

Cassini Spacecraft In-Flight Swap To Backup Attitude Control Thrusters

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NASA's Cassini Spacecraft, launched on October 15th, 1997 and arrived at Saturn on June 30th, 2004, is the largest and most ambitious interplanetary spacecraft in history. In order to meet the challenging attitude control and navigation requirements of the orbit profile at Saturn, Cassini is equipped with a monopropellant thruster based Reaction Control System (RCS), a bipropellant Main Engine Assembly (MEA) and a Reaction Wheel Assembly (RWA). In 2008, after 11 years of reliable service, several RCS thrusters began to show signs of end of life degradation, which led the operations team to successfully perform the swap to the backup RCS system, the details and challenges of which are described in this paper. With some modifications, it is hoped that similar techniques and design strategies could be used to benefit other spacecraft.

Acronyms

<i>AACS</i>	= Attitude and Articulation Control Subsystem
<i>DOY</i>	= Day of Year
<i>FSW</i>	= Flight Software
<i>GSW</i>	= Ground Software
<i>msec</i>	= milli-second (0.001 seconds)
<i>MTA</i>	= Mono-propellant Tank Assembly
<i>NASA</i>	= National Aeronautics and Space Administration
<i>NAV</i>	= Navigation
<i>ORS</i>	= Optical Remote Sensing
<i>OTM</i>	= Orbit Trim Maneuver
<i>RCS</i>	= Reaction Control System
<i>rpm</i>	= revolutions per minute
<i>RWA</i>	= Reaction Wheel Assembly
<i>S/C</i>	= Spacecraft

I. Introduction

The Cassini spacecraft was launched on 15 October 1997 by a Titan 4B launch vehicle. After an interplanetary cruise of almost seven years, it arrived at Saturn on June 30, 2004. To save propellant, Cassini made several gravity-assist flybys: two at Venus and one each at Earth and Jupiter. Figure 1 shows the interplanetary trajectory design of the Cassini mission.

In order to meet the attitude control and navigation requirements of the orbit profile at Saturn, Cassini is equipped with a bipropellant Main Engine Assembly (MEA), a monopropellant thruster-based Reaction Control System (RCS), and a Reaction Wheel Assembly (RWA). The Main Engine is generally used for large maneuvers requiring a translational change in velocity (ΔV) of more than 0.3 m/sec. The RCS thrusters are used for smaller maneuvers, and for special instances of attitude control. The RCS thrusters have more control authority than the RWA, and for this reason they are used to control the spacecraft during low altitude Titan flybys, in order to maintain attitude control in the presence of Titan atmospheric torque. The RCS system is also needed to maintain attitude during momentum biases of the RWAs, which are performed periodically to optimize the RWA momentum

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vector to minimize wheel rate regimes that are deemed unhealthy. The RWA subsystem controls the attitude for most other situations, as it provides better pointing and does not consume hydrazine.

CASSINI INTERPLANETARY TRAJECTORY

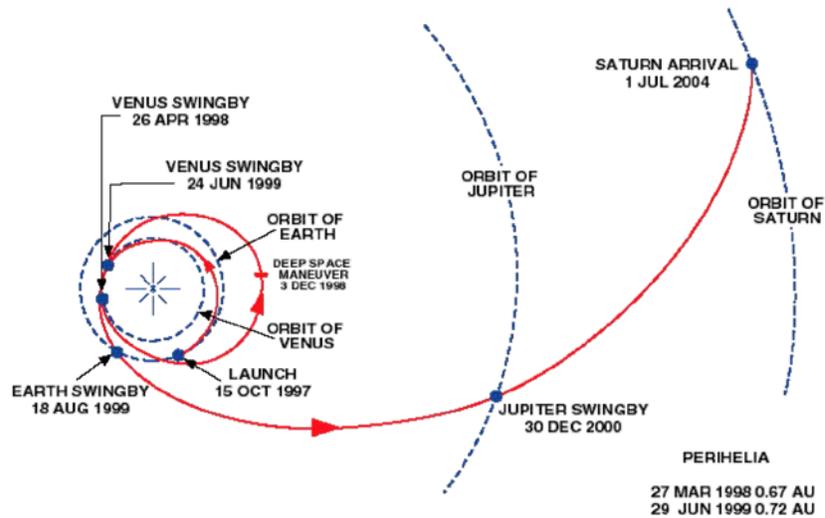


Figure 1. Cassini Interplanetary Trajectory

II. Cassini Reaction Control Subsystem Description

Cassini has two independent branches of monopropellant hydrazine RCS thrusters¹, a prime and offline backup, each capable of providing translational velocity changes and maintaining complete 3 axis control. The arrangement of the thrusters with respect to spacecraft coordinates is shown below in Figures 2 and 3.

The Z-facing thrusters are not couples, so RCS attitude control about the spacecraft X and Y axes induce a translational delta V, which needs to be incorporated into the trajectory design and analysis. Cassini is equipped with two independent branches of RCS thrusters, as shown below in Figure 4.

Both 'A' and 'B' branches share the same helium pressurized monopropellant hydrazine fuel tank, which made use of a single helium pressurant recharge bottle in 2006. The system is not regulated, and has been operating in blow down mode ever since. Downstream of the helium pressurized hydrazine tank, the system is entirely redundant. Both thruster branches are isolated from the pressurized hydrazine tank via latch valves (LV), with LV 40 set to open at launch for the 'A' branch, and LV 41 closed at launch, such that the 'B' branch thrusters remained unused, albeit in a 'wet' pressurized state, for 11 years until needed. The 'A' branch was designated the prime

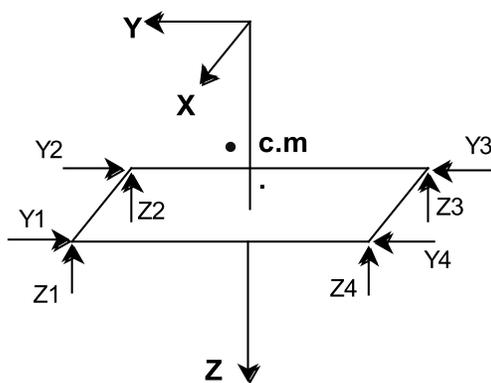


Figure 2. Cassini RCS Thruster Orientation

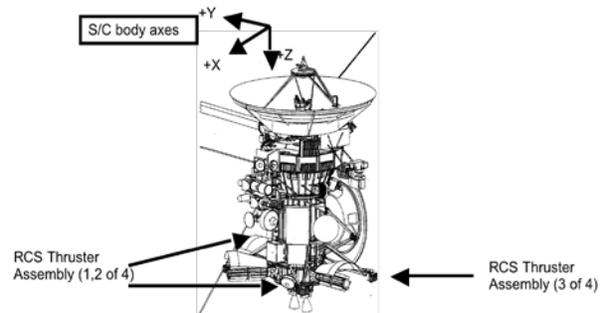


Figure 3. Cassini RCS Thruster Location

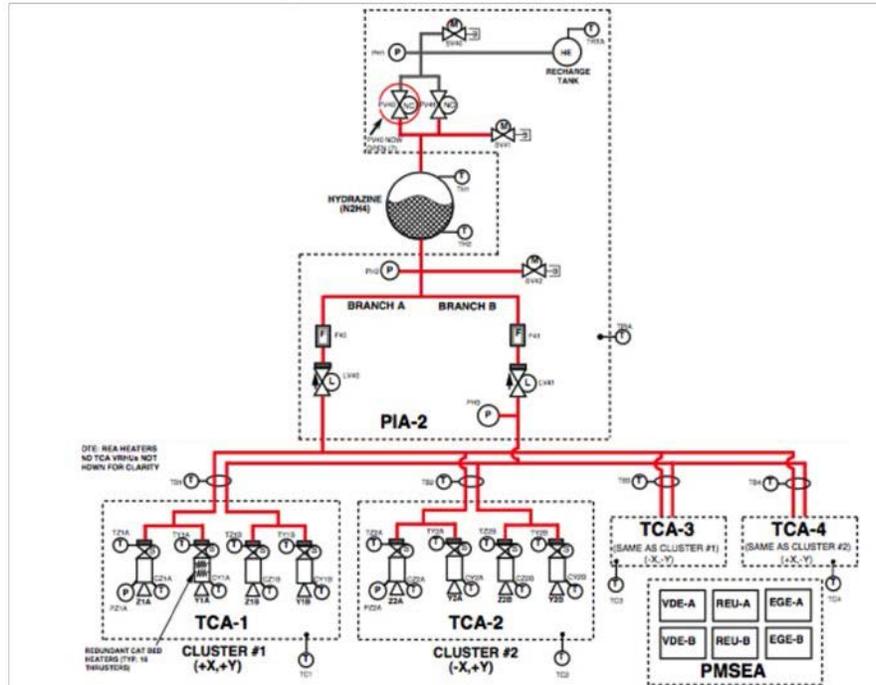


Figure 4. Cassini RCS Schematic

branch at launch. The intention was to keep branch ‘B’ as a dedicated backup- it remained unused until branch ‘A’ began to show signs of degradation.

The RCS thrusters are separated into four clusters based on location, such that the ‘A’ branch thrusters are essentially collocated with their corresponding ‘B’ branch thrusters. Each thruster has a pair of redundant catalyst bed heaters (CBH), with temperature sensors located at the thruster inlets and catalyst bed heater locations. The ‘A’ branch Z-facing thrusters have combustion chamber pressure sensors, a feature that is unique for monopropellant thrusters of this size, but which has proven to be invaluable in determining the health of the thrusters.

For an RCS Orbit Trim Maneuver (OTM), Cassini employs the “Turn and Burn” Strategy. The spacecraft turns the $-Z$ body axis to the delta V direction under RWA control. It then transitions to RCS control, and all four Z-facing thrusters fire, off pulsing as needed to maintain the desired burn attitude about the spacecraft X and Y body axes, with the Y-facing thrusters firing to maintain the roll attitude about the Z axis. The RWA subsystem is not used for attitude control during the burn.

III. Problem With Branch ‘A’ Thrusters

In October 2008, two of the eight ‘A’ branch RCS thrusters, which had been used flawlessly since launch for 11 years as the prime set, began to show signs of degradation.² As part of the reconstruction of the 169th Orbit Trim Maneuver (OTM 169), it was discovered that the error in the achieved velocity change with respect to the commanded velocity change was an order of magnitude larger than usual in the under burn direction, implying that at least one of the four Z-facing thrusters had underperformed. Cassini’s propulsion engineers were able to provide corroborating evidence by examining the RCS combustion chamber pressure sensor measurements, which are only available in the RCS system on the ‘A’ branch Z-facing thrusters³. The propulsion engineers used a term “chamber pressure roughness,” which they defined as the standard deviation of the pressure measurements of a given burn, divided by the mean pressure of the burn. Chamber pressure roughness provides a measure of the pressure variations during a burn. In general, thrusters that are nearing their end of life begin to burn more roughly³. By October of 2008, the Z-facing thrusters had experienced approximately two times as much throughput as the Y-facing thrusters (due to the fact that RCS OTMs almost exclusively use the Z-facing thrusters and RWA momentum biases tend to mostly use the Z-facing thrusters), so it fit expectations that the Z-facing thrusters should be the first to show signs of end of life degradation.

The Cassini propulsion team recommended an in-flight swap to the backup thruster branch ‘B’ because this branch had never been used in flight, and thus had pristine thrusters and catalyst beds. Additionally, the team recommended performing as many upcoming RWA momentum biases as possible using primarily the Y-facing

thrusters. RWA momentum biases are a significant contributor to total thruster throughput. Changing the RWA momentum bias process to emphac is a significant change in operations that decreases the throughput on the Z-facing thrusters, while simultaneously increasing the usage of the Y-facing thrusters. The development and implementation of these “Y-thruster” RWA momentum biases is a significant undertaking, and is described in Ref. 4.

IV. Swap To The ‘B’ Branch

The swap to the ‘B’ thruster branch was completed in flight over the course of nine days in March 2009. We took a very conservative and systematic approach, since the ‘B’ branch thrusters had never been used. All swap related events were to be performed while Earth pointed over a downlink pass, which occurs for about 8-9 hours every day. For the sake of safety, the normal background science sequence was cancelled, and several commanding events required ground controller confirmation before continuing with the swap process. Now that the hardware necessary for a swap has been exercised successfully, the process could be accelerated if a swap (or partial swap) is ever needed in the future.

A. Pressurize The ‘B’ Branch

The ‘B’ branch thrusters were isolated from the hydrazine tank by Latch Valve (LV) 41, as shown in Figure 4. In order to open this valve, the AACS computer needed to turn on the Monopropellant Driver ‘B’ (MPDB) assembly first, as this is the electronics box that controls the valve (along with the RCS ‘B’ branch primary CBHs). Thus on day of year 2009-069, the MPDB was turned on and LV41 was opened.

AACS was able to verify via contact switch telemetry that the valve had opened, and the propulsion team was able to see the expected change in line pressure, as the line pressure equilibrated with the hydrazine tank pressure. The AACS team then watched the RWA rates and verified that the rates remained constant, which precluded the possibility of a ‘B’ Branch thruster leak, as a leak would induce a torque on the spacecraft, which would be countered by the RWA control algorithm, causing the wheel rates to change in order to compensate.

After verification of the successful ‘B’ Branch pressurization, the ‘B’ branch primary catalyst bed heaters were turned on. The thermal team verified proper heating of the catalyst beds via telemetry, as shown in Figure 5. Each RCS thruster has two redundant catalyst bed heaters; either one is sufficient for proper thruster performance. Under nominal operation, one catalyst bed heater warms the catalyst bed whenever the thruster is not actively firing.

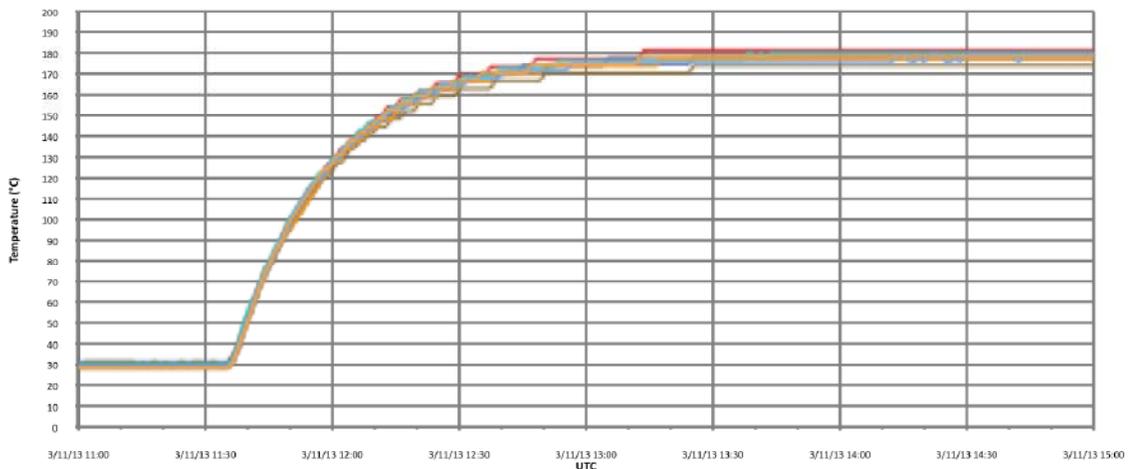


Figure 5. ‘B’ Branch Cat Bed Heater Power On Temperature

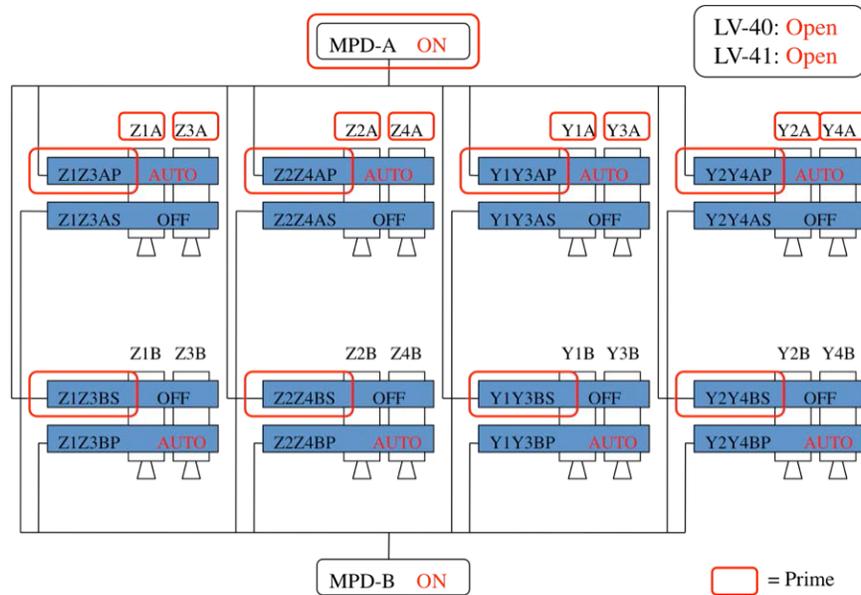


Figure 6. State of RCS System After 'B' Branch Pressurization and 'B' Branch CBH Power On

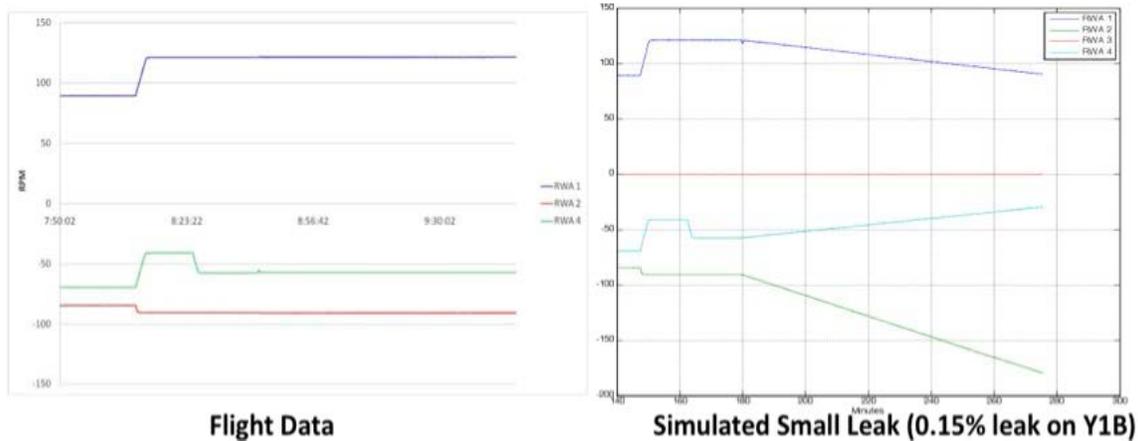
The catalyst bed heaters are designated primary and secondary, which is a permanent designation, but the AACS Fault Protection (AACS FP) designates a prime and backup, which changes based on the perceived health of the device. In addition to the FP designations, each catalyst bed heater can be in one of three states: ON, which means the catalyst bed heater is on constantly, even when its corresponding thruster is firing, OFF, which means it is not powered at all, and AUTO, which means it is on when it's corresponding thruster is not firing, and off when it is firing. Figure 6 illustrates the state of the MPDs and CBHs at the end of the downlink pass on DOY 2009-069.

B. Swap To B Branch

Once the B branch thrusters had been successfully connected to the hydrazine tank and verification that the B branch catalyst bed heaters had been powered on, the operations team gave a "go" to proceed with the swap, and the background sequence was deactivated. The next available downlink pass was on 2009-071. The operations team took advantage of that day by radiating a file of commands that performed the following. First, the AACS engineering telemetry schedules were modified to accommodate 'B' Branch thruster information. The B branch RCS thrusters were then designated as "prime" by the AACS FSW. The 'B' branch primary catalyst bed heaters were designated as prime, and the secondary 'A' branch catalyst bed heaters were designated as prime, which are commanded by MPDB.

At this point, Cassini was on the 'B' branch RCS system, but the spacecraft was under RWA control, and the 'B' branch thrusters had not yet been used. Once the ground verified that all was well, another set of commands was radiated to the spacecraft which exercised the 'B' branch thrusters for the first time, in the safest way possible. The commands first caused the AACS control mode to go from RWA control to RCS control. At that point, the spacecraft was "dead banding," using the RCS 'B' Branch thrusters to maintain attitude, and the firings were short and as expected. In RCS control, the RWA wheel rates were then commanded to change in a special manner such that the reaction torques from the RWA motors acting on the spacecraft would cause the RCS control algorithm to fire all eight thrusters enough times to characterize their performance. Using the RWA wheels in this manner allowed for the spacecraft to remain quiescent and Earth-pointed. If any thruster had been stuck closed, ground simulations showed that the remaining thrusters would have to fire much more to make up for it. AACS engineers verified real time that the thruster firing on-times strongly matched what was predicted from ground simulations, which lent confidence to the fact that none of the thrusters were stuck closed.

The final commanding on DOY 2009-071 caused a transition from RCS to RWA control. The remaining hour of downlink was used to confirm that the RWA rates remained constant, which verified that none of the 'B' branch thrusters were stuck open after their first time usage. Ground simulation showed that a small thruster leak induced large changes in RWA wheel rates, but the flight telemetry was constant, as shown in Figure 7. The state of the RCS system following the activities on 2009-071 is shown below in Figure 8.



C. v Figure 7. Flight RWA Rate Data Confirming No Thruster Leak After First 'B' Branch Usage

The following day, DOY 2009-072, the plan for the operations team was to verify the RCS 'B' branch ability to maintain pointing control at various commanded dead band values, all the while maintaining two way communication with the spacecraft. Once the initial health of the spacecraft was evaluated at the beginning of the downlink pass (still in RWA control), commands were radiated to transition from RWA to RCS control, the RWA wheels were spun down to 0 rpm and turned off, and the RCS control system maintained three axis control to within 2 mrad about the spacecraft X axis, 2 mrad about the Y axis and 20 mrad about the Z axis. This is a common dead band limit for downlink, where the spacecraft is permitted to drift about the Z axis by +/- 20 mrad and still maintain communication with Earth, as the High Gain Antenna (HGA) is pointed along the spacecraft -Z axis. The RCS system performance was entirely as expected, as shown in Figure 9.

This was followed by periods of dead banding with 2,2,2 mrad, 0.5, 2, 0.5 mrad, and 0.5,0.5,0.5 mrad. The spacecraft maintained excellent pointing control through all four periods and then transitioned back to RWA control near the end of the downlink pass.

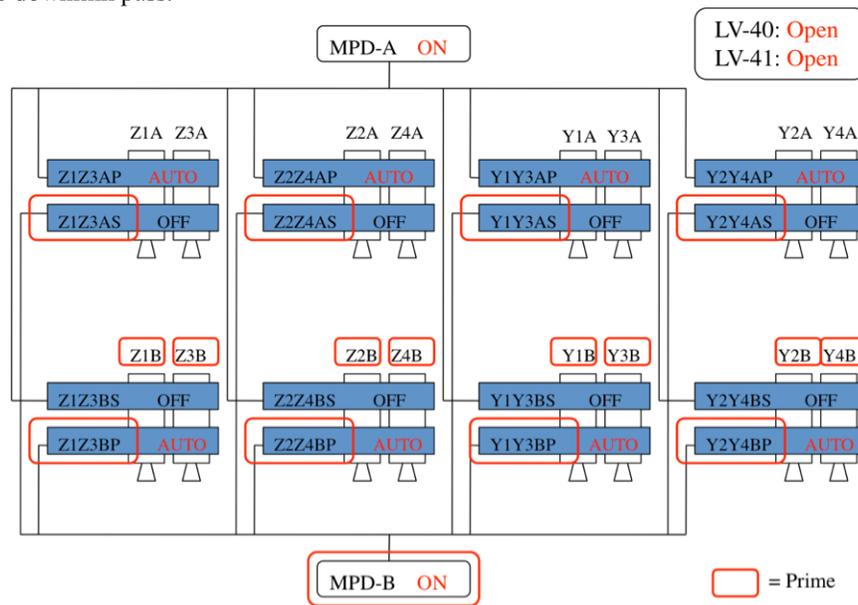


Figure 8. State of RCS System After 'B' Branch Swap on DOY 2009-071

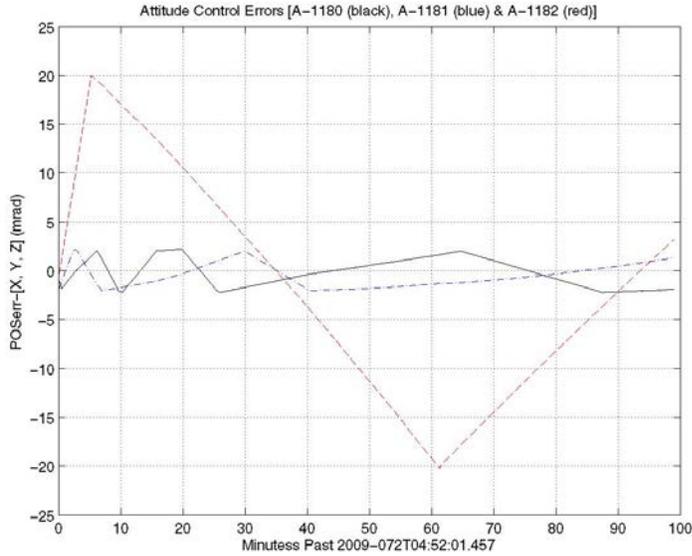


Figure 9. ‘B’ Branch Dead Banding on DOY 2009-072

90° “slow” turns about the Y and X body axes, respectively, and then performed identical fast turns.

The AACS analysis team made use of these turns to estimate the average thrust of the thruster pairs that fired for each turn. Making use of the knowledge of the spacecraft inertia (I), moment arms ($L + CM$), spin rate delta ($\Delta\omega$), and thruster on-times (ΔT), in the following representative equation, the average thrust (F_{RCS}) was calibrated to be 0.78 N, which closely matched the propulsion team estimate of 0.81 N, which was based on models of the tank pressures and temperatures.

$$F_{RCS} = \frac{I_{xx}\Delta\omega_x}{(L_y + CM_y)(\Delta T_{on,Z3} + \Delta T_{on,Z4})} \quad (1)$$

After returning to Earth at the end of the pass, the spacecraft was left in the RCS control mode overnight, to verify proper control behavior. Namely, the transition from RCS “high rate” mode to RCS “low rate” mode was

verified, which incorporates different gains and shorter pulse widths, designed to minimize dead band firing for periods where an attitude is maintained quiescently over long duration, see Figure 10.

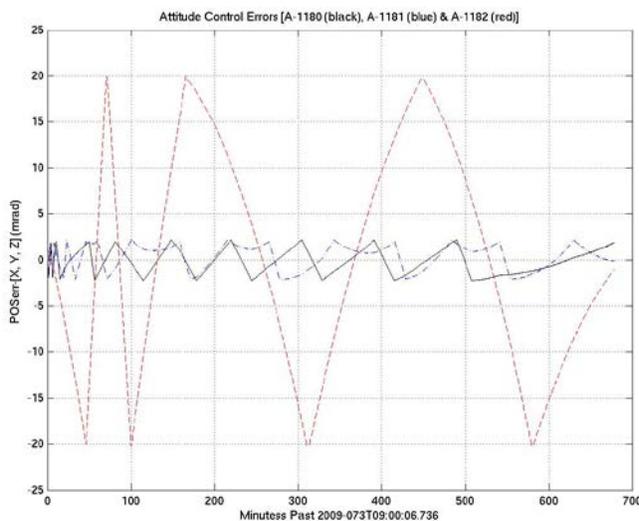


Figure 10. Long Term ‘B’ Branch ‘Low Rate’ Deadbanding on DOY 2009-073

D. Verify B Branch Turning Ability

The next downlink pass occurred on DOY 2009-073. The operations team verified the initial spacecraft health once again, and then radiated commands to perform various slews about all three body axes, to determine the ability of the RCS ‘B’ branch thrusters to achieve the desired rates and attitudes.

First the spacecraft was once again commanded to transition from RWA to RCS control, and the wheels were spun down to 0 rpm and turned off. Then, the spacecraft performed “slow” 90° turns (at 1.1 mrad/sec) about the spacecraft +Z and -Z axis. A similar set of 90° “fast” turns (at 4.54 mrad/sec) was also commanded and two way communication with Earth was maintained. The next set of turns, however, would force the spacecraft to break communication with Earth for the first time, while under ‘B’ branch control. The spacecraft performed

E. Post Swap Clean Up

After the RCS system was allowed to maintain pointing for two days, the team performed clean up activities on DOY 2009-074. This released the spacecraft from engineering checkout activities and freed it for scientific use.

The RWA wheels were spun up to the desired rates necessary to maintain wheel health, given the upcoming scientific slews that would be performed. The spacecraft transitioned from RCS to RWA control, and some final telemetry schedules were reconfigured to optimize for ‘B’ Branch visibility. At last, the ‘A’ branch primary catalyst bed heaters and the MPD A were turned off, so the final spacecraft configuration matched that shown in

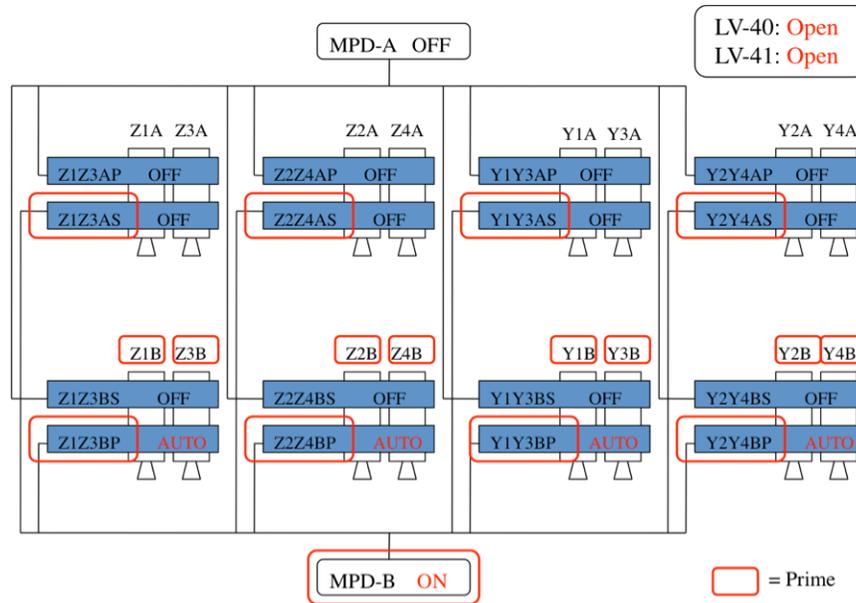


Figure 11. Final State of RCS System After ‘B’ Branch Swap

Figure 11.

The propulsion team decided to leave LV-40, the latch valve that pressurizes the ‘A’ branch, in the open state. If we ever need to swap back to the ‘A’ branch, it is already in position, alleviating the stuck closed possibility. Additionally, there is no pressure transducer on the ‘A’ branch line, so if LV-40 were closed, the team would not have any visibility into the operation of the back pressure relief capability of LV-40, which is needed to handle the temperature driven pressure changes that accompany a locked liquid line.

Additional calibrations were performed over the following days after the swap, to further refine and improve the ‘B’ branch performance. Jerry Jones, from the Cassini Navigation team, devised a method to calibrate the thrust of the Z-facing thrusters, using a novel approach that made use of Doppler data, RWA momentum change, and thruster on-times⁵. For small RCS thruster pulses, the error in the knowledge of the thrust decay time constant becomes significant, so the average thruster decay time constant was estimated, using a technique described in Ref. 6.

F. Conclusion

The Cassini spacecraft has encountered many operational challenges over the span of its 13 year mission since launch, not the least of which was the serious degradation of the ‘A’ branch Reaction Control System thrusters that necessitated an in-flight swap to the ‘B’ branch. The swap was successfully performed over several days in March of 2009, and consisted a complex procedure of multiple teams providing analysis and ground in the loop control, the details of which are described in this paper.

Cassini continues to operate flawlessly on the ‘B’ branch, providing unparalleled science return from Saturn and its moons.

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