Managing Cassini Safe Mode Attitude at Saturn

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The Cassini spacecraft was launched on October 15, 1997 and arrived at Saturn on June 30, 2004. It has performed detailed observations and remote sensing of Saturn, its rings, and its satellites since that time. In the event safe mode interrupts normal orbital operations, Cassini has flight software fault protection algorithms to detect, isolate, and recover to a thermally safe and commandable attitude and then wait for further instructions from the ground. But the Saturn environment is complex, and safety hazards change depending on where Cassini is in its orbital trajectory around Saturn. Selecting an appropriate safe mode attitude that insures safe operation in the Saturn environment, including keeping the star tracker field of view clear of bright bodies, while maintaining a quiescent, commandable attitude, is a significant challenge. This paper discusses the Cassini safe table management strategy and the key criteria that must be considered, especially during low altitude flybys of Titan, in deciding what spacecraft attitude should be used in the event of safe mode.

Acronyms

b/g	=	background
BVT	=	Body Vector Table
FOV	=	field of view
FSW	=	flight software
HGA	=	High-Gain Antenna
IVT	=	Inertial Vector Table
LGA	=	Low-Gain Antenna
MAG	=	Magnetometer
ME	=	Main Engine
NAC	=	Narrow Angle Camera
ORS	=	Optical Remote Sensing
RAM	=	Cassini velocity vector (in this case, with respect to Titan)
RCS	=	Reaction Control System
RWA	=	Reaction Wheel Assembly
SID	=	Star Identification
SRU	=	Stellar Reference Unit
UTC	=	Universal Coordinated Time
XBAND	=	X-Band radio-frequency boresight vector

I. Introduction

The Cassini spacecraft arrived at Saturn on June 30, 2004 after a 6.7 year cruise that included gravity-assists from Venus, Earth, Venus again, and Jupiter. In Saturn orbit since that time, Cassini has flown within 25 km of Enceladus, and routinely flies by Titan at an altitude less than 1000 km. During normal operations[1], the attitude of the spacecraft is continuously commanded to meet the needs of the dozen scientific instruments onboard. Daily downlinks of 1 to 2 gigabits of data to Earth is followed by a series of science pointing objectives that involve turning the spacecraft to point one of the 14 science instrument boresights at Saturn, the rings, the Saturnian moons, or other objects. A typical day is 9 hours of data playback at Earth-point (often rolling about the Earth-line to gather more science in parallel with the downlink), followed by 15 hours of turning, tracking, and recording science data.

Cassini attitude control flight software performs many autonomous functions such as star identification and attitude control.[2] But ground operators command all science and engineering activities by way of sequences of commands uplinked and stored as programs onboard until they are ready to execute. These sequences are time-ordered sets of commands, with each command issued at a designated UTC time. The bulk of these commands are in "background" (b/g) sequences which are typically 5 to 10 weeks in duration, and each new b/g sequence is

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uplinked to the spacecraft about 5 days before it is scheduled to begin execution. These b/g sequences contain dozens of individual science and engineering activities merged together. If a fault causes the flight software to enter a “safe mode”, all stored sequences are suspended, most science instruments are powered off, and the spacecraft turns its High Gain Antenna (HGA) towards the Sun and Earth and awaits ground controller action.

Although safe mode has not yet been triggered at Saturn (excepting a single event upset of a power switch in the onboard telecommunications system), Cassini has flight software algorithms to detect, isolate, and recover to a thermally safe and commandable attitude and then wait for further instructions from the ground. But the Saturn environment is complex, and safety hazards change depending on where Cassini is in its trajectory. For example, Cassini must be able to safely flyby Titan at a 955 km altitude in the safing attitude, even though all ground-commanded sequences have been stopped due to the safe mode event. If Cassini is flying over Saturn’s north pole (when in a high-inclination orbit), the “safe attitude”, as explained below, may be different than if Cassini is in a low-inclination orbit near the ring plane.

The safe attitude that is used in the event of a fault should achieve: (1) a commandable attitude so that the ground can communicate with the spacecraft, (2) a thermally safe attitude so that, if it takes several days to re-establish the ground link, the spacecraft does not suffer any permanent thermal damage, (3) an attitude that can be maintained without being overwhelmed by aerodynamic forces and torques if a low-altitude flyby of Titan occurs at this attitude, (4) an attitude that allows the star tracker a clear field of view (FOV) to acquire stars and maintain 3-axis attitude knowledge.

Cassini has two control modes: (1) RCS control – eight thrusters (whose magnitudes were approximately 1 N at launch) provide 3-axis attitude control, (2) RWA control – reaction wheel assemblies (RWA) that store momentum. Three RWAs are mounted orthogonally with fixed orientations in the spacecraft body frame. A fourth RWA is mounted on an articultable platform. The platform could be steered to align the fourth RWA with anyone of three fixed RWA that might have degraded. Almost all science observations and data playback occur in RWA control. If safe mode is triggered while in RWA control, the spacecraft autonomously switches to RCS control and powers off the RWAs. The 11-m long magnetometer boom was deployed in August 1999 before Earth swingby. The Huygens probe, deployed on December 24, 2004, was mounted on the –X side of the spacecraft. Data playback to Earth is via the 4-meter High Gain Antenna which is co-aligned with the spacecraft –Z axis (see Figure 1). There are two low-gain antennas (LGAs) on the spacecraft: (1) LGA1 is co-aligned with the HGA, (2) LGA2 is aligned with the –X body axis. At Saturn, LGA1 is used for emergency uplink/downlink if a severe safe mode condition occurs. The nominal safe mode response commands LGA1 (NEG_Z) to point at the Sun and await ground controller response.

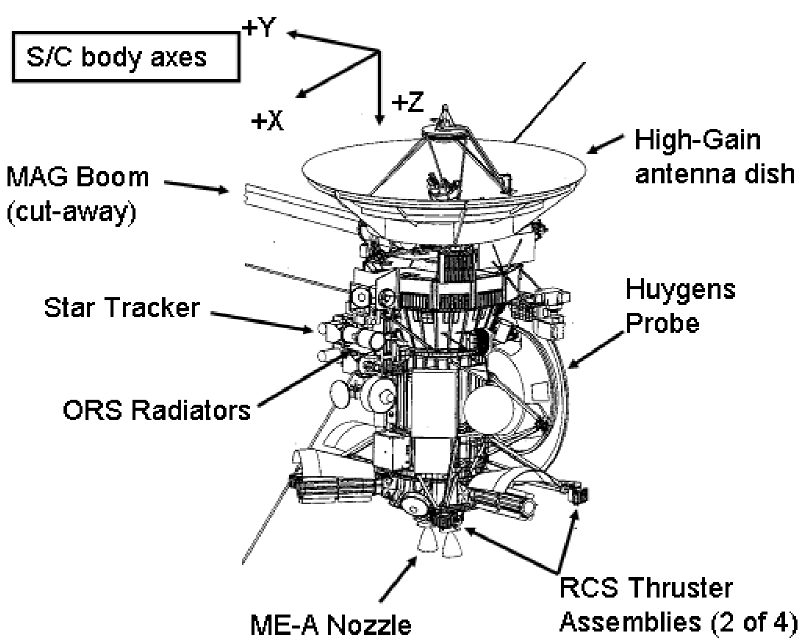


Figure 1. Cassini Spacecraft before the release of the Huygens Probe in 2004

Throughout the mission the effects of solar radiation are minimized by using the HGA as a Sun shade and by keeping the Sun-line, wherever possible, on the –X (thermally safe) side of the spacecraft Y-Z plane. Sensitive Optical Remote Sensing (ORS) radiators point in the +X direction and even at a solar distance of 9 astronomical units will degrade science if heated significantly. A single 450-newton main engine (ME) -- with a twin backup -- is used for large delta velocity trajectory changes. A single accelerometer mounted parallel to the –Z axis is used to command cutoff for ME burns. Two main engine gimbal actuators are used for 2-axis thrust vector control during ME burns, with Z-axis control via the reaction control system (RCS) thrusters.

II. Cassini Attitude Pointing System

Pointing the Cassini spacecraft is achieved using two "inertial" vectors and two "body" vectors[3] to command a unique inertial attitude in space[4]. For example, the X-Band radio-frequency boresight vector (XBAND) of the HGA is defined as a unit vector in the spacecraft body coordinate frame (XBAND is nearly collinear with the spacecraft's –Z body axis). XBAND is an example of a primary body vector. The fundamental requirement is to point a selected primary body vector at a "primary inertial" vector object. For example, during data playback to Earth, the primary pointing is commanded to be "XBAND" to "EARTH" where the Earth is an inertial vector from the spacecraft to Earth (at Saturn, this inertial vector is time-varying and is propagated by onboard software continuously, but changes very slowly). To establish a complete 3-axis inertial attitude a secondary pair of body and inertial vectors are specified. For example, a secondary pair could be "NAC" to "SATURN" where NAC is the narrow angle camera boresight body vector, and Saturn is the time-varying inertial vector from the spacecraft to the center of Saturn (which is also propagated continuously by onboard software). The primary pointing is always achieved, while the angle between the secondary pair is minimized given the constraint that the primary vectors must be collinear. In practice, this means the secondary body vector is commanded into the plane defined by the primary and secondary inertial vectors (see Figure 2).

Table 1. Example Cassini attitude definitions.

	Primary Vectors			Secondary Vectors		
	Body Vector		Inertial Vector	Body Vector		Inertial Vector
Earth-pointed example:	XBAND	to	EARTH	NAC	to	SATURN
Sun-pointed example:	NEG_Z	to	SUN	POS_X	to	J2000Z

In the Sun-pointed example in Table 1, NEG_Z is the –Z spacecraft body axis, POS_X is the +X spacecraft body axis (the star tracker boresight) while J2000Z is a fixed inertial vector from Cassini pointing in the same direction as the Earth's spin axis at the January 1, 2000 epoch (called the J2000 epoch).

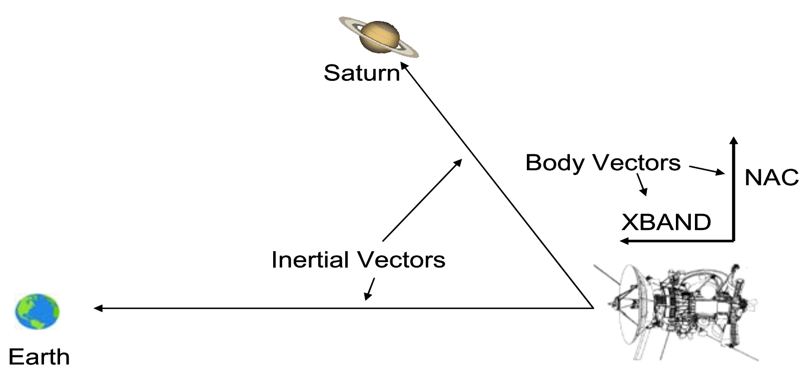


Figure 2. Cassini attitude commanding uses two inertial vectors and two body vectors. *In this example, the XBAND body vector is pointed exactly at Earth, NAC body vector is pointed as close as possible to Saturn. The secondary vectors define, in this case, the orientation, or twist, about the XBAND body vector. This orientation puts the NAC body vector into the plane defined by the Earth and Saturn inertial vectors.*

A. Spacecraft Pointing Vectors Used in Safe Mode

If safe mode is triggered, the spacecraft turns to the "nominal" safe mode attitude. This attitude can be changed via sequenced command. During the cruise from launch until Saturn approach, the nominal safe mode attitude was commanded to be: NEG_Z to SUN (primary), NEG_X to EARTH (secondary). This insured a thermally safe spacecraft. After the Earth swing-by in August, 1999, the spacecraft continued outbound towards Saturn and this nominal safe mode attitude always kept LGA1 (Low-Gain Antenna 1 which is approximately co-aligned with the HGA) within 30° of the Earth, ensuring commandability via LGA1.

As the spacecraft moved into the outer solar system, ground controllers began preparations for intensive science gathering as Saturn was approached. About 16 months before Saturn arrival, ground controllers uplinked new flight software that updated the on-board safe mode fault response. The goal was to try to minimize the complexity of re-establishing normal operations if a fault were to occur. The safe mode response will still begin by commanding the nominal Sun-pointed safe mode attitude, but after 60 minutes fault protection will command a "High-Gain safing" algorithm. Part of this algorithm is to command the "other" safe mode attitude. The "other" safe mode attitude can also be changed via sequenced command. The primary pointing for the "nominal" safe mode attitude is still NEG_Z to SUN, but for the "other" safe mode attitude, NEG_Z to EARTH becomes the primary pointing vectors, and the HGA is used for uplink and downlink. By pointing the HGA towards Earth, engineering telemetry data will be received at a much higher rate and this allows ground controllers to more rapidly assess and respond to the spacecraft anomaly that triggered the safe mode response. Both attitudes need to be thermally safe – in the nominal case the HGA is pointed directly at the Sun and shades the spacecraft; in the Earth-pointed case, the Sun-line is at least 90° away from the +X spacecraft body axis.

Table 2. Example "nominal" and "HGA" safe table entries.

	Primary Vectors			Secondary Vectors		
	Body Vector		Inertial Vector	Body Vector		Inertial Vector
Nominal Safe Attitude:	NEG_Z	to	SUN	NEG_X	to	EARTH
HGA Safe Attitude:	NEG_Z	to	EARTH	NEG_X	to	SUN

The only cases where the High-Gain safing algorithm will not run are those that involve severe computer or severe attitude control faults. For those cases, the spacecraft will command the Sun-pointed attitude and use the –Z low-gain antenna until ground operators can deal with the problem.

Another issue for Cassini is the ability of the flight software to maintain good attitude estimation in the presence of bright bodies that can be in or near the star tracker field of view (FOV). In Saturn orbit, the planet, the rings, and Titan are bright, large bodies and can affect star identification. The rings of Saturn, and the planet itself, often subtend an angle of 30 to 90 degrees from Cassini's perspective. During a close flyby, Titan can also approach 90° angular diameter and still appear larger than 0.5° angular diameter even 24 hours after a Titan flyby. Cassini's orbital period around Saturn is often 16 days so repeated periods of bright body interference from Saturn, the rings, and Titan are common.

The pointing needs of science observations will often cause these bright bodies to be near or in the star tracker FOV. Before reaching Saturn in 2004, a new attitude estimation mode and ground command called "star identification suspend" (SID Suspend) was developed and implemented in the flight software. When a SID Suspend command is issued (with a time duration as its argument), attitude estimation FSW will propagate the estimated spacecraft attitude using only gyro-derived spacecraft body rates. At the end of the "suspend" period, SID will resume tracking stars as usual. In practice, when a SID Suspend ends, a small attitude correction occurs as the estimator corrects for the small gyro-only propagation errors. The small propagation error is caused by the imperfect onboard flight software knowledge of the gyro's parameters such as its scale factors.

During normal operations, SID Suspends are usually driven by science pointing needs and the geometry at Saturn. But a strategy had to be developed for safe mode, so that bright objects stayed outside the star tracker bright body field-of-view (in most cases, this is a cone with a half-angle of 30°) once the safing attitude is achieved. If safe mode were to occur, several hours or days could elapse before ground controllers can respond, so the strategy is to select secondary safing vectors that keep the SRU star field free of bright bodies. After fault protection issues the safe mode command, the spacecraft turns from its current attitude (usually tracking a science object) to the attitude ground controllers have pre-selected for the "nominal" safe mode. An hour later, fault protection commands the "HGA" safe attitude, to re-establish a high data-rate link with ground controllers.

The spacecraft attitude that is commanded in the event of safe mode is defined in a table of vector names (see Table 2) that ground controllers can manage via ground command. The vectors themselves reside in tables called the inertial vector table (IVT) and the body vector table (BVT). Issuing the commands to update the contents of the safe table has no effect on normal operations. Only if fault protection FSW commands safe mode is the safe table used to establish what spacecraft attitude to command.

One important caveat is that the vectors that the safe table references must always be available. There are very few inertial vectors that are permanently in the IVT (most inertial vectors are created for science observations that exist only for a short time), but safe mode requires that the safe table only use permanent vectors. Table 3 contains a list of permanent inertial vectors that are always available for the safe table:

Table 3. Permanent vector objects in the Cassini Inertial Vector Table flight software image. Safe mode must command an attitude using two inertial vector objects that are permanently available in the flight software.

Inertial Vector Object	Description
SUN	The Sun is the root of the inertial vector tree
EARTH	The time-varying Sun-to-Earth vector in J2000 frame
J2000X	The fixed vector from Cassini to J2000X which is defined as the intersection of Earth's equatorial plane and the plane of the ecliptic, in the direction of the Ares constellation, at the J2000 epoch
J2000Z	The Earth's spin axis at the J2000 epoch
J2000Y	The cross product of J2000Z and J2000X
CASSINI	The time-varying vector that defines Cassini's position in space in the J2000 frame

The Cassini vector resides in the active random access memory IVT to support high accuracy science pointing needs. The active vector from the Sun to Cassini is actually the vector sum of two vectors: (1) The Sun-to-Saturn vector (an accurate conic vector). (2) The Saturn-to-Cassini vector. This active vector from Saturn to Cassini is updated quite frequently (via stored sequence commands). It is accurate to better than 40 µrad, but will degrade in accuracy after a few weeks if not updated via stored sequence command. Safe mode will use this active Cassini vector, and thus will be able to accurately point to Earth (HGA Safe attitude) for at least two weeks without any further updates from ground controllers.

If a safe mode results from a very severe attitude control fault (e.g., a reset of the attitude control flight computer), a "default" Cassini vector is used. This is because the updateable active Cassini vector is resident in random access memory but not in the FSW image itself and is thus lost after a flight computer reset. The default Cassini vector is permanently defined in the flight software image, though it is not as accurate (at Saturn, pointing using the default Cassini vector can be several milli-radians in error) as the active Cassini vector and is only used if the random access memory IVT is lost. In such a severe fault condition, fault protection autonomously uses the low-gain antenna (LGA1) for communication with Earth and thus precision pointing is not immediately required. If the flight computer were to reset, one of the first steps in re-establishing normal operations is to re-populate the active Inertial Vector Table with an accurate Saturn-to-Cassini inertial vector. The J2000X, J2000Y, and J2000Z vectors are "fixed" vectors and are always available. An accurate (on the order of 0.15 mrad) Sun-to-Earth vector is resident in both the FSW image and the active random access memory IVT and is always available.

B. Selection Criteria for Safe Mode Secondary Vector Pairs

Selecting the secondary vector pair to place in the safe table is strongly influenced by Cassini's orbital geometry around Saturn. Figures 3 through 5 depict the distance from Cassini to Saturn and how large the planet and the rings appear from the perspective of the spacecraft during the first 6 years of the orbital mission. These figures use the reference trajectory to represent the position of Cassini over time. This trajectory, called the spacecraft ephemeris, is the planned position of Cassini over time. In practice, the trajectory actually flown is slightly different than the reference. Deviations from the reference trajectory will be corrected by the Navigation team via trajectory correction maneuvers to keep the spacecraft on the reference trajectory throughout the mission[5].

Figure 3 plots Cassini's distance from Saturn, expressed in R_s (Saturn radii, where 1 R_s is 60,268 km). During periapse, Cassini can fly within 2.6 R_s of the planet. At this distance, the planet can subtend over 45° of the sky from Cassini's perspective (Figure 4) and the rings can subtend over 80° (Figure 5). The rings are considered a thin disk (actually, the "depth" of the rings is only about 0.1 km), centered at the center of Saturn, with a radius of 2.26 R_s. A proper safe table attitude strategy must ensure that these very large objects do not enter the star tracker bright body field of view.

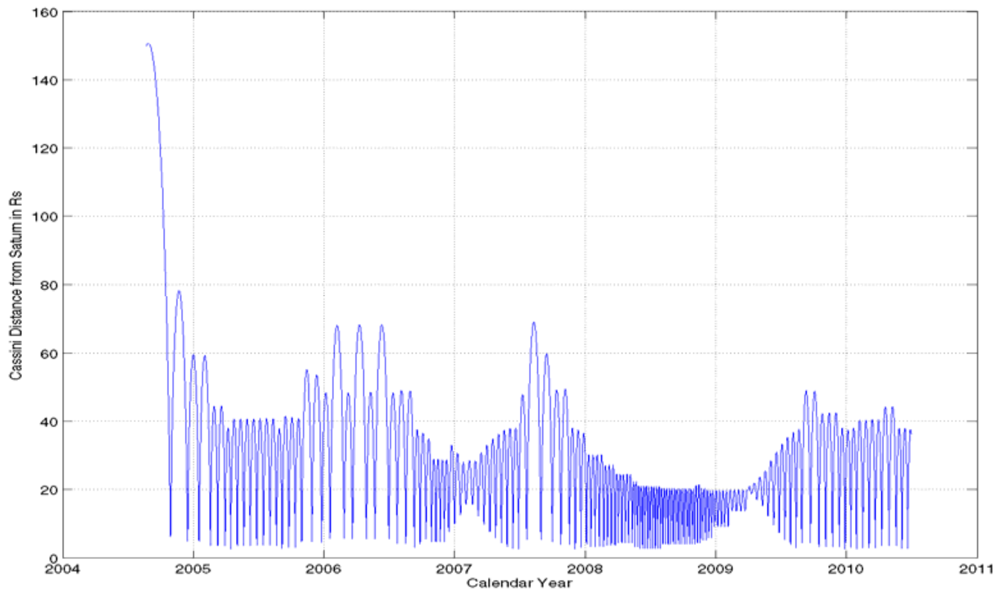


Figure 3. The distance from Cassini to the center of Saturn during the first six years of the orbital mission, expressed in R_s (Saturn radii).

Although part of the rings is in Saturn's shadow, we generally consider the rings and Saturn to always act as bright objects and the star tracker bright body keep-out cone of 30° always applies to Saturn and the rings. The orbital period of Cassini about Saturn is typically 16-20 days, thus the planet and rings quite frequently subtend an angular diameter of 30° or more. The safe table design strategy needs to ensure these bright objects are always outside the 30° star tracker bright-body FOV when at the safe attitude. Titan can subtend an angle as large as Saturn or even the rings, but only during close flybys.. The apparent angular size of Saturn and the rings, as a function of time, is depicted in Figures 4 and 5.

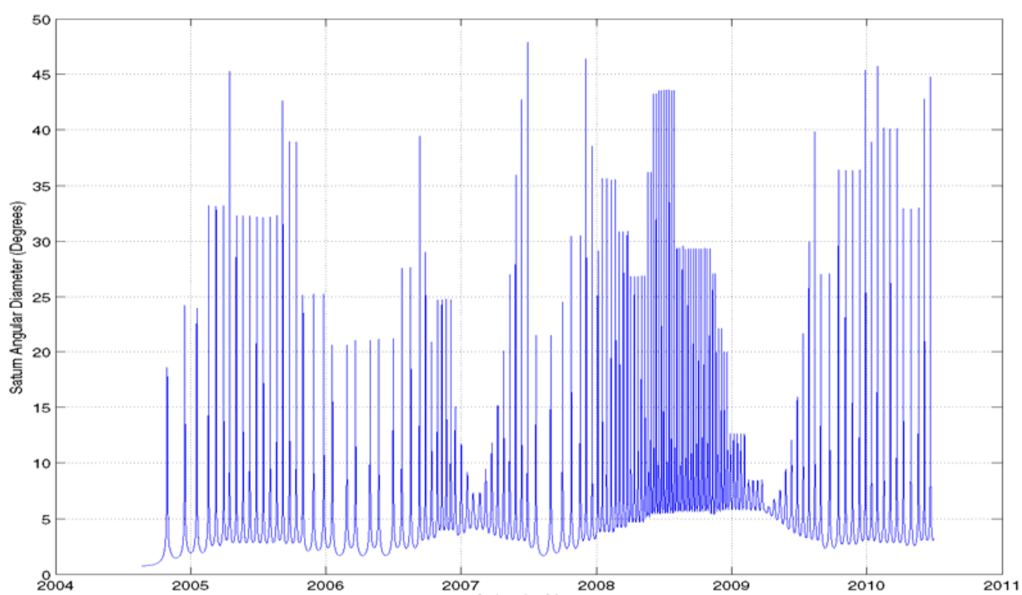


Figure 4. The angular size (in degrees) of the planet Saturn from the perspective of Cassini during the first six years of the orbital mission.

The ideal secondary vector pair, if the inertial vectors were always available, to ensure Saturn and the rings stay outside the SRU bright body FOV, would be: NEG_X to SATURN. The SATURN inertial object is just the base of the Saturn-to-Cassini inertial vector, which is always available in the active IVT. This secondary vector pair would effectively keep the SRU boresight (POS_X) pointed opposite Saturn (and the rings) and would always allow the star tracker to have a clear star field (ignoring Titan for the moment). This is true independent of Cassini's orbital inclination. However, the Saturn-to-Cassini inertial vector is not a "permanent" inertial vector, thus the Saturn inertial object cannot be used in the safe table because accurate knowledge of Saturn's position relative to Cassini cannot always be guaranteed (i.e. after a flight computer reset).

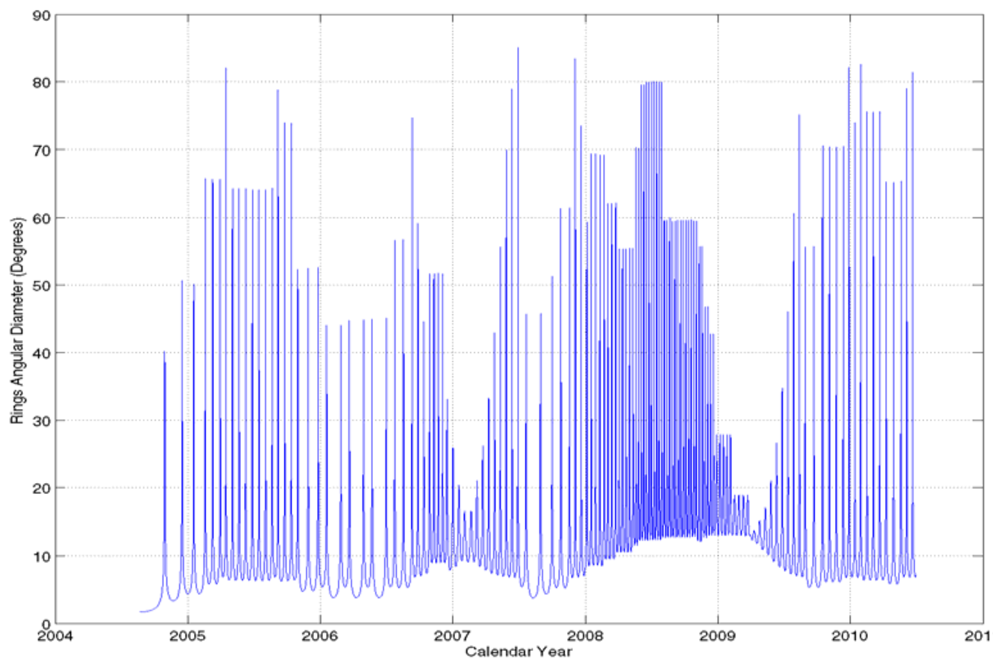


Figure 5. The angular diameter of the rings (in degrees) from the perspective of Cassini during the first six years of the orbital mission.

Figure 6 depicts the orbital inclination of the spacecraft relative to Saturn between 2004 and 2010. The orbital inclination of the spacecraft is changed almost exclusively via gravity assist during low altitude flybys of Titan. The trajectory was designed such that the spacecraft orbital inclination would be relatively small between 2004 and mid-2006, and would slowly rise to about 60° by early 2007, before returning to near zero by mid-2007, and then increasing to a maximum near 75° throughout the second half of 2008.

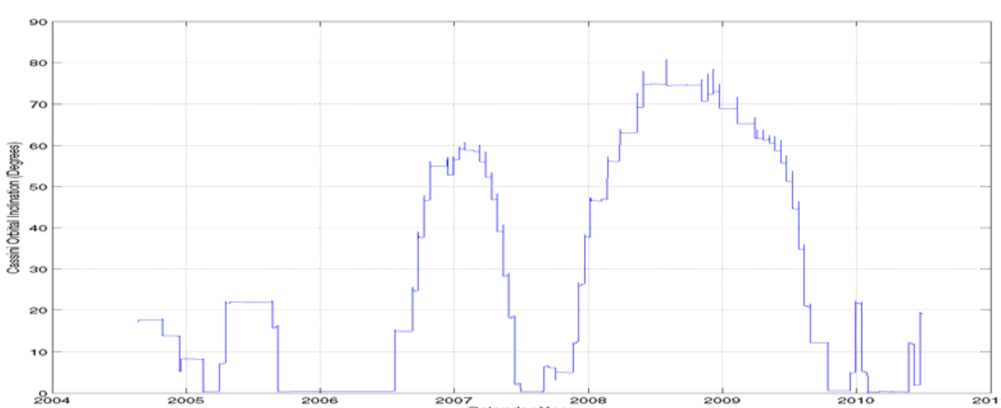
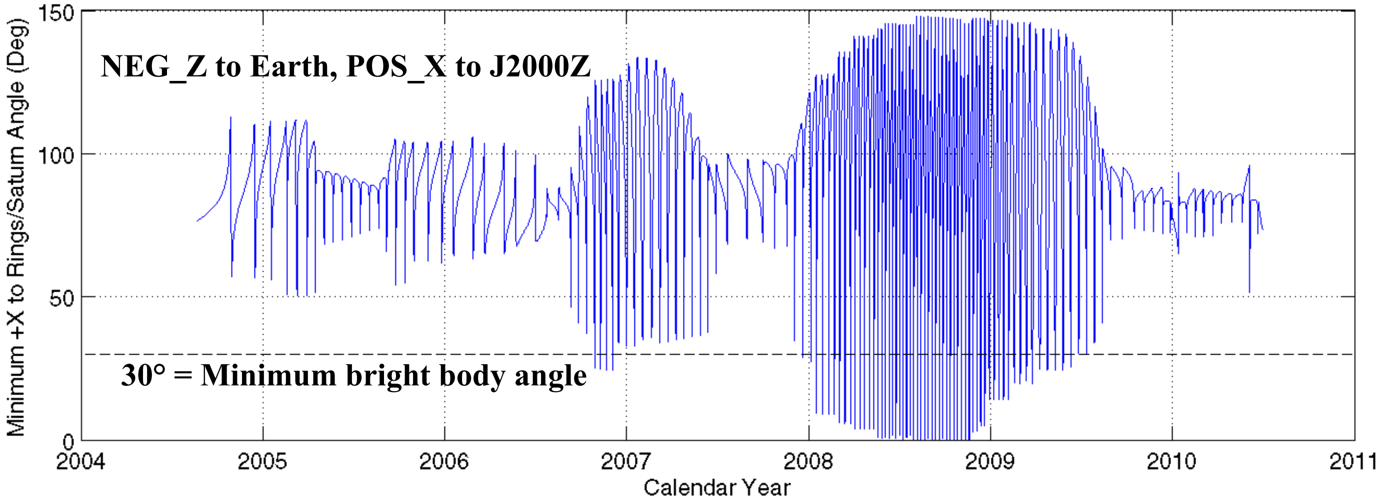


Figure 6. The orbital inclination (in degrees) of Cassini with respect to Saturn.

One satisfactory choice for the safe table secondary vector pair would be POS_X to J2000Z. The vector J2000Z has Cassini as a vector base, and a vector head pointing in the same direction as the Earth's spin axis. Although J2000Z is not precisely normal to Saturn's ring plane, it is only about 6.5 degrees from Saturn's spin axis. This makes J2000Z a good candidate for the secondary inertial vector, especially when the spacecraft's orbital inclination is less than 60 degrees. Figure 7 depicts the minimum angle between the SRU boresight and the edge of the rings or Saturn (whichever angle is smaller) for two cases: (1) The upper plot uses POS_X as the secondary body vector. (2) The lower plot uses NEG_X as the secondary body vector. Both examples use J2000Z as the secondary inertial vector.



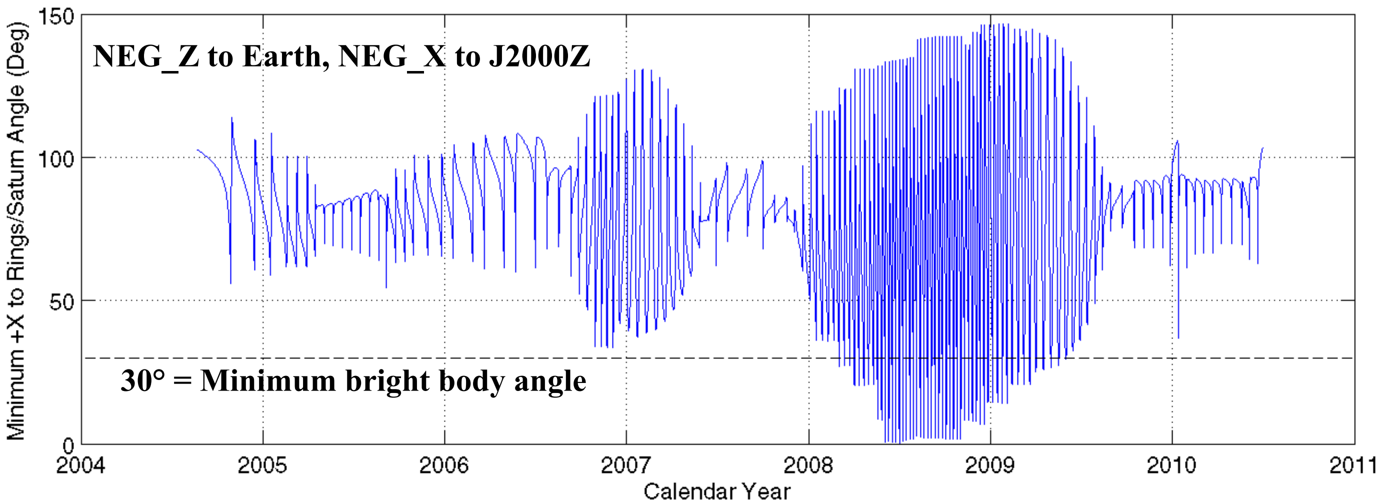


Figure 7. The angle from the SRU boresight to the edge of the rings (or Saturn, whichever is smaller) from the perspective of Cassini during the first six years of the orbital mission. The figure compares two different safing attitudes.

Figure 7 demonstrates that using J2000Z and NEG_X (or POS_X) are satisfactory choices for the safing secondary vector pair from 2004 through 2007. However, these secondary vector pairs should not be used during 2008 through mid-2009 while the spacecraft's high inclination orbit would cause the resulting safe attitude to point the star tracker at the planet and rings during parts of each orbit. By mid-2009, J2000Z can again be used with POS_X or NEG_X as the safing secondary vector pair.

It is the basic Cassini-Saturn-Rings geometry described above, and the need to use permanently-available vector objects, that drives the baseline selection of the nominal safing attitude. The first priority in the choice of a safing attitude is commandability – the primary target is the Sun with emergency telecommunications via LGA1 aligned with the NEG_Z direction. The HGA safing response (NEG_Z to EARTH as primary vectors) provides both good commandability and high-rate data playback to allow ground controllers to gather recorded fault protection-related data for ground analyses. Ensuring that Saturn and the rings do not enter the bright body field of view of the star tracker is an additional priority. Close flybys of the moons, especially Titan, can also lead to periods where the moon can fill the field of view of the star tracker, and there can also be thermal or control margin constraints during low altitude Titan flybys that further constrain the preferred spacecraft attitude during safe mode.

The contents of the safe table, and thus the safing attitude selected when the safe mode is invoked, can be changed via stored sequence command. This is useful near Titan flybys where the moon can fill the entire star tracker field of view. The safe mode attitude that ensures that Saturn and the rings do not enter the star tracker bright body FOV may put Titan right into the SRU FOV near Titan. A set of stored sequence commands can modify the contents of the safe table prior to the Titan flyby, and then return the safe table to its original contents once past Titan. Because all stored sequences are suspended upon safing (no more commands are issued), the Titan-avoidance safe table contents need to be issued by the b/g sequence several days before an actual flyby. If safing prevents the command from being issued by the b/g sequence, ground controllers will still have time to send a contingency file to turn to the safing attitude that avoids the Titan bright body, thermal, or control margin issues.

The command to update the contents of the safe table attitude also includes a selectable angular rotation "offset" angle with respect to each spacecraft body axis. Since the primary body vector used as the safing attitude is NEG_Z (the centerline of the High Gain Antenna), a Z-axis rotation angle about this line does not affect communications with Earth. It is this Z-axis offset, in the command to select the safe attitude, that gives ground controllers the flexibility to adjust the safing attitude during Titan flybys, and then return to the normal "zero offset" after the flyby is complete. The current approach ensures that this Titan-specific safing offset will also be safe, in terms of thermal, control, and bright body issues, for at least 72 hours before and after closest approach to Titan. When an offset is identified that meets all the criteria for acceptability, the specific safe table commands are added to the background sequence during sequence development, The flyby-specific offset command is issued via background sequence command two downlinks (about 48 hours) before the actual closest approach, and then returned (also via the b/g sequence) to the zero offset configuration during the first downlink after the flyby. This provides near real-time ground controller visibility of the safe table management. Contingency command files are also generated to command the flyby-specific safe attitude (if safing were to stop the background sequence more than 48 hours before the flyby) and to return to the zero offset attitude (again, if safing prevents the background sequence from issuing the zero offset post-flyby).

Some flybys require no safe table management at all: the zero offset case works fine throughout the flyby. Other flybys require a search through all possible Z-axis offsets to find the best offset. The five criteria to evaluate are:

1. Star tracker bright body field of view for Saturn and Rings – Saturn and the rings must stay at least 30 degrees away from the star tracker boresight (spacecraft +X body axis). A considerable range of Z-axis offsets typically violate this restriction.
2. Solar heating of sensitive science instrument radiators. While Earth-pointed, there are periods each year where the Sun-Cassini-Earth angle can grow as large as 6 to 7 degrees. Although the HGA shades these radiators out to 4 degrees, it is important to select the safe table secondary vector pair such that the POS_X to Sun angle is never less than 86 degrees. Some Z-axis offsets do violate this restriction.
3. Star tracker bright body field of view for the moon during the flyby: the limbs of the nearby moons must stay at least 30 degrees away from the star tracker boresight. This also restricts the allowable range of candidate Z-offsets.
4. Flyby aerodynamic heating (for Titan flybys) must be acceptable on sensitive science instruments' radiators. This can be ensured by keeping the aerodynamic RAM direction at least 90 degrees from the science instrument radiators (spacecraft POS_X body axis). The RAM direction is defined as the direction of the incoming atmospheric molecules as the spacecraft flies through the upper Titan atmosphere, which is effectively the direction of the spacecraft velocity vector with respect to Titan. This restriction only applies during Titan flybys with flyby altitudes lower than 1,000 km (Titan atmospheric density decays exponentially with altitude).
5. Adequate margin to control the attitude of the spacecraft. The RCS thrusters must have enough control torque to maintain a stable attitude in the presence of Titan aerodynamic torques. This was actually a critical criterion during the T70 flyby of Titan in June of 2010. The Titan closest approach altitude was 880 km, which was 70 km lower than any previous Titan flyby. The flyby was so low (done for magnetometer and other science reasons) that a "minimum torque" attitude was selected for the nominal flyby attitude. Otherwise, a flyby this low would cause the spacecraft to tumble due to aerodynamic torques exceeding the thruster control authority. One very fortunate aspect

of this particular flyby was that the safing attitude could be selected so that its orientation was very close to the minimum torque attitude. Both attitude choices point the HGA towards Earth, with a particular Z-axis offset to minimize aerodynamic torques.

C. Selected Secondary Vector Pairs for Cassini in 2004-2010

From 2004 through January of 2008, there were two attractive candidates for the safe table secondary vector pair: Option 1: POS_X to J2000Z. Option 2: NEG_X to J2000Z. Option 1 points the star tracker approximately in the direction of Saturn's spin axis, while Option 2 points the star tracker opposite Option 1. Both were acceptable from a Saturn and rings bright body perspective, and both keep the Sun within the HGA shading angle. To choose between these two options, it was decided to evaluate the other selection criteria mentioned in Section II.B. Particular emphasis (Tables 4 and 5 below) is given to the Titan bright body and Titan aerodynamic heating criteria.

Table 4. Key parameters during Titan closest approach. *Values of key parameters at Titan closest approach during selected Titan flybys through June of 2007. This table uses Option 1 (POS_X to J2000Z) as the safe mode secondary vector pair and assumes an Earth-pointed safing attitude. Values in red denote problematic values for safe operation.*

		+X-to-Saturn	+X-to-Titan	+X-to-Titan	Closest Approach	
Flyby	Date	Angle (Deg)	Angle (Deg)	RAM Angle (Deg)	Altitude (km)	Latitude (Deg)
Ta	November 12 2004	109.3	127.8	99.5	1174	39
Tb	December 13 2004	109.7	142.8	105.7	1192	59
T3	February 15 2005	111.3	121.4	111.2	1579	30
T4	March 31 2005	92.6	144.6	97.5	2404	33
T5	April 16 2005	92.5	140.0	103.4	1027	74
T7	September 7 2005	87.4	13.3	102.7	1075	-66
T8	October 28 2005	103.8	91.0	108.4	1353	1
T10	January 15 2006	103.1	85.6	108.8	2042	0
T11	February 27 2006	71.8	97.0	109.2	1812	0
T12	March 19 2006	97.6	77.2	106.1	1949	0
T13	April 30 2006	67.1	87.6	110.6	1856	0
T14	May 20 2006	87.8	71.5	97.5	1879	1
T15	July 2 2006	69.3	78.0	104.6	1906	0
T16	July 22 2006	78.5	160.4	92.4	950	85
T17	September 7 2006	78.7	128.4	98.6	1000	22
T18	September 23 2006	78.9	163.4	105.5	960	71
T19	October 9 2006	79.1	155.7	114.1	980	61
T20	October 25 2006	79.1	110.0	120.0	1029	6
T21	December 12 2006	79.3	121.0	124.5	1000	43
T22	December 28 2006	79.1	137.0	131.0	1297	40
T23	January 13 2007	78.8	127.5	139.1	1000	30
T24	January 29 2007	78.6	123.4	146.3	2631	33
T25	February 22 2007	96.2	107.8	20.9	1000	31
T26	March 10 2007	96.4	112.3	27.0	981	32
T27	March 26 2007	96.6	120.4	33.5	1010	41
T28	April 10 2007	96.7	129.8	40.8	991	51
T29	April 26 2007	96.7	137.8	48.5	981	59
T30	May 12 2007	96.7	146.4	56.5	959	69
T31	May 28 2007	96.6	153.9	63.6	2299	77
T32	June 13 2007	96.3	161.4	70.9	965	85
T33	June 29 2007	95.9	104.7	76.2	1933	8

Table 5. Values of key parameters at Titan closest approach during Titan flybys below 3,000 km through June of 2007. *This table uses Option 2 (NEG_X to J2000Z) as the safe mode secondary vector pair and assumes an Earth-pointed safing attitude. Values in red denote problematic values for safe operation.*

Flyby	Date	+X-to-Saturn Angle (Deg)	+X-to-Titan Angle (Deg)	+X-to-Titan RAM Angle (Deg)	Saturn-Relative Orbital Inclination (Deg)	Titan Angular Diameter (Deg)
Ta	November 12 2004	65.0	52.2	80.5	17.3	86
Tb	December 13 2004	64.5	37.1	74.3	10.8	86
T3	February 15 2005	63.0	69.9	68.8	3.0	77
T4	March 31 2005	81.9	33.7	82.5	4.0	62
T5	April 16 2005	82.0	40.3	76.6	17.5	91
T7	September 7 2005	87.0	166.6	77.3	9.1	90
T8	October 28 2005	70.5	89.0	71.6	0.4	82
T10	January 15 2006	71.2	94.4	71.2	0.4	68
T11	February 27 2006	102.7	83.0	70.9	0.4	72
T12	March 19 2006	76.8	102.8	73.9	0.4	69
T13	April 30 2006	107.4	92.4	69.5	0.4	71
T14	May 20 2006	86.7	108.5	82.5	0.4	71
T15	July 2 2006	105.1	102.0	75.4	0.4	70
T16	July 22 2006	96.0	19.6	87.6	9.0	94
T17	September 7 2006	95.8	51.6	81.4	22.3	92
T18	September 23 2006	95.5	16.6	74.5	36.2	94
T19	October 9 2006	95.4	24.2	65.9	47.4	93
T20	October 25 2006	95.4	70.0	60.0	56.0	91
T21	December 12 2006	95.2	59.0	55.5	59.0	92
T22	December 28 2006	95.4	43.0	49.0	59.0	83
T23	January 13 2007	95.6	52.5	40.9	62.2	92
T24	January 29 2007	95.8	56.6	33.7	61.8	59
T25	February 22 2007	77.9	72.2	159.1	62.3	92
T26	March 10 2007	77.7	67.7	153.0	61.2	93
T27	March 26 2007	77.6	60.0	146.5	58.3	92
T28	April 10 2007	77.5	50.2	139.2	54.0	92
T29	April 26 2007	77.5	42.2	131.5	47.6	93
T30	May 12 2007	77.5	33.6	123.5	38.3	94
T31	May 28 2007	77.5	26.1	116.4	25.8	64
T32	June 13 2007	77.8	18.6	109.1	12.0	93
T33	June 29 2007	78.2	75.2	103.8	1.4	70

Managing the safe table attitude near Titan flybys involves a considerable amount of work (building and testing contingency command files, checking near each affected flyby that the safe table management commands properly execute, etc.). If Option 2, for example, results in significantly fewer Titan-flyby-specific safe table management work, this is advantageous.

Tables 4 and 5 summarize key geometric, bright body angles, and thermally-important quantities during Titan closest approach for flybys with altitudes below 3,000 km from 2004 through June of 2007. With reference to Table 5, note that Option 2 causes consistent aerodynamic heating problems (+X-RAM angle < 90°) during all low altitude

Titan flybys from Ta in November of 2004 through T24 in January of 2007. To use Option 2 for these flybys would require extensive use of Titan-specific Z-axis offset angles for all these flybys which is definitely undesirable. Given the geometric information shown in Tables 4 and 5, ground controllers decided that Option 1 (POS_X to J2000Z) should be used as the safing secondary vector pair from 2004 through January of 2007. In early February of 2007, Option 2 (NEG_X to J2000Z) should be selected as the safing secondary vector pair. Option 2 is valid until January of 2008 (see Figure 7) when neither Option 1 or 2 is viable. This approach still leaves three Titan flybys (T7, T31, and T32) as potential Titan bright body problems, so non-zero Z-axis offsets should be utilized for those flybys.

Figure 8 depicts the +X-to-Saturn or +X-to-Rings angle (whichever is smaller) at the Earth-pointed safing attitude using POS_X to J2000Y as the secondary vector pair. During 2008, Cassini's Saturn-relative orbital inclination was so high (almost in polar orbit) that POS_X to J2000Y became the preferred safing secondary vector pair. This safing attitude was used and was safe from a Saturn and rings bright body standpoint from January of 2008 through June of 2009. This attitude put the +X spacecraft body axis quite near the ecliptic plane, however, and solar heating of sensitive science instruments would occur on the +X side of the spacecraft during Spring of 2008 and 2009 (where the Earth-pointed +X-Sun angle goes below 86°). A 25° Z-axis offset during Spring of 2008 and 2009 thus was adopted to avoid the solar heating while still keeping Saturn and the rings outside the star tracker bright body field of view.

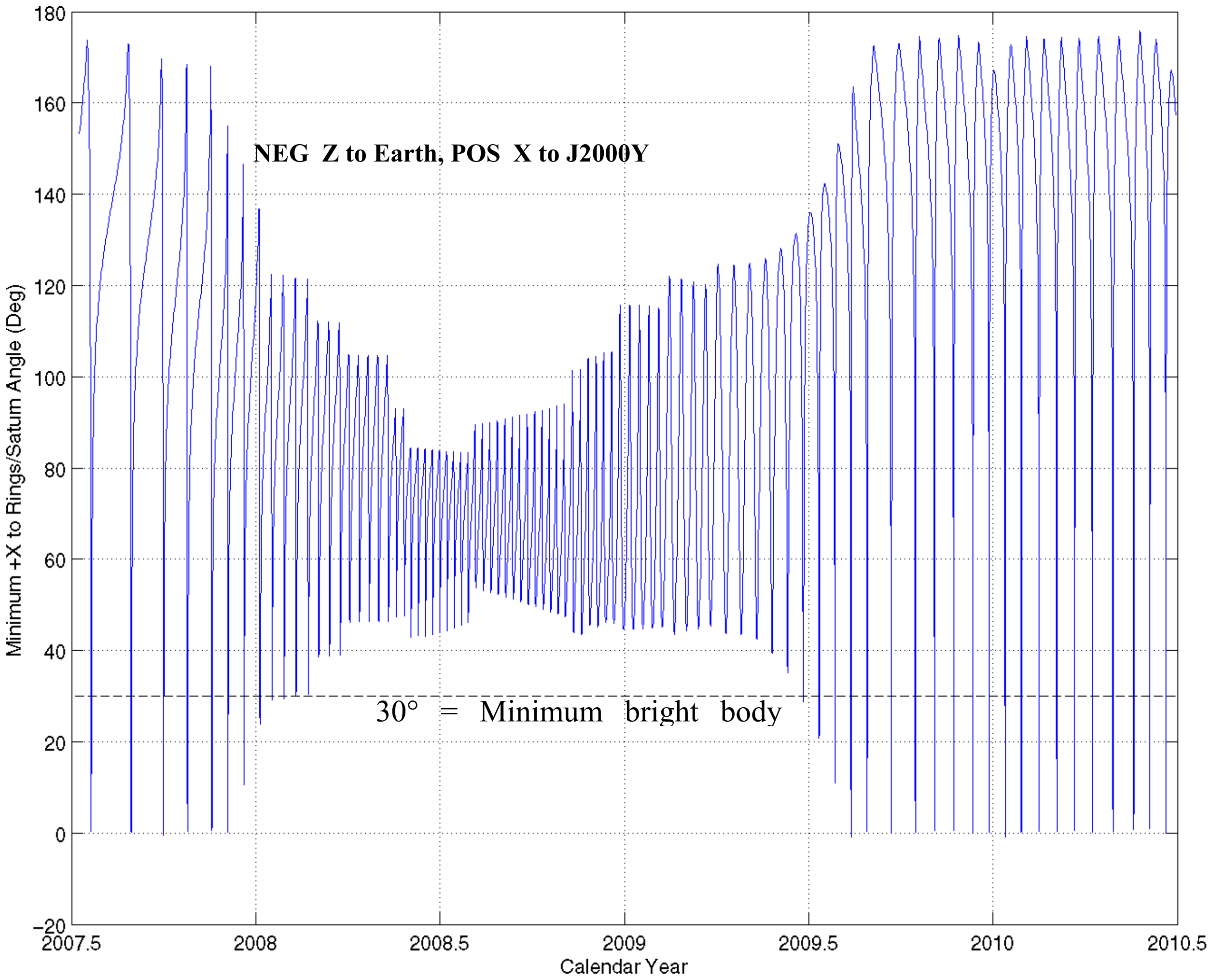


Figure 8. The angle between the SRU boresight and the edge of the rings (or Saturn, whichever is smaller) from the perspective of Cassini from mid-2007 through mid-2010. *The figure is based on an Earth-pointed attitude using POS_X to J2000Y as the safing secondary vector pair.*

Tables 4 and 5 above provide a useful snapshot of key parameters during Titan closest approach (a single moment in time). In actual practice, selecting a safe mode attitude during Titan flybys requires evaluating bright body and thermal-related angles throughout the entire flyby – in fact, for the 3 days before the flyby and the 3 days following. Figure 9 depicts some of these parameters for a rather difficult Titan flyby (T48, a 960 km Titan flyby on December 5, 2008). For this case, the baseline or "zero offset" safe mode attitude is NEG_Z to Earth, POS_X to J2000Y. For this flyby the range of offset angles that satisfy all the appropriate criteria is quite limited.

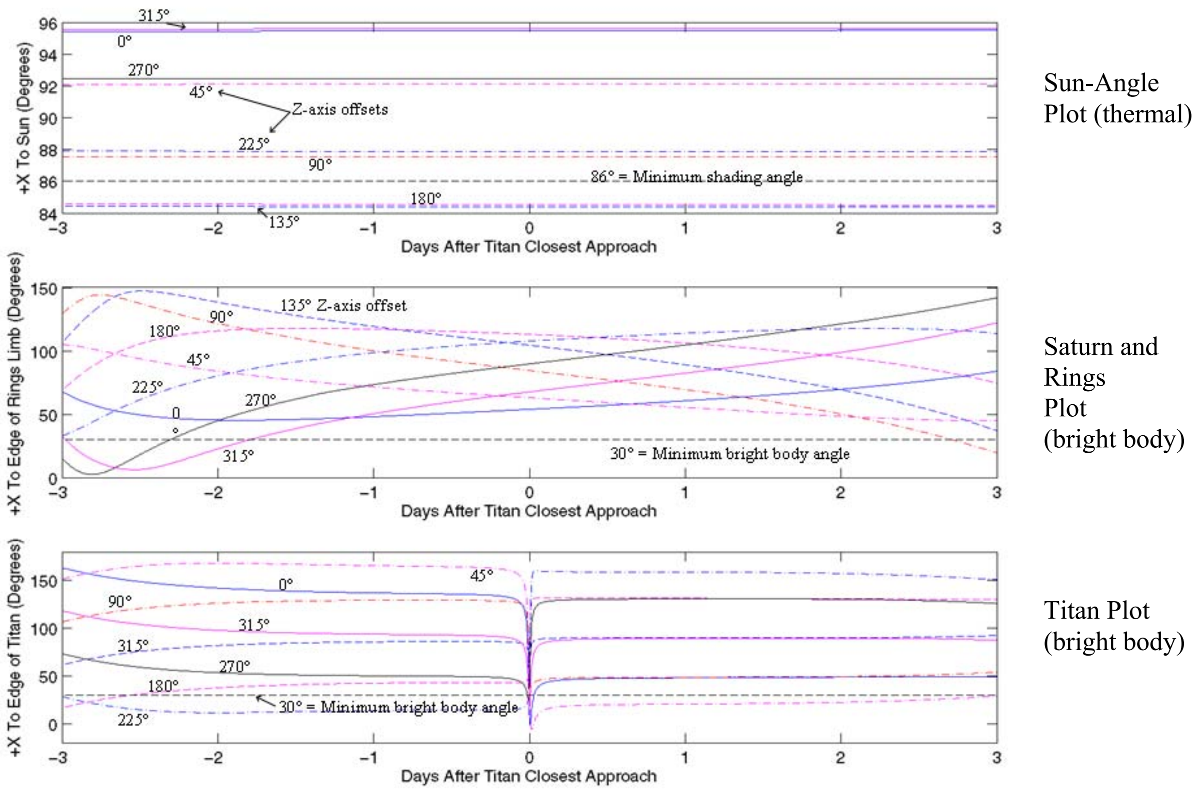


Figure 9. Bright-body (Titan and Saturn/rings) and thermal (Sun angle) plot for various Z-axis offset angles at the Titan 48 flyby. *The safe mode Zero-offset attitude depicted here is NEG_Z to Earth, POS_X to J2000Y.*

The star tracker boresight to the edge of the Titan limb is especially dynamic within 60 minutes of Titan closest approach due to the apparent motion of Titan with respect to the spacecraft. Also, the +X-to-RAM angle (which must be greater than 90° to avoid aerodynamic heating of science radiators) becomes relevant within 15 minutes of Titan closest approach. These quantities are plotted near Titan closest approach in Figure 10. For this flyby a Z-axis offset of 104° was selected.

The periods when Cassini is in a nearly-polar orbit around Saturn causes ground controllers to more actively manage the contents of the safe table. The geometry of Saturn and the rings combined with solar heating if the +X-to-Sun angle shrinks to less than 86° required more active management of the contents of the safe table during 2008 through June of 2009. At least 10 Titan flybys during this period required additional management of the contents of the safe table to mitigate risks in the event that safing were to occur during these flybys. Planning the safe table management strategy many months ahead of time was especially important during this period. Additional high-inclination orbits are planned for 2013 and 2017. Between July of 2009 and late 2012, the low-inclination of

Cassini's orbits allows ground controllers to return to using NEG_X to J2000Z as the safing secondary vector pair throughout this period. Some Titan flybys, especially those that flyby near Titan's north pole, require additional safe table management.

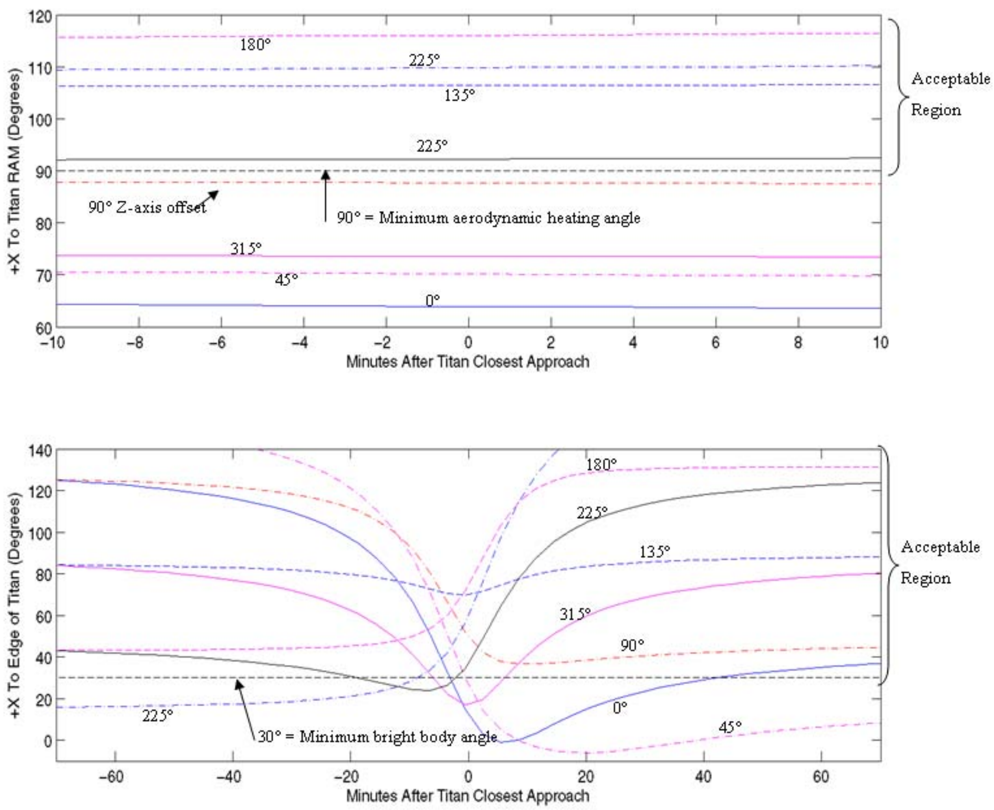


Figure 10. Bright-body (+X-to Titan) and thermal (+X-to-RAM) angle plots for various Z-axis offset angles at Titan 48 flyby very near Titan closest approach. *Safe mode Zero-offset attitude is NEG_Z to Earth, POS_X to J2000Y.*

III. Conclusions

Cassini attitude control flight software provides a safe table that allows ground controllers to select the appropriate spacecraft safe mode attitude throughout the mission. If a safe mode condition were to occur, the spacecraft would autonomously command the spacecraft to orient itself with this safe attitude and then await further commands from ground controllers. In the presence of a spacecraft fault (that triggered the transition to safe mode) it is important that the safe mode attitude truly be safe, thus mitigating the risk of causing further damage. The safe mode attitude needs to ensure spacecraft commandability and to avoid thermal stress to sensitive science instruments and engineering equipment.

The Saturn environment is complex and the changing size of various bright objects, especially Saturn, the rings, and Titan, make managing the contents of the safe table a challenging task. This management is accomplished using a single set of inertial and body vectors for several years at a time, but changes in the spacecraft orbital inclination require changes in the contents of the safe table due to the altered bright body geometry. Other sequenced updates to the safe table need to be made during some flybys of Titan due to bright body, aerodynamic heating, or control margin issues. Forward planning, placing safe table management commands in background sequences, putting contingency files "on the shelf" to support maintaining a truly safe attitude in the event safe mode is triggered, is an ongoing ground controller responsibility as the Cassini spacecraft extends its mission at Saturn into the future.

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