTPATH    83
      IF (T.GE.TDONE) TRNDONE=1.                              FLTPATH    84
      IF (IPLOT.EQ.1) CALL ARAYFIL                            FLTPATH    85
      IF (IPRNT.EQ.1) CALL PRNTOUT                            FLTPATH    86
      IF (IRITE.EQ.1) CALL RITEOUT                            FLTPATH    87
      IF (T.LT.TF) GO TO 50                                   FLTPATH    88
      RETURN                                                  FLTPATH    89
C                                                             FLTPATH    90
C                                                             FLTPATH    91
C         ***   SINUSOIDAL HEADING CHANGE   ***               FLTPATH    92
C                                                             FLTPATH    93
C                                                             FLTPATH    94
   60 H=HLIMIT(T,TF,H,HMN)                                    FLTPATH    95
      CALL HLIM3(H,RRCOEF)                                    FLTPATH    96
      CALL KUTMER(N,T,X,H,F,MDE,ERR,HMX,HMN)                  FLTPATH    97
      IF (IPLOT.EQ.1) CALL ARAYFIL                            FLTPATH    98
      IF (IPRNT.EQ.1) CALL PRNTOUT                            FLTPATH    99
      IF (IRITE.EQ.1) CALL RITEOUT                            FLTPATH   100
      IF (T.LT.TF) GO TO 60                                   FLTPATH   101
      RETURN                                                  FLTPATH   102
C                                                             FLTPATH   103
C                                                             FLTPATH   104
C         ***   STRAIGHT FLIGHT   ***                         FLTPATH   105
C                                                             FLTPATH   106
C                                                             FLTPATH   107
   70 H=HLIMIT(T,TF,H,HMN)                                    FLTPATH   108
      CALL KUTMER(N,T,X,H,F,MDE,ERR,HMX,HMN)                  FLTPATH   109
      IF (IPLOT.EQ.1) CALL ARAYFIL                            FLTPATH   110
      IF (IPRNT.EQ.1) CALL PRNTOUT                            FLTPATH   111
      IF (IRITE.EQ.1) CALL RITEOUT                            FLTPATH   112
      IF (T.LT.TF) GO TO 70                                   FLTPATH   113
      RETURN                                                  FLTPATH   114
      END                                                     FLTPATH   115
```

```
      SUBROUTINE ACCLRTN(FX,FY,FZ)                                      ACCLRTN     2
                                                                        ACCLRTN     3
C**   ACCLRTN COMPUTES SPECIFIC FORCE WHICH IS THE TOTAL INERTIAL       ACCLRTN     4
C**   ACCELERATION MINUS THE MASS-ATTRACTION GRAVITATIONAL ACCELERATION. ACCLRTN    5
C**   SPECIFIC FORCE IS THE ACCELERATION THAT AN ACCELEROMETER MEASURES. ACCLRTN    6
C**   THE SPECIFIC FORCE RESULTS ARE EXPRESSED IN NAV COORDINATES.      ACCLRTN     7
                                                                        ACCLRTN     8
      COMMON /FIXED/FIXED(15)                                           ACCLRTN     9
      COMMON /STATE/STATE(23)                                           ACCLRTN    10
                                                                        ACCLRTN    11
      EQUIVALENCE (FIXED(8),WEI)                                        ACCLRTN    12
      EQUIVALENCE (STATE( 1),VX)                                        ACCLRTN    13
      EQUIVALENCE (STATE( 2),VY)                                        ACCLRTN    14
      EQUIVALENCE (STATE( 3),VZ)                                        ACCLRTN    15
      EQUIVALENCE (STATE(15),CEN11)                                     ACCLRTN    16
      EQUIVALENCE (STATE(16),CEN21)                                     ACCLRTN    17
      EQUIVALENCE (STATE(17),CEN31)                                     ACCLRTN    18
      EQUIVALENCE (RHO(1),RHOX)                                         ACCLRTN    19
      EQUIVALENCE (RHO(2),RHOY)                                         ACCLRTN    20
      EQUIVALENCE (RHO(3),RHOZ)                                         ACCLRTN    21
                                                                        ACCLRTN    22
      DIMENSION RHO(3)                                                  ACCLRTN    23
                                                                        ACCLRTN    24
      CALL VDOT(VXDOT,VYDOT,VZDOT)                                      ACCLRTN    25
      CALL GRAVITY(GX,GY,GZ)                                            ACCLRTN    26
      CALL RHONE(RHO)                                                   ACCLRTN    27
      WEIX=WEI*CEN11                                                    ACCLRTN    28
      WEIY=WEI*CEN21                                                    ACCLRTN    29
      WEIZ=WEI*CEN31                                                    ACCLRTN    30
      FX=VXDOT+(RHOY+2.*WEIY)*VZ-(RHOZ+2.*WEIZ)*VY-GX                   ACCLRTN    31
      FY=VYDOT+(RHOZ+2.*WEIZ)*VX-(RHOX+2.*WEIX)*VZ-GY                   ACCLRTN    32
      FZ=VZDOT+(RHOX+2.*WEIX)*VY-(RHOY+2.*WEIY)*VX-GZ                   ACCLRTN    33
      RETURN                                                            ACCLRTN    34
      END                                                               ACCLRTN    35
```

```
FUNCTION ALFA        74/74    OPT=2                    FTN 4.5+414        06/11/76  13.22.47        PAGE     6

               REAL FUNCTION ALFA(DMY)                                             ALFA       2
                                                                                   ALFA       3
         C**   ALFA COMPUTES WANDER ANGLE, ALPHA                                   ALFA       4
                                                                                   ALFA       5
               COMMON /STATE/STATE(23)                                             ALFA       6
               EQUIVALENCE (STATE(15),CEN11)                                       ALFA       7
               EQUIVALENCE (STATE(16),CEN21)                                       ALFA       8
                                                                                   ALFA       9
               ALFA=ATAN2(-CEN21,CEN11)                                            ALFA      10
               RETURN                                                              ALFA      11
               END                                                                 ALFA      12
```

```
      REAL FUNCTION ALFADOT(LLMECH)                                ALFADOT   2
                                                                   ALFADOT   3
C**   ALFADOT COMPUTES THE ANGULAR RATE-OF-CHANGE OF ALPHA         ALFADOT   4
                                                                   ALFADOT   5
      COMMON /FIXED/FIXED(15)                                      ALFADOT   6
      COMMON /STATE/STATE(23)                                      ALFADOT   7
                                                                   ALFADOT   8
      EQUIVALENCE (FIXED( 8),WFI)                                  ALFADOT   9
      EQUIVALENCE (STATE(17),SINEPHI)                              ALFADOT  10
                                                                   ALFADOT  11
      REAL J,LAMDOT                                                ALFADOT  12
                                                                   ALFADOT  13
      GO TO (10,20,30,40) LLMECH                                   ALFADOT  14
   10 ALFADOT=-LAMDOT(DMY)*SINEPHI                                 ALFADOT  15
      RETURN                                                       ALFADOT  16
   20 ALFADOT=0.                                                   ALFADOT  17
      RETURN                                                       ALFADOT  18
   30 J=SIGN(1.,PHI(DMY))                                          ALFADOT  19
      ALFADOT=-J*LAMDOT(DMY)                                       ALFADOT  20
      RETURN                                                       ALFADOT  21
   40 ALFADOT=-(WEI+LAMDOT(DMY))*SINEPHI                           ALFADOT  22
      RETURN                                                       ALFADOT  23
      END                                                          ALFADOT  24
```

```
      SUBROUTINE ARAYFIL                                                ARAYFIL    2
CC                                                                      ARAYFIL    3
CC     STORES DATA FOR POST-RUN PLOTTING EVERY DTO SECONDS              ARAYFIL    4
CC                                                                      ARAYFIL    5
      COMMON /FIXED/FIXED(15)                                           ARAYFIL    6
      COMMON /GLON/GLON(1001)                                           ARAYFIL    7
      COMMON /GLAT/GLAT(1001)                                           ARAYFIL    8
      COMMON /GTIM/GTIM(1001)                                           ARAYFIL    9
      COMMON /GALT/GALT(1001)                                           ARAYFIL   10
      COMMON /GETX/GETX(1001)                                           ARAYFIL   11
      COMMON /GETY/GETY(1001)                                           ARAYFIL   12
      COMMON /GETZ/GETZ(1001)                                           ARAYFIL   13
      COMMON /NPLOT/NPLTPTS,NPLTSEG(50)                                 ARAYFIL   14
      COMMON /STATE/X(23)                                               ARAYFIL   15
      COMMON /SUPLE/SUPLE(9)                                            ARAYFIL   16
                                                                        ARAYFIL   17
      EQUIVALENCE (SUPLE(1),T)                                          ARAYFIL   18
      EQUIVALENCE (SUPLE(3),TI)                                         ARAYFIL   19
      EQUIVALENCE (SUPLE(5),ISEG)                                       ARAYFIL   20
      EQUIVALENCE (FIXED(2),RADPERD)                                    ARAYFIL   21
      EQUIVALENCE (X(5),ALT)                                            ARAYFIL   22
                                                                        ARAYFIL   23
      REAL LAMDA                                                        ARAYFIL   24
                                                                        ARAYFIL   25
      DATA I/0/,IFULL/0/                                                ARAYFIL   26
                                                                        ARAYFIL   27
      IF (IFULL.EQ.1) RETURN                                            ARAYFIL   28
      TOUTNEW = TOUT(DMY)                                               ARAYFIL   29
      IF (T.EQ.TI) GO TO 10                                             ARAYFIL   30
      IF (TOUTOLD.EQ.TOUTNEW) RETURN                                    ARAYFIL   31
      IF (I.EQ.1001) WRITE(6,1000)                                      ARAYFIL   32
      IF (I.EQ.1001) IFULL = 1                                          ARAYFIL   33
      IF (I.EQ.1001) RETURN                                             ARAYFIL   34
                                                                        ARAYFIL   35
10    I = I+1                                                           ARAYFIL   36
      NPLTPTS = I                                                       ARAYFIL   37
      IF (T.EQ.TI) NPLTSEG(ISEG) = I+1                                  ARAYFIL   38
      GLON(I) = LAMDA(DMY)/RADPERD                                      ARAYFIL   39
      GLAT(I) = PHI(DMY)/RADPERD                                        ARAYFIL   40
      GTIM(I) =  T                                                      ARAYFIL   41
      GALT(I) = ALT                                                     ARAYFIL   42
      GETX(I) = ETAX(DMY)/RADPERD                                       ARAYFIL   43
      GETY(I) = ETAY(DMY)/RADPERD                                       ARAYFIL   44
      GETZ(I) = ETAZ(DMY)/RADPERD                                       ARAYFIL   45
      TOUTOLD = TOUTNEW                                                 ARAYFIL   46
      RETURN                                                            ARAYFIL   47
1000  FORMAT(/T2,"****** W A R N I N G :  PLOT ARRAYS ARE FULL.  ONLY FIRARAYFIL   48
     1ST 1001 POINTS WILL APPEAR ON PLOT.")                             ARAYFIL   49
      END                                                               ARAYFIL   50
```

```
      SUBROUTINE AXB(A,B,R,M,K,N)
C
C     ...............................................................
C
C        SUBROUTINE AXB
C
C        PURPOSE
C           MULTIPLY TWO GENERAL MATRICES TO FORM A RESULTANT
C           GENERAL MATRIX
C
C        USAGE
C           CALL AXB(A,B,R,M,K,N)
C
C        DESCRIPTION OF PARAMETERS
C           A - NAME OF FIRST INPUT MATRIX
C           B - NAME OF SECOND INPUT MATRIX
C           R - NAME OF OUTPUT MATRIX
C           M - NUMBER OF ROWS IN A AND R
C           K - NUMBER OF COLUMNS IN A AND ROWS IN B
C           N - NUMBER OF COLUMNS IN B AND R
C
C        REMARKS
C           MATRIX R CAN BE IN THE SAME LOCATION AS EITHER
C           MATRIX A OR MATRIX B.
C           NUMBER OF COLUMNS OF MATRIX A MUST BE EQUAL TO NUMBER
C           OF ROWS OF MATRIX B.
C           MATRIX D IS USED FOR TEMPORARY STORAGE AND MUST HAVE
C           FIXED DIMENSIONS AT LEAST AS LARGE AS THOSE OF R.
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C     ...............................................................
C
      DIMENSION A(M,K), B(K,N), R(M,N), D(3,3)
      DO 10 I=1,M
      DO 10 J=1,N
      D(I,J)=0.0
      DO 10 L=1,K
   10 D(I,J)=D(I,J)+A(I,L)*B(L,J)
      DO 20 I=1,M
      DO 20 J=1,N
   20 R(I,J)=D(I,J)
      RETURN
      END
```

```
      BLOCK DATA                                                        BLKDAT   2
                                                                        BLKDAT   3
C                                                                       BLKDAT   4
C**   SOME DEFINITIONS AND PROBLEM INFORMATION                          BLKDAT   5
C                                                                       BLKDAT   6
C        COMMON BLOCK "STATE" CONTAINS THE STATE VECTOR                 BLKDAT   7
C           STATE(1)    AIRCRAFT VELOCITY W.R.T. EARTH ALONG NAV X-AXIS BLKDAT   8
C           STATE(2)    AIRCRAFT VELOCITY W.R.T. EARTH ALONG NAV Y-AXIS BLKDAT   9
C           STATE(3)    AIRCRAFT VELOCITY W.R.T. EARTH ALONG NAV Z-AXIS BLKDAT  10
C           STATE(4)    AIRCRAFT VELOCITY W.R.T. EARTH ALONG PATH X-AXIS BLKDAT 11
C           STATE(5)    AIRCRAFT ALTITUDE                               BLKDAT  12
C           STATE 6-14  ELEMENTS OF PATH TO NAV DIRECTION COSINE MATRIX BLKDAT  13
C           STATE 15-23 ELEMENTS OF EARTH TO NAV DIRECTION COSINE MATRIX BLKDAT 14
C              THESE TWO 3X3 MATRICES ARE STORED AS FOLLOWS:            BLKDAT  15
C                 CPN=(6  9 12)      CEN=(15 18 21)                     BLKDAT  16
C                     (7 10 13)          (16 19 22)                     BLKDAT  17
C                     (8 11 14)          (17 20 23)                     BLKDAT  18
C                                                                       BLKDAT  19
C        COMMON BLOCK "PRBLK" CONTAINS DATA FROM PRDATA NAMELIST        BLKDAT  20
C           PRBLK(1)    LLMECH, LOCAL LEVEL MECHANIZATION INDEX         BLKDAT  21
C           PRBLK(2)    TSTART, INITIAL TIME                            BLKDAT  22
C           PRBLK(3)    VTO, INITIAL VELOCITY MAGNITUDE                 BLKDAT  23
C           PRBLK(4)    PHEADO, INITIAL PATH HEADING                    BLKDAT  24
C           PRBLK(5)    PPITCHO, INITIAL PATH PITCH                     BLKDAT  25
C           PRBLK(6)    ALFAO, INITIAL ALPHA ANGLE                      BLKDAT  26
C           PRBLK(7)    LATO, INITIAL LATITUDE                          BLKDAT  27
C           PRBLK(8)    LONO, INITIAL LONGITUDE                         BLKDAT  28
C           PRBLK(9)    ALTO, INITIAL ALTITUDE                          BLKDAT  29
C           PRBLK(10)   IPRNT, PRINT CONTROL PARAMETER                  BLKDAT  30
C           PRBLK(11)   IRITE, TAPE OUTPUT CONTROL PARAMETER            BLKDAT  31
C           PRBLK(12)   IPLOT, PLOT CONTROL PARAMETER                   BLKDAT  32
C           PRBLK(13)   ROLRATE, AIRCRAFT ROLL RATE                     BLKDAT  33
C                                                                       BLKDAT  34
C        COMMON BLOCK "SUPLE" CONTAINS SUPLEMENTARY VARIABLES           BLKDAT  35
C           SUPLE(1)    T, TIME                                         BLKDAT  36
C           SUPLE(2)    TF, FINAL TIME OF A SEGMENT                     BLKDAT  37
C           SUPLE(3)    TI, INITIAL TIME OF A SEGMENT                   BLKDAT  38
C           SUPLE(4)    TRNDONE, COMPLETED TURN INDICATOR               BLKDAT  39
C           SUPLE(5)    TDONE, TIME WHEN TURN COMPLETE                  BLKDAT  40
C           SUPLE(6)    ISEG, FLIGHT SEGMENT INDEX                      BLKDAT  41
C           SUPLE(7)    TOFF, TIME WHEN ROLL-UP STOPS                   BLKDAT  42
C           SUPLE(8)    TON, TIME WHEN ROLL-DOWN STARTS                 BLKDAT  43
C           SUPLE(9)    RRCOEF, ROLL CONTROL COEFFICIENT                BLKDAT  44
C                                                                       BLKDAT  45
C        COMMON BLOCK "FIXFD" CONTAINS CONSTANTS                        BLKDAT  46
C           FIXFD(1)    N, DIMENSION OF STATE VECTOR                    BLKDAT  47
C           FIXFD(2)    RADPERD, RADIANS PER DEGREE                     BLKDAT  48
C           FIXFD(3)    TWOPI, 2*PI                                     BLKDAT  49
C           FIXFD(4)    PI                                              BLKDAT  50
C           FIXFD(5)    HALFPI, PI/2                                    BLKDAT  51
C           FIXFD(6)    RE, EQUATORIAL EARTH RADIUS                     BLKDAT  52
C           FIXFD(7)    ESQ, EARTH ECCENTRICITY SQUARED                 BLKDAT  53
C           FIXFD(8)    WEI, EARTH ANGULAR VELOCITY                     BLKDAT  54
C           FIXFD(9)    COEFFICIENT FOR LEVEL GRAVITY COMPONENTS        BLKDAT  55
C           FIXFD 10-15 COEFFICIENTS FOR RADIAL GRAVITY COMPONENT       BLKDAT  56
C                                                                       BLKDAT  57
C        THE NAV FRAME IS MECHANIZED AS LOCAL-LEVEL, ALPHA-WANDER.      BLKDAT  58
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C        THE NAV FRAME IS ORIENTED AS FOLLOWS:                         BLKDAT    59
C           X - LIES IN A PLANE TANGENT TO THE REFERENCE ELLIPSOID: X IS  BLKDAT    60
C               ROTATED ALPHA DEGREES CCW FROM NORTH                    BLKDAT    61
C           Z - PERPENDICULAR TO THE REFERENCE ELLIPSOID AND POINTED UP BLKDAT    62
C           Y - ORIENTED TO COMPLETE A RIGHT-HANDED, ORTHOGONAL TRIAD   BLKDAT    63
C                                                                       BLKDAT    64
C        THE PATH FRAME IS ORIENTED AS FOLLOWS:                        BLKDAT    65
C           X - LIES ALONG THE AIRCRAFT VELOCITY VECTOR                 BLKDAT    66
C           Y - POINTS OUT THE RIGHT WING                               BLKDAT    67
C           Z - ORIENTED TO COMPLETE A RIGHT-HANDED, ORTHOGONAL TRIAD   BLKDAT    68
C                                                                       BLKDAT    69
                                                                        BLKDAT    70
      COMMON /FIXED/FIXED(15)                                           BLKDAT    71
      COMMON /SEGLNT/SEGLNT(50)  /RESTART/RESTART(50)                   BLKDAT    72
      COMMON /TURN/TURN(50)      /NPATH/NPATH(50)     /PACC/PACC(50)    BLKDAT    73
      COMMON /TACC/TACC(50)      /HEAD/HEAD(50)       /PITCH/PITCH(50)  BLKDAT    74
      COMMON /MODE/MODE(50)      /ERROR/ERROR(50)     /HMAX/HMAX(50)    BLKDAT    75
      COMMON /HMIN/HMIN(50)      /DTO/DTO(50)                           BLKDAT    76
                                                                        BLKDAT    77
      EQUIVALENCE (FIXED( 1),   N    )                                  BLKDAT    78
      EQUIVALENCE (FIXED( 2),RADPERD)                                   BLKDAT    79
      EQUIVALENCE (FIXED( 6),   RE   )                                  BLKDAT    80
      EQUIVALENCE (FIXED( 7),   ESQ  )                                  BLKDAT    81
      EQUIVALENCE (FIXED( 8),   WEI  )                                  BLKDAT    82
      EQUIVALENCE (FIXED( 9), GLHSC  )                                  BLKDAT    83
      EQUIVALENCE (FIXED(10), GRCNT  )                                  BLKDAT    84
      EQUIVALENCE (FIXED(11),  GRS2  )                                  BLKDAT    85
      EQUIVALENCE (FIXED(12),  GRS4  )                                  BLKDAT    86
      EQUIVALENCE (FIXED(13),  GRH   )                                  BLKDAT    87
      EQUIVALENCE (FIXED(14), GRHS2  )                                  BLKDAT    88
      EQUIVALENCE (FIXED(15),  GRH2  )                                  BLKDAT    89
                                                                        BLKDAT    90
      INTEGER RESTART,TURN                                              BLKDAT    91
                                                                        BLKDAT    92
      DATA SEGLNT/50*0./, RESTART/50*0/, TURN/50*4/, NPATH/50*2/,       BLKDAT    93
     1     PACC/50*0./, TACC/50*0./, HEAD/50*0./, PITCH/50*0./,         BLKDAT    94
     2     MODE/50*1/, ERROR/50*1.E-06/, HMAX/50*1.E+04/, HMIN/50*1./,  BLKDAT    95
     3     DTO/50*1.E+08/                                               BLKDAT    96
      DATA N/23/,                                                       BLKDAT    97
     1     RADPERD/1.745329251994E-2/, RE/2.0925640E+7/,                BLKDAT    98
     2     ESQ/6.694317778E-3/,          WEI/7.292115147E-5/,           BLKDAT    99
     3     GLHSC/1.63E-8/,                                              BLKDAT   100
     4     GRCNT/32.0877257/,          GRS2/0.16930681/,                BLKDAT   101
     5     GRS4/7.528105E-4/,          GRH/3.6227E-8/,                  BLKDAT   102
     6     GRHS2/6.4089E-10/,          GRH2/6.8512E-15/                 BLKDAT   103
      END                                                               BLKDAT   104
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      SUBROUTINE CHKSHC                                                   CHKSHC    2
                                                                          CHKSHC    3
C**   BEFORE EACH SINE-HEADING-CHANGE MANEUVER, CHKSHC CHECKS TO SEE IF   CHKSHC    4
C**   THE MANEUVER CAN BE PERFORMED AS REQUESTED.  IF IT CAN'T, THE       CHKSHC    5
C**   RUN IS TERMINATED AND A BRIEF EXPLANATORY MESSAGE IS PRINTED OUT.   CHKSHC    6
                                                                          CHKSHC    7
      COMMON /FIXED/FIXED(15)                                             CHKSHC    8
      COMMON /HEAD/HEAD(50)                                               CHKSHC    9
      COMMON /HMIN/HMIN(50)                                               CHKSHC   10
      COMMON /PITCH/PITCH(50)                                             CHKSHC   11
      COMMON /PRBLK/PRBLK(13)                                             CHKSHC   12
      COMMON /STATE/STATE(23)                                             CHKSHC   13
      COMMON /SUPLE/SUPLE(9)                                              CHKSHC   14
                                                                          CHKSHC   15
      EQUIVALENCE (FIXED(5),HALFPI)                                       CHKSHC   16
      EQUIVALENCE (PRBLK(13),ROLRATE)                                     CHKSHC   17
      EQUIVALENCE (STATE(4),VT)                                           CHKSHC   18
      EQUIVALENCE (SUPLE(6),ISEG)                                         CHKSHC   19
                                                                          CHKSHC   20
      TEST=VT*PITCH(ISEG)*PITCH(ISEG)*ABS(HEAD(ISEG))/16.1                CHKSHC   21
      TEST=AMIN1(ROLRATE,TEST)                                            CHKSHC   22
      TEST=TEST*HMIN(ISEG)                                                CHKSHC   23
      IF (TEST.LT.HALFPI) RETURN                                          CHKSHC   24
      WRITE (6,100)                                                       CHKSHC   25
      STOP                                                                CHKSHC   26
  100 FORMAT(//T2,*CHKSHC MESSAGE  -  THE PRODUCT OF COMPUTED ROLL RATE   CHKSHC   27
     1AND MINIMUM STEP SIZE EXCEEDS 90 DEGREES.*/T2,*BANK ANGLES IN EXCE  CHKSHC   28
     2SS OF 90 DEGREES ARE NOT ALLOWED.  PROGRAM TERMINATED.*)            CHKSHC   29
      END                                                                 CHKSHC   30
```

```
      SUBROUTINE ETADOT(ETAXDOT,ETAYDOT,ETAZDOT)                     ETADOT     2
C**   ETADOT COMPUTES ROLL RATE, PITCH RATE AND YAW RATE.             ETADOT     3
                                                                      ETADOT     4
      COMMON /STATE/STATE(23)                                         ETADOT     5
      EQUIVALENCE (STATE(8),SY)                                       ETADOT     6
      EQUIVALENCE (WPN(1),P)                                          ETADOT     7
      EQUIVALENCE (WPN(2),Q)                                          ETADOT     8
      EQUIVALENCE (WPN(3),R)                                          ETADOT     9
                                                                      ETADOT    10
      DIMENSION WPN(3)                                                ETADOT    11
                                                                      ETADOT    12
      CY=COS(ETAY(DMY))                                               ETADOT    13
      IF (CY.EQ.0.) GO TO 10                                          ETADOT    14
      ETZ=ETAZ(DMY)                                                   ETADOT    15
      SZ=SIN(ETZ)                                                     ETADOT    16
      CZ=COS(ETZ)                                                     ETADOT    17
      CALL OMEGAPN(WPN)                                               ETADOT    18
      FACTOR=P*CZ-Q*SZ                                                ETADOT    19
      ETAXDOT= FACTOR/CY                                              ETADOT    20
      ETAYDOT=-P*SZ-Q*CZ                                              ETADOT    21
      ETAZDOT=-R+(SY/CY)*FACTOR                                       ETADOT    22
      RETURN                                                          ETADOT    23
   10 ETAXDOT=ETAYDOT=ETAZDOT=0.                                      ETADOT    24
      WRITE (6,100)                                                   ETADOT    25
  100 FORMAT(T2,*ROLL AND YAW RATES ARE UNDEFINED WHEN PITCH IS 90 DEGRE ETADOT    26
     1ES. THUS ALL RATES HAVE BEEN TEMPORARILY ZEROED.*)              ETADOT    27
      RETURN                                                          ETADOT    28
      END                                                             ETADOT    29
                                                                      ETADOT    30
```

```
      REAL FUNCTION ETAX(DMY)                                  ETAX     2
C                                                              ETAX     3
C**   ETAX COMPUTES THE PATH-TO-NAV ROLL ANGLE                 ETAX     4
C                                                              ETAX     5
      COMMON /STATE/STATE(23)                                  ETAX     6
      EQUIVALENCE (STATE(11),CPN32)                            ETAX     7
      EQUIVALENCE (STATE(14),CPN33)                            ETAX     8
C                                                              ETAX     9
      ETAX=ATAN2(-CPN32,-CPN33)                                ETAX    10
      RETURN                                                   ETAX    11
      END                                                      ETAX    12
```

```
      REAL FUNCTION ETAY(DMY)                                   ETAY   2
C**   ETAY COMPUTES THE PATH-TO-NAV PITCH ANGLE                 ETAY   3
                                                                ETAY   4
      COMMON /STATE/STATE(23)                                   ETAY   5
      EQUIVALENCE (STATE(9),CPN31)                              ETAY   6
                                                                ETAY   7
      ETAY=ASIN(CPN31)                                          ETAY   8
      RETURN                                                    ETAY   9
      END                                                       ETAY  10
                                                                ETAY  11
```

```
      REAL FUNCTION ETAZ(DMY)                                       ETAZ       2
                                                                    ETAZ       3
C**   ETAZ COMPUTES THE PATH-TO-NAV YAW ANGLE                       ETAZ       4
                                                                    ETAZ       5
      COMMON /STATE/STATE(23)                                       ETAZ       6
      EQUIVALENCE (STATE(6),CPN11)                                  ETAZ       7
      EQUIVALENCE (STATE(7),CPN21)                                  ETAZ       8
                                                                    ETAZ       9
      ETAZ=ATAN2(-CPN21,CPN11)                                      ETAZ      10
      RETURN                                                        ETAZ      11
      END                                                           ETAZ      12
```

```
      SUBROUTINE F(N,TIME,Y,DY)

C**   THIS SUBROUTINE COMPUTES THE DERIVATIVES THAT ARE
C**   NUMERICALLY INTEGRATED IN SUBROUTINE KUTMER.

      COMMON /PACC/PACC(50)
      COMMON /STATE/STATE(23)
      COMMON /SUPLE/SUPLE(9)

      EQUIVALENCE (STATE(3),VZ)
      EQUIVALENCE (STATE(6),CPN(1,1) )
      EQUIVALENCE (STATE(15),CEN(1,1) )
      EQUIVALENCE (SUPLE(1),T)
      EQUIVALENCE (SUPLE(6),ISEG)

      DIMENSION Y(N),DY(N)
      DIMENSION WPN(3),SWPN(3,3),CPN(3,3),CPNDOT(3,3)
      DIMENSION RHO(3),SRHO(3,3),CEN(3,3),CENDOT(3,3)

C
C**   ADVANCE TIME AND UPDATE STATE VECTOR TO AGREE WITH PROGRESS
C**   IN KUTMER
C
      T=TIME
      DO 10 I=1,N
   10 STATE(I)=Y(I)
C
C**   DERIVATIVE COMPUTATIONS
C
      CALL OMEGAPN(WPN)
      CALL RHONE(RHO)
      DO 20 I=1,3
   20 RHO(I)=-RHO(I)
      CALL SKEW(WPN,SWPN)
      CALL SKEW(RHO,SRHO)
      CALL AXB(SWPN,CPN,CPNDOT,3,3,3)
      CALL AXB(SRHO,CEN,CENDOT,3,3,3)
      CALL VDOT(DVX,DVY,DVZ)
C
C**   FILL DY FOR RETURN TO KUTMER
C
      DY(1)=DVX
      DY(2)=DVY
      DY(3)=DVZ
      DY(4)=PACC(ISEG)
      DY(5)=VZ
      DY(6)=CPNDOT(1,1)
      DY(7)=CPNDOT(2,1)
      DY(8)=CPNDOT(3,1)
      DY(9)=CPNDOT(1,2)
      DY(10)=CPNDOT(2,2)
      DY(11)=CPNDOT(3,2)
      DY(12)=CPNDOT(1,3)
      DY(13)=CPNDOT(2,3)
      DY(14)=CPNDOT(3,3)
      DY(15)=CENDOT(1,1)
      DY(15)=CENDOT(2,1)
```

```
            DY(17)=CENDOT(3,1)                          F   59
60          DY(18)=CENDOT(1,2)                          F   60
            DY(19)=CENDOT(2,2)                          F   61
            DY(20)=CENDOT(3,2)                          F   62
            DY(21)=CENDOT(1,3)                          F   63
            DY(22)=CENDOT(2,3)                          F   64
65          DY(23)=CENDOT(3,3)                          F   65
            RETURN                                      F   66
            END                                         F   67
```

```
      SUBROUTINE GRAVITY(GX,GY,GZ)                                   GRAVITY   2
                                                                     GRAVITY   3
C**   GRAVITY COMPUTES THE THREE COMPONENTS OF THE EARTH'S PLUMB-BOB GRAVITY   4
C**   GRAVITY VECTOR, A VECTOR THAT CONSISTS OF BOTH MASS ATTRACTION GRAVITY   5
C**   AND CENTRIPETAL COMPONENTS.                                    GRAVITY   6
                                                                     GRAVITY   7
      COMMON /FIXED/FIXED(15)                                        GRAVITY   8
      COMMON /STATE/STATE(23)                                        GRAVITY   9
                                                                     GRAVITY  10
      EQUIVALENCE (FIXED( 9),GLHSC)                                  GRAVITY  11
      EQUIVALENCE (FIXED(10),GRCNT)                                  GRAVITY  12
      EQUIVALENCE (FIXED(11),GRS2)                                   GRAVITY  13
      EQUIVALENCE (FIXED(12),GRS4)                                   GRAVITY  14
      EQUIVALENCE (FIXED(13),GRH)                                    GRAVITY  15
      EQUIVALENCE (FIXED(14),GRHS2)                                  GRAVITY  16
      EQUIVALENCE (FIXED(15),GRH2)                                   GRAVITY  17
      EQUIVALENCE (STATE( 5),ALT)                                    GRAVITY  18
      EQUIVALENCE (STATE(15),CEN11)                                  GRAVITY  19
      EQUIVALENCE (STATE(16),CEN21)                                  GRAVITY  20
      EQUIVALENCE (STATE(17),CEN31)                                  GRAVITY  21
                                                                     GRAVITY  22
      S2PHI=CEN31*CEN31                                              GRAVITY  23
      COEF=-GLHSC*ALT*CEN31                                          GRAVITY  24
      GX=COEF*CEN11                                                  GRAVITY  25
      GY=COEF*CEN21                                                  10JUN76   1
      GZ=-(GRCNT+GRS2*S2PHI+GRS4*S2PHI*S2PHI) *                      GRAVITY  27
     1    (1.0-(GRH-GRHS2*S2PHI)*ALT+GRH2*ALT*ALT)                   GRAVITY  28
      RETURN                                                         GRAVITY  29
      END                                                            GRAVITY  30
```

```
FUNCTION HCHOP       74/74    OPT=2                      FTN 4.5+414         06/11/76  13.22.47         PAGE     20

              REAL FUNCTION HCHOP(H,T,TEVENT)                                          HCHOP        2
                                                                                       HCHOP        3
      C**  HCHOP BEGINS BY COMPUTING THE TIME INTERVAL FROM T (PRESENT                 HCHOP        4
      C**  TIME) TO TEVENT (A FUTURE TIME WHEN SOME EVENT MUST OCCUR).                 HCHOP        5
      C**  IF THE PLANNED INTEGRATION STEP, H, WILL CARRY T BEYOND                     HCHOP        6
      C**  TEVENT, A NEW STEP, HCHOP, IS COMPUTED SO THAT                              HCHOP        7
      C**                T + HCHOP = TEVENT                                            HCHOP        8
      C**  TO PREVENT LOSS OF SIGNIFICANCE IN KUTMER WHERE T ADDED TO H/3              HCHOP        9
      C**  MUST BE GREATER THAN T, HCHOP MUST BE KEPT ABOVE A WORKING                  HCHOP       10
      C**  MINIMUM. FOR THE 48 BIT MANTISSA OF THE 60 BIT CDC WORD,                    HCHOP       11
      C**  THE ABSOLUTE MINIMUM WOULD BE T*(2**-48)/3=T*(1.2*10**-15).                 HCHOP       12
      C**  TO BE CONSERVATIVE THE WORKING MINIMUM WAS SET TO T*(10**-13).              HCHOP       13
                                                                                       HCHOP       14
           HCHOP=H                                                                     HCHOP       15
           IF (T.GT.TEVENT) RETURN                                                     HCHOP       16
           HNOM=TEVENT-T                                                               HCHOP       17
           HMIN=ABS(T)*(1.E-13)                                                        HCHOP       18
           HNOM=AMAX1(HMIN,HNOM)                                                       HCHOP       19
           HCHOP=AMIN1(H,HNOM)                                                         HCHOP       20
           RETURN                                                                      HCHOP       21
           END                                                                         HCHOP       22
```

```
      SUBROUTINE HEADER
C**   HEADER PRINTS A DESCRIPTION OF EACH SEGMENT
C**   AT TI, THE INITIAL TIME OF THE SEGMENT.

      COMMON /MODE/MODE(50)
      COMMON /NPATH/NPATH(50)
      COMMON /PRBLK/PRBLK(13)
      COMMON /SUPLE/SUPLE(9)
      COMMON /TURN/TURN(50)

      EQUIVALENCE (PRBLK(1),LLMECH)
      EQUIVALENCE (SUPLE(1),T)
      EQUIVALENCE (SUPLE(2),TF)
      EQUIVALENCE (SUPLE(6),ISEG)

      INTEGER TURN
      DIMENSION AA(8),BB(4),CC(2),DD(8)

      DATA (AA(I), I=1,8) /10H VERTICAL ,5HTURN.,10H HORIZONTA,7HL TURN.
     1,10H SINE HEAD,10HING CHANGE,10H STRAIGHT ,7HFLIGHT.  /,
     2 (BB(J),J=1,4) /10H GREAT CIR,4HCLE.,10H RHUMB LIN,2HE. /,
     3 (CC(K),K=1,2) /7H FIXED.,10H VARIABLE. /,
     4 (DD(L),L=1,8) /10H AZIMUTH W,6HANDER.,10H CONSTANT ,6HALPHA.,
     5 10H UNIPOLAR.,1H ,10H FREE AZIM,4HUTH./

      IA=2*TURN(ISEG)-1
      IB=2*NPATH(ISEG)-1
      IC=MODE(ISEG)+1
      ID=2*LLMECH-1
      WRITE (6,100) ISEG,T,TF,AA(IA),AA(IA+1),BB(IB),BB(IB+1),
     1CC(IC),DD(ID),DD(ID+1)
  100 FORMAT (1H1,T5,*BEGIN SEGMENT NUMBER*,I3/
     1         T5,*INITIAL TIME *,T18,F12.5/
     2         T5,*FINAL TIME *,T18,F12.5/
     3         T5,*THIS FLIGHT SEGMENT IS A*,2A10/
     4         T5,*THE NOMINAL FLIGHT PATH OVER THE EARTH IS A*,2A10/
     5         T5,*THE INTEGRATION STEP SIZE IS*,A10/
     6         T5,*THE LOCAL LEVEL MECHANIZATION IS*,2A10)
      RETURN
      END
```

```
      REAL FUNCTION HLIMIT(T,TF,H,HMN)
C**   HLIMIT BEGINS BY RAISING THE STEP SIZE TO AN OPERATING MINIMUM.      HLIMIT   2
C**   HLIMIT ADJUSTS THE STEP SIZE SO THAT THE PROGRAM WILL NOT STEP        HLIMIT   3
C**   PAST THE END OF A FLIGHT SEGMENT OR PAST A REQUIRED OUTPUT TIME.      HLIMIT   4
                                                                             HLIMIT   5
                                                                             HLIMIT   6
      HLIMIT=AMAX1(H,HMN)                                                    HLIMIT   7
      HLIMIT=HCHOP(HLIMIT,T,TF)                                              HLIMIT   8
      HLIMIT=HCHOP(HLIMIT,T,TOUT(DMY))                                       HLIMIT   9
      RETURN                                                                 HLIMIT  10
      END                                                                    HLIMIT  11
                                                                             HLIMIT  12
```

```
      SUBROUTINE HLIM2(H,RRCOEF)                                       HLIM2     2
                                                                       HLIM2     3
C**   HLIM2 ADJUSTS THE STEP SIZE IN A HORIZONTAL TURN SO THAT THE     HLIM2     4
C**   PROGRAM WILL PAUSE AT POINTS WHERE THE AIRCRAFT IS FINISHING OR  HLIM2     5
C**   BEGINNING A ROLL MANEUVER, I.E. AT TOFF, TDONE AND TON. HLIM2 ALSO HLIM2   6
C**   SETS THE ROLL CONTROL COEFFICIENT FOR MAKING ROLRATE PLUS, ZERO  HLIM2     7
C**   OR MINUS IN SUBROUTINE ROLDOTC.                                  HLIM2     8
                                                                       HLIM2     9
      COMMON /SUPLE/SUPLE(9)                                           HLIM2    10
      EQUIVALENCE (SUPLE(1),T)                                         HLIM2    11
      EQUIVALENCE (SUPLE(2),TF)                                        HLIM2    12
      EQUIVALENCE (SUPLE(5),TDONE)                                     HLIM2    13
      EQUIVALENCE (SUPLE(7),TOFF)                                      HLIM2    14
      EQUIVALENCE (SUPLE(8),TON)                                       HLIM2    15
                                                                       HLIM2    16
C                                                                      HLIM2    17
C            TRANSFER TO PROPER SUBSEGMENT                             HLIM2    18
      IF (T.LT.TOFF) GO TO 10                                          HLIM2    19
      IF (T.GE.TOFF  .AND. T.LT.TON) GO TO 20                          HLIM2    20
      IF (T.GE.TON   .AND. T.LT.TDONE) GO TO 40                        HLIM2    21
      IF (T.GE.TDONE .AND. T.LT.TF) GO TO 50                           HLIM2    22
C                                                                      HLIM2    23
C            SET RRCOEF AND LIMIT H IF NECESSARY                       HLIM2    24
   10 RRCOEF=+1.                                                       HLIM2    25
      H=HCHOP(H,T,TOFF)                                                HLIM2    26
      RETURN                                                           HLIM2    27
   20 RRCOEF=0.                                                        HLIM2    28
      H=HCHOP(H,T,TON)                                                 HLIM2    29
      RETURN                                                           HLIM2    30
   40 RRCOEF=-1.                                                       HLIM2    31
      H=HCHOP(H,T,TDONE)                                               HLIM2    32
      RETURN                                                           HLIM2    33
   50 RRCOEF=0.                                                        HLIM2    34
      RETURN                                                           HLIM2    35
      END                                                              HLIM2    36
```

```
      SUBROUTINE HLIM3(H,RRCOEF)                                 HLIM3      2
                                                                 HLIM3      3
C**   HLIM3 ADJUSTS THE STEP SIZE IN A SINE HEADING MANEUVER SO  HLIM3      4
C**   THAT THE PROGRAM WILL PAUSE EACH HALF-PERIOD.  HLIM3 ALSO  HLIM3      5
C**   SETS THE ROLL CONTROL COEFFICIENT FOR MAKING ROLL RATE PLUS HLIM3     6
C**   OR MINUS IN SUBROUTINE ROLDOTC.                            HLIM3      7
                                                                 HLIM3      8
      COMMON /FIXED/FIXED(15)                                    HLIM3      9
      COMMON /PITCH/PITCH(50)                                    HLIM3     10
      COMMON /SUPLE/SUPLE(9)                                     HLIM3     11
                                                                 HLIM3     12
      EQUIVALENCE (FIXED(4),PI)                                  HLIM3     13
      EQUIVALENCE (SUPLE(1),T)                                   HLIM3     14
      EQUIVALENCE (SUPLE(3),TI)                                  HLIM3     15
      EQUIVALENCE (SUPLE(6),ISEG)                                HLIM3     16
                                                                 HLIM3     17
C                                                                HLIM3     18
C             LIMIT H SO INTEGRATOR DOES NOT ATTEMPT TO          HLIM3     19
C             STEP PAST A HALF-PERIOD DEMARCATION POINT          HLIM3     20
      DT=T-TI                                                    HLIM3     21
      HP=PI/ABS(PITCH(ISEG))                                     HLIM3     22
      THP=TI+HP*(1.+AINT(DT/HP))                                 HLIM3     23
      H=HCHOP(H,T,THP)                                           HLIM3     24
C                                                                HLIM3     25
C             SET ROLL CONTROL COEFFICIENT                       HLIM3     26
      M1=INT((DT+H/2.)/HP)                                       HLIM3     27
      MOE=MOD(M1,2)                                              HLIM3     28
      IF (MOE.EQ.0) RRCOEF=+1.                                   HLIM3     29
      IF (MOE.EQ.1) RRCOEF=-1.                                   HLIM3     30
      RETURN                                                     HLIM3     31
      END                                                        HLIM3     32
```

```
               SUBROUTINE KMPERF                                      KMPERF     2
                                                                      KMPERF     3
C**   KMPERF PRINTS A SHORT SUMMARY OF THE                            KMPERF     4
C**   NUMERICAL INTEGRATOR'S PERFORMANCE.                             KMPERF     5
                                                                      KMPERF     6
      COMMON /IKUT/IK1,IK2                                            KMPERF     7
                                                                      KMPERF     8
      IK3=5*IK2                                                       KMPERF     9
      WRITE (6,100) IK1,IK3                                           KMPERF    10
  100 FORMAT(///T5,*THIS FLIGHT REQUIRED*,I10,5X,    *PASSES THROUGH THE KMPERF    11
     1NUMERICAL INTEGRATOR, KUTMER.*/T5,*KUTMER IN TURN MADE*,I11,5X,  KMPERF    12
     2*CALLS TO SUBROUTINE F, THE DERIVATIVE SUBPROGRAM.*)             KMPERF    13
      RETURN                                                          KMPERF    14
      END                                                             KMPERF    15
```

```
      SUBROUTINE KUTMER(N,TO,X,H,F,MODE,ERROR,HMAX,HMIN)                KUTMER     2
C                                                                       KUTMER     3
C     ................................................................. KUTMER     4
C                                                                       KUTMER     5
C        SUBROUTINE KUTMER                                              KUTMER     6
C                                                                       KUTMER     7
C        PURPOSE                                                        KUTMER     8
C           TO INTEGRATE A (POSSIBLY NONLINEAR) SET OF FIRST-ORDER      KUTMER     9
C           DIFFERENTIAL EQUATIONS FROM "TO" TO "TO+H"                  KUTMER    10
C                                                                       KUTMER    11
C        REFERENCE                                                      KUTMER    12
C           "AN EFFICIENCY STUDY OF SEVERAL TECHNIQUES FOR THE          KUTMER    13
C           NUMERICAL INTEGRATION OF THE EQUATIONS OF MOTION FOR        KUTMER    14
C           MISSILES AND SHELL", BY HAROLD J. BREAUX, FEBRUARY,1967,    KUTMER    15
C           AD 812362.                                                  KUTMER    16
C                                                                       KUTMER    17
C        USAGE                                                          KUTMER    18
C           CALL KUTMER(N,TO,X,H,F,MODE.ERROR,HMAX,HMIN)                KUTMER    19
C                                                                       KUTMER    20
C        DESCRIPTION OF PARAMETERS                                      KUTMER    21
C           N  - NUMBER OF DIFFERENTIAL EQUATIONS (MAX = 25)            KUTMER    22
C           TO - INITIAL TIME (DESTROYED). CONTAINS T-FINAL ON RETURN.  KUTMER    23
C           X  - INITIAL STATE VECTOR (DESTROYED). CONTAINS FINAL STATE KUTMER    24
C                ON RETURN.                                             KUTMER    25
C           H  - STEP SIZE. IF VARIABLE STEP SIZE OPTION IS USED,       KUTMER    26
C                H CONTAINS ADJUSTED STEP SIZE ON RETURN.               KUTMER    27
C           -  - EXTERNAL SUBROUTINE F(N,T,X,DX) CONTAINING N           KUTMER    28
C                DIFFERENTIAL EQUATIONS IN THE FORM DX=F(T,X). THIS     KUTMER    29
C                SUBROUTINE NAME MUST BE DECLARED AN EXTERNAL IN THE    KUTMER    30
C                PROGRAM THAT CALLS KUTMER.                             KUTMER    31
C           MODE  - IF MODE=1 THE STEP SIZE IS "VARIABLE", I.E. H IS    KUTMER    32
C                   ADJUSTED AUTOMATICALLY TO MAINTAIN THE INTEGRATION  KUTMER    33
C                   ERROR BELOW ITS ALLOWED VALUE.                      KUTMER    34
C                 - IF MODE NOT EQUAL 1, STEP SIZE IS "FIXED".          KUTMER    35
C           ERROR - ALLOWED INTEGRATION ERROR PER STEP WHEN MODE=1.     KUTMER    36
C           HMAX  - MAXIMUM STEP SIZE                                   KUTMER    37
C           HMIN  - MINIMUM STEP SIZE                                   KUTMER    38
C                                                                       KUTMER    39
C        EQUATIONS                                                      KUTMER    40
C           YO=X(TO)                                                    KUTMER    41
C           Y1=YO+(H/3)F(TO,YO)                                         KUTMER    42
C           Y2=YO+(H/6)F(TO,YO)+(1H/6)F(TO+H/3,Y1)                      KUTMER    43
C           Y3=YO+(H/8)F(TO,YO)+(3H/8)F(TO+H/3,Y2)                      KUTMER    44
C           Y4=YO+(H/2)F(TO,YO)-(3H/2)F(TO+H/3,Y2)+(2H)F(TO+H/2,Y3)     KUTMER    45
C           Y5=YO+(H/6)F(TO,YO)+(2H/3)F(TO+H/2,Y3)+(H/6)F(TO+H,Y4)      KUTMER    46
C             =X(TO+H)                                                  KUTMER    47
C                                                                       KUTMER    48
C        REMARKS                                                        KUTMER    49
C           SUBROUTINE F CAN DESTROY X WITHOUT AFFECTING KUTMER.        KUTMER    50
C           BOTH FOURTH ORDER AND FIFTH ORDER INTEGRATIONS ARE          KUTMER    51
C           PERFORMED. IF STEP SIZE IS FIXED, THE FIFTH ORDER ANSWER IS KUTMER    52
C           RETURNED IMMEDIATELY. IF STEP SIZE IS VARIABLE, THE FIFTH   KUTMER    53
C           ORDER ANSWER IS SUBTRACTED FROM THE FOURTH ORDER ANSWER     KUTMER    54
C           AND THE DIFFERENCE IS CHECKED AGAINST THE ERROR CRITERION.  KUTMER    55
C           IF THE ERROR IS IN BOUNDS, THE STEP SIZE IS INCREASED PRIOR KUTMER    56
C           TO RETURNING THE FIFTH ORDER ANSWER. IF THE ERROR IS OUT OF KUTMER    57
C           BOUNDS, THE STEP SIZE IS REDUCED, THE INTEGRATION IS        KUTMER    58
```

```
C           REDONE AND THE ERROR CHECKING PROCESS IS REPEATED.  THIS
C           SEQUENCE (LOWER H, INTEGRATE, CHECK ERROR) CONTINUES UNTIL
C           THE ERROR CRITERION IS SATISFIED OR UNTIL HMN IS REACHED.
C           IN THE LATTER CASE, A WARNING MESSAGE IS PRINTED BEFORE
C           RETURNING THE BEST AVAILABLE ANSWER.  H, HMAX, HMIN, AND
C           ERROR MUST ALL BE POSITIVE.
C
C        SUBROUTINES REQUIRED
C           SUBROUTINE F(N,T,X,DX) MUST BE FURNISHED BY THE USER.
C
C     ..............................................................
C
      COMMON /IKUT/IK1,IK2
      DIMENSION X(N),YO(25),Y(25,5)
      DATA IK1,IK2/2*0/

C     SAVE X(TO) IN YO AND "TO" IN TI TO INSULATE THEM AGAINST
C     DESTRUCTION BY SUBROUTINE F.  ALSO FIND HMN AND INCREMENT A
C     COUNTER TO KEEP TRACK OF CALLS TO KUTMER.
         DO 10 I=1,N
   10    YO(I)=X(I)
         TI=TO
         HMN=AMIN1(HMIN,H)
         IK1=IK1+1
C
C  ********* SOLVE FOR Y1 THROUGH Y5 *********
C
   15    T=TI
         IK2=IK2+1
C     OBTAIN F(TO,YO), COMPUTE Y1 AND ADVANCE TIME
         CALL F(N,T,X(1),Y(1,1))
         DO 20 I=1,N
   20    Y(I,4)=YO(I)+H*Y(I,1)/3.
         T=TI+H/3.
C     OBTAIN F(TO+H/3,Y1) AND COMPUTE Y2
         CALL F(N,T,Y(1,4),Y(1,2))
         DO 25 I=1,N
   25    Y(I,4)=YO(I)+H*Y(I,1)/6.+H*Y(I,2)/6.
C     OBTAIN F(TO+H/3,Y2), COMPUTE Y3 AND ADVANCE TIME
         CALL F(N,T,Y(1,4),Y(1,2))
         DO 30 I=1,N
   30    Y(I,4)=YO(I)+H*Y(I,1)/8.+.375*H*Y(I,2)
         T=TI+H/2.
C     OBTAIN F(TO+H/2,Y3), COMPUTE Y4 AND ADVANCE TIME
         CALL F(N,T,Y(1,4),Y(1,3))
         DO 35 I=1,N
   35    Y(I,4)=YO(I)+H*Y(I,1)/2.-1.5*H*Y(I,2)+2.*H*Y(I,3)
         T=TI+H
C     OBTAIN F(TO+H,Y4) AND COMPUTE Y5
         CALL F(N,T,Y(1,4),Y(1,2))
         DO 40 I=1,N
   40    Y(I,5)=YO(I)+H*Y(I,1)/6.+2.*H*Y(I,3)/3.+H*Y(I,2)/6.
         IF (MODE.NE.1) GO TO 75
C
C  ********* VARIABLE STEP-SIZE COMPUTATIONS *********
C
C     COMPUTE P, THE LARGEST DIFFERENCE BETWEEN
```

```
      C     CORRESPONDING ELEMENTS OF Y4 AND Y5.                              KUTMER     116
               P=0.                                                           KUTMER     117
               DO 45 I=1,N                                                    KUTMER     118
       45      P=AMAX1(P,ABS(Y(I,4)-Y(I,5)))                                  KUTMER     119
      C     TRANSFER TO STEP-SIZE-ADJUSTMENT COMPUTATION                      KUTMER     120
      C     ACCORDING TO RELATIVE MAGNITUDES OF P AND ERROR                   KUTMER     121
               IF (P.EQ.0.) GO TO 50                                          KUTMER     122
               IF (P.LE.ERROR) GO TO 55                                       KUTMER     123
               IF (P.GT.ERROR) GO TO 60                                       KUTMER     124
      C     DOUBLE STEP SIZE                                                  KUTMER     125
       50      IF (H.EQ.HMAX) GO TO 75                                        KUTMER     126
               H=2.*H                                                         KUTMER     127
               IF (H.GT.HMAX) H=HMAX                                          KUTMER     128
               GO TO 75                                                       KUTMER     129
      C     INCREASE STEP SIZE USING ALGORITHM                                KUTMER     130
       55      IF (H.EQ.HMAX) GO TO 75                                        KUTMER     131
               H=H*(ERROR/P)**0.2                                             KUTMER     132
               IF (H.GT.HMAX) H=HMAX                                          KUTMER     133
               GO TO 75                                                       KUTMER     134
      C     REDUCE H AND PREPARE TO REPEAT THE ENTIRE NUMERICAL INTEGRATION   KUTMER     135
       60      IF (H.EQ.HMN) GO TO 70                                         KUTMER     136
               H=H*(0.1*ERROR/P)**0.2                                         KUTMER     137
               IF (H.LT.HMN) H=HMN                                            KUTMER     138
               DO 65 I=1,N                                                    KUTMER     139
       65      X(I)=YO(I)                                                     KUTMER     140
               GO TO 15                                                       KUTMER     141
       70      WRITE (6,100)                                                  KUTMER     142
      C                                                                       KUTMER     143
      C   ********* FILL X VECTOR AND ADVANCE TIME FOR RETURN *********        KUTMER     144
      C                                                                       KUTMER     145
       75      DO 80 I=1,N                                                    KUTMER     146
       80      X(I)=Y(I,5)                                                    KUTMER     147
               TO=T                                                           KUTMER     148
               RETURN                                                         KUTMER     149
      100      FORMAT(/T5,*THE INTEGRATION ERROR EXCEEDS ITS ALLOWED VALUE*)  KUTMER     150
               END                                                            KUTMER     151
```

```
      REAL FUNCTION LAMDA(DMY)                                LAMDA     2
                                                              LAMDA     3
C**   LAMDA COMPUTES LONGITUDE.                               LAMDA     4
                                                              LAMDA     5
      COMMON /STATE/STATE(23)                                 LAMDA     6
      EQUIVALENCE (STATE(20),CEN32)                           LAMDA     7
      EQUIVALENCE (STATE(23),CEN33)                           LAMDA     8
                                                              LAMDA     9
      LAMDA=ATAN2(-CEN32,CEN33)                               LAMDA    10
      RETURN                                                  LAMDA    11
      END                                                     LAMDA    12
```

```
FUNCTION LAMDOT      74/74    OPT=2                          FTN 4.5+414        06/11/76  13.22.47        PAGE    39

               REAL FUNCTION LAMDOT(DMY)                                              LAMDOT       2
C**   LAMDOT COMPUTES THE ANGULAR RATE-OF-CHANGE OF LONGITUDE.                        LAMDOT       3
                                                                                      LAMDOT       4
               COMMON /STATE/STATE(23)                                                LAMDOT       5
               EQUIVALENCE (STATE(5),ALT)                                             LAMDOT       6
                                                                                      LAMDOT       7
               LAMDOT=VEAST(DMY)/((RP(DMY)+ALT)*COS(PHI(DMY)))                        LAMDOT       8
               RETURN                                                                 LAMDOT       9
               END                                                                    LAMDOT      10
                                                                                      LAMDOT      11
```

```
            SUBROUTINE MAXMIN(XARRAY,YARRAY,XMAX,XMIN,YMAX,YMIN)          MAXMIN     2
      CC                                                                  MAXMIN     3
      CC     DETERMINES THE MAXIMUM AND MINIMUM FOR XARRAY AND            MAXMIN     4
      CC     YARRAY FOR PLOTTING PURPOSES.                                MAXMIN     5
      CC                                                                  MAXMIN     6
            COMMON /NPLOT/NPLTPTS,NPLTSEG(50)                             MAXMIN     7
                                                                          MAXMIN     8
            DIMENSION XARRAY(1001),YARRAY(1001)                           MAXMIN     9
                                                                          MAXMIN    10
            XMAX = XARRAY(1)                                              MAXMIN    11
            YMAX = YARRAY(1)                                              MAXMIN    12
            DO 10 I=2,NPLTPTS                                             MAXMIN    13
            IF (XARRAY(I).GT.XMAX)XMAX=XARRAY(I)                          MAXMIN    14
            IF (YARRAY(I).GT.YMAX)YMAX=YARRAY(I)                          MAXMIN    15
       10   CONTINUE                                                      MAXMIN    16
            WRITE(6,1000) XMAX,YMAX                                       MAXMIN    17
            XMIN = XARRAY(1)                                              MAXMIN    18
            YMIN = YARRAY(1)                                              MAXMIN    19
            DO 20 I=2,NPLTPTS                                             MAXMIN    20
            IF (XARRAY(I).LT.XMIN)XMIN=XARRAY(I)                          MAXMIN    21
            IF (YARRAY(I).LT.YMIN)YMIN=YARRAY(I)                          MAXMIN    22
       20   CONTINUE                                                      MAXMIN    23
            WRITE(6,1100) XMIN,YMIN                                       MAXMIN    24
     1000   FORMAT(2X,"XMAX = ",1PE13.6,2X,"YMAX = ",1PE13.6/)            MAXMIN    25
     1100   FORMAT(2X,"XMIN = ",1PE13.6,2X,"YMIN = ",1PE13.6/)            MAXMIN    26
            END                                                           MAXMIN    27
```

```
      SUBROUTINE NEWUNIT                                                NEWUNIT   2
                                                                        NEWUNIT   3
C**   NEWUNIT CONVERTS INPUT DATA IN DEGREES AND G'S TO DATA            NEWUNIT   4
C**   IN RADIANS AND FEET/SEC./SEC. RESPECTIVELY.                       NEWUNIT   5
                                                                        NEWUNIT   6
      COMMON /FIXED/FIXED(15)                                           NEWUNIT   7
      COMMON /HEAD/HEAD(50)                                             NEWUNIT   8
      COMMON /PACC/PACC(50)                                             NEWUNIT   9
      COMMON /PITCH/PITCH(50)                                           NEWUNIT  10
      COMMON /PRBLK/PRBLK(13)                                           NEWUNIT  11
      COMMON /TACC/TACC(50)                                             NEWUNIT  12
                                                                        NEWUNIT  13
      EQUIVALENCE (FIXED(2),RADPERD)                                    NEWUNIT  14
      EQUIVALENCE (PRBLK(4),PHEADO)                                     NEWUNIT  15
      EQUIVALENCE (PRBLK(5),PPITCHO)                                    NEWUNIT  16
      EQUIVALENCE (PRBLK(6),ALFAO)                                      NEWUNIT  17
      EQUIVALENCE (PRBLK(7),LATO)                                       NEWUNIT  18
      EQUIVALENCE (PRBLK(8),LONO)                                       NEWUNIT  19
      EQUIVALENCE (PRBLK(13),ROLRATE)                                   NEWUNIT  20
                                                                        NEWUNIT  21
      REAL LATO,LONO                                                    NEWUNIT  22
                                                                        NEWUNIT  23
      DO 10 I=4,8                                                       NEWUNIT  24
   10 PRBLK(I)=PRBLK(I)*RADPERD                                         NEWUNIT  25
      ROLRATE=ROLRATE*RADPERD                                           NEWUNIT  26
      DO 20 I=1,50                                                      NEWUNIT  27
      PACC(I)=PACC(I)*32.2                                              NEWUNIT  28
   20 TACC(I)=TACC(I)*32.2                                              NEWUNIT  29
      DO 30 I=1,50                                                      NEWUNIT  30
      HEAD(I)=HEAD(I)*RADPERD                                           NEWUNIT  31
   30 PITCH(I)=PITCH(I)*RADPERD                                         NEWUNIT  32
      RETURN                                                            NEWUNIT  33
      END                                                               NEWUNIT  34
```

```
      SUBROUTINE OMEGAPN(WPN)

C**   OMEGAPN SPECIFIES THE NAV FRAME COMPONENTS OF WPN (THE ANGULAR
C**   VELOCITY OF THE PATH FRAME WITH RESPECT TO THE NAV FRAME)
C**   THAT ARE REQUIRED TO EXECUTE THE MANEUVER.

      COMMON /PITCH/PITCH(50)
      COMMON /PRBLK/PRBLK(13)
      COMMON /STATE/STATE(23)
      COMMON /SUPLE/SUPLE(9)
      COMMON /TACC/TACC(50)
      COMMON /TURN/TURN(50)

      EQUIVALENCE (PRBLK(1),LLMECH)
      EQUIVALENCE (STATE(4),VT)
      EQUIVALENCE (STATE(6),CPN11)
      EQUIVALENCE (STATE(7),CPN21)
      EQUIVALENCE (STATE(8),CPN31)
      EQUIVALENCE (STATE(9),CPN12)
      EQUIVALENCE (STATE(10),CPN22)
      EQUIVALENCE (STATE(11),CPN32)
      EQUIVALENCE (SUPLE(4),TRNDONE)
      EQUIVALENCE (SUPLE(6),ISEG)

      INTEGER TURN
      DIMENSION WPN(3)

C
C           YAW INDUCED PORTION
      WPN(1)=0.
      WPN(2)=0.
      WPN(3)=-ALFADOT(LLMECH)-PSIDOT(DMY)
      IF (TURN(ISEG).EQ.4) RETURN
      IF (TURN(ISEG).EQ.1) GO TO 10
C
C           ROLL INDUCED PORTION
      DROLL=ROLDOTC(TURN(ISEG))
      WPN(1)=CPN11*DROLL
      WPN(2)=CPN21*DROLL
      WPN(3)=CPN31*DROLL+WPN(3)
      RETURN
C
C           PITCH INDUCED PORTION
   10 AN=(1.-TRNDONE)*SIGN(1.,PITCH(ISEG))*TACC(ISEG)
      DPITCH=AN/VT
      WPN(1)=CPN12*DPITCH
      WPN(2)=CPN22*DPITCH
      WPN(3)=CPN32*DPITCH+WPN(3)
      RETURN
      END
```

```
            REAL FUNCTION PHI(DMY)                                  PHI       2
                                                                    PHI       3
      C**   PHI COMPUTES LATITUDE.                                  PHI       4
                                                                    PHI       5
            COMMON /STATE/STATE(23)                                 PHI       6
            EQUIVALENCE (STATE(17),CEN31)                           PHI       7
                                                                    PHI       8
            PHI=ASIN(CEN31)                                         PHI       9
            RETURN                                                  PHI      10
            END                                                     PHI      11
```

```
          SUBROUTINE PLOTTER(NSEGT)                                       PLOTTER     2
    CC                                                                    PLOTTER     3
    CC     PLOTS THE FOLLOWING GRAPHS USING DISSPLA, A USERS LIBRARY      PLOTTER     4
    CC     CREATED 1/22/75:                                               PLOTTER     5
    CC      *  LATITUDE VS. LONGITUDE                                     PLOTTER     6
    CC      *  ALTITUDE VS. TIME                                          PLOTTER     7
    CC      *  ROLL VS. TIME                                              PLOTTER     8
    CC      *  PITCH VS. TIME                                             PLOTTER     9
    CC      *  YAW VS. TIME                                               PLOTTER    10
    CC                                                                    PLOTTER    11
          COMMON /GLON/GLON(1001)                                         PLOTTER    12
          COMMON /GLAT/GLAT(1001)                                         PLOTTER    13
          COMMON /GTIM/GTIM(1001)                                         PLOTTER    14
          COMMON /GALT/GALT(1001)                                         PLOTTER    15
          COMMON /GETX/GETX(1001)                                         PLOTTER    16
          COMMON /GETY/GETY(1001)                                         PLOTTER    17
          COMMON /GETZ/GETZ(1001)                                         PLOTTER    18
          COMMON /NPLOT/NPLTPTS,NPLTSEG(50)                               PLOTTER    19
                                                                          PLOTTER    20
    CC                                                                    PLOTTER    21
    CC  INITIALIZE CALCOMP PLOTTER                                        PLOTTER    22
          CALL COMPRS                                                     PLOTTER    23
    CC                                                                    PLOTTER    24
    CC     **********  BEGIN LATITUDE/LONGITUDE PLOT  **********          PLOTTER    25
    CC                                                                    PLOTTER    26
    CC  INITIALIZE DISSPLA COMMON AREA                                    PLOTTER    27
          CALL BGNPL(1)                                                   PLOTTER    28
    CC                                                                    PLOTTER    29
    CC   ROTATE PLOT 90 DEGREES AND TRANSLATE                             PLOTTER    30
          CALL BANGLE(-90.)                                               PLOTTER    31
          CALL BSHIFT(0.,6.)                                              PLOTTER    32
    CC                                                                    PLOTTER    33
    CC  DETERMINE MAXIMUM AND MINIMUM VALUES                              PLOTTER    34
          CALL MAXMIN(GLON,GLAT,XMAX,XMIN,YMAX,YMIN)                      PLOTTER    35
    CC                                                                    PLOTTER    36
    CC  POSITION PLOT ORIGIN                                              PLOTTER    37
          CALL PHYSOR(1.5,1.0)                                            PLOTTER    38
    CC                                                                    PLOTTER    39
    CC  ANNOTATE PLOT                                                     PLOTTER    40
          CALL BASALF("STANDARD")                                         PLOTTER    41
          CALL MIXALF("L/CSTD")                                           PLOTTER    42
          CALL TITLE(1H ,-1,"L(ONGITUDE (DEG))$",100,"L(ATITUDE (DEG))$",100 PLOTTER 43
         1,6.,8.)                                                         PLOTTER    44
          CALL HEADIN("L(ATITUDE/)L(ONGITUDE) F(LIGHT) P(ROFILE)$",-100,-3,1 PLOTTER 45
         1)                                                               PLOTTER    46
    CC                                                                    PLOTTER    47
    CC  DETERMINE SCALING FACTORS                                         PLOTTER    48
          CALL SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)           PLOTTER    49
          IF (((XLEN/YLEN).GT.6.).OR.((YLEN/XLEN).GT.6.)) GO TO 30        PLOTTER    50
          IF (XSTEP.GT.YSTEP) YSTEP = XSTEP                               PLOTTER    51
          IF (YSTEP.GT.XSTEP) XSTEP = YSTEP                               PLOTTER    52
    30    CONTINUE                                                        PLOTTER    53
    CC                                                                    PLOTTER    54
    CC  DRAW FRAME TO ENHANCE PLOT                                        PLOTTER    55
          CALL FRAME                                                      PLOTTER    56
    CC                                                                    PLOTTER    57
    CC  SET UP GRAPH                                                      PLOTTER    58
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          CALL GRAPH(XMIN,XSTEP,YMIN,YSTEP)                             PLOTTER    59
      CC                                                                PLOTTER    60
      CC  ANNOTATE START AND FINISH OF FLIGHT                           PLOTTER    61
          CALL HEIGHT(0.05)                                             PLOTTER    62
          CALL RLMESS("*START$",100,GLON(1),GLAT(1))                    PLOTTER    63
          CALL RLMESS("*FINISH$",100,GLON(NPLTPTS),GLAT(NPLTPTS))       PLOTTER    64
      CC                                                                PLOTTER    65
      CC  MARK FLIGHT SEGMENTS                                          PLOTTER    66
          CALL HEIGHT(0.06)                                             PLOTTER    67
          DO 40 I=2,NSEGT                                               PLOTTER    68
          IM = I                                                        PLOTTER    69
          ENCODE(4,1200,LABEL)IM                                        PLOTTER    70
          MM = NPLTSEG(I)                                               PLOTTER    71
          CALL RLMESS(LABEL,100,GLON(MM),GLAT(MM))                      PLOTTER    72
      40  CONTINUE                                                      PLOTTER    73
          CALL RESET("HEIGHT")                                          PLOTTER    74
      CC                                                                PLOTTER    75
      CC   DRAW DASHED COASTAL OUTLINE ON GRAPH                         PLOTTER    76
          CALL DASH                                                     PLOTTER    77
          CALL MAPDTA                                                   PLOTTER    78
          CALL RESET("DASH")                                            PLOTTER    79
      CC                                                                PLOTTER    80
      CC  DRAW CURVE                                                    PLOTTER    81
          CALL CURVE(GLON,GLAT,NPLTPTS,0)                               PLOTTER    82
      CC                                                                PLOTTER    83
      CC  END LATITUDE/LONGITUDE PLOT                                   PLOTTER    84
          CALL ENDPL(1)                                                 PLOTTER    85
      CC                                                                PLOTTER    86
      CC     **********  BEGIN ALTITUDE PLOT  **********                PLOTTER    87
      CC                                                                PLOTTER    88
      CC  INITIALIZE DISSPLA COMMON AREA                                PLOTTER    89
          CALL BGNPL(2)                                                 PLOTTER    90
      CC                                                                PLOTTER    91
      CC   ROTATE PLOT 90 DEGREES AND TRANSLATE                         PLOTTER    92
          CALL BANGLE(-90.)                                             PLOTTER    93
          CALL BSHIFT(0.,6.)                                            PLOTTER    94
      CC                                                                PLOTTER    95
      CC  DETERMINE MAXIMUM AND MINIMUM VALUES                          PLOTTER    96
          CALL MAXMIN(GTIM,GALT,XMAX,XMIN,YMAX,YMIN)                    PLOTTER    97
      CC                                                                PLOTTER    98
      CC  POSITION PLOT ORIGIN                                          PLOTTER    99
          CALL PHYSOR(1.5,1.0)                                          PLOTTER   100
      CC                                                                PLOTTER   101
      CC  ANNOTATE PLOT                                                 PLOTTER   102
          CALL BASALF("STANDARD")                                       PLOTTER   103
          CALL MIXALF("L/CSTD")                                         PLOTTER   104
          CALL TITLE(1H ,-1,"T(IME (SEC))$",100,"A(LTITUDE (FEET))$",100,6.,  PLOTTER   105
         19.)                                                           PLOTTER   106
          CALL HEADIN("A(LTITUDE) F(LIGHT) P(ROFILE)$",-100,-3,1)       PLOTTER   107
      CC                                                                PLOTTER   108
      CC  DETERMINE SCALING FACTORS                                     PLOTTER   109
          CALL SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)         PLOTTER   110
      CC                                                                PLOTTER   111
      CC  DRAW FRAME TO ENHANCE PLOT                                    PLOTTER   112
          CALL FRAME                                                    PLOTTER   113
      CC                                                                PLOTTER   114
      CC  SET UP GRAPH                                                  PLOTTER   115
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```
                CALL GRAPH(XMIN,XSTEP,YMIN,YSTEP)                              PLOTTER   116
          CC                                                                   PLOTTER   117
          CC                                                                   PLOTTER   118
          CC  MARK FLIGHT SEGMENTS                                             PLOTTER   119
                CALL HEIGHT(0.06)                                              PLOTTER   120
                DO 50 I=2,NSEGT                                                PLOTTER   121
                IM = I                                                         PLOTTER   122
                ENCODE(4,1200,LABEL) IM                                        PLOTTER   123
                MM = NPLTSEG(I)                                                PLOTTER   124
                CALL RLMESS(LABEL,100,GTIM(MM),GALT(MM))                       PLOTTER   125
          50    CONTINUE                                                       PLOTTER   126
                CALL RESET ("HEIGHT")                                          PLOTTER   127
          CC                                                                   PLOTTER   128
          CC  DRAW CURVE                                                       PLOTTER   129
                CALL CURVE(GTIM,GALT,NPLTPTS,0)                                PLOTTER   130
          CC                                                                   PLOTTER   131
          CC  END ALTITUDE PLOT                                                PLOTTER   132
                CALL ENDPL(2)                                                  PLOTTER   133
          CC                                                                   PLOTTER   134
          CC   **********  BEGIN ROLL PLOT  **********                         PLOTTER   135
          CC                                                                   PLOTTER   136
          CC  INITIALIZE DISSPLA COMMON AREA                                   PLOTTER   137
                CALL BGNPL(3)                                                  PLOTTER   138
          CC                                                                   PLOTTER   139
          CC   ROTATE PLOT 90 DEGREES AND TRANSLATE                            PLOTTER   140
                CALL BANGLE(-90.)                                              PLOTTER   141
                CALL BSHIFT(0.,6.)                                             PLOTTER   142
          CC                                                                   PLOTTER   143
          CC  DETERMINE MAXIMUM AND MINIMUM VALUES                             PLOTTER   144
                CALL MAXMIN(GTIM,GETX,XMAX,XMIN,YMAX,YMIN)                     PLOTTER   145
          CC                                                                   PLOTTER   146
          CC  POSITION PLOT ORIGIN                                             PLOTTER   147
                CALL PHYSOR(1.5,1.0)                                           PLOTTER   148
          CC                                                                   PLOTTER   149
          CC  ANNOTATE PLOT                                                    PLOTTER   150
                CALL BASALF("STANDARD")                                        PLOTTER   151
                CALL MIXALF("L/CSTD")                                          PLOTTER   152
                CALL TITLE(1H ,-1,"T(IME (SEC))$",100,"R(OLL (DEG))$",100,6.,8.)  PLOTTER   153
                CALL HEADIN("R(OLL) F(LIGHT) P(ROFILE)$",-100,-3,1)            PLOTTER   154
          CC                                                                   PLOTTER   155
          CC  DETERMINE SCALING FACTORS                                        PLOTTER   156
                CALL SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)          PLOTTER   157
          CC                                                                   PLOTTER   158
          CC  DRAW FRAME TO ENHANCE PLOT                                       PLOTTER   159
                CALL FRAME                                                     PLOTTER   160
          CC                                                                   PLOTTER   161
          CC  SET UP GRAPH                                                     PLOTTER   162
                CALL GRAPH(XMIN,XSTEP,YMIN,YSTEP)                              PLOTTER   163
          CC                                                                   PLOTTER   164
          CC                                                                   PLOTTER   165
          CC  MARK FLIGHT SEGMENTS                                             PLOTTER   166
                CALL HEIGHT(0.06)                                              PLOTTER   167
                DO 60 I=2,NSEGT                                                PLOTTER   168
                IM = I                                                         PLOTTER   169
                ENCODE(4,1200,LABEL) IM                                        PLOTTER   170
                MM = NPLTSEG(I)                                                PLOTTER   171
                CALL RLMESS(LABEL,100,GTIM(MM),GETX(MM))                       PLOTTER   172
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   60   CONTINUE                                                        PLOTTER   173
        CALL RESET ("HEIGHT")                                           PLOTTER   174
   CC                                                                   PLOTTER   175
   CC  DRAW CURVE                                                       PLOTTER   176
        CALL CURVE(GTIM,GETX,NPLTPTS,0)                                 PLOTTER   177
   CC                                                                   PLOTTER   178
   CC  END ROLL PLOT                                                    PLOTTER   179
        CALL ENDPL(3)                                                   PLOTTER   180
   CC                                                                   PLOTTER   181
   CC     **********  BEGIN PITCH PLOT  **********                      PLOTTER   182
   CC                                                                   PLOTTER   183
   CC  INITIALIZE DISSPLA COMMON AREA                                   PLOTTER   184
        CALL BGNPL(4)                                                   PLOTTER   185
   CC                                                                   PLOTTER   186
   CC   ROTATE PLOT 90 DEGREES AND TRANSLATE                            PLOTTER   187
        CALL BANGLE(-90.)                                               PLOTTER   188
        CALL BSHIFT(0.,6.)                                              PLOTTER   189
   CC                                                                   PLOTTER   190
   CC  DETERMINE MAXIMUM AND MINIMUM VALUES                             PLOTTER   191
        CALL MAXMIN(GTIM,GETY,XMAX,XMIN,YMAX,YMIN)                      PLOTTER   192
   CC                                                                   PLOTTER   193
   CC  POSITION PLOT ORIGIN                                             PLOTTER   194
        CALL PHYSOR(1.5,1.0)                                            PLOTTER   195
   CC                                                                   PLOTTER   196
   CC  ANNOTATE PLOT                                                    PLOTTER   197
        CALL BASALF("STANDARD")                                         PLOTTER   198
        CALL MIXALF("L/CSTD")                                           PLOTTER   199
        CALL TITLE(1H ,-1,"T(IME (SEC))$",100,"P(ITCH (DEG))$",100,6.,8.) PLOTTER   200
        CALL HEADIN("P(ITCH) F(LIGHT) P(ROFILE)$",-100,-3,1)            PLOTTER   201
   CC                                                                   PLOTTER   202
   CC  DETERMINE SCALING FACTORS                                        PLOTTER   203
        CALL SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)           PLOTTER   204
   CC                                                                   PLOTTER   205
   CC  DRAW FRAME TO ENHANCE PLOT                                       PLOTTER   206
        CALL FRAME                                                      PLOTTER   207
   CC                                                                   PLOTTER   208
   CC  SET UP GRAPH                                                     PLOTTER   209
        CALL GRAPH(XMIN,XSTEP,YMIN,YSTEP)                               PLOTTER   210
   CC                                                                   PLOTTER   211
   CC                                                                   PLOTTER   212
   CC  MARK FLIGHT SEGMENTS                                             PLOTTER   213
        CALL HEIGHT(0.06)                                               PLOTTER   214
        DO 70 I=2,NSEGT                                                 PLOTTER   215
        IM = I                                                          PLOTTER   216
        ENCODE(4,1200,LABEL) IM                                         PLOTTER   217
        MM = NPLTSEG(I)                                                 PLOTTER   218
        CALL RLMESS(LABEL,100,GTIM(MM),GETY(MM))                        PLOTTER   219
   70   CONTINUE                                                        PLOTTER   220
        CALL RESET ("HEIGHT")                                           PLOTTER   221
   CC                                                                   PLOTTER   222
   CC  DRAW CURVE                                                       PLOTTER   223
        CALL CURVE(GTIM,GETY,NPLTPTS,0)                                 PLOTTER   224
   CC                                                                   PLOTTER   225
   CC  END PITCH PLOT                                                   PLOTTER   226
        CALL ENDPL(4)                                                   PLOTTER   227
   CC                                                                   PLOTTER   228
   CC     **********  BEGIN YAW PLOT  **********                        PLOTTER   229
```

```
      CC
      CC  INITIALIZE DISSPLA COMMON AREA
            CALL BGNPL(5)
      CC
      CC   ROTATE PLOT 90 DEGREES AND TRANSLATE
            CALL EANGLE(-90.)
            CALL BSHIFT(0.,6.)
      CC
      CC  DETERMINE MAXIMUM AND MINIMUM VALUES
            CALL MAXMIN(GTIM,GETZ,XMAX,XMIN,YMAX,YMIN)
      CC
      CC  POSITION PLOT ORIGIN
            CALL PHYSOR(1.5,1.0)
      CC
      CC  ANNOTATE PLOT
            CALL BASALF("STANDARD")
            CALL MIXALF("L/CSTD")
            CALL TITLE(1H ,-1,"T(IME (SEC))$",100,"Y(AW (DEG))$",100,6.,8.)
            CALL HEADIN("Y(AW) F(LIGHT) P(ROFILE)$",-100,-3,1)
      CC
      CC  DETERMINE SCALING FACTORS
            CALL SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)
      CC
      CC  DRAW FRAME TO ENHANCE PLOT
            CALL FRAME
      CC
      CC  SET UP GRAPH
            CALL GRAPH(XMIN,XSTEP,YMIN,YSTEP)
      CC
      CC
      CC  MARK FLIGHT SEGMENTS
            CALL HEIGHT(0.06)
            DO 80 I=2,NSEGT
            IM = I
            ENCODE(4,1200,LABEL) IM
            MM = NPLTSEG(I)
            CALL RLMESS(LABEL,100,GTIM(MM),GETZ(MM))
      80    CONTINUE
            CALL RESET ("HEIGHT")
      CC
      CC  DRAW CURVE
            CALL CURVE(GTIM,GETZ,NPLTPTS,0)
      CC
      CC  END YAW PLOT
            CALL ENDPL(5)
      CC
      CC  SIGNAL DISSPLA TO TERMINATE THE PLOT
      100   CALL DONEPL
      1200  FORMAT(I3,"$")
            END
```

```
      SUBROUTINE PRNTOUT

C**   PRNTOUT PRINTS OUTPUT IN G FORMAT AND
C**   LABELS EACH OUTPUT VARIABLE.

      COMMON /FIXED/FIXED(15)
      COMMON /PACC/PACC(50)
      COMMON /STATE/X(23)
      COMMON /SUPLE/SUPLE(9)

      EQUIVALENCE (FIXED(2),RADPERD)
      EQUIVALENCE (X(1),VX)
      EQUIVALENCE (X(2),VY)
      EQUIVALENCE (X(3),VZ)
      EQUIVALENCE (X(4),VT)
      EQUIVALENCE (X(5),ALT)
      EQUIVALENCE (SUPLE(1),T)
      EQUIVALENCE (SUPLE(3),TI)
      EQUIVALENCE (SUPLE(6),ISEG)

      REAL LAMDA

      TOUTNEW=TOUT(DMY)
      IF (T.EQ.TI) GO TO 10
      IF (TOUTOLD.EQ.TOUTNEW) RETURN
   10 OPHI=PHI(DMY)/RADPERD
      OLAMDA=LAMDA(DMY)/RADPERD
      OALFA=ALFA(DMY)/RADPERD
      OETAX=ETAX(DMY)/RADPERD
      OETAY=ETAY(DMY)/RADPERD
      OETAZ=ETAZ(DMY)/RADPERD
      OPSI=PSI(DMY)/RADPERD
      CALL ACCLRTN(FX,FY,FZ)
      CALL ETADOT(ETAXDOT,ETAYDOT,ETAZDOT)
      ETAXDOT=ETAXDOT/RADPERD
      ETAYDOT=ETAYDOT/RADPERD
      ETAZDOT=ETAZDOT/RADPERD
      WRITE (6,100) T,
     1          OPHI,         OLAMDA,       OALFA,        ALT,
     2          OETAX,        OETAY,        OETAZ,        OPSI,
     3          ETAXDOT,      ETAYDOT,      ETAZDOT,
     4          VX,           VY,           VZ,           VT,
     5          FX,           FY,           FZ,           PACC(ISEG)
  100 FORMAT(//,T3,*TIME*,T9,F12.5/T8,*LAT*,T13,G20.10,T37,*LON*,T43,
     A      G20.10,T67,*ALPHA*,T73,G20.10,T97,*ALT*,T103,G20.10/
     B      T8,*ROLL*,T13,G20.10,T37,*PITCH*,T43,G20.10,T67,*YAW*,
     C      T73,G20.10,T97,*PSI*,T103,G20.10/
     D      T8,*DROLL*,T13,G20.10,T37,*DPITCH*,T43,G20.10,T67,*DYAW*,
     E      T73,G20.10/
     F      T8,*VX*,T13,G20.10,T37,*VY*,T43,G20.10,T67,*VZ*,T73,
     G      G20.10,T97,*VPATH*,T103,G20.10/
     H      T8,*FX*,T13,G20.10,T37,*FY*,T43,G20.10,T67,*FZ*,T73,
     I      G20.10,T97,*APATH*,T103,G20.10 )
      TOUTOLD=TOUTNEW
      RETURN
      END
```

```
          REAL FUNCTION PSI(DMY)                                        PSI      2
                                                                        PSI      3
C**  PSI COMPUTES THE GROUND TRACK HEADING ANGLE WHICH IS MEASURED      PSI      4
C**  POSITIVE CW FROM NORTH. THE INITIAL VALUE OF PSI IS PHEADO.        PSI      5
C**  PSI'S RANGE IS (-PI,+PI).                                          PSI      6
                                                                        PSI      7
          COMMON /FIXED/FIXED(15)                                       PSI      8
          EQUIVALENCE (FIXED(3),TWOPI)                                  PSI      9
          EQUIVALENCE (FIXED(4),PI)                                     PSI     10
                                                                        PSI     11
          PSI=ETAZ(DMY)-ALFA(DMY)                                       PSI     12
          IF (PSI.LT.-PI) PSI=PSI+TWOPI                                 PSI     13
          IF (PSI.GT. PI) PSI=PSI-TWOPI                                 PSI     14
          RETURN                                                        PSI     15
          END                                                           PSI     16
```

```
      REAL FUNCTION PSIDOT(OMY)

C**  PSIDOT COMPUTES THE ANGULAR RATE-OF-CHANGE OF AIRCRAFT HEADING.

      COMMON /NPATH/NPATH(50)
      COMMON /STATE/STATE(23)
      COMMON /SUPLE/SUPLE(9)
      COMMON /TURN/TURN(50)

      EQUIVALENCE (STATE(4),VT)
      EQUIVALENCE (SUPLE(4),TRNDONE)
      EQUIVALENCE (SUPLE(6),ISEG)

      INTEGER TURN

C
C            GREAT CIRCLE CONTRIBUTION
      PSIDOT=0.
      IF (NPATH(ISEG).EQ.1) PSIDOT=PSIDOTG(OMY)
      GO TO (19,20,30,10) TURN(ISEG)
C
C            VERTICAL TURNS AND STRAIGHT FLIGHT PATHS
   10 RETURN
C
C            HORIZONTAL TURNS
   20 PSIDOT=PSIDOT+32.2*TAN(ETAX(OMY))*(1.-TRNDONE)/VT
      RETURN
C
C            SINE HEADING CHANGES
   30 PSIDOT=PSIDOT+32.2*TAN(ETAX(OMY))/VT
      RETURN
      END
```

```
      REAL FUNCTION PSIDOTG(DMY)                                          PSIDOTG     2
                                                                          PSIDOTG     3
C**   PSIDOTG COMPUTES THE PSI RATE REQUIRED TO                           PSIDOTG     4
C**   KEEP THE AIRCRAFT IN A GREAT CIRCLE PLANE.                          PSIDOTG     5
C**   REMARK:  FOR A SPHERICAL EARTH (ESQ=0), THE CORRECT PSI RATE        PSIDOTG     6
C**   IS LAMDOT*SIN(PHI), A FACT THAT CAN BE DEDUCED FROM THE EQUATIONS   PSIDOTG     7
C**   BELOW.  USING LAMDOT*SIN(PHI) OVER AN ELLIPSOIDAL EARTH PRODUCES    PSIDOTG     8
C**   SMALL TURNING-RATE ERRORS THAT CAUSE THE AIRCRAFT TO STRAY FROM     PSIDOTG     9
C**   THE GREAT CIRCLE PLANE.  IF SMALL GREAT CIRCLE ERRORS ARE TOLER-    PSIDOTG    10
C**   ABLE, THE USER MAY WISH TO SUBSTITUTE LAMDOT*SIN(PHI) FOR THE       PSIDOTG    11
C**   EQUATIONS BELOW TO SAVE COMPUTING TIME.                             PSIDOTG    12
                                                                          PSIDOTG    13
      COMMON /FIXED/FIXED(15)                                             PSIDOTG    14
      COMMON /STATE/STATE(23)                                             PSIDOTG    15
                                                                          PSIDOTG    16
      EQUIVALENCE (FIXED(6),RE)                                           PSIDOTG    17
      EQUIVALENCE (FIXED(7),ESQ)                                          PSIDOTG    18
      EQUIVALENCE (STATE(1),VX)                                           PSIDOTG    19
      EQUIVALENCE (STATE(2),VY)                                           PSIDOTG    20
      EQUIVALENCE (STATE(3),HDOT)                                         PSIDOTG    21
      EQUIVALENCE (STATE(5),H)                                            PSIDOTG    22
      EQUIVALENCE (STATE(17),SFI)                                         PSIDOTG    23
                                                                          PSIDOTG    24
      REAL LAMDOT                                                         PSIDOTG    25
C                                                                         PSIDOTG    26
C         TRIG FUNCTIONS OF PSI, PHI AND DV (GEOGRAPHIC                   PSIDOTG    27
C         MINUS GEOCENTRIC LATITUDE)                                      PSIDOTG    28
      SI=PSI(DMY)                                                         PSIDOTG    29
      SSI=SIN(SI)                                                         PSIDOTG    30
      IF (SSI.EQ.0.) PSIDOTG=0.                                           PSIDOTG    31
      IF (SSI.EQ.0.) RETURN                                               PSIDOTG    32
      CSI=COS(SI)                                                         PSIDOTG    33
      CSISQ=CSI*CSI                                                       PSIDOTG    34
      FI=PHI(DMY)                                                         PSIDOTG    35
      CFI=COS(FI)                                                         PSIDOTG    36
      SFISQ=SFI*SFI                                                       PSIDOTG    37
      CFISQ=CFI*CFI                                                       PSIDOTG    38
      B1=1.-ESQ*SFISQ                                                     PSIDOTG    39
      B2=SQRT(B1)                                                         PSIDOTG    40
      B3=H/RE                                                             PSIDOTG    41
      R=RE*SQRT((1.-(2.-ESQ)*ESQ*SFISQ)/B1+2.*B2*B3+B3*B3)                PSIDOTG    42
      SDV=(RE*ESQ*SFI*CFI/(R*B2))                                         PSIDOTG    43
      DV=ASIN(SDV)                                                        PSIDOTG    44
      CDV=COS(DV)                                                         PSIDOTG    45
      TDV=SDV/CDV                                                         PSIDOTG    46
C                                                                         PSIDOTG    47
C         DERIVATIVES OF PHI, R AND DV                                    PSIDOTG    48
      ALPHA=ALFA(DMY)                                                     PSIDOTG    49
      VNORTH=VX*COS(ALPHA)-VY*SIN(ALPHA)                                  PSIDOTG    50
      FIDOT=VNORTH/(RM(DMY)+H)                                            PSIDOTG    51
      RDOT=(RE/R)*(HDOT*(B2+B3)-RE*ESQ*SFI*CFI*FIDOT*                     PSIDOTG    52
     1     ((1.-ESQ)/(B1*B1)+B3/B2))                                      PSIDOTG    53
      DVDOT=(RE*ESQ/(R*B2*CDV))*((CFISQ/B1-SFISQ)*FIDOT-RDOT*SFI*CFI/R)   PSIDOTG    54
C                                                                         PSIDOTG    55
C         DERIVATIVE OF PSI FOR GREAT CIRCLE FLIGHT                       PSIDOTG    56
      PSIDOTG=LAMDOT(DMY)*SIN(FI-DV)*CDV*(1.+CSISQ*TDV*TDV) +             PSIDOTG    57
     1        DVDOT*SSI*CSI*TDV                                           PSIDOTG    58
```

```
      RETURN                                                     PSIDOTG    59
      END                                                        PSIDOTG    60
```

```
      SUBROUTINE QUADRT(A,B,C,IWARN,XR,XI)
C
C**  QUADRT SOLVES THE QUADRATIC EQUATION
C**         A X**2 + B X + C = 0
C**  A, B AND C MUST BE REAL. ON RETURN, THE
C**  TWO ROOTS ARE AVAILABLE AS FOLLOWS:
C**        X1 = XR(1) + XI(1)*SQRT(-1)
C**        X2 = XR(2) + XI(2)*SQRT(-1)
C**  IWARN IS SET TO 1 IF ROOTS DON'T EXIST OR IF
C**  THE EXISTING ROOTS HAVE NONZERO IMAGINARY PARTS.
C
      LOGICAL BPOS, COANEG
      DIMENSION XR(2), XI(2)
C
      IWARN = 0
      IF(A.EQ.0.) GO TO 40
C
C**         TWO ROOTS (A NOT EQUAL 0)
C
      IF(B.EQ.0.) GO TO 10
      BPOS = .TRUE.
      IF(B.LT.0.) BPOS = .FALSE.
      D = B*B-4.*A*C
      IF(D.EQ.0.) GO TO 20
      IF(D.LT.0.) GO TO 30
C
C           TWO REAL UNEQUAL ROOTS (D>0 AND B NOT 0)
      XI(1) = XI(2) = 0.
      D = SQRT(D)
      IF(BPOS) XR(1) = -2.*C/(B + D)
      IF(BPOS) XR(2) = -(B + D)/(2.*A)
      IF(BPOS) RETURN
      XR(1) = (-B + D)/(2.*A)
      XR(2) = 2.*C/(-B+D)
      RETURN
C
C           TWO ROOTS OF EQUAL MAGNITUDE BUT OPPOSITE SIGN (B=0)
   10 COANEG = .TRUE.
      COA = C/A
      IF(COA.GE.0.) COANEG = .FALSE.
      IF(COANEG) XR(1) = SQRT(-COA)
      IF(COANEG) XR(2) = -XR(1)
      IF(COANEG) XI(1) = XI(2) = 0.
      IF(COANEG) RETURN
      XR(1) = XR(2) = 0.
      XI(1) = SQRT(COA)
      XI(2) = -XI(1)
      IWARN = 1
      RETURN
C
C           TWO REAL EQUAL ROOTS (D=0 AND B NOT 0)
   20 XI(1) = XI(2) = 0.
      XR(1) = XR(2) = -B/(2*A)
      RETURN
C
C           TWO IMAGINARY ROOTS (D<0 AND B NOT 0)
   30 D = SQRT(-D)
```

```
      XI(1) = D/(2.*A)                                                QUADRT    59
      XI(2) = -XI(1)                                                  QUADRT    60
      XR(1) = XR(2) = -B/(2.*A)                                       QUADRT    61
      IWARN = 1                                                       QUADRT    62
      RETURN                                                          QUADRT    63
   40 IF(B.EQ.0.) GO TO 50                                            QUADRT    64
C                                                                     QUADRT    65
C**          ONE REAL ROOT (A=0 BUT B NOT 0)                          QUADRT    66
C                                                                     QUADRT    67
      XR(1) = -C/B                                                    QUADRT    68
      XR(2) = XI(1) = XI(2) = 0.                                      QUADRT    69
      RETURN                                                          QUADRT    70
C                                                                     QUADRT    71
C**          NO ROOTS (A AND B BOTH ZERO)                             QUADRT    72
C                                                                     QUADRT    73
   50 XR(1) = XR(2) = XI(1) = XI(2) = 0.                              QUADRT    74
      IWARN = 1                                                       QUADRT    75
      WRITE (6,100)                                                   QUADRT    76
      RETURN                                                          QUADRT    77
  100 FORMAT(T2,"QUADRT MESSAGE -  SINCE A AND B ARE ZERO, NO SOLUTIONS QUADRT    78
     1COULD BE FOUND.")                                               QUADRT    79
      END                                                             QUADRT    80
```

```
      SUBROUTINE RHONE(RHO)                                             RHONE      2
                                                                        RHONE      3
C**   RHONE COMPUTES THE ANGULAR RATES OF THE NAV FRAME WITH RESPECT TO RHONE      4
C**   THE EARTH FRAME. THESE RATES ARE COORDINATIZED IN THE NAV FRAME.  RHONE      5
                                                                        RHONE      6
      COMMON /FIXED/FIXED(15)                                           RHONE      7
      COMMON /PRBLK/PRBLK(12)                                           RHONE      8
      COMMON /STATE/STATE(23)                                           RHONE      9
                                                                        RHONE     10
      EQUIVALENCE (FIXED(8),WEI)                                        RHONE     11
      EQUIVALENCE (PRBLK(1),LLMECH)                                     RHONE     12
      EQUIVALENCE (STATE(1),VX)                                         RHONE     13
      EQUIVALENCE (STATE(2),VY)                                         RHONE     14
      EQUIVALENCE (STATE(5),ALT)                                        RHONE     15
      EQUIVALENCE (STATE(17),SINEPHI)                                   RHONE     16
                                                                        RHONE     17
      REAL J,LAMDOT                                                     RHONE     18
      DIMENSION RHO(3)                                                  RHONE     19
                                                                        RHONE     20
      A=ALFA(DMY)                                                       RHONE     21
      CA=COS(A)                                                         RHONE     22
      SA=SIN(A)                                                         RHONE     23
      VWEST=-VEAST(DMY)                                                 RHONE     24
      VNORTH=VX*CA-VY*SA                                                RHONE     25
      RHOWEST=VNORTH/(RM(DMY)+ALT)                                      RHONE     26
      RHONRTH=-VWEST/(RP(DMY)+ALT)                                      RHONE     27
      RHO(1)= RHONRTH*CA+RHOWEST*SA                                     RHONE     28
      RHO(2)=-RHONRTH*SA+RHOWEST*CA                                     RHONE     29
      GO TO (10,20,30,40) LLMECH                                        RHONE     30
   10 RHO(3)=0.                                                         RHONE     31
      RETURN                                                            RHONE     32
   20 RHO(3)=LAMDOT(DMY)*SINEPHI                                        RHONE     33
      RETURN                                                            RHONE     34
   30 J=SIGN(1.,PHI(DMY))                                               RHONE     35
      RHO(3)=LAMDOT(DMY)*(SINEPHI-J)                                    RHONE     36
      RETURN                                                            RHONE     37
   40 RHO(3)=-WEI*SINEPHI                                               RHONE     38
      RETURN                                                            RHONE     39
      END                                                               RHONE     40
```

```
          SUBROUTINE RITEOUT                                                    RITEOUT     2
                                                                                RITEOUT     3
C**    RITEOUT WRITES OUTPUT ON TAPE3 WITH NO FORMAT CONVERSION.                RITEOUT     4
C**    EACH CALL TO RITEOUT CREATES ONE BINARY RECORD.                          RITEOUT     5
                                                                                RITEOUT     6
          COMMON /PRBLK/PRBLK(13)                                               RITEOUT     7
          COMMON /STATE/X(23)                                                   RITEOUT     8
          COMMON /SUPLE/SUPLE(6)                                                RITEOUT     9
                                                                                RITEOUT    10
          EQUIVALENCE (PRBLK(2),TSTART)                                         RITEOUT    11
          EQUIVALENCE (X(1),VX)                                                 RITEOUT    12
          EQUIVALENCE (X(2),VY)                                                 RITEOUT    13
          EQUIVALENCE (X(3),VZ)                                                 RITEOUT    14
          EQUIVALENCE (X(5),ALT)                                                RITEOUT    15
          EQUIVALENCE (SUPLE(1),T)                                              RITEOUT    16
                                                                                RITEOUT    17
          REAL LAMDA                                                            RITEOUT    18
                                                                                RITEOUT    19
          TOUTNEW=TOUT(DMY)                                                     RITEOUT    20
          IF (T.EQ.TSTART) GO TO 10                                             RITEOUT    21
          IF (TOUTOLD.EQ.TOUTNEW) RETURN                                        RITEOUT    22
    10    CALL ACCLRTN(FX,FY,FZ)                                                RITEOUT    23
          WRITE (3) T,PHI(DMY),LAMDA(DMY),ALFA(DMY),ALT,FTAX(DMY),FTAY(DMY),    RITEOUT    24
         1          FTAZ(DMY),VX,VY,VZ,FX,FY,FZ                                 RITEOUT    25
          TOUTOLD=TOUTNEW                                                       RITEOUT    26
          RETURN                                                                RITEOUT    27
          END                                                                   RITEOUT    28
```

```
      REAL FUNCTION RM(DMY)                                      RM      2
C                                                                RM      3
C**   RM COMPUTES THE RADIUS OF CURVATURE OF AN EARTH            RM      4
C**   MERIDIAN LINE AT LATITUDE PHI.                             RM      5
C                                                                RM      6
      COMMON /FIXED/FIXED(15)                                    RM      7
      COMMON /STATE/STATE(23)                                    RM      8
C                                                                RM      9
      EQUIVALENCE (FIXED(6),RE)                                  RM     10
      EQUIVALENCE (FIXED(7),ESQ)                                 RM     11
      EQUIVALENCE (STATE(17),SINEPHI)                            RM     12
C                                                                RM     13
      RM=RE*(1.-ESQ)/(1.-ESQ*SINEPHI*SINEPHI)**1.5               RM     14
      RETURN                                                     RM     15
      END                                                        RM     16
```

```
      REAL FUNCTION ROLDOTC(ITURN)                                  ROLDOTC    2
                                                                    ROLDOTC    3
C**   ROLDOTC COMPUTES COMMANDED ROLL RATE FOR BOTH                 ROLDOTC    4
C**   HORIZONTAL TURNS AND SINE HEADING CHANGES.                    ROLDOTC    5
                                                                    ROLDOTC    6
      COMMON /HEAD/HEAD(50)                                         ROLDOTC    7
      COMMON /PITCH/PITCH(50)                                       ROLDOTC    8
      COMMON /PRBLK/PRBLK(13)                                       ROLDOTC    9
      COMMON /STATE/STATE(23)                                       ROLDOTC   10
      COMMON /SUPLE/SUPLE(9)                                        ROLDOTC   11
                                                                    ROLDOTC   12
      EQUIVALENCE (PRBLK(13),ROLRATE)                               ROLDOTC   13
      EQUIVALENCE (STATE(4),VT)                                     ROLDOTC   14
      EQUIVALENCE (SUPLE(1),T)                                      ROLDOTC   15
      EQUIVALENCE (SUPLE(3),TI)                                     ROLDOTC   16
      EQUIVALENCE (SUPLE(6),ISEG)                                   ROLDOTC   17
      EQUIVALENCE (SUPLE(9),RRCOEF)                                 ROLDOTC   18
                                                                    ROLDOTC   19
      IF (ITURN.EQ.3) GO TO 10                                      ROLDOTC   20
C                                                                   ROLDOTC   21
C**   ROLL RATE COMMAND FOR A HORIZONTAL TURN                       ROLDOTC   22
C                                                                   ROLDOTC   23
      RTLF=SIGN(1.,HEAD(ISEG))                                      ROLDOTC   24
      ROLDOTC=ROLRATE*RTLF*RRCOEF                                   ROLDOTC   25
      RETURN                                                        ROLDOTC   26
C                                                                   ROLDOTC   27
C**   ROLL RATE COMMAND FOR A SINE MANEUVER                         ROLDOTC   28
C                                                                   ROLDOTC   29
   10 TWOWT=2.*PITCH(ISEG)*(T-TI)                                   ROLDOTC   30
      WA=PITCH(ISEG)*HEAD(ISEG)                                     ROLDOTC   31
      SIDOT1=RRCOEF*WA*SIN(TWOWT)                                   ROLDOTC   32
      SIDOT2=RRCOEF*2.*WA*PITCH(ISEG)*COS(TWOWT)                    ROLDOTC   33
      ROLDOTC=32.2*VT*SIDOT2/(32.2*32.2+VT*VT*SIDOT1*SIDOT1)        ROLDOTC   34
      ROLDOTC=SIGN(1.,ROLDOTC)*AMIN1(ROLRATE,ABS(ROLDOTC))          ROLDOTC   35
      RETURN                                                        ROLDOTC   36
      END                                                           ROLDOTC   37
```

```
      REAL FUNCTION RP(DMY)                                          RP       2
                                                                     RP       3
C**   RP COMPUTES THE RADIUS OF CURVATURE OF THE EARTH ELLIPSOID IN A RP       4
C**   PLANE THRU THE NORMAL AND AT RIGHT ANGLES TO THE MERIDIAN.     RP       5
                                                                     RP       6
      COMMON /FIXED/FIXED(15)                                        RP       7
      COMMON /STATE/STATE(23)                                        RP       8
                                                                     RP       9
      EQUIVALENCE (FIXED(6),RE)                                      RP      10
      EQUIVALENCE (FIXED(7),ESQ)                                     RP      11
      EQUIVALENCE (STATE(17),SINEPHI)                                RP      12
                                                                     RP      13
      RP=RE/SQRT(1.-ESQ*SINEPHI*SINEPHI)                             RP      14
      RETURN                                                         RP      15
      END                                                            RP      16
```

```
            SUBROUTINE SCALE(XMAX,XMIN,YMAX,YMIN,XSTEP,YSTEP,XLEN,YLEN)
C
CC    ROUTINE TO SCALE VARIABLES FOR PLOTTING ROUTINES.
C
            IFLAG = 1
   10       M = 0
            I=0
            XLEN = XMAX - XMIN
            YLEN = YMAX - YMIN
            IF (XLEN.EQ.0.) GO TO 140
            XSTEP = XLEN/6.
            IF(XSTEP.EQ.0.) XSTEP = 0.1
            IF (XSTEP.EQ.0.) GO TO 70
            IXSTEP = INT(XSTEP)
   30       IF (IXSTEP.GT.9) GO TO 40
            M = M+1
            IXSTEP = INT(XSTEP*(10.**M))
            GO TO 30
   40       IF (IXSTEP.GE.99) GO TO 50
            XSTEP = XSTEP*(10.**M)
            IXSTEP = INT(XSTEP)
            XSTEP = FLOAT(IXSTEP)/(10.**M)
            GO TO 60
   50       XSTEP = FLOAT(IXSTEP)/(10.**M)
   60       IF ((XSTEP*6.).GE.XLEN) GO TO 70
            XSTEP = XSTEP*(10.**M)
            N = N + 1
            IXSTEP = INT(XSTEP) + N
            XSTEP = FLOAT(IXSTEP)/(10.**M)
            GO TO 60
   70       CONTINUE
            MY=0
            NY=0
            YSTEP = YLEN/8.
            IF (YSTEP.EQ.0.) YSTEP = 0.1
            IF (YSTEP.EQ.0.1) GO TO 130
            IYSTEP = INT(YSTEP)
   80       IF (IYSTEP.GT.9) GO TO 90
            MY = MY+1
            IYSTEP = INT(YSTEP*(10.**MY))
            GO TO 80
   90       IF (IYSTEP.GE.99) GO TO 100
            YSTEP = YSTEP*(10.**MY)
            IYSTEP = INT(YSTEP)
            YSTEP = FLOAT(IYSTEP)/(10.**MY)
            GO TO 110
  100       YSTEP = FLOAT(IYSTEP)/(10.**MY)
  110       IF ((YSTEP*8.).GE.YLEN) GO TO 120
            YSTEP = YSTEP*(10.**MY)
            NY = NY + 1
            IYSTEP = INT(YSTEP) + NY
            YSTEP = FLOAT(IYSTEP)/(10.**MY)
            GO TO 110
  120       CONTINUE
            IF (IFLAG.LE.0) GO TO 130
            XNEGINC = XMIN/XSTEP
            IXNEGIN = INT(XNEGINC)
```

```
      IF ((ABS(AMOD(XMIN,XSTEP))).GT.0.) XMIN = FLOAT(IXNEGIN - 1)*XSTEP SCALE
      XLEN = XMAX - XMIN                                                 SCALE
      XPOSINC = XMAX/XSTEP                                               SCALE
      IXPOSIN = INT(XPOSINC)                                             SCALE
      IF ((ABS(AMOD(XLEN,XSTEP))).GT.0.) XMAX = FLOAT(IXPOSIN + 1)*XSTEP SCALE
      YNEGINC = YMIN/YSTEP                                               SCALE
      IYNEGIN = INT(YNEGINC)                                             SCALE
      IF ((ABS(AMOD(YMIN,YSTEP))).GT.0.) YMIN = FLOAT(IYNEGIN - 1)*YSTEP SCALE
      YLEN = YMAX - YMIN                                                 SCALE
      YPOSINC = YMAX/YSTEP                                               SCALE
      IYPOSIN = INT(YPOSINC)                                             SCALE
      IF ((ABS(AMOD(YLEN,YSTEP))).GT.0.) YMAX = FLOAT(IYPOSIN + 1)*YSTEP SCALE
      IFLAG = IFLAG - 1                                                  SCALE
      IF (IFLAG.GE.0) GO TO 10                                           SCALE
 130  CONTINUE                                                           SCALE
      RETURN                                                             SCALE
 140  WRITE(6,1000)                                                      SCALE
      CALL EXIT                                                          SCALE
 1000 FORMAT(2X"******  YOU ARE TRYING TO GRAPH A NULL PLOT. PROGRAM WILL SCALE
     1 BE TERMINATED  ******")                                           SCALE
      END                                                                SCALE
```

```
      SUBROUTINE SKEW(A,B)                                   SKEW       2
C**   SKEW FORMS THE 3X3 SKEW-SYMMETRIC MATRIX, B,           SKEW       3
C**   CORRESPONDING TO THE 3X1 VECTOR, A.                    SKEW       4
                                                             SKEW       5
      DIMENSION A(3),B(3,3)                                  SKEW       6
                                                             SKEW       7
      B(1,1)=0.0                                             SKEW       8
      B(1,2)=-A(3)                                           SKEW       9
      B(1,3)=A(2)                                            SKEW      10
      B(2,1)=A(3)                                            SKEW      11
      B(2,2)=0.0                                             SKEW      12
      B(2,3)=-A(1)                                           SKEW      13
      B(3,1)=-A(2)                                           SKEW      14
      B(3,2)=A(1)                                            SKEW      15
      B(3,3)=0.0                                             SKEW      16
      RETURN                                                 SKEW      17
      END                                                    SKEW      18
                                                             SKEW      19
```

```
      SUBROUTINE SVSETUP
C**   SVSETUP INCORPORATES THE INITIAL PROBLEM DATA INTO THE
C**   STATE VECTOR. THIS IS ALWAYS DONE BEFORE BEGINNING THE FIRST
C**   FLIGHT SEGMENT. IT CAN BE REPEATED AT THE BEGINNING OF OTHER
C**   SEGMENTS IF THE USER WISHES ADDITIONAL FLIGHT PROFILES BEGINNING
C**   FROM THE ORIGONAL STARTING POINT.

      COMMON /PRBLK/PRBLK(13)
      COMMON /STATE/X(23)

      EQUIVALENCE (PRBLK(3),VTO)
      EQUIVALENCE (PRBLK(4),PHEADO)
      EQUIVALENCE (PRBLK(5),PPITCHO)
      EQUIVALENCE (PRBLK(6),ALFO)
      EQUIVALENCE (PRBLK(7),PHIO)
      EQUIVALENCE (PRBLK(8),LAMO)
      EQUIVALENCE (PRBLK(9),ALTO)
      EQUIVALENCE (X(1),V(1),VX)
      EQUIVALENCE (X(2),V(2),VY)
      EQUIVALENCE (X(3),V(3),VZ)
      EQUIVALENCE (X(4),VT)
      EQUIVALENCE (X(5),ALT)
      EQUIVALENCE (X(6),CPN(1,1))
      EQUIVALENCE (X(15),CEN(1,1))

      REAL LAMO
      DIMENSION CEN(3,3),CPN(3,3),V(3)

      ETAXO=XO=0.
      ETAYO=YO=PPITCHO
      ETAZO=ZO=ALFO+PHEADO
      CPN(1,1)= COS(ZO)*COS(YO)
      CPN(2,1)=-SIN(ZO)*COS(YO)
      CPN(3,1)= SIN(YO)
      CPN(1,2)= COS(ZO)*SIN(YO)*SIN(XO)-SIN(ZO)*COS(XO)
      CPN(2,2)=-SIN(ZO)*SIN(YO)*SIN(XO)-COS(ZO)*COS(XO)
      CPN(3,2)=-COS(YO)*SIN(XO)
      CPN(1,3)= COS(ZO)*SIN(YO)*COS(XO)+SIN(ZO)*SIN(XO)
      CPN(2,3)= COS(ZO)*SIN(XO)-SIN(ZO)*SIN(YO)*COS(XO)
      CPN(3,3)=-COS(YO)*COS(XO)
      CEN(1,1)= COS(ALFO)*COS(PHIO)
      CEN(2,1)=-SIN(ALFO)*COS(PHIO)
      CEN(3,1)= SIN(PHIO)
      CEN(1,2)= SIN(ALFO)*COS(LAMO)+COS(ALFO)*SIN(PHIO)*SIN(LAMO)
      CEN(2,2)= COS(ALFO)*COS(LAMO)-SIN(ALFO)*SIN(PHIO)*SIN(LAMO)
      CEN(3,2)=-COS(PHIO)*SIN(LAMO)
      CEN(1,3)= SIN(ALFO)*SIN(LAMO)-COS(ALFO)*SIN(PHIO)*COS(LAMO)
      CEN(2,3)= COS(ALFO)*SIN(LAMO)+SIN(ALFO)*SIN(PHIO)*COS(LAMO)
      CEN(3,3)= COS(PHIO)*COS(LAMO)
      V(1)=VTO
      V(2)=V(3)=0.
      CALL AXB(CPN,V,X(1),3,3,1)
      VT=VTO
      ALT=ALTO
      RETURN
      END
```

```
               REAL FUNCTION TOUT(DMY)                                    TOUT        2
                                                                          TOUT        3
          C**  TOUT COMPUTES THE TIME AT WHICH THE NEXT OUTPUT IS REQUIRED TOUT        4
                                                                          TOUT        5
               COMMON /DTO/DTO(50)                                        TOUT        6
               COMMON /SUPLE/SUPLE(9)                                     TOUT        7
                                                                          TOUT        8
               EQUIVALENCE (SUPLE(1),T)                                   TOUT        9
               EQUIVALENCE (SUPLE(6),ISEG)                                TOUT       10
                                                                          TOUT       11
               TOUT=(AINT(T/DTO(ISEG))+1.)*DTO(ISEG)                      TOUT       12
               RETURN                                                     TOUT       13
               END                                                        TOUT       14
```

```
           SUBROUTINE TSETUP1(TDONE)                                     TSETUP1      2
                                                                         TSETUP1      3
      C**  PRIOR TO EACH VERTICAL TURN, TSETUP1 COMPUTES THE TIME AT WHICH TSETUP1     4
      C**  THE CHANGE IN PITCH ANGLE WILL EQUAL "PITCH".  IF AND WHEN SUCH TSETUP1     5
      C**  TIME IS REACHED, THE TURN IS COMPLETE AND THE VERTICAL TURN    TSETUP1      6
      C**  ACCELERATION IS SWITCHED OFF IN SUBROUTINE FLTPATH.            TSETUP1      7
                                                                         TSETUP1      8
           COMMON /PITCH/PITCH(50)                                       TSETUP1      9
           COMMON /PACC/PACC(50)                                         TSETUP1     10
           COMMON /SUPLE/SUPLE(9)                                        TSETUP1     11
           COMMON /STATE/STATE(23)                                       TSETUP1     12
           COMMON /TACC/TACC(50)                                         TSETUP1     13
                                                                         TSETUP1     14
           EQUIVALENCE (SUPLE(3),TI)                                     TSETUP1     15
           EQUIVALENCE (SUPLE(6),ISEG)                                   TSETUP1     16
           EQUIVALENCE (STATE(4),VT)                                     TSETUP1     17
                                                                         TSETUP1     18
           IF (PACC(ISEG).EQ.0.) GO TO 10                                TSETUP1     19
      C                                                                  TSETUP1     20
      C            ACCELERATED PATH MOTION                               TSETUP1     21
           DT=VT*(EXP(PACC(ISEG)*ABS(PITCH(ISEG))/TACC(ISEG))-1.)/PACC(ISEG) TSETUP1 22
           TDONE=TI+DT                                                   TSETUP1     23
           RETURN                                                        TSETUP1     24
      C                                                                  TSETUP1     25
      C            UNACCELERATED PATH MOTION                             TSETUP1     26
   10      DT=VT*ABS(PITCH(ISEG))/TACC(ISEG)                             TSETUP1     27
           TDONE=TI+DT                                                   TSETUP1     28
           RETURN                                                        TSETUP1     29
           END                                                           TSETUP1     30
```

```
      SUBROUTINE TSETUP2(TOFF,TON,TDONE)                                  TSETUP2     2
                                                                          TSETUP2     3
C**   PRIOR TO EACH HORIZONTAL TURN, TSETUP2 COMPUTES THE TIME AT WHICH   TSETUP2     4
C**   ROLL-UP SHOULD CEASE (TOFF=T1), THE TIME AT WHICH ROLL-DOWN         TSETUP2     5
C**   SHOULD BEGIN (TON=T2), AND THE TIME AT WHICH ROLL WILL BE           TSETUP2     6
C**   RETURNED TO ZERO (TDONE).                                           TSETUP2     7
                                                                          TSETUP2     8
      COMMON /HEAD/HEAD(50)                                               TSETUP2     9
      COMMON /PACC/PACC(50)                                               TSETUP2    10
      COMMON /PRBLK/PRBLK(13)                                             TSETUP2    11
      COMMON /SEGLNT/SEGLNT(50)                                           TSETUP2    12
      COMMON /STATE/STATE(23)                                             TSETUP2    13
      COMMON /SUPLE/SUPLE(9)                                              TSETUP2    14
      COMMON /TACC/TACC(50)                                               TSETUP2    15
                                                                          TSETUP2    16
      EQUIVALENCE (PRBLK(13),ROLRATE)                                     TSETUP2    17
      EQUIVALENCE (STATE(4),VT)                                           TSETUP2    18
      EQUIVALENCE (SUPLE(2),TT)                                           TSETUP2    19
      EQUIVALENCE (SUPLE(3),TI)                                           TSETUP2    20
      EQUIVALENCE (SUPLE(5),ISEG)                                         TSETUP2    21
                                                                          TSETUP2    22
      DIMENSION YR(2),YI(2)                                               TSETUP2    23
                                                                          TSETUP2    24
      DT=SEGLNT(ISEG)                                                     TSETUP2    25
      CY=COS(ETAY(DMY))                                                   TSETUP2    26
      T1=ATAN(TACC(ISEG)/32.2/CY)/ROLRATE                                 TSETUP2    27
      T2LEST1=0.                                                          TSETUP2    28
      IF ((2.*T1).LT.DT) T2LEST1=DT-2.*T1                                 TSETUP2    29
      CALL YAWCHG(T1,T2LEST1,DYAW1,DYAW)                                  TSETUP2    30
      IF (DYAW.GE.ABS(HEAD(ISEG))) GO TO 10                               TSETUP2    31
      IF (DYAW.LT.ABS(HEAD(ISEG))) GO TO 20                               TSETUP2    32
    1 IF (DYAW1.GE.ABS(HEAD(ISEG))) GO TO 20                              TSETUP2    33
C                                                                         TSETUP2    34
C           CASE 1  -  MAX ROLL REACHED AND TURN COMPLETED                TSETUP2    35
   10 TOFF=TT+T1                                                          TSETUP2    36
      TON=0.                                                              TSETUP2    37
      VTDOT=PACC(ISEG)                                                    TSETUP2    38
      B0=32.2*CY*ALOG(COS(ROLRATE*T1))/ROLRATE                            TSETUP2    39
      B1=ABS(HEAD(ISEG))*CY                                               TSETUP2    40
      B2=VT+VTDOT*T1/2.                                                   TSETUP2    41
      A=VTDOT*(0.5*B1*VTDOT+0.5*B0*VTDOT/B2-TACC(ISEG))                   TSETUP2    42
      B=1.5*B1*B2*VTDOT+2.*B0*VTDOT+TACC(ISEG)*(VTDOT*T1-B2)              TSETUP2    43
      C=B2*(B1*B2+2.*B0+TACC(ISEG)*T1)                                    TSETUP2    44
      CALL QUADRT(A,B,C,IWARN,YR,YI)                                      TSETUP2    45
      IF (IWARN.EQ.1) WRITE (6,100)                                       TSETUP2    46
      IF (IWARN.EQ.1) STOP                                                TSETUP2    47
      IF (YR(1).GE.T1 .AND. YR(1).LE.DT) TON=TT+YR(1)                     TSETUP2    48
      IF (YR(2).GE.T1 .AND. YR(2).LE.DT) TON=TT+YR(2)                     TSETUP2    49
      IF (TON.EQ.0.) WRITE (6,101)                                        TSETUP2    50
      IF (TON.EQ.0.) STOP                                                 TSETUP2    51
      TDONE=TON+(TOFF-TT)                                                 TSETUP2    52
      RETURN                                                              TSETUP2    53
C                                                                         TSETUP2    54
C           CASE 2  -  MAX ROLL NOT REACHED BUT TURN COMPLETED            TSETUP2    55
   20 TOFF=0.                                                             TSETUP2    56
      A=-40.7*ROLRATE*ROLRATE                                             TSETUP2    57
      B=ROLRATE*ABS(HEAD(ISEG))*PACC(ISEG)                                TSETUP2    58
```

```
      C=ROLRATE*ABS(HEAD(ISEG))*VT
      CALL QUADRT(A,B,C,IWARN,YR,YI)
      IF (IWARN.EQ.1) WRITE (6,100)
      IF (IWARN.EQ.1) STOP
      IF (YR(1).GT.0. .AND. YR(1).LE.DT) TOFF=TON=TI+YR(1)
      IF (YR(2).GT.0. .AND. YR(2).LE.DT) TOFF=TON=TI+YR(2)
      IF (TOFF.EQ.0.) WRITE(6,102)
      IF (TOFF.EQ.0.) STOP
      IF (TOFF.GT.TF) TOFF=TON=TI+DT/2.
      TDONE=TOFF+(TOFF-TI)
      RETURN
   30 IF (T2LEST1.EQ.0.) GO TO 40
C
C           CASE C  -  MAX ROLL REACHED BUT TURN NOT COMPLETED
      TOFF=TI+T1
      TON=TI+DT-T1
      TDONE=TF
      RETURN
C
C           CASE D  -  MAX ROLL NOT REACHED AND TURN NOT COMPLETED
   40 TOFF=TON=TI+DT/2.
      TDONE=TF
      RETURN
  100 FORMAT(T2,*TSETUP2 MESSAGE - IWARN=1. PROGRAM TERMINATED.*)
  101 FORMAT(T2,*TSETUP2 MESSAGE - CASE A FAILURE. PROGRAM TERMINATED*)
  102 FORMAT(T2,*TSETUP2 MESSAGE - CASE B FAILURE. PROGRAM TERMINATED*)
      END
```

```
      SUBROUTINE VALDATA(NSEGT)                                         VALDATA   2
                                                                        VALDATA   3
C**   VALDATA PERFORMS A RANGE CHECK ON ALL INPUT PARAMETERS THAT HAVE A VALDATA   4
C**   RESTRICTED USEFUL RANGE.  IF ANY ARE OUT OF RANGE, AN INFORMATIVE  VALDATA   5
C**   MESSAGE IS PRINTED ABOUT EACH AND THEN THE RUN IS TERMINATED.      VALDATA   6
                                                                        VALDATA   7
      COMMON /DTO/DTO(50)        /ERROR/ERROR(50)     /HEAD/HEAD(50)     VALDATA   8
      COMMON /HMAX/HMAX(50)      /HMIN/HMIN(50)                         VALDATA   9
      COMMON /MODE/MODE(50)      /NPATH/NPATH(50)     /PITCH/PITCH(50)   VALDATA  10
      COMMON /PRBLK/PRBLK(13)    /SEGLNT/SEGLNT(50)                     VALDATA  11
      COMMON /TACC/TACC(50)      /TURN/TURN(50)                         VALDATA  12
                                                                        VALDATA  13
      EQUIVALENCE (PRBLK(1),LLMECH)                                     VALDATA  14
      EQUIVALENCE (PRBLK(3),VTO)                                        VALDATA  15
      EQUIVALENCE (PRBLK(4),PHEADO)                                     VALDATA  16
      EQUIVALENCE (PRBLK(5),PPITCHO)                                    VALDATA  17
      EQUIVALENCE (PRBLK(6),ALFAO)                                      VALDATA  18
      EQUIVALENCE (PRBLK(7),LATO)                                       VALDATA  19
      EQUIVALENCE (PRBLK(8),LONO)                                       VALDATA  20
      EQUIVALENCE (PRBLK(13),ROLRATE)                                   VALDATA  21
                                                                        VALDATA  22
      INTEGER TURN                                                      VALDATA  23
      REAL LATO,LONO                                                    VALDATA  24
      DIMENSION FINMESS(18),IERR(21)                                    VALDATA  25
                                                                        VALDATA  26
      DATA IERR,ISTOP,HALFPI,PI/22*0,90.,180./                          VALDATA  27
      DATA (FINMESS(I),I=1,18)/                                         VALDATA  28
     1 10H  NSEGT    ,10H  LLMECH   ,10H  VTO      ,10H  PHEADO   ,     VALDATA  29
     2 10H  PPITCHO  ,10H  ALFAO    ,10H  LATO     ,10H  LONO     ,     VALDATA  30
     3 10H  ROLRATE  ,10H  SEGLNT   ,10H  TURN     ,10H  NPATH    ,     VALDATA  31
     4 10H  TACC     ,10H  DTO      ,10H  MODE     ,10H  ERROR    ,     VALDATA  32
     5 10H  HMAX     ,10H  HMIN     /                                   VALDATA  33
                                                                        VALDATA  34
C                                                                       VALDATA  35
C           RANGE-CHECK PRDATA                                          VALDATA  36
      IF (NSEGT.LT.1 .OR. NSEGT.GT.50) IERR(1)=1                        VALDATA  37
      IF (LLMECH.LT.1 .OR. LLMECH.GT.4) IERR(2)=1                       VALDATA  38
      IF (VTO.LT.0.) IERR(3)=1                                          VALDATA  39
      IF (PHEADO.LT.-PI .OR. PHEADO.GT.PI) IERR(4)=1                    VALDATA  40
      IF (PPITCHO.LT.-HALFPI .OR. PPITCHO.GT.HALFPI) IERR(5)=1          VALDATA  41
      IF (ALFAO.LT.-PI .OR. ALFAO.GT.PI) IERR(6)=1                      VALDATA  42
      IF (LATO.LE.-HALFPI .OR. LATO.GE.HALFPI) IERR(7)=1                VALDATA  43
      IF (LONO.LT.-PI .OR. LONO.GT.PI) IERR(8)=1                        VALDATA  44
      IF (ROLRATE.LE.0.) IERR(9)=1                                      VALDATA  45
C                                                                       VALDATA  46
C           RANGE-CHECK PASDATA                                         VALDATA  47
      DO 10 I=1,50                                                      VALDATA  48
         IF (SEGLNT(I).LT.0.) IERR(10)=1                                VALDATA  49
         IF (TURN(I).LT.1 .OR. TURN(I).GT.4) IERR(11)=1                 VALDATA  50
         IF (NPATH(I).LT.1 .OR. NPATH(I).GT.2) IERR(12)=1               VALDATA  51
         IF (TACC(I).LT.0.) IERR(13)=1                                  VALDATA  52
         IF (DTO(I).LE.0.) IERR(14)=1                                   VALDATA  53
         IF (MODE(I).LT.0 .OR. MODE(I).GT.1) IERR(15)=1                 VALDATA  54
         IF (ERROR(I).LE.0.) IERR(16)=1                                 VALDATA  55
         IF (HMAX(I).LE.0.) IERR(17)=1                                  VALDATA  56
         IF (HMIN(I).LE.0.) IERR(18)=1                                  VALDATA  57
         IF (TURN(I) NE.3) GO TO 5                                      VALDATA  58
```

```
          IF (HEAD(I).LE.-HALFPI .OR. HEAD(I).GE.HALFPI) IERR(19)=1        VALDATA   59
          IF (PITCH(I).EQ.0.) IERR(20)=1                                   VALDATA   60
    5     IF (TURN(I).NE.1 .AND. TURN(I).NE.2) GO TO 10                    VALDATA   61
          IF (TACC(I).EQ.0.) IERR(21)=1                                    VALDATA   62
   10  CONTINUE                                                            VALDATA   63
C                                                                          VALDATA   64
C           PRINT MESSAGES IF REQUIRED                                     VALDATA   65
       DO 20 I=1,9                                                         VALDATA   66
          IF (IERR(I).EQ.0) GO TO 20                                       VALDATA   67
          WRITE (6,100) FINMESS(I)                                         VALDATA   68
          ISTOP=1                                                          VALDATA   69
   20  CONTINUE                                                            VALDATA   70
       DO 30 I=10,18                                                       VALDATA   71
          IF (IERR(I).EQ.0) GO TO 30                                       VALDATA   72
          WRITE (6,110) FINMESS(I)                                         VALDATA   73
          ISTOP=1                                                          VALDATA   74
   30  CONTINUE                                                            VALDATA   75
       IF (IERR(19).EQ.1) WRITE (6,120)                                    VALDATA   76
       IF (IERR(20).EQ.1) WRITE (6,130)                                    VALDATA   77
       IF (IERR(21).EQ.1) WRITE (6,140)                                    VALDATA   78
       IF (IERR(19).EQ.1 .OR. IERR(20).EQ.1 .OR. IERR(21).EQ.1) ISTOP=1    VALDATA   79
       IF (ISTOP.EQ.1) WRITE (6,150)                                       VALDATA   80
       IF (ISTOP.EQ.1) STOP                                                VALDATA   81
       RETURN                                                              VALDATA   82
  100  FORMAT(/T2,*THIS PRDATA PARAMETER IS OUT OF RANGE : *,A10)          VALDATA   83
  110  FORMAT(/T2,*AT LEAST ONE ELEMENT OF THIS PASDATA PARAMETER IS OUT   VALDATA   84
      1 OF RANGE : *,A10)                                                  VALDATA   85
  120  FORMAT(/T2,*THE HEADING VARIATION (HEAD) FOR ONE OF THE SINE HEADI  VALDATA   86
      1NG CHANGE MANEUVERS IS GREATER THAN 90 DEGREES.*)                   VALDATA   87
  130  FORMAT(/T2,*THE OSCILLATION FREQUENCY (PITCH) FOR ONE OF THE SINE   VALDATA   88
      1HEADING CHANGE MANEUVERS IS 0.*)                                    VALDATA   89
  140  FORMAT(/T2,*TURN ACCELERATION (TACC) IS ZERO FOR SOME VERTICAL OR   VALDATA   90
      1HORIZONTAL TURN.*)                                                  VALDATA   91
  150  FORMAT(/T2,*THE ABOVE ERROR(S) COULD BE FATAL IN EXECUTION SO PROF  VALDATA   92
      1GEN IS TERMINATED HERE.*)                                           VALDATA   93
       END                                                                 VALDATA   94
```

```
      SUBROUTINE VDOT(DVX,DVY,DVZ)                                      VDOT   2
                                                                        VDOT   3
C**   VDOT COMPUTES THE DERIVATIVES OF THE EARTH FRAME                  VDOT   4
C**   VELOCITIES (VX,VY,VZ) AS COORDINATIZED IN THE NAV FRAME.          VDOT   5
                                                                        VDOT   6
      COMMON /PACC/PACC(50)                                             VDOT   7
      COMMON /STATE/STATE(23)                                           VDOT   8
      COMMON /SUPLE/SUPLE(9)                                            VDOT   9
                                                                        VDOT  10
      EQUIVALENCE (STATE(1),VX)                                         VDOT  11
      EQUIVALENCE (STATE(2),VY)                                         VDOT  12
      EQUIVALENCE (STATE(3),VZ)                                         VDOT  13
      EQUIVALENCE (STATE(6),CPN11)                                      VDOT  14
      EQUIVALENCE (STATE(7),CPN21)                                      VDOT  15
      EQUIVALENCE (STATE(8),CPN31)                                      VDOT  16
      EQUIVALENCE (SUPLE(6),ISEG)                                       VDOT  17
      EQUIVALENCE (WPN(1),WPNX)                                         VDOT  18
      EQUIVALENCE (WPN(2),WPNY)                                         VDOT  19
      EQUIVALENCE (WPN(3),WPNZ)                                         VDOT  20
                                                                        VDOT  21
      DIMENSION WPN(3)                                                  VDOT  22
                                                                        VDOT  23
      DVT=PACC(ISEG)                                                    VDOT  24
      CALL OMEGAPN(WPN)                                                 VDOT  25
      DVX=CPN11*DVT-WPNZ*VY+WPNY*VZ                                     VDOT  26
      DVY=CPN21*DVT-WPNX*VZ+WPNZ*VX                                     VDOT  27
      DVZ=CPN31*DVT-WPNY*VX+WPNX*VY                                     VDOT  28
      RETURN                                                            VDOT  29
      END                                                               VDOT  30
```

```
      REAL FUNCTION VEAST(DMY)                               VEAST    2
                                                             VEAST    3
C**   VEAST COMPUTES THE EAST COMPONENT OF VELOCITY          VEAST    4
                                                             VEAST    5
      COMMON /STATE/STATE(23)                                VEAST    6
      EQUIVALENCE (STATE(1),VX)                              VEAST    7
      EQUIVALENCE (STATE(2),VY)                              VEAST    8
                                                             VEAST    9
      A=ALFA(DMY)                                            VEAST   10
      VEAST=-VX*SIN(A)-VY*COS(A)                             VEAST   11
      RETURN                                                 VEAST   12
      END                                                    VEAST   13
```

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      SUBROUTINE YAWCHG(T1,T2LEST1,DYAW1,DYAW)

C**   YAWCHG COMPUTES THE ANGLE THROUGH WHICH THE AIRCRAFT COULD YAW
C**   IF IT REMAINED IN A HORIZONTAL TURN FOR THE ENTIRE FLIGHT SEGMENT.

      COMMON /PACC/PACC(50)
      COMMON /PRBLK/PRBLK(13)
      COMMON /SEGLNT/SEGLNT(50)
      COMMON /STATE/STATE(23)
      COMMON /SUPLE/SUPLE(9)
      COMMON /TACC/TACC(50)

      EQUIVALENCE (PRBLK(13),ROLRATE)
      EQUIVALENCE (STATE(4),VT)
      EQUIVALENCE (SUPLE(6),ISEG)

      DTROLL=SEGLNT(ISEG)/2.
      IF (T2LEST1.GT.0.) DTROLL=T1
      T2=SEGLNT(ISEG)-DTROLL
      VTDOT=PACC(ISEG)
C
C             COMPUTE YAW CHANGE THAT OCCURS WHILE ROLLING
C             INTO AND OUT OF THE TURN.
      DYAW1=(-32.2*ALOG(COS(ROLRATE*DTROLL))/ROLRATE) *
     1       (1./(VT+VTDOT*DTROLL/2.) + 1./(VT+VTDOT*(T2+DTROLL/2.)))
C
C             COMPUTE YAW CHANGE THAT OCCURS WHILE HOLDING
C             CONSTANT ROLL ANGLE DURING THE TURN.
      VT1=VT+VTDOT*T1
      IF (VTDOT.EQ.0.) DYAW2=TACC(ISEG)*T2LEST1/(VT1*COS(ETAY(DMY)))
      IF (VTDOT.NE.0.) DYAW2=TACC(ISEG)*ALOG(1.+VTDOT*T2LEST1/VT1)/
     1   (VTDOT*COS(ETAY(DMY)))
C
C             TOTAL YAW CHANGE
      DYAW=DYAW1+DYAW2
      RETURN
      END
```

***********   IPU02A0   //// END OF LIST ////

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