Paper AAS 02-122

American Astronautical Society

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AAS/AIAA Space Flight Mechanics Meeting

San Antonio, Texas 27-30 January, 2002

AAS Publications Office, P.O. Box 28130, San Diego, CA 92129

NOMENCLATURE

AACS	Attitude and Articulation Control Subsystem
ACC	Accelerometer
AFC	AACS Flight Computer
ATB	Analytical Test Bed
BPLVD	Bi-Propellant Latch Valve Driver
CBH	Catalyst Bed Heater
CDS	Command Data System
EGA	Engine Gimbal Assembly
EGAPA	Engine Gimbal Assembly Servo P-axis
EGAQA	Engine Gimbal Assembly Servo Q-axis
EGECU	Engine Gimbal Electronic Controller Unit
EGED	Engine Gimbal Electronic Driver
FSDS	Flight Software Development System
FSW	Flight Software
G&C	Guidance and Controls
HeLVD	Helium Latch Valve Driver
HGA	High Gain Antenna
IRU	Inertial Reference Unit
ITL	Integrated Test Laboratory
LGA	Low Gain Antenna
ME	Main Engine
MEVD	Main Engine Valve Driver
MP	Mono Propellant System
MPD	Mono Propulsion Driver
NAC	Narrow Angle Camera
PMS	Propulsion Management System
RCS	Reaction Control System
REA	Rocket Engine Assembly
RTI	Real Time Interrupt
RWA	Reaction Wheel Assembly
S/C	Spacecraft
SOI	Saturn Orbit Insertion
SRU	Stellar Reference Unit
SSA	Sun Sensor Assembly
TCL	Tool Commanding Language
TCM	Trajectory Correction Maneuver
TVC	Thrust Vector Control
VDECU	Valve Drive Electronic Controller Unit
ΔV	velocity change

USE OF GUIDANCE AND CONTROL TEST CASES TO VERIFY SPACECRAFT ATTITUDE CONTROL SYSTEM DESIGN

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A simulation and analysis approach is introduced for verification of attitude control flight software performance in a deep space mission. The Cassini Guidance and Control test cases simulate typical and mission-critical spacecraft scenarios under nominal and stress conditions. Plots compare simulation results against "pass/fail" curves traced back to functional requirements. The analysis also provides useful insight into performance margin. Comparisons of test results with flight telemetry provide an assessment of simulation fidelity. The method demonstrates the value of software simulation in qualifying an attitude control system to perform in the expected environment.

CASSINI MISSION AND SPACECRAFT

The Cassini spacecraft was launched on October 15, 1997 on a Titan 4B launch vehicle. After an interplanetary cruise of nearly seven years, the spacecraft will arrive at Saturn by July 1, 2004. In order to conserve propellant, Cassini must make several gravity-assist flybys: two at Venus, one at Earth, and a final assist at Jupiter. As of today, each of these flybys has successfully been conducted, with the Jupiter gravity-assist occurring on December 30, 2000. Figure 1 illustrates the interplanetary trajectory design of the Cassini mission.

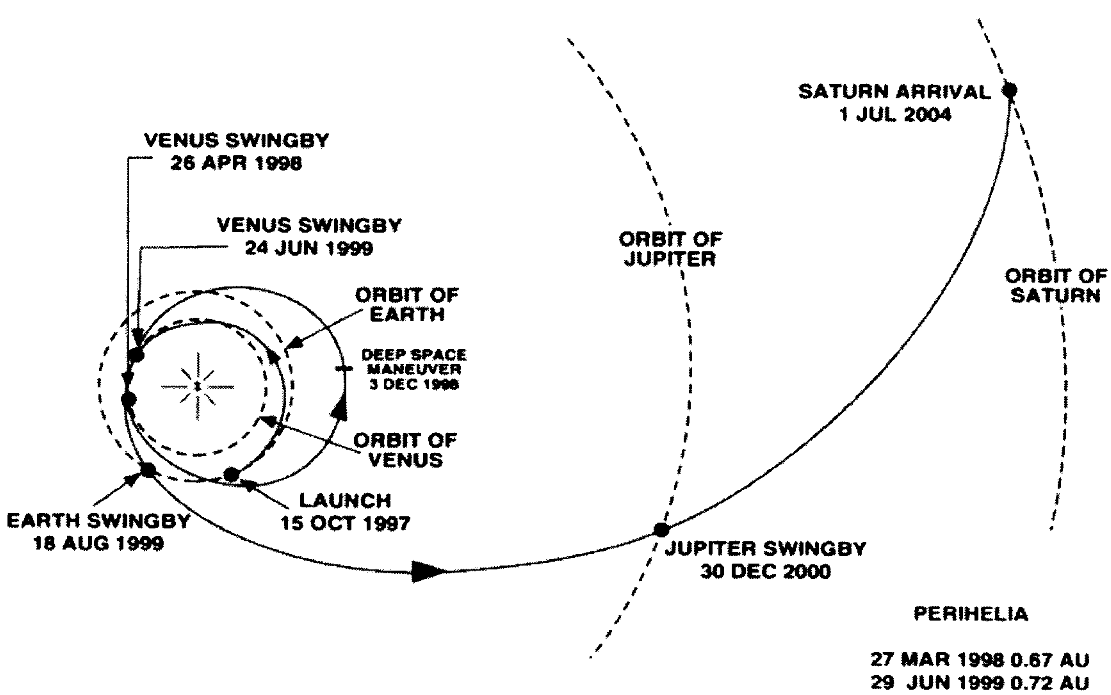

Figure 1. Cassini Interplanetary Trajectory

Cassini will not be the first NASA spacecraft to encounter Saturn. The Pioneer 11 spacecraft (1979) and Voyagers 1 and 2 (1980 and 1981, respectively) have accomplished successful flybys of the ringed planet. Cassini, though, will be the first to orbit the planet for a 4-year tour. Major Cassini science activities during the tour will include investigation of the configuration and dynamics of Saturn's magnetosphere, the exploration of the structure and composition of the planet's rings, and the characterization of Titan, the only moon in the solar system with a substantial atmosphere, as well as several of the planet's icy satellites.

In order to achieve these science objectives, the Cassini spacecraft was designed to include a Saturn orbiter and a Titan atmospheric probe. The Huygens probe, developed by the European Space Agency, will be released in November 2004, and will study Titan and its atmosphere. The orbiter (Figure 2) is a three-axis stabilized spacecraft consisting of an upper equipment module, a propulsion module, and a lower equipment module. The 4-meter High Gain Antenna (HGA) is mounted on top of the upper equipment module, while the two Low Gain Antennas (LGAs) are mounted separately. One LGA is co-boresighted and collocated with the HGA, and the other mounted just underneath the Huygens probe. An 11-meter magnetometer boom is also attached to the upper equipment module. The propulsion module incorporates two redundant gimbaled 445-Newton engines. At launch, the bipropellant tanks used for this system held roughly 3000 kg of fuel. The lower equipment module supports the three radioisotope thermoelectric generators that provide power for the spacecraft. A detailed description of the eighteen science instruments carried onboard the Cassini spacecraft is given in Reference 1.

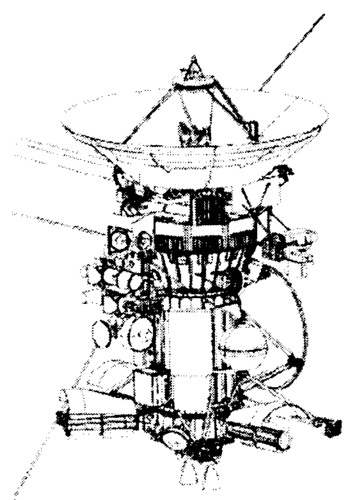

Figure 2. Cassini Orbiter with the attached Huygens Probe

ATTITUDE AND ARTICULATION CONTROL SUBSYSTEM (AACS)

Cassini's Attitude and Articulation Control Subsystem is in charge of estimating and controlling the spacecraft attitude. The system also responds to ground-commanded pointing goals for the spacecraft's science instruments and communication antennas. Another important function performed by AACS is to execute ground-commanded spacecraft velocity changes (ΔVs) required to adjust the spacecraft's trajectory.

The three-axis stabilized Cassini spacecraft employs the use of either a set of eight prime thrusters or a set of three Reaction Wheel Assemblies (RWAs) to maintain control of the spacecraft attitude. Eight backup thrusters and one redundant articulatable reaction wheel can also be used, in the case of a failure. Thrusters are used primarily during the cruise phase of the mission, pointing the spacecraft's antenna to an accuracy of several milli-radians to Earth in order to achieve the desired telecommunication rates. When higher accuracy is required of the spacecraft, such as during Saturn orbital tour, the reaction wheel assemblies are employed. The RWAs provide high spacecraft pointing accuracy and stability, and also allow the spacecraft to be repositioned frequently.

A stellar reference unit (SRU) and an inertial reference unit (IRU) primarily provide the attitude sensing function of AACS. Both the prime and backup SRUs are star trackers that determine the orientation of the spacecraft by comparing the stars captured in their 15-degree field-of-view with the approximately 3648 stars in the onboard star catalogs. The IRUs contain four hemispheric resonator gyroscopes arranged in an orthogonal-triad-plus-skew configuration. Each gyroscope measures the S/C's angular rate about its independent sensing axis.

The AACS system also entails the necessary equipment to implement trajectory correction maneuvers. Once the maneuver is commanded from the ground, the accelerometer is powered on to measure changes in the spacecraft's velocity. The prime engine control units and gimbal electronics are also powered on to position the engine in the correct direction. Once the spacecraft is aligned with the velocity vector, the main engine is fired for the specified duration or until the desired ΔV is achieved.

Along with keeping the spacecraft safe with constraint monitoring and fault protection, the AACS flight software (FSW) contains control algorithms used to manage and coordinate the function of all AACS resources. A high level description of these control algorithms is given in Reference 2, while the development process of these guidance and control algorithms is presented in the next section.

GUIDANCE AND CONTROL ALGORITHM DEVELOPMENT PROCESS

The high-level process used in the development of the Cassini AACS Guidance and Control (G&C) algorithms is depicted in Figure 3. The inputs to this process are imposed by the science and mission requirements, while the output of this process is a set of tested and coded G&C algorithms imbedded in the FSW. An iterative approach is then taken in the final algorithm design, implementation, and testing.

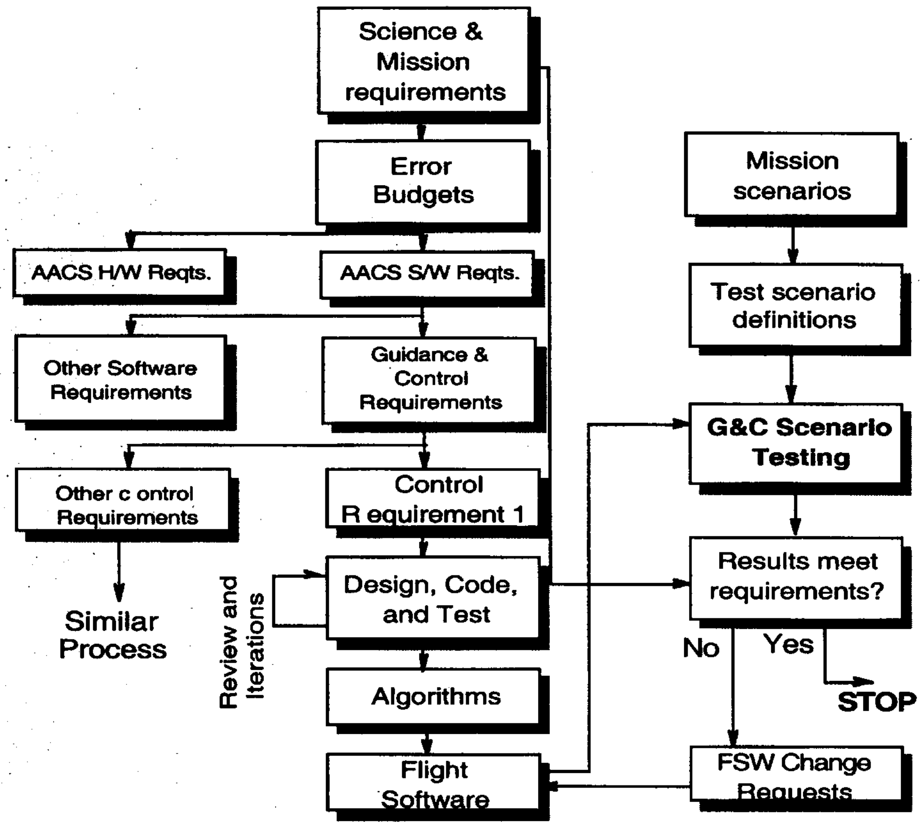

Figure 3. High-Level G&C Algorithm Development Process

Guidance and Control algorithms must be designed to satisfy all sets of science and mission requirements. For example, there is the need to point the narrow angle camera to its target with a pointing accuracy better than 2 milli-radians (99% confidence level). Another requirement is the accuracy of all trajectory correction maneuvers. During the critical Saturn Orbit Insertion (SOI) burn, the magnitude error of the burn must not exceed 1.05%, and the pointing error must be lower than 30 mrads, all to within 3σ accuracy. Requirements such as these two examples are what the G&C algorithms aim to achieve.

Error budgets are next constructed to assess the feasibility of meeting these requirements. The outputs from the error budget process include both AACS software requirements and hardware specifications. These error budgets also levy requirements on several non-AACS subsystems. For example, the acceptable SOI maneuver execution error budget levied requirements on the damping ratio and natural frequency of the magnetometer boom.

Requirements imposed on AACS are often times challenging, and iterations must be made in order to achieve them. To support this iterative design process, an Analytical Test Bed (ATB), consisting of finite-element models of the spacecraft at different mission phases and analytical models of the AACS hardware, was developed. The ATB provided the ability for the control algorithm designers to test their pseudo-code against all applicable G&C requirements. Once tested and peer reviewed, the final control algorithms are integrated into the AACS flight software and readied for G&C scenario testing.

GUIDANCE AND CONTROL SCENARIO TESTING

A set of G&C scenario test cases is created to verify that the integrated AACS FSW build does indeed meet all the applicable system-level requirements. It is not meant to repeat all the testing done during the design phase of the individual control algorithms. Differences between the G&C scenario tests and the algorithm unit test cases are presented in Table I.

Table I. Differences between G&C Scenario and Algorithm Tests

Criteria	**G&C Scenario Tests**	**Algorithm Unit Tests**
Requirements to verify	System-level	Subsystem-level
Test Bed	FSDS	ATB
Code Tested	FSW builds	Pseudo code
Test Engineers	AACS Systems Engineers	Control Algorithm Designers

Covering a wide range of mission scenarios, the G&C scenario test cases are designed to verify AACS performance and functionality. Through simulation of the spacecraft motion and the deep space environment, these tests assess the spacecraft's ability to meet various science and mission requirements. The test approach starts with engineers developing a collection of scenario descriptions and test details. The collection is then peer reviewed by the entire AACS team. Table II summarizes the set of G&C scenario test cases used to verify the Cassini AACS flight software at the time of launch.

Table II. Cassini AACS G&C Scenario Test Case Descriptions

Test Case	Test Description
1	To detumble the spacecraft to a quiescent state after separation from the launch vehicle within 20 minutes
2	To capture the Sun inside the sun sensor's FOV within 30 minutes after a loss of spacecraft inertial attitude reference
3	To regain attitude control of the spacecraft after the spin-up/ejection of the Huygens probe and bring the spacecraft to an Earth pointed attitude within 1 hour
4	To track the Huygens probe as it makes its 3.5 hour descent through Titan's atmosphere to an accuracy of 3.6 mrad (99% confidence)
5	To perform a main engine-based trajectory correction maneuver with performance that meets maneuver magnitude and pointing accuracy requirements
6	To perform a thrusters-based trajectory correction maneuver with performance that meets maneuver magnitude and pointing accuracy requirements
7	To perform a thrusters-based trajectory correction maneuver with performance that meets maneuver magnitude and pointing accuracy requirements, but with the turn to burn and post-burn attitudes performed using reaction wheels instead of thrusters
8	To point the HGA to a pointing accuracy of 3.14 mrad (99%) using reaction wheels, and perform a 2-by-2 mosaic of a science target to a pointing accuracy of 2 mrad (99%) and a pointing reconstruction requirement of 1.1 mrad (95%)
9	To perform the Saturn Orbit Insertion maneuver that meets a set of maneuver magnitude and pointing accuracy requirements
10	To complete an unloading of the reaction wheels' angular momentum in less than 10 minutes. Throughout the unloading, the HGA must maintain an Earth-pointed attitude to an accuracy of 3.14 mrad (99%)
11	To maintain a nadir-pointed attitude at Titan with the HGA throughout a 950 km flyby to an accuracy of 3.5 mrad (95%), all in the presence of Titan atmospheric torque

During the course of the Cassini mission, selected test cases are retired (for example, Test Case 1), while new test cases are added. Two upgrades to the AACS flight software will be made while the spacecraft is en route to Saturn. The first upgrade was completed on March 2000, and the final upgrade is planned for Spring 2003. With each new FSW upgrade, improvements to the current flight software are made. New commands are also added to the spacecraft's growing suite of capabilities. Paramount in the development and updating of the FSW is the need to perform comprehensive regression testing, thus new G&C scenario test cases are made to verify these new spacecraft capabilities. A new test case that verifies the new targeting with rotating coordinate systems ability is a good example. New cases based on improved Titan atmospheric density models, new command sequence practices, and pointing constraint situations are also under development. Ongoing updates also incorporate the latest environmental models and expand the range of activities and variants examined.

GUIDANCE AND CONTROL SCENARIO TEST BED

Two different test beds are used to test Cassini's overall AACS capabilities. The highest fidelity test bed is hardware based and is named the Integrated Test Laboratory (ITL). This laboratory runs a simulation of the spacecraft using the flight software interfaced with real flight computers, flight spares, prototype flight boards, and engineering models. Motion of the Sun and stars are simulated, and the spacecraft dynamics are modeled. Most of the tests ran in this laboratory require it to be critical to mimic the spacecraft as accurate as possible, down to the Real Time Interrupt (RTI) level. The G&C scenario test cases focus on the total performance of the overall spacecraft and AACS. The amount of detail required, however, does not justify the time and resources needed to setup the ITL for this type of test. The G&C scenario test cases are not run on this system, but employ a faster and more flexible test bed.

This second test bed was specifically designed for flight software development and testing. Extensively used since 1994, this system is called the Flight Software Development System (FSDS), and supports closed-loop simulation without hardware in the loop. Figure 4 illustrates the simulation model used in FSDS. An in-depth description of FSDS can be found in Reference 3 The primary function of this test bed was to create a simulation environment for the Cassini AACS subsystem, in such a way to:

1. Use the same dynamics models, allowing multiple S/C configurations, mass depletion, user-programmed external forces and torques, and star image emulation,
2. Model AACS actuators, sensors, CDS commanding, and AACS bus models,
3. Allow simulation and flight software variable collection,
4. Possess fault injection capability, and
5. Execute faster than real-time, which is a necessity for debugging and scenario development.

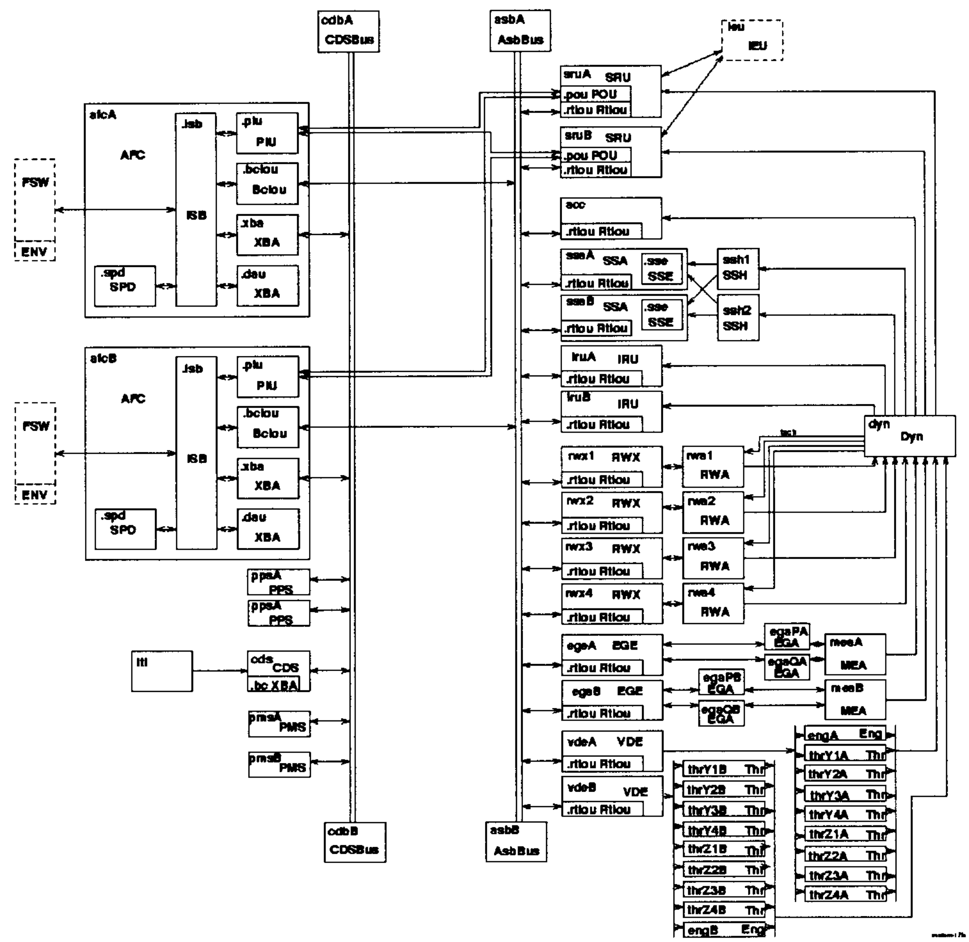

Figure 4. FSDS Model Diagram

The FSDS test bed was used for the majority of the G&C scenario testing. Employing a TCL command engine, the users can, interactively or through scripts, retrieve and set variables in the hardware, peek and poke global variables in flight software, and send commands and check telemetry values. This could all be done without interruption of the test runs. Multiple sets of S/C mass properties (finite element models) are available to simulate different phases of the Cassini mission. FSDS runs as fast as the host CPU. Currently, a Sun Ultra 10 Unix workstation can run the AACS Flight Software and FSDS at 2 to 4 times faster than real-time. Due to the faster than real-time capability, some disadvantages can occur which could mask out timing issues. The FSDS test bed cannot simulate a flight computer reset and recovery or a CDS to AACS communication loss, which can affect fault protection testing. However, these drawbacks are less important to G&C scenario testing.

GUIDANCE AND CONTROL SCENARIO TEST CASE PROCESS

Each science or engineering activity is represented as a nominal test scenario along with numerous off-nominal variants. The nominal cases provide a baseline confirmation that the mission requirements can be met. The variants provide insight into the margin available to accommodate extreme conditions. Each test possesses its own subset of test variants, where the variants were created to probe the different conditions and major environments the spacecraft might encounter in that particular mission scenario. Changes in the variants included adjusting the thrust levels of the thrusters during the Probe ejection scenario, reconfiguring the spacecraft's prime/backup engine configuration for Saturn Orbit Insertion, and shutting the main engine down short of reaching the intended ΔV during TCMs, for example. In the spirit of the "test it as you fly it" philosophy, care was taken to represent each test as accurate as possible. This entailed using the same commands and in some cases, the same timing practice as the actual mission scenarios.

Each test is provided with a standard procedure containing information describing the necessary details to simulate the test environment and to judge the results. Table III lists the general format of all G&C scenario test cases.

Table III. General Procedural Format for all G&C Scenario Test Cases

Procedure Format	**Description**
Scenario Description	A brief general description of the test case is first given.
Purpose	The purpose of running the test is then stated.
Applicable Requirements	The test case must satisfy a list of system and subsystem requirements forming the pass/fail criteria.
Initial Conditions	The initial hardware states and configurations, the initial attitude and dynamic states, the angular rate and acceleration limits, and the AACS mode are indicated.
Inputs	Other inputs required: external torque, inertia properties
Test Execution Summary and Expected Results	A summary of the test execution sequence is given, pointing out the main activities and the predicted results.
Variants	Test variants provide a method to assess AACS capability under various stress conditions and different mission scenarios.

As a good representation of a typical G&C test case, the procedure used to construct the main engine turn-to-burn ΔV control test case (Test Case 5) is presented in the Appendix.

Using FSDS simulation output, MATLAB* scripts were generated to analyze each test in the form of statistical analyses and plots. This data was then compared to pass/fail criteria based on functional requirements, and the generated results were then presented to the test team. The analysis for each test covers generic requirements that all test scenarios must satisfy, such as acceptable rate control error, rate estimation error, and attitude control error. Other standard plots provide a visual inspection of the flight modes and the turn rate profile during the course of the test. Along with examining the standard set of requirements that span all test cases, requirements specific to the test scenario are also investigated in the analysis. Functional sanity checks also play a large role in the analysis of each test, paying close attention to triggered fault protection alarms. Run in conjunction with FSDS's ability to provide accurate software simulation of the spacecraft and the deep space environment, the G&C scenario tests provide the ability to flush out even the minor of problems through ground testing rather than in-flight.

* MATLAB is a registered trademark of The Math Works, Inc.

TEST RESULTS AND FLIGHT DATA

In order to verify that the G&C scenario test cases prove to be an accurate test of AACS performance, the test cases must be compared to similar maneuvers performed in-flight. At this current stage of the mission, some of the test case results cannot yet be verified with comparison to telemetry (ie. Probe ejection, Saturn Orbit Insertion). The test cases that can be compared, however, provide confidence that the G&C scenario test cases offer a platform where AACS's capabilities can be tested prior to actually performing future maneuvers.

On July 19, 1999, the Cassini spacecraft performed TCM 10 with a ΔV of 5.13 m/sec to move the trajectory closer to Earth for an upcoming gravity assist (Reference 4). The results from this in-flight maneuver give the ability to gage the accuracy of the main engine turn to burn ΔV control nominal G&C test case (Test Case 5). Both the test and the TCM require the spacecraft to turn the spacecraft to the desired inertial ΔV direction, execute a commanded ΔV burn using the main engine, and then turn the spacecraft back to its nominal sun-pointed attitude. All relevant accuracy requirements must also be met while performing the maneuver. Given in the test procedures, the primary pass/fail criteria identified for this test and its variants are:

1. AACS properly opens and closes the necessary latch valves (implied by proper burn performance and lack of fault activity)
2. Complete the turns and burns in the predicted times
3. Accomplish the entire sequence in less than 30 minutes
4. Meet the ME propulsive maneuver execution error requirements
5. Meet rate control and estimation 3σ error requirements of less than 1 mrad/sec
6. Meet the attitude control 3σ error requirement of less than 1 mrad

Since the G&C scenario test cases were conceived pre-launch, the exact turns and size of ΔV had not yet been determined, and so a representative case with a ΔV of 4.75 m/sec was chosen. Since the G&C test case and TCM 10 differ in turn angles and ΔV direction and magnitude, the two scenarios are not identical, but the results from both should fulfill the above requirements.

The results from the FSDS simulation are compared with the results from the in-flight TCM. Figures 5 and 6 reveal the rate profile for the FSDS run against the rate profile taken from telemetry. In both cases, the entire maneuver accomplishes the necessary turns to the burn attitude, completes the ΔV, and returns to the initial attitude. The requirement to achieve the entire maneuver within 30 minutes does not, however, apply to the TCM 10 case. This requirement was created to avoid thermal constraint violations at a Sun – spacecraft distance of 0.67 A.U. and is not applicable when the Sun – spacecraft distance is near 1 A.U. Examining the turn rate profile, the second turn to the ΔV attitude and the corresponding turn back in the G&C test and TCM 10 are noticeably different. The actual TCM required a roll of -93.29° about the Y-axis in order to align the spacecraft with the required ΔV vector, while the simulated run made a 25° turn to reach its ΔV direction. Since the test was created prior to the actual TCM, the turns are not identical, and this difference was expected. In the actual TCM, the data is subsampled, and therefore do not show the peak spikes seen in the G&C simulation. The results from TCM 10 also show small offset turns just prior to and after the burn. This small offset is used to correct for a Rocket Engine Assembly (REA) misalignment discovered following the Deep Space Maneuver on December 3, 1998. By incorporating this change in TCM scenario to the list of other ongoing updates, the G&C scenario test cases provide an evolving resource to test AACS performance.

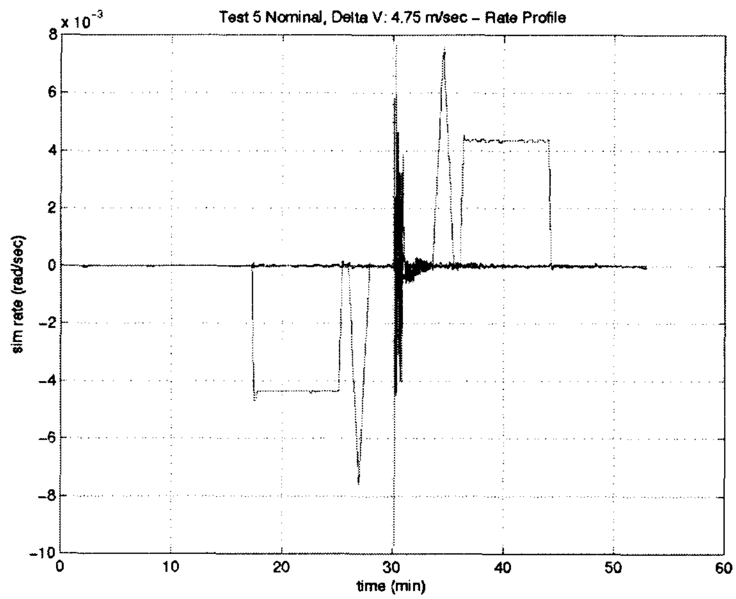

Figure 5. G&C Test Case 5 Nominal Turn Rate Profile

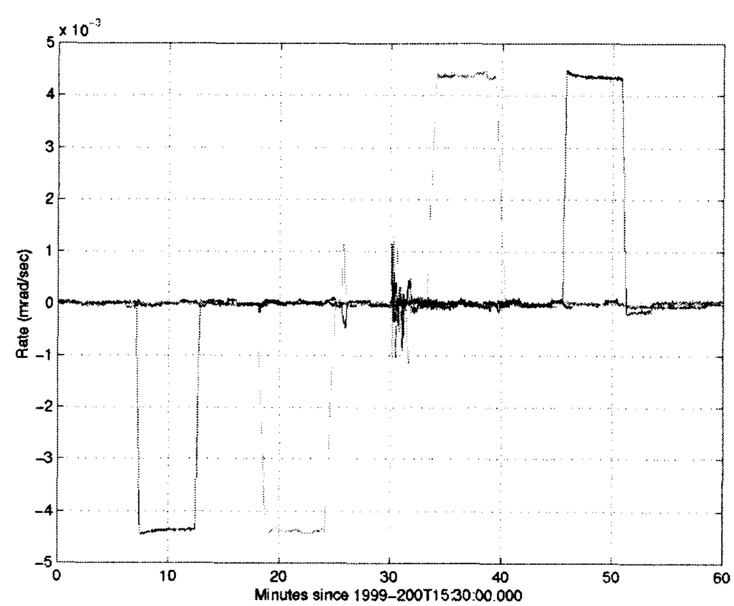

Figure 6. TCM #10 Turn Rate Profile

Figures 7 and 8 compare the rate control error from both the G&C test case simulation and TCM 10, while figures 9 and 10 show the attitude error. Threshold curves are plotted to identify the requirements of 1 mrad/sec for the allowable amount of rate control error and 1 mrad for the amount of attitude error. The errors are allowed to exceed the limit, but as long as the errors remain inside the requirement for 99.7% of the total time for the rate control error case and 99.7% of the burn time for the attitude error case. As seen in the figures, firing the main engine in both the simulated G&C test case and the actual TCM jolts the spacecraft and causes an abrupt change in rates and attitude.

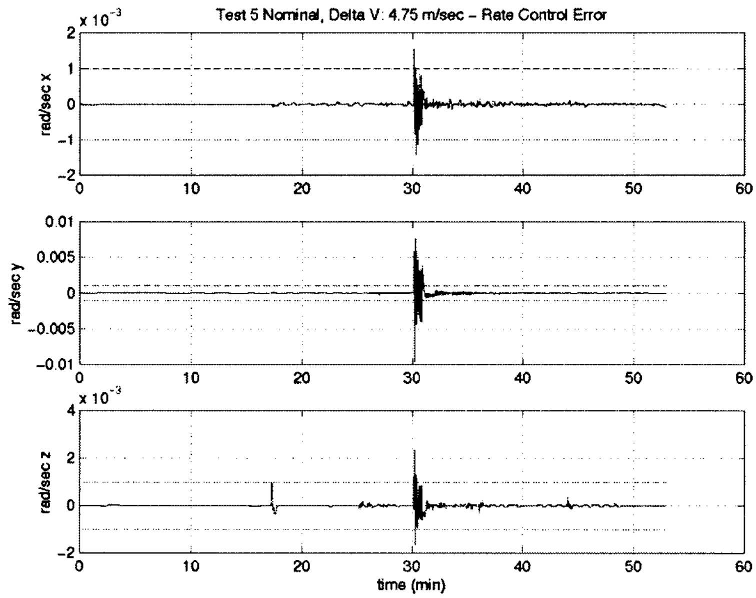

Figure 7. G&C Test Case 5 Nominal Rate Control Error

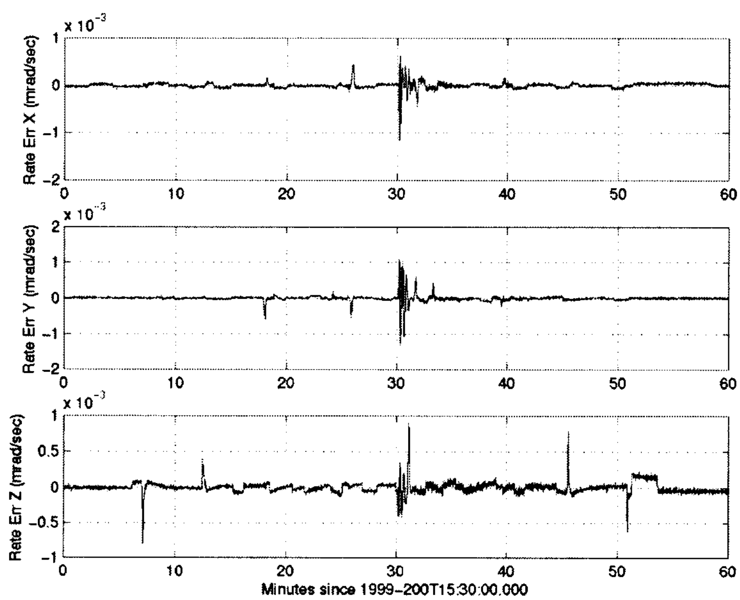

Figure 8. TCM #10 Rate Control Error

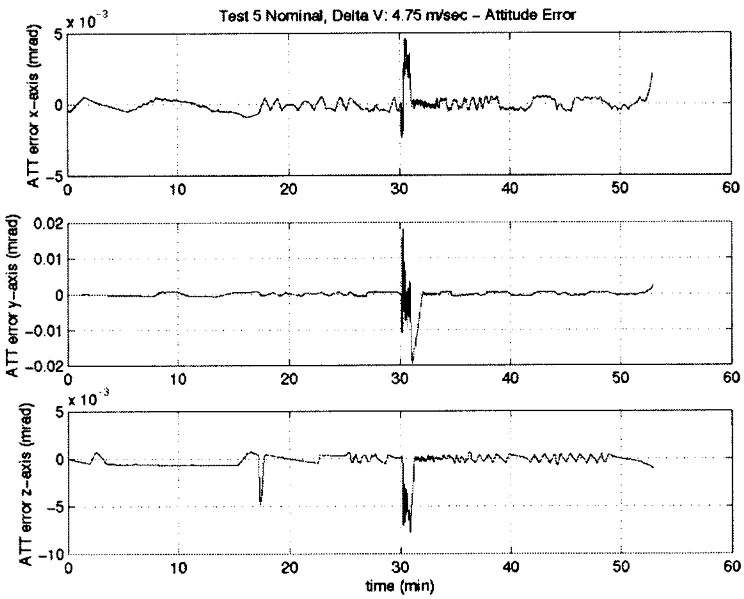

Figure 9. G&C Test Case 5 Nominal Attitude Error

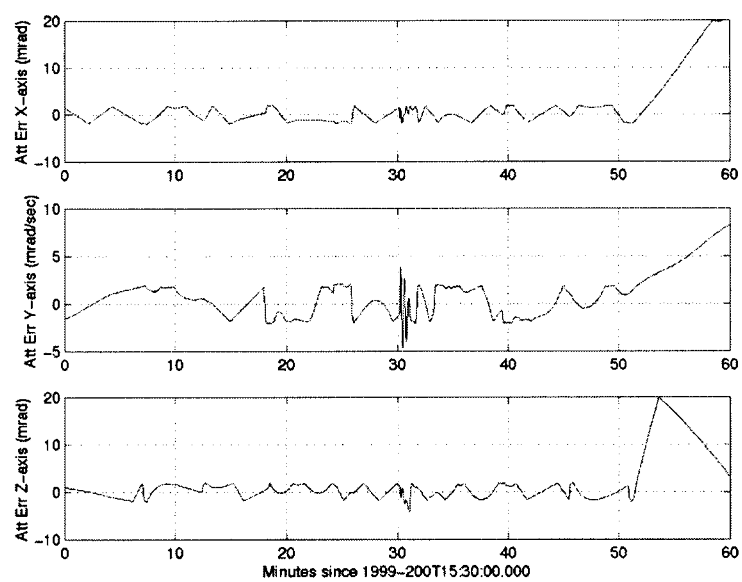

Figure 10. TCM #10 Attitude Error

Table IV assesses the maneuver performance for both TCM 10 and the G&C test case. Both scenarios are required to perform their respective amounts of ΔV with a maneuver execution error constrained by fixed and proportional quantities for both pointing and magnitude errors. By comparing the executed ΔV vector against the desired ΔV vector for the G&C test case, the burn magnitude error was determined to be 0.0087 m/sec and the burn pointing error was calculated to be 0.0177 m/sec. These errors are well below the 3σ requirements of 0.0798 m/sec for magnitude error and 0.1950 m/sec for pointing error using a ΔV of 4.75 m/sec. The results from TCM 10 also prove to be very close and fall within the same magnitude of error. For a 5.13 m/sec maneuver, the magnitude error and pointing error were 0.005 m/sec and 0.0739 m/sec, respectively. For this maneuver, the total magnitude requirement was 0.0838 m/sec and the pointing requirement was 0.2064 m/sec. Further review of Cassini accuracy requirements and system capabilities can be found in Reference 5.

Table IV. TCM Performance Maneuver Execution Error

Performance Parameter	**Requirements (m/sec)**	**G&C Test Results ΔV = 4.75 m/sec**	**TCM 10 Results ΔV = 5.13 m/sec**
ΔV burn magnitude error	< ΔV*0.0105+0.030	0.0087 m/sec (0.0798 m/sec)	0.005 m/sec (0.0838 m/sec)
ΔV burn pointing error	< ΔV*0.030+0.0525	0.0177 m/sec (0.1950 m/sec)	0.0739 m/sec (0.2064 m/sec)

Although there were differences between the G&C test case and TCM 10, comparing the results show that the G&C test does in fact accurately simulate AACS performance during a ΔV maneuver. This provides important assurance that the simulation fidelity is sufficient to generate confidence in results of testing for future mission activities.

CONCLUSION

A set of Guidance & Control test cases was used to verify the Cassini spacecraft Attitude and Control System design. Starting from science and mission requirements, AACS engineers developed these test cases to verify G&C control algorithms embedded in the AACS FSW. At this time, only certain test case results can be compared to actual spacecraft flight data. By comparing the maneuver execution error from the Main Engine Turn to Burn ΔV Control G&C scenario test case and TCM 10 conducted on July 19, 1999, the results prove to be very close and fall within the same magnitude of error. Flight data from future activities, such as Probe ejection, Saturn Orbit Insertion, Probe tracking, and Titan flyby should provide further means of validating G&C test results. Major differences discovered between actual flight data and the simulation are incorporated to the list of new commands, environmental models, and other ongoing updates to the G&C test cases. These changes, as well as with the addition of new G&C test scenarios and the retirement of existing cases, provide an evolving resource in testing AACS performance. Using a reliable test environment and interactive peer reviews, the G&C approach used to verify the Cassini spacecraft Attitude and Control System design can prove to be an effective method for AACS engineers to test their design against mission and science requirements prior to actually performing spacecraft activities. From the initial confirmation that the launch load would properly control the spacecraft to the continued regression testing that verifies compliance to the latest FSW build, the Guidance and Control test cases ensure continued mission success. The Cassini team believes that the excellent behavior of the spacecraft to-date has justified the time and resources invested to develop and maintain this tool.

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ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors wish to thank D. Lam, S. Sarani, G. Hanover, L.Won, and M. Wette, their colleagues at the Jet Propulsion Laboratory, for many helpful discussions.

APPENDIX

5. Test Case 5: Main Engine Turn-to-Burn ΔV Control

5.1 Scenario Description

A main engine burn, TCM2 (Trajectory Correction Maneuver #2), will be executed in the Early Cruise phase of the Cassini mission. This maneuver, like all six Venus-Earth TCMs, is carried out as follows: the sun-pointed S/C is first "sprint" turned to its burn attitude to avoid violating a thermal protection requirement. The main engine ΔV is then carried out at that off-sun attitude before the S/C is "sprint" turned back to its nominal sun-pointed attitude.

5.2 Purpose

The purpose of this test is to ensure that AACS can successfully (a) "sprint" turn the S/C to a desired ΔV inertial direction, (b) execute a commanded ΔV burn using the main engine while meeting all relevant accuracy requirements, and (c) "sprint" turn the S/C back to its nominal sun-pointed attitude. The complete TCM sequence is to be accomplished in less than 30 minutes.

5.3 Applicable Requirements

[565]	24155, 65468
[3-160]	5362, 72335, 73241, 73272
[3-170]	9836, 9838, 9840, 9842, 51028, 51029, 51030, 51031, 51067
[3-200]	67193
[4-2007]	56880, 56901, 57007, 57009, 58118, 69407-8, 69181, 69407, 70106, 70112-3, 70119-20, 70122-24, 70126-28, 70131, 70171, 77664

5.4 Initial Conditions

5.4.1 Hardware state: Prime AFC, IRU, SRU, SSA, VDECU, and MPD are on. The bi-propellant latch valves, ME valve, and both the high and low-pressure helium latch valves are closed, while the MP latch valve is open. All prime CBH's for both the prime and backup thrusters are placed in the auto mode. All others, in particular the ACC, MEVD, BPLVD, HeLVD, EGECU, and EGED, are off (or closed). Main engine A is selected as the prime engine.

The backup AFC is in a "hot backup" state.

5.4.2 S/C's dynamic states:

5.4.2.1 Inertial angular rates: quiescent with rates of 0 deg/sec on all axes.

5.4.2.2 Inertial attitude: The unit vectors of the sunline and the Sun-to-Earth vector in J-2000 coordinate frame are $[1,0,0]^T$ and $[0,1,0]^T$, respectively. Selected base attitude vectors are:

Base Attitude Vectors	Vector Selected
Primary Body	S/C's –Z axis
Primary Inertial	S/C to Sun
Secondary Body	LGA 2
Secondary Inertial	Sun to Earth

5.4.3 AACS Modes:

AACS mode	Home Base
Attitude Determination mode	Celestial-Cruise
Attitude Control mode	RCS Attitude Command

5.4.4 The S/C turns described in Section 5.6 are constrained by the following rate/acceleration limits:

turn order	turn axis	rate (deg/sec)	acceleration (deg/sec^2)	remarks
1	Z-axis	0.25	0.0150	to an intermediate attitude
2	Y-axis	0.75	0.0075	to burn attitude
3	Y-axis	0.75	0.0075	to an intermediate attitude
4	Z-axis	0.25	0.0150	back to sun-pointed

The corresponding turn rate and acceleration limits about the S/C's X-axis are 0.25 deg/sec and 0.0098 deg/sec^2, respectively.

5.4.5 The RCS controller deadband for the S/C turns is 0.5 mrads.

5.5 Inputs

5.5.1 External torques: small external torques are neglected in this test.

5.5.2 S/C's mass and inertia property:

Mass (kg)	**C.M. in body frame** (m)			**Inertia Matrix** ($kg\text{-}m^2$)					
	ex	ey	ez	Ixx	Iyy	Izz	Ixy	Ixz	Iyz
4536.8	-0.029	0.009	1.428	8954.70	8203.91	4807.86	-127.40	112.11	174.87

5.5.3 Desired ΔV: magnitude ΔV = 4.75 m/sec, and the inertial attitude has an unit vector $[+0.906,+0.305,-0.294]^T$ in the J-2000 coordinate frame.

5.5.4 RCS thrust level assumed for this test is 0.85 N.

5.5.5 The center of gimbal rotation of main engine A is located at (0, 241.3, 3317.2) mm in the S/C mechanical coordinate frame. A vector joining the center of gimbal rotation of main engine A to the S/C's c.m. is called the S/C's "pre-aim" vector. Using data from Section 5.5.2, the unit vector of that pre-aim vector in S/C's mechanical frame is [-0.015 –0.122 –0.992].

5.6 Test Execution Summary

Let the S/C's initial conditions be per those given in Section 5.4. The following steps are carried out on receiving the command to execute the TCM:

(1) Alignment of the ME axis:
On/off and open/close the following equipment in the indicated sequence: on the HeLVD, and open the high-pressure helium latch valve. Ten minutes after the high-pressure helium latch valve is open, open first the oxidizer and then the fuel low-pressure helium latch valve. Then off both HeLVDs. On the prime IRU, ACC, EGECU and EGED (full power), and activate the servo loops [EGAPA,EGAQA].

Since the EGAs have been exercised periodically inflight, we assume here that there is not need to perform any additional exercising before the actual ME burn. We simply use the EGAs to align the axis of the prime main engine with the S/C's "pre-aim" vector. Switch to the "celestial-inertial" attitude determination mode.

With the S/C in a quiescent state, perform an inflight ACC bias calibration. This consists of simply reading the ACC output over a 1-minute time duration. If the ACC's accumulated ΔV over this time duration is ΔV_{acc} (m/sec), then the correction to the ACC's bias is given by $\Delta V_{acc}/60$ (m/s^2). The expected value of the bias correction term is less than 2e-3 m/s^2.

(2) Turn the S/C to the desired burn attitude:
Use the thrusters to execute two S/C turns: first about the S/C's Z-axis and the second about the S/C's Y-axis in order to align the pre-aim vector with the desired ΔV attitude. First rotate -119.3 degrees about the Z-axis, followed by a -25.0 degree rotation about the Y-axis. The second approach is adopted here. It can be shown that the unit vector of the S/C's Y-axis at the end of the Z turn (in J-2000 frame) is $[0, -0.8720, -0.4895]^T$. Hence, the base attitude vectors for the Z-axis and Y-axis turns are:

Base Attitude Vectors	Vector Selected	
	Z-axis turn	Y-axis turn
Primary Body	S/C's –Z axis	Pre-Aim vector
Primary Inertial	S/C to Sun	ΔV vector
Secondary Body	S/C's +Y axis	S/C's +Y axis
Secondary Inertial	$[0, -0.8720, -0.4895]^T$	$[0, -0.8720, -0.4895]^T$

The rate and acceleration limits of these turns are given in Section 5.4.4. The estimated total turn time is:

Z-axis rotation:

acceleration time	= 0.25/0.0150	= 16.67 sec
acceleration angle	= $0.5*0.0150*16.67^2$	= 2.08 deg
coast time	= (119.3-2*2.08)/0.25	= 460.56 sec
coast angle	= 0.25*597.04	= 149.26 deg
deceleration time	= 0.25/0.0150	= 16.67 sec
deceleration angle	= $0.5*0.0150*16.67^2$	= 2.08 deg

Summing up the three different phases in the turn, the total Z-axis rotation time is predicted to be about 494 seconds.

Y-axis rotation:

acceleration time	= sqrt(25/0.0075)	= 57.73 sec
acceleration angle	= $0.5*0.0075*57.73^2$	= 12.5 deg
coast time		= 0 sec
coast angle		= 0 deg
deceleration time	= sqrt(25/0.0075)	= 57.7 sec
deceleration angle	= $0.5*0.0075*57.73^2$	= 12.5 deg

Total Y-axis rotation time is 116 seconds.

Hence, the total turn time is 494+300+116 = 910 seconds (15.17 minutes), where we have allowed for a 5-minutes settling time between the turns.

(3) PMS settling time:
Upon the completion of the Y-axis sprint turn, allow for a 3-minute settling time before initializing the ME burn.

(4) ME burn:
Turn on the BPLVD and MEVD. Open first the oxidizer and then the fuel latch valve. Switch to the "ME ΔV control" AACS mode, with the "TVC" attitude control mode. Begin the "burn" by opening the ME valve. During the burn, both the X and Y axes of the S/C are controlled by gimballing the main engine. The motion about the Z-axis is controlled by pulsing the RCS Y-facing thrusters in couple. An accelerometer is used to provide estimate of the magnitude of the accumulated ΔV during the burn, and maneuver termination is scheduled accordingly. The expected burn time is:

$$4.75 \text{ m/sec} * 4536 \text{ kg}/445 \text{ N} = 48.4 \text{ seconds.}$$

The min/max burn times are selected as follow: the S/C's mass knowledge uncertainty is 2.2% (3-170 58548), and the main engine thrust level uncertainty is 5% (3-170 58449). Hence,

$$t_{min} = 4.75*4536*(1-0.022)/[445*(1+0.05)] = 45.1 \text{ sec}$$

$$t_{max} = 4.75*4536*(1+0.022)/[445*(1-0.05)] = 52.1 \text{ sec}$$

When the burn is terminated, an autonomous transition back to a "Home Base" AACS mode with a "RCS Attitude Command" mode is made.

(5) AACS settling time:
Close the fuel and oxidizer latch valves, and the ME valve. Allow for a 2 minutes settling time between the termination of the burn and the beginning of the sprint turn back to the sun-pointed attitude. During this settling time, thrusters will be used to control the S/C. Also, the ACC and the prime EGECU, EGED, MEVD, and BPLVD are turned off.

(6) Turn back to the sun-pointed attitude:
Use the thrusters to execute an unwind turn in order to bring the S/C back to its initial sun-pointed attitude. The turn time is identical to that estimated in (2). Upon the completion of the unwind turn, use the thrusters to bring the sun-pointed S/C to a quiescent state with inertial rates below 0.01 deg/sec on all axes.

On/off and open/close the following equipment in the indicated sequence: on both HeLVDs, close first the fuel and then the oxidizer low-pressure helium latch valves. Wait ten minutes before closing the high-pressure helium latch valve. Then turn off both HeLVDs. Transition back to the "Home Base" AACS mode with a "Celestial-Cruise" attitude determination mode and a "RCS Attitude Command" mode, then turn off the prime IRU.

Determine the total time duration with the S/C off sun-pointed: from the beginning of the Y-axis turn (in step (2)) to the end of Y-axis turn (in step (6)). Let ΔV_{actual} be the component of the ΔV vector (that was generated across step (4)) that is in the desired ΔV direction. Let ΔV_{perp} be the component that is perpendicular to the desired ΔV direction. Ascertain that the following ME propulsive maneuver execution error requirements are met:

(a) $|\Delta V_{actual} - \Delta V|$ < 80 mm/sec;
and (b) $|\Delta V_{perp}|$ < 153 mm/sec.

where $(4.75 \cdot 0.0105+0.03) \cdot 1000=80$, and $(4.75 \cdot 0.021+0.053) \cdot 1000=153$ mm/sec. See also Tables 3-170:-01, 02, 03, and 04 for details.

5.7 Expected Results

AACS can: (a) open/close and on/off various latch valves and AACS equipment to support the turn-burn-turn sequence, (b) complete the turns and burn in time duration that were estimated in Section 5.6, (c) accomplish the entire sequence in less than 30 minutes, and (d) meet the above stated ME propulsive maneuver execution error requirements.

5.8 Test Variants

5.8.1 Repeat the entire TCM sequence with a much larger ΔV of 166 m/sec. The expected burn time is:

166 m/sec*4536 kg/445 N = 1692.1 seconds

The min/max burn times are selected as follow: the S/C's mass knowledge uncertainty is 2.2% (3-170 58548), and the main engine thrust level uncertainty is 5% (3-170 58449). Hence,

$$t_{min} = 166*4536*(1-0.022)/[445*(1+0.05)] = 26 \text{ m } 16.1 \text{ s}$$
$$t_{max} = 166*4536*(1+0.022)/[445*(1-0.05)] = 30 \text{ m } 20.3 \text{ sec}$$

Hence, AACS can accomplish the entire turn-burn-turn sequence in less than 30 minutes. The ΔV generated should satisfy the following inequality:

$$|\Delta V_{actual} - \Delta V_{new}| < 1.773 \text{ m/sec},$$
$$|\Delta V_{perp}| < 3.539 \text{ m/sec}.$$

5.8.2 Perform the entire TCM sequence without the "pre-aiming" (see step(1)). That is, the ME axis is placed in its "null" position at the start of the turn-burn-turn sequence. The expected result is identical to that stated in Section 5.7, because the spacecraft should automatically perform the preaim adjustment during the transition from homebase to ME ΔV mode.

5.8.3 Change the minimum/maximum burn termination times used in Section 5.6 to the following combinations:

(a) [min,max] = [40,45] seconds.
In this case, the burn will be terminated by the specified maximum burn time (= 45 seconds), and the ΔV generated in step (4) should satisfy the following new inequality:

$$\Delta V_{new} = 45*445/4536 = 4.415 \text{ m/sec},$$
$$|\Delta V_{actual} - \Delta V_{new}| < 76 \text{ mm/sec},$$
$$|\Delta V_{perp}| < 145 \text{ mm/sec}.$$

Other results are identical to those given in Section 5.7.

(b) [min,max] = [55,60] seconds. In this case, the burn will be terminated by the specified minimum burn time (= 55 seconds), and the ΔV generated in step (4) should satisfy the following new inequality:

$$\Delta V_{new} = 55*445/4536 = 5.39 \text{ m/sec},$$

	$\|\Delta V_{actual} - \Delta V_{new}\|$	< 86.6 mm/sec,
and	$\|\Delta V_{perp}\|$	< 166.2 mm/sec.

Other results are identical to those given in Section 5.7.

5.8.4 Repeat the entire TCM sequence with a much larger ΔV of 750 m/sec. The expected burn time is:

750 m/sec*45364536 kg/445 N = 2 hr 7 min 24.9 sec.

The min/max burn times are selected as follow: the S/C's mass knowledge uncertainty is 2.2% (3-170 58548), and the main engine thrust level uncertainty is 5% (3-170 58449). Hence,

t_{min} = 750*4536*(1-0.022)/[445*(1+0.05)] = 01:58:41
t_{max} = 750*4536*(1+0.022)/[445*(1-0.05)] = 02:07:25

Hence, AACS <u>cannot</u> accomplish the entire turn-burn-turn sequence in less than 30 minutes. However, the ΔV generated should satisfy the following new inequality:

$\|V_{actual} - \Delta V_{new}\|$	< 7.905 m/sec,
$\|\Delta V_{perp}\|$	< 22.553 m/sec.

5.8.5 Perform the entire nominal sequence using the engine B as the prime engine. The expected result is identical to that stated in Section 5.7. Make sure that the preaim vector is adjusted to accommodate engine B.