

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

MSC - 04217

VOL. 4



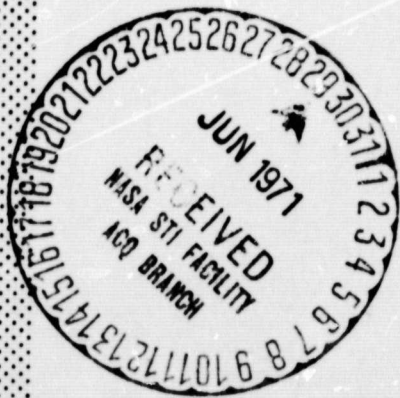
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PROJECT/SPACE SHUTTLE

SPACE SHUTTLE GUIDANCE, NAVIGATION AND CONTROL DESIGN EQUATIONS

VOLUME IV DEORBIT AND ATMOSPHERIC OPERATIONS

APRIL 15, 1971



FACILITY FORM 602

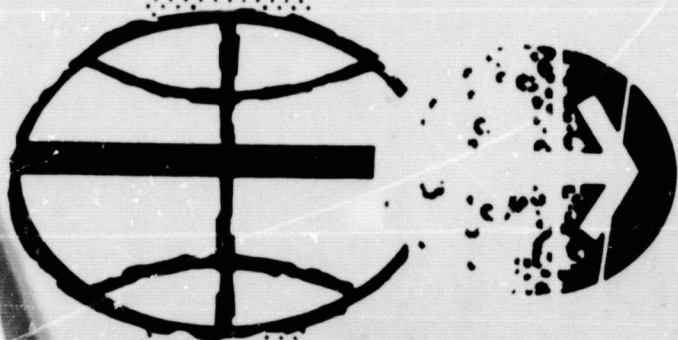
N71-32298
(ACCESSION NUMBER)

49
(PAGES)

TMX-67219
(NASA CR OR TMX OR AD NUMBER)

THRU
63
(CODE)

30
(CATEGORY)



SYSTEMS ANALYSIS BRANCH
GUIDANCE AND CONTROL DIVISION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Int-145299

MSC - 04217

NASA SPACE SHUTTLE PROGRAM WORKING PAPER

SPACE SHUTTLE GUIDANCE, NAVIGATION
AND CONTROL
DESIGN EQUATIONS

VOLUME IV
DEORBIT AND ATMOSPHERIC OPERATIONS

April 15, 1971

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Prepared by
Systems Analysis Branch
Guidance and Control Division

K. J. Cox
K. J. Cox, Chief
Systems Analysis Branch

Authorized for
Distribution William C. Bradford
Maxime A. Faget
Director of Engineering and Development

TABLE OF CONTENTS

	<u>PAGE</u>
VOLUME I	
1. PURPOSE	1-1
2. SCOPE	2-1
3. APPLICABILITY	3-1
4. DEFINITION OF TERMS	4-1
5. REFERENCE DOCUMENTS	5-1
6. GN&C SYSTEM DESCRIPTION	6-1
7. GN&C SOFTWARE FUNCTIONAL REQUIREMENTS	7-1
8. COORDINATE SYSTEMS AND TRANSFORMATIONS	8-1
VOLUME II -- PREFLIGHT THROUGH ORBIT INSERTION	
9. DESCRIPTION OF EQUATIONS	9-1
9.1 Preflight	9.1-1
9.1.1 GN&C System Initialization, Monitor, Test and Checkout.	9.1-1
9.1.2 Prelaunch Targeting	9.1-1
9.1.3 Sensor Calibration and Alignment	9.1-1
9.2 Boost Phase Program	9.2-1
9.2.1 Rapid Real-Time State Advancement During Specific Force Sensing	9.2-4
9.2.2 Boost Monitor	9.2-15
9.3 Separation	9.3-1
9.3.1 Attitude Control	9.3-1
9.4 Orbit Insertion Program	9.4-1
9.4.1 Navigation	9.4-1
9.4.2 Powered Ascent Guidance	9.4-3
9.4.3 Attitude Control.	9.4-25

TABLE OF CONTENTS (CONTINUED)

	<u>PAGE</u>
9.5 Ascent Aborts	9.5-1
9.5.1 Abort Decision and Mode Determination	9.5-1
9.5.2 Abort Targeting	9.5-1
9.5.3 Abort Guidance	9.5-1
9.5.4 Navigation	9.5-1
9.5.5 Attitude Control	9.5-1
VOLUME III - ORBITAL OPERATIONS	
9.6 Orbital Coast	9.6-1
9.6.1 Navigation	9.6-1
9.6.1.1 Conic State Extrapolation	9.6-3
9.6.1.2 Precision State and Filter Weighting Matrix Extrapolation	9.6-33
9.6.2 Sensor Calibration and Alignment	9.6-62
9.6.3 Orbital Coast Attitude Control	9.6.62
9.7 Orbital Powered Flight	9.7-1
9.7.1 Targeting	9.7-2
9.7.2 Navigation	9.7-2
9.7.3 Guidance	9.7-2
9.7.4 Attitude Control	9.7-2
9.8 Rendezvous Mission Phase	9.8-1
9.8.1 Rendezvous Targeting	9.8-3
9.8.2 Relative State Updating	9.8-90
9.8.3 Rendezvous Guidance	9.8-132
9.8.4 Rendezvous Attitude Control	9.8-132
9.9 Station Keeping Mission Phase	9.9-1
9.9.1 Relative State Estimation	9.9-2
9.9.2 Station Keeping Guidance	9.9-2
9.9.3 Station Keeping Attitude Control	9.9-2

TABLE OF CONTENTS (CONTINUED)

	<u>PAGE</u>
9.10 Docking and Undocking	9.10-1
9.10.1 Docking and Undocking Navigation	9.10-5
9.10.2 Automatic Docking Control Law	9.10-32
9.11 Docked Operations	9.11-1
APPENDIX A - APPLICABLE APOLLO SOFTWARE	A-1

VOLUME IV - DEORBIT AND ATMOSPHERIC OPERATIONS

9.12 Deorbit and Entry	9.12-1
9.12.1 Deorbit Targeting	9.12-1
9.12.2 Entry Navigation	9.12-1
9.12.3 Entry Guidance	9.12-4
9.12.4 Reentry Autopilot	9.12-16
9.13 Transition.	9.13-1
9.13.1 Transition Attitude Control	9.13-2
9.14 Cruise and Ferry Cruise	9.14-1
9.14.1 Navigation	9.14-1
9.14.2 Guidance	9.14-1
9.14.3 Attitude Control	9.14-1
9.15 Approach and Landing	9.15-1
9.15.1 Navigation	9.15-1
9.15.2 Guidance	9.15-1
9.15.3 Control	9.15-1
9.16 Horizontal Takeoff	9.16-1
9.17 Communications and Pointing	9.16-1
9.18 Failure Detection	9.16-1

VOLUME V - FLOW DIAGRAMS

10. FLOW DIAGRAMS	
-----------------------------	--

TABLE OF CONTENTS (CONTINUED)

PAGE

VOLUME VI - CONSTANTS AND KEYBOARD
ACCESSIBLE PARAMETERS

11. SUMMARY OF CONSTANTS

12. REQUIRED KEYBOARD ACCESSIBLE PARAMETERS

PURPOSE

The purpose of this document is to specify the equations necessary to perform the guidance, navigation and control onboard computation functions for the space shuttle orbiter vehicle. This equations document will: (1) establish more specifically, than on a functional level, the GN&C computational requirements for computer sizing, (2) provide GN&C design equations specification to develop demonstration software for hardware feasibility testing, and (3) define the hardware interface requirements with the GN&C subsystem software. The document will provide a standard of communication of information concerning the GN&C equations, and will provide a means of coordination of GN&C equation development.

SCOPE

This is Volume IV of the document which defines the Guidance, Navigation and Control (GN&C) design equations sequencing and interfaces for the computations required in the GN&C Subsystem for all mission phases of the Shuttle Orbiter flight. The equations are intended to satisfy the functional requirements specified in Reference a. This document will describe in mathematical, logical, and operational language all the details necessary to initiate and carry out the design of the required computer modules (subprograms) for the GN&C functions.

The document will be organized into six volumes. Volume I contains Sections 1 through 8, which provide introductory information for the document. Volume II contains the current detailed equations for the preflight, boost, separation, orbit insertion and ascent abort phases of the Orbiter operation. Detailed equations for orbital operations of the Orbiter, which include the orbital coast, orbital powered flight, rendezvous, station keeping, docking and undocking, and docked operations phases, are presented in Volume III. Volume IV contains the current detailed equations for the deorbit and entry, transition, cruise and ferry, approach and landing, and horizontal takeoff phases of the Orbiter. Also, this volume will contain the equations for communications and pointing functions and the failure detection function. For this issue of the document, only Volumes I through IV are being published. In future issues, Volume V will contain the detailed flow diagrams for the equations. For the initial issue, the flow diagrams for the approved equations are included with the equations in Volumes II, III or IV. For future issues, the constants used in the equations will be summarized in Section 11 and the GN&C parameters and variables which can be entered or called via the keyboard will be enumerated in Section 12. These two sections will be contained in Volume VI of the document.

APPLICABILITY

This document is applicable to the Guidance, Navigation, and Control (GN&C) Subsystem of the Electronics System of the Space Shuttle Orbiter Vehicle. It is applicable to the definition of the shuttle computational requirements for the subsystem listed above. It is applicable to the Phase B and Phase C subsystem development. It defines the Manned Spacecraft Center Guidance and Control Division inhouse study baseline equations design.

9. DESCRIPTIONS OF EQUATIONS

The detailed equations for the GN&C functions are defined in this section. The organization of this section is tentative and will be modified so as to present the equations as they are designed in as clear a fashion as possible. As an introduction to each major subsection (usually a mission phase), the general GN&C software functions to be implemented will be identified and, where appropriate, a conceptual discussion and top level flow of the computations, inputs and outputs will be included in order to understand and summarize what is to be covered. This should be an order of magnitude less detailed than the flow diagrams of the equations which come later.

A GN&C Equation Submittal sheet will introduce each of the GN&C equation submittals and summarize the GN&C functions, and identify the source and NASA contact for each.

The detailed data to be presented for each GN&C function within each of the major subsections (usually a mission phase) is summarized below. Although items 6 through 10 are to be referenced only in the equations document, they are required submittals before the equations can be approved and finalized for flight software development.

1. Functional Requirements

The specific functional requirements (from the GN&C Software Functional Requirements Document) which are satisfied by the equations should be identified.

2. Functional Diagram

A brief functional explanation and description of the overall concept and approach. A functional block diagram should be used where clarity is enhanced. Inputs, outputs, and interfaces will be provided.

3. Equations and Flows

Detailed equations and a descriptive text which guides the reader through the flows of Section 10 should be provided. The minimum frequency of the computations shall be specified and rationale given or referenced.

4. Coordinate System

The coordinate systems used shall be defined.

5. Constants/Variables Summary

Constants and variables shall be summarized in tabular form with the following information:

- a. Variables/constants symbols and definitions
- b. Units
- c. Allowable quantization
- d. Range of values

6. FORTRAN Coding

The FORTRAN coding of the function for verification using the Space Shuttle Flight Simulation (SSFS) will be referenced.

7. Simulation

The SSFS specifications, description and user's guide used to verify each GN&C function will be referenced.

8. Testing

Test plans and test results will be referenced.

9. Derivation

The mathematical derivation of the equations including all mathematical assumptions shall be referenced.

10. Assumptions

The following will be referenced:

- a. Avionics baseline system assumed
- b. Reference missions assumed
- c. Vehicle mass properties assumed
- d. Propulsion models assumed
- e. Environment models assumed
- f. Error models assumed

The major subsections of this section are identified and partially expanded in the following.

9.12 DEORBIT AND ENTRY

The Deorbit and Entry phase of the Shuttle mission begins with the Shuttle performing the Deorbit Targeting for the Deorbit (or Deorbit phasing, if required) burn and terminates at the beginning of transition to low angle of attack. The primary landing point and the required orbit maneuvers have been determined from pre-phase planning computations. The GN&C Software functions to be performed during this phase are:

1. Deorbit Targeting will be performed in the coast period prior to the deorbit burn(s). Targeting outputs (for a specified landing site input) will include parameters as time(s) of ignition, initial attitude for the burn(s), burn time, total ΔV for each burn, IMU realignment schedule, time of reentry, transition time, cross and downrange required, jet engines ignition time, and time of touchdown.
2. Orbital navigation using ground beacon or star/horizon measurements as required to update Shuttle State prior to thrusting maneuvers and aerodynamic entry augmented by available external measurements.
3. Powered Flight guidance resulting in commands to autopilot (attitude), thrust vector controls, or thrust throttle commands to achieve desired conditions (state and attitude) for transition and limit entry g-loading and heating.
4. Autopilot computations to compute reaction control system commands to achieve the proper attitude.

Figure 1 displays a functional flow diagram of the Deorbit and Entry Software Functions.

9.12.1 DEORBIT TARGETING (TBD)

9.12.2 ENTRY NAVIGATION (TBD)

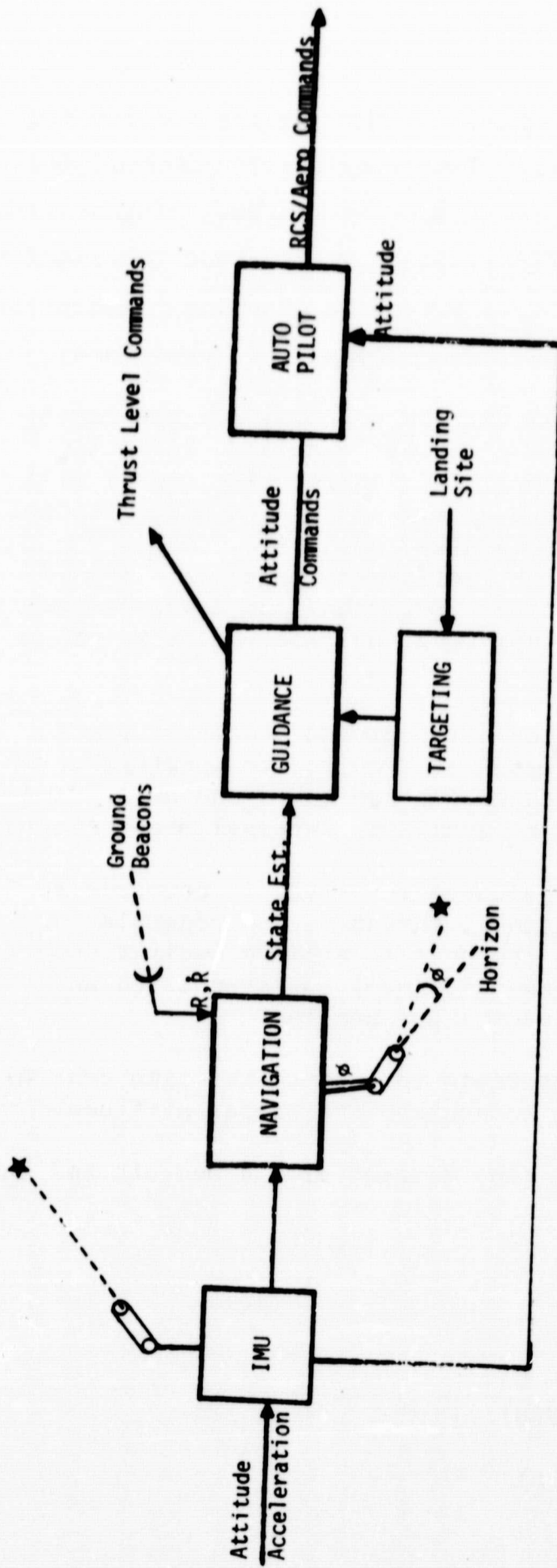


FIGURE 1. FUNCTIONAL DIAGRAM OF GN&C SOFTWARE FUNCTIONS DURING DEORBIT AND ENTRY

SPACE SHUTTLE
GN&C SOFTWARE EQUATION SUBMITTAL

Software Equation Section: Reentry Guidance Submittal No. 2

Function: Provide guidance commands during entry

Module No. OG5 Function No. 9,10,11 (MSC 03690)

Submitted by: John W. Sunkel Co. GCD

Date: Dec 1970

NASA Contact: W. Peters Organization: GCD

Approved by Panel III: K. J. Cox Date: 1/28/71

Summary Description: A fast-time-prediction (FTP) guidance scheme is used which is based on sequential rapid integrations of the equations of motion. Sensitivities of all the future states to a control change are known from perturbation solutions. The predictor is a fourth-order Adams-Bashforth formula; the correction is a fourth-order Adams Moulton formula.

Shuttle Configuration: Not provided; however, the general concept should be independent of shuttle configuration.

Comments:

(Design Status) Coded and in test.

(Verification Status) Preliminary test results provided.

Panel Comments:

9.12.3 Entry Guidance

1. Introduction

The Fast-Time Prediction (FTP) Guidance method documented in refs. (1) and (2) applied only to flight in a vertical plane over a spherical nonrotating earth. The method has now been upgraded to include a more accurate dynamic model as well as predictive crossrange logic. The significant revisions are described in the next three sections of this memo. Reference 4 presents some typical results obtained during checkout of the new routine. Table 1 defines nomenclature used in the memorandum.

2. Equations of Motion

FTP guidance is based on sequential rapid integrations of the differential equations of motion. The previous version of the FTP guidance routine used Chapman's equation which applies only to flight in a vertical plane and in regions where drag is significant and where the flightpath angle is small. Furthermore, coriolis terms are not included. These restrictions have been removed in the FTP-4D program without significantly increasing the complexity of the equations that are integrated. Velocity is used as the independent variable to eliminate one equation. In addition, the set is nondimensionalized since, in general, well-conditioned equations can be integrated with larger step-sizes. Therefore, the equations that are integrated in the FTP-4D guidance program take the following forms:

$$\frac{d\hat{y}}{d\hat{v}} = f_1 = \frac{1}{\hat{v}'} \left\{ \frac{1}{2} \frac{L}{D} \hat{\rho}_0 e^{-\beta \hat{h} R_0} \hat{v} \hat{S} C_D \cos \hat{\phi} \right. \\ \left. - \cos \hat{\gamma} \left[\frac{\hat{g}}{\hat{v}} - \frac{\hat{r}}{\hat{v}} \hat{\omega}_e^2 \cos^2 i - \frac{\hat{v}}{\hat{r}} \right] + 2 \hat{\omega}_e \cos i \right\} \quad (1)$$

$$\frac{d\hat{h}}{d\hat{v}} = f_2 = \frac{1}{\hat{v}'} \left\{ \hat{v} \sin \hat{\gamma} \right\} \quad (2)$$

$$\frac{d\hat{x}}{d\hat{v}} = f_3 = \frac{1}{\hat{v}'} \left\{ \frac{\hat{r}_e}{\hat{r}} \hat{v} \cos \hat{\gamma} \right\} \quad (3)$$

9.12.3 Entry Guidance (cont'd)

Table 1

DEFINITION OF TERMS

Variable		Dimensions (ND=nondimensional)
β	scale height in exponential atmosphere	ft^{-1}
BIAS	The control parameter which increases or decreases the in-plane L/D	ND
C_D	drag coefficient	ND
$f(\hat{v})$	a prespecified function determining the shape of the in-plane component of L/D	ND
\hat{g}	gravitational acceleration	ND
$\hat{\gamma}$	flight path angle	ND
\hat{h}	altitude	ND
i	instantaneous trajectory inclination angle	ND
$\hat{\ell}$	crossrange distance (+ to right of track)	ND
L/D	maximum lift-to-drag ratio	ND
M.	nondimensionalizing-mass	4.21×10^3 slugs
μ	angle of latitude	ND
$\hat{\phi}$	angle bank about velocity vector (+ rolled right)	ND
$\hat{\psi}$	azimuth with respect to downrange direction (+ to right of track)	ND
\dot{Q}	heating rate	$\text{Btu}/\text{ft}^2/\text{sec}$
\hat{r}	distance from earth center	ND

9.12.3 Entry Guidance (cont'd)

Variable		Dimensions (ND=nondimensional)
R_0	nondimensionalizing length	2.133×10^7 ft.
\hat{r}_e	earth radius	ND
$\hat{\rho}_0$	assumed sea-level atmospheric density in exponential atmosphere.	ND
\hat{S}	reference area	ND
\hat{v}	velocity relative to a rotating atmosphere	ND
v_0	nondimensionalizing speed	2.57×10^4 ft/sec
$\hat{\omega}_e$	earth spin rate	ND
\hat{x}	downrange distance	ND

9.12.3 Entry Guidance (cont'd)

FACTORIZATION TERMS

T1	$\frac{1}{2} \hat{\rho}_0 C_D \hat{S}$
T2	$\hat{\omega}_e \cos i$
T3	$e^{-\beta \hat{h} R_0}$
T5	$\cos \hat{\gamma}$
T6	$\sin \hat{\phi}$
T7	$\cos \hat{\phi}$
T8	$\sin \hat{\psi}$
T9	$\cos \hat{\psi}$
T10	$\sin \hat{\zeta}$
T11	$(T24)/(T19)$
T12	\hat{v}^2
T13	$-(T11)(T5)(T30)$
T14	$-(T11)[(T1)(T3)(T15)(T12) + (T10)(T21)]$
T15	$(\beta)(R_0)$
T17	\hat{g}/\hat{v}
T19	$-(T1)(T3)(T12) - (T10)(T30)$
T20	$\hat{r}_e + \hat{h}$
T21	$(T2)^2$
T22	\hat{r}/\hat{v}
T23	$1/(T22)$
T24	$1/(T19)$

9.12.3 Entry Guidance (cont'd)

- T25 \hat{r}_e (T23)
- T26 T17 - (T22)(T21) - T23
- T27 (T1)(T3)(\hat{v})(T7)
- T28 (T10)(T25)
- T29 (T25)(T5)
- T30 \hat{g} - (T20)(T21)

9.12.3 Entry Guidance (cont'd)

$$\frac{d\hat{\psi}}{d\hat{v}} = f_4 = \frac{1}{\hat{v}^2} \left\{ \frac{1}{2} \hat{\rho}_0 \hat{v} e^{-\beta \hat{h} R_0} C_D \hat{S} \frac{L}{D} \sin \hat{\phi} + 2 \hat{\omega}_e \sin i \sin \mu \right\} \quad (4)$$

$$\frac{d\hat{\lambda}}{d\hat{v}} = f_5 = \frac{1}{\hat{v}^2} \left\{ \hat{v} \sin \hat{\psi} \right\} \quad (5)$$

Factorization of these equations using the terms defined in the appendix results in the following equivalent equations:

$$\frac{d\hat{\psi}}{d\hat{v}} = (T24) \left[(T27) \frac{L}{D} - (T5)(T26) + 2(T2) \right] \quad (1a)$$

$$\frac{d\hat{b}}{d\hat{v}} = (T24) (\hat{v}) (T10) \quad (2a)$$

$$\frac{d\hat{x}}{d\hat{v}} = (T24) (T25) (T5) \quad (3a)$$

$$\frac{d\hat{\psi}}{d\hat{v}} = (T24) \left[\frac{(T27)}{(T7)} (T6) \frac{L}{D} + 2 \hat{\omega}_e \sin i \sin \mu \right] \quad (4a)$$

$$\frac{d\hat{\lambda}}{d\hat{v}} = (T24) (\hat{v}) (T8) \quad (5a)$$

The bank angle $\hat{\phi}$ used in the integration of equations (1) - (3) is obtained from the expression

$$\hat{\phi} = \cos^{-1} \left| \frac{f(\hat{v}) + \text{BIAS}}{L/D} \right| \quad (6)$$

where $f(\hat{v})$ is a predetermined function that specifies the shape of the vertical plane component of L/D as a function of \hat{v} . BIAS is the vertical shift of the $L/D \cos \hat{\phi}$ curve obtained from the previous guidance cycle. Thus each new guidance command is followed by a prediction of the range error using that command.

9.12.3 Entry Guidance (cont'd)

The gain used in the downrange guidance is obtained by integrating the set of perturbation equations associated with equations (1) - (3). These equations are:

$$\begin{aligned} \frac{d}{d\hat{V}} \left[\frac{\partial \hat{Y}}{\partial (L/D \cos \hat{\phi})} \right] &= \frac{\partial f_1}{\partial \hat{Y}} \frac{\partial \hat{Y}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_1}{\partial \hat{h}} \frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})} \\ &+ \frac{\partial f_1}{\partial \hat{x}} \frac{\partial \hat{x}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_1}{\partial (L/D \cos \hat{\phi})} \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{d}{d\hat{V}} \left[\frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})} \right] &= \frac{\partial f_2}{\partial \hat{Y}} \frac{\partial \hat{Y}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_2}{\partial \hat{h}} \frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})} \\ &+ \frac{\partial f_2}{\partial \hat{x}} \frac{\partial \hat{x}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_2}{\partial (L/D \cos \hat{\phi})} \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{d}{d\hat{V}} \left[\frac{\partial \hat{x}}{\partial (L/D \cos \hat{\phi})} \right] &= \frac{\partial f_3}{\partial \hat{Y}} \frac{\partial \hat{Y}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_3}{\partial \hat{h}} \frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})} \\ &= \frac{\partial f_3}{\partial \hat{x}} \frac{\partial \hat{x}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial f_3}{\partial (L/D \cos \hat{\phi})} \end{aligned} \quad (9)$$

Three partial derivatives indicated in equations (7) - (9) can be factored and simplified considerably before programming to reduce computation time. The resulting forms are:

$$\begin{aligned} \frac{\partial f_1}{\partial \hat{Y}} &= (T26) [(-T5)(T13) + (T24)(T10)] + (T13) [(T27)L/D \\ &+ 2(T2)] \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{\partial f_1}{\partial \hat{h}} &= \{(T27)L/D - (T5)(T26) + 2(T2)\}(T14) \\ &+ T24 \left\{ (T27)(T15)L/D + (T5)(T21)1/\hat{V} - (T23) \frac{(T5)}{(T20)} \right\} \end{aligned} \quad (11)$$

$$\frac{\partial f_1}{\partial \hat{x}} = 0 \quad (12)$$

$$\frac{\partial f_2}{\partial \hat{Y}} = \hat{V} \{ (-T24)(T5) + (T10)(T13) \} \quad (13)$$

9.12.3 Entry Guidance (cont'd)

$$\frac{\partial f_2}{\partial \hat{h}} = \hat{V}(T10)(T14) \quad (14)$$

$$\frac{\partial f_2}{\partial \hat{x}} = 0 \quad (15)$$

$$\frac{\partial f_3}{\partial \hat{Y}} = (T28) \left[(T5) \frac{(T13)}{(T10)} - (T24) \right] \quad (16)$$

$$\frac{\partial f_3}{\partial \hat{h}} = (T29)(T14) - (T24)(T29) \quad (17)$$

$$\frac{\partial f_3}{\partial \hat{x}} = 0$$

$$\frac{\partial f_1}{\partial (L/D \cos \phi)} = (T24)(T27)/(T7) \quad (19)$$

The T-factors in equations (10)-(19) are defined in Table .

The gain for the downrange guidance is $1 / \left(\frac{\partial \hat{x}}{\partial (L/D \cos \phi)} \right)$ at cutoff altitude. Since equations (7)-(9) are integrated simultaneously with equations (1)-(5) on each guidance call, the gain used is always based on the latest control history. The result is a very stable guidance response exhibiting little or no overshoot.

Integration of equations (1)-(3) and (7)-(9) provides an abundance of information that is useful. At every guidance call, all future state variables are predicted. Thus accurate predictions of the magnitudes and locations of the maximum load factor and heating rate are obtained. These could be displayed to the crew or used to alter the flightpath if their magnitudes are excessive. Note also that the sensitivities of all the future states to a control change are known from the perturbation solutions. Therefore, if it is necessary to alter the command to avoid exceeding a load factor or a heating rate limit, the proper gain is known

9.12.3 Entry Guidance (cont'd)

for that control loop. For example, if the maximum heat rate predicted is \dot{Q}_{\max} and the allowable limit is 100 Btu/ft² sec, the first-order estimate of the change in $\hat{\phi}$ required to avoid the excess could be obtained from the expression

$$\Delta(L/D \cos \hat{\phi}) = G(\dot{Q}_{\max} - 100) \quad (20)$$

where

$$\frac{1}{G} = \frac{\partial \dot{Q}}{\partial \hat{\gamma}} \frac{\partial \hat{\gamma}}{\partial (L/D \cos \hat{\phi})} + \frac{\partial \dot{Q}}{\partial \hat{h}} \frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})} \quad (21)$$

Both $\frac{\partial \dot{Q}}{\partial \hat{\gamma}}$ and $\frac{\partial \dot{Q}}{\partial \hat{h}}$ are simple algebraic expressions;

$\frac{\partial \hat{\gamma}}{\partial (L/D \cos \hat{\phi})}$ and $\frac{\partial \hat{h}}{\partial (L/D \cos \hat{\phi})}$ are available from the solutions to equations (7)-(9).

3. Integration Method

To reduce the number of function evaluations, a predictor-corrector integration method is used in the FPT-4D guidance routine. The predictor is the fourth-order Adams-Bashforth formula and the corrector is the fourth-order Adams-Moulton formula (see ref. 3). Four steps of a fourth-order Runge-Kutta method are used to start the method. The integration formulae are built into the guidance routine to eliminate calls to external modules. The predictor-corrector formulae together with nondimensionalization and proper factorization of the equations allows the integration to proceed very rapidly. A preliminary checkout run made 311 guidance calls in 111 seconds on the 1108. Simulations to date assume that the guidance is called every 3 seconds of real time. It is probable that lower-order integration formulae and larger integration stepsizes could be tolerated if necessary.

4. Crossrange Logic

Currently, integrated crossrange predictions are used as the basis for the crossrange guidance logic in the FPT-4D routine. The

9.12.3 Entry Guidance (cont'd)

differential equations used to calculate the crossrange are

$$\frac{d\hat{\psi}}{d\hat{v}} = \frac{1}{\hat{v}'} \left\{ \frac{1}{2} \hat{\rho}_0 \hat{v} e^{-\beta \hat{h} R_0} C_D \hat{S} \frac{L}{D} \sin \hat{\phi} + 2\hat{\omega}_e \sin \hat{i} \sin \hat{\mu} \right\} \quad (22)$$

$$\frac{d\hat{\lambda}}{d\hat{v}} = \frac{1}{\hat{v}'} \left\{ \hat{v} \sin \hat{\psi} \right\} \quad (23)$$

During each guidance pass, equations (22) and (23) are integrated using the most recent history multiplied by minus one. Thus the result of the integration is a prediction of the crossrange that would result if the sign of the roll command were reversed. A five-degree per second reversal rate (over the top) is assumed to improve the accuracy of the predicted reverse crossrange capability. The ratio of the vehicle's current crossrange to its reverse crossrange capability is used as the basis for commanding a roll reversal. The threshold values increase linearly as \hat{v} decreases. Typically, the threshold is set at 80% for $\hat{v} \approx .8$ and 100% for $\hat{v} \approx .15$. Accurate crossrange capability predictions obtained from integrating equations (22) and (23) allow large percentages of the crossrange capability to be 'used up' during each roll segment of the trajectory. The result is a minimization of the number of roll reversals required. Furthermore, the logic does not tend to command reversals in rapid succession near the end of the trajectory.

Several refinements are being examined. Most are directed toward improving the crossrange accuracy. Among these are compensation for the lag introduced by finite computation times and improved design of the switch curve. As suggested in Ref. (2), a stable downrange channel is not seriously affected by reversal commands from the crossrange logic. However, the downrange logic strongly affects crossrange accuracies because as downrange errors are nulled, crossrange capabilities are altered significantly. Several possibilities are being examined to minimize the downrange-to-crossrange interference.

REFERENCES:

- (1) Willoughby, J. K.: "FTP Guidance Subroutine,"
LEC/EAS/66, April 6, 1970.
- (2) Willoughby, J. K. and Rao, T. C.: A Study of
Alternative Guidance Concepts for Shuttle
Reentry, LEC Tech. Rept. 67542C/025402,
September, 1970.
- (3) Henricci, P.: Discrete Variable Methods in
Ordinary Differential Equations, J. Wiley &
Sons, Inc. New York, 1962.
- (4) Willoughby, J. K.: FTP Reentry Guidance,
LEC Memo 67542B/036201, December 30, 1970.

SPACE SHUTTLE

GN&C SOFTWARE EQUATION SUBMITTAL

Software Equation Section Deorbit and Entry Submittal No. 1

Function Reentry Autopilot

Module No. OC5 Function No. -1, -3 (MSC 03690)

Submitted By: G. L. Zacharias Co. MSC/GCD
(Name)

Date: December 2, 1970

NASA Contact: W. H. Peters Organization EG2
(Name)

Approved by Panel III K. J. Cox ^{*K.J. Cox*} Date December 2, 1970
(Chairman)

Summary Description: The objective of the autopilot is to provide attitude control of the vehicle from deorbit to transition. Control implies following the roll commands from guidance about wind velocity vector, maintaining trim angle of attack and maintaining zero sideslip angle. No direct control is exercised over the pitch angle and roll is controlled by yawing the vehicle.

Shuttle Configuration: (Vehicle, Aero Data, Sensor, Et Cetera) Low L/D vehicle, angular rates and sideslip angle and rate available, control torques from RCS jets only, negligible aerodynamic torques.

Comments: _____

(Design Status) _____

(Verification Status) Some preliminary simulations have been performed.

Panel Comments:

9.12.4 Reentry Autopilot

1. INTRODUCTION

The objective of the Reentry Autopilot is to provide attitude control of the vehicle from deorbit to transition. Control in this case implies following the roll commands from guidance about the wind velocity vector, maintaining the trim angle of attack and maintaining zero sideslip angle. No direct control is exercised over the pitch angle, however pitch rate damping is used. Roll is controlled by yawing the vehicle. The present autopilot has been designed for velocities only as low as Mach 5 but efforts are being made to extend this to include velocities as low as Mach 2.

Nomenclature

B	Scaled value of sideslip angle (β)
I_{xx}, I_{yy}, I_{zz}	Moments of inertia about principal axes
p, q, r	Body angular rates about the x, y, z axes
\mathcal{R}	Roll error
R	Roll rate (about \underline{v})
R_c	Roll commands from guidance
U_x, U_y, U_z	RCS control accelerations ($U_x = \tau_x / I_{xx}$)
\underline{v}	Relative wind velocity
X_B, Y_B, Z_B	Body axis system
α	Angle of attack
α_T	Trim angle of attack
β	Sideslip angle
Δ	Pitch rate deadband
τ_1, τ_2	Computed switch times
τ_x, τ_y, τ_z	RCS roll torques about body axes

9.12.4 Reentry Autopilot (cont'd)

2. FUNCTIONAL FLOW DIAGRAM

The chronological sequencing of functions performed by the Reentry Autopilot is described in this section and illustrated by the functional flow diagram in Figure 1.

The Reentry Autopilot assumes control after deorbit has been performed. It is assumed that the trim angle of attack has been achieved. The first function performed is to process any roll commands and monitor the vehicle roll rate. The necessary roll jet on-times are computed on the basis of these inputs. Next, the roll coordinator portion of the autopilot is executed. Sideslip control is coordinated with roll control and the body roll acceleration U_x is chosen to aid in a coordinated roll. During roll rate hold (i.e., $U_z = 0$), sideslip and sideslip rate are directly controlled in the next portion of the autopilot. Finally, the pitch rate control commands are computed in the last portion of the autopilot.

3. PROGRAM INPUT-OUTPUT

The required inputs to the Reentry Autopilot are roll commands and actual roll angle, sideslip angle and sideslip angle rate, body angular rates, and the RCS control accelerations. It is possible that the autopilot may be able to estimate its own accelerations based on some parameter such as mass. The outputs of this autopilot are predicted jet on-time histories for the various RCS jets.

Input Parameters

q	Body angular pitch rate
R	Roll angle about \underline{y}
R_c	Roll angle command
r	Body angular roll rate

9.12.4 Reentry Autopilot (cont'd)

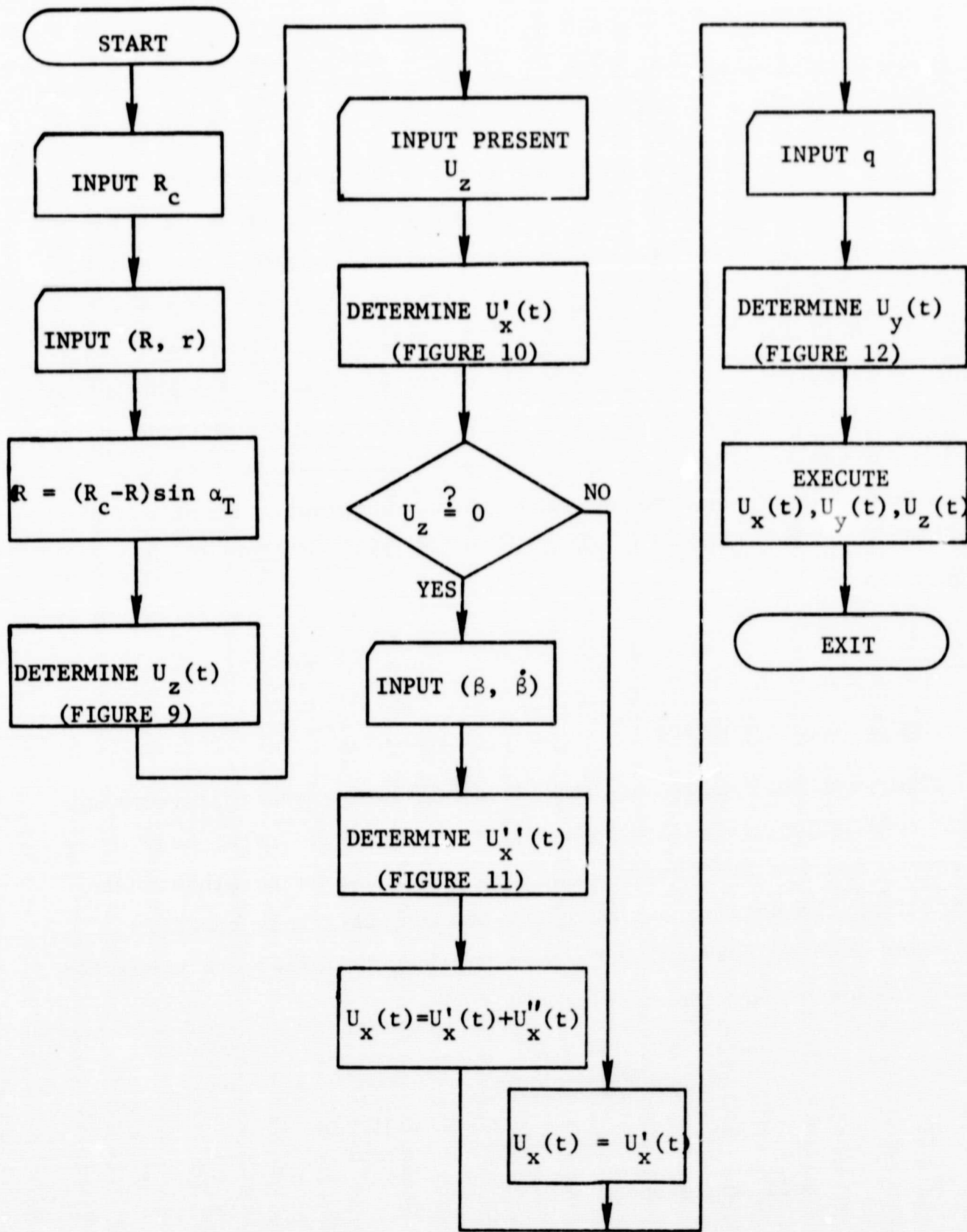


Figure 1. Functional Flow Diagram

9.12.4 Reentry Autopilot (cont'd)

U_z	RCS control acceleration about Z-body axis
β	Sideslip angle
$\dot{\beta}$	Sideslip angle rate
Δ	Pitch rate deadband

Output Parameters

$U_x(t)$	Predicted X-axis jet firings
$U_y(t)$	Predicted Y-axis jet firings
$U_z(t)$	Predicted Z-axis jet firings

4. DESCRIPTION OF EQUATIONS

The Reentry Autopilot is divided into four sections, the roll controller, the roll coordinator, sideslip controller and the pitch rate damper. The following four sections describe the equations for each of the sections of the autopilot. Figure 2 contains a description of the coordinate system and variable definition. The system block diagram is illustrated in Figure 3.

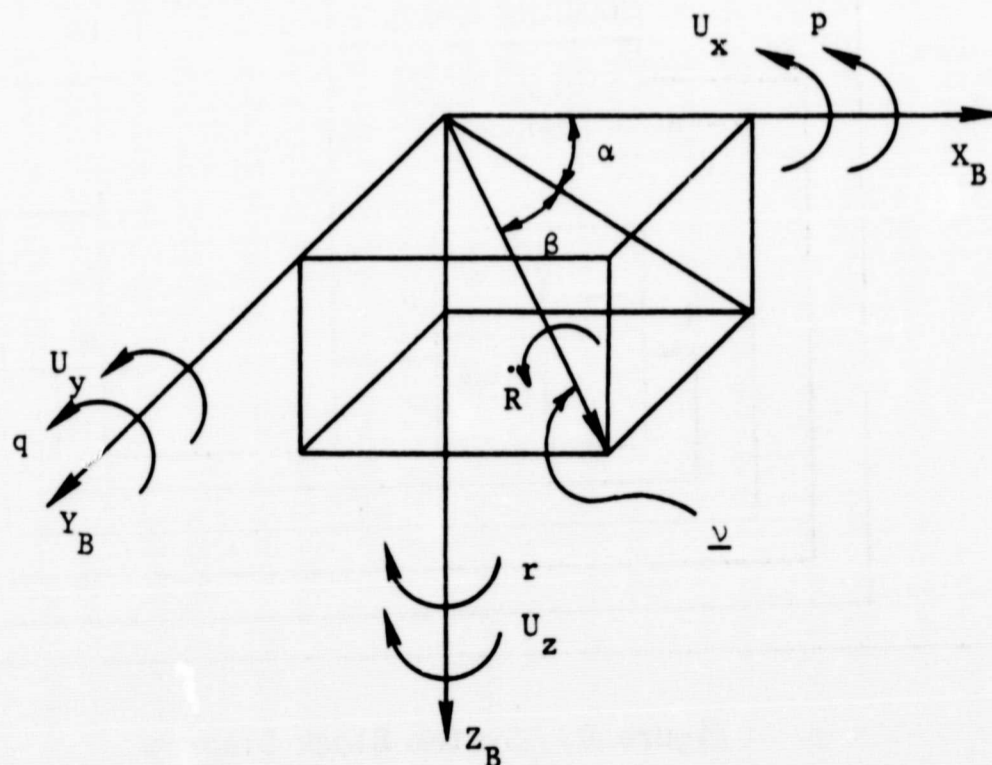


Figure 2. Coordinate System and Variable Definition

9.12.4 Reentry Autopilot (cont'd)

4.1 Roll Controller

The following four assumptions are made for the roll dynamics:

- 1) The sideslip angle (β) is zero
- 2) The vehicle is trimmed in angle of attack ($\alpha = \alpha_T$)
- 3) There is negligible inertia cross-coupling ($I_{xz} \approx 0$)
- 4) There are negligible aerodynamic torques about the Z-axis

Based on the above assumptions and the coordinate system defined in Figure 2, it can be shown that the dynamics are given by:

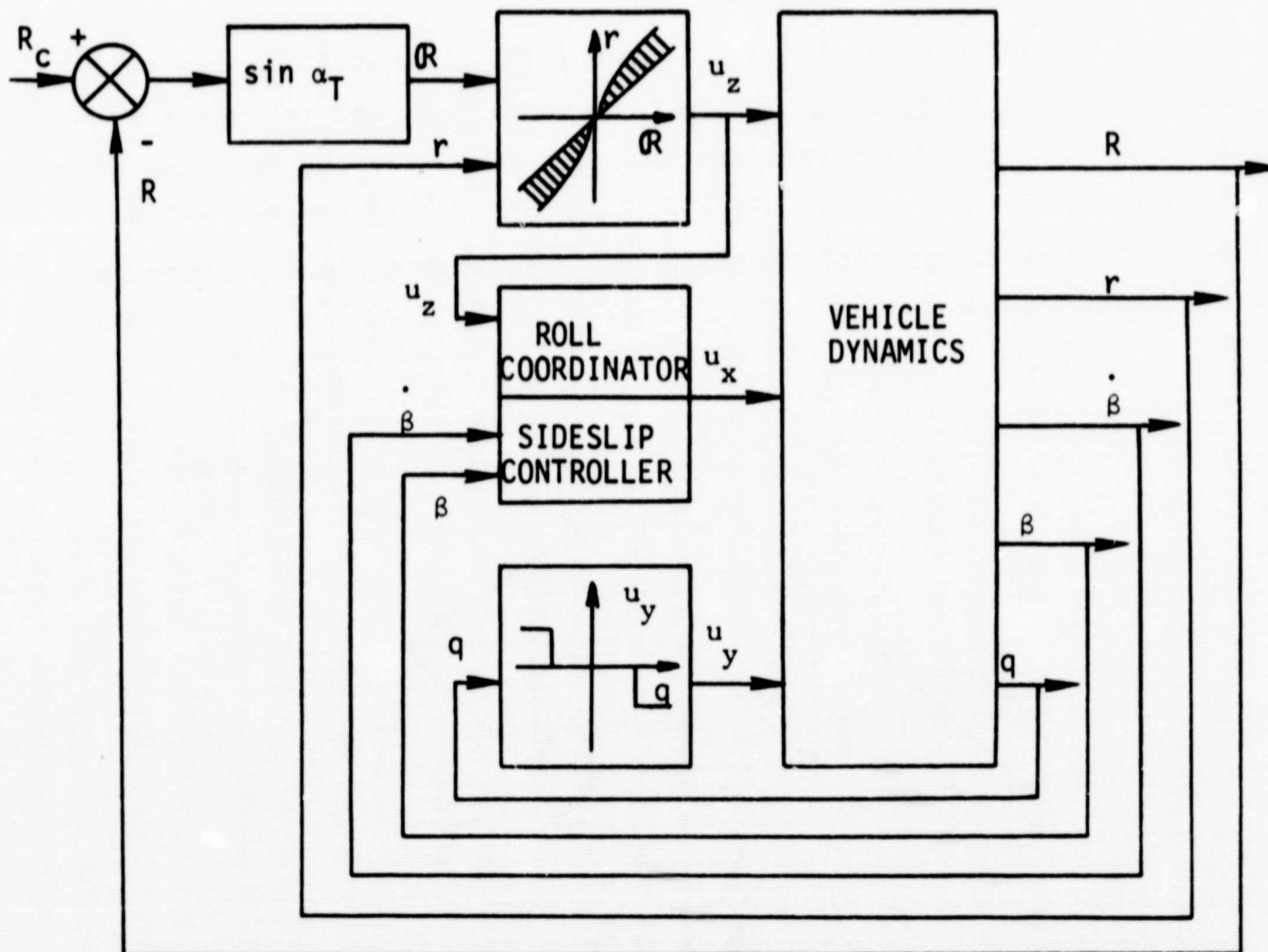


Figure 3. System Block Diagram

9.12.4 Reentry Autopilot (cont'd)

$$\dot{R} \sin \alpha_T = r$$

$$r = U_z$$

The roll error, \mathcal{R} , is defined by:

$$\mathcal{R} = (R_c - R) \sin \alpha_T$$

where R_c is commanded by guidance.

Substituting the expression for the roll error into the dynamic equations yields:

$$\dot{\mathcal{R}} = -r$$

$$r = U_z$$

The above results indicate that an appropriate model for the vehicle dynamics is that of a double integrator. With double integrator dynamics, parabolic switch logic may then be used in the (\mathcal{R}, r) phase plane. That is, the state trajectory under the influence of a constant acceleration will be a parabola in the phase plane. A typical phase plane and trajectory are shown in Figure 4.

Given an initial error and error rate (\mathcal{R}_0, r_0) , the phase plane switch points may be computed. Then, using the simplified dynamic modeling, the switch times (T_1, T_2, T_3) may be computed. Thus, the roll controller predicts the necessary control history $U_z(t)$ to drive the errors to zero.

9.12.4 Reentry Autopilot (cont'd)

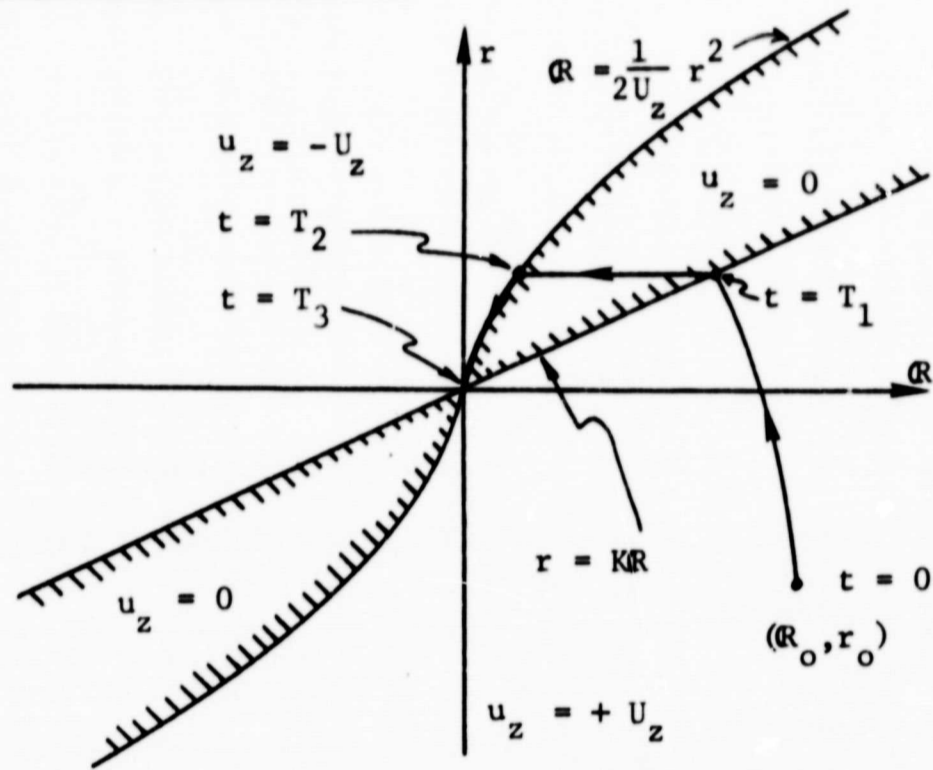


Figure 4. Roll Control Phase Plane

4.2 Roll Coordinator

A typical phase plane trajectory for a roll maneuver was shown in Figure 4. In this example, the Z-axis jets fired in a positive sense from 0 to T_1 , were off from T_1 to T_2 and fired in a negative sense from T_2 to T_3 . This typical U_z thrust-coast-thrust sequence during a roll maneuver is depicted in Figure 5.

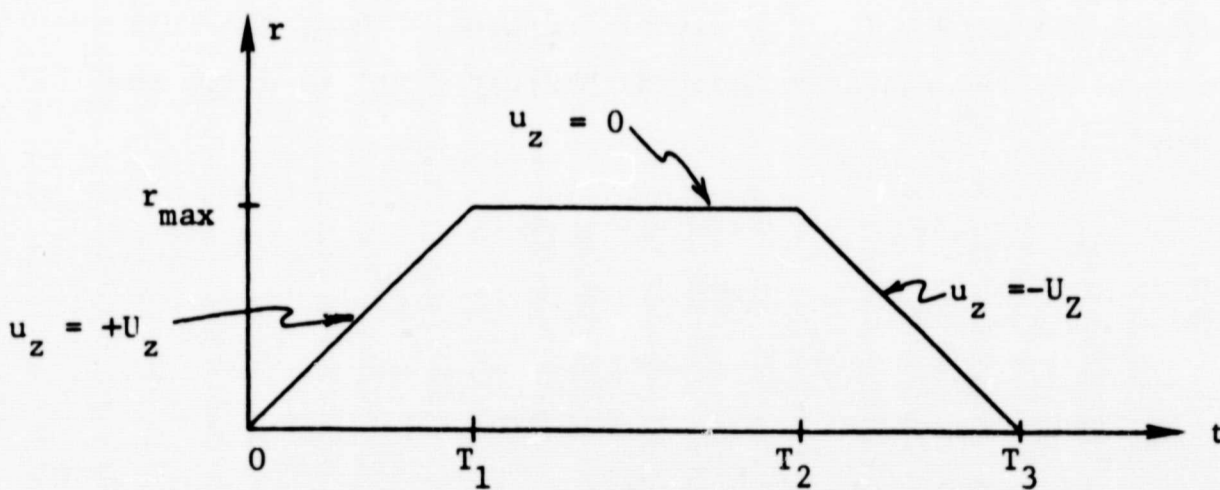


Figure 5. Typical Jet History for Roll Maneuver

9.12.4 Reentry Autopilot (cont'd)

Sideslip control is achieved through the use of a dual-mode controller. The two modes of operation are:

- 1) When $U_Z \neq 0$, the body roll acceleration U_X is chosen in a way such as to aid in a coordinated roll.
- 2) When $U_Z = 0$ (roll rate hold), sideslip and sideslip rate are directly controlled.

The second of these modes is covered in Section 4.3 and the first mode is discussed herein.

A necessary condition for zero sideslip is:

$$p(t) = (\cot \alpha_T) r(t) \text{ for all } t.$$

During the time interval $[0, T_1]$, this relation is approximated by choosing the U_X pulse width, Δt , to satisfy:

$$p(T_1) - p(0) = U_X \Delta t$$

where $p(T_1)$ is computed from

$$p(T_1) = r(T_1) (\cot \alpha_T) = r_{\max} (\cot \alpha_T)$$

r_{\max} is the maximum value of the Z-body angular rate obtained from the U_Z roll firing. The U_X pulse is then centered about $T_1/2$ as shown in Figure 6. A similar choice is made for the interval $[T_2, T_3]$.

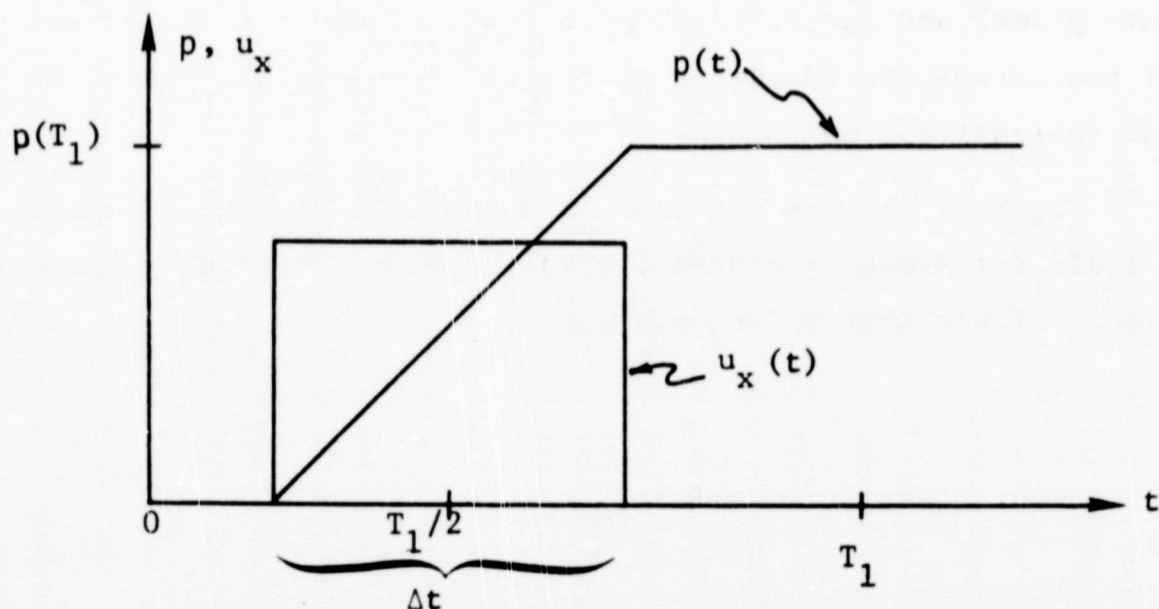


Figure 6. Jet History for Coordinated Roll

9.12.4 Reentry Autopilot (cont'd)

4.3 Sideslip Controller

During the periods of roll rate hold ($\dot{\omega}_r \approx 0$), sideslip and sideslip rate may be directly controlled. A simplified oscillator model of the sideslip dynamics may be derived from the linearized lateral equations of motion. Restricting attention to the hypersonic regime ($M \geq 5$), all aerodynamic torques except $C_{\ell\beta}$ are assumed to be zero, since those that do not contribute to damping are negligible. Further, if the cross product of inertia I_{XZ} is neglected, the following approximation results:

$$\ddot{\beta} + \omega^2 \beta = U$$

where

$$\omega^2 \equiv - (\hat{q} S_b / I_{xx}) C_{\ell\beta} \sin \alpha_T$$

$$U \equiv U_X \sin \alpha_T$$

By defining the variable \mathcal{B} , where

$$\mathcal{B} \equiv \omega\beta$$

the $(\mathcal{B}, \dot{\beta})$ phase plane trajectories are circles, and the switch curves may be obtained using conventional optimal control techniques. The cost function used in determining the switch curves is a weighted function of the time-optimal and fuel-optimal solutions. The exact shapes and placement of the curves are functions of the relative weights placed on the time and fuel-optimal solutions.

Figure 7 shows a straight line approximation to a typical optimal switch logic for sideslip control; also shown is a typical phase plane trajectory. (Note that $U \equiv U_X \sin \alpha_T$).

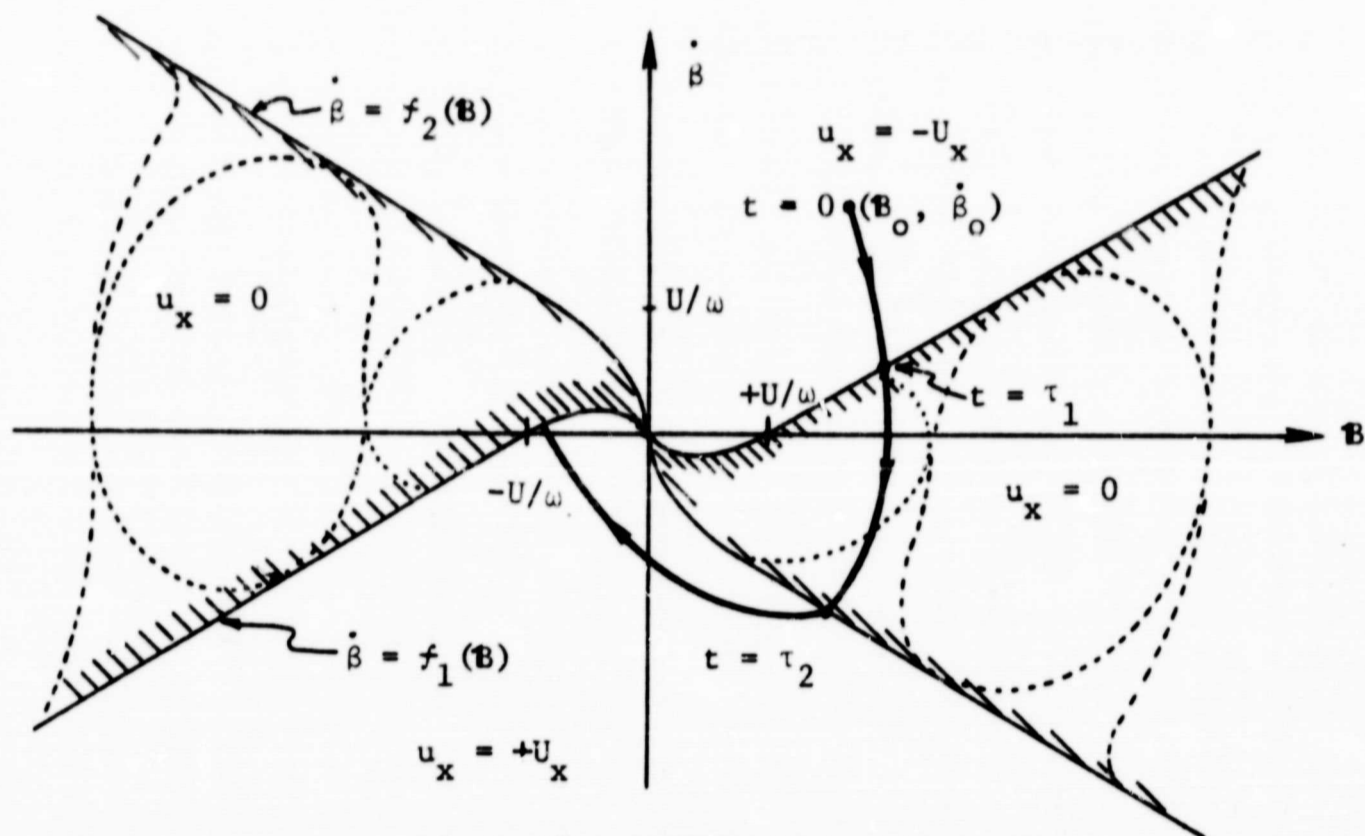


Figure 7. Sideslip Logic

Given an initial error and error rate $(\beta_0, \dot{\beta}_0)$, the phase plane switch points may be found. Then, using the oscillator modeling, the switch times (τ_1, τ_2, \dots) may be computed. Thus, the sideslip controller predicts the necessary control history $U_x(t)$ to drive $(\beta, \dot{\beta})$ to $(0, 0)$.

4.4 Pitch Rate

The pitch rate damper control logic is based on the assumption that the pitch rate, q , is uncoupled from the lateral dynamics. The control law is:

- 1) If $|q| \geq \Delta$ fire U_y to oppose the rotation
- 2) If $|q| < \Delta$ do not fire U_y

where Δ is the pitch rate deadband.

Graphically, this control law is depicted in Figure 8. Note that the pulse time may be predicted from

$$\Delta t = |q| / U_y$$

9.12.4 Reentry Autopilot (cont'd)

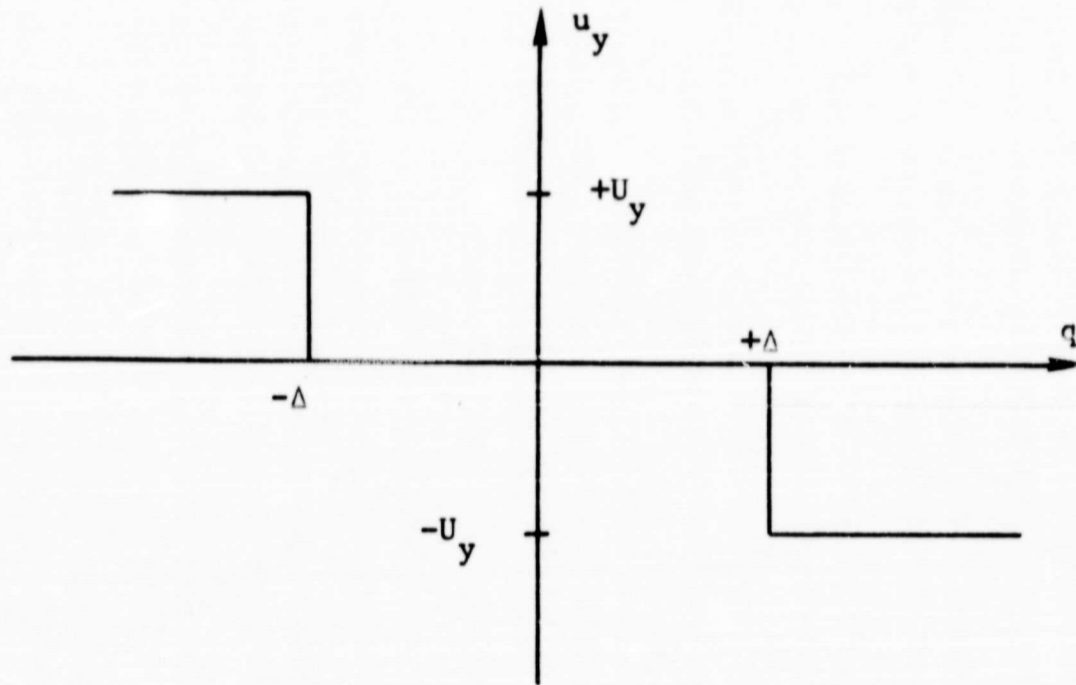


Figure 8. Pitch Rate Damper

5. DETAILED FLOW DIAGRAMS

This section contains the detailed flow diagrams for the roll controller, roll coordinator, sideslip controller and the pitch rate damper portions of the Reentry Autopilot. The overall flow diagram contained in Figure 1 indicates how the individual controllers fit into the overall flow.

9.12.4 Reentry Autopilot (cont'd)

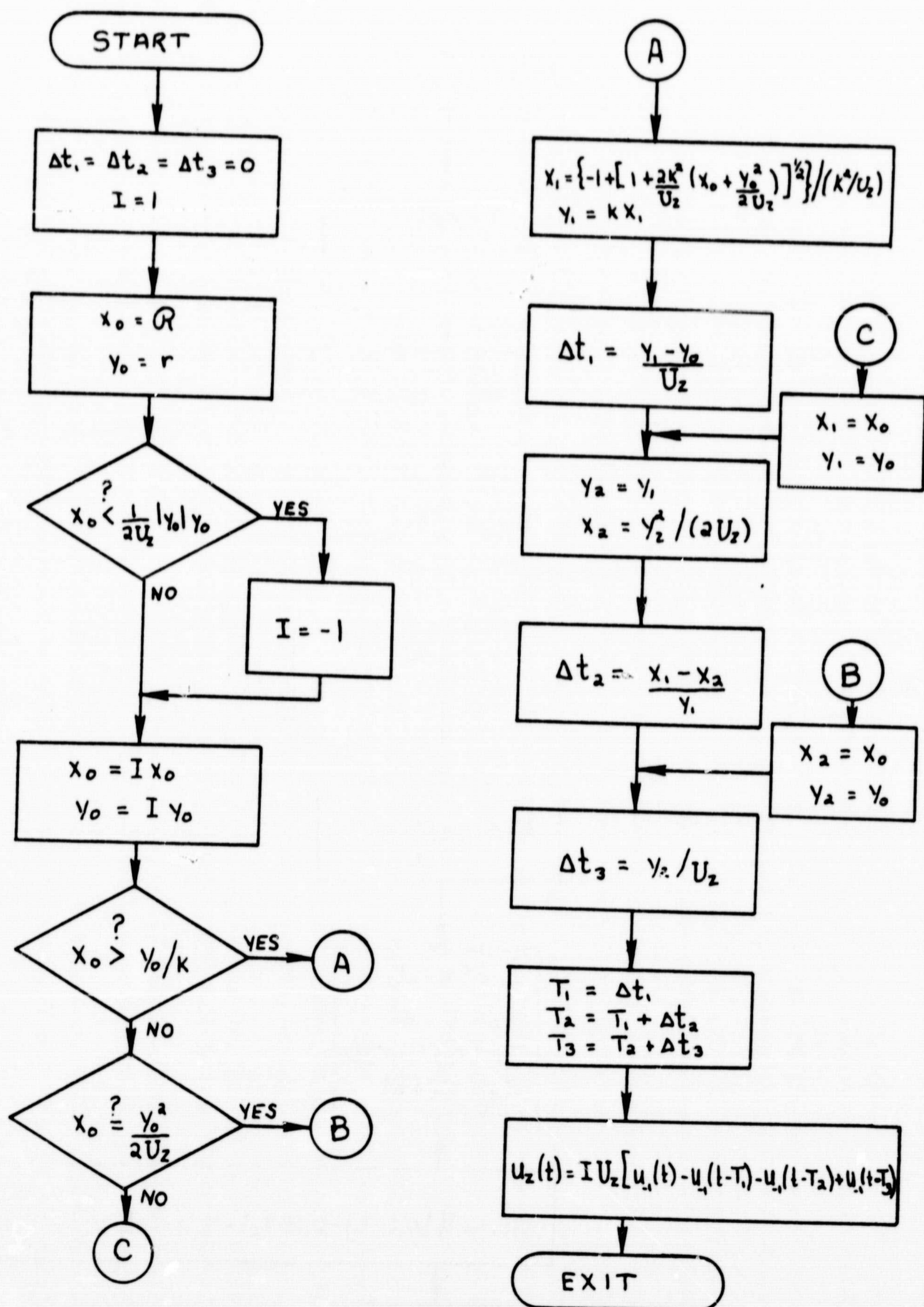


Figure 9. Detailed Flow Diagram, Roll Control

9.12.4 Reentry Autopilot (cont'd)

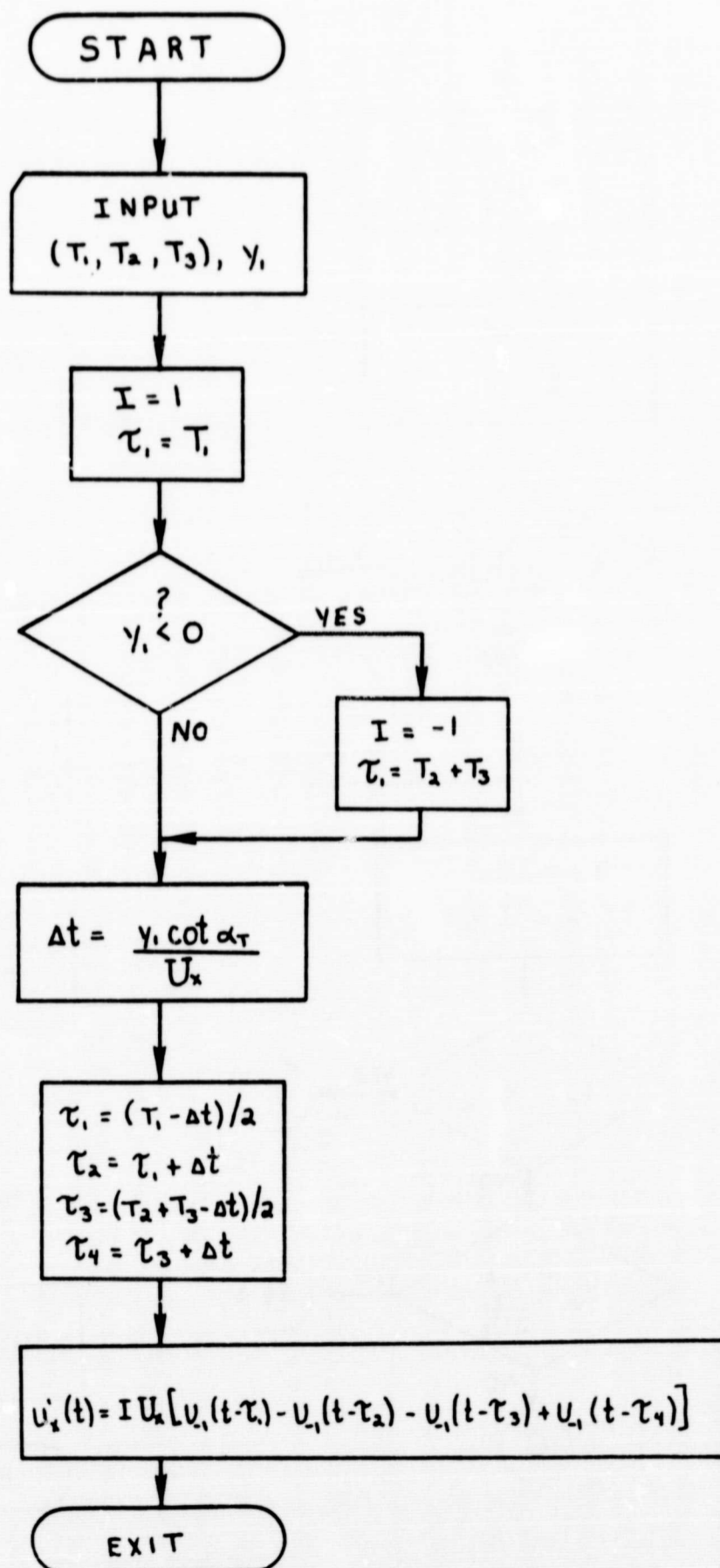


Figure 10. Detailed Flow Diagram, Roll Coordinator

9.12.4 Reentry Autopilot (cont'd)

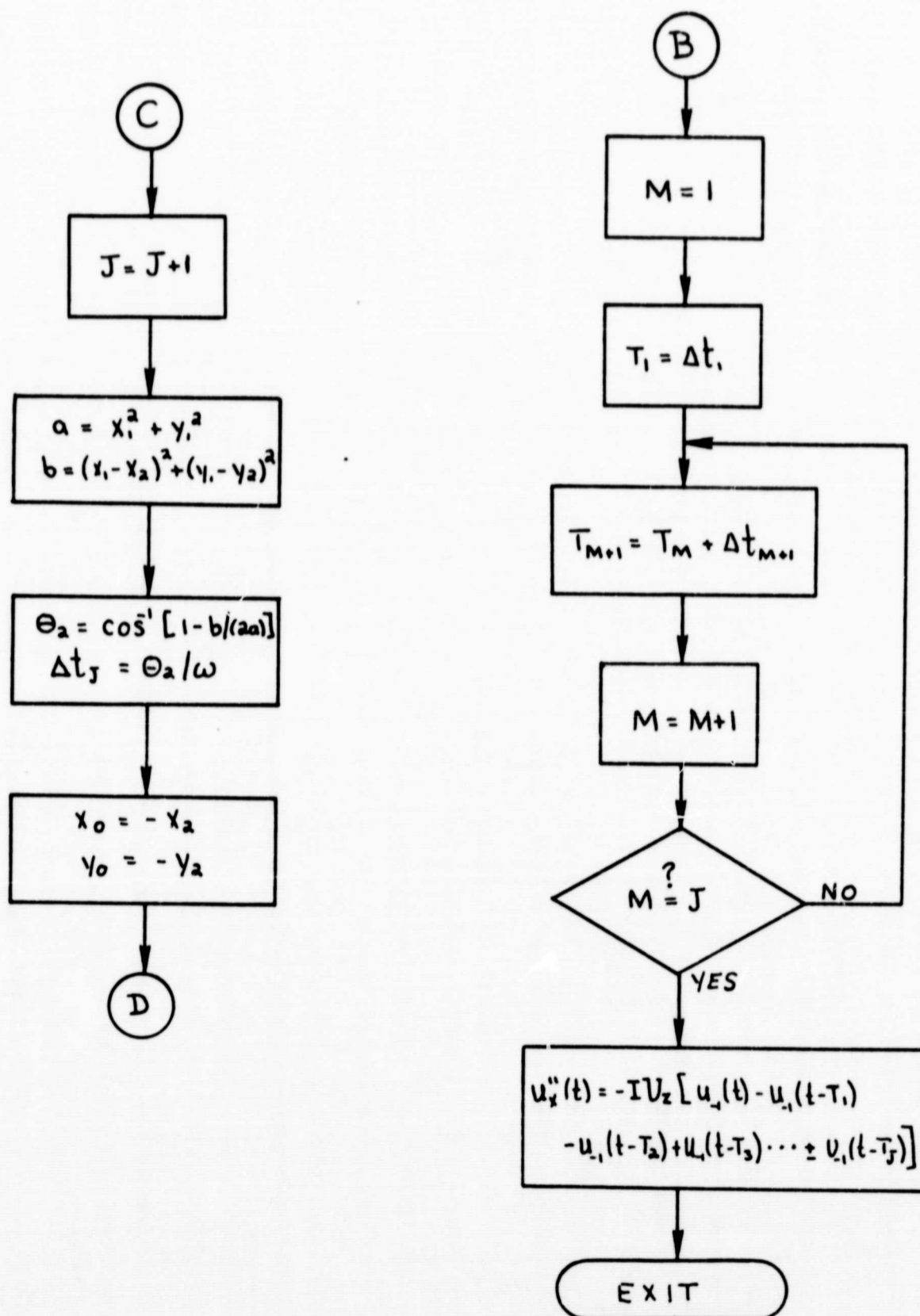


Figure 11b. Detailed Flow Diagram, Sideslip Control

9.12.4 Reentry Autopilot (cont'd)

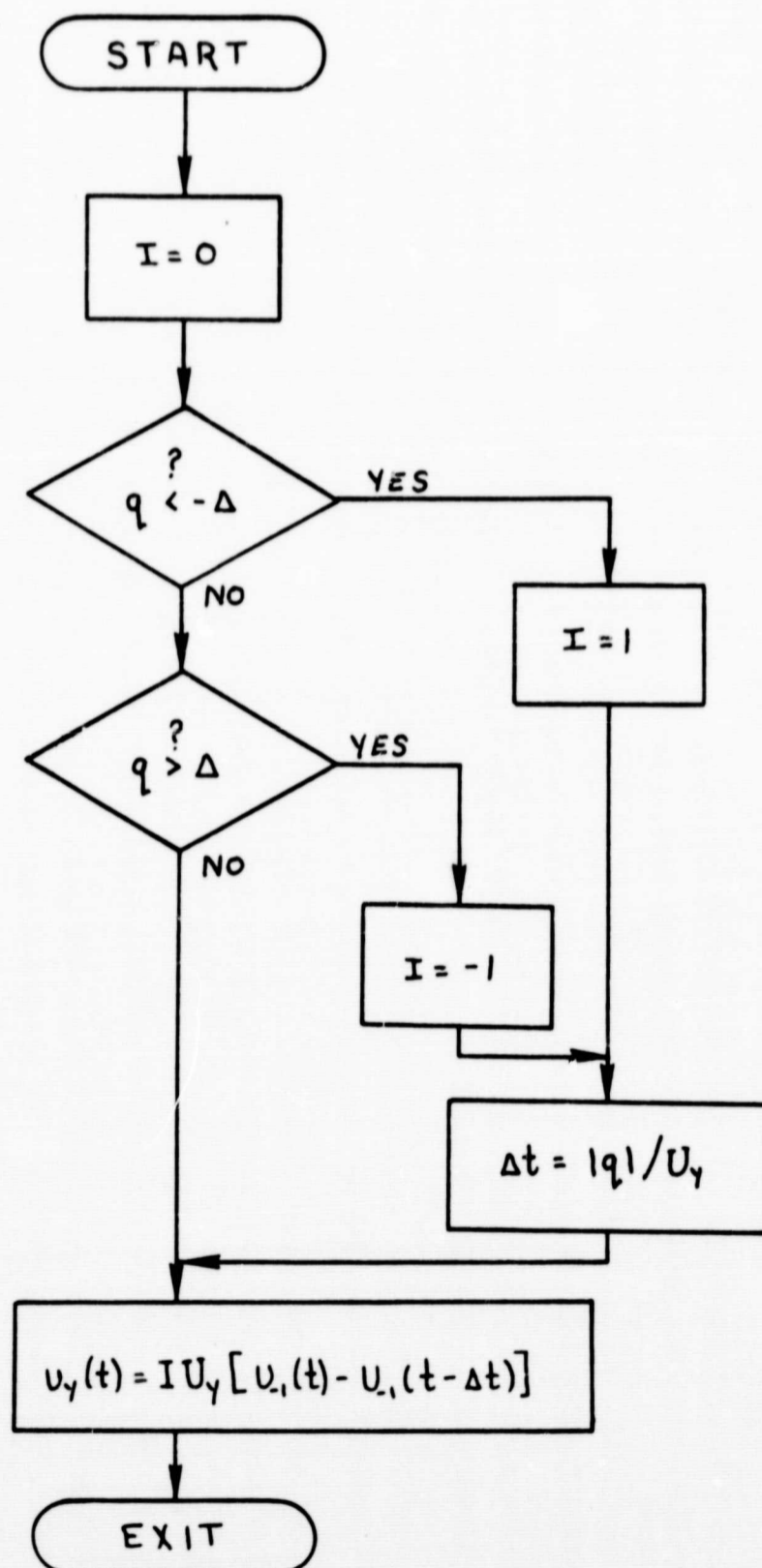


Figure 12. Detailed Flow Diagram, Pitch Rate Damper

9.12.4 Reentry Autopilot (cont'd)

REFERENCES

1. Zacharias, G. L., Unpublished presentation "Preliminary Baseline Design for Reentry Autopilot."

9.13 TRANSITION

The transition phase starts at the end of the entry phase just prior to the pitchover from a high angle of attack to the cruise angle of attack. This period of pitchover constitutes the transition phase. The transition phase ends with the attainment of the nominal cruise angle of attack. Two distinct functions which are performed during this are:

1. Transition from entry control which is basically RCS attitude control to cruising flight control, which is basically full aerodynamic control.
2. Transition from entry angle of attack (high α) to cruising angle of attack (low α).

The GN&C software functions to be performed during this phase are:

1. State advancement during specific force sensing.
2. Control transition maneuver from high angle of attack entry profile to low angle of attack cruise profile.
3. Provide aerodynamic control (RCS backup).
4. Initiate cruise engine commands.
5. Initiate cruise navigation and control.

A flow of software functions during transition appears in Figure 1.

Open Items

The following items constitute areas where requirements and/or systems implementation are unclear and may have significant impact on the GN&C software:

1. Vehicle stability characteristics during transition must be defined.
2. The control effectiveness of the RCS jets and the aerodynamic surfaces under the conditions encountered from entry to cruise must be defined in order to determine their use during transition.

9.13 TRANSITION (cont'd)

3. The transition sensor configuration must be defined.

Transition Equations

Baseline equations have not been approved by the GN&C Software Equation Formulation and Implementation Panel. The following reference is provided to identify the work which has been done.

1. MIT "Task 11 - Digital Autopilot For SSV Orbiter Transition," R. F. Stengel, dated December 16, 1970.

9.13.1 Transition Attitude Control (TBD)

9.13.1 Transition Attitude Control (cont'd)

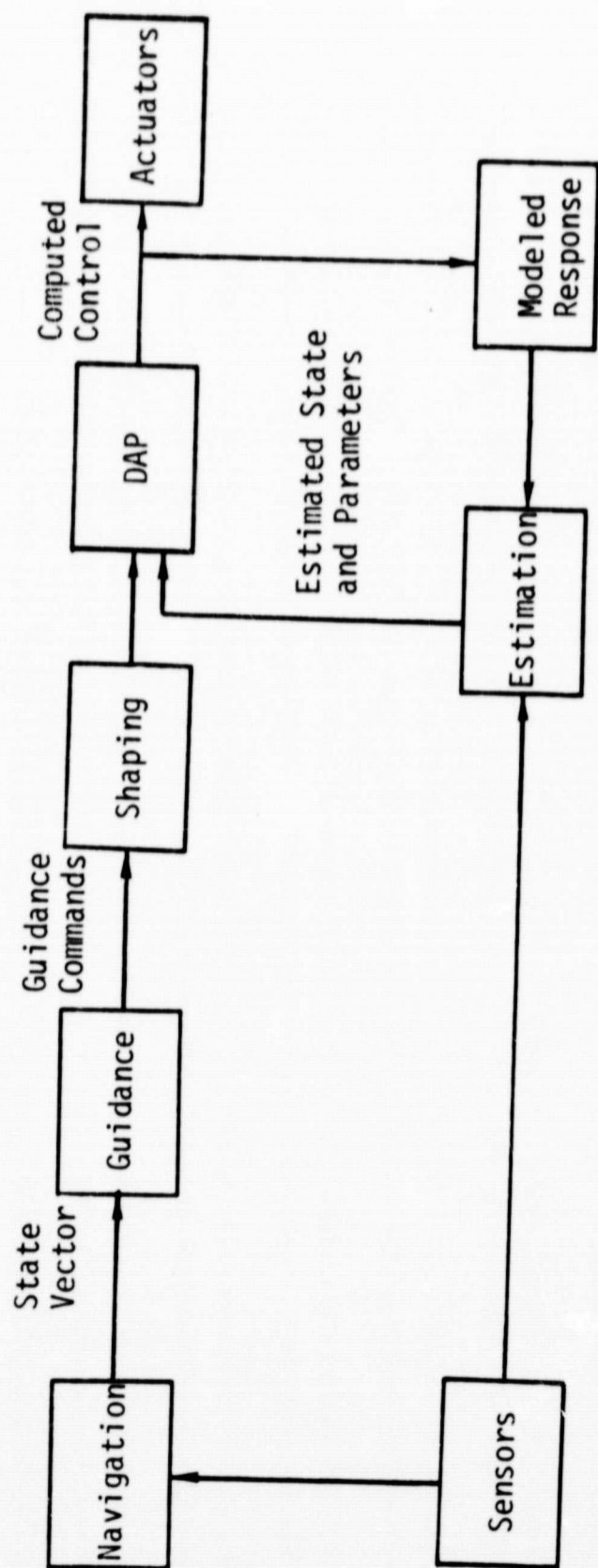


FIGURE 1

FLOW OF SOFTWARE FUNCTIONS DURING TRANSITION

9.14 CRUISE AND FERRY CRUISE

The Cruise and Ferry Cruise phases of the Shuttle apply to the atmospheric powered, constant altitude flight conditions prior to final descent to terminal landing. This phase includes low altitude earth-relative navigation and guidance and aerosurface control. The SW functions required in this mission phase are the following:

1. Powered flight navigation augmented by external data to maintain earth-relative position.
2. Powered flight guidance resulting in thrust level control and autopilot (attitude) commands required to achieve desired intersection with terminal approach navigation for landing.
3. Autopilot computations to result in proper aerodynamic surface control and trim settings, to maintain desired heading and altitude.

Figure 1 displays a functional flow diagram of the Cruise and Cruise Ferry Software Functions.

9.14.1 Navigation (TBD)

9.14.2 Guidance (TBD)

9.14.3 Attitude Control (TBD)

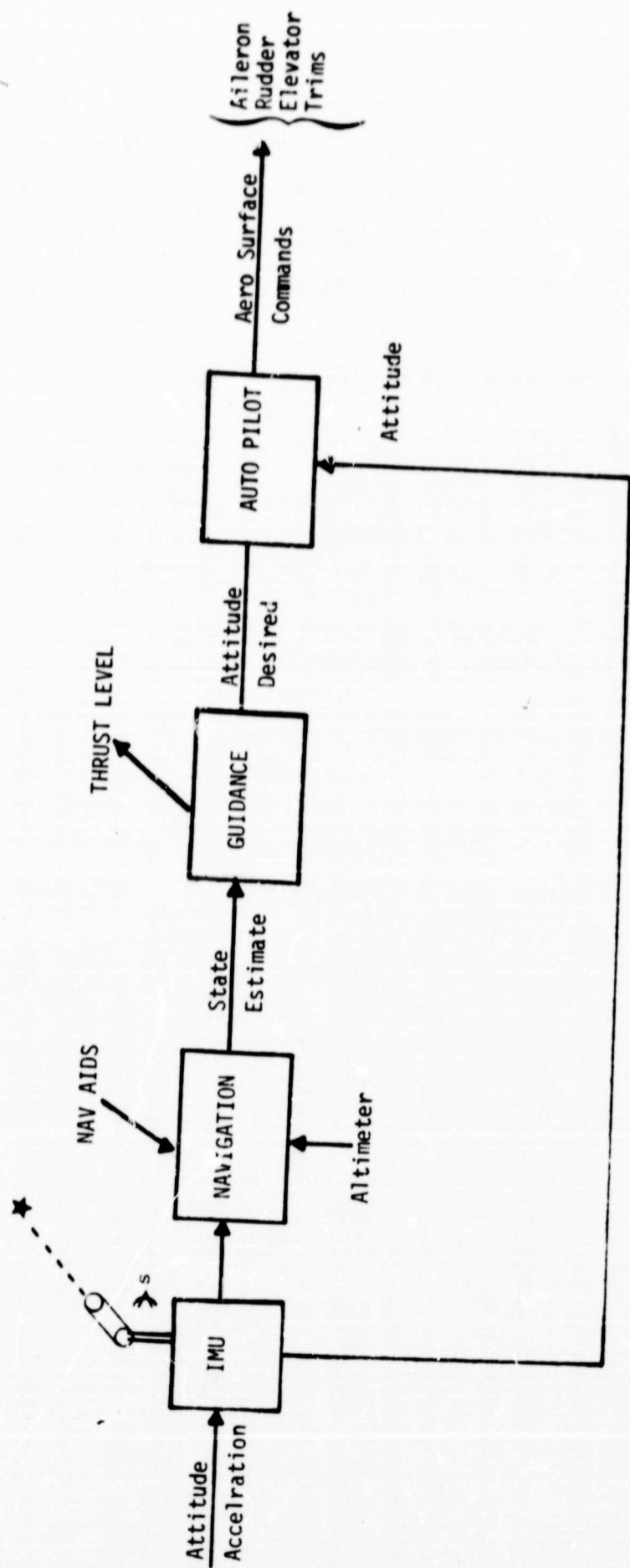


FIGURE 1. FUNCTIONAL FLOW DIAGRAM FOR CRUISE AND FERRY

9.15 APPROACH AND LANDING

"Approach" begins as the shuttle advances to the vicinity of the landing site with the appropriate position, velocity and attitude for landing and has gained acquisition of the ground transponders located at the landing site. Landing begins at touchdown and continues until the craft reaches ground taxi speed. The GN&C software functions to be performed during this phase are:

1. Approach navigation using measurements from the IMU and the ground transponders. Both the shuttle state and the landing site state may be estimated.
2. Approach and landing guidance resulting in commands to the autopilot (attitude), thrust throttle commands, braking and/or lift flap commands.
3. Autopilot computations to compute control surface commands in order to achieve the command attitude.

Figure 1 displays a functional flow diagram of the Approach and Landing GN&C Software functions.

Open Items

The following items constitute areas where requirements and/or system implementation are unclear and may have significant impact on the GN&C software:

1. Approach navigation accuracy requirements have not been established.
2. A capability to automatically guide during taxi under "blind" conditions must be established as a requirement or not a requirement.

9.15.1 Navigation (TBD)

9.15.2 Guidance (TBD)

9.15.3 Attitude Control (TBD)

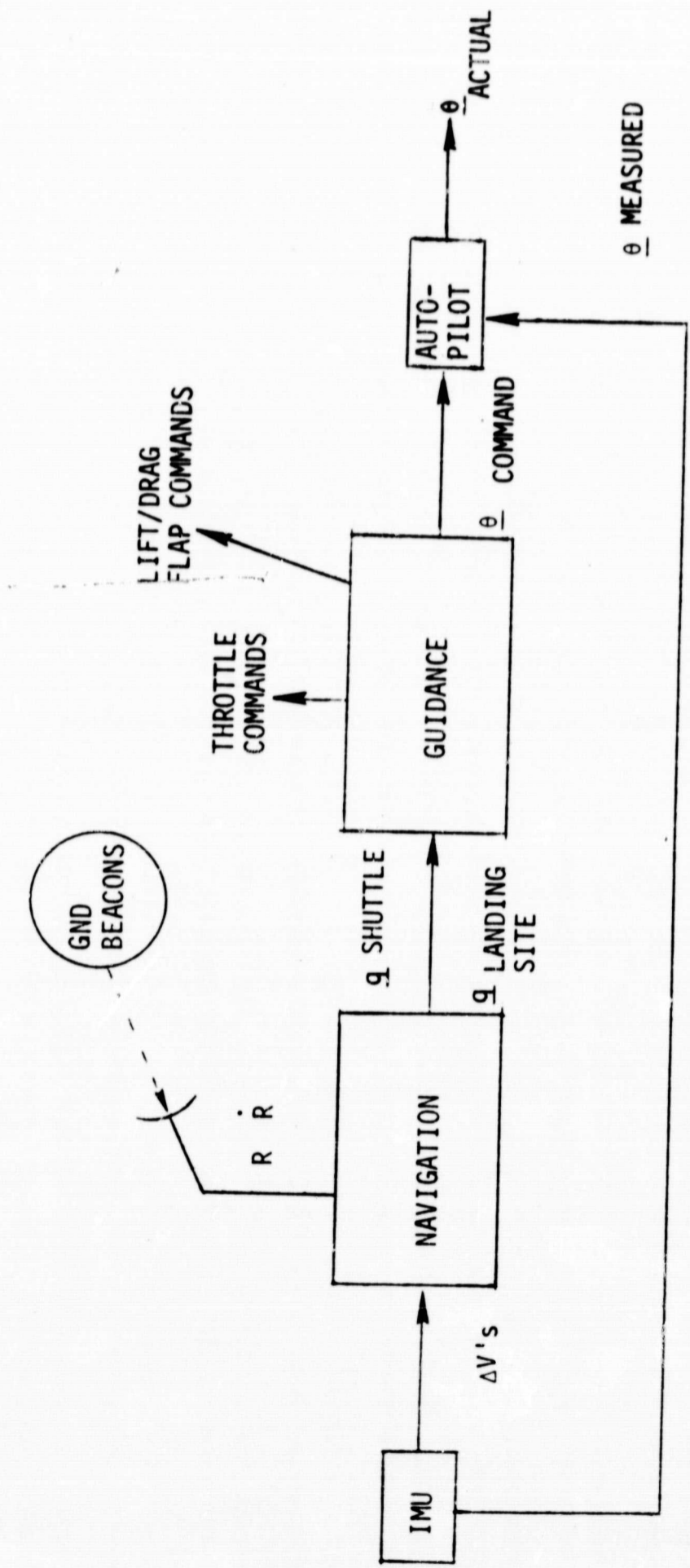


FIGURE 1. FUNCTIONAL FLOW DIAGRAM OF GN&C SOFTWARE FUNCTIONS DURING APPROACH AND LANDING

9.16 HORIZONTAL TAKEOFF (TBD)

9.17 COMMUNICATIONS AND POINTING (TBD)

9.18 FAILURE DETECTION (TBD)