Cassini Attitude and Articulation Control Subsystem Fault Protection Challenges During Saturn Proximal Orbits

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NASAs Cassini Spacecraft, launched on October 15th, 1997 arrived at Saturn on June 30th, 2004, is the largest and most ambitious interplanetary spacecraft in history. As the first spacecraft to achieve orbit at Saturn, Cassini has collected science data throughout its four-year prime mission (2004–08), and has since been approved for a first and second extended mission through 2017. As part of the final extended mission, Cassini will begin an aggressive and exciting campaign of high inclination low altitude flybys within the inner most rings of Saturn, skimming Saturn's outer atmosphere, until the spacecraft is finally disposed of via planned impact with the planet. This final campaign, known as the proximal orbits, presents unique fault protection related challenges, the details of which are discussed in this paper.

Nomenclature

AACS	=	Attitude and Articulation Control Subsystem
CBH	=	Catbed Heater
FP	=	Fault Protection
FSDS	=	Flight Software Development Suite
FSW	=	Flight Software
ITL	=	Integrated Test Laboratory
ME	=	Main Engine
MPD	=	Mono-propellant Driver Unit
RCS	=	Reaction Control System
RWA	=	Reaction Wheel Assembly
S/C	=	Spacecraft
VDECU	=	Valve Driver Electronics Controller Unit

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. The prime mission extended from June 2004 to June of 2008, during which Cassini successfully performed 41 encounters with the moon Titan. Ground controllers deployed the Huygens probe in December of 2004 and a successful Probe Relay of Huygens science data occurred during its descent and landing on Titan in January of 2005. The operation of Cassini was given a 2-year extension in from mid-2008 to September of 2010. This "Equinox" mission included the period where the sunline lay in the ring plane and consisted of twenty-eight flybys of Titan, and eight Enceladus flybys.

A final extension to the mission, the Solstice mission, is underway, with plans to continue 4 months beyond Saturn's Northern hemisphere summer solstice in May 2017. To ensure Cassini does not contaminate any of Saturn's moons, it will intentionally crash into Saturn -- ending the mission on September 15, 2017. Leading up to this spectacular end, Cassini will perform a set of 22 proximal orbits, where the spacecraft will cross Saturn's equator of the inner most rings, dropping to as low as 1620 km of the 1-bar atmospheric pressure altitude of the planet.

This five month ballistic portion of the mission is called the proximal phase, with the spacecraft repeatedly flying through a 3000 km band, previously imaged by Cassini to be relatively clear from obstructions. Cassini has never before skimmed through Saturn's atmosphere, or come this close to dense ring material.

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The proximal orbit portion of Cassini's mission poses several unique challenges that need to be managed and overcome by the operations team. Fuel is a consideration, as the spacecraft is extremely low on bipropellant needed for main engine maneuvers. Should the fuel or oxidizer be depleted in the middle of a crucial burn, the on board fault protection software needs to respond in a manner that will keep the spacecraft safe, and not prevent the operations team from completing the required velocity change using reaction control subsystem (RCS) thrusters.

Particle impacts at the high velocity ring plane crossings are a concern, as the on board fault protection software needs to be robust to sensor damage, particularly to that of the sun sensor assemblies (SSAs). Statistical analysis has been performed to show the risk of SSA damage during a proximal ring plane crossing is low[1], but the SSAs are considered vital AACS sensors, and many fault protection responses rely on a healthy SSA to find the sun and reacquire celestial reference. Should both SSAs be damaged, the FSW will need to be patched to preclude dropping celestial reference due to fault responses. This mode of operating is called Deluxe Attitude Initialization (Deluxe AI), and has never been tested in flight, but has been extensively tested in multiple platforms on the ground.

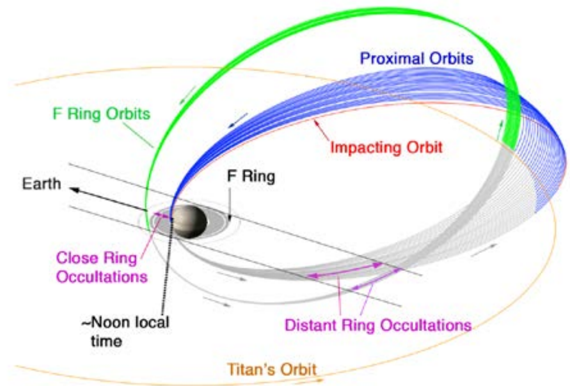

Figure 1. Cassini Proximal Orbits.

The geometry of the proximal orbits presents challenges never faced before. The Stellar Reference Unit (SRU) provides celestial reference to the FSW, and when bright bodies, such as Saturn and its rings, enter the SRU field of view, the star identification (SID) algorithm needs to be suspended. During this period of suspension, the attitude estimate is propagated by the gyros alone. Much simulation work has been done to show that the proximal orbit flybys can be accomplished without the need to suspend the star identification algorithm for periods of time that would be too long for the gyros to accurately propagate an attitude estimate.

Electrical power margin is a concern at the end of the mission, as well. Cassini makes use of three radioisotope thermoelectric generators (RTGs), which currently provide the spacecraft with about 600 watts of power. Near the end of the mission, operational changes will need to be adopted such that unnecessary power loads can be shed, depending on the needs of the spacecraft at that time. One such example, the incorporation of mixed branch catbed heaters in the contingency case of a mixed branch RCS configuration, was extensively tested, and is described in this paper.

II. Cassini Attitude Control Subsystem Fault Protection

Since Cassini operates far from Earth, where the where the one-way light time can be up 92 minutes, the Attitude and Articulation Control Subsystem (AACS) flight software (FSW) makes use of an extensive suite of fault protection (FP), which was designed and included from the beginning as an integral part of the FSW, rather than an add-on. These Fault Protection algorithms perform autonomous detection, isolation, and recovery from failures of AACS assemblies and AACS-controlled propulsion units. The primary components of the fault protection software are: *Error Monitors*, which test performance measures against expectations, *Activation Rules*, which evaluate subsets of the error monitor outputs to

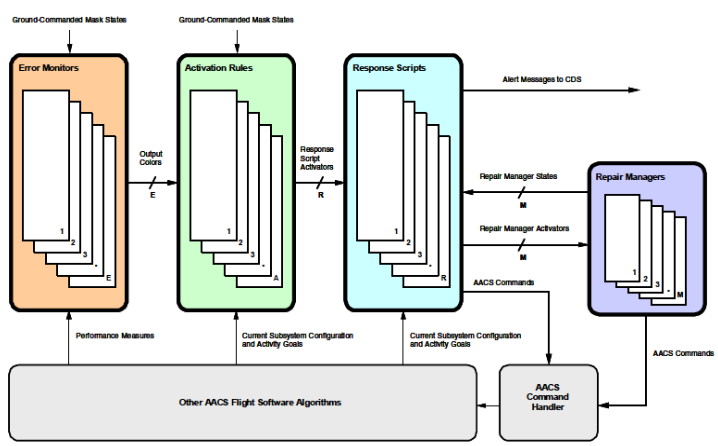

Figure 2. Architecture of AACS Fault Protection[1]

make a diagnosis, *Response Scripts*, which are called on by activation rules to isolate failed equipment and recover a level of subsystem functionality, and *Repair Managers*, which track the success or failure of past corrective measures[1].

III. Cassini Attitude Control Hardware

Cassini is stabilized about its three axes via one of two independent methods: reaction control subsystem (RCS) thrusters, and a reaction wheel assembly (RWA). The RCS thrusters have more control authority, 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 torques. Thrusters are also used to bias the reaction wheels' angular momenta, to de-tumble the spacecraft after release from the launch vehicle, to perform a spiral search for the Sun as the first step in its acquisition of inertial attitude, to perform small trajectory correction maneuvers, and to slew the spacecraft to a thermally safe and command-able safe attitude in case of spacecraft anomaly, among others. The arrangement of the thrusters with respect to spacecraft coordinates is shown below in Figures 3 and 4.

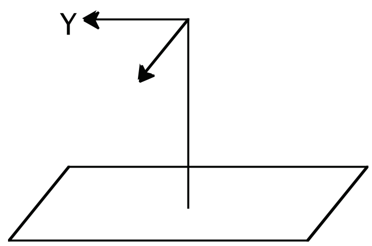

Figure 3. Cassini RCS Thruster Orientation

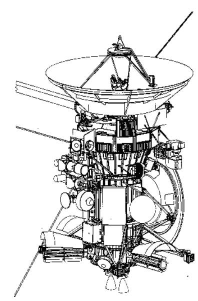

Figure 4. Cassini RCS Thruster Location

The Cassini Attitude AACS FSW performs attitude initialization by acquiring the sun using one of two available Sun Sensor Assembly units (SSA), for fault recovery. Attitude determination is performed using a three degree-of-freedom Stellar Reference Unit (SRU), of which Cassini has two- a prime and offline backup. Between updates from the SRU, the spacecraft attitude reference is propagated by one of two available Inertial Reference Units (IRU), which each contain four hemispheric resonator one degree-of-freedom gyroscopes.

IV. End of Mission Fuel Considerations

In order to meet the navigation requirements of the orbit profile during the proximal orbits[2] at Saturn, Cassini is equipped with a bipropellant Main Engine Assembly (MEA), along with the monopropellant thruster-based Reaction Control System (RCS). The Main Engine is generally used for large maneuvers requiring a translational change in velocity of more than 0.3 m/sec. Attitude control during a Main Engine burn is performed by two linear engine gimbal actuators that provide two-axis control about the spacecraft body X and Y axes (Figure 5), while the roll about the thrust vector is controlled by Y-facing RCS thrusters. The RCS thrusters are used for smaller maneuvers, and for special instances of attitude control.

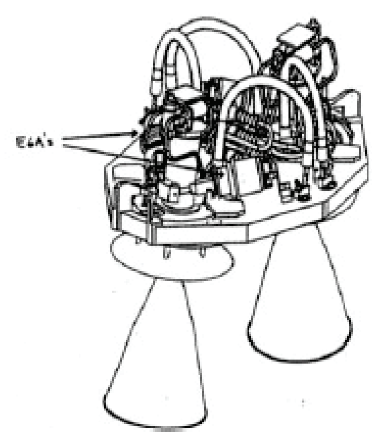

Figure 5. Main Engine Assembly

At this point in the mission, the amount of bipropellant fuel remaining is very low. Different methods have been used to estimate the fuel remaining, and these methods all show sufficient margin for completion of the mission, but there is a non-zero statistical probability that the Cassini Attitude Control Fault Protection may have to gracefully handle a case where either the fuel or oxidizer is depleted before a burn has completed [3]. The propulsion team has completed analysis to show that if the fuel runs out during a burn, the outgassing of the remaining oxidizer will provide thrust on the order of one fifth of the nominal thrust until the main engine valve is commanded closed. The science teams are currently investigating the possible damage to science instruments caused by the resultant oxidizer plume that may settle on instrument optics.

In order to verify the capability to recover from loss of fuel during a Main Engine burn, the operations team performed many simulations on two different platforms: the software based simulation known as the Flight Software Development System (FSDS)[4], and a system level flight hardware-in-the-loop test bed known as the Integrated Test Laboratory (ITL)[5]. Additionally, an Operational Readiness Test was performed, whereby the ITL was utilized to mimic a flight like scenario where the fuel ran out in the middle of the burn, and the operations team had to respond in a flight like manner.

A. Main Engine Burn Related Fault Monitors

The AACS fault protection monitors several aspects of a Main Engine burn, and most of the responses to anomalous conditions consist of terminating the burn in a nominal fashion, and continuing on with the background sequence, without initiating a safing response. This is the desired behavior at this stage of the mission, because if we were to run out of fuel during a main engine burn, we would need to quickly build commands to complete the required change in velocity on the RCS thrusters. The longer the delay before the RCS completion of the burn, the greater the penalty downstream, such that a delay of merely a few days could derail the entire reference mission, as there would not be enough fuel to stay on the planned trajectory (which requires returning repeatedly to encounters with Titan for gravity assist).

The AACS Fault Protection software contains several accelerometer-specific burn-related fault monitors. The Accelerometer Illegitimate Output monitor checks to see if the delta velocity reports from the accelerometer are impossibly large in either the positive or negative direction, based on the largest possible acceleration given a worst case low spacecraft mass and nominal engine thrust value. This monitor trips if the accelerometer based delta velocity is greater than forty percent more than the maximum expected in the positive direction, or greater than fifty percent more in the negative direction, for more than one second. This monitor should not trip if the fuel runs out, as the resultant decrease in thrust will certainly not be in the negative direction, which is what would be required for this monitor to trip. This assumption has been confirmed via extensive testing in the Flight Software Development System simulation.

The Accelerometer Excessive Bias Change Monitor compares the computed accelerometer bias from an accelerometer calibration with the expected bias given by the manufacturer. If the difference is larger than a preset value, this monitor will trip. This test is performed once each time a bias calibration sequence is carried out, which happens once before each burn maneuver. In flight, the accelerometer calibrations have been remarkably stable, and this error threshold has never been close to violation, but if a serious problem were to occur with the accelerometer, this monitor would trip before the burn starts.

The output of the accelerometer is read every eighth of a second whenever it is powered. The accelerometer reports a 16-bit word, which contains the change in velocity since it was last read, and a roll over status bit. The velocity counter bits are reset after each read, but if the counter rolls over before the next read, a roll over bit is set. The Accelerometer Over/Underflow fault monitor tests the roll over/under bit status to detect unreliable change in velocity readings. The maximum acceleration the spacecraft would ever experience would be with an empty spacecraft and the main engine firing. Under these conditions, it would take a minimum of 36 seconds for the counter to rollover. Since it is read every 0.125 seconds while powered, an overflow or underflow of the counter would indicate a serious problem with the accelerometer.

The Unexpected Acceleration fault monitor checks for an unintended main engine firing whenever the accelerometer is powered on and is not being calibrated and a main engine burn is not in progress. This threshold is set to ¼ nominal main engine acceleration, which is 40% higher than accelerometer quantization noise and more than 25 times what the Reaction Control Thrusters (RCS) delta velocity can reach. At the end of the mission, when most of the fuel is consumed, the lighter spacecraft will experience greater acceleration, and the threshold for this monitor will be about 11% of the total acceleration from the main engine.

The aforementioned fault monitors all verify the health of the accelerometer, the knowledge of which is crucial if we are to believe the accelerometer for the case where the fuel is depleted in the middle of a Maine Engine burn. In this case, the accelerometer will cause the Burn Acceleration Error fault monitor to trip. This monitor compares the filtered acceleration measured from the accelerometer with the predicted acceleration, based on pre-loaded estimates of spacecraft mass and engine thrust force. If the difference between the two values is greater than fifteen percent for longer than ten seconds, the monitor trips and calls the terminate burn response. The response terminates the burn by closing the main engine valve, and continuing with the same sequence of burn termination activities that would have executed if the commanded change in velocity had been nominally achieved. The safe mode response is not called, and the maneuver sequence continues, along with the background sequence, uninterrupted. Early termination via the Burn Acceleration Error monitor will set the “Burn Aborted” setting of the burn status telemetry, so ground operators will have a clear indication of the monitor response.

B. Main Engine Burn Fuel Depletion Testing

The AACS team makes use of two main test environments to simulate first time or unusual spacecraft activities. The Flight Software Development System (FSDS) and the Integrated Test Laboratory (ITL).

FSDS is a workstation-based simulation without any hardware in the loop[4]. The spacecraft hardware and environmental inputs are simulated in this environment via software, but it runs a compiled version of the Flight Software (FSW), and is very accurate for modeling software command interactions. FSDS runs relatively quickly, approximately 8 times real time, and can be scripted to run several instances in parallel. This allows for easy repeatability and updating of test runs, which make evaluating multiple test cases easier.

The ITL is a very high fidelity system mode integrated hardware test facility, with the AACS FSW running on a flight spare Avionics Flight Computer (AFC), and multiple flight spare avionic hardware units in the loop[5]. The ITL platform is very flight like, and as such is very resource intensive. It can only run one test at a time in real time, and takes several hours to boot up and prepare each test.

Dozens of test cases were designed and performed to evaluate the FSW response to a Main Engine burn depletion maneuver. A nominal main engine burn essentially proceeds as follows: the spacecraft first rolls about the z axis, spins down the RWA wheels, yaws about the y axis, until the spacecraft vector from the center of mass to the engine output is pointed in the direction of the desired delta velocity vector. The engine is initiated, and an accelerometer measures the accumulating change in velocity, and commands the engine to turn off once the desired change in velocity is achieved. Then, the spacecraft yaws and rolls back to the original attitude.

For the burn to depletion testing, a large main engine maneuver that had been successfully flown previously was modified such that the simulated engine thrust would drop from the nominal to various lower values at different times during the burn. Recall that the Burn Acceleration Error monitor will trip if the filtered measure acceleration from the accelerometer is more than fifteen percent less than the predicted acceleration. Because the comparison is based on the filtered measurement, there is a time lag for the fault monitor to begin incrementing.

The vast majority of the FSDS tests showed that once the simulated thrust dropped, the Burn Acceleration Error Monitor tripped and gracefully terminated the burn after ten seconds. Spacecraft safe mode was not initiated, and the clean up burn commands and background sequence continued as planned. There were two cases, however, when the simulated thrust was dropped completely to zero percent that caused another fault monitor, Excessive Attitude Error, to trip after Burn Acceleration Tripped. Excessive Attitude Error called safing, which terminated the burn and the background sequence. During a Main Engine burn, engine gimbal actuators control the spacecraft attitude about pitch and yaw. In a small subset of cases, the attitude error and rate error present at the moment the main engine thrust went away was large enough to trip Excessive Attitude Error once the RCS thrusters took over. This is not seen as a credible scenario, as the propulsion team analysis has shown that the thrust will not completely drop to zero, nor will it do so instantly, as was simulated. If the fuel or oxidizer runs out, there will still be cold gas thrust from the remaining constituent, to provide thrust on the order of 20% of the nominal. In all the simulations, a thrust value of greater than 1% provided enough control authority such that Excessive Attitude Error did not trip.

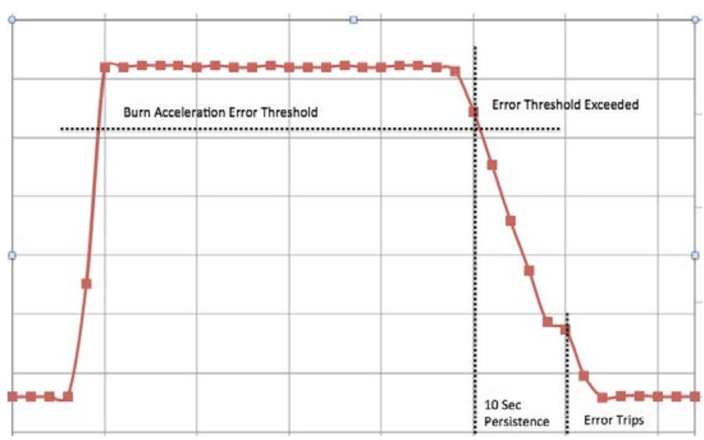

Figure 6. ORT Simulation of Burn Depletion

The ITL was utilized for an Operation Readiness Test (ORT) of what was then an upcoming large main engine burn, but with the simulated thrust dropping off part way through the burn to mimic a loss of fuel. An ORT is a flight like practice test of an actual event, where the ITL based flight like telemetry is routed to the spacecraft operators consoles, and the flight team has to behave and respond as though they were operating the real spacecraft. There were several objectives of this ORT. The first was to verify graceful response of the spacecraft fault protection software to the loss of fuel scenario. The second was to verify that the flight team could respond, correctly diagnose the problem, and design and build another maneuver to achieve the remaining delta velocity via a maneuver that utilizes the RCS thrusters alone, and in a timely manner, as a delay of more than a day or two could throw the spacecraft irreparably off the reference trajectory, effectively ruining a majority of the remaining science objectives of the mission.

The ORT succeeded beautifully. The team accurately diagnosed the spacecraft condition, as the Burn Acceleration Error fault monitor tripped, terminated the burn, and allowed the remaining commands to continue nominally (Figure 6). The team was able to quickly build a contingency maneuver that completed the desired change in velocity using the RCS thrusters on the next day, with a minimal cost increase of hydrazine expended. The fact that the Burn Acceleration Error did not call safing was crucial, as this allowed the flight team to use the ground tools to build the replacement maneuver, without having to worry about replacing commands that were missed once the background sequence was cancelled.

V. Potential Sun Sensor Loss Mitigation

Toward the end of the proximal orbits, Cassini will ambitiously fly, for the first time, through Saturn's inner D-ring, where damage due to solid particle hyper-velocity impacts may occur. The spacecraft will most likely be pointed such that the High Gain Antenna (HGA) will face the incoming flow of particles, which will allow the HGA to act as a shield for the rest of the spacecraft. The sun sensors, however, are exposed to the flow of particles, as they are co-located with the HGA (Figure 7). There are two redundant sun sensors, Sun Sensor Assembly A (SSA A) and Sun Sensor Assembly B (SSA B). They each have two heads, and the heads mounted perpendicular to one another, with each SSA head mounted in the same housing, with a thin alloy separating them (Figure 8). The concern is that a particle, or set of particles, could impact either of the two head assemblies, thereby damaging both SSAs. An extensive statistical analysis was performed to show that this was unlikely[6], but given the uncertainty of flying through a ring gap for the first time, the operations team has deemed it prudent to develop a plan to recover and operate the spacecraft in the face of a failure to both SSAs.

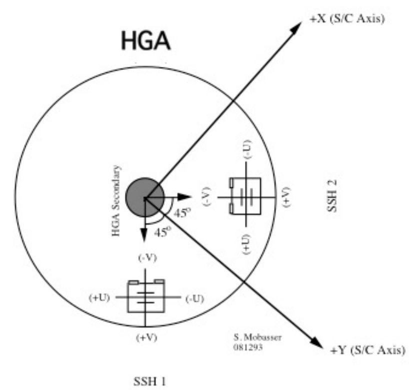

Figure 7. Sun Sensor A and B Position on HGA

The sun sensors are redundant, and the sun reference they provide is not used in nominal attitude estimation and control. If the FSW loses or intentionally drops attitude reference due to a fault, an SSA is needed to successfully navigate the Find_Sun and Center_Sun modes, or else celestial attitude reference will not be attained, and the spacecraft may be lost.

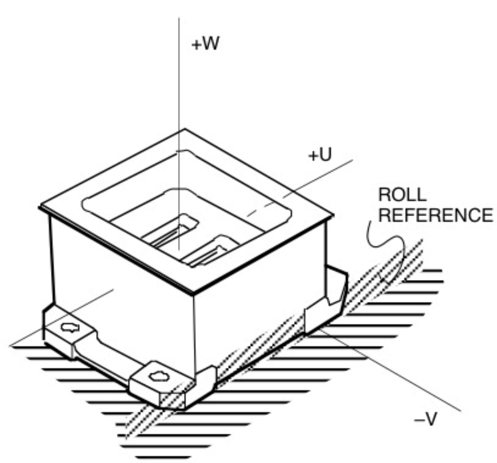

Figure 8. Sun Sensor Head Separation

Before the spacecraft passes through a ring plane gap considered potentially hazardous, the operations team plans to send a command originally intended to notify the fault protection that the sun will be eclipsed, which will thereby disable all sun sensor related fault protection. One of the monitors is called Unexpected Sun Presence Loss. In the presence of sun sensor failures, this monitor would trip without the eclipse command, and its response would ultimately cause the FSW attitude estimator to drop its estimate, which would cause the spacecraft to get stuck in sun search mode indefinitely. This eclipse command can be extended indefinitely, such that if needed, the Sun Sensor fault protection can be effectively disabled indefinitely, in the presence of both failed Sun Sensors.

This is not enough protection, however, as other fault monitors, such as Excessive Attitude Error, also call responses that can drop attitude reference, so something needs to be done about them. To mitigate this risk, the operations team will send a patch to a flag that enables Deluxe Attitude Initialization, or

Deluxe AI. This flag prevents all fault protection responses from dropping attitude reference, so that the sun search mode is never entered, which is exactly what is desired if both sun sensors have failed.

Extensive FSDS testing was performed to verify the effectiveness of both commands. The eclipse command and the Deluxe AI command both need to be sent for complete protection against a sun search attempt in the presence of a failure to both Sun Sensors.

Tests were performed on the flight build of these commands in the Integrated Test Laboratory (ITL) in system mode. First, it was verified that the sun simulation could be failed and the expected fault monitor, Unexpected Sun Presence Loss, tripped, which dropped the attitude reference, and stuck the spacecraft in the sun search mode indefinitely, as expected. The sun was re-aquired after turning the sun simulation back on, and the eclipse command was tested and shown to prevent sun sensor fault protection from tripping with the sun sensor failed. The sun simulation was turned back on, and the eclipse command was commanded to expire. Then the patch to enable the Deluxe AI was sent, and the sun simulation was turned off. As expected, the unexpected sun presence loss fault monitor tripped, but this time it did not drop attitude reference, and the sun search mode was skipped directly to acquire stars. These files have been completely verified functionally, and are ready for uplink as contingency commands, should the need arise.

VI. Low Power Mixed Thruster Branch Catbed Heater Configurations

Electrical power margin during the proximal orbits is a concern. Cassini is powered by three radioisotope thermoelectric generators (RTGs), which currently provide the spacecraft with approximately 600 Watts of power. The power output of the RTGs decreases in proportion to the half-life of the plutonium dioxide that powers them, so the operational power margin continues to grow thinner. Near the end of the mission, operational changes will need to be adopted such that unnecessary power loads will need to be shed, depending on the needs of the spacecraft at that time. One such example is the incorporation of selective powering of mixed branch catbed heaters in the contingency case of a mixed branch RCS configuration.

Cassini has two independent branches of monopropellant hydrazine RCS thrusters, a prime and offline backup, each capable of providing translational velocity changes and maintaining complete 3 axis control. In 2008, after 11 years of reliable service, two of the eight prime branch RCS thrusters began to show signs of end of life degradation, which led the operations team to successfully perform the swap from the prime branch 'A' to the backup branch 'B'[7].

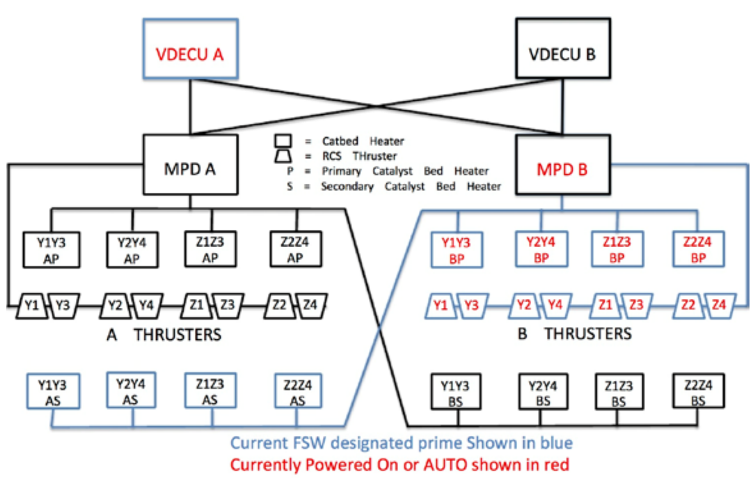

Figure 9. RCS Hardware Driver Block Diagram

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), which are currently powered on at all times, unless one of the thruster pairs corresponding to an individual CBH is firing. There is a Monopropellant Driver (MPD) dedicated to each branch, which controls the thruster valves and catbed heater power states. A pair of Valve Drive Electronic Control Units (VDECU) is cross-strapped to each MPD, as shown in figure 9.

At the present time, the 'B' branch thrusters are designated as prime, with the four Y facing thrusters and four Z facing thrusters heated by the 'B' branch primary catbed heaters. These heaters are currently powered at all times, even when the spacecraft attitude is being controlled by the Reaction Wheel Assembly (RWAs), usage of the RCS thrusters is not needed. For proximal orbits, the plan is to adjust the power operation modes such that these catbed heaters are turned off in RWA mode, and turned on, with sufficient warm up time, before ground commanded transitions to RCS control. If a fault occurs in RWA mode, the AACS fault protection will cause an autonomous transition to RCS mode, without observance of the desired warm up time. This type of transition is called a cold start. The thrusters have been qualified for 75 cold starts, and none have occurred in flight thus far, so the risk of damage to the thrusters or catbed heaters in this mode is considered acceptable.

But what happens if one of the 'B' branch thrusters begins to degrade like what was seen on the 'A' branch? AACS has the capability to designate individual thrusters from both branches as prime[3], such that a mixed thruster configuration could be used for all subsequent RCS activities. Normally this would require power to all the catbed heaters on both branches. But multiple selective CBH and thruster power configurations were tested in FSDS, and later, a proof of concept was performed in-flight, that confirmed the capability of only powering the catbed heaters associated with the thrusters being used. This method of selective powering of the catbed heaters has the potential to save 4 watts per catbed heater, for a potential total of 12 watts, depending on which subset of mixed thrusters is needed.

A. Flight Software Development System Testing of Low Power Mixed Branch Catbed Heater Configuration

A multitude of testing was performed on the Flight Software Development System to verify the proper fault protection responses in a mixed branch RCS control mode[8]. These tests all assumed a nominal power margin, however, and as such, both branches of catbed heaters- the 'A' branch secondary, and the 'B' branch primary, were commanded in the auto mode. There was no selective powering of the catbed heaters to minimize power draw.

For the proximal orbits, RCS thruster degradation and electrical power constraints may dictate a catbed heater power arrangement designed to minimize power draw. The concept had never been tested in ATLO, so before proof of concept and verification of actual power savings in flight, extensive testing on the FSDS platform provided the proper command configuration and verified proper flight software response. One of the test cases involved the theoretical assumption of a sufficient degradation to the Z1B thruster to warrant its removal from the prime set. This meant that Z1A was marked as prime, with the remaining RCS thrusters being filled in by the 'B' branch. Normally, the entire 'A' branch secondary catbed heater suite would be commanded to the auto mode, but in this case, due to power constraints, only the Z1Z3 'A' branch secondary catbed heater was commanded to auto, as shown in figure 10.

Multiple configurations, and multiple flight like thruster intensive scenarios were tested, and all of them showed the proper behavior, but there was no way to prove the savings in the power draw would be as expected, since the catbed heaters had never been commanded this way on actual flight hardware, whether in Assembly Test and Launch Operations (ATLO), or flight.

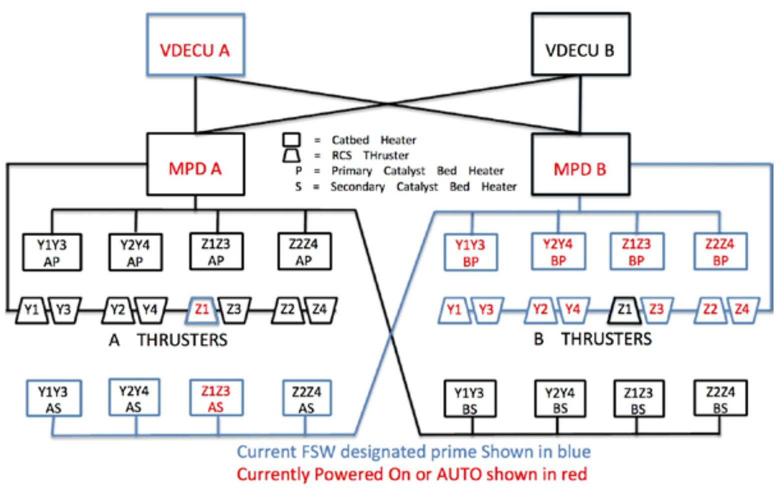

Figure 10. FSDS Tested Low Power Configuration

B. In Flight Demonstration of Low Power Mixed Branch Catbed Heater Configuration

Cassini project management decided that software based simulations were not sufficient to verify the savings in power draw of the mixed branch catbed heater configuration, so in March of 2014, the capability was demonstrated in flight.

As can be seen in figure 9, the current spacecraft RCS hardware state is configured to enable power commanding to the 'A' branch secondary catbed heaters, if necessary, which meant that the commands to perform the verification were very simple. While the spacecraft was under the control authority of the Reaction Wheel Assembly (RWAs), the individual 'A' branch secondary Y1Y3, Y2Y4, Z1Z3, and Z2Z4 catbed heaters were individually commanded to

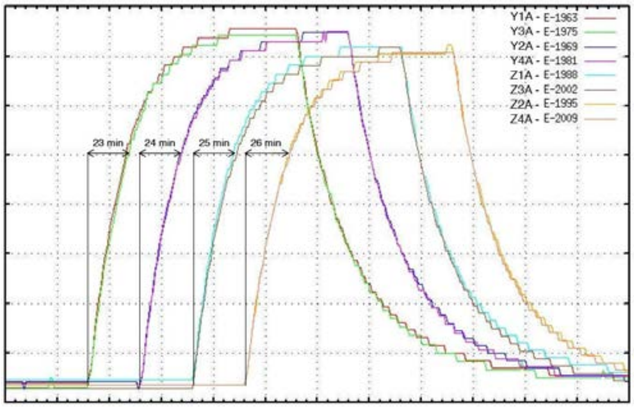

Figure 11. Flight Telemetry CBH Thermal Response

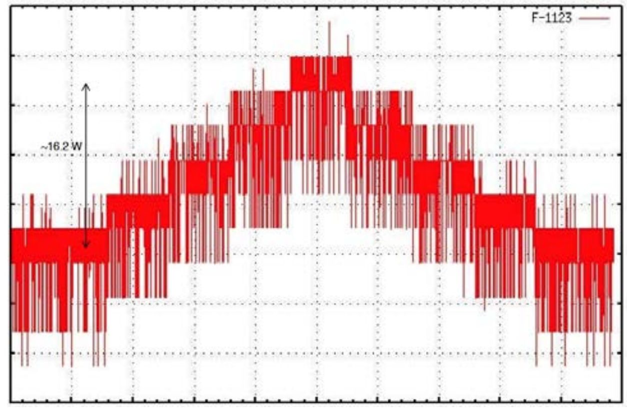

Figure 12. Flight Telemetry CBH Power Draw

auto mode, one by one, and then individually turned off in the same order, one by one. There was sufficient time between the auto mode and the off mode transitions to allow the heaters to reach steady state, which would be required if the heaters were going to support thruster firings.

The operations team verified proper thermal response, as shown in figure 11, and the expected four watts consumed per catbed heater pair was evident in the flight power telemetry shown in figure 12.

VII. Conclusion

The Cassini Attitude and Articulation Control Fault Protection planning, analysis, and testing that solved the challenges of the proximal orbits was a huge undertaking, the success of which required the collaboration of many talented individuals. This paper describes these challenges, and the solutions we came up with, in the hopes that it may aid other flight missions solve problems of a similar nature.

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