

Challenges of the Cassini Test Bed Simulating the Saturnian Environment

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The Cassini-Huygens mission is a joint NASA and European Space Agency (ESA) mission to collect scientific data of the Saturnian system and is managed by the Jet Propulsion Laboratory (JPL). After having arrived in Saturn orbit and releasing the ESA's Huygens probe for a highly successful descent and landing mission on Saturn's moon Titan, the Cassini orbiter continues on its tour of Saturn, its satellites, and the Saturnian environment. JPL's Cassini Integrated Test laboratory (ITL) is a dedicated high fidelity test bed that verifies and validates command sequences and flight software before upload to the Cassini spacecraft. The ITL provides artificial stimuli that allow a highly accurate hardware-in-the-loop test bed model that tests the operation of the Cassini spacecraft on the ground. This enables accurate prediction and recreation of mission events and flight software and hardware behavior. As we discovered more about the Saturnian environment, a combination of creative test methods and simulation changes were necessary to simulate the harmful effect that the optical and physical environment has on the pointing performance of Cassini. This paper presents the challenges experienced and overcome in that endeavor to simulate and test the post Saturn Orbit Insertion (SOI) and Probe Relay tour phase of the Cassini mission.

ACRONYMS

<i>AACS</i>	=	Attitude and Articulation Control Subsystem
<i>AFC</i>	=	AACS Flight Computer
<i>BAIL</i>	=	Backdoor Alf Injection Loader
<i>CATS</i>	=	Cassini AACS Test Station
<i>CCD</i>	=	Charged Coupled Device
<i>CDS</i>	=	Command and Data Subsystem
<i>CPU</i>	=	Central Processing Unit
<i>ESA</i>	=	European Space Agency
<i>FOV</i>	=	Field of View
<i>FSW</i>	=	Flight Software
<i>FSDS</i>	=	FSW Development Station
<i>H/W</i>	=	Hardware
<i>HGA</i>	=	High Gain Antenna
<i>IEU</i>	=	Image Emulation Unit
<i>ITL</i>	=	Integrated Test Laboratory
<i>JPL</i>	=	Jet Propulsion Laboratory
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>RCS</i>	=	Reaction Control System
<i>RWA</i>	=	Reaction Wheel Assembly
<i>S/C</i>	=	Spacecraft
<i>SID</i>	=	Star Identification and Tracking
<i>SE</i>	=	Support Equipment
<i>SOI</i>	=	Saturn Orbit Insertion
<i>SPICE</i>	=	Spacecraft Planet Instrument C-matrix Events
<i>SRU</i>	=	Stellar Reference Unit
<i>SSA</i>	=	Sun Sensor Assembly
<i>SSPS</i>	=	Solid State Power Switch
<i>SSR</i>	=	Solid State Recorder
<i>S/W</i>	=	Software

1.0 Introduction

The Cassini/Huygens project is a joint NASA, European Space Agency (ESA), and Italian Space Agency (ISA) collaboration to explore in detail the Saturnian system. The Cassini orbiter was assembled at the Jet Propulsion Laboratory (JPL) and the Huygens probe was built by ESA. The Cassini/Huygens mission was launched on October 15, 1997. After being captured in Saturn's orbit and successfully delivering the Huygens probe to Titan, the Cassini orbiter continues on its science rich tour of the Saturnian system in which it will complete over 74 orbits around Saturn during its prime mission. Cassini will use its more than 3-dozen science instruments to examine Saturn, its rings and satellites, and the composition of the Saturnian environment including taking measurements of the magnetic, radiation, and gravitational fields. During its prime tour mission, Cassini will pass Titan 45 times, execute 8 targeted flybys of the icy satellites Enceladus, Dione, Rhea, Hyperion, and Iapetus, and perform ~30 non targeted flybys of the icy satellites.

The Cassini Integrated Test Laboratory (ITL) that resides at JPL is a high fidelity ground based test bed whose purpose is to verify and validate selected software updates and command sequences prior to being sent to the Cassini spacecraft. The ITL consists of hardware and software that replicates some of the main engineering subsystems of the Cassini spacecraft on the ground and simulates the environmental and spacecraft dynamics necessary to adequately test these sequences and software updates. The engineering subsystems that are replicated as hardware-in-the-loop entities in ITL are the Command and Data Subsystem (CDS) and the Attitude and Articulation Control Subsystem (AACS). The CDS consists of two (redundant) MIL_STD-1750A computers and two Solid State Recorders (SSRs). The CDS function is to execute programmed or real time commands and pass them to the appropriate subsystem via its dual redundant 1553B data bus. The AACS consists of two redundant MIL_STD-1750A computers and a local dual redundant bus that connects to 6 different sensors and actuators, a valve interface that controls valves, thrusters, and the main rocket engines in the Propulsion Module Subsystem (PMS), and a backup load device called the Backdoor Alf Injection Loader (BAIL). The AACS sensors include a star tracking Stellar Reference Unit (SRU), a Sun Sensor Assembly (SSA) that senses the sun direction, an Accelerometer (ACC) that senses linear acceleration along the High Gain Antenna (HGA) pointing axis of the spacecraft, and an Inertial Reference Unit (IRU) that senses angular rates in three axes. The AACS actuators are the Reaction Wheel Assemblies (RWA) that change the spacecraft angular rates and the Engine Gimbal Assemblies that move the 445 N main rocket engine for trajectory control. All of the AACS hardware is either flight or engineering model hardware except for 3 out of 4 of the RWAs, and 1 of 2 of the IRUs, which are hardware simulators.

The ITL can be configured in either of two modes, a system mode or a subsystem mode configuration. The system mode configuration consists of connecting the CDS and AACS subsystems together with their associated support equipment during ITL testing⁶. The system mode configuration is the highest fidelity mode in ITL because it allows for testing actual sequenced and real time command files sent to the Cassini S/C. System mode also combines full AACS and CDS flight software and hardware capabilities, including their associated simulators. In subsystem mode, the CDS and AACS are tested in standalone mode, with the CDS and SSR simulated in the AACS standalone mode, while the AACS is simulated in the CDS standalone mode. Some tests described herein were run in an additional AACS standalone test area called the Cassini AACS Test Station (CATS). The simulation modifications that are discussed in this paper fall exclusively in the AACS test setup that is used both in system and subsystem modes.

2.0 AACS Support Equipment

The AACS Support Equipment is a multiprocessor system. It is divided into a near real time and real time environment (Figure 1). The near real time portion includes a SUN Ultra 80 host computer running in Solaris with peripherals whose primary function is to provide control functions to the user and to collect data from the simulation and test environment. The near real time system provides services such as simulation and flight hardware stimuli command requests, and data retrieval and archival from the real time system. The host computer communicates with the real-time system through a dedicated Ethernet connection and also provides initialization services to the real time side. The real-time portion is a series of Power PC (PPC) single board computers (SBCs) that run in VxWorks each on a dedicated bus with associated custom interface panels. The real-time system provides the time critical functions of running a dynamics simulation, asynchronous monitoring of flight hardware

events, and synchronous digital or analog stimulation of the AACS flight hardware sensors (i.e. SSA, SRU, ACC, and IRU), as well as IRU and RWA hardware simulation. Data between all but the IRU and RWA Hardware simulators is shared asynchronously through a shared reflective memory database called a blackboard³.

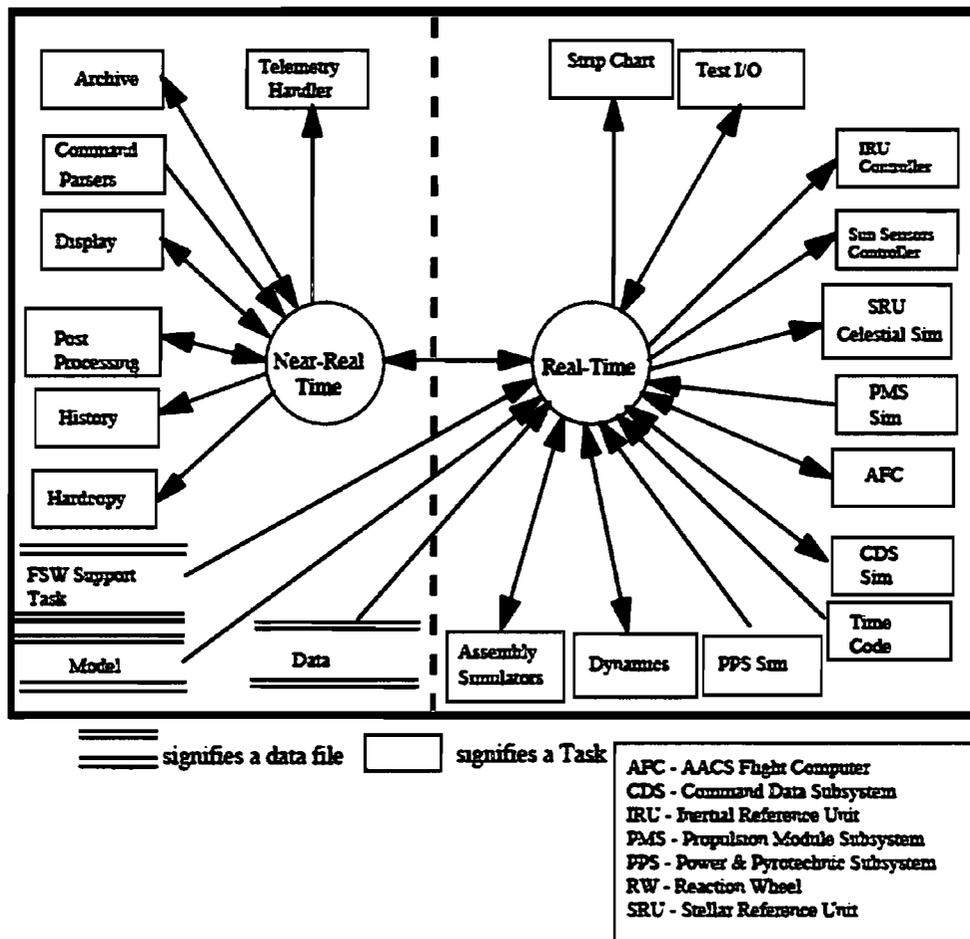


Figure 1 – ITL AACS Near-Real Time and Real Time simulation software (excerpt from Reference 4)

In both ITL subsystem and system modes, the AACS subsystem sensors are stimulated by the AACS Support equipment to simulate the forces and torques (for the accelerometer and gyros) and optical data (for the SRU and Sun Sensor) experienced by the Cassini spacecraft during a test scenario. The closed loop AACS test simulation consists of a dynamics simulation running every 62.5 milliseconds providing simulated spacecraft acceleration and attitude information to AACS hardware sensors in order to simulate stars, bodies, accelerations, and rates. The AACS sensors feed their information to the AACS Flight Software in the AACS Flight Computers (AFCs), which in turn calculates and commands attitude control responses to its actuators (EGAs, RWAs) and thrusters. The positions and/or rates of the actuators and the thruster valve on times are then captured by the AACS simulation S/W and are translated into forces and torques which then close the loop with the S/C dynamics simulation.

3.0 Ephemeris Updates

In order to determine the planetary body forces and simulate the presence of objects in the sensors field of view (FOV) during a test, the ITL simulation requires the positions and velocities of the planets and their satellites relative to the Cassini spacecraft for a given trajectory. To accomplish this end, the ITL regularly calls a program known as the Ephemeris Tool. The Ephemeris Tool is unique in that it updates the parameters of the simulation that are used to stimulate the SRU, SSA, and dynamics in the real-time system, but it resides in the near real-time ITL

AACS host computer. This is partly because the Ephemeris tool interface calls an institutionally delivered utility that uses the Spacecraft Planet Instrument C-matrix Events (SPICE) toolkit (See Figure 2).

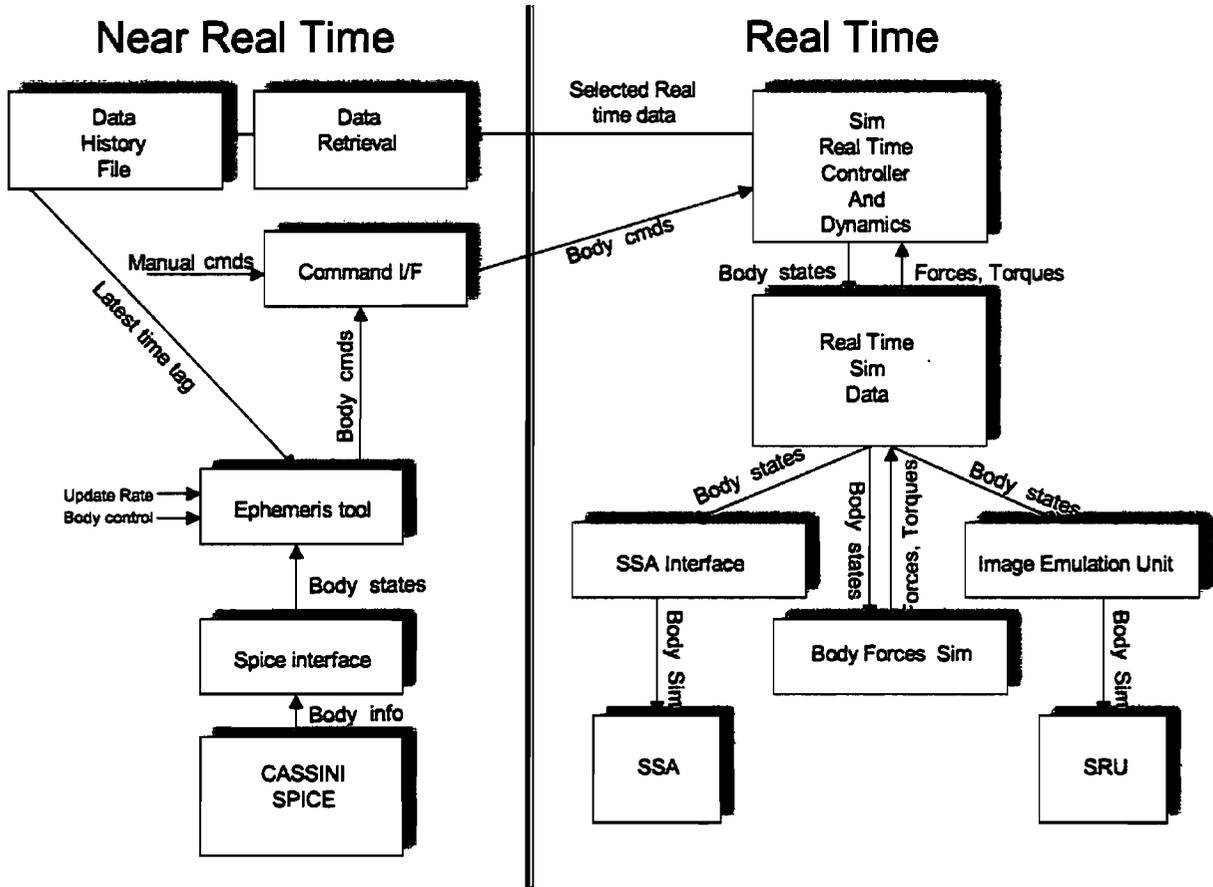


Figure 2 - SPICE driven Body Simulation

The SPICE toolkit is designed for multiplatform use, but it was more easily integrated in the near real time UNIX environment than in the VxWorks SBC real time environment. With SPICE, the Ephemeris tool determines the position and velocity of a planetary body as a function of time. This program queries a series of ephemeris files made available to the ITL that store the state of the desired planets and bodies as well as the Cassini spacecraft position for a given fixed trajectory. The SPICE data files are modified regularly using updated information supplied by the Cassini navigation, engineering, and science teams, mainly as a consequence of trajectory changes in flight and onboard clock drift. The ITL can keep track of up to 14 bodies - the Sun, Earth, Moon, Venus, Mars, Jupiter, as well as Saturn and seven of its satellites - Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Hyperion. Manually commanding of additional bodies is possible using the existing slot of a body whose simulation is not enabled. The SPICE update is performed at a user specified interval of usually every 5 seconds (except for Titan flybys). It is with this information that ITL can now calculate the position of bodies whose illumination and radiation may be detected by engineering sensors and calculate the external forces that may significantly affect the S/C pointing performance simulation in ITL.

4.0 Bright Body Simulation

The simulation of the illumination and radiation produced by bright bodies in the field of view of the engineering sensors in ITL are performed by two distinct simulations - the Sun Sensor interface and the Image Emulation Unit (IEU) interface to the Stellar Reference Unit (SRU). The Sun Sensor Assemblies (SSAs) consist of two dual channel orthogonally mounted detector heads that are located atop the High Gain Antenna (HGA) on the Cassini spacecraft and their associated electronics. Each light detector channel has a slit to allow illumination from

a bright body. The detector has a nominal Field of View of +/- 32 degrees and detects the presence, direction, and intensity of the Sun relative to the pointing direction of the High Gain Antenna. The SRU is a 2-channel redundant engineering star field tracker which uses a CCD sensor mounted orthogonally to the High Gain Antenna pointing direction to record star field images. The star tracker has an imaging field of view of 15 degrees. The star field images are sent to the AACS Flight Computer (AFC) and are processed by the AACS Flight software to determine the three-axis attitude of the spacecraft. Both the Sun Sensor Interface and the Image Emulation Unit (IEU) get Bright body updates from the SPICE program called on the ITL host computer (Figure 2).

4.1 Sun Sensor

Each channel in the Sun Sensor head contains a set of detectors overlaid with a mask pattern such that the sun angle in one axis is deterministic from the selection of cells that are illuminated by the mask after it passes through the slit. Combining the information of two orthogonally mounted heads allows 2-axis attitude determination on the spacecraft with an accuracy of 1.5 degrees¹ which provides basic thermal protection information and also facilitates the initialization of the Star Identification algorithm. The ITL uses an analog voltage interface to connect to the electronics of each of the 4 Sun Sensor channels. Illumination of a particular Sun Sensor cell is simulated in ITL by a Digital to Analog (D/A) voltage input to the associated circuitry in the Sun Sensor Electronics³. Support Equipment software simulates the effect of the Sun on the Sun Sensor detector cells by determining the relative location of the Sun in the simulation using SPICE, then calculating which cells would be illuminated using the slit and mask pattern geometry of each head. The relative intensity input to the electronics must also be simulated by calibrating the SE input with the known sensitivity of the Sun detectors in the Sun Sensor.

There are several unique factors in the Cassini tour mission that warrant adjustments to the Sun Sensor simulation. The obvious difference in Sun intensity between tour and the outer solar phases of the Cassini mission requires a different input magnitude in the Sun Sensor stimulation interface during tour. This was performed by creating a separate Sun Sensor calibration file to meet the lower expected output of the Sun detector cells in the Tour phase. Solar occultation from a bright body can occur more frequently during tour and is simulated by ramping down the simulated intensity of the Sun during a known event manually using a synchronized time-tagged command script. In addition, a modification to the SPICE interface was performed where the Sun intensity is shut off in the simulation whenever another bright body is occulting the sun. The ability to simulate the albedo of a planet in the Sun Sensor's detectors is available, but rarely used, although updated intensity values for the bodies may be a future enhancement.

4.2 Stellar Reference Unit

The Stellar Reference Unit is a precision CCD camera that provides star images digitally to the AACS Flight Software. The SRU reads any of its 1024X1024 pixels by serially shifting the captured CCD pixel information in 2 dimensions (up/down and across) to a charge sensitive FET output amplifier⁵. The resultant output (voltage) is then digitized before being sent to the AFC on a dedicated pixel bus. In practice, the AACS Flight Software selects up to five rectangular regions in the SRU CCD image for digitization and sends the selected commanded window locations and sizes to the SRU. The SRU then only digitizes those regions and sends the digitized data to the AFC. The AACS flight software in the AFC then uses the Star Tracking and Identification (SID) capability to determine the identity and position of stars from the images captured by the SRU in order to obtain an accurate update of the spacecraft's 3-axis attitude^{1,5}.

In ITL, the Image Emulation Unit simulates a star field and illuminated bodies on the SRU via a custom test interface that accepts and clocks in external pixel inputs. The IEU simulates an image in real time by capturing the "take picture" command and window information from the AFC simultaneous with the SRU, then constructing the appropriate pixel image from the simulation's knowledge of the pointing direction of the SRU FOV and its onboard celestial star body and real time body information. The IEU is able to simulate a high fidelity model of a point source as well as many relevant CCD and noise effects⁵. The IEU simulates a basic spherical body whose features usually include two constant brightness regions separated by a terminator. There is also an option to add a ring to Saturn. For the tour phase of the mission, Saturn, its rings, and seven of its satellites are simulated by default. The IEU gets the location and size of the bodies using the body commands generated by the SPICE interface program. Manual body configuration and state commands can also be sent separate from the SPICE interface program.

4.3 Bright Body Tests

Since there is a greater number of bright bodies that can potentially come near the field of view of the SRU during the tour phase of the Cassini mission, there is greater risk of misidentifying or obscuring the stars required to obtain an accurate 3-axis attitude. For tour, there was special work done to ameliorate concerns in this regard. AACS flight software regression tests were enhanced to include a number of manually simulated extended bodies of large and small dimensions while the SRU was pointed to particular regions of interest in order to stress the Star Identification and tracking capability. In addition, special rolling scenario tests were designed with simulated noise from Saturn and with the FOV full of extended bodies to simulate large blooming from a planetary body.

Early on in the AACS test program, there were AACS flight software tests designed to check the effects of a variety of star field patterns and their effects on the ability of the AACS Flight Software to estimate attitude using SID. The so-called Star Field Checkout Functional Test performed twelve thirty degree turns about three regions in the sky - the Southern galactic pole, along the galactic plane, and perpendicular to the galactic plane. As the tour phase of the Cassini mission approached, it was decided to enhance this test to include a variety of extended bodies of arbitrary size and position in the star tracker's FOV. Extended body patterns were constructed that consisted of: [1] One 6-degree body (with and without a ring), [2] three 1-degree bodies, [3] One 15-degree body in the center of field of view (only in middle of turn), [4] three 2-degree bodies, [5] three 1.5-degree bodies, and [6] four 0.5-degree bodies. Different combinations of 3 of these patterns were used during each 30 degree turn. A sample 90 degree pattern is illustrated in Figure 3. Nominal results were observed during these tests, which increased confidence of the robustness of the SID algorithm in AACS.

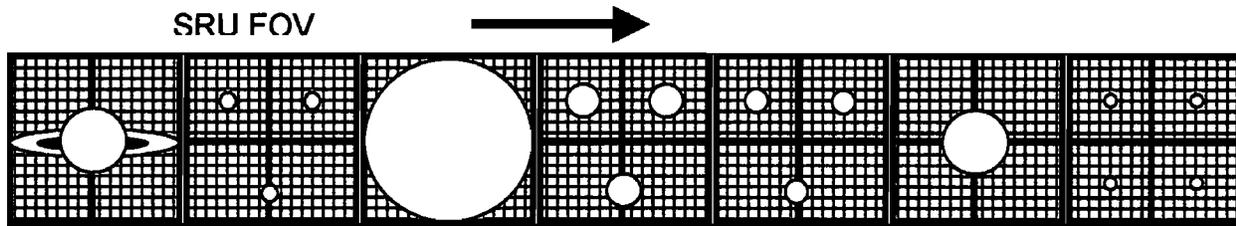


Figure 3 – Example of Extended Body pattern as viewed by the Star Tracker's FOV (not exactly to scale)

It was desired to simulate the effect of a relatively bright object with a large angular diameter, and the radiation and blooming effects of such a body as Cassini performs a common roll maneuver. Simulation software was modified to allow bodies with angular diameters larger than 22 degrees to be simulated. Testing was then performed in which multiple 50 and 22-degree bodies were overlapped to simulate the blooming illumination of a very bright body during a flyby such as Saturn or Titan (See Figure 4). Roll rates of 2.0 and 3.9 mrad/sec were tested.

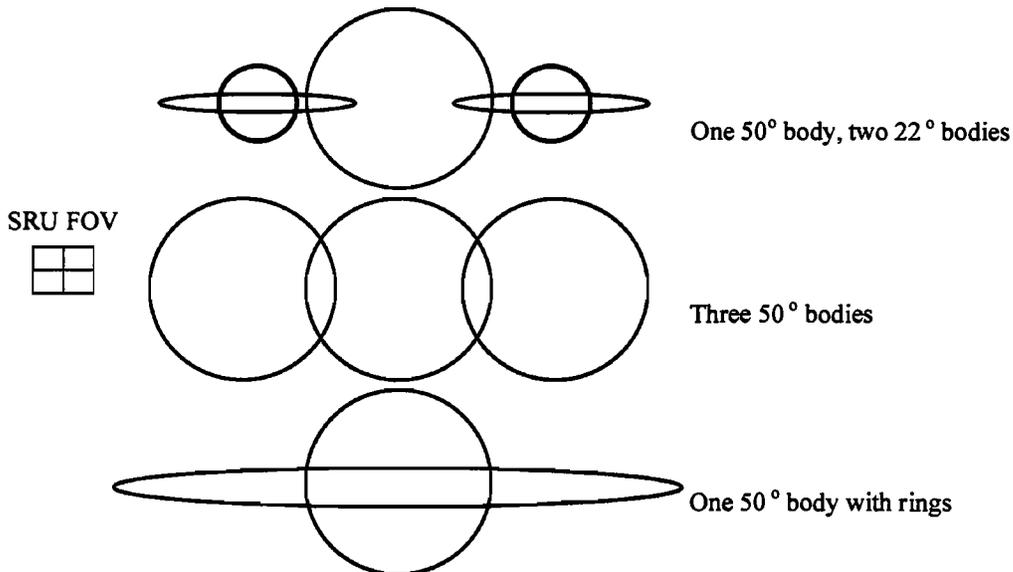


Figure 4 - Bright body patterns simulating blooming effects (not exactly to scale)

Another method of simulating the effect of stray radiation affecting the SRU imaging was to manually use the IEU's noise model that allows a commandable noise level in the CCD model with Poisson distribution. Empirically it was determined that an IEU noise command value of 4000 dn would approximate a signal to noise ratio of 0. Again roll tests at various rates were performed. The noise level was slowly ramped up to a maximum value and ramped down such that the angular swath the SRU scanned during each revolution of the roll that contained noise was 143 degrees and the maximum noise was present for 90 degrees (see Figure 5) of each 360 degree roll. The maximum noise model commands that were tested were 512 dn and 4000 dn. The star simulation was turned off while the 4000 dn noise was commanded. Roll rates of 1.3 mrad/s and 3.9 mrad/s were tested (Figure 5). Random proton hits were also simulated at 1000 hits/sec in the IEU model.

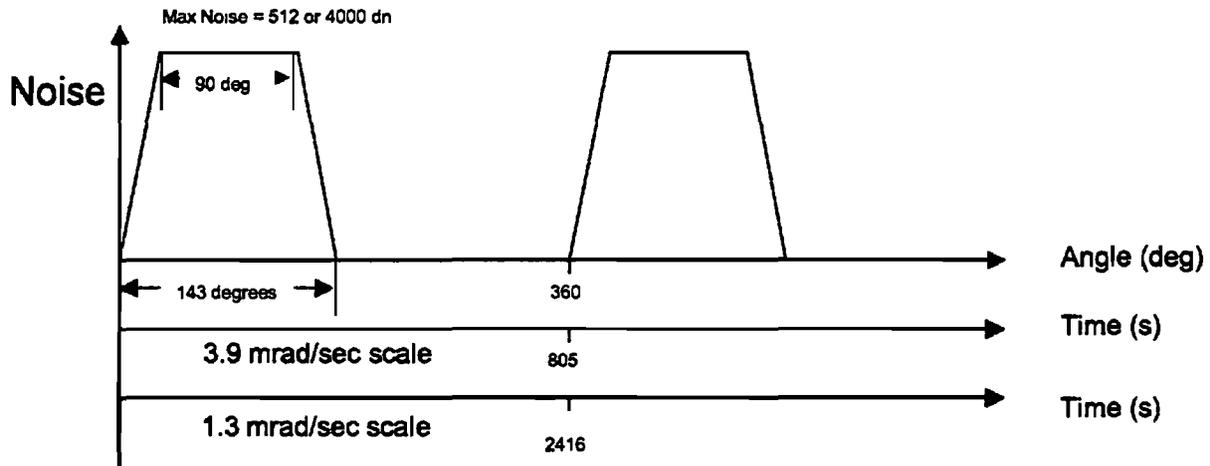


Figure 5 – Noise profiles during Z-axis rolls of 1.3 mrad/s and 3.9 mrad/s

Interestingly, the worst-case test result occurred using the 512 dn noise test, which tripped an attitude error fault when the high noise level in the SRU apparently caused a faulty attitude estimate. It was also determined that SID was on average only providing an attitude estimate half of the time during each revolution with either maximum noise level (512 dn or 4000 dn), or with bright bodies of angular diameter of 50 degrees being simulated. The blooming and noise tests were generally agreed to be conservative, but nonetheless showed that the SID does have its limits even when there are stars visible in the SRU. Through these tests and flight experience it was deemed prudent to be conservative and suspend the operation of SID¹ during roll maneuvers where bright objects can pass through the SRU's FOV.

In conclusion, the Sun Sensor and Star Tracker simulations do have their limits, but the test team has created ways of replicating stressful tour scenarios that affect the sensors. Autonomous occultation of the Sun simulation was added to the Sun Sensor simulation to help mitigate the workload on the test team in ITL, and creative use of the extended body model and the high fidelity star simulation features such as noise model and proton hit simulation was also used to supplement the extended body model in the IEU.

5.0 Titan Atmospheric Torque Model

The ITL AACS Simulation software has the capability to simulate generic external forces and torques, models the magnetic disturbances and the gravity gradient torques caused by selected bodies in the Saturnian system, and models the atmospheric torque caused by Titan's atmosphere during a low flyby of Titan. The generic forces and torques are user specified constant body-fixed torque and force vectors that the ITL uses to typically simulate a small external force on the spacecraft (such as solar radiation) that is not related to the modeled magnetic, gravitational, or atmospheric torques. The magnetic disturbance model in ITL computes simulated magnetic disturbance torques caused by Jupiter and Saturn (Saturn only is relevant during tour). The magnetic disturbance torques are based on the spherical harmonic models and are updated every time the body position changes relative

to the spacecraft after an update from SPICE. The gravitational disturbances are due to the unbalanced geometry of the spacecraft and the proximity to the bodies in the Saturnian system. The ITL software simulates gravity gradient torques generated by Saturn, Mimas, Enceladus, Tethys, Dione, Rhea, Titan, and Hyperion. During planned close flybys of Titan (less than 3000 km altitude), the atmospheric drag effects impart significant external torques on the spacecraft. These torques are a function of orientation of the spacecraft with respect to the direction of the relative flow, the altitude, and the velocity of Cassini relative to Titan. The most significant impact of all of the external torques is from Titan's atmospheric drag. One year before the start of the Cassini Tour mission it became clear a major modification to the ITL Titan flyby simulation was required.

5.1 Torque Generated by Titan's Atmosphere and Imparted on the Spacecraft

Titan's atmosphere imparts a torque on the Cassini spacecraft as it flies through its atmosphere. In general the aerodynamic drag torque on a body is²

$$\vec{T}_{aero} = \vec{l} \times \vec{F}_d \quad (1)$$

where:

$$\begin{aligned} \vec{l} &= \text{Moment arm of drag force relative to spacecraft cm} \\ \vec{F}_d &= \text{Drag force on the Cassini spacecraft caused by Titan's atmosphere} \end{aligned}$$

The moment arm of the Drag Force is expressed using the spacecraft center of pressure, cp , and the center of mass, cm :

$$\vec{l} = (\vec{cp} - \vec{cm}) \quad (2)$$

If the standard drag equation is applied, then \vec{F}_d the drag force on the spacecraft is⁷

$$\vec{F}_d = C_d \frac{1}{2} \rho V^2 A \hat{u} \quad (3)$$

where:

$$\begin{aligned} C_d &= \text{Drag coefficient} \\ \rho &= \text{Density of the Titan atmosphere} \\ V &= \text{Titan S/C-relative flyby velocity} \\ A &= \text{Reference area} \\ \hat{u} &= \text{Unit direction of Titan's atmospheric flow relative to S/C} \end{aligned}$$

Substituting for Moment arm and Drag:

$$\vec{T}_{aero} = (\vec{cp} - \vec{cm}) \times (\hat{u}) \left(C_d \frac{1}{2} \rho V^2 A \right) \quad (4)$$

Of the variables in Equation (4), only the spacecraft center of mass, cm , and Titan's velocity relative to the S/C, V , were available in ITL without any modifications to the simulation software. The SPICE program interrogation in ITL provides the S/C relative Titan velocity and the dynamics simulation retains the S/C center of mass information. Work within JPL resulted in a determination of 2.1 for the S/C drag coefficient². Models for the Titan atmospheric density, center of pressure, and the reference area were still needed.

5.2 Titan Atmospheric Density Model

An atmospheric model developed by Yelle et al⁹ provided a relatively simple formula which approximates the density of Titan's atmosphere as a function of altitude for the lower Titan flyby altitudes (800 km to 3000 km)⁹ in

the Cassini mission. In that formula, density, ρ (in kg/m^3), is a function of altitude from Titan, z (in km), and stratospheric temperature, T (in Kelvin):

$$\rho(z) = 6.35 \times 10^{-6} e^{-\frac{11400(z-76)}{T(z+2575)}} + 5.13 \times 10^{-7} e^{-\frac{8030(z+429)}{T(z+2575)}} + 7.35 \times 10^{-5} e^{-\frac{15000(z-44)}{T(z+2575)}} \quad (5)$$

The stratospheric temperature in this model is: $T = 175 + 10\gamma$. Here, γ is a parameter that the ITL test team can change to simulate increase or decrease in the Titan atmospheric density. This model was used for atmospheric density in ITL from mid-2003 until 2005 and later slightly adjusted to reduce curve fit errors at lower altitudes using inputs obtained from the Cassini spacecraft operations AACs team.

5.3 ITL Area Model

Early work done to estimate the reference area of the S/C to Titan's atmosphere involved approximations using projected area measurements performed on only one side of the S/C mechanical model. In 2005 further area measurements were taken about the whole S/C model. Projected area and center of pressure measurements were tabularized across the spacecraft in azimuth and elevation and delivered to the Cassini Operations team in 2005. This was used to update Titan atmospheric drag models across several test beds including the ITL. The ITL Titan atmospheric drag model was enhanced by making use of the updated projected area and center of pressure information. The atmospheric data and moment arm information were modified accordingly.

The tabularized data contained projected area and center of pressure (Figure 6) as a function of azimuth and Z-to-flow angle. Azimuth is defined as the angle between the Cassini X-axis and the projection of the atmospheric flow direction on the spacecraft X-Y plane. The so-called Z-to-flow angle is that angle measured from the Z-axis to the velocity vector of the atmospheric flow. The center of pressure is measured from a coordinate system whose horizontal and vertical axes form a plane perpendicular to the flow direction as shown in Figure 6. Data (total and centroidal) was taken at combinations of 13 Z-to-flow angles and 25 azimuth angles. ITL's implementation of the tables included creating three 2-dimensional files and two 1-dimensional files. The three 2-dimensional files are for projected area, center of pressure horizontal (cph), and center of pressure vertical (cpv). The two 1-dimensional files define the Z-to-flow and azimuth angles that are used in the area data rows and columns respectively. The files are read at initialization of the simulation but can also be read and modified during run time.

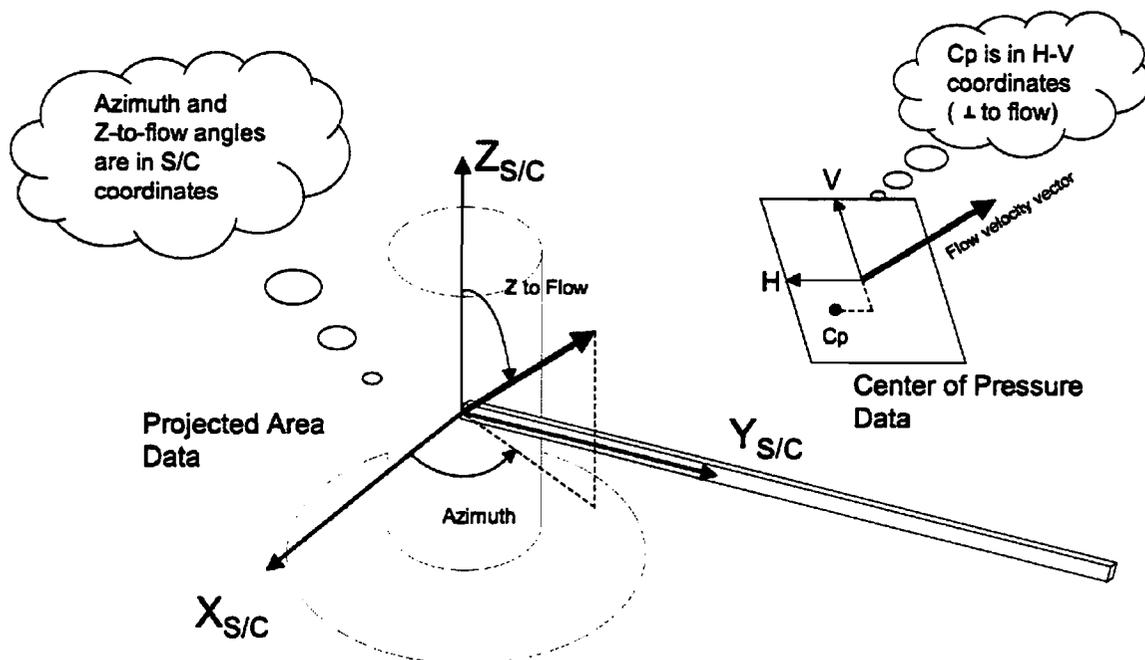


Figure 6 – S/C Area data coordinate systems (Projected Area, and Center of Pressure)

5.4 Titan Flyby Testing

While still developing the ITL Titan flyby drag model, it became clear that the lower flyby altitude and densities were not being simulated correctly due to an oversubscribed ITL AACS host computer delaying the Titan ephemeris updates from the ITL Ephemeris Tool. This delay was eliminated by simply reducing the amount of real time simulation telemetry data that was being sent to the ITL AACS host during Titan flybys. As a consequence of using the ITL AACS host to provide Titan ephemeris updates, however, the Titan velocity and position provided to the model are updated at the most often every 1 or 2 seconds. This is deemed an acceptable fidelity for the flyby scenarios. Moreover, in ITL it is common to adjust the atmospheric density (using the Gaussian variable in stratospheric temperature) to a higher than nominal value during a Titan flyby simulation with the corresponding higher atmospheric torques on the spacecraft. This provides a greater degree of confidence that the engineering pointing requirements can be met once performed in flight.

The first implementation of the more advanced Titan atmospheric torque model was performed outside of ITL. The AACS Team's Titan atmospheric drag torque model was compared with flight data⁷ (once available) using the Flight Software Development Station (FSDS)⁸. Several studies were performed using FSDS to compare the fidelity of the Titan Atmospheric Torque model with good results⁷. Figure 7 shows an example in which the FSDS simulation of a Titan Flyby is compared with flight data.

Approach [1]: Actual vs. Estimated Z-axis Torque (n=2)

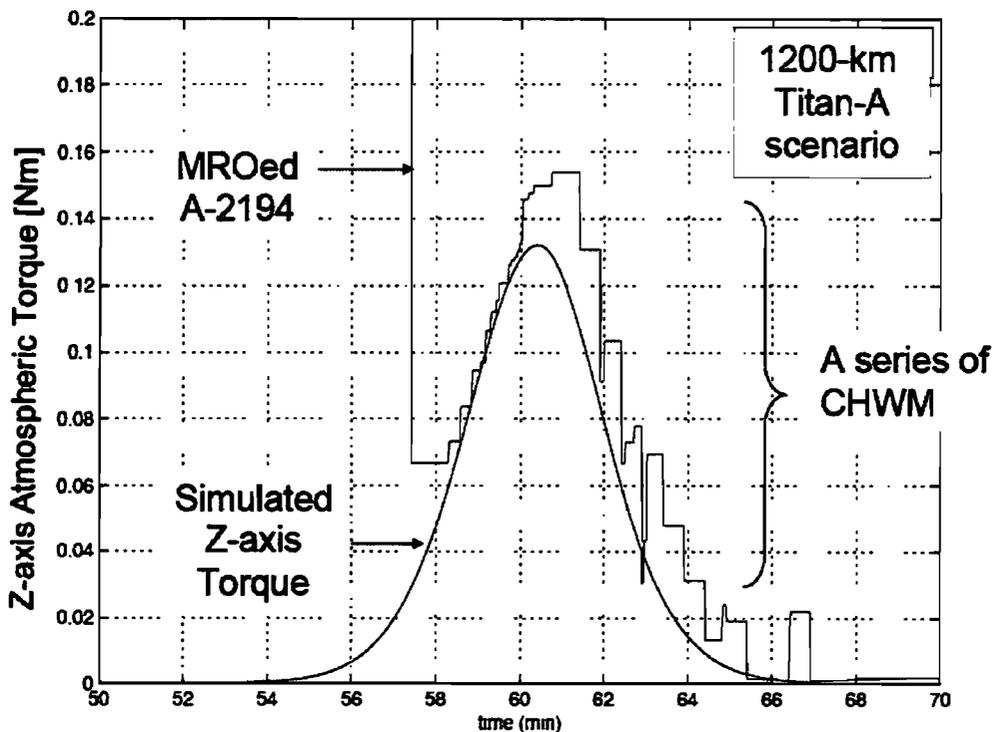


Figure 7 - FSDS Model vs. flight data (Taken from Reference 7)

During implementation of the latest Titan atmospheric torque model in ITL, comparative tests were performed against the FSDS test scenario results. That way more data could be compared and the atmospheric density model modifications could be tested as well. Overall the agreement with FSDS was good (Examples are given in Figures 8 - 10). Slight variations were noted in some tests due to center of mass differences between the models that have not been resolved. These variations are a consequence of the underlying mass property simulation differences between the two test beds and not the Titan atmospheric drag model.

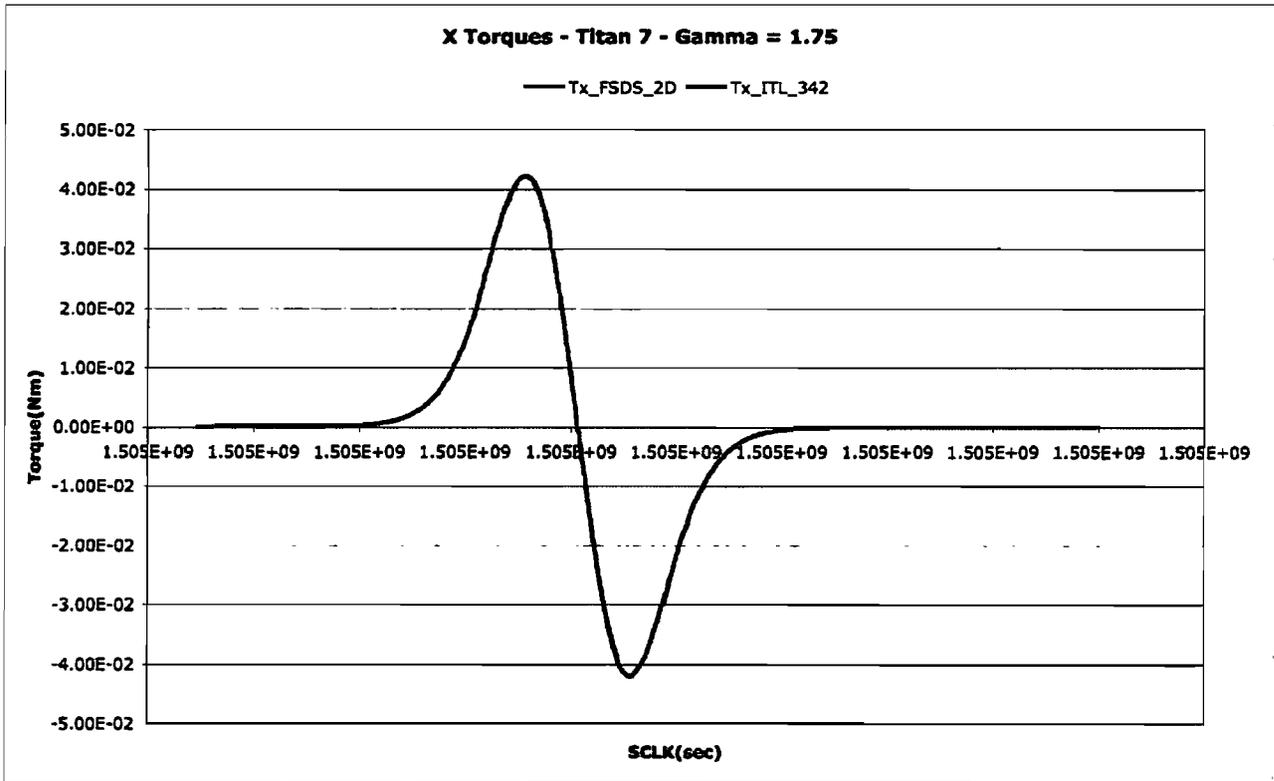


Figure 8 – FSDS vs. ITL comparison: X Torque

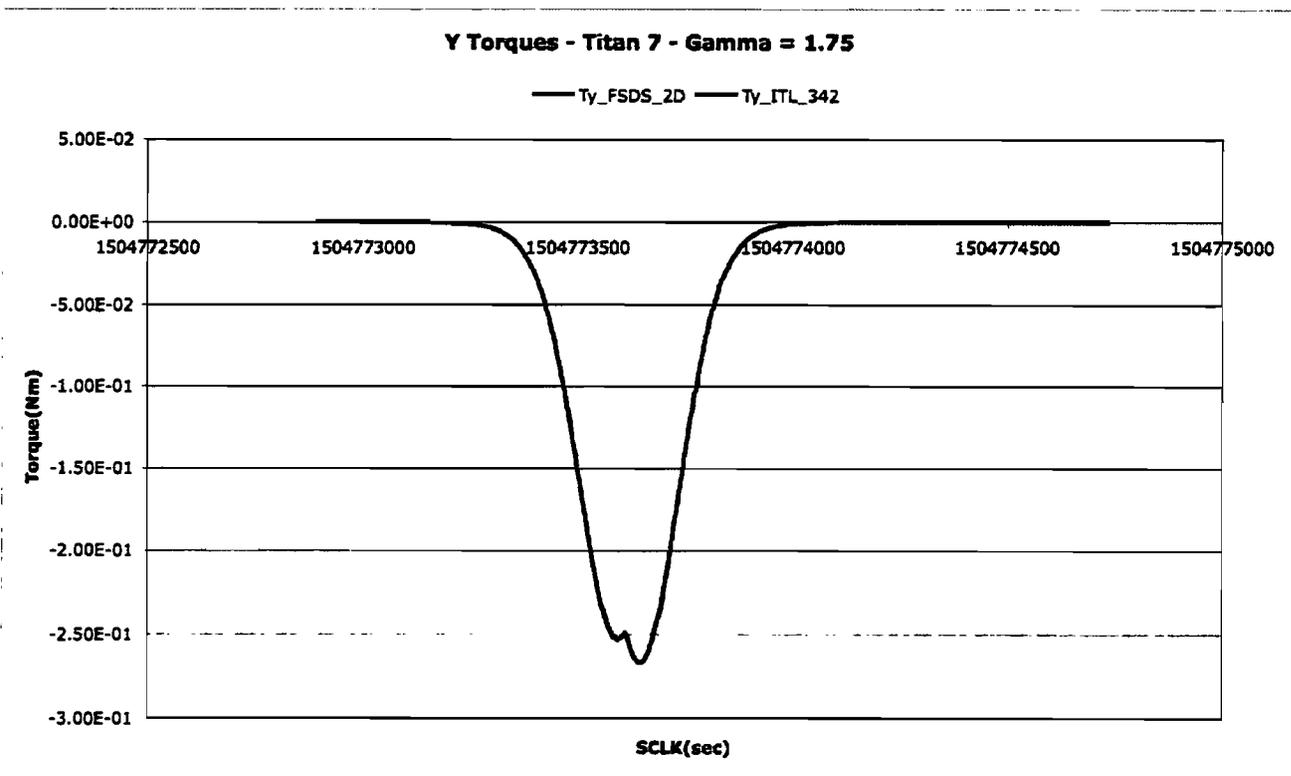


Figure 9 – FSDS vs. ITL comparison: Y Torque

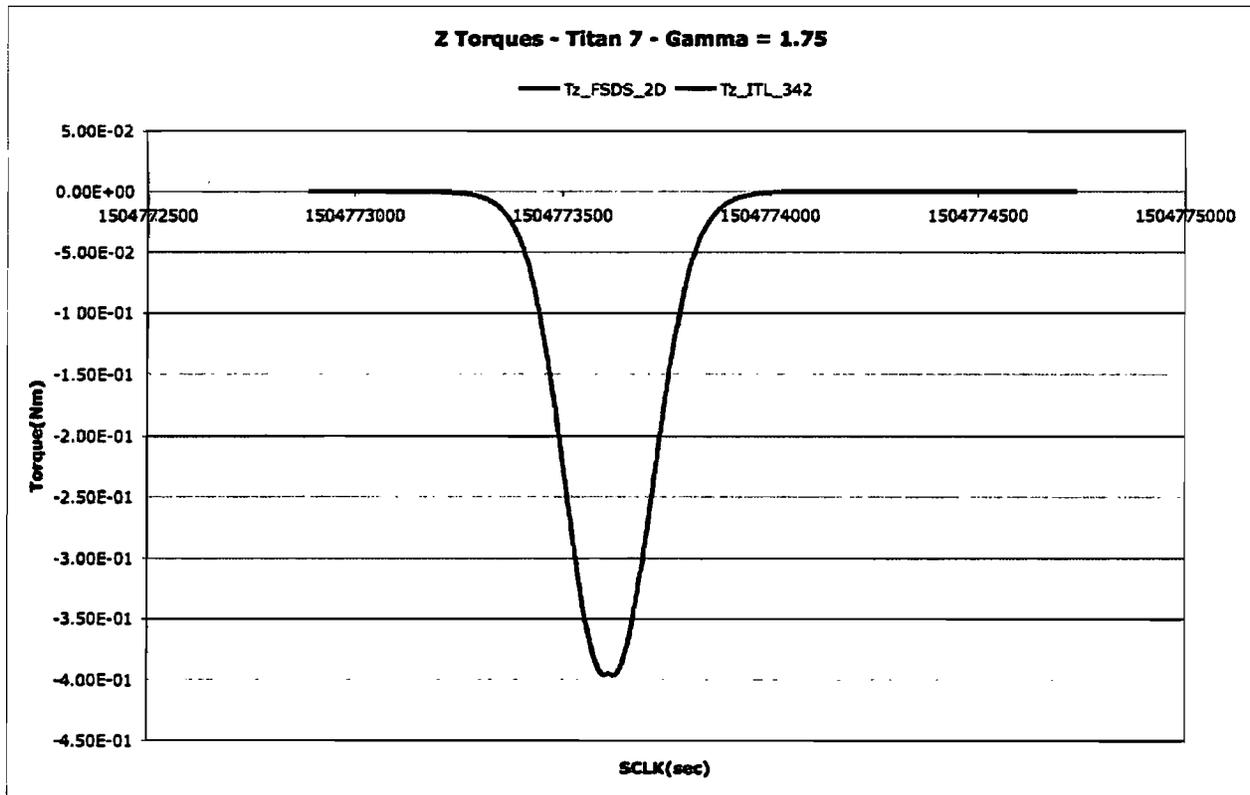


Figure 10 – FSDS vs. ITL comparison: Z torque

Sequence testing was done with the new Titan atmospheric drag model in ITL starting with Titan 16. In some lower altitude testing in ITL, atmospheric densities were used that purposely exceeded the control authority of the S/C in order to check the ability of the S/C to recover from such scenarios. For more nominal command sequence validation tests prior to execution on the S/C, slightly higher atmospheric density settings are typically used in ITL than are expected in flight. For example, in the 950 km Titan 16 flyby, the ITL used conservative stratospheric temperature settings of 196.3 K and 194 K (using γ settings of 2.13 and 1.93). These correspond to peak atmospheric densities of $40\text{E-}10 \text{ kg/m}^3$ and $34\text{E-}10 \text{ kg/m}^3$ respectively. No problems with control authority were found in these tests. Reconstruction of the flight data after the event was performed by the operations team⁷ and the actual maximum density was estimated to be $24\text{E-}10 \text{ kg/m}^3$ during Titan 16.

After Titan 16, a test was run in ITL with the peak atmospheric density closely matched to the flight estimated value for that flyby. This was accomplished by adjusting the γ setting in the ITL Titan flyby atmospheric drag model such that the density at 950 km (altitude at Titan 16 closest approach) was approximately $24\text{E-}10 \text{ kg/m}^3$. It was determined that a γ setting of 1.613 (using the corrected version of the formula) would correspond to this density value. The Z-axis torque during this last Titan 16 flyby test in ITL compared well with the actual Titan 16 Z-axis torque estimated from flight data by the AACS operations team (Figures 11 and 12).

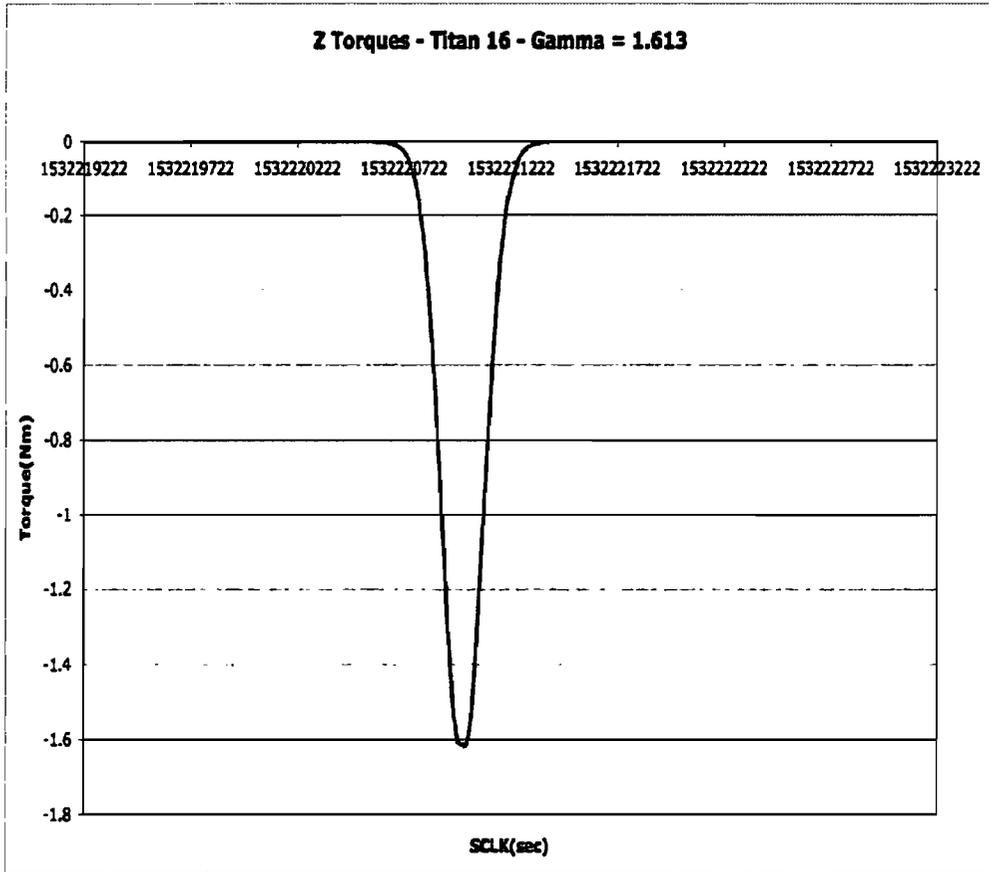


Figure 11 – ITL Titan 16 Test, Z Torque

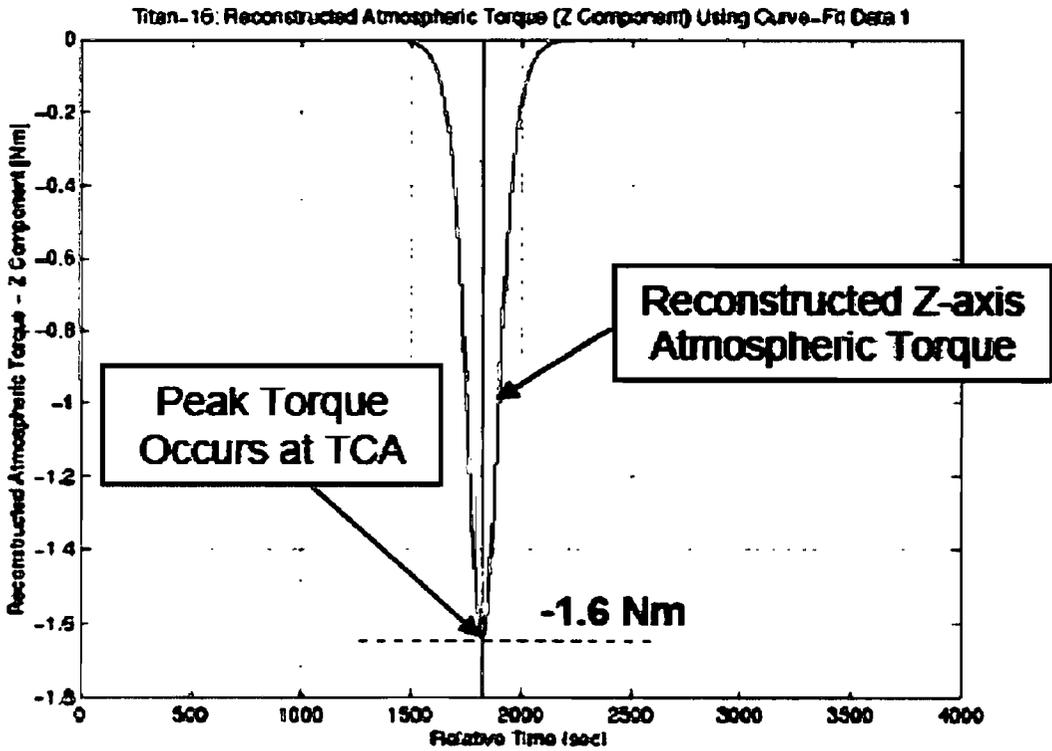


Figure 12 – Flight Titan 16 Z Torque estimate (excerpt from internal JPL memo by Sarani, S.)

6.0 Conclusion

Adequate simulations of the Saturnian environment in ITL have presented some challenges that were not anticipated in the original design of the AACCS Support Equipment. The delivered Image Emulation Unit had a very sophisticated star field and CCD emulator, but the more basic extended body simulation was augmented to roughly simulate planetary optical influences that were more stressful to the sensors but nonetheless commonplace during tour. Some basic simulation capabilities were supplemented with the creative use of the basic extended body and sophisticated CCD noise simulation to roughly approximate bright body blooming and radiation effects on the Stellar Reference Unit to assist in formulating flight operation rules during tour. Similarly, the external force simulation was enhanced to include the atmospheric force and torque model for Titan. The Titan atmospheric drag model was improved as more refined computations became available for both the estimated projected area of the spacecraft and the atmospheric density of Titan. With these models and creative testing methods to supplement the simulation, the ITL is able to provide the needed verification and validation tool for command sequence and software testing during the remainder of the Saturnian tour

Acknowledgements

We would like to thank Jay Brown, Daniel Cervantes, Allan Y. Lee, Sam Sarani, and Eric Wang, our colleagues at JPL for their support. The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with National Aeronautics and Space Administration.

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