Cassini at Saturn Proximal Orbits – Attitude Control Challenges

Thomas A. Burk[1]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109

The Cassini mission at Saturn will come to an end in the spring and summer of 2017 with a series of 22 orbits that will dip inside the rings of Saturn. These are called proximal orbits and will conclude with spacecraft disposal into the atmosphere of the ringed world on September 15, 2017. These unique orbits that cross the ring plane only a few thousand kilometers above the cloud tops of the planet present new attitude control challenges for the Cassini operations team. Crossing the ring plane so close to the inner edge of the rings means that the Cassini orientation during the crossing will be tailored to protect the sensitive electronics bus of the spacecraft. This orientation will put the sun sensors at some extra risk so this paper discusses how the team prepares for dust hazards. Periapsis is so close to the planet that spacecraft controllability with RCS thrusters needs to be evaluated because of the predicted atmospheric torque near closest approach to Saturn. Radiation during the ring plane crossings will likely trigger single event transients in some attitude control sensors. This paper discusses how the attitude control team deals with radiation hazards. The angular size and unique geometry of the rings and Saturn near periapsis means that star identification will be interrupted and this paper discusses how the safe mode attitude is selected to best deal with these large bright bodies during the proximal orbits.

Nomenclature

EM	=	Equinox Mission
ESA	=	European Space Agency
HGA	=	High Gain Antenna
HRG	=	Hemispheric Resonator Gyroscopes
IRU	=	Inertial Reference Unit
MMH	=	Mono Methyl Hydrazine
NTO	=	Nitrogen Tetroxide
RCS	=	Reaction Control System
RTG	=	Radioisotope Thermoelectric Generator
RWA	=	Reaction Wheel Assembly
SID	=	star identification
SOI	=	Saturn Orbit Insertion
SRU	=	Stellar Reference Unit (star tracker)
SSA	=	Sun Sensor Assembly
XXM	=	Extended-Extended Mission
XM	=	Extended Mission

I. Introduction

THe Cassini mission at Saturn is completing its ninth year in orbit around the majestic ringed world. Launched on October 15, 1997 from Cape Canaveral Air Station in Florida, the Cassini spacecraft reached Saturn on June 30, 2004, after a 6.7-year cruise. A 626 m/s orbit insetion burn was performed upon arrival to slow the spacecraft down and allow it to be captured by Saturn's gravity. On Christmas Eve, 2004, the 320 kg ESA-designed Huygens atmospheric and surface probe was deployed from Cassini. Huygens subsequently entered the atmosphere of the

[1] Cassini Attitude Control Product Delivery Manager, Guidance and Control Section, M/S 230-104, 4800 Oak Grove Dr., Pasadena, California, 91109, thomas.a.burk@jpl.nasa.gov

moon Titan on Jaunary 14, 2005, relaying data throughout the whole descent and continuing through landing and even on the surface until the Cassini orbiter moved below the horizon of Titan. The Huygens probe relay was but one highlight of the four year "Prime" Cassini mission at Saturn, extending from June 2004 through mid-2008 and including 45 close flybys of Titan and 7 of the moon Enceladus. Other major discoveries include synthetic aperture radar imaging of hydrocarbon lakes near Titan's poles, continuous cryovolcanic plumes of water venting from near the south pole of Enceladus, polar storms on Saturn (north polar hexagon and south polar vortex), and propeller-like formations in the rings of Saturn.

Cassini arrived at Saturn in 2004 – early in the "winter" of Saturn's northern hemisphere. Saturn takes 29 years to orbit the sun. A two-year "extended mission" (XM) from mid-2008 through September of 2010 was funded, highlighted by 28 additional flybys of Titan and 8 of Enceladus. The extended mission was given the name "Equinox Mission" (EM) because in mid-2009 the rays of the Sun were exactly parallel with the ring plane (vernal equinox), allowing unique observations of the rings by Cassini. One of the XM Titan flybys occurred with closest approach to Titan only 880 km from the surface (the closest approach ever to Titan for the entire mission). A final extended-entended mission (XXM) was approved and is currently executing. During the planned 7-year XXM, from September 2010 through September of 2017, 56 additional Titan flybys are planned, 19 of which have already occurred along with 12 more low-altitude Enceladus flybys (9 of which were completed by the end of 2012).

The XXM was given the name "Solstice" because the Northern hemisphere summer solstice will occur in May 2017 during Cassini's 275th orbit of the ringed planet (see Figure 1). A major driver for the design of the XXM was to observe the effects of seasonal changes on Saturn and its many moons.[1] At the very end of the XXM, to ensure that Cassini cannot contaminate Titan, Enceladus, or any of the other moons, Cassini will be steered into the atmosphere of giant Saturn itself, ending the mission. The Galileo mission at Jupiter also disposed of the spacecraft in this way (meeting NASAs planetary protection requirements). But Cassini's ultimate fate will only come after a remarkable "final encore" of proximal orbits where the spacecraft crosses Saturn's equator *inside* the radius of the rings 22 times and gets as close as 1840 km from the 1-bar atmospheric pressure altitude of the planet itself.

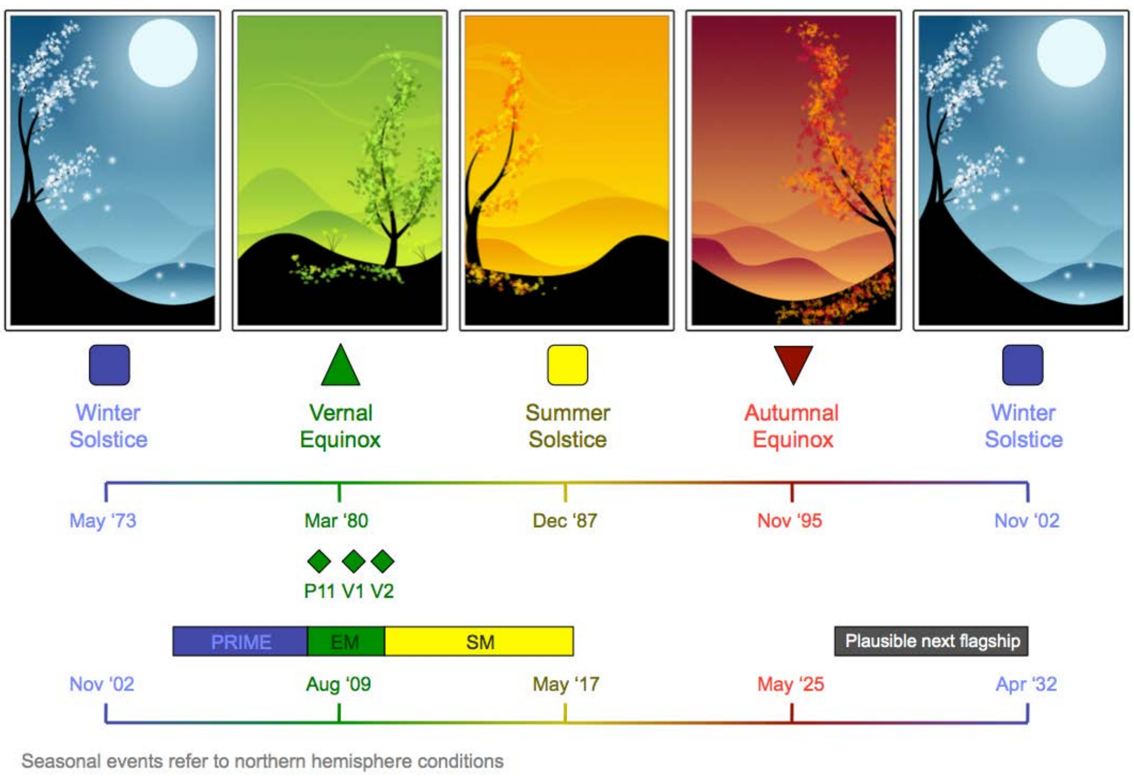

Figure 1. Saturn seasonal timeline. *The 3 phases of the Cassini mission at Saturn (Prime, Extended Mission, and Solstice Mission) are depicted in this graphic which also shows northern hemisphere seasons. The flybys of Pioneer 11, and Voyager 1 and 2 are also shown. (Graphic courtesy of David Seal, Jet Propulsion Laboratory)*

During the early study of the end-of-mission disposal of the Cassini spacecraft, one finding was that, starting from a high-inclination orbit with an orbital period of roughly 7 days, a Titan gravity-assist could be utilized to jump over the rings of Saturn and place Cassini on a ballistic trajectory with a Saturn impact end point.[2] This unique trajectory can be designed so that it passes inside the rings (just above the Saturn cloud tops) for multiple orbits prior to Saturn impact. The entire 5-month ballistic trajectory is called the “proximal” phase of the mission and includes 22 orbits with periapsis inside the rings. Cassini imagery of the rings of Saturn reveal a 3,000 km wide “clear area” inside the rings and above the cloud tops of Saturn. Since this is the very end of the Cassini mission, even if the spacecraft is disabled due to debris impact during the proximal orbits, the ballistic trajectory will ensure safe disposal of Cassini into Saturn.

The proximal orbits will provide an unprecented opportunity for new science. By flying so close to Saturn, Cassini can map its magnetic field and gravity in great detail. By flying between the planet and the rings, Cassini can separate the gravitational effects of the rings from Saturn itself. To understand the age and evolution of the rings, Cassini will be able to establish their aggregate mass (which is uncertain now by as much as a factor of ten). Cassini will directly sample the composition of Saturn’s atmosphere, just like it has done at Titan and Enceladus. Spectacular Earth and Sun occultations of the rings make the proximal orbits especially exciting.

But the science rewards of the proximal orbits also present challenges. Can the spacecraft safely travel through the ring plane so close to dense ring material? Can spacecraft attitude control be maintained as Cassini dips so close to the atmosphere of Saturn while traveling at 34 km/s? Will radiation upset the inertial reference units or the star tracker? Will the sun sensors be compromised due to debris impacts during the ring plane crossings?

II. Cassini Attitude Control System Design

Cassini is a 3-axis stabilized spacecraft with an 11-m magnetometer boom (deployed just before Earth swingby in mid-1999) and three 10-m Radio and Plasma Wave Science antennas. Virtually all the science and engineering instruments on Cassini have fixed orientations on the spacecraft. To point a science instrument at an object of interest, the whole spacecraft must be slewed to achieve the desired pointing. Most science gathering is done without a real-time communications link with Earth. The data is recorded on two 2-Gbit solid state recorders and played back to Earth every day or two. Cassini is powered by 3 RTGs which produced 880W at launch, and are currently producing about 644 W of power.

Cassini has a body-fixed 4-meter diameter Cassegrain HGA parabolic reflector dish for telecommunications. Uplink and downlink uses X-band for commanding, telemetry, and radiometry. Radar uses Ku-band and radioscience also uses S-Band and Ka-band. The HGA is mounted on top of the spacecraft stack and points parallel to the spacecraft –Z body axis. The HGA is used as a Sun shield and also as a shield during hazardous Saturn ring plane crossings. Cassini has dual redundant 2-axis sun sensors mounted on the HGA. The two SSAs are coaligned with the spacecraft –Z axis and have a ±32° field of view.

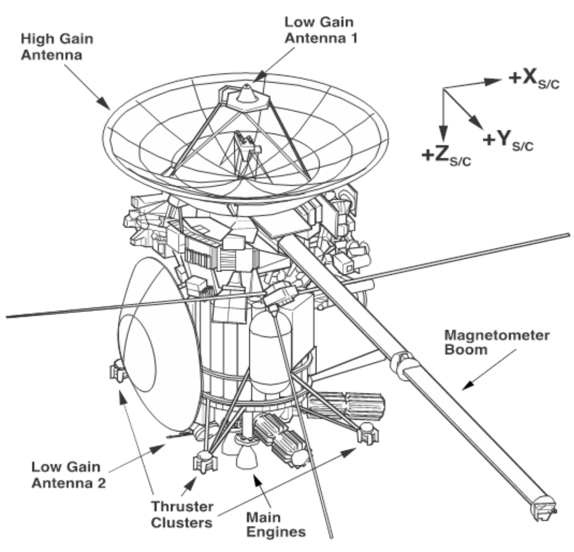

Figure 2. Cassini configuration at Saturn arrival.

The Cassini propulsion system includes a mono-propellant thruster-based reaction control system (RCS), and a bi-propellant system (NTO/MMH) supporting main engine ΔV maneuvers. The mono-propellant system consists of a single blowdown hydrazine tank, eight prime and eight backup 0.9 N Voyager-vintage hydrazine thrusters, and a pyro-isolated one-time helium recharge tank (used in April 2006). The main engine is used for large (> 0.3 m/s) Delta V maneuvers[3], while the RCS system is used for small Delta V corrections (< 0.3 m/s). The propulsion system was sized for about 2500 m/s of Delta V total. Of this 570 m/s was used prior to reaching Saturn, 1590 was used during the prime mission, about 180 m/s was used during the XM, and the remaining 160 m/s is available for the XXM.

For Delta V maneuvers, Cassini has a 445 N main engine (with a backup that has not been used to date). Control during main engine burns is provided by gimbaling the main engine. Two linear engine gimbal actuators provide 2-axis control and the third axis (roll about the thrust vector) is controlled by the Y-facing RCS thrusters. The ΔV imparted on the spacecraft during a main engine burn is measured by an accelerometer that is mounted parallel to the spacecraft's Z-axis. There is one accordion-like cover that protects both main engines from micrometeorite impacts. Typically the cover is left open, but is closed during dust hazard crossings of the ring plane.

The prime RCS system has 4 thrusters that fire parallel to the spacecraft –Z body axis (one on each of four thruster clusters. These thrusters are used for Z-axis translational ΔV maneuvers as well as attitude control about the spacecraft ± X and ± Y body axis. Note that attitude control about these axes does impart ΔV to the spacecraft that must be predicted and accounted for in orbit determination and maneuver planning. The prime RCS system has 4 thrusters that fire as couples parallel to the spacecraft Y body axis for attitude control about the spacecraft Z body axis. The eight thrusters (4 Y and 4 Z) constitute the prime thruster set.

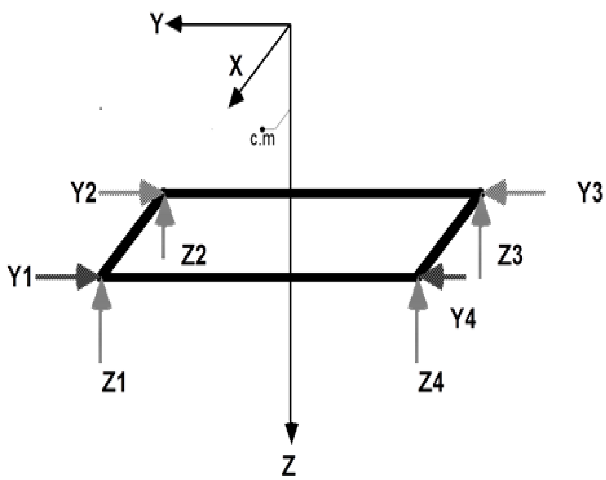

Figure 3. Cassini Thruster Configuration.

At launch, the Cassini spacecraft mass was 5575 kg. Of this, 3000 kg was bi-propellant for the main engine and 132 kg was hydrazine for the RCS thrusters. Less than 100 kg of bi-propellant remains, and about 53 kg of hydrazine remains to date. The current spacecraft mass is about 2275 kg. On Cassini, inertial attitude knowledge sensors include a star tracker and gyroscope sensors (a sun sensor is explicitly utilized only when 3-axis attitude knowledge is lost or dropped). Cassini has dual redundant IRUs each containing four HRGs. Three of the four HRGs are used as prime inertial sensors while the fourth gyroscope is used as a "parity checker."

Cassini has dual redundant stellar reference units (star trackers) which are coaligned with their boresights parallel to the spacecraft +X body axis (90° from HGA). Each SRU is capable of full-sky determination of the spacecraft 3-axis attitude. The optical field of view of these trackers is a square: ±7.5° by ±7.5°. The straylight field-of-view of the SRU is circular with a radius of 30°. Valid star identification (SID) can be suspended up to 5 hours if Saturn, the rings, or other bright bodies enter the straylight field-of-view.[4] During SID suspends, attitude estimation uses IRU-only attitude propagation. Upon exit of SID suspend, a small attitude correction typically occurs as the star tracker reacquires celestial attitude knowledge and corrects for small propagated attitude errors due to IRU scale factor and misalignment errors.

To conserve hydrazine propellant and for precise and stable pointing, the Cassini spacecraft uses 3 strap-down reaction wheel assemblies (RWAs). Each RWA spin axis is fixed in the spacecraft body frame but are not coaligned with the spacecraft body axes. Together the three RWAs form an orthogonal set. Each RWA has a 34 Nms momentum storage capability and a motor torque capable of .165 Nm. A fourth RWA is articulable and can thus be oriented to match any of the other three RWA's spin axis orientation. This RWA was originally the backup RWA but since July of 2003 it has been used as one of the three prime RWAs. Only three RWAs can be used for control simultaneously so one RWA is normally powered off. Since arriving at Saturn, Cassini has used RWA control the vast majority of the time.

RCS thrusters are used to control the spacecraft during low-altitude flybys of Titan where atmospheric torque could exceed the control authority of the RWAs. Thrusters are also used during RWA momentum "biases", ΔV maneuvers, and during some slews when the RWAs are powered off (including during safe mode). Thrust force magnitude and moment arms are such that RCS control torques of 1 to 2 Nm are provided about each spacecraft axis.

Thermal control is achieved via a variety of processes. Waste heat from the RTGs helps heat the central body of the spacecraft. Louvers, heaters, and small Radioisotope Heater Units also assist in thermal control. Sensitive science instrument radiators are oriented parallel to the spacecraft +X body axis. When the HGA is pointed at the Sun, the sensitive science radiators are shaded. The spacecraft can be pointed up to 4.5º away from –Z-so-Sun and the radiators will still be shaded by the HGA from solar heat. But even at 9 astronomical units from the Sun, the +X-to-Sun angle has to be carefully managed to maintain robust performance of some science instruments. With few exceptions, all science and engineering activities must factor in these thermal constraints. Models for heating and cooldown are used extensively in activity design in order to insure thermal control is maintained. Saturn itself contributes some heat to the spacecraft especially when Cassini is relatively close to the planet.

The rings of Saturn are dense with material out to about 136,770 km from the center of Saturn. If the equatorial radius of Saturn (roughly 60,268 km) is referred to as 1 R_S, the outer edge of the main rings is at a radius of about 2.27 R_S. Outside this, there is a narrow gap and then a significant ring called the F ring (at 2.33 R_S). The ring system of Saturn is divided into bands with each band given a letter. The bright outer band is the A ring, with B and C the bright bands closer to the planet. The innermost ring is the D ring. The A through D rings are at most a few tens of meters thick. There is a relatively clear region outside the F ring, but a significant ring outside that is called the G ring. Cassini has found the G ring to be wider (from about 2.74 to 2.92 R_S) with more material than was previously thought. The most diffuse ring is furthest from the planet and is called the E ring (Figure 4). Figure 5 is a close-up of the bright and dense A, B, and C rings and the very faint innermost D ring.

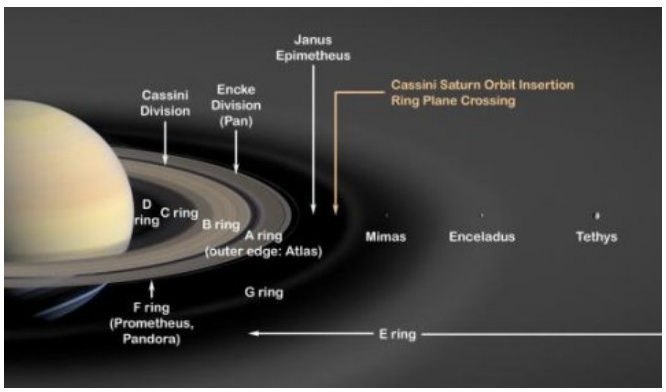

Figure 4. The rings of Saturn.

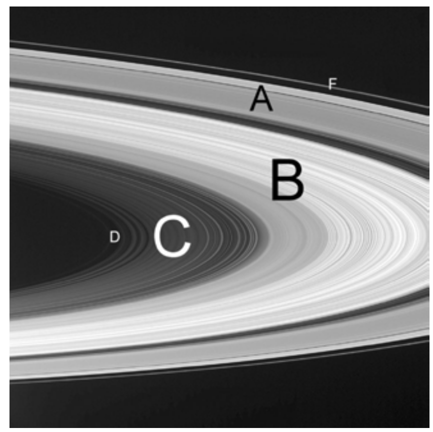

Figure 5. The inner rings of Saturn

III. Proximal Mission Design

Titan is the anchor for all Cassini tour design at Saturn.[5] A single Titan gravity-assist can provide over 800 m/s of trajectory change ΔV, while the Cassini propulsion system has only about 160 m/s ΔV available for the entire 7-year Solstice mission! To a great extent, unless Cassini can be steered back repeatedly to Titan, the spacecraft would be left in a single, inertially-fixed orbit around Saturn. But with Titan gravity-assists[6] (Figure 6), the spacecraft has made vast orbital changes: looping up as high as 75° inclination (looking down on the rings from near the poles of Saturn) and then stepping the inclination down to zero to observe the rings edge-on.

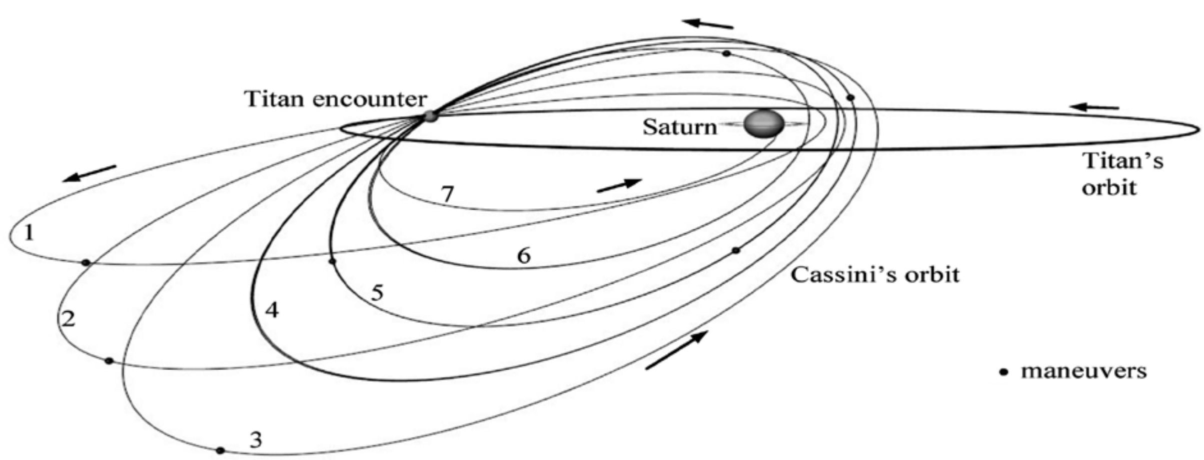

Figure 6. Titan gravity-assists. *This is an illustration of how the orbital plane of Cassini can be changed by repeated flybys of the moon Titan.*

In late 2016, in preparation for the proximal mission, Cassini will use a Titan gravity assist (the 125th flyby of Titan) to bring the spacecraft's periapsis down from 3.6 R_S to 2.5 R_S. The spacecraft's orbital period will be around 7 days and its inclination will be near 63.8°. This begins the "F Ring" phase of the mission (Figure 7). Cassini has never flown this close to Saturn and the rings (except during Saturn Orbit insertion on June 30, 2004). Cassini will perform 20 F ring orbits from late November 2016 to mid April 2017. A total of three ΔV maneuvers are planned during this five month period, setting up for the final close Titan flyby (at 979 km closest approach altitude) on April 22, 2017. This flyby that will reduce the periapsis of the spacecraft from 2.5 R_S down to 1.06 R_S and setup the proximal trajectory. A final cleanup ΔV maneuver is planned shortly after the Titan-126 flyby on April 22. From that point on, Cassini will be on a completely ballistic trajectory that will impact Saturn on September 15th, after 22 proximal orbits with periapsis just above the Saturn cloud tops (Figure 8).

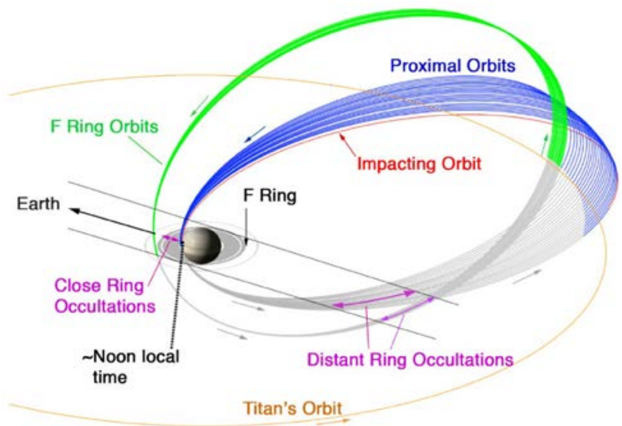

Figure 7. F Ring and Proximal Orbits

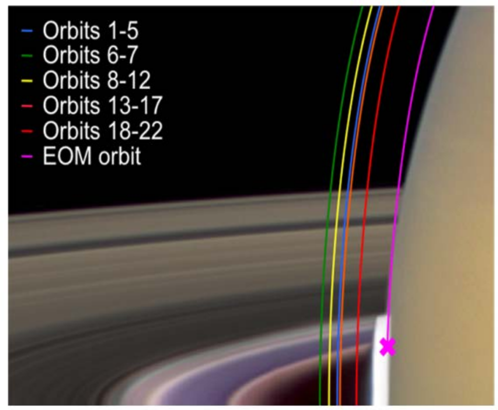

Figure 8. Proximal Orbit trajectory near Saturn

Cassini will begin each proximal flyby of Saturn by gliding down from Saturn's northern hemisphere as it skims above the rings themselves. Each approach will be on the sunlit side of Saturn (near Noon local Saturn time). Cassini will pass inside the inner D ring in the 3,000 km gap just above Saturn's cloud tops. Cassini will reach its periapsis just three minutes after the descending ring plane crossing and will be roughly 5° below Saturn's equator. The Earth and Sun will also be occulted by the rings for about 27 minutes during this time. About 42 minutes after closest approach, Cassini will come within 51000 km of the south pole of Saturn. The more distant Sun and Earth rings occultations begins about 4.5 hours after closest approach and lasts for over 8 hours. Saturn itself will occult Cassini from the Sun and Earth soon after ring occultation starts. The Saturn occultation lasts for about 5 hours.

IV. Dust Hazard Risk for Proximal Orbits

Cassini has never had plans to penetrate the main rings of Saturn (A, B, and C rings). Even the so-called gaps or divisions within these ring bands are far too dense with material to risk a hypervelocity impact with Cassini. The proximal flybys inside the D rings are not the only region that Cassini has or will fly through that pose a potential hazard to the spacecraft. Regions close to the center of the G ring also are considered quite hazardous, as are other regions.[7]

Dust hazard risk involves four main factors: (1) the spacecraft hardware; (2) the dust environment where Cassini is traveling; (3) the design of the trajectory itself (avoiding known hazardous regions, for example); and (4) adjusting the orientation of the spacecraft so that hazards can perhaps be minimized. The spacecraft has a variety of vulnerable areas, but to first order the spacecraft electronics bus is considered the most vulnerable region. It has an exposed area of around 0.81 m^2. Other areas of note are the main engines, star trackers, and sun sensors. The main engines have some level of protection due to the accordion-like cover that is deployed during hazardous ring plane crossings. Louvers provide some protection to the electronics bus.

Prior to Cassini arrival, there had been three spacecraft that had flown by Saturn: Pioneer 11 and the two Voyager spacecraft. All have successfully transited the Saturn ring plane – in fact Pioneer 11 and Voyager 2 crossed right through what is now considered the center of the G ring. The Cassini trajectory near Saturn orbit insertion was designed to avoid the G ring (see Figures 9 and 10) but some protective measures were taken, in addition, because of significant uncertainty in the distribution of ring particles in the region where Cassini needed to cross the ring plane.

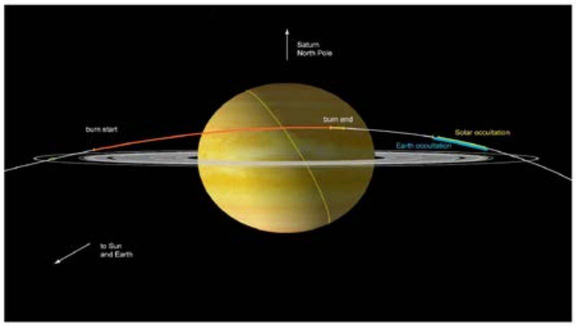

Figure 9. Cassini trajectory near Saturn Orbit Insertion. *Orange depicts actual burn* period.

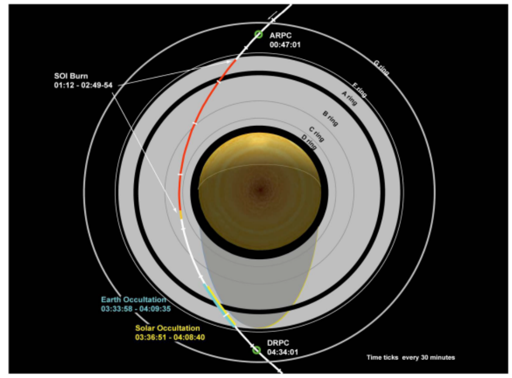

Figure 10. Cassini trajectory near Saturn Orbit Insertion. *Looking down from Saturn north pole.*

One measure taken was to point the HGA in the dust RAM direction during both ring plane crossings, so that the more sensitive electronics bus was not facing into the dust stream during the crossings. The dust RAM direction is the relative velocity direction of the ring particles (assuming a circular orbital velocity around Saturn) with respect to Cassini. The wavelengths used by telecommunications, radar, and radioscience are long enough that the high gain antenna (HGA) is relatively insensitive to impacts of millimeter-sized or smaller particles which dominate particle distributions in the less-dense rings. Along with closing the main engine cover, using the HGA-to-RAM attitude has since become standard practice for high risk dust hazard ring plane crossings. The Cassini SOI transit was very successful – as was the burn itself – and proximal planning is to utilize similar protective measures as were used at SOI.

A HGA-to-RAM pointing strategy has been used not just during the SOI ring plane crossings but also during repeated ring plane crossings near the G ring throughout Cassini's mission at Saturn. It is also a likely strategy during proximal ring plane crossings too. One issue presented by the HGA-to-RAM strategy is that both Cassini sun sensors are mounted on the HGA and thus are at risk of damage even if the rest of the HGA is not. A functional sun sensor – although not used in normal attitude estimation -- is vital for fault recovery, so using the HGA as a debris shield needs scrutiny. Because of the SSA risk, ground controllers typically power on both SSAs prior to each hazardous crossing. Ground controllers also disable SSA fault protection during each dust hazard crossing so that an actual debris-caused SSA fault is not misinterpreted by fault protection as some other attitude-knowledge related problem. At the first opportunity after a dust hazard crossing (that is, during the first downlink to Earth after the crossing), a Z-axis slew (rolling about the Earth-line) is commanded. This puts all four quadrants of each sun sensor into the Sun-line during the slew, so the readings from both SSAs (sun location and intensity) can be evaluated (and compared) to detect any debris-caused damage in a timely fashion.

To evaluate the risk to the sun sensors from debris impacts during the proximal crossings inside the D ring, a threshold penetration distance of a particle into the SSA is established. For this analysis, an SSA failure is defined as a single particle penetration exceeding one half the total glass thickness of an SSA window glass cover. Then an estimate is made of what minimum particle mass would be required to penetrate to this depth, given maximum expected micro-particle velocity and density. The next step is to estimate the number of particles per unit area as a function of particle mass. This estimate, known as integral fluence, is estimated based on Cassini science instrument (including photographic analysis) measurements earlier in the mission. This fluence can even be expressed as a sum of all 22 proximal orbit dust hazard crossings inside the D ring. This fluence, expressed as number of damaging particles per square meter, is multiplied by the SSA window glass area to produce an estimate of the number of expected damaging hits for the proximal mission. Given the current best evidence of inner D ring dust density, this admittedly uncertain calculation produces less than 0.025 damaging "hits" for the proximal mission. So the chances of damage due to a penetrating hit on the Cassini sun sensors appears to be small enough that the HGA-to-RAM strategy will continue be used as needed during the proximal flybys.

The predicted altitude of each of the 22 passages inside the D ring is presented in Figure 11. The right vertical axis (in blue) denotes the distance from Saturn's center at the time of the ring plane crossing. The left vertical axis (in red) denotes the altitude (above the cloud tops) of the closest approach to Saturn (a few minutes after the ring plane crossing). Note that the mid-to-late August and September flybys are closest to the planet, while the earlier ones are relatively closer to the D ring. To protect the electronics bus and other regions sensitive to debris impact, it is likely that ground controllers will command an HGA-to-RAM attitude for some or all of the earlier proximal flybys as these tend to be closer to the D ring dust inner radius.

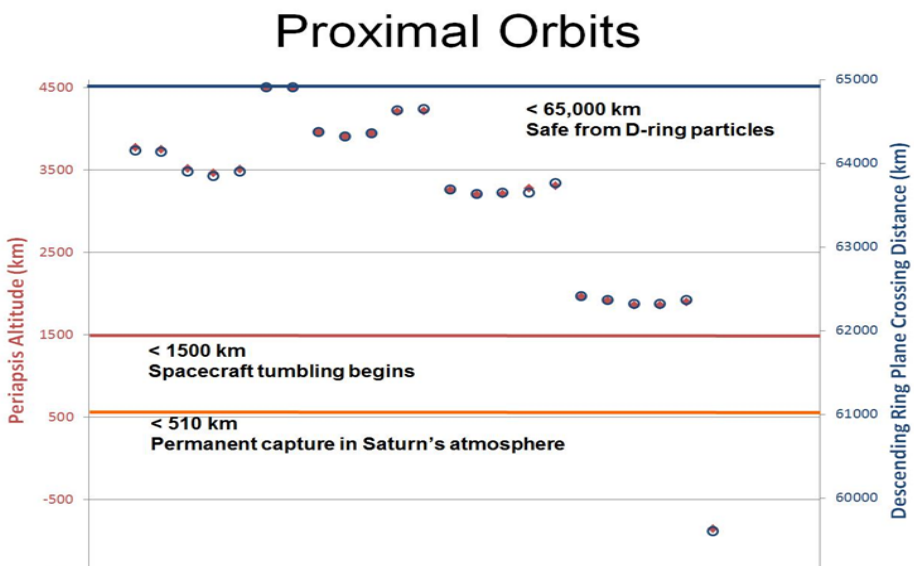

Figure 11. Periapses for each of the 22 proximal orbits.

V. Spacecraft Controllability During Proximal Flybys

During the proximal flybys at Saturn, Cassini will fly close enough to the planet that, at least for the lowest-altitude flybys, RCS control will be needed to insure robust controllability margin. This is similar to Titan flybys, where flybys with a closest-approach altitude below 1300 km require RCS control, while those above this altitude typically use RWA control even during closest approach. During low-altitude Titan flybys, the spacecraft flies through the upper Titan atmosphere at a relative-velocity of roughly 6 km/s. Near closest approach, aerodynamic forces impart torques about each of the three spacecraft body axes. These torques are also a function of spacecraft orientation during the flyby. The aerodynamic torques are linearly related to atmospheric density – the flybys with the highest atmospheric densities tend to result in the highest torques. At Titan, atmospheric torques on some flybys have required the RCS thrusters to fire at up to 70% duty cycle to maintain control.

The velocity of Cassini at Saturn (relative to the atmosphere) will be roughly 34 km/s. Near the end of their 20 year usage, the Cassini RCS thrust forces will be the lowest magnitude of the entire mission (due to hydrazine tank pressure decay as propellant is depleted). The thrust force could be as low as 50% what it was during the first low-altitude Titan flyby in 2006. To assess controllability, a Saturn aerodynamic model will need to be implemented in ground software. Also, representative spacecraft orientation profiles will be needed to compute realistic aerodynamic center-of-pressure and moment arms. The torque model will be analogous to that used for Titan, but the mass density model of Saturn's atmosphere at Cassini closest-approach is being studied and reviewed by the Cassini science teams. The mass density model needs to incorporate the latest (and potentially changing) results from Cassini observations that image the region between the inner D ring and the planet. These observations also include stellar and solar occultations as observed by the science instruments on Cassini. An estimate of the model's uncertainty is also needed to provide appropriate bounding conditions to address controllability margins.

Rough approximations of the aerodynamic model to date assumes a factor of two (conservative) larger mass density than the current atmospheric predictions from the science teams. Other uncertainties, such as drag coefficient, relative velocity, moment arm, and projected area, are currently estimated to be about 3 percent, one sigma. These rough estimates show that, currently, the proximal flybys do not present a controllability problem for the Cassini RCS system. The peak atmospheric torque, for the lowest of the proximal flybys, is currently estimated at roughly 0.7 Nm, given the factor of two conservative atmospheric mass density. This compares with total thruster torque capability of from 1.0 to 1.6 Nm, per axis, at the end of the proximal mission. But the mass density uncertainty of Saturn's atmosphere will continue to be evaluated, especially as new science data develops between now and 2017. In order to "test the waters" the proximal trajectory is being shaped so that the earlier flybys are further away from the planet. As Figure 11 shows on the previous page, the last five periapsis are the closest and are expected to impart the largest atmospheric torque on the spacecraft.

There are other sources of torque besides atmospheric torque at Saturn, but they all are at least three orders of magnitude smaller than current estimates of the atmospheric torque. These include gravity gradient torque (< 1.0e-4 Nm), solar radiation and RTG radiation torque (roughly 2.0e-6 Nm), and the torque induced by Cassini's residual magnetic field interacting with Saturn's magnetic field (roughly 1.0e-4 Nm).

There are other factors that could complicate the controllability analysis. For the lowest flybys, for example, spinning reaction wheels could induce gyroscopic torque when the spacecraft body rates are non-zero. To avoid this complication, ground controllers are currently planning on spinning the RWAs down to zero and powering then off prior to the low-altitude proximal approaches. Some RCS control torque might need to be devoted to "target motion compensation" even at closest approach. This torque is the torque required to track an object – for example a ring feature – which induces angular accelerations and which could tend to reduce the RCS control torque available for atmospheric torque compensation. The project is currently evaluating what, if any, target motion compensation is permissible during Saturn closest approach. An inertially-fixed quiescent attitude is preferred from the standpoint of maximizing margin for uncertain atmospheric torque.

There are onboard fault protection monitors that check for thruster leaks.[8] These monitors compare expected angular momentum accumulation with estimates of commanded RWA and RCS control quantities. If deviations rapidly accumulate, a leak detection error monitor will trigger and fault protection response will occur. One response could be to swap to the other thruster branch as a way to stop the leak. These monitors are not currently able to recognize the angular momentum accumulation of a Titan flyby (or a proximal flyby) as "expected" external torque, so currently these monitors are disabled during low-altitude Titan flybys. A similar approach will likely be followed during the proximal flybys.

VI. Radiation Hazard During Proximal Flybys

When Cassini passes inside the D ring, it will encounter a radiation environment perhaps more intense than any it has experienced to date. Cassini has traveled through some fairly significant radiation regions throughout its mission. In August of 1999, Cassini flew by the Earth at a closest-approach altitude of 1175 km. The inner radiation belt that Cassini flew through at Earth has energetic ions, mostly protons, and something similar is anticipated during the proximal flybys. The field lines inside the D ring (that is, those that do not intersect the rings themselves) are most likely to produce single event transients due to ion impacts. Cassini has experienced these transients before (not just at Earth or Saturn, but throughout the mission) and they do produce transient spikes in the HRG outputs. The magnitude of the rate spike has been observed up to about 0.25 mrad/s, and persists for up to .375 seconds. At Earth flyby, at least 14 spikes were observed in the 20 minutes surrounding closest approach. The time that Cassini will spend in the high radiation environment near proximal periapsis is currently estimated to be of similar duration as during the flyby of Earth. The radiation environment inside the D ring is still being studied and reviewed by the Cassini science teams.

It is important that the fault protection monitor "thresholds" on Cassini are not set so tight that single event transients, by themselves, cause undesirable onboard responses (like autonomously invoking safe mode). These monitor thresholds have been loosened by Cassini ground controllers in the past, and the proximal flybys need to be evaluated to determine if these thresholds are still adequate. A spike in attitude and rate error can feed into RWA current and power errors, so those and other monitor thresholds also need to be examined.[9] Ground simulations will inject representative spikes into the HRG outputs to test the robustness of the attitude control fault protection design in the Saturn radiation environment. Other precautions may be performed in preparation for the proximal flybys. For example, powering on the backup IRU several hours ahead of each proximal flyby is prudent. The Cassini

HRGs take two hours to warm up to good operating condition, so if fault protection were to autonomously swap to the backup IRU, having it already warmed up is a good precaution.

VII. Safe Mode Attitude Management – Bright Bodies at Saturn Periapsis

Preparing for anomalies before they happen is vital throughout the Cassini mission.[10] Managing the attitude that will be commanded in the event of safe mode is a key task because all significant anomalies will suspend normal operational command sequences and the spacecraft will autonomously turn to the safing attitude to await ground response. If this safe mode attitude were to present additional complications (for example, blinding the star tracker) it would make it even harder for ground controllers to assess and respond to the original anomaly. The safe mode attitude needs to ensure good commandability, a benign thermal environment, a clear star field, and the ability to play back data at a rate that allows ground controllers to assess the spacecraft state. The safe mode attitude is the life boat that needs to be safe and ready to use at any time.[11]

In Saturn orbit, the safe mode attitude is normally chosen to keep Saturn and the rings out of the star tracker bright body field of view (a 30° cone centered on the SRU boresight). If Cassini's trajectory is in a high-inclination orbit that takes the spacecraft over the north and south poles of Saturn, a properly designed safe mode attitude will point the star tracker in a direction that keeps the 30° bright body cone away from the large disk of Saturn's rings at all times. An onboard flight software "safe table" allows ground controllers to make changes in the safing attitude when needed. If a safing response were to occur, the contents of the table would be used by the flight software to autonomously command the safing attitude. During some Titan flybys, the normal safing attitude that avoids Saturn and the rings bright bodies causes Titan to enter the SRU field of view near closest approach. To avoid this, ground controllers sequence a change to the safe table so that a clear star field is maintained throughout the Titan flyby. The safe table is then returned to normal after the Titan flyby. The safing response normally commands the HGA to point at the Sun, but as long as the fault is not a significant attitude control anomaly, an hour later the safing response algorithm commands a slew to point the HGA at the Earth to permit good telemetry visibility. Managing the safe table allows the twist about the HGA boresight to be selected to maintain a clear star field for the SRU.

The proximal orbits present unique problems because the spacecraft moves so close to Saturn and the rings. Whatever SRU orientation that avoids Saturn and the rings before crossing the ring plane inside the D ring, will suddenly put the rings into the SRU bright body field of view the moment Cassini crosses (from north to south) the ring plane. During the design of proximal sequences for nominal operation, commands will be included to "suspend" star identification while the rings and Saturn are in the SRU bright body field of view. If Cassini enters safe mode, however, all nominal sequences are stopped and an entire proximal flyby may occur while at the safing attitude without any suspension of star identification.

The geometry of Saturn and the rings in the 2 to 3 hours surrounding Saturn closest approach for each proximal flyby is not only unprecedented for the Cassini mission but it is truly unique in all the solar system. To be that close to the sunlit rings and the planet would challenge even the most imaginative space artists just to depict the scene. There literally is no single attitude that will allow the SRU a clear field of stars during even a single proximal flyby. The best that can be done is to minimize the time that the rings and planet spend inside the SRU bright body cone. The attitudes that best minimize bright body exposure for the first 11 of the 22 proximal flybys turn out to be poor from a solar heating standpoint for the latter 11 proximal orbits. The likely best safe table management strategy is to select as favorable an orientation as possible for the first half of the proximal orbits, and use a different orientation for the second half. Minimizing the number of changes to the safe table is also a good practice.

By careful selection of the safing attitude during the proximal orbits, the amount of time that the SRU may be blinded by the planet and rings can be kept to roughly 60-90 minutes per encounter in a worst-case safing situation. Analysis to date indicates that the current fault protection monitors will not trigger autonomous fault protection responses if the "no stars" in the SRU time duration can be limited to this short a duration. The IRU will be used to propagate attitude during this period so that when star data becomes available again the attitude correction should be less than what is currently experienced following a rolling downlink with SID suspended. Fault scenarios near Saturn closest approach need to be regression tested including the star identification limitations to determine if other response thresholds need adjustment.

VIII. Other Operational Issues

A considerable amount of work remains before a complete assessment can be made of the proximal orbits phase of the Cassini mission. Thermal models that estimate the heat on sensitive science radiators due to Saturn while Cassini is inside 2.5 R_S need to be developed and integrated in ground simulations. Near Saturn periapsis, aeroheating of the spacecraft due to the Saturn atmosphere needs to be evaluated using actual science observation designs (still being developed). The sequence development process itself is being scrutinized because the navigation uncertainty in the predicted Cassini proximal trajectory means that ephemeris updates may need to be incorporated much later in the sequence development process than occur today.

The possibility of using RWA control during some of the higher-altitude proximal flybys needs more analysis. In particular, the RWA have a limited about of momentum storage capability (34 Nms). Uncertainty in atmospheric torque requires that a lot of margin be planned for in any flyby that uses RWA control near closest approach. The Saturn mass density model will be updated as more science data comes in and this may affect the control mode (RCS versus RWA) and the acceptable attitudes and slew rates (if any) during the proximal periapsis periods. The backup SSA, SRU, and IRU may be powered on to provide good redundancy and hardware health visibility during proximal flybys. The accelerometer may be powered on near periapsis to provide an additional data source for aerodynamic force and torque reconstructions.

IX. Summary and Conclusions

There are 22 proximal orbits planned for the Cassini mission spanning from late April 2017 to Saturn impact in mid-September 2017. These orbits will present unprecedented scientific opportunities but also present new challenges for ground controllers. The 22 passages through the ring plane at 34 km/s just inside the inner edge of the D ring presents debris impact risks to the spacecraft. One method to lessen the risk to the spacecraft electronics bus is to use the HGA as a shield during these crossings. This orientation places the sun sensors directly into the oncoming particle stream. The SSA window area is small so current estimates of debris density in the crossing region give a predicted penetration probability of less than 5 percent for the whole proximal mission. But the dust density in this region is uncertain so SSA health will need to be checked by ground controllers soon after each crossing. Plans include suspending SSA fault protection responses near each crossing until controllers can evaluate the SSA health status.

Preliminary analysis shows that the current mass density estimates for Saturn’s atmosphere at closest approach do not overwhelm the ability of the RCS thrusters to maintain good attitude control during the proximal periapses. But the Saturn atmosphere mass density model will likely change as more science is gathered so avoiding spacecraft slews near closest approach will help maximize control authority margins. A Saturn atmospheric torque model with parameterized density needs to be incorporated into Cassini ground software simulations. Saturn atmospheric torque, similar to Titan low-altitude flybys, will require that thruster leak detection monitors that use angular momentum accumulation be temporarily suspended during closest approach to avoid unwanted fault responses.

Saturn radiation may require that some fault protection monitor thresholds be relaxed during the proximal flybys. The Earth flyby radiation environment demonstrated that single event transients are expected on the HRGs and that thresholds for parity violation persistence may need to be raised. Rate transients due to radiation can also cause other monitor thresholds (for example, RWA monitors) to be exceeded so attention is needed here too.

The unique geometry of the proximal flybys will make finding clear star field orientations for the SRU very challenging. Star identification can be suspended for up to 5 hours during nominal proximal flyby sequence design, but safing attitude orientations need to be planned to minimize SRU exposure to bright bodies. There is no single orientation that will always avoid these bright bodies, but analysis shows that the optimal orientation can limit the exposure to less than 90 minutes for each proximal flyby. Fault scenarios near Saturn closest approach need to be evaluated including the star identification limitations to determine if other fault response thresholds need adjustment.

Work is still in progress but the Cassini operations team is determined to make sure that the Cassini spacecraft is configured so that these remarkable proximal flybys can be successfully and safely accomplished.

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