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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PROJECT/SPACE SHUTTLE

SPACE SHUTTLE GUIDANCE, NAVIGATION AND CONTROL DESIGN EQUATIONS

VOLUME I

APRIL 15, 1971

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

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NASA SPACE SHUTTLE PROGRAM WORKING PAPER

SPACE SHUTTLE GUIDANCE, NAVIGATION AND CONTROL DESIGN EQUATIONS

VOLUME I

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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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 for

Maxime A. Faget
Director of Engineering and Development

FOREWORD

This is the initial issue of this document and the equations included only partially fulfill the GN&C requirements. Equations will be added as they are developed and approved by the Guidance and Control Division - GN&C Software Equation Formulation and Implementation Panel. Equations may be submitted to this panel by anyone. They are then assessed by an independent reviewer and the evaluation presented to the panel. Approved equations are then incorporated into this document.

The GN&C Design Equations Document is the result of the efforts of many people from NASA and support contractors. The following companies have made contributions:

a. TRW Systems Group, Inc., Houston Operations

b. MIT/Charles Stark Draper Laboratory

c. Lockheed Electronics Co., Inc., Houston Aerospace Systems Division

The following individuals have made contributions to this document;

Coordination, editing and writing

E. E. Smith, Jr., EG2	D. K. Phillips, TRW
C. F. Lively, Jr., EG2	R. L. Haken, TRW
R. Lee, TRW	C. W. Clark, TRW

Design Equation submittals

Lt. G. L. Zacharias, EG2	G. M. Levine, MIT/DL
J. N. Sunkel, EG2	W. M. Robertson, MIT/DL
E. T. Kubiak, EG2	E. S. Muller, Jr., MIT/DL
J. P. Higgins, MIT/DL	R. E. Phillips, MIT/DL
J. H. Suddath, EG2	W. H. Tempelman, MIT/DL
T. J. Brand, MIT/DL	P. M. Kachmar, MIT/DL
E. P. Blanchard, MIT/DL	

FOREWORD (con't)

Panel Members

K. J. Cox, EG2
C. F. Lively, Jr., EG2
W. H. Peters, EG2
J. H. Suddath, EG2
E. E. Smith, Jr., EG2
J. A. Lawrence, EG3
P. E. Sollack, EG4
C. E. Manry, EG5
R. Reid, EG6
C. T. Hackler, EG7
R. O. Nobles, FM7
A. W. Hambleton, FD35

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VOLUME VI - CONSTANTS AND KEYBOARD ACCESSIBLE PARAMETERS

1. 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.

2. SCOPE

This is Volume I 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.

3.0 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.

4. DEFINITION OF TERMS

Because of the large number of abbreviations and terms contained within this document, the abbreviations and terms used in the equations are listed in Section 9 with the applicable equations.

5. REFERENCE DOCUMENTS

The reference sources from which data are compiled include the following:

a. MSC-03690, "Project/Space Shuttle, Space Shuttle Guidance, Navigation and Control Software Functional Requirements," 12 October 1970.

b. Minutes of Guidance and Control Division Panel III Meetings - GN&C Software Equation Formulation and Implementation Panel.

c. MSC-03439, "Space Shuttle Orbiter GN&C Design Data Book," 6 October 1970.

d. EG7-70-120, "Shuttle GN&C Baseline System," 10 November 1970.

e. Lockheed Technical Report 67542D/032201, "Space Shuttle Functional Simulator Detailed Design Specifications," 2 November 1970.

f. MSC-02542, "Typical Shuttle Mission Profiles and Attitude Timelines, Volume I-Space Station Resupply Missions," 23 June 1970.

g. MSC-02542, "Typical Shuttle Mission Profiles and Attitude Timelines, Volume II-Four Scientific Support Missions," 28 September 1970.

h. MSC-02542, "Typical Shuttle Mission Profiles and Attitude Timelines, Volume III-First 10 Shuttle Missions," 11 December 1970.

i. MSC-02542, "Typical Shuttle Mission Profiles and Attitude Timelines, Volume IV-Four Shuttle Mission Profiles," 1 March 1971.

j. Derivation of GN&C equations. References are made to applicable studies in the "Submittal Status Sheets" for the equations contained within this document.

Other applicable reference sources yet to be published include:

a. Vehicle and environmental data

- Error models
- Mass properties
- Propulsion models

b. Simulation specifications, descriptions and user's guides.

6. GN&C SYSTEM DESCRIPTION

The Baseline GN&C System description is included here to define the hardware configuration assumed for these equations (where a dependency on the hardware might exist). Figure 6-1 summarizes the GN&C baseline system as of the writing of this document. This system is based on Reference Document d. A computer capability (Block 1) for the GN&C system (which may be several computers or part of a single centralized computer) is assumed as part of the Data Management System along with a four gimbal inertial platform (Block 2). The transponder ranging system (Block 5) may prove feasible as a navigation aid for boost, orbital coast, cooperative target rendezvous, cruise, approach and landing. The uncooperative target rendezvous mission will require another sensor (Block 6) which is assumed to be in the payload. The optical sensor (Block 3) will be used for IMU alignment as well as a rendezvous navigation aid with a sun-lit or flashing-light target vehicle. Although a station keeping and docking sensor (Block 8) is not yet baselined, such a sensor was assumed in the docking control equations of this document. The components shown enclosed in dashed lines do not have firm requirements established for them.

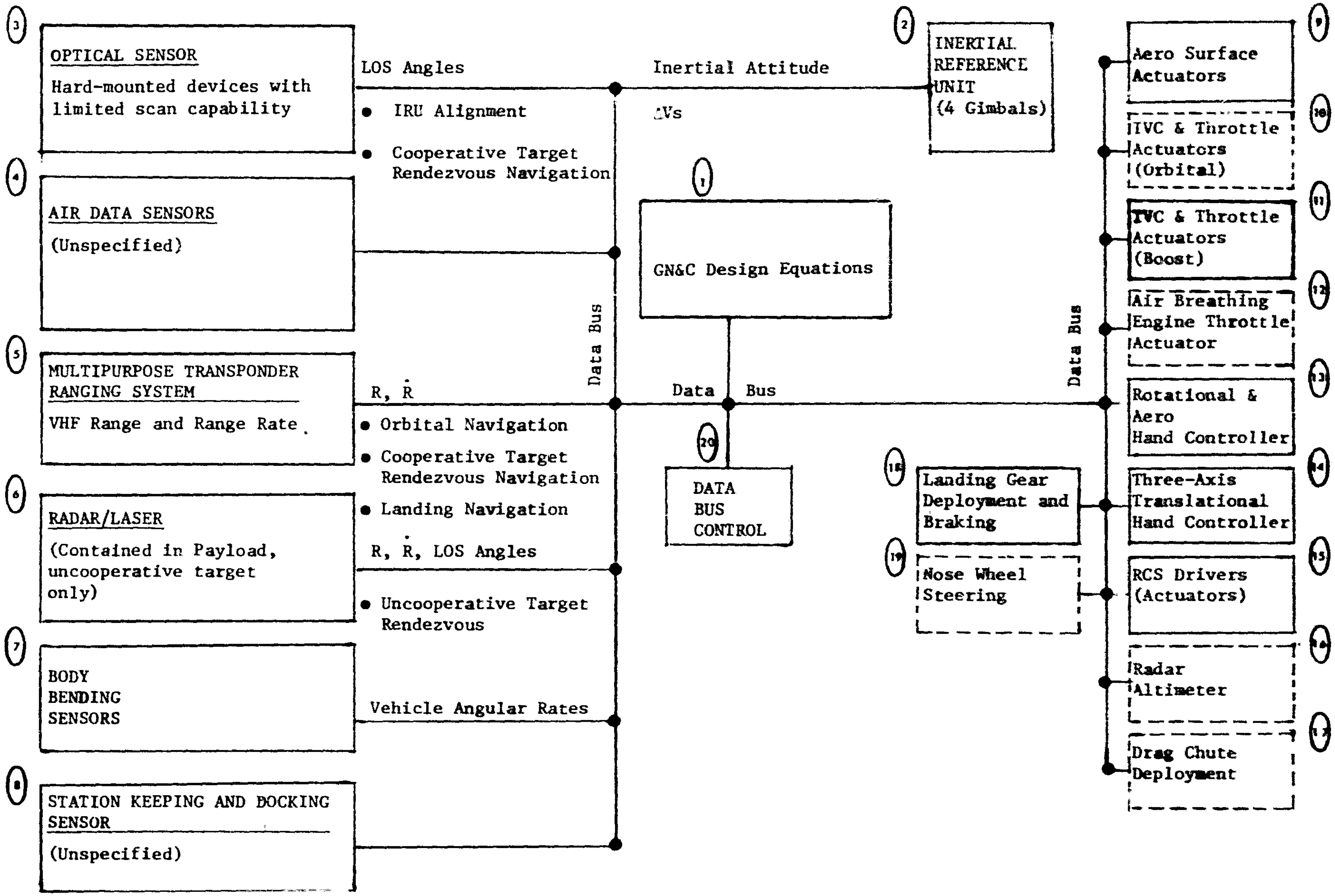

Figure 6-1 - GN&C Baseline System

7. GN&C SOFTWARE FUNCTIONAL REQUIREMENTS

The GN&C software functional requirements from Reference a are summarized here for easy reference. A detailed definition of the GN&C software functional requirements for the orbiter is given in Reference a. These functional requirements are summarized in the following matrices, which also identify the related higher level requirements, the reference for the requirement, and related ground or station/base support functions. The sources used to develop these requirements are:

1. MSC-00141, Rev M, "Guidelines and Constraints Document - Space Station Program Definition (Phase B)," 20 March 1970.
2. "Statement of Work - Space Shuttle Systems Program Definition (Phase B) - Appendix C - Desired System Characteristics," 20 February 1970.
3. NASA/MSC Document, "Technical Requirements for Space Shuttle Vehicle Avionics System," 22 December 1969.
4. Assumed or inferred from more general requirements.

The requirement source is identified in the matrices by paragraph number in the source document, e.g., (1) 6.213.

Table 7-1 presents the functional requirements for the orbiter. Also, Table 7-2 is included to cross reference the defined functions with the software modules defined in detail in the GN&C Software Functional Requirements Document (Reference a).

It should be noted that functions listed in the "GN&C Software Function" column of the matrices are generally not defined explicitly in the source of reference. That is, the GN&C software functions represent interpolations of the more general mission/system requirements which are defined in the reference sources.

Certain requirements such as failure detection, processing manual commands, and communications are common to most GN&C activities and may be considered appropriate to each subsection of the tables. Such functions are not listed in the "GN&C Software Function" columns because of their repetitious nature and the length of the tables that would result.

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER

MISSION/SYSTEM REQUIREMENT	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
1.0 Prelaunch	(1) 6.213	• Activate GN&C system.	• Monitor automatic checkout.		• Avionics checkout may be automatic and autonomous.
1.1 Checkout and calibrate avionics system.	(3) 3.2.4.2 (1) 6.40501	• Perform automatic onboard checkout of avionics through subsystem self-test utilizing operational stimuli: Isolate failures to replacement module level. • Calibrate GN&C system and sub-systems. • Verify all calibrations. • Perform control hardware checkout			
1.2 Perform targeting for launch utilizing all azimuth launch capability.	(1) 6.40501	• Perform targeting computations based on ground supplied target data. • Navigate orbiter and target to launch time.	• Provide target trajectory data for both cooperative & non-cooperative targets. • Provide erasable load.		• Launch targeting performed onboard.
1.3 Align, calibrate and verify inertial reference automatically.	(3) 3.5.1.2.1 (a)	• Align inertial reference utilizing surface alignment techniques and instruments through automatic sequencing. • Calibrate inertial reference through automatic sequencing. • Verify alignment of inertial reference.			• Alignment and calibration of inertial reference are automatic.
2.0 Vertical launch into orbit	(2) Appendix (1) 6.209 (4)	• Initialize powered flight navigation. • Initialize the launch control system monitor. • Initialize timing functions. • Perform a checklist search to determine that all systems are configured properly for launch.	• Monitor launch.		
2.1 Booster powered flight with maximum 3g load factor	(1) 6.201A Williamsburg meeting (4)	• Perform powered flight navigation. • Monitor booster/performance. • Provide data for abort decision			
2.2 Stage orbiter from booster.	(4)	• Continue powered flight navigation. • Command staging sequence (booster positive separation). • Perform RCS separation maneuver. • Command orbiter engine on. • Perform attitude control during coast			• Staging configuration unique to shuttle

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENT	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
2.3 Orbiter powered flight with maximum 3g load factor.	Williamsberg meeting. (1) 6.201A	° Continue powered flight navigation ° Provide insertion phase guidance. ° Control vehicle roll attitude. ° Control orbiter engine thrust vector. ° Perform abort monitor. ° Trim residual ΔV.			° G-level maintenance
3.0 Launch aborts with intact return of both booster and orbiter.	(1) 6.104 (3) 3.1.2.2(e)	° Determine mode of abort. ° Accept and process abort commands from crew. ° Continue powered flight navigation. ° Perform targeting for orbiter. ° Command staging sequence at appropriate time. ⎫ ° Perform separation maneuver. ⎬ If abort during boost ° Command orbiter engine on ⎭ ° Sequence orbiter into proper mission phase at the completion of the abort maneuver. ° Provide lateral and axial load relief.	° Monitor abort, but do not participate in abort decision. ° Alert landing facilities to abort situation.		° Abort decision solely onboard. ° Onboard launch abort targeting.
4.0 Orbital coast					
4.1 Perform orbital navigation	(3) 3.5.1.1.4 (1) 6.40702 (3) 3.5.2.3 (4)	° Perform autonomous orbital navigation by incorporating fix data from navigation sensors. ° Provide capability of automatic pointing and acquisition for each navigational instrument.	Provide external data for calibration of navigation sensors.		° Autonomous orbital navigation.
4.2 Realign and calibrate inertial reference.	(3) 3.5.1.2.1(L)	° Perform automatic realignment of the inertial reference using sequential star sightings. ° Automatically acquire sequential stars to provide fixes for the alignment process. ° Provide automatic attitude maneuvers to present suitable star pairs. ° Calibrate inertial reference using measured trend data.			° Automatic realignment and calibration of the inertial reference. ° Inflight calibration of onboard sensors
4.3 Provide crew flight controls.	(3)3.5.2.5	° Provide manual 3-axis translation control inputs. ° Provide manual 3-axis rotational control. ° Provide manual thrust vector control. ° Provide direct RCS control including rate, direct acceleration, and minimum impulse control modes.			° Translation and rotation jets are independent.

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENT	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
4.4 Provide automatic vehicle control.	(3)3.5.4(d) (3)3.5.6(m)	• Provide attitude hold vehicle control during free flight with a selectable deadband. • Provide jet selection and jet failure logic to automatic and manual RCS control modes.			
4.5 Provide switching of communication antennas, transmitter, and receiver.	(3)3.6.2.6.2(e)	• Provide automatic switching of omni-antennas. • Provide continuous antenna pointing information.			

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENT	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
5.0 Rendezvous with both cooperative and passive targets	(3) 3.5.1.1.5 (1) 6.2.1.2			• Monitor Rendezvous. • Provide ranging transponder and flashing light.	• Rendezvous capability required with uncooperative target. • Rendezvous capability required in daylight. • Direct rendezvous required. • Earth orbit rendezvous without ground updates after insertion required.
5.1 Maintain relative state with respect to target		• Provide automatic search and acquisition capability for rendezvous tracking system. • Perform rendezvous navigation utilizing outputs of tracking systems.		• Provide backup rendezvous navigation.	• Autonomous rendezvous navigation. • Automatic optical search, acquisition and tracking system.
5.2 Perform required maneuvers to place orbiter in coelliptic orbit with target.		• Perform targeting to provide maneuver to adjust the phase angle and orbital characteristics so that the orbiter is coelliptic with respect to the target with the required differential height and phase angle at TPI. Typical sequences of maneuvers are (1) phasing adjustment, (2) height adjustment, and (3) a concentric maneuver. • For each of these maneuvers, perform the following functions: *Terminate rendezvous navigation; *Realign, if necessary, the inertial reference using star sighting data; *Determine if RCS or orbiter engine is required for the maneuver. *Perform pre-thrust computations utilizing targeted data; *Maneuver the orbiter to the thrust attitude and maintain that attitude; *Perform checklist search to determine that all systems are configured properly for the maneuver; *Initiate powered flight navigation and continue through maneuver; *Perform automatic guidance and control of maneuvers and insure that ΔV residuals are small. *Perform thrust vector control. *Provide for manual control of maneuver by crew including capability to respond to crew attitude, translation and engine thrust and on-off commands. *Terminate powered flight navigation. *Reacquire target, reinitialize navigation system, and resume rendezvous navigation.		• Provide backup rendezvous targeting.	• All rendezvous targeting performed onboard. • Orbital maneuvers are automatic.

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENTS	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
5.3 Perform required maneuvers to initiate intercept transfer.		• Perform Terminal Phase initiation targeting to place the orbiter on an intercept course with the intended target. Perform targeting of the midcourse maneuvers required to keep the orbiter on an intercept course. • All functions described in 5.2 are required for each of the terminal phase maneuvers.			
5.4 Perform automatic braking to place the orbiter in a station-keeping attitude with respect to the target.		• Perform targeting computations required to brake orbiter into station-keeping attitude with respect to target. • Terminate rendezvous navigation. • Initiate powered flight navigation with tracking systems operating to provide relative data for braking computations. • Perform automatic guidance and control of RCS braking maneuvers. • Terminate powered flight navigation at the completion of the braking maneuver. • Provide for manual control of the braking maneuver.		• Monitor braking.	• Onboard braking computations. • Automatic RCS braking.
6.0 Station-keeping and Docking					
6.1 Perform automatic station-keeping	(3)3.5.1.1.6	• Maintain orbiter placement with respect to target such that it will not interfere with target LOS requirements. • Perform station-keeping navigation utilizing rendezvous tracking system outputs. • Maintain orbiter in perferred tracking attitude. • Provide for manual control of station-keeping.		• Monitor station-keeping. • Provide reflector(s) or radiation for relative state navigation.	• Automatic station-keeping.
6.2 Perform automatic docking.	(3)3.5.1.1.7 (3)3.5.1.2.1(g)	• Perform computations to control orbiter attitude with respect to the target. • Perform station-keeping navigation utilizing tracking systems and/or docking sensors. • Compute maneuvers required to place orbiter on the required approach corridor to the docking port. • Perform automatic guidance and control of the RCS docking maneuvers. • Sense soft dock. • Allow for crew maneuver to hard dock.		• Monitor undocking. • Provide reflector(s) or radiation for relative state navigation.	• Docking sensors. • Automatic docking.
7.0 Docked operations.	(4)	• Perform ΔV maneuvers while docked to the space station/base to provide space base orbit maintenance.		• Provide decision for Shuttle maneuvers.	Docked ΔV maneuvers

TABLE 7-1

MISSION FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENTS	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
7.1 Perform docked maneuver.		• Provide for attitude hold and rate damping of Space Station/Base • Activate GN&C system.		• Insure control transfer to Shuttle.	• Inflight GN&C activation. • Inflight automatic checkout.
7.2 Initialize avionics for undocking	(4)	• Perform automatic checkout of avionics. • Align inertial reference while docked.			
8.0 Undocking					
8.1 Perform undocking.	(4)	• Perform checklist search to determine if all systems are configured for undocking. • Update onboard state vector from either space base (if existent) or ground. • Initiate powered flight navigation and maintain until the end of the docking maneuver. • Perform automatic guidance and control of RCS docking maneuver • Maintain orbiter placement with respect to target such that it will not interfere with target LOS requirements. • Initiate coasting flight navigation upon completion of the undocking maneuver.	• Provide state vector to orbiter.	• Provide state vector to orbiter. • Monitor undocking.	• Automatic undocking.
9.0 Deorbit and Reentry		• Checkout the TVC and aerosurface control hardware by manual and automatic inputs prior to deorbit.			
9.1 Perform deorbit (may consist of one or two maneuvers).	(3)3.5.1.2(3) (3)3.5.1.1.4 (b)	• Perform targeting to provide desired trajectory conditions at entry interface based upon ground supplied landing point. • Terminate orbital navigation. • Realign inertial reference using star sighting data. • Perform pre-thrust computations utilizing targeted data. • Maneuver orbiter to the thrust attitude and maintain that attitude. • Perform checklist search to determine that all systems are configured for the deorbit maneuver. • Initiate powered flight navigation and continue through maneuver. • Perform automatic guidance and control of maneuver and insure that ΔV residuals are small. • Perform thrust vector control of orbiter engines. • Terminate powered flight navigation. • Provide for manual control of the deorbit maneuver.	• Provide landing point.		• Onboard deorbit targeting.
9.2 Perform reentry with a maximum load factor of 3g.	(3)3.5.1.1.8	• Orient orbiter to the correct attitude for atmospheric reentry. • Perform checklist search to determine if all systems are configured for reentry. • Initiate powered flight navigation just prior to entry interface. • Provide guidance and control of orbiter through atmospheric reentry including q-limiting capability. • Provide for manual control of the reentry maneuvers. • Provide RCS control			• High L/D crossrange reentry • Guidance control may employ sensed thermal data, and aerodynamic surface control. • Combination of RCS and Aerodynamic control • External nav aids may be used during specific force sensing navigation

TABLE 7-1

MISSION/SYSTEM FUNCTIONAL GN&C SOFTWARE REQUIREMENTS FOR ORBITER (Continued)

MISSION/SYSTEM REQUIREMENT	SOURCE OF REQUIREMENT	GN&C SOFTWARE FUNCTION	SUPPORT FUNCTION	BASE FUNCTION	DELTA FROM APOLLO/SKYLAB
10.0 Transition and cruise					
10.1 Transition	(3)3.5.1.1.8 (a)	° Continue powered flight navigation. ° Control transition maneuver from high angle of attack entry profile to low angle of attack cruise profile. ° Provide aerodynamic control of orbiter. ° Issue cruise engine-on command. ° Provide cruise engine throttle control. ° Initiate cruise navigation			° Transition phase unique to Shuttle
10.2 Cruise phase	(3)3.5.1.1.9	° Continue powered flight navigation. ° Continue cruise navigation. ° Provide orbiter guidance in conjunction with ground commands to perform those maneuvers required to attain the required approach corridor. ° Provide aerodynamic surface control. ° Provide cruise-engine throttle control. ° Provide for manual control during cruise. ° Provide data for ground controllers.	° Monitor cruise. ° Provide collision avoidance. ° Provide ground aids for approach, i.e., Transponders. ° Monitor other aircraft for possible go-around command.		° Cruise phase unique to Shuttle.
11.0 Approach and landing.	(1) 6.202				
11.1 Approach	(3)3.5.1.2.1 (k) (1) 6.215	° Continue powered flight navigation. ° Continue autonomous cruise navigation utilizing airways, navigational aids and radar altimeter. ° Provide orbiter approach corridor guidance utilizing approach and landing sensors. ° Provide aerodynamic surface control ° Initiate landing gear deployment. ° Provide cruise-engine throttle control. ° Monitor for possible go-around. ° Provide for crew manual takeover of approach phase.	° Provide ground aids for approach.		° Approach phase unique to Shuttle.
11.2 Landing	(3)3.5.1.2.1 (k) (1) 6.204 (1) 6.40704 (3)3.1.1.1(d)	° Continue powered flight navigation. ° Continue approach guidance until landing. ° Provide aerodynamic surface control. ° Deploy drag chute. ° Provide nose wheel steering commands. ° Provide cruise-engine throttle control. ° Provide reverse thrust and landing gear braking. ° Provide for manual control of landing phase.	° Monitor landing. ° Provide ground control. ° Provide landing nav aids.		° Landing phase unique to Shuttle.
12.0 Provide uplink and downlink.	(3) 3.5.6(h) (3) 3.5.6(g)	° Provide downlink GN&C information. ° Accept uplink GN&C information.	° Accept and Process downlink GN&C information. ° Prepare and transmit uplink GN&C information.		

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
1.0 Prelaunch	1.1 Initialization	o Activate GN&C system. o Navigate orbiter and target to launch time.	OS2-1,2,3, OS1-19
	1.2 Targeting	o Perform targeting computations based on ground supplied target data.	OS1-6
	1.3 Sensor Calibration and Alignment	o Align inertial reference utilizing surface alignment techniques and instruments through automatic sequencing. o Calibrate inertial reference through automatic sequencing. o Verify alignment of inertial reference.	OS3-1,2,3
	1.4 GN&C System Monitor, Test and Checkout	o Perform automatic onboard checkout of avionics through subsystem self-test utilizing operational stimuli: Isolate failures to replacement module level.	OS2-4
2.0 Boost	2.1 Rapid Real-Time State Advancement During Specific Force Sensing[2]	o Perform powered flight navigation.	ON1-1
	2.2 Boost Monitor	o Monitor boost performance and provide data to abort decision.	OS5-1
3.0 Separation	3.1 Separation Control	o Command staging sequence (booster positive separation). o Perform RCS separation maneuver. o Command orbiter engine on. o Perform attitude control during coast.	OC2-1,2,3,4 OG1-7
4.0 Orbit Insertion	4.1 Navigation	o Continue powered flight navigation.	ON1-1,2
	4.2 Powered Ascent Guidance[2]	o Provide insertion phase guidance.[2] o Trim residual ΔV.	OG1-2,3,4,8

[1] As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.

[2] Equations are included in this document for these subprograms and functions.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
4.0 (cont'd)	4.3 Attitude Control	o Control vehicle roll attitude. o Control orbiter engine thrust vector.	OC1-1,3,5,6 OC2-1,2,3,4 OC4-3
	4.4 Abort Monitor	o Perform abort monitor.	OS5-1
5.0 Ascent Abort	5.1 Abort Decision and Mode Determination	o Determine mode of abort. o Accept and process abort commands from crew.	OG8-1,2 OS1-8
	5.2 Abort Targeting	o Perform targeting for orbiter.	OG8-3
	5.3 Guidance	o Command staging sequence at appropriate time. } If abort during boost o Perform separation maneuver. o Command orbiter engine on. o Sequence orbiter into proper mission phase at the completion of the abort maneuver.	
	5.4 Navigation	o Continue powered flight navigation.	ON1-1,2
	5.5 Attitude Control	o Control vehicle attitude. o Provide lateral and axial load relief.	OC2-1,2,3,5
6.0 Orbital Coast	6.1 Orbital Navigation		
	6.1.1 Conic State Extrapolation[2]	o Advance state vector with conic solutions[2]	ON2-1
	6.1.2 Precision State and Filter Matrix Extrapolation[2]	o Augment conic solutions with numerical solutions[2] o Perform autonomous orbital navigation by incorporating fix data from ground transponders.	ON2-2 ON2-3,4
	6.2 Sensor Calibration and Alignment	o Provide capability of automatic pointing and acquisition for each navigational instrument. o Perform automatic realignment of the inertial reference using sequential star sightings.	OS1-4 OS3-4,5

[1]As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.
[2]Equations are included in this document for these subprograms and functions.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
6.0 (cont'd)		o Automatically acquire sequential stars to provide fixes for the alignment process. o Calibrate inertial reference using measured trend data.	
	6.3 Orbital Coast Attitude Control	o Provide automatic attitude maneuvers to present suitable star pairs. o Provide direct RCS control including proportional rate, direct acceleration, minimum impulse control modes. o Provide attitude hold vehicle control during free flight with a selectable deadband. o Provide jet selection and jet failure logic to automatic and manual RCS control modes. o Provide manual 3-axis translation control inputs. o Provide manual 3-axis rotational control. o Provide manual thrust vector control.	OC3, OC7
7.0 Orbital Powered Flight	7.1 Targeting	o Perform targeting for orbit modifications.	
	7.2 Navigation (Same as 2.1)	o Perform powered flight navigation	ON1-1,2
	7.3 Guidance	o Compute initial thrust attitude o Command axial engines on. o Compute velocity to be gained. o Provide attitude (steering) commands. o Compute time-to-cutoff, and issue engine-off commands. o Null residual velocities (if required).	OG1-2,3,4
	7.4 Attitude Control	o Provide RCS and TVC commands to achieve the commanded attitude.	OC1-1,3,5,6 OC2-4 OC4-2,3

[1]As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
8.0 Rendezvous	8.1 Rendezvous Targeting[2]	[2]o Perform targeting to provide maneuver to adjust the phase angle and orbital characteristics so that the orbiter is coelliptic with respect to the target with the required differential height and phase angle at TPI. [2]o Perform Terminal Phase initiation targeting to place the orbiter on an intercept course with the intended target. Perform targeting of the midcourse maneuvers required to keep the orbiter on an intercept course. o Perform targeting computations required to brake orbiter into station-keeping attitude with respect to target.	OG3-2,3,4,5
	8.2 Relative State Updating[2]	[2]o Perform relative navigation utilizing outputs of tracking systems. o Provide automatic search and acquisition capability for tracking system.	ON1-1, ON3-1,2,3,7 ON3-4,5
	8.3 Guidance	o Compute initial thrust attitude. o Command axial engines on. o Compute velocity to be gained. o Provide attitude (steering) commands. o Compute time-to-cutoff, and issue engine-off commands. o Null residual velocities (if required).	OG2
	8.4 Attitude Control	o Provide RCS and TVC commands to achieve the commanded attitude.	OC3-1,2 OC4-1,2,3,4,5,7 OC7-1 2,3,6

[1]As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.

[2]Equations are included in this document for these subprograms and functions.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
9.0 Station keeping	9.1 Navigation	o Perform station-keeping navigation utilizing radar, optics, and/or laser tracking system outputs.	ON3-1,2,3
	9.2 Guidance	o Maintain orbiter placement with respect to target such that it will not interfere with targe` LOS requirements.	OG3-1,2
	9.3 Attitude Control	o Maintain orbiter in preferred tracking attitude.	OC3-2,3 OC7-1,3
10.0 Docking & Undocking	10.1 Docking and Undocking Navigation[2] 10.2 Automatic Docking Control Law[2] (Guidance and Control)	[2]o Perform automatic guidance and control of the RCS docking maneuvers. [2]o Perform computations to control orbiter attitude with respect to the target. o Compute maneuvers required to place orbiter on the required approach corridor to the docking port. o Sense soft dock. o Allow for crew maneuver to hard dock.	OG4-1,2,4,5 OC3-2, OC4-3,4,6 OC7-1 OG4-3 ON3-6
11.0 Docked Operations	11.1 Targeting	TBD	TBD
	11.2 System Initialization		
	11.3 Navigation	TBD	
	11.4 Guidance	TBD	
	11.5 Attitude Control	TBD	

[1]As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.
[2]Equations are included in this document for these subprograms and functions.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
11.0 (cont'd)	11.6 Sensor Calibration and Alignment	TBD	
	11.7 System Monitor, Test, and Checkout	TBD	OS2-7
12.0 Deorbit and Entry	12.1 Deorbit Targeting	o Perform targeting to provide desired trajectory conditions at entry interface based upon specified landing point.	OG2-2,4 OG5-2,3,4,5,6
	12.2 Entry Navigation	o Perform coasting and powered flight navigation. o Initiate powered flight navigation and continue through maneuver.	ON2-1, ON1-1
	12.3 Entry Guidance[2]	o Perform automatic guidance and control of maneuver and insure that ΔV residuals are small. [2] o Perform thrust vector control of orbiter engines. o Provide guidance and control of orbiter through atmospheric reentry including g-limiting capability.	OG2-2,4,5,6,7 OG5-8,9,10,11
	12.4 Reentry Autopilot[2]	o Achieve commanded attitude during powered flight and entry.[2]	OC5-1,2,3
		o Maneuver orbiter to the thrust attitude. o Orient orbiter to the correct attitude for atmospheric reentry.	OC3-1,2,6,7 OC4-1,2,3,4,5,7 OC7-1,2,3,4,6
13.0 Transition	13.1 Transition Attitude Control	o Control transition maneuver from high angle of attack profile to low angle of attack cruise profile. o Provide aerodynamic control of orbiter.	ON1-1,2; ON4-1,2 OG6-3; OC5-1,2,3,4

[1] As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.
[2] Equations are included in this document for these subprograms and functions.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS	MODULES[1]
14.0 Cruise and Ferry	14.1 Navigation	o Continue powered flight navigation. o Continue autonomous cruise navigation utilizing airways navigational aids and radar altimeter.	[illegible]4-[illegible],2
	14.2 Guidance	o Provide orbiter guidance in conjunction with ground to perform those maneuvers required to attain the required approach corridor. o Provide cruise-engine throttle control.	[illegible]-1,2,4,5,7
	14.3 Attitude Control	o Provide aerodynamic surface control.	[illegible]5-[illegible]; [illegible]-4
15.0 Approach and Landing	15.1 Navigation	o Continue powered flight navigation. o Continue autonomous cruise navigation utilizing airways navigational aids and radar altimeter.	[illegible]-1,2,3
	15.2 Guidance	o Provide orbiter approach corridor guidance utilizing airborne and landing sensors. o Provide cruise-engine throttle control. o Provide braking and steering commands after touchdown.	[illegible]6 [illegible] [illegible]-1,2,3
	15.3 Attitude Control	o Provide aerodynamic surface control.	[illegible]-2,4; [illegible]-4,[illegible]
16.0 Horizontal Takeoff	16.1 Navigation	o Provide powered flight navigation.	[illegible],2
	16.2 Guidance	o Provide attitude and thrust throttle commands.	[illegible]9-1,2,[illegible],4
	16.3 Attitude Control	o Achieve commanded attitude.	[illegible]-3,4, [illegible] through 6.
17.0 Communications and Pointing	17.1 Antenna/Sensor Switching	o Provide auto switching of omni-antennas	[illegible]4-1

[1] As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.

TABLE 7-2

MISSION PHASE PROGRAMS VERSUS
GN&C FUNCTIONS AND MODULES (Continued)

MISSION PHASE PROGRAM	MISSION PHASE SUBPROGRAM	FUNCTIONS[1]	MODULES[1]
17.0 (cont'd)	17.2 Antenna/Sensor Pointing	o Provide continuous antenna pointing information.	OS4-2
	17.3 Transmission Frequency Selection	o Provide auto selection of transmission frequency.	OS4-3
	17.4 Provide Communications Link Data	o Process downlink data. o Process uplink data.	OS4-4,5
18.0 Failure Detection	18.1 Preflight Failure Detection	o Provide data for automatic preflight and inflight GN&C system checkout and failure detection.	OS5-1,2,3
	...2 Inflight Failure Detection		

[1]As identified in "Space Shuttle GN&C Software Functional Requirements," MSC03690, 12 October 1970.

8. COORDINATE SYSTEMS AND TRANSFORMATIONS

The coordinate systems which will be established for the Space Shuttle missions will be defined in this section. The following represents a preliminary identification of the coordinate system envisioned.

1. Earth Centered Inertial (ECI) (same as Apollo Basic Reference Coordinate System)

2. Earth Centered - Earth Fixed Systems (several orientations may be desirable)

3. Launch Centered, Earth Fixed

4. Landing Site Centered, Earth Fixed

5. IMU stable member (a function of the IMU alignment)

6. Navigation Base Coordinate System(s) (vehicle fixed systems for convenient reference to sensors)

7. Sensor Centered Coordinate Systems (fixed to onboard and ground sensors and transponders)

8. Vehicle or Body Coordinate System (along the axes of geometric symetry)

9. Vehicle Centered Control System Coordinate System(s) (specific orientations to be based on mass properties, propulsion properties, and aerodynamic conditions)

10. Vehicle Centered Local Vertical Coordinate System (along the local vertical, downrange, cross range)

11. Docking Port Centered, Target Vehicle Fixed Coordinate System

12. Docking Port Centered, Shuttle Vehicle Fixed

Transformations between the coordinate systems will be provided in later editions of this document when the coordinate systems are more firmly defined.