Extended Bright Bodies – Flight and Ground Software Challenges on the Cassini Mission at Saturn

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Extended bright bodies in the Saturn environment such as Saturn's rings, the planet itself, and Saturn's satellites near the Cassini spacecraft may interfere with the star tracker's ability to find stars. These interferences can create faulty spacecraft attitude knowledge, which would decrease the pointing accuracy or even trip a fault protection response on board the spacecraft. The effects of the extended bright body interference were observed in December of 2000 when Cassini flew by Jupiter. Based on this flight experience and expected star tracker behavior at Saturn, the Cassini AACS operations team defined flight rules to suspend the star tracker during predicted interference windows. The flight rules are also implemented in the existing ground software called Kinematic Predictor Tool to create star identification suspend commands to be uplinked to the spacecraft for future predicted interferences. This paper discusses the details of how extended bright bodies impact Cassini's acquisition of attitude knowledge, how the observed data helped the ground engineers in developing flight rules, and how automated methods are used in the flight and ground software to ensure the spacecraft is continuously operated within these flight rules. This paper also discusses how these established procedures will continue to be used to overcome new bright body challenges that Cassini will encounter during its dips inside the rings of Saturn for its final orbits of a remarkable 20-year mission at Saturn.

Nomenclature

AACS	=	Attitude and Articulation Control Subsystem
AFC	=	Attitude Control Flight Computer
AU	=	Astronomical Units
B/S	=	Boresight
CCD	=	Charge-Coupled Device
HGA	=	High Gain Antenna
HRG	=	Hemispheric Resonator Gyroscope
IRU	=	Inertial Reference Unit
KPT	=	Kinematic Predictor Tool
NAIF	=	Navigation and Ancillary Information Facility
NASA	=	National Aeronautics and Space Administration
R_S	=	Radius of Saturn body
RWA	=	Reaction Wheel Assembly
SID	=	Star identification
SRU	=	Stellar Reference Unit
SSA	=	Sun Sensor Assembly
$\omega_{x,y,z}$	=	Spacecraft body rotation rate about the body X, Y, Z axis

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I. Introduction

THE Cassini spacecraft was launched on October 15, 1997 from Cape Canaveral Air Force Station, Florida atop a Titan 4B launch vehicle. The spacecraft then embarked on a seven-year cruise, during which Cassini performed a series of gravity-assist flybys with Venus (twice), Earth, and Jupiter, before finally arriving at Saturn on June 30, 2004. Since then, the Cassini spacecraft has gathered a wealth of science information on Saturn's dynamic magnetic environment, its complex rings, and its amazing assortment of satellites. The rings were revealed as active and dynamic; icy plumes were discovered on Enceladus; and a very frigid but somewhat Earth-like world with hydrocarbon rain, rivers, lakes, and seas was found on Titan. In order to gather observations like these with high fidelity, precise pointing of the Cassini scientific instruments towards the targets must be maintained. Therefore, it is imperative that the knowledge of the spacecraft's orientation, or attitude, in space also be continuously estimated with high accuracy.

There are three key sensors in the Cassini Attitude and Articulation Control Subsystem (AACS) onboard of the spacecraft that work together to establish the attitude knowledge: the Inertial Reference Unit (IRU), the Stellar Reference Unit (SRU), and, during initialization, the Sun Sensor Assembly (SSA).[1] Two IRUs are mounted on the inner -Y side of the Cassini spacecraft body frame, two SRUs are mounted on the outer +X side with its optics pointing towards the spacecraft +X direction, and two SSAs are mounted on the -Z side of the spacecraft inside the High Gain Antenna (HGA) dish. The majority of Cassini's science instruments, including imaging cameras, are also rigidly mounted on the +X side of the spacecraft. Since these instruments are rigidly fixed onto the spacecraft body, the entire spacecraft must be slewed to achieve proper instrument pointing when performing science observations. Figure 1 below illustrates the positions these sensors are located on the Cassini spacecraft.

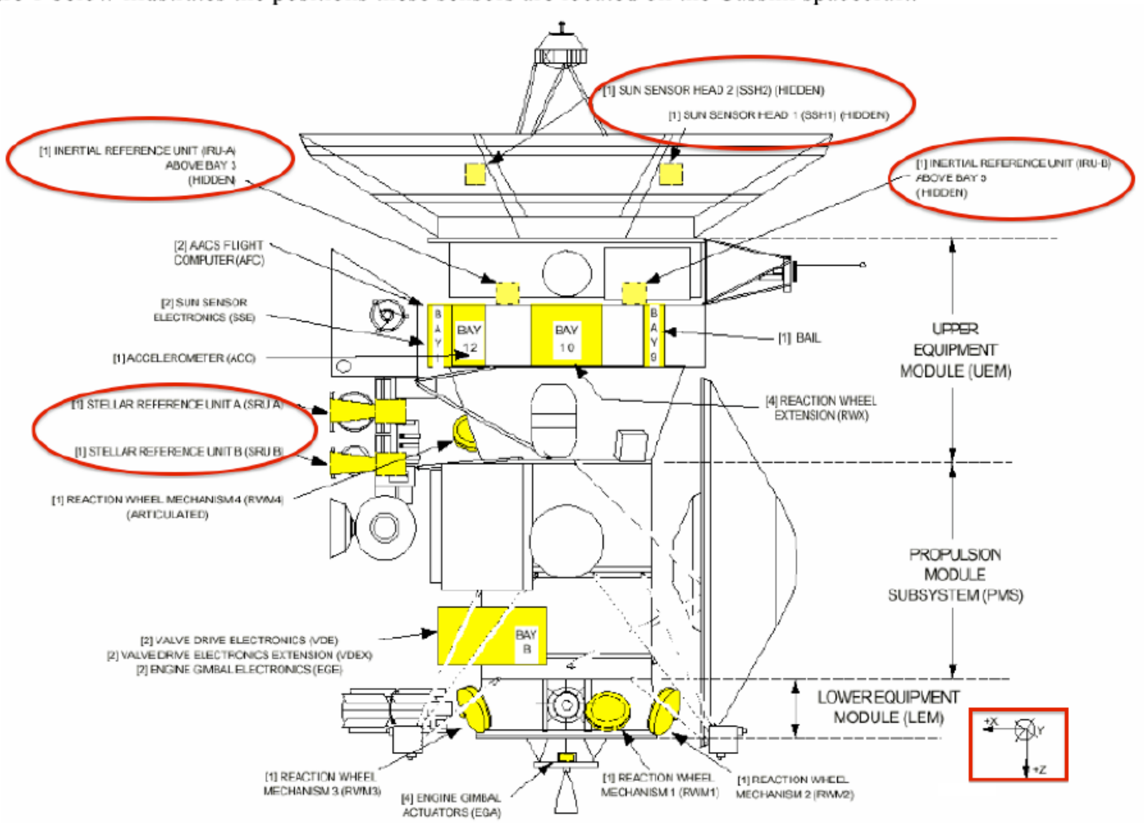

Figure 1. Cassini spacecraft diagram showing Attitude and Articulation Control Subsystems.[1]

Cassini's two identical two-axis Sun Sensor Assemblies provide sun data to the Attitude Control Flight Computer (AFC), one nominally powered on and actively used throughout the mission and the other serviced as a backup. The SSAs are mounted on Cassini's High Gain Antenna dish (HGA) and have boresights aligned with the HGA boresight, with a square ±32 by ±32 degrees field-of-view. The flight software uses the sun data obtained by the SSA to construct a "sun line" vector. The knowledge of the Sun position is typically used to initialize the spacecraft attitude estimation. In situations when the spacecraft attitude is completely lost due to anomalies, the spacecraft would first perform a sun search with the SSA before acquiring 3-axis stellar reference with star identification.

The Cassini's Inertial Reference Unit consists of four Hemispheric Resonator Gyroscopes (HRGs); three orthogonal units are used as prime inertial sensors and one skew-oriented unit used as a parity checker. The HRG accurately senses rotational motion using the resonant vibrations (similar to a wine glass) of an axis-symmetric fused-silica shell (which has no moving parts). Since there is a very small amount of energy and mechanical stress imparted to the shell, these IRUs are reliable for long-duration operations in missions like Cassini. One IRU is actively used throughout the mission while the other is a backup. The IRU obtains and supplies the spacecraft attitude change data to the AFC, and the AFC flight software filters this data into spacecraft body-rate and the 3-axis inertial attitude knowledge is updated. The IRUs are periodically calibrated using an onboard extended Kalman filter. Angular rate biases are actively estimated via the Kalman filter, and scale factor errors[1] and axis misalignments can be updated via ground commands. IRU scale factor errors and misalignment can induce attitude knowledge errors over time if not corrected by star tracker celestial updates. Therefore, Cassini attitude determination nominally uses a Stellar Reference Unit as the prime sensor, supplemented with IRU measurements in between star updates.

The SRUs are star trackers that detect stars in its field-of-view and compares them with Cassini's onboard star catalog.[1,2] The catalog contains position, color, magnitude, and usability flags of the stars used for star identification (SID). Three-axis attitude reference is determined based on star data from two up to five stars in the SRU's field-of-view. Cassini has two identical SRUs, one nominally powered on and actively used throughout the mission and the other normally powered off and used only as a backup. As shown in Figure 1, both SRUs are co-aligned with their boresight vectors parallel to the spacecraft's +X-axis. Each has an optical field-of-view of ±7.5 by ±7.5 degree (a square 15 degrees across). Figure 2 depicts the SRU field-of-view with Saturn and the rings near the boresight.

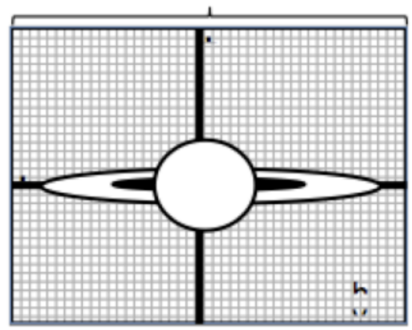

Figure 2. The Stellar Reference Unit's field-of-view (15 degree square).

During the voyage to Saturn, Cassini flew by Jupiter in December of 2000. Science gathering during this flyby served as a "trial run" for the prime mission at Saturn to begin in July of 2004. An extended bright body such as Jupiter or Saturn, if in or near the star tracker field-of-view, could degrade the SRU's ability to track stars (see Figure 2). Although Cassini's passage by Jupiter was rather distant (Jupiter never reached 1 degree angular diameter from Cassini's perspective), a "blooming effect" on the SRU Charge-Coupled Device (CCD) was repeatedly observed during a nine-hour X-axis spin activity. The SRU was oriented about 10.5 degree from Jupiter throughout the spin, resulting in Jupiter repeatedly crossing the corners of the SRU field-of-view. While star identification was maintained for much of the spin, each time Jupiter entered the corner of the SRU field-of-view, all stars were usually lost. This resulted in perturbations to the attitude estimate, which in turn introduced pointing errors of up to 15 mrad. Figure 3 shows the X-axis attitude error spikes for this case.

The need to "suspend" star identification (SID) due to bright bodies at Saturn was anticipated pre-launch, but the actual flight and ground software logic to implement the suspension was deferred until after the Jupiter flyby. During an SID suspend period, the flight software must propagate inertial attitude knowledge using the IRU data alone. IRU gyro scale factor errors and misalignments will degrade the IRU-only estimates over time. At the end of each SID suspend period, star identification is re-enabled and any attitude error introduced by IRU-only estimation is quickly corrected. A suspend duration limit must be enforced to avoid excessive attitude error corrections that could cause fault protection monitors to interrupt normal operations. In flight, the attitude error due to IRU-only propagation can also be reduced by careful calibration of the IRU scale factors and misalignments. Updates to these IRU flight software parameters were made during the mission, and Figure 4 gives a summary of the attitude error correction time-history after each lengthy SID suspend.

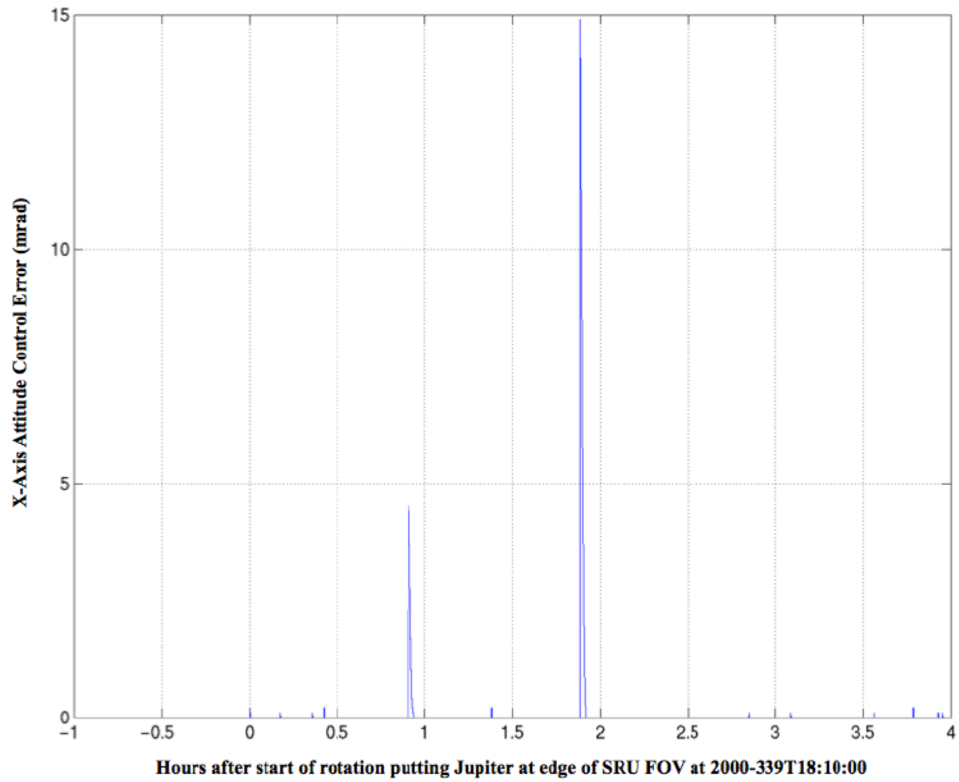

Figure 3. X-axis attitude control error induced by Jupiter's interference to star identification.

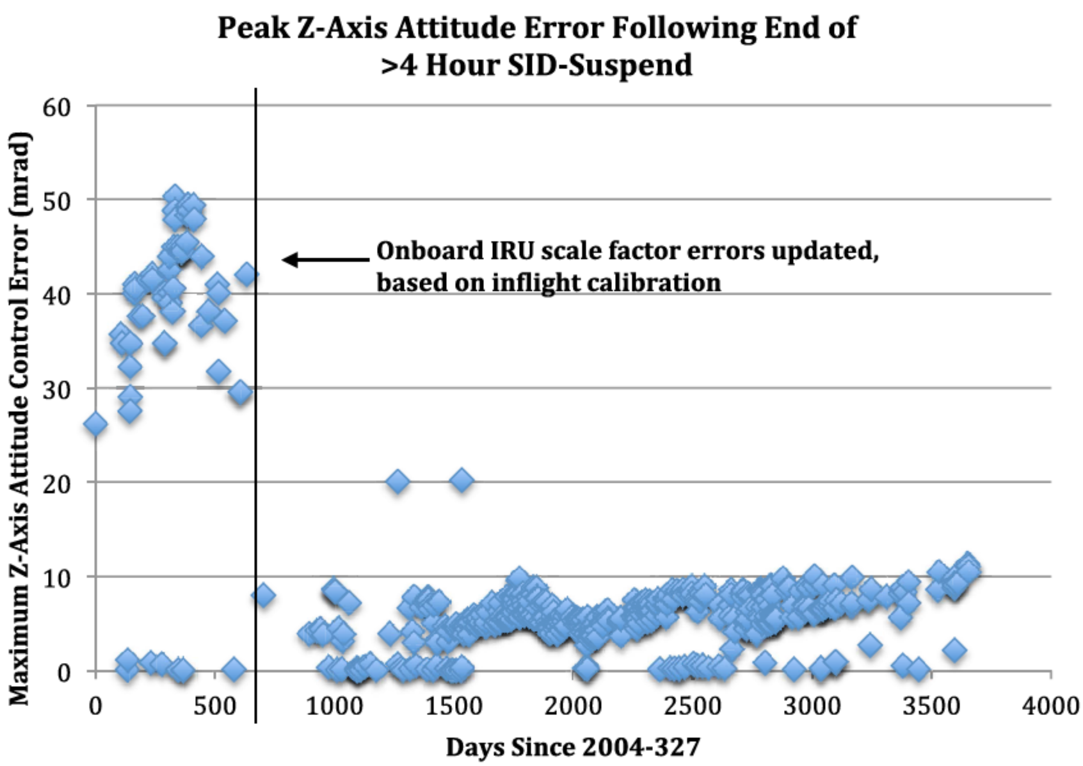

Figure 4. Attitude control error correction following SID suspends.

A new flight software command was added so that ground operators could issue a series of SID suspends when the spatial geometry at Saturn warranted. Each suspend command has a single argument: the duration of the suspend. The logic to determine when to issue the suspends, and for how long, was added to an existing ground software tool. This tool, the Kinematics Predictor Tool (KPT), is a time-based simulator that models all Cassini slews and celestial body directions and angular sizes. Spacecraft and celestial body positions in space are loaded into KPT via ephemeris files. Also loaded into KPT is the time-ordered sequence of pointing commands that will ultimately be sent to the spacecraft. These commands include spacecraft slews as well as inertial and body vector commands that define the desired pointing time history. Based on a set of SID suspend flight rules (discussed below), KPT processes the time-ordered sequence of pointing commands and generates a series of SID suspend commands consistent with the geometry of the Saturnian system. These commands are merged with the rest of the flight sequence and then uplinked to the spacecraft.

II. Development of SID Suspend Flight Rules

Based on flight data at Jupiter, expected albedo of objects in the Saturnian system, the star tracker, and star identification flight software, a set of flight rules was established to define when to suspend star identification. A cone centered at the star tracker boresight can be defined. A cone with a half-angle of about 10.6 degrees $(7.5\sqrt{2})$ would circumscribe the actual star tracker field-of-view. But stray light from an extended bright body can reflect light off the inner barrel of the optical housing and onto the CCD even when the edge of the bright body is beyond the optical field-of-view of the star tracker. A set of thresholds and cone angles was established to define when an SID suspend was needed. Prior to an SID suspend, the spacecraft body rates need to be below a defined threshold to ensure good star knowledge exists just before the suspend. Similarly, a quiescent spacecraft is needed at the end of a suspend to ensure rapid and accurate star re-acquisition. In some cases, multiple bright bodies may enter the stray light cone in succession, and logic is needed to establish when to extend a single SID suspend to cover multiple objects. Spacecraft body rates above a threshold also warrant an SID suspend, because star tracking can fail if the visible star field is changing too fast. Also, an SID suspend duration limit must be enforced to protect against excessive accumulating attitude knowledge and control error.

The initial design of the SID suspend flight rules is given below.[3] Limitations on when to perform gyro and SRU calibrations is also included as these activities pre-suppose continuous good star identification. A limitation in the onboard fault protection requires a star identification fault monitor be masked throughout an SID suspend.

1. SID must be suspended whenever the edge of the un-occulted Sun is within ±30° of the SRU boresight (B/S) for longer than 6 minutes.
2. SID must be suspended when the spacecraft body rate is "fast" such that $|\omega_y| + 0.131\times|\omega_x| > 9.6$ mrad/sec.
3. SID must be suspended when the spacecraft body rate is "fast" such that $|\omega_z| + 0.131\times|\omega_x| > 9.6$ mrad/sec.
4. SID must be suspended when any part of an object with a diameter > 0.5° is inside the SRU's B/S ±12° cone.
5. SID must be suspended when any part of an object with a diameter > 1.7° is inside the SRU's B/S ±18° cone.
6. SID must be suspended when any part of an object with a diameter > 2.0° is inside the SRU's B/S ±30° cone.
7. The duration of a SID suspend event must not exceed 5 hours.
8. All SID suspend events must be preceded by a 10 minute period in which the total spacecraft rate is quiescent (< 0.5 mrad/sec) and followed by a 20 minute period in which the total spacecraft rate is also quiescent (< 0.4 mrad/sec).
9. SID suspend must not occur during IRU or SRU calibrations since these activities require celestial reference from the SID algorithm.
10. Commands that modify the star catalog or initialize star identification algorithms must not be issued during SID suspends.
11. The "No Star In Inertial" fault monitor must be properly masked during SID suspends since the monitor would still expect to see continuous star updates.

The above rules were designed incorporating the best knowledge of expected performance at Saturn. Upon arrival at Saturn, flight data showed that a few other geometric situations could perturb star identification. The Z-Sigma fault protection monitor reports any unreasonably large deviations (based on propagated covariance) between a new SRU attitude measurement and the current propagated attitude (based on IRU and previous SRU measurements). At Saturn, it was found that moons below the 0.5 degree angular diameter threshold, if they were in the SRU optical field-of-view, could sometimes cause a jump in the Z-Sigma ratio. Since this situation could reoccur at any time, an update to the SID suspend flight rule was implemented into KPT. One new condition (a small moon sitting within the SRU optical field-of-view for longer than 30 minutes) was considered serious enough to warrant an SID suspend for that case:

12. SID must be suspended when any part of an object with a diameter > 0.2° is inside the SRU's B/S ±12° cone for ≥ 30 continuous minutes.

Flight data showed some other cases that were not severe enough to need an SID Suspend, but did warrant masking of the Z-Sigma monitor to protect against short incursions into the SRU optical field-of-view. This monitor, if its threshold were to be exceeded for long enough, could cause fault protection to issue a spacecraft safing event. To avoid this risk during known periods when small moons entered the SRU optical field-of-view, masking of the monitor for short periods was seemed appropriate. When an SID suspend is not already in effect, mask the Z-Sigma ratio monitor if:

1. Any part of the object with diameter ≥ 1.5° is inside the SRU's B/S ±12° cone for < 1 minute.
2. Any part of the object with diameter ≥ 0.5° and < 1.5° is inside the SRU's B/S ±12° for < 4 minute.
3. Any part of the object with diameter ≥ 0.2° and < 0.5° is inside the SRU's B/S ±12° for ≥ 1 minute and < 30 minutes.

Similar to SID suspend flight rules, it is possible to combine Z-Sigma masking commands to accommodate multiple interference in succession in certain scenarios. The timing of the Z-Sigma masking and unmasking commands relative to the entry and exist of extended bright bodies into the SRU's field-of-view is also defined:

4. Multiple Z-Sigma fault protection error monitor mask/unmask events can be combined into a single mask/unmask event if they are < 40 minutes apart.
5. All Z-Sigma masking commands must be issued 5 minutes before bright body enters the field-of-view, and unmask commands must be issued 5 minutes after bright body exists the field-of-view.

Attitude control analysts began manually creating short Z-Sigma mask events after flight data uncovered the first Z-Sigma spike event in 2006. By 2009, the Z-Sigma monitor mask criteria were added to KPT. Since then, about 100 of these events were briefly masked in flight. Subsequent analysis showed that not all of these cases actually had spikes in the Z-Sigma ratio, but some did and this protection has remained a part of the SID suspend flight rule.

III. Ground Software and Operational Processes

An automated method of constructing SID suspend commands became a new capability of an already-existing ground software tool called the Kinematic Predictor Tool (KPT). All pointing-related commands in an uplinkable sequence, including slewing to and tracking science targets, are modeled on the ground in KPT prior to uploading onboard to the spacecraft. KPT uses the same approach as the actual flight software and profiles turns and performs target motion compensation to simulate a sequence of Cassini's turn and tracking events. KPT also models the geometry (angular size of celestial bodies and angles between them and spacecraft body-fixed vectors) of Cassini with respect to the Sun, Earth, Saturn, the rings, and the Saturnian moons. KPT flags any pointing, geometric, or thermal flight rule violations, and the ground operators must carefully analyze and resolve them. The sequence must run through KPT cleanly before it is ready to be uplinked to the spacecraft. The SID suspend criteria given above were added to KPT and the resulting SID suspend commands are then merged with the sequence prior to sequence uplink.

There are a wealth of functions in NASA's Navigation and Ancillary Information Facility (NAIF) toolkit that are available to calculate the position and relative geometry between celestial bodies and a spacecraft. KPT uses NAIF functions to load and read ephemeris files for Cassini and all relevant celestial bodies. These ephemeris files, along with physical constant files for celestial object geometry, provide the data needed to utilize the mathematical functions available in the NAIF toolkit.[4] The navigation team keeps these input files current, and with this information, distance and geometry of objects with respect to Cassini are modeled in KPT. Celestial bodies like Saturn and the moons are modeled as tri-axial ellipsoids in KPT. When an ellipsoid is viewed from any location at a distance, it would appear to the viewer as an ellipse. This is the same concept as finding the intersection of the plane perpendicular to the instrument boresight with the largest portion of the ellipsoid as seen from the viewpoint. The closer the viewpoint is from the target, the larger the ellipse appears to be. The edge of the visible disk is called a "limb" – an ellipse normal to the vector from Cassini to the celestial object. The minimum angle between an extended bright body and the SRU boresight can then be obtained by finding the minimum angular separation between the SRU's boresight, or "ray", and the limb of that body. The point of minimum angular separation is not necessarily the nearest point on the ellipse to the viewpoint. This is especially apparent for a very eccentric ellipse. A very thin but wide ellipse is exactly what the rings of Saturn appear from Cassini's perspective. The NAIF function does a rapid search of points on the ellipse to find the minimum angular separation. Figure 5 illustrates the concept of how the NAIF tools determine the proximity and the geometry of celestial bodies to an instrument field-of-view. The acceptable size of this viewing ellipse and the minimum angle between the SRU ray and the limb of the obstructing bright body are defined by the SID suspend flight rules as mentioned in the previous section.

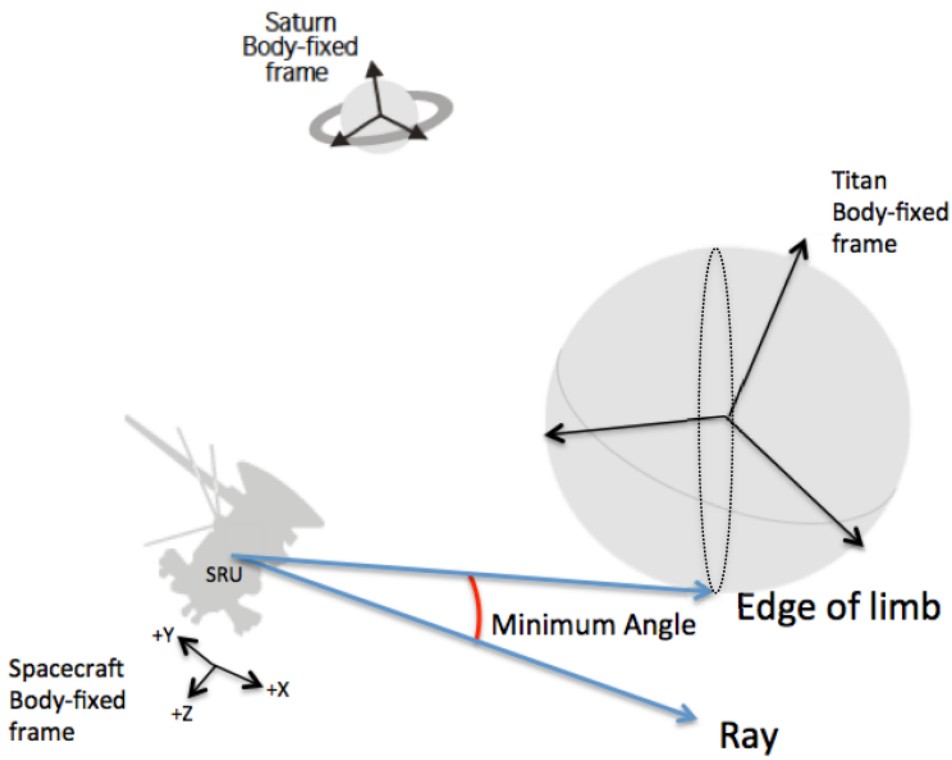

Figure 5. Finding minimum angle of SRU boresight to bright body limb.[4]

The implementation of the SID suspend flight rules in KPT requires dealing with multiple instances of celestial objects near the stray light cone of the SRU. The KPT logic has to include when to extend the duration of a single SID suspend, and when to create two suspends separated by a quiescent period. Some science observations with multiple slews near each other in time may not have enough quiescent time to place an SID suspend without violation the 5 hour suspend duration limit. Science teams must then adjust their pointing or timing of their slews in order to avoid SID suspend violations. The key is to always find a quiescent period with a clear star field so that SID suspends can be placed. In practice, SID suspends are only needed about 7 percent of the time while in Saturn orbit. They tend to occur most frequently during multi-revolution rolls (which often happen during Earth downlinks, spinning about the HGA boresight). A recent example is given in Figure 6. This figure depicts a 9-hour downlink that includes a 4.6-hour spin about the Z-axis, then a quiescent period, then a 3.5-hour spin about the Z-axis. Cassini is in Reaction Wheel Assembly (RWA) control throughout this time period. Figure 7 shows that the edge of Saturn comes within 20 degrees of the SRU boresight during each revolution. The SID suspend spans the entire 4.6-hour spin, and Figure 8 depicts the 13-mrad Z-axis attitude error correction when star knowledge is reacquired. Figure 9 magnifies the attitude error correction at the time of the re-acquisition. It takes about 1.5 minutes for the RWA controller to fully correct the pointing error introduced by IRU-only propagation (the error about the other axes is negligible) after re-acquiring SID attitude estimates.[5]

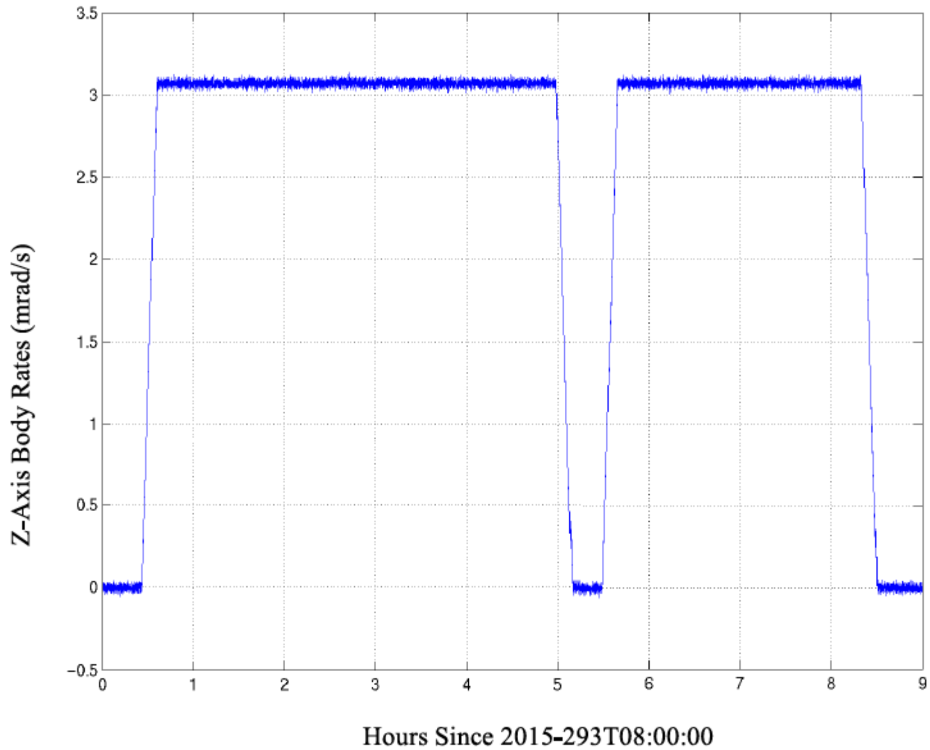

Figure 6. Cassini's spacecraft body Z-axis rotation rate that depicts the spin about Z-axis during a 9-hour downlink roll.

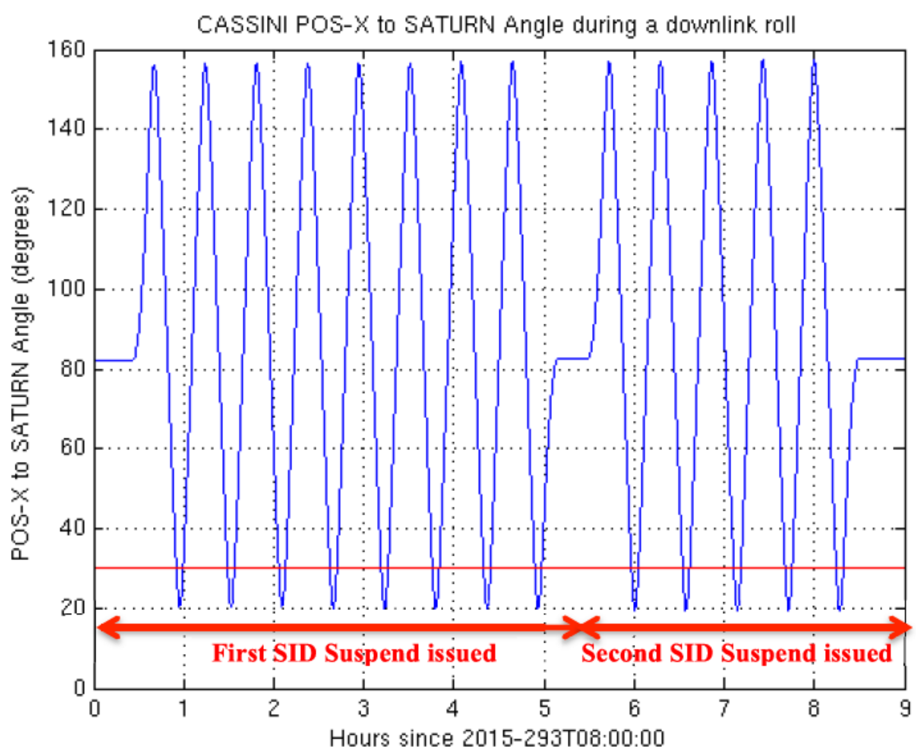

Figure 7. Cassini's spacecraft body +X axis angle to Saturn during a 9-hour downlink roll.

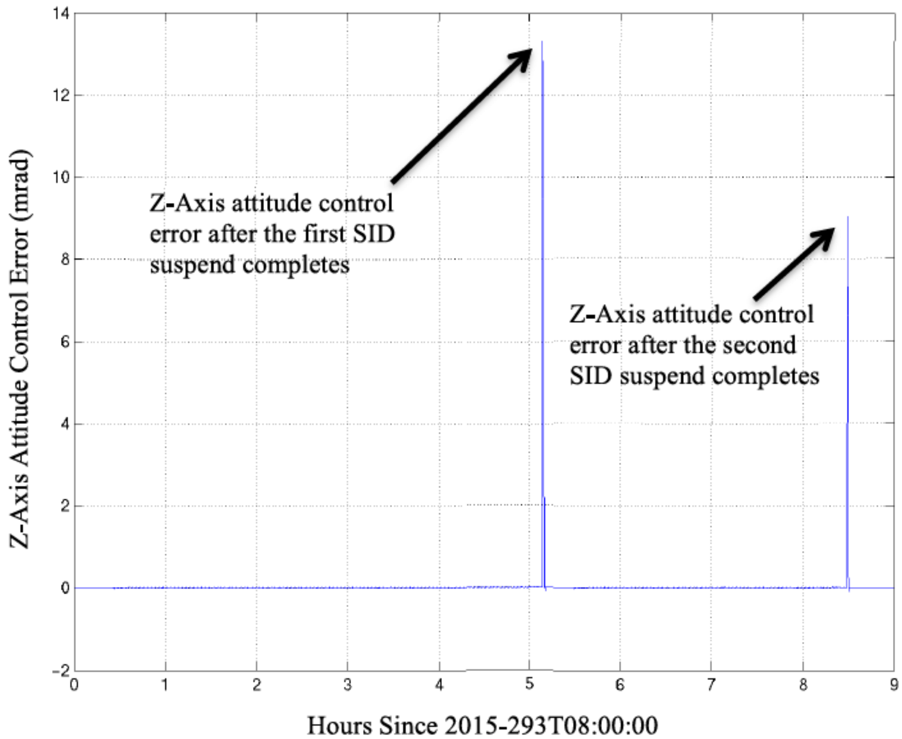

Figure 8. Cassini's body Z-axis attitude control error.

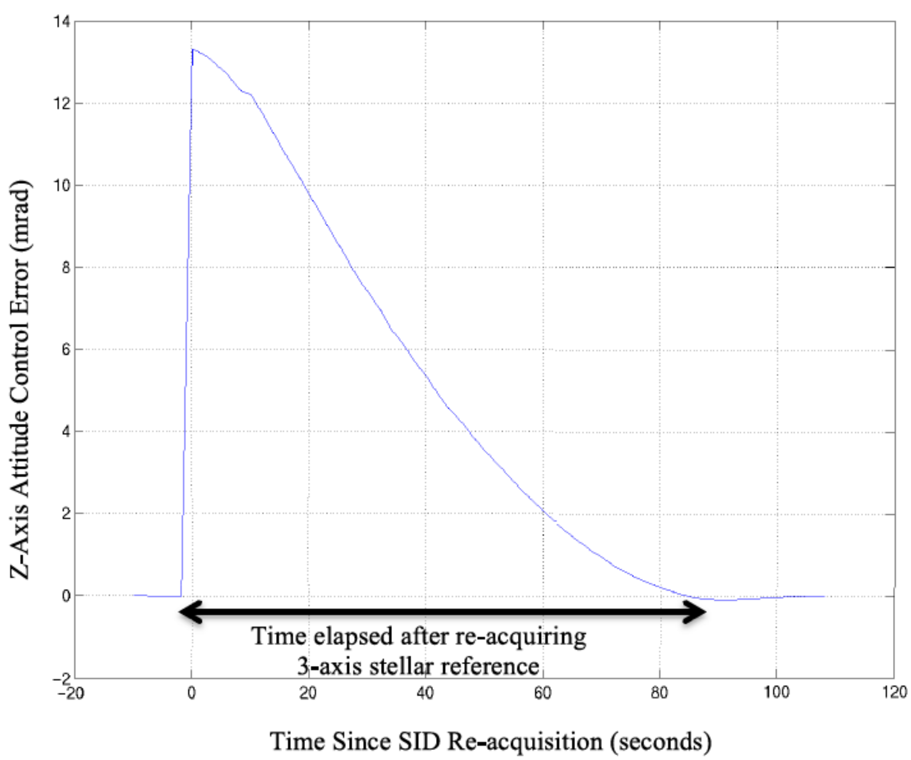

Figure 9. Cassini's body Z-axis attitude control error correction zoomed in.

IV. SID Suspends for Saturn and Rings Interferences

Saturn and the rings, from Cassini's perspective, presents a challenge because of the ever-changing set of bright bodies that must be kept out of the SRU field-of-view or managed with SID suspend commands. Although not as bright as Jupiter, and at 9 astronomical units (AU) from the Sun compared to 5 AU for Jupiter, Saturn dominates the sky from Cassini's perspective. Cassini follows an elliptical path around Saturn, and this path changes frequently as Cassini is carefully guided to encounters with the various Saturnian moons. So Saturn can be as small as only 2 degrees of angular diameter (at apoapsis) from Cassini's perspective. At periapsis, Saturn can grow to over 150 degrees – essentially filling half the sky like the Earth does to a low-orbiting satellite around the Earth. It is this constantly changing geometry that is especially unique about the Cassini mission – that and the presence of Saturn's brilliant array of rings. Saturn, like the Earth, is an oblate spheroid flattened at the poles. Although Cassini occasionally passes into Saturn's shadow, most of the time Saturn appears to Cassini as a bright disk or crescent. Almost all of the SID suspends issued on Cassini are due to Saturn and the rings. For simplicity, both Saturn and the rings are treated as bright objects whether or not they are fully illuminated from Cassini's perspective.

The rings are treated as an extremely thin ellipsoid (a very thin plate) with a circular radius 2.26 times the radius of Saturn (R_S). The angular size of the rings, because of its very large semi-major axis and Cassini's trajectory, can vary from about 4 degrees up to 180 degrees from Cassini's perspective. Because of the rings disk-like appearance to Cassini, at times Saturn can enter the SRU field-of-view first, other times the rings enter first. Typically, a single SID suspend is constructed that spans the time both bodies are within the 30 degrees stray light field-of-view.

Cassini's orbital inclination with respect to Saturn has varied from up to 75 degrees down to zero. When Cassini's inclination is near zero, the rings appear as a wide but extremely narrow ellipse – part of which is occulted by the enormous planet. When in a high inclination orbit, the rings appear to Cassini as a wide ellipse that can almost become circular with a radius of 2.26 R_S. In all cases, the algorithm to calculate the rings' angular separation from the SRU boresight is the same – a rapid search of points on the ring ellipse to find the smallest separation.

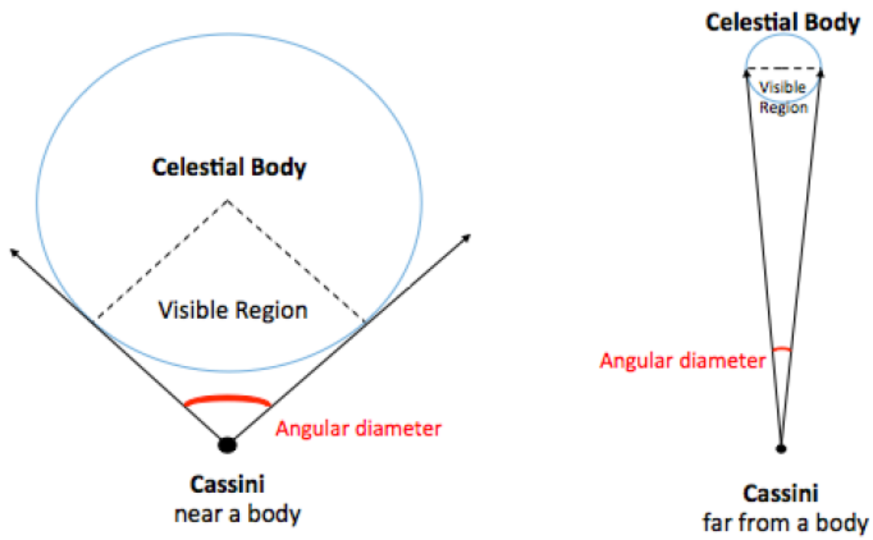

Figure 10. Visible region of a celestial body with respect to Cassini is illustrated.

Calculating the angular diameter of the rings is really no different than the Saturn (or the moons) calculation – begin with constructing a ray from Cassini to the center of the object (the center of the rings is of course the same as the center of Saturn), then construct a cone centered on that ray of an ever-increasing angular diameter. When the object is fully circumscribed by the cone, that is the angular diameter of the body. When that body is near Cassini, the tangent points on the body that define its angular diameter (with respect to Cassini) span much less than 50% of the body (see Figure 10). At great distances, the visible region is just under 50% of the ellipsoid. Figure 11 depicts the angular diameter of the rings and Saturn from Cassini's perspective during an orbit late in 2015. In this case, Cassini comes in very close to the rings – only 2.54 R_S from the center of Saturn at periapsis. This puts Cassini only 0.28 R_S from the outer edge of the rings. Being so close to the rings is what causes the rings to have an apparent angular diameter greater than 2.26 that of Saturn – in this case, its angular diameter reaches 2.7 times that of Saturn. Even so, there is still a large fraction of the sky that is clear of bright bodies – even at a periapsis of only 0.28 R_S outside the edge of the rings. For the proximal orbits in 2017, this is not always still true.

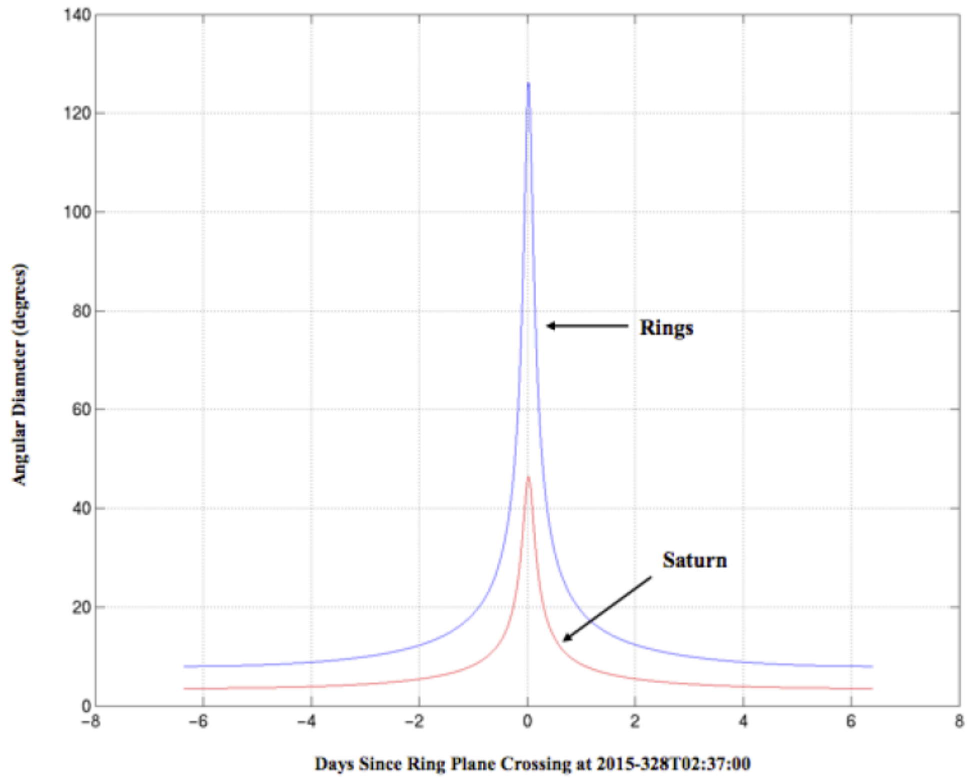

Figure 11. Angular diameter of Saturn and its rings from Cassini's perspective during periapsis crossing.

V. Challenges of the Proximal Orbits

In the spring, summer, and fall of 2017, the Cassini spacecraft will embark on a truly unique operation that has never been done before – the "Grand Finale", where Cassini will fly through the ring plane just above Saturn's cloud tops for 22 high inclination orbits, called "proximal orbits" (Figures 12 and 13), before finally ending its incredible 20-year long mission.[6] The science opportunities are tremendous. By flying so close to a sun-lit Saturn, Cassini can map its magnetic field and gravity in great detail, directly sample the composition of Saturn's atmosphere, and gain further knowledge of the age and evolution of Saturn's rings. However, the close proximity that Cassini will travel in between Saturn and its rings also pose unprecedented challenges to the spacecraft – including the SRU's ability to track stars.

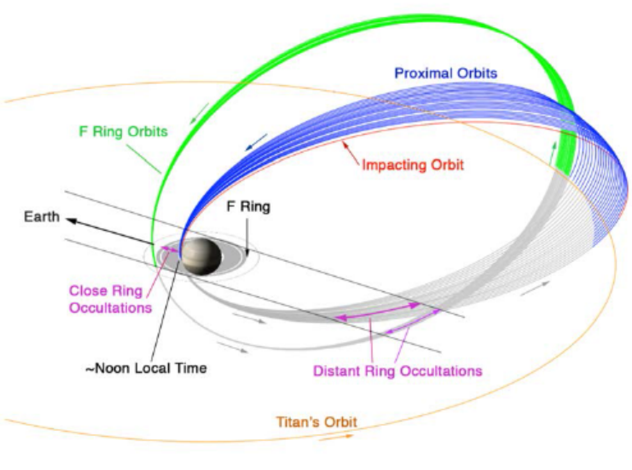

Figure 12. Proximal Orbit trajectory during mission "Grand Finale".[6]

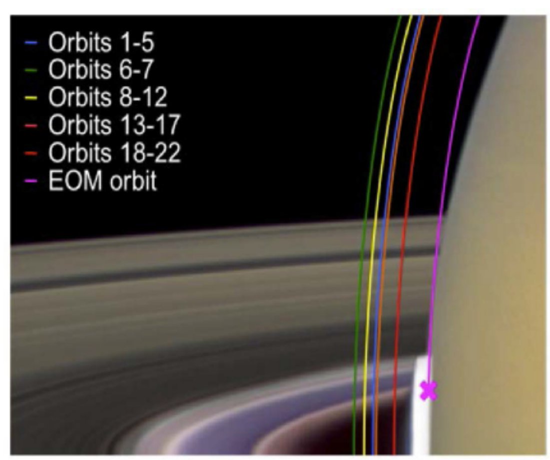

Figure 13. Proximal Orbit trajectory zoomed in near Saturn.[6]

The time periods near proximal periapsis will be unique in the history of the mission. Never will Cassini have passed so close to the planet. Near the ring plane crossing, Saturn will span up to 160 degrees of the sky from Cassini's perspective. And the rings, both before and after the crossing, will extend this bright body region by another 90 degrees or so. Figure 14 shows the bright body angular diameter when the visible part of the rings extends the Saturn bright body region during a typical proximal periapsis period. So, if the 30-degree stray light cone is factored in, near the ring plane crossing only a tiny sliver of a star field, perhaps a solid angle of roughly 30 degrees by 30 degrees will be visible. And even that field changes abruptly from "above" the ring plane, to "below" the ring plane, at the moment that Cassini crosses between the rings and the planet. At the exact moment of crossing, technically Cassini is inside the ring ellipsoid, but the ellipsoid is so thin (<100m) that Cassini passes through it in less than 0.01 seconds. All 22 proximal periapsis are being designed to include SID suspend commands that span this closest approach period. Fortunately, the time period where the combined Saturn/rings bright body exceeds 180 degrees is only about 45 minutes, with Cassini traveling at about 34 km/s near closest approach.

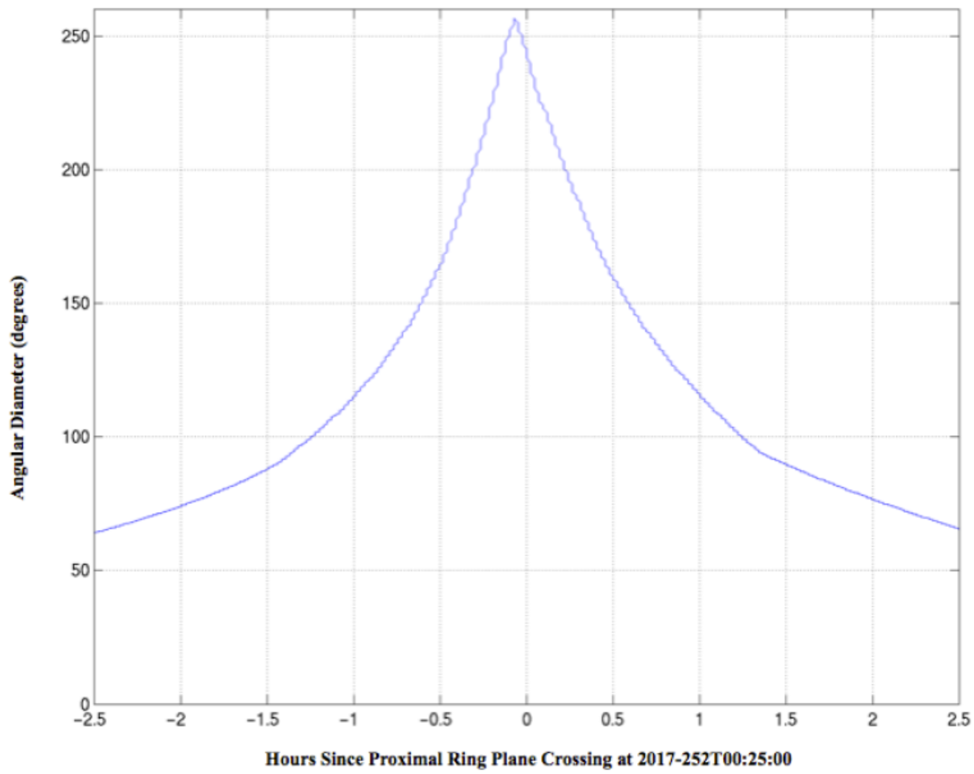

Figure 14. Angular diameter of the combined Saturn/rings bright body during closest approach of a proximal flyby as seen by the Cassini spacecraft.

There is literally no single attitude that will allow the SRU a clear field of stars in any of the 22 proximal orbits during the few hours surrounding the closest flyby across the ring plane. Even if the Cassini SRU was oriented with a clear view of stars that avoids Saturn and the rings prior to the ring plane crossing, it would still be suddenly obstructed the moment Cassini crosses the ring plane. In the proximal sequences during nominal operations, SID suspend commands can be issued per usual procedures and flight rule restrictions as previously discussed. The far bigger challenge would be to anticipate an acceptable safe mode attitude that the spacecraft would be oriented should an anomaly occur. If Cassini enters safe mode, all nominal sequences would be stopped, the spacecraft would autonomously turn to the safing attitude to await ground response, and an entire proximal flyby may occur at the safing attitude without any suspension of star identification.[7]

During current science operations, the safe mode attitude is normally chosen to keep Saturn and the rings outside of the 30-degree cone centered on the SRU boresight. If Cassini enters safe mode, the safe mode attitude needs to ensure a commandable spacecraft, a benign thermal environment, a clear star field, and the ability to play back data to help ground controllers assess the spacecraft anomaly. A commandable spacecraft requires that the High Gain Antenna always be Earth or Sun-pointed as the primary pointing during safing recovery. Ground controllers have flexibility as to where the SRU shall point, because its boresight is perpendicular to the HGA. A poorly chosen safe mode attitude that puts the SRU towards a bright body for a very long time could complicate the anomaly investigation or further risk the health of the spacecraft. Since there is no single attitude that provides a clear star field throughout closest approach, the best alternative would be to utilize an attitude that minimizes the time of SRU bright body interference as much as possible. After careful and detailed analysis conducted by ground operators, safe mode attitudes have been selected where the SRU field-of-view is obstructed by Saturn and the rings for no more than 60-90 minutes at a time in a safing situation. Two different safe mode attitudes have been chosen: the first spans the first 11 proximal orbits and the second covers the last 11 proximal orbits. It is not practical to switch safing attitudes at the moment of the ring plane crossing, because safing could inhibit the switch from occurring.

Rigorous testing is needed to ensure that the safe mode attitudes are, in fact, safe for the spacecraft in case of anomalies.[8] Testing in ground software simulators indicates that the current fault protection monitors will not trigger autonomous fault protection response if "no stars" are visible to the SRU for time periods limited to 60-90 minutes. The IRU will be used to propagate the attitude during this period until star updates becomes available again. Ground testing shows that the IRU propagation errors within the 60-90 minutes window would still be less than currently experienced following a rolling downlink with SID suspend as previously shown. The results of this test shows that the safing attitude selected should overcome the bright body challenges anticipated during the proximal orbit operations.

VI. Conclusions

In-flight testing and observations of the Jupiter flyby in December of 2000 allowed ground engineers to develop precise flight rules based on the bright body diameters and the minimum angles between the SRU ray and bright body limb that were problematic to star identification. After arriving at Saturn, these flight rules were further refined to include smaller bright body interferences and the need to mask Z-sigma fault protection monitor. The flight rules and procedures developed are especially beneficial to Saturn and ring interferences, whose angular diameter can span from 2 to 150 degrees for Saturn or 4 to 180 degrees for rings in Cassini's perspective. Automated methods have been developed in the KPT ground software to generate the to-be-uplinked SID suspend commands as well as enforcing the flight rules by issuing violations to problematic designs. The smooth operation of the Cassini spacecraft to date reflects that the operational processes used by the attitude control team, along with vital ground software tools, provide constraint-free commands that permit precise attitude determination and pointing overcoming the bright body interferences on the SRU so that science objectives can be met. Test cases conducted have shown that these existing flight rules and the ground software are also sufficient to support the new challenges presented by the even closer proximity and geometry of Saturn and its rings during the "Grand Finale" operations. In case of spacecraft anomalies during the proximal orbit flybys where Cassini must rely on the safing attitude instead of SID suspends, ground engineers have selected two safe mode attitudes that limit the extended bright body interference to star identification to 60-90 minutes, which is acceptable to fault protection. The Cassini spacecraft AACS Operations Team will continue to provide care in sequence design and flight rule checking to maintain a healthy spacecraft with maximal science return through the final orbits of the Cassini mission at Saturn.

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