Cassini Attitude Control Operations Flight Rules and How They are Enforced

Thomas Burk[*] and David Bates[†]
Jet Propulsion Laboratory, California Institute of Technology

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. Cassini deployed the European-built Huygens probe which descended through the Titan atmosphere and landed on its surface on January 14, 2005. Operating the Cassini spacecraft is a complex scientific, engineering, and management job. In order to safely operate the spacecraft, a large number of flight rules were developed. These flight rules must be enforced throughout the lifetime of the Cassini spacecraft. Flight rules are defined as any operational limitation imposed by the spacecraft system design, hardware, and software, violation of which would result in spacecraft damage, loss of consumables, loss of mission objectives, loss and/or degradation of science, and less than optimal performance. Flight rules require clear description and rationale. Detailed automated methods have been developed to insure the spacecraft is continuously operated within these flight rules. An overview of all the flight rules allocated to the Cassini Attitude Control and Articulation Subsystem and how they are enforced is presented in this paper.

Acronyms

AACS	=	Attitude and Articulation Control Subsystem
AFC	=	Attitude Control Flight Computer
b/g	=	background
CDS	=	Command and Data Subsystem
CMT	=	Constraint Monitor
DOY	=	Day of Year
EGA	=	Engine Gimbal Actuator
FSW	=	flight software
HGA	=	High-Gain Antenna
IRU	=	Inertial Reference Unit
IVP	=	Inertial Vector Propagation
KPT	=	Kinematic Predictor Tool
LGA	=	Low-Gain Antenna
MAG	=	Magnetometer
ME	=	Main Engine
ORS	=	Optical Remote Sensing
PEF	=	Predicted Events File
RCS	=	Reaction Control System
rpm	=	revolutions per minute
RWA	=	Reaction Wheel Assembly
S/C	=	Spacecraft
SCET	=	Spacecraft Event Time
SCLK	=	Spacecraft Clock Time
SID	=	Star Identification
SRU	=	Stellar Reference Unit
SSA	=	Sun Sensor Assembly
SSR	=	Solid State Recorder
TCM	=	Trajectory Correction Maneuver
UTC	=	Universal Coordinated Time

[*] Sr. Engineer, Multimission Operations, M/S 230-104, 4800 Oak Grove Dr., Pasadena, California 91109, thomas.a.burk@jpl.nasa.gov
[†] Sr. Engineer, Multimission Operations, M/S 230-104, 4800 Oak Grove Dr., Pasadena, California 91109, david.m.bates@jpl.nasa.gov

I. Introduction

The Cassini spacecraft was launched on 15 October 1997 atop a Titan 4B launch vehicle. After a 7-year cruise through the solar system that included gravity-assist flybys of Venus (twice), the Earth, and Jupiter, the Cassini spacecraft went into Saturn orbit on June 30, 2004. Since that time, Cassini has remained in orbit around Saturn making discoveries and gathering a wealth of science information which it records and plays back to Earth via a High-Gain Antenna. One major accomplishment of this Saturn Tour phase of the mission was the successful release of the European Space Agency Huygens Probe on December 24, 2004 and its subsequent entry into the Titan atmosphere on January 14, 2005. The Cassini spacecraft tracked Huygens throughout its descent and recorded every single frame of data that Huygens transmitted from its initial entry through its landing on the surface of Titan. Other major discoveries include imaging the icy geysers erupting near the south pole of the moon Enceladus, synthetic aperture radar mappings of lakes of liquid hydrocarbons near the north pole of Titan, and many radio science occultations of the rings of Saturn and the atmospheres of Saturn and Titan.

There are 12 different science instruments on the Cassini spacecraft. Science and engineering data are stored on two solid-state data recorders and played back daily to Earth via the Deep Space Network. A typical "day" for Cassini at Saturn includes executing dozens of turns to and from scientific targets, tracking these targets, and gathering data for "prime" science instruments and well as "ride along" science instruments. Cassini does not have an independent scan platform for science instruments, so the imaging cameras, along with most of the other science instruments, are rigidly mounted to the spacecraft. Thus science observations require the entire spacecraft to turn and track any object of scientific interest. The data-gathering typically occupies 15 hours each day, and the remaining 9 hours are devoted to playing back the data to Earth via a 4-meter High Gain Antenna. Some science instruments continue to gather data during the Earth-downlink, so the downlink actually involves rolling the spacecraft about the radio frequency boresight vector of the antenna during the playback and collecting data simultaneously. The Cassini spacecraft is shown in Figure 1.

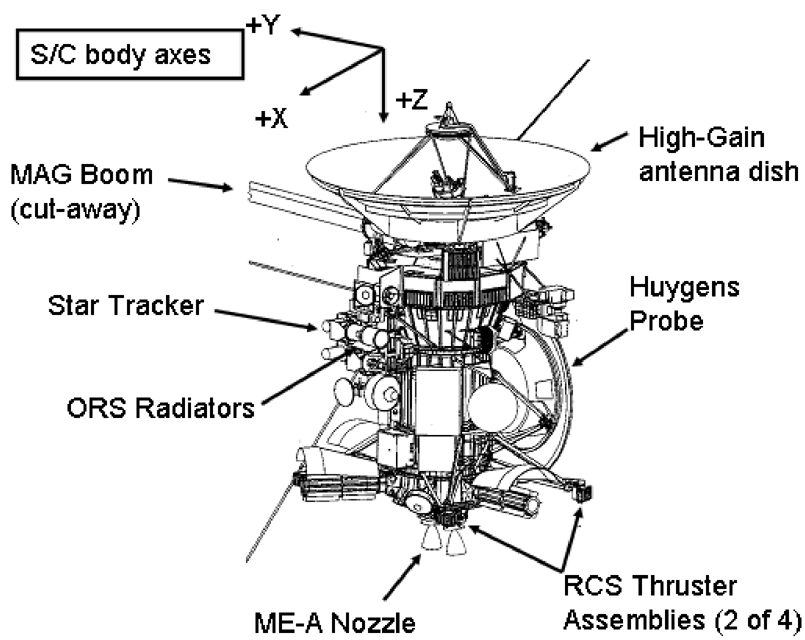

Figure 1. Cassini Spacecraft

The Cassini spacecraft began as a set of designs and specifications that met the requirements and mission objectives established by NASA and ESA in the early-1990s. As the designs matured and led into the building and testing of the spacecraft, the design team developed a growing body of knowledge of the actual capabilities and limitations of the flight hardware and software. This "knowledge base" was clearly going to be important to the team that was to operate the spacecraft after launch. Turning this knowledge base into a set of clear and concise "flight rules" was an essential part of preparing the spacecraft for flight. Flight rules are operational limitations imposed by the spacecraft system design, hardware and software, violation of which would possibly result in spacecraft damage, loss of consumables, loss of mission objectives, loss and/or degradation of science, and less than optimal performance.

The Cassini operations team established a flight rules document that the project maintains throughout the life of the mission. All Cassini flight rules must be documented, and configuration controlled, in this repository. Each rule must be clearly and concisely written and each rule must include a cognizant individual responsible for explaining and commenting upon the rule should questions arise. Each rule must include a clear and concise rationale for its existence, and provide details of how it is checked. All flight rules must be checked and met throughout the lifetime of the mission. Any exception must be documented in a "waiver" which must be approved by the project manager. New flight rules, based on mission experience or lessons learned during spacecraft operations, must also be approved by the project manager prior to incorporation into the flight rules database. Occasionally, old flight rules no longer applicable are retired.

Cassini performs many autonomous functions such as star identification and attitude control.[1] But ground operators command all science and engineering activities by way of stored 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 6 weeks in duration, and each new b/g sequence is 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. On Cassini, each science team designs not only their instrument commands (shutter triggers, etc.) but also the pointing commands that are needed for their observations. A vital task of Cassini attitude control ground operations is to check that these observations not only meet all flight rules individually, but that when all of the observations are merged together there are no flight rule violations.

Ground operators sometimes need to uplink additional commands to the spacecraft while a background sequence is executing. These are called "real time" command files and include such things as trajectory correction maneuvers and "late updates" to the pointing commands of certain observations. Real time command files are considered necessary but need to be subjected to even more scrutiny than b/g sequences. This is because they need to execute at the same time the b/g sequence is executing. Are there any conflicts introduced by the real time commands as they "overlay" the b/g sequence? Do they change the state of the spacecraft in such a way that the b/g sequence, or the next b/g sequence still to be uplinked, is not prepared to handle? These are critical questions that need to be systematically handled on the ground. Flight rules and their rigorous enforcement are a key aspect of insuring that all commands sent to the spacecraft will execute seamlessly, maximize quality science return, and keep the spacecraft operating as planned for the remainder of the mission.

Cassini attitude control flight hardware and software are designed to avoid gross errors in commanding. For example, there are many commands that will be rejected by the flight software if the spacecraft hardware and software states are not in the proper configuration. But there are inevitable limitations in a spacecraft's ability to operate smoothly that can only be dealt with seamlessly if ground operations always follow prescribed rules. In particular, an integral part of the flight software is fault protection. It might be thought that flight software fault protection could reduce the need for ground operations flight rules. In practice, fault protection on a spacecraft is mainly designed for in-flight hardware problems and, when it needs to act, fault protection algorithms must often "safe" the spacecraft which means, for example, stopping any onboard background or real-time sequence and turning off non-vital flight hardware (in particular, science instruments). There is a large amount of ground operations extra work if a spacecraft ever goes into spacecraft safing. It could take more than a week to return the spacecraft to normal operations if a b/g sequence is interrupted by a safing event. Flight rules are intended to insure an uplinked sequence is trouble-free, will require a minimum of ground interaction, and will not cause any fault protection reactive responses.

Below is a short summary of important attitude control flight hardware that requires flight rules to insure optimum flight performance:

<u>Attitude Control Flight Compute</u>r. Cassini has two identical attitude control flight computers. Since launch, AFC-A has been continuously powered and is currently the prime AFC. The prime AFC interfaces with all attitude control flight hardware and performs all flight software processing, executes all ground commands, and outputs most of the attitude control telemetry. The backup AFC is always powered on and is available to become "prime", but executes limited ground commands and outputs limited telemetry.

<u>Inertial Reference Unit</u>. Cassini has two identical IRUs that provide quantized (0.25 μrad) spacecraft attitude change data to the attitude control flight computer (AFC). The AFC flight software edits and filters this gyro data into spacecraft body-rate data which is used to update 3-axis inertial attitude knowledge. One IRU is actively used throughout the mission while the other is a backup. Although Cassini has the ability to maintain attitude knowledge

without any inputs from the IRU (i.e., a star tracker can be used as the sole source of attitude knowledge), ground operators have chosen to always have an IRU powered on and active.

Stellar Reference Unit. Cassini has two identical SRUs that provide star data to the AFC. Flight software uses this star data to construct 3-axis inertial attitude knowledge. One SRU is nominally powered on and actively used throughout the mission while the other SRU is a backup. In the Saturn environment, bright bodies such as the rings or Saturn itself may interfere with the SRUs ability to acquire and track stars. Ground operators must plan for this and issue star identification "suspend" commands before an objects enters the SRU bright body field of view. When star identification is suspended, the flight software propagates inertial attitude knowledge using gyro data alone.

Sun Sensor Assembly. Cassini has two identical SSAs that provide sun data to the AFC. Flight software uses this sun data to construct a "sun line" vector. One SSA is nominally powered on and actively used throughout the mission while the other SSA is a backup. The SSAs are mounted in the Cassini High Gain Antenna dish (which is rigidly mounted fixed to the spacecraft) and their boresights are aligned with the HGA boresight. The HGA was used as a sun shield during the inner solar system cruise phase of the mission (from launch through 1999). At Saturn, the spacecraft occasionally crosses the ring plane of Saturn at a point considered hazardous due to the potential of ring particle impacts. For these crossings, the spacecraft is pointed so that the HGA acts as a ring particle shield (the spacecraft and HGA are pointed in the direction of the spacecraft velocity vector with respect to the ring particles). Although most of the spacecraft is protected for these crossings, there is some risk to the SSAs due to potential ring particle impacts. During these crossings, both SSAs are powered on so that ground operators can get timely information on the health of the SSAs immediately after the crossing.

Reaction Wheel Assembly. Cassini is equipped with four RWAs, three of which are nominally used for precision pointing control (the fourth is a backup). RWA-1, 2, and 3 have fixed orientations (with respect to the spacecraft) and are mounted orthogonally to each other for 3-axis pointing control. RWA-4 is mounted with a spin axis parallel to RWA-1 at launch. RWA-4 is mounted on a rotatable platform designed to permit the ground to change its spin axis orientation. Due to bearing hardware problems in RWA-3, RWA-4 was rotated in 2003 so that its spin axis is now parallel to RWA-3 and has replaced RWA-3 as the third RWA used for precision pointing control.

Reaction Control System. Cassini has two strings of reaction control system hardware. Each string includes eight 1 Newton thrusters, valves, and catalyst bed heaters as well as a latch valve and mono-propellant valve drive electronics. String A is prime and has been used since launch. String B is fully redundant and has not been used in flight. RCS control was the sole control mode during the first two years after launch. In the spring of 2000, new flight software was uplinked to allow control using the reaction wheels. RWA control is used almost exclusively during Saturn Tour operations. Exceptions are: (1) During low-altitude Titan flybys RCS control is required due to atmospheric torques. (2) During trajectory correction maneuvers that require the main engine or RCS thrusters. (3) RWA bias activities where the momentum of the reaction wheels must be explicitly changed while in RCS control. (4) During certain science observations where the RWAs need to be powered off to avoid interference with the science. (5) If spacecraft safing were to occur, a transition from RWA to RCS control is also commanded (RWAs powered off). (6) During Huygens Probe release and tracking.

Main Engine. Cassini has two bi-propellant main rocket engines for large Delta-V maneuvers (thrust 445 N). Each engine uses two engine gimbal actuators (EGAs) for 2-degree-of-freedom thrust vector control (the third axis is controlled via reaction control system thrusters). Both engines share the bi-propellant tanks but each has its own propellant lines, valves, and electronics. Engine-A is prime has been used since launch. Engine-B is a backup (not used to date).

Accelerometer. Cassini has a single accelerometer used during main engine burns. A one-minute calibration of the accelerometer bias is performed before each main engine burn. All main engine burns to date have used the accelerometer for the commanded shut down at the targeted Delta V.

Backdoor Alf Injection Loader. Cassini has an avionics component that contains non-volatile copies of AACS flight software. Normally, if an AFC has to ever be reloaded with FSW, it receives the load from one of two Solid State Recorders (SSR). In the event of a very unlikely onboard fault, it is possible that the AFC will not be able to receive a valid FSW load from either SSR, resulting in an AFC that is not able to provide attitude control. For this situation, fault protection allows the AFC to be loaded from the BAIL which has non-volatile EEPROM copies of the AFC FSW and has a direct connection to the AFC.

II. Flight Rule Descriptions

Restrictions on Usage of AACS Equipment

One set of AACS flight rules concern powering on AACS hardware. The ACC, SRU, and IRU each need pre-selected warm-up times after they are powered on to reach thermal equilibrium. The flight rule rationales refer to "warm up" time for each instrument with values based on manufacturer specifications and prior flight experience. The SSAs, RWAs, and RWAs need between 10 seconds and one minute after power on before usage. This warm up time insures that each of these devices are not only on but ready to function. Onboard flight software doesn't check on a device's readiness – only its "on" state, so these warm up times need to be enforced in operational flight rules. These flight rules are:

1. The Accelerometer must be powered on at least 1 hour prior to its use.
2. The Inertial Reference Unit (IRU) must be powered on at least 2 hours prior to its use.
3. The Stellar Reference Unit (SRU) must be powered on at least 1 hour prior to its use.
4. The power state of the SRU supplemental heater must be ON and the SRU replacement heater must be OFF when the associated SRU is ON.
5. The SRU decontamination heaters must not be turned on after launch + 7 months, as reverse annealing may occur which could damage the CCD.
6. A sun sensor must be powered on at least 1 minute prior to its use.
7. The reaction wheels must be powered on at least 10 seconds prior to their use.
8. The main engine must not be gimbaled to its pre-burn orientation (called the pre-aim direction) unless the EGA electronics driver has been powered on for at least 10 seconds.
9. Propulsion valves must not be commanded until after their associated valve drive electronics has been on for at least 10 seconds.
10. Only one backup device can be powered on at any one time, as the attitude control flight software can only safely accommodate all prime devices being on, plus one backup device. Flight computer sub-frame overruns could occur which could lead to a reset of the flight computer.
11. Attitude control hardware must be turned on at least one minute prior to when it is required because the flight software does not check device readiness, it only checks the power state of a device.

Frequency of In-Flight Calibrations of AACS Equipment

Another set of flight rules concern the frequency of in-flight calibrations and characterizations. Each EGA (both prime and backup) should be exercised every 90 days, for example, to prevent cold welding of brushes to the commutator and to redistribute lubricants on the O-ring. Each RWA needs its lubricant distributed periodically if not being operated. Each SRU needs to be calibrated periodically to capture detailed pixel data so that long-term thermal stresses that could affect pointing or instrument health are not neglected. The BAIL is checked periodically to determine if it continues to contain uncorrupted copies of AACS FSW or if any further ground action is needed to maintain the integrity of its FSW.

SRU calibrations must be done on a regular basis in order to determine scale factor, distortion, dark current spikes, and magnitude sensitivity errors of the SRUs, as well as the misalignment between the two trackers. If this information is not obtained, pointing accuracy might degrade over time and unexpected failure modes that threaten the SRU health will not be detected in a timely manner. These flight rules are:

1. Engine gimbal actuators must be exercised every 90 ± 10 days.
2. Reaction wheel assemblies must be exercised every 90 ± 10 days.
3. Stellar reference units must be calibrated every year (±90 days).
4. Reaction wheel bearing drag torque must be characterized every 90 ± 21 days.
5. BAIL maintenance must be performed every 90 ± 10 days
6. Accelerometer calibration should be at least one minute in duration, to allow enough time to calibrate the accelerometer bias to better than 4 micro-g.

Minimum Post Slew Settling Times

A set of flight rules concern settling times before and after ME and RCS burns. These settling times insure that the propellant slosh excited by turns to and from the burn attitude don't adversely affect either pointing during the burn or cause RWA torque oscillations when returning to RWA control after a burn. These flight rules are:

1. The settling time between the end-time of the roll turn and the start-time of the yaw turn to the main engine burn attitude must be at least 5 minutes.
2. The settling time between the end-time of the roll turn and the start-time of the yaw turn to the thruster burn attitude must be at least 5 minutes.
3. The settling time between the end-time of the yaw turn and the ignition of the main engine must be at least 5 minutes.
4. The settling time between the end-time of the yaw turn and the start-time of the thruster burn must be at least 5 minutes.
5. The settling time between the end-time of the engine (or thruster) burn and the start-time of the "un-yaw" turn must be at least 5 minutes.

Restrictions Related to Reaction Control System Thruster Control

The following flight rules are intended to maintain proper pointing accuracy for various mission related events that occur under reaction control system pointing control. In RCS control, no thrusters fire to correct attitude control error until that error reaches a large enough value. These "deadbands" are especially important when the spacecraft is communicating with Earth. The smaller the deadband, the more accurate the pointing but the more hydrazine is used due to more frequent thruster firing.

1. All per-axis attitude control deadbands must not exceed 2 mrad prior to a main engine burn.
2. Both the Y- and Z-axis deadband must not exceed 2 mrad prior to the release of the Huygens Probe.
3. Both the X- and Y-axis deadband must not exceed 2 mrad during HGA downlink to Earth.
4. Both the X- and Y-axis deadband must not exceed 20 mrad during LGA downlink to Earth.
5. All per-axis deadband must not exceed 2 mrad prior to a thruster to reaction wheel attitude control mode transition.
6. Low altitude Titan flybys must be on RCS thruster control, as the aerodynamic torques from Titan's atmosphere might be enough to overcome the control authority of the Reaction Wheels.
7. During low altitude Titan flybys, adjust the parameters for the thruster leak detection error monitors. Otherwise, the fault protection may confuse the external torque caused by Titan's atmosphere with that of a leaking thruster, and begin to execute fault protection responses under that false diagnosis.

Parameter Update Restrictions

The AACS flight software requires periodic updates to various parameters to maintain proper modeling of mass properties, thruster characteristics, and fault protection. Some of these parameters must be updated in spacecraft modes that do not cause undesirable discontinuities in control and performance. The following flight rules enforce such constraints.

1. Internal RCS attitude controller parameters must be updated when the spacecraft is on reaction wheel control.
2. Reaction wheel-related FSW parameters must be updated when the spacecraft is on thruster control.
3. Spacecraft inertia tensor must be updated when the spacecraft is on thruster control.
4. Spacecraft inertia tensor must be updated after the following events that significant change their values: Deep space maneuver in 1998, Deployment of the magnetometer boom in 1999, Saturn orbit insertion in 2004, and the release of the Huygens probe in late 2004. It must be updated while the spacecraft is on thruster control.
5. Flight software knowledge of the thruster magnitudes must be updated while the spacecraft is using both SRU and IRU. Gyro-less flight control (not yet used in flight) is especially sensitive to these parameter settings.
6. Only flight software "variables" are allowed to be updated in flight. Patching an instruction or constant requires the checksum and flight software version number to be updated also, or the backup flight computer will not transition to normal operations following a flight computer swap.

SID Suspend Related Restrictions

The AACS software uses a Star Identification (SID) algorithm to determine the spacecraft attitude using relative star position input from the Stellar Reference Unit (SRU). The SID algorithm is not programmed with the capability to autonomously ignore bright bodies (Saturn and its moons) that enter the field of view and obscure targeted stars, thereby degrading the quality of the SID attitude estimate. For this reason, the ground operators must command the SID algorithm to suspend star updates for the period of predicted bright body interference. This is called an "SID Suspend". Attitude and rate estimates are propagated solely from gyro information during SID suspends.

The following flight rules define SID suspend commanding characteristics. The symbol ω denotes the spacecraft body rate and the term "B/S ± an angle" defines a cone centered on the star tracker boresight.

1. SID must be suspended if the edge of the un-occulted Sun is inside the SRU's boresight (B/S) ±30° for longer than 6 minutes.
2. SID must be suspended if the S/C's rate is "fast" such that $|\omega_Y| + 0.131 \times |\omega_X| > 9.6$ mrad/s.
3. SID must be suspended if the S/C's rate is "fast" such that $|\omega_Z| + 0.131 \times |\omega_X| > 9.6$ mrad/s.
4. SID must be suspended if any part of an object with a diameter > 0.5° is inside the SRU's B/S ±12°.
5. SID must be suspended if any part of an object with a diameter > 1.7° is inside the SRU's B/S ±18°.
6. SID must be suspended if any part of an object with a diameter > 2.0° is inside the SRU's B/S ±30°.
7. The duration of a SID suspend event must not exceed 5 hours.
8. SID suspends must not occur during IRU or SRU calibrations.
9. Commands that modify the star catalog or initialize star identification algorithms must not be issued during SID suspends.
10. Do not perform tasks that require celestial reference from the SID algorithm, such as an IRU calibration, during an SID suspend.
11. Properly mask the "No Star In Inertial" fault monitor during SID suspends, as the monitor does not know the SID algorithm has been suspended, and expects to see continuous star updates.
12. All SID suspend events must be preceded by 10 minutes of quiescent spacecraft body rates (< 0.5 mrad/s) and followed by 20 minutes of quiescence, to allow pointing errors to subside after and to insure good star knowledge prior to an SID suspend.

Geometric and Dynamic Constraint Restrictions

An onboard flight software object called the Constraint Monitor (CMT) continuously checks the commanded body attitude, rates and accelerations. Any discontinuity in these quantities (beyond the capabilities of the spacecraft) will trigger CMT to smooth out the discontinuity. Ground operators need to be careful that these "dynamic" constraint violations do not occur in routine operations.

Another function of the CMT algorithm is to enforce geometric keep out zones. Ground operators populate a constraint table that defines these geometric constraint cones. An example is a cone centered along the Cassini-to-Sun line. The angular size of these cones is defined by ground command. CMT will override the commanded pointing if it determines that a body vector boresight is in imminent danger of entering a geometric keep out cone. CMT will attempt to slew around the edge of the cone and ultimately return to the user-defined pointing when the cone has been avoided. This insures that sensitive star tracker and camera boresights are never exposed to the sun. Even with this protection, it is important that ground operators design sequences that do not violate these constraint cones.

The geometric cones can be reduced or disabled by ground command. This can occur, for example, when the sun is occulted by Saturn or a moon. Ground operators must insure that these cones are safely managed given occultation timing uncertainties. These cones are honored even during spacecraft safing events, so ground operators must reestablish the nominal cones before an occultation ends. The science observation slew to exit the cone must also have exited the cone before the cones are re-established.

1. The angle between a vector from the spacecraft to any part of the un-occulted Sun and the positive X-axis of the spacecraft must exceed 83°. This is for science radiator thermal reasons.
2. The angle between a vector from the spacecraft to any part of the un-occulted Sun and the negative Y-axis of the spacecraft must exceed 12°. This is for camera boresight protection.

Slew Restrictions

The Reaction Control System thrusters have greater control authority than do the Reaction Wheels, and for this reason are capable of slewing the spacecraft with larger rates and accelerations. The following flight rules ensure that turns are properly designed given the attitude control mode currently being used.

1. Reaction wheel-based profile limits must be commanded before a thruster-to-reaction-wheel control mode transition has occurred.
3. Reaction wheel-based slew profile limits must be selected consistent with the RWA power allocation.
4. A turn (with a small slew rate and a large slew angle) that takes >1 year to complete must not be commanded.
5. Do not transition from RCS to RWA control while turning unless the commanded rate and acceleration is compatible with RWA control authority, or excessive rate and pointing errors may accumulate.
5. The spacecraft must not be commanded to slew such that the total rate (commanded + target motion compensation) is greater than 4.5 mrad/s about the spacecraft Z axis or 2.3 mrad/s about any other spacecraft axis unless the RCS control mode includes IRU data. The star tracker alone cannot properly estimate attitude at spacecraft body rates greater than these.
6. The spacecraft (using either the reaction wheels or the RCS thrusters) must not have per axis total rate and acceleration (commanded + target motion compensation) greater than the onboard Constraint Monitor per-axis rate limit minus 17%. This insures margin so that commanded turns do not exceed the CMT dynamic constraint limits.
7. A slew to a new target must not be commanded if that slew is within 0.5 degrees of 180 degrees. The flight software always chooses the shortest turn direction to the target. For turns close to 180 degrees, this choice becomes ambiguous. This may pose a problem if, for example, the chosen turn direction results in a path that violates a geometric CMT constraint.

Restrictions Related To ME and RCS burns

Approximately three times per Saturn orbit, the AACS team must build real-time command files to perform main engine or thruster-based trajectory correction maneuvers to keep the spacecraft following a desired trajectory. The following flight rules ensure the AACS flight software is properly configured for such events.

1. A special flight software operating mode is used during TCM burns. This mode is explicitly “blocked” (via command) during normal operations to prevent an accidental ΔV burn. Before a TCM, a command must be issued to un-block this mode and after the burn a command must be issued to re-establish the block protection. This insures that an inadvertent burn command will not cause an actual burn to be performed.
2. Each time the engine gimbal actuator is powered on, the first actuator stroke command after closing the servo loops must be an extension of at least 2 mm.
4. The Main Engine valve driver must not be powered on while AACS is in a SRU-only attitude estimation mode, as the IRU is needed to detect anomalous rates induced by a faulty ME burn.
5. If both engine gimbal electronics control units are powered ON, the electronics drivers must not be operated in a cross strapped configuration, as the control of the EGAs in the cross strapped configuration is not stable.
6. The RCS attitude control deadband must be tightened to a value of 2 mrad or less at least 5 minutes prior to a main engine burn. Larger attitude control errors could trip the excessive thrust vector control error fault protection monitor.
7. Each engine gimbal actuator stroke command should be allowed to complete before a new command is sent, or an undesirable EGA position will result.
8. Bi-propellant latch valves must be commanded in pairs, to preclude problems from a propellant leak.

Restrictions Related To Use Of Reaction Wheels

During Saturn Tour the spacecraft is almost continuously using reaction wheels for control. Not only is this a challenge to the long-term health of RWA hardware, but ground operators must be extremely careful when explicitly commanding RWA biases or any activity where the RWAs must be powered off or on.

1. Reaction wheels shall not be powered off until after their spin rates are all within ±5 rpm. This insures the flight computer has accurate knowledge of RWA momentum after the RWAs are powered off.

2. To avoid RWA hardware degradation, slews of 60° or more under RWA control are performed at maximum slew rates about 33% lower than normal. Large turns tend to create "spikes" in RWA momentum, which make it difficult for ground operators to keep the RWA spin rates within the recommended bounds.
3. Do not command a rate change on the backup RWA while in RWA control, or the reaction torque may overwhelm the control authority of the RWA controller.

Restrictions Related To The Maintenance Of Inertial and Body Vectors

Inertial vector propagation (IVP) is the core of the onboard pointing model used on the spacecraft.[2] It allows any scientific instrument boresight to be pointed at any celestial object using fixed or time-varying inertial and fixed spacecraft body vectors. Pointing commands do not reference underlying entities like right ascension, declination, or spacecraft body rates. On Cassini, pointing commands reference celestial objects themselves. If the target is Saturn, a single command causes the spacecraft to turn to Saturn. Once there, the spacecraft tracks Saturn until commanded to turn to another object. This means that target motion compensation is inherent in the design. An onboard table of inertial and body vectors is maintained, with the flight software autonomously propagating active vectors when needed to point at objects of interest. Each inertial vector has a user-defined "head" object and "base" object and the vectors are linked to form a "tree" so that pointing is a simple process of vector addition and subtraction.

The following flight rules ensure that proper pointing is maintained, and that no mathematical singularities or ambiguities exist that may cause improper commanded pointing.

1. Time-varying active inertial IVP vectors must be updated before they expire, otherwise pointing degradation occurs. Each "segment" of an active vector must meet a high accuracy pointing tolerance. This is of course fundamental for good scientific observations, but it is also important, while tracking, to avoid any discontinuity when transitioning from one IVP vector segment to the next.
2. A fixed inertial vector, a rotating vector, or a body vector should not be updated while it is active (being used for pointing). A sudden change in an active vector will cause a pointing discontinuity that will cause CMT to smooth out the discontinuity but is not desirable in normal operations (could cause unexpected RWA momentum changes as well as ground operations anomaly recovery).
3. No more than 15 vectors should be connected in the tree because this can overwhelm the allowed AFC processing time.
4. An IVP vector must not be deleted until after (at least) 10 seconds after its last use.
5. A non-existent body or inertial vector must not be deleted.
6. The head and base objects of all vectors must be different.
7. There cannot be parallel paths for a given head-base IVP pair.

Command Sequencing Restrictions

Attitude control commands are routed to the AFC through the CDS command handler. This command handler has a command queue that can handle the proper routing of several commands at once, but this queue must not be exceeded, or sequenced commands can be dropped. Also, telemetry-related commands must meet important restrictions or data will be lost or the AFC could autonomously reset (has never occurred in flight). IRU failure recovery needs extra care because of its interaction with fault protection.

1. No more than three commands per second may be sent to the AACS command handler from all command sources (background sequences, mini-sequences, etc.).
2. Never issue ground-test-related commands in flight sequences.
3. Never issue commands that are reserved for onboard fault protection response logic.
4. Only one large AACS command > 32 words may be sent from any sequence source in a given second, and no other AACS commands from sequence sources are allowed in that second, as such a situation may oversubscribe the input queue for AACS commands.
5. Do not issue more than one targeting command in a two second interval, as the CDS does not guarantee the order in which commands are issued in a given second. This could cause turns to be ignored.
6. A very restricted set of commands are allowed when an AFC is in start-up read-only memory mode. These commands must be placed at least one second apart to avoid overfilling the command queue.
7. Telemetry and memory readout commands must cover initialized memory addresses only, or a reset of the

prime AFC will result.

8. A command to mark an IRU as failed must be followed by a command to mark each of that IRU's gyros as failed, as the AACS fault protection software only recognizes ground-provided health state information on individual gyro axes, not on entire IRUs.
9. The safing attitudes must not be inside of a geometric constraint region, or AACS FSW will avoid the constraint region and may not achieve a commandable attitude.
10. Telemetry and memory readout commands must be spaced such that the readouts complete before subsequent readout commands are issued, or loss of data may occur.
11. Do not oversubscribe the downlink telemetry bandwidth or loss of data may occur.
12. Occultations of the sun must be anticipated with a command to suspend sun sensor fault protection at least 5 minutes before an occultation starts, and must remain in effect at least 5 minutes after an occultation ends.

III. Flight Rule Enforcement

A suite of ground software tools help ground operators ensure that the above flight rules are correctly and consistently enforced. Ground software is fundamental to not only enforcing flight rules but for constructing and checking the commands to be uplinked themselves. All types of AACS commands are defined and specified in a command database. This database defines the syntax of all commands, as well as how they are translated into binary form, allowable ranges of all parameters, word lengths, and constraints on command acceptance by the FSW. An AACS command dictionary provides users with this information including examples and other relevant information.

<u>SEQ_GEN</u>

A core ground software tool for the Cassini project is a program called SEQ_GEN. This tool is used to generate all commands to be executed onboard. Individual scientists or engineers build their own activities (sets of commands) using SEQ_GEN or other tools that have SEQ_GEN imbedded in them. SEQ_GEN is used to assemble all the commands that are executed across all of the flight computers (attitude control, command and data subsystem, and all science instrument flight computers). The commands are organized in requests that define the science observations and engineering activities. These are merged into a complete background sequence program by the sequence uplink engineers. One of the outputs of SEQ_GEN is a complete time-ordered listing (called a Predicted Events File or PEF) of all the commands the spacecraft flight computers will execute during the sequence.

SEQ_GEN automatically performs syntax and range checking on all commands and their parameters. It also uses the time-ordered listing of commands to maintain models of the "states" of the spacecraft subsystem elements needed for flight rule and constraint checking. States are considered to be any spacecraft parameter that is affected by a command. For example, whether a star tracker is on or off is considered a spacecraft state. The time since it was last powered on is also a spacecraft state. These states are used by SEQ_GEN to enforce flight rules that relate to spacecraft commands.

The flight rules that are checked by SEQ_GEN are those where a spacecraft command causes a state change that is directly related to a flight rule. For example, the flight rule that states a star tracker must be powered on for at least an hour before use implies the following model in SEQ_GEN: (1) when a command to power on a star tracker is issued, SEQ_GEN models the power state of “on” and notes the time it occurs. (2) When a command to make that star tracker prime (that is, for the flight computer to actively use the output of the star tracker) is issued, this flight rule is checked (once). If at least an hour has elapsed, the flight rule is satisfied and no flight rule violation is output. If less than an hour has elapsed, a flight rule violation is output. Part of this output is the time tag of the violation and the values of the states that are being modeled by the SEQ_GEN implementation of the flight rule check.

Thus SEQ_GEN flight rule modeling is essentially a command-driven “finite state machine”. SEQ_GEN operates only on commands and is not really modeling time in any continuous fashion. SEQ_GEN processes a command, updates the states affected by that command and performs all flight rule checks associated with that command then SEQ_GEN reads the next command and repeats these functions. The only time-incrementing that SEQ_GEN does is when it reads the next command in the time-ordered listing. Whether it is a second, a minute, or an hour after the previous command is immaterial to SEQ_GEN.

This method of command-driven flight rule checking requires that the flight rules clearly state the commands (including command parameters if necessary) associated with a given flight rule, and any mode or duration dependencies. For any state that is part of a flight rule, the flight rule must list the commands that relate to that flight rule. When a command is read by SEQ_GEN, it first performs command syntax and range checking, then it performs state modeling, then it performs flight rule checking of all flight rules affected by that command.

Like all programs, a vital aspect of SEQ_GEN is to initialize SEQ_GEN properly. With over 100 types of AACS commands and several hundred flight rules modeled (AACS and others), the state modeling that SEQ_GEN performs becomes quite large. A required input file for any SEQ_GEN flight rule modeling is an initial conditions file, which contains the values of every state that SEQ_GEN models at the start time of the SEQ_GEN run (nominally the beginning of a sequence). At the end of a SEQ_GEN run, a final conditions file (containing the values of every state at that end time) is output to be used by the next sequence as initial conditions.

SEQ_GEN flight rule modeling is vital for checking that a complete background sequence is flight rule violation-free prior to uplink. It is also used for real-time commands that are to be issued in the middle of a background sequence. In this case, SEQ_GEN starts at the beginning of the background sequence so that all the modeling is up to date at the time the real-time command activity begins. It then models the real-time commands and the b/g sequence, interleaving commands if both sequences are issuing commands during the same time periods.

IVP

A ground software IVP tool is essential to populate and manage the onboard inertial and body vector tables.[3] The tool creates all the IVP commands that are uplinked as part of stored background sequences. The IVP tool accepts as inputs the complete background sequence, the latest ephemeris files for the spacecraft and all celestial bodies relevant to the sequence, the state of the onboard inertial vector and body vector tables at the start of the sequence, and any additional pointing definitions that are not already built into the standard set of pointing target option provided to all science users. Physical constants (radii, oblateness, gravity, rotational information, etc.) of all relevant celestial bodies are also loaded into the tool. The tool insures that all IVP-related flight rules are met including checks that the onboard vector tables are never over-subscribed (too many vectors to fit in the tables) or under-subscribed (vectors not available or not spanning the full duration of an observation). A critical requirement is that all celestial body-related vectors are always accurate to within 40 micro-radians of their true ephemeris positions. Fixed vectors must be explicitly deleted by the tool after they are no longer active, otherwise the vector table would be quickly over-subscribed.

The IVP tool is also imbedded within science design tools so that individual scientists can define their observations stand-alone and at a more user-friendly level of pointing abstraction, while letting the underlying IVP tool perform the geometric and ephemeris calculations that are needed to form the actual IVP vectors.

KPT

Another core ground software tool important for flight rule verification is called the Kinematic Predictor Tool (KPT). This tool processes all the pointing-relating commands in a sequence, models all the pointing (slewing to and tracking targets) throughout an entire sequence, and models all flight rules that relate to spacecraft attitude (including the position of the sun and other celestial bodies). KPT uses the same approach as the actual flight software in terms of constructing the desired spacecraft attitude but it does not include thruster or RWA controller logic. It profiles turns (i.e. constructs the turn axis, turn angular rate, turn angular acceleration profiles) and performs target motion compensation just like the actual flight software. Comparison of KPT attitude prediction with actual telemetry (throughout the 4 year nominal Tour mission) shows excellent agreement – differences are on the order of 0.1 mrad while tracking targets. During a slew, KPT can be 1 to 3 mrad in error (leading or lagging the actual spacecraft) because KPT doesn't issue the turn command at exactly the same instant as the spacecraft (due to the conversion of SCET to SCLK and the truncation of fractional seconds in uplinked commands).

KPT models CMT dynamic constraints, geometric constraint cones, and their associated sequence commands. KPT outputs a violation if CMT avoidance logic is triggered (e.g. a slew is going to enter a geometric cone). Each cone in KPT has a padded cone 6 mrad bigger than the actual onboard cone. This allows ground operators to see if a slew is extremely close to a cone. Normal practice is to insure slews do not enter the padded cones either.

KPT also models reaction wheel momentum, torque, and power usage. It estimates total torque and power usage by using a user-selectable set of reaction wheel viscous and coulomb friction coefficients. One of the most important recurring engineering activities during the Tour is the management of RWA momentum. Every 1 to 5 days, an RWA momentum "bias" is commanded. This activity commands an explicit change in RWA momentum while Earth-pointed (nominally) so that navigation has visibility of the Earth-line Delta V imparted during the bias due to RCS thruster usage. The purpose of the bias is to allow all the upcoming science pointing activities to occur at "acceptable" RWA wheel speeds. If an RWA reaches too high a spin rate, fault protection will autonomously power off the reaction wheels and force the spacecraft to use RCS control. If an RWA dwells at too low a wheel speed, Cassini flight experience has shown that large and persistent friction spikes can occur which could lead to RWA bearing failure over time.

The wheel speeds commanded in an RWA bias are carefully selected to avoid these issues throughout the period of the RWA "segment" (the time from one RWA bias to the next RWA bias). Figure 2 shows a typical time-history of RWA wheel speeds during 24 hours of science pointing activities. Note the dashed red lines that signify the low-rpm region. RWA health requires that any dwell inside the red lines longer than 30 consecutive minutes be minimized. High-rpm is a hard constraint in the selection of the RWA bias momentum. Many candidate RWA bias wheel speeds are considered (in fact, an RWA Bias Optimization Tool – RBOT[4] has been developed just for this purpose) before a particular set of bias values are chosen for a given RWA segment. Each segment is unique and requires RWA bias wheel speeds tailored just for that segment. It is the science pointing time-history that is unique in each segment, and frequently some science observations must be adjusted, even with an RBOT optimal design, to avoid any of the RWAs dwelling in the low-rpm region.

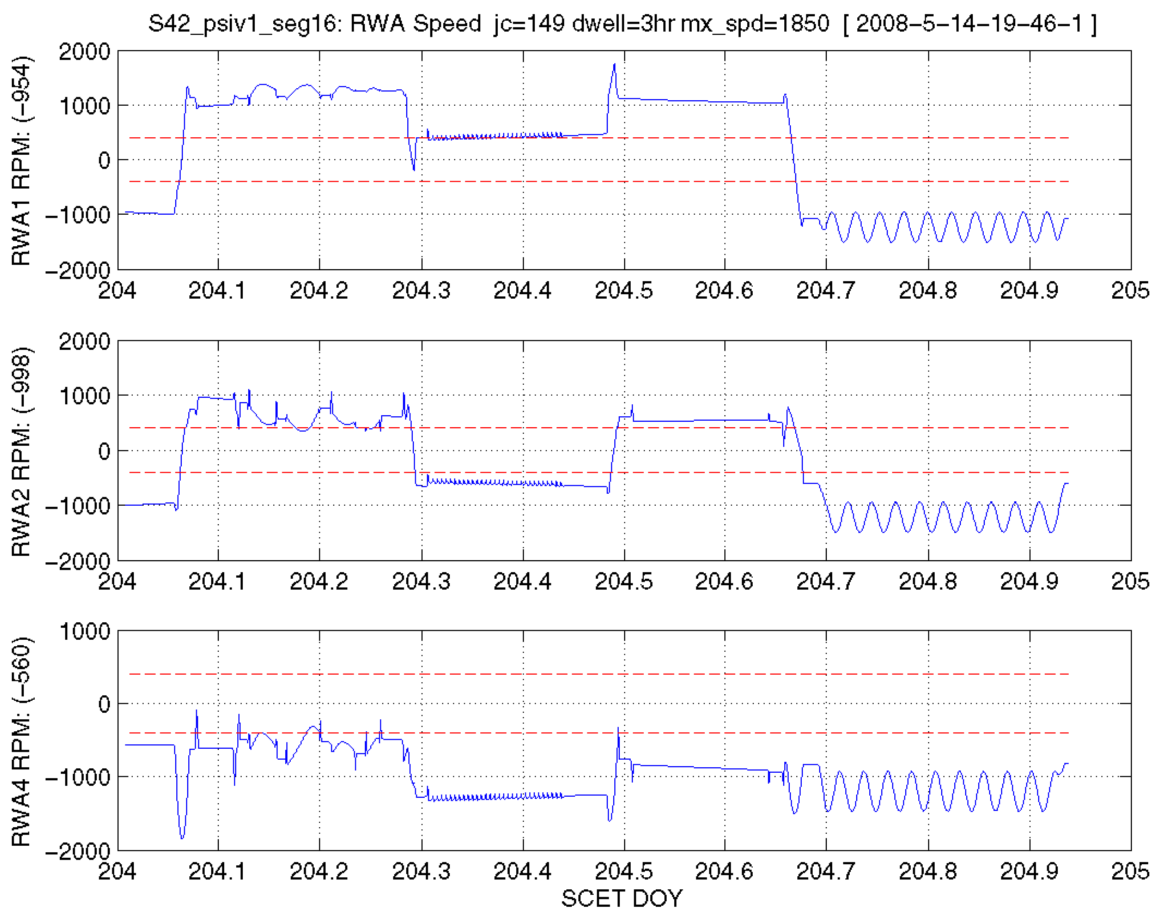

Figure 2. RWA Momentum Profile (Time vs. revolutions per minute)

An important flight rule that KPT checks related to RWA bias activities is the duration of the bias. Bias duration is the amount of time in RCS control allotted for the RWA momentum change. A nominal bias duration of 20 minutes normally (but not always) provides sufficient time for each RWA to change its momentum from its setting at the end of an RWA segment, to the new setting needed for the next segment. If the attitude control operations team ever chooses a duration that is not sufficient to complete the momentum change, KPT flags this as a flight rule violation, so this can be corrected before the RWA bias is merged into the background sequence. The result of an incomplete momentum change would be an incorrect RWA momentum at the beginning, and therefore throughout, an RWA segment. This could lead to excessive dwell time at low RWA wheels speeds which could damage RWA lubrication or the bearing itself.

Another set of flight rules enforced in KPT are the flight rules relating to suspension of star identification. These flight rules are vital to safe attitude estimation in Saturn orbit where many bodies (especially Saturn and its rings) are large enough to cause star identification problems when they enter the star tracker bright body field of view. Not only are these rules checked in KPT, but KPT constructs the SID Suspend commands themselves. Based on the spacecraft pointing throughout a sequence, and the geometry of the Saturn system celestial bodies relative to Cassini, KPT constructs the SID Suspend commands and writes a file output containing them which is then merged with the background sequence. In some cases, KPT might not be able to construct a given SID Suspend command and still meet the maximum suspend duration flight rule. In this case, KPT outputs a flight rule violation and the sequence must be re-designed so that the maximum suspend duration is met.

A number of flight rules that KPT checks involve inertial vector propagation. A separate ground software tool manages all vectors and creates all vector commands to be merged with the background sequence. This separate tool internally performs vector creation and management consistent with all vector-related flight rules, but KPT provides an additional check that all vectors completely span the durations over which they are needed. It also checks to be sure that ground operators never delete a vector prematurely (i.e. while it is still active).

Many flight rules checked by KPT are actually flight rules related to scientific instruments that require the pointing model that KPT provides. Some scientific instrument boresights must stay at least 12 degrees away from the sunline, for example. Some spectrometer radiator/coolers need to be kept at least 83 degrees away from the sunline (except during occultations). KPT enforces flight rules that insure that the sequence design keeps radiators at least 90 degrees from the RAM direction (the wind direction with respect to the spacecraft) during low-altitude flybys of the moon Titan to insure atmospheric heating does not exceed requirements.

KPT also contains detailed thermal models for some scientific instruments. Temperatures are continuously modeled in KPT based on solar and Saturn distance and on the geometry of the sun and Saturn with respect to the spacecraft body coordinate frame. Flight rules requiring temperatures to always stay below certain thresholds are checked and reported by KPT if they are ever violated. Other flight rules checked by KPT require an even smaller temperature excursion if a scientific instrument trigger-command occurs when the temperature is elevated. These thermal models are configuration controlled by the Cassini project to insure that all science temperature modeling -- whether by individual scientists designing a single observation or by KPT on a complete background sequence -- uses a single set of approved models.

All slew and RWA related flight rules are enforced in KPT. One of the KPT output files is a violation summary report that provides the violations, their times of violation and their duration, the science user request identification that causes the violation, the depth of the violation (for example, how far into the geometric cone a slew puts a boresight) and other relevant parameters that allow users to correct the observation designs. Other outputs include detailed digital data of attitude, body angular rate, body angular acceleration, boresight-to-celestial-body angles, thermal model temperatures, and RWA and spacecraft momentum, torque, and power predicts. The attitude and body rate data are then used as inputs to the RWA Bias Optimization Tool so that detailed RWA bias designs can be performed.

Like the IVP ground software tool, KPT is imbedded in the tools that science users design their observations with. This permits most flight rule violations to be detected and corrected at an early stage of the sequence design process. Problems can arise when observations are merged together and the impact of this merge can only be determined when the complete background sequence is run through KPT by the attitude control analyst for that sequence. KPT emulates the actual flight software in that many algorithms are run at a time step of 0.125 seconds. The Euler equations of motion and the RWA momentum equations are run at even higher frequency to insure accurate numerical precision. Since an actual background sequence takes 5 or 6 weeks to execute, a critical performance requirement of KPT is that it runs at least 400 times real-time, so that a complete sequence can be processed through KPT in a few hours on the workstation of the AACS analyst.

<u>Flight_Rule_Checker</u>

The Flight_Rule_Checker was written early in the Saturn Tour in an attempt to decrease the amount of manual checking performed on flight rules not covered by SEQ_GEN, IVP, and KPT, the benefits of which are obvious -- decreased workload and probability of error from a missed check. At first the code was merely a substitution for a set of Unix-based "grep" commands that the ground operator executed on the Predicted Events File (PEF), searching for key AACS commands, the absence of which precluded individual flight rule violations. Gradually, however, the code evolved in complexity to check for increasingly subtle violations of 40 flight rules and other lessons learned that had not been elevated to the status of a flight rule.

The code works by first stripping out the AACS commands from the PEF. This is done because the PEF files contain commands from all the spacecraft subsystems, along with a tremendous amount of SEQ_GEN state model information and notes. The stripped-down version of the file allows for much faster processing, as the reduction in file size is often on the order of 2000 to 1. Then the code checks each flight rule one by one by reading through the AACS commands and building a record of the relevant AACS states pertaining to each flight rule. Violations are flagged and written to an output file, along with a description of the violation and a listing of the relevant commands. In this manner, the program is able to successfully verify things as diverse as: (1) Do not perform a gyro calibration with the SID algorithm disabled, and (2) Do not update an active rotating vector tied to a rotating coordinate frame.

The program has greatly eased the workload of AACS analysts as its flexibility and simplicity of code allow for relatively rapid additions as new lessons are learned. Its reliability has been proven by its ability to catch flight rule violations before the sequence was uplinked to the spacecraft.

IV. Conclusions

The Cassini spacecraft has successfully completed its nominal 4-year Saturn Tour in very good health. It is currently beginning the first year of its extended mission. The need for exacting flight rule enforcement was recognized early in the spacecraft design process, and has evolved to a full suite of ground software checking hundreds of flight rules so that each day Cassini can perform its observations and data transmission in a robust, efficient, and seamless way, while minimizing the level of manpower required to operate such a complex spacecraft. The training that ground operators need is significant, but their tools have been made as user-friendly as possible. Flight rule checklists for background sequence, real-time command files, and trajectory correction maneuvers document each flight rule and how it is enforced. The evolution of these checklists over time shows clearly that more and more flight rule checks are performed automatically in ground software. Virtually all flight rule violations are flagged and solved early in the sequence design process. The smooth operation of the Cassini spacecraft to date reflects the care taken in sequence design and flight rule checking by the ground operations team. The spacecraft designers conceived and built an extremely capable spacecraft. Flight rule enforcement is an integral part of maintaining a healthy spacecraft and maximizing its science return.

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