Integration of Spacecraft Telemetry into Navigation Operations for the Cassini-Huygens Mission

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The Cassini orbiter is the largest and most complex interplanetary spacecraft ever built. Since attaining orbit around Saturn in the summer of 2004, Cassini, along with its Huygens probe, have been continually improving our understanding Saturn, its satellites, its enigmatic rings system, and of the solar system. One of the hallmarks of the Cassini-Huygens Project is the close working relationship between the many teams required to operate such a sophisticated spacecraft. Their ingenuity has enabled them to find new and different ways to improve their processes during Cassini's prime 4-year orbital tour. This paper will discuss the relationship between Cassini's Navigation and Spacecraft Teams and the work required to properly configure Cassini's telemetry system for Navigation. A detailed explanation of how the Navigation Team utilizes spacecraft telemetry and analysis demonstrating the benefits will also be provided. Finally, telemetry requirements for Navigation for future missions will be addressed.

I. Introduction

Since the summer of 2004, the Cassini spacecraft orbiting Saturn has been working around the clock collecting historic science data and returning it to Earth. The science results have been well documented in papers, journals, mass media, and websites. What is not as extensively documented is the creativity and adaptability of the Cassini Project flight team members to continually improve the manner in which they operate the spacecraft.

There are many teams within a project such as Cassini, each with respective responsibilities vital to the success of the mission, and each who must forge close working relationships. This paper will discuss in particular the relationship between the navigation team & the spacecraft operations team, especially the Attitude & Articulation Control Subsystem (AACS), and how continual collaboration between the two teams dramatically improved the spacecraft's performance and the process in which the spacecraft is flown. Much of the joint effort between the two teams has been spent addressing AACS's growing concern for the health and safety of the Reaction Wheel Assembly (RWA).

A major source of the improvement for Navigation operations was from an extensive reconfiguration of the AACS telemetry. Examples of how the Navigation team makes the most of the AACS telemetry and its advantages will be presented. Finally, based on the experience gained from Cassini, requirements of how to configure telemetry in order to better serve Navigation's needs for future missions will be offered.

II. Cassini-Huygens Mission & Navigation Background

Cassini-Huygens, a joint mission between the United States National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI), was launched on 15 October 1997 on a Titan-IVB. After a seven-year interplanetary journey, the spacecraft successfully achieved orbit around Saturn on 30 June 2004. The project released ESA's Huygens probe on 25 December 2004, and on 14 January 2005, Huygens penetrated the thick atmosphere of Saturn's largest moon, Titan, sending unprecedented science data through the Cassini orbiter back to Earth.

Following the achievement of Huygens, Cassini embarked on its remaining 3.5 year, 70-orbit Saturnian tour to study the composition, structure and dynamical processes of Saturn's atmosphere, magnetosphere, rings, and satellites. It is believed that the complex dynamic processes that formed the Saturnian system are similar to those that created our solar system. In addition, it is also believed that Titan holds fundamental clues to the evolution of life on Earth. Scientists have referred to Titan as "a young Earth in a deep-freeze." The rich organic chemistry on Titan's surface is much like what scientists think existed on Earth before life developed. Also, Titan's atmosphere, a dense yellow smog made up of nitrogen and methane, is much like that of Earth in her primordial days.

Saturn's other satellites are also of great interest to Cassini scientists. They vary drastically in shape, size, age, and origin. Many show the cratered scars from billions of years of heavy bombardment, while others appear to be smooth by comparison and are believed much younger. Some show evidence of tectonic activity and one moon in particular has been revealed to be geologically active. Enceladus captured the imagination of the Cassini project, and the world, when it was discovered that Enceladus is the fourth geologically active body in the solar system, and the second body to have water geysers. This fascination has directed the mission to utilize about 20% of the targeted flybys to study Enceladus further in the 2-year extended mission (compared to about 6% during the 4-year prime mission).

The Navigation Team's role with the project can be broken down into three areas: 1) trajectory design; 2) orbit determination (with optical navigation); and 3) maneuver design. These three elements work together to ensure that Cassini achieves its science objectives.

Trajectory design establishes the orbital tour of the Saturnian system. The tour includes the sequence of targeted flybys and orbital geometries to meet the diverse set of science objectives. Orbit determination (OD), amongst other things, estimates the current state of the spacecraft using radiometric data and predicts how well the spacecraft is charting along the designed reference trajectory. In addition, optical navigation is utilized in the OD process in order to improve the ephemerides of the major Saturnian satellites, and thus improve the knowledge of the spacecraft's relationship to the satellites. Given the reference trajectory and the estimated spacecraft state from OD, the maneuver design team determines the required change in velocity (ΔV) in order to correct any trajectory deviations and return the spacecraft back on its proper course. Further details of these elements can be found in Buffington, et al[1], Antreasian, et al[2], and Williams, et al[3].

Cassini's trajectory design includes 53 targeted flyby encounters of Saturn's largest moons, most of which are low altitude flybys of Titan (950-1300 km), along with a handful of higher altitude Titan flybys and icy satellite flybys (50-11000 km). Even though the time between targeted flybys is as little as 16 days and as much as 48, science is collected and played back nearly every day between flybys. This poses additional challenges to balancing the overall science objectives with spacecraft operations, especially scheduling activities required to maintain health and safety of critical spacecraft hardware, and minimizing the impact of these activities on navigation operations.

III. Relationship between Spacecraft Engineering & Navigation

A. Orbit Trim Maneuvers

A close relationship between spacecraft operations and navigation exists within every deep space mission. At the most basic level for the Cassini-Huygens Project, the Navigation Office (Nav) schedules opportunities for three Orbit Trim Maneuvers (OTMs) between targeted encounters, and it is the responsibility of the Spacecraft Office (SCO) to execute any OTMs deemed necessary by Nav.

These three OTMs are broken down as follows (see Figure 1 for illustration[3]):

a) "Cleanup-OTM" is typically about three days after the targeted encounter (may be longer if there are multiple orbits between flybys). This maneuver is used to correct any spacecraft trajectory prediction errors from the previous satellite flyby due to mis-modeling. This OTM may also have a deterministic component to it as a part of a two-maneuver optimization strategy for the next targeted encounter.

b) "Apoapsis-OTM" is used to shape the spacecraft trajectory properly in order to achieve the desired conditions for the upcoming flyby. This maneuver can have a significant deterministic component and may be designed in conjunction with the cleanup-OTM in order to optimize propellant usage.

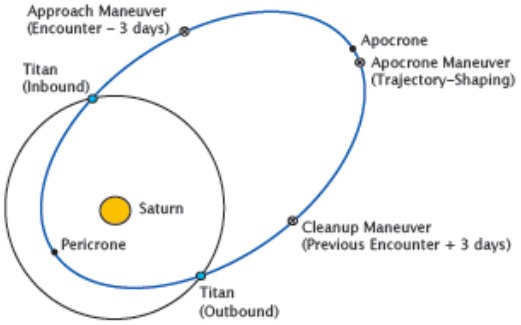

Figure 1. Cassini OTM Strategy

c) "Approach-OTM" is typically about three days before the targeted encounter. This maneuver serves as the last control point to realign the spacecraft trajectory to the desired flyby conditions. The spacecraft may have deviated from its intended trajectory due to errors from the previous OTM, as well as any prediction errors from small force events since the last OTM, and orbit determination dispersions. This OTM is a purely statistical maneuver (i.e., there is no deterministic component). Given the purely statistical nature of the approach-OTM, this maneuver has the greatest likelihood of being canceled of the three.

SCO is able to perform the OTMs with either the 445-N bipropellant Main Engine (ME) or the 0.9-N monopropellant Reaction Control System (RCS) thrusters that are aligned along the z-axis of the spacecraft (see Figure 2). The only use of the ME is for trajectory control. However the RCS thrusters aligned with the y and z-axes are also used for other science and engineering activities. Therefore, in an effort to minimize the use of monopropellant, OTMs greater than about 0.3 m/s are performed using the ME.

All OTMs execute in the following similar manner. First the spacecraft rolls about the z-axis, keeping its fixed High Gain Antenna (HGA) pointed at Earth, to an intermediate attitude. This is followed by a yaw turn about the y-axis, away from Earth-point, to the final burn attitude. This two-turn method ensures that no thermal constraints are violated. Once the two "wind turns" are complete, the engine of choice performs the main burn. After the burn is completed, the spacecraft "unwinds" the yaw turn followed by "unwinding" the roll turn, returning the spacecraft to its original Earth-pointed attitude.[4] Even though all OTMs fit into this basic pattern, there are some differences between ME and RCS OTMs that have an impact on Nav.

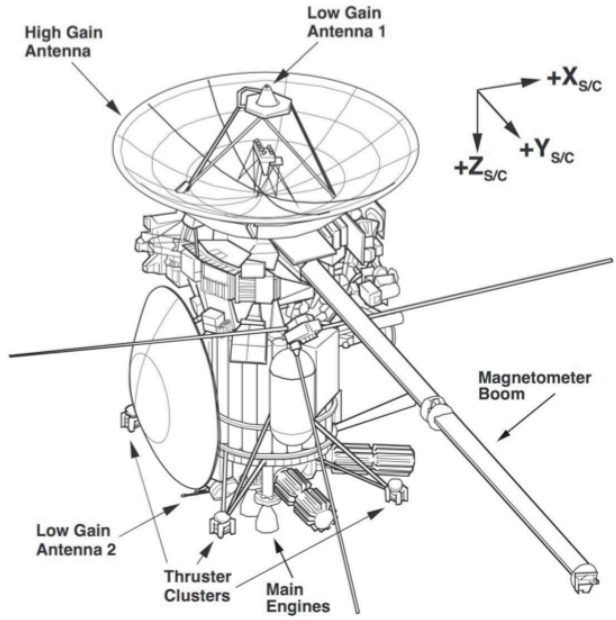

Figure 2. Cassini-Huygens Spacecraft

For OTMs requiring the ME, the RWAs must be powered off during the firing of the ME. So after the roll turn to the intermediate Earth-pointed attitude, the RWAs are spun down, causing disturbance torques on the spacecraft. As the disturbance torque perturbs the spacecraft attitude, the RCS thrusters fire to keep the HGA pointed at Earth. Not all of Cassini's eight RCS thrusters are balanced when they are fired. To control the spacecraft's attitude about the z-axis, the four thrusters along the y-axis fire as coupled pairs, thus imparting nearly no ΔV on the spacecraft. However, the four thrusters along the z-axis, which are used to maintain the spacecraft's attitude along the x & y axes during the RWA spin-down, are uncoupled. As a result, the z-thruster firings do impart a small ΔV.

After the RWAs are turned off, the uncoupled z-axis thrusters are then used to perform the y-axis yaw turn to the final burn attitude. As this slews the spacecraft away from Earth, Nav has no visibility into this small ΔV. While at the final burn attitude, an unbalanced 0.9° offset turn is induced to correct for a mounting misalignment of the ME gimbal actuators.[5] The offset ensures that the burn vector will be properly aligned in the direction specified by Navigation's maneuver design.

Following a ME burn cutoff by the AACS accelerometer, each turn is unwound in reverse order using the un-balanced z-axis thrusters, beginning with the 0.9° offset and then the yaw turn. All of these small ΔVs from using the un-balanced z-axis thrusters to turn have an impact on the spacecraft trajectory and need to be into account during the maneuver design process. After the unwind yaw turn has completed and tracking of the spacecraft has been re-established, the RWAs are turned on and spun up to some intermediate rate, again imparting a small ΔV. After this, attitude control is transferred from the RCS back to the RWA, and the unwind roll turn places the spacecraft and the RWA rates at their desired end state as determined by AACS.[4]

OTMs executed using the RCS thrusters operate a little differently. The RWAs are not required to be powered off during the firing of the RCS. Therefore, the roll and yaw turns necessary to place the spacecraft at the burn attitude are done using the RWA (no 0.9° offset turn is required for the RCS). Only the RCS thrusters along the z-axis are fired and the entire ΔV that takes place is at the burn attitude and there are no other small force ΔV events necessary. Most of the time, during the same tracking pass, AACS will also execute an RWA bias (RWA biases will be discussed in the next section). The RWA bias executes while the spacecraft is at Earth-point.

B. RWA Biases

Outside of these OTMs planned during the seven-year interplanetary cruise, AACS occasionally requires additional health and safety events for the Reaction Wheel Assembly. These activities also result in imparting a

"small force" ΔV on the spacecraft from the RCS thrusters. They include "RWA Momentum Biases" and "RWA Friction Tests" performed by AACS.

For many other spacecraft, periodic RWA momentum unloads are required because external torques cause the RWA to accumulate momentum over time. However, that is hardly the case with Cassini. While it is true that Cassini is a 3-axis stabilized spacecraft and uses its RWA to maintain attitude control, external torques for sources such as solar radiation pressure and thermal radiation pressure from the radioisotope thermoelectric generators have a very small effect on the spacecraft. Therefore there is no need to simply dump momentum. Rather, Cassini manages its RWAs in a different manner.

Since Cassini has no scan platform, all of its remote sensing science instruments are attached to the spacecraft frame. As a result, the RWAs must be used frequently in order to slew the spacecraft from one science attitude to the next. These slews place a heavy toll on RWA usage and AACS must continually manage the RWA in order to optimize their performance and protect the hardware. The primary method of management employed is to bias the RWAs to a set of initial rates as selected by optimization software. Also, the science pointing profile is scrutinized in order to determine how often the RWAs need to be re-biased.

During RWA biasing activities, the spacecraft transitions to thruster control. As the RWAs are spun up to attain their set of pre-selected spin rates, the RCS thrusters fire in order to maintain the spacecraft attitude that has been perturbed by the disturbance torques from the RWA. Depending on which axis of the spacecraft attitude is exceeding the deadband limit, either a pair of coupled y-thrusters fire or the uncoupled z-thrusters fire. Recall the coupled thrusters do not impart a ΔV, whereas the uncoupled thrusters do.

RWA bias activities typically occur while the spacecraft is Earth-pointed and has radiometric tracking. However, recently increased concern over the RWA health and safety has caused AACS to explore executing biases while there is no ground visibility. In the past, the Navigation Office would have had a greater issue with performing "biases in the blind" as it would decrease the precision of the OD solutions and increase the uncertainty. But due to the positive results from the use of spacecraft telemetry in Navigation processing, concerns over the impact of "blind biases" on the OD solution have decreased. This will be discussed in greater detail later in the paper.

C. RWA Friction Tests

AACS performs RWA biases in order to maintain RWA health. In order to monitor the health of the RWAs, AACS performs friction tests. In these tests, the RWA are spun to a specified spin rate and then they are simply allowed to coast down to 0 rpm. Given the orientation of the RWAs on the spacecraft, if they coasted down at precisely the same rate, then the spacecraft attitude would not be perturbed and thus no z-thruster firing would occur. However, since they are coasting down at different rates, then the spacecraft attitude is disturbed and the z-facing thrusters fire causing ΔV.

At the start of the orbital tour in 2004, these RWA friction tests occurred two to three times annually. As concern for the health of the RWAs increased, not only have the number of RWA biases increased, but it was also requested to double the frequency of the RWA friction tests. The increased number of RWA biases and RWA friction tests brought on a set of scheduling challenges for the Navigation team.

The dramatic increase of the number of RWA friction tests required a significant integration strategy between the Nav and SCO. Given the short timelines between target satellite encounters and the OTMs associated with them, guidelines were established to properly place these new RWA friction tests.

Given the decreased ability to accurately predict the amount of ΔV from the friction tests, they were placed between cleanup-OTMs and apoapsis-OTMs. This was done in order to maximize the possibility of cancellation of the approach-OTM. Tracking requirements between these two OTMs also limited the opportunities to execute the friction tests. The rationale for the tracking requirements is to be able to gain sufficient radiometric data to resolve the OTMs and the RWA friction tests. And finally, since Cassini is ostensibly a science mission, these additional engineering activities needed to be placed in such a manner that minimized their impact on science collection.

Since RWA biases are required to maintain the health and safety of the RWA, looser considerations are made compared to the RWA friction tests, which monitor the RWA health and safety. Namely, RWA biases are permitted to execute between apoapsis-OTMs and approach-OTMs. In general, ΔV predictions for RWA biases can be determined fairly accurately, within 10%. Also, since the ΔV from RWA biases are significantly smaller than the RWA friction tests, the tracking requirements for the RWA biases are more relaxed. And finally, since the Cassini science community recognized that maintaining the continued good health of the RWAs is vital to their ability to collect science data into the extended mission, they have also been willing to accept more impact on their data collection.

D. Science Related Events

Besides OTMs and other AACS-related activities, there are science-related events where AACS operations affect navigation. Low altitude Titan flybys are especially challenging to spacecraft operations due to the impact of atmospheric torques on the spacecraft. In order to protect the spacecraft from tumbling, AACS transfers attitude control of the spacecraft from the RWA to the RCS because the RCS has more control authority to counteract the atmospheric torque. The momentum is unloaded from the RWA before the spacecraft encounters Titan's atmosphere and, once Cassini is safely out of the atmosphere and in no danger of tumbling, the RWAs are initialized to a new set of biased spin rates and attitude control is transfer back to the RWA. All of the uncoupled thruster firings under RCS control during these low altitude Titan flybys result in ΔV on the spacecraft. This has an impact on the OD solution, which will be discussed in part C of the "Utilization" section of this paper.

Since the start of the orbital tour, one instrument, the Radio and Plasma Wave Science (RPWS) instrument, has noticed increasing interference from the operation of the RWAs. Early in the mission, the RWAs did not affect the electric field channels of the RPWS. But, at present, they represent a noise source a factor of 1000 above the electric field sensitivity threshold of their channels at frequencies below about 2 kHz.[*] As a result, they made a request that, at locations for high priority science, the RWAs be turned off while their data is being collected. In order to accomplish this, AACS must again transfer attitude control from the RWA to the RCS. However, unlike the periods of low altitude Titan encounters where the RCS slews the spacecraft and maintains attitude in the presence of drag torques, the RCS in this activity is only required to preserve an Earth-pointed attitude for a few hours.[6] This results in an order of magnitude less ΔV than in the case of the Titan-targeted flybys.

E. Configuration of Cassini Telemetry to Better Suit Navigation

Prior to Cassini-Huygens entering orbit around Saturn on 30 June 2004, spacecraft telemetry was exclusively used to characterize and calibrate the behavior of spacecraft hardware, monitor the performance and health of spacecraft hardware and software, and diagnose spacecraft anomalies as they occurred. Of course, once the orbital tour began, spacecraft telemetry was still used in a similar manner as before. But as Cassini engaged in its campaign flying into Titan's atmosphere, spacecraft telemetry, particularly AACS telemetry, was occasionally reconfigured in order to determine the atmospheric density[7,8].

AACS changed the precision of the ΔV telemetry in order to better assess the performance of the spacecraft during OTMs and other small force ΔV activities. Originally, AACS set the ΔV telemetry to report 2-mm/s per telemetry unit. This was so that AACS could observe how much ΔV the ME generated during maneuvers without risk of overflowing the telemetry counter. The respective telemetry channels in EME2000 coordinates would peg at 1000 m/s with a resolution of 2-mm/s per telemetry unit. The 2-mm/s resolution for the ΔV telemetry allowed AACS to capture the ME performance for the three largest maneuvers in the mission: the 450 m/s Deep Space Maneuver 14 months after launch; the 625 m/s Saturn Orbit Insertion 30 June 2004; and the 391 m/s Periapsis Raise Maneuver two months later.

About three-quarters of the maneuvers between launch and the probe mission were less than 20 m/s in all three of the EME2000 axes, and all but the three large maneuvers mentioned earlier were less than 50 m/s. However, AACS did not want to frequently update its flight software (FSW) in order to change the resolution of the ΔV telemetry. Changing FSW is always a risky proposition, so there was no practical justification to make multiple changes to the FSW during interplanetary cruise. It is preferable to make a change like this to FSW only once.

After successful completion of the Huygens Probe portion of the Cassini-Huygens Mission, in May 2005, AACS updated the ΔV telemetry resolution to 0.04-mm/s per telemetry unit. This allowed for a max ΔV telemetry in any of the EME2000 coordinates to be 20 m/s. Of the nearly 140 OTMs remaining in the prime mission, only two would exceed this ΔV telemetry limit, and AACS handled those OTMs when appropriate with direct memory readouts of the ΔV addresses in AACS FSW. For AACS, higher fidelity ΔV telemetry allows them to better characterize their ME and RCS thruster performance during OTMs.

With regard to the other small force ΔV activities, the majority of them are on the order of tens of mm/s (or even smaller). The exception is the ΔV during low altitude Titan flyby, where the ΔV can be a couple of hundred mm/s. Increasing the fidelity of the ΔV telemetry allows AACS to better determine the density of Titan's atmosphere, to better assess the subsystem's performance during these events, and to better gauge the accuracy of the predictive capabilities of these events.

Even though the rationale for this change was for AACS to better evaluate their ΔV predictions, reporting with greater precision how much ΔV AACS telemetry is estimating has been an unexpectedly great resource for Navigation. Besides improving the resolution of the ΔV telemetry, the frequency of the ΔV telemetry was increased

[*] Personal communication, W.S. Kurth, RPWS Research Scientist, 2008

during OTMs. Navigation's uses and benefits of both will be discussed in greater detail later in the following section.

Another piece of AACS telemetry was later identified by Navigation to be of benefit. AACS telemetry reports the duration of RCS thruster valves actuation (i.e., RCS thruster on-time). However the frequency at which this data was being sampled was too sparse to be of any use to Navigation. Navigation requested AACS to increase the sample rate of RCS thruster on-time telemetry by a factor of 32 (from a sampling rate of every 512 seconds to every 16 seconds). Since AACS shares the engineering telemetry stream with other SCO subsystems, AACS is allocated a certain amount of bandwidth. AACS was generous enough to reduce the sampling rate of lower priority telemetry in order to free up the bandwidth necessary to meet Navigation's request.

IV. Utilization of AACS telemetry for Navigation

A. Editing Radiometric Data During Small Force ΔV Events

As mentioned earlier, most small force ΔV events occur while on Earth-point and when 2-way radiometric tracking is available. To recap, these events include: RWA spin-down and spin-up during ME-OTM events; RWA biases; RWA friction tests; RWA spin-down, Earth-pointed deadbanding while under RCS control, and RWA spin-up during specified RPWS data collection periods. Executing these events during 2-way tracking allows for a precise estimation of their ΔV by the OD team.

The OD team models the thrusting due to these small force events as impulsive maneuvers, where the ΔV magnitude and pointing are estimated. Figure 3 shows the 2-way Doppler residuals of a typical RWA bias event. The Doppler measures the spacecraft's Earth-line-of-sight velocity relative to the tracking station, and the residuals display the difference between the observed tracking data and the computed data based on the dynamic model of the spacecraft's motion. When the residuals lie along the zero-line, then the modeling is in agreement with the tracking data. Conversely, when the residuals move away from the zero-line, then there is some mis-modeling with the computed data. In the case of these small force events, the mis-modeling exists because these activities are not truly impulsive in nature, but rather occur over a span of time. This is clearly indicated in Figure 3 by the Doppler points with boxes around them. As the RCS thrusters fire, the Doppler residuals start to move below the zero-line. The sudden spike in the Doppler indicates where the impulsive model is applied. The amplitude of the spike is roughly equivalent to the magnitude of the ΔV that was modeled. The Doppler points that move down back toward the zero-line indicate additional thrusting. Once the thrusting has completed, the Doppler signature is no longer present. The difference between the period of flat Doppler residuals before and after the impulsive maneuver model represents the amount of Earth-line ΔV prediction error in the model.

As can be seen in Figure 3, the impulsive maneuver model used for the RWA bias cannot properly resolve the Doppler where RCS thrusting occurs. Therefore, in order to make the data fit the impulsive maneuver model, all points as a result of

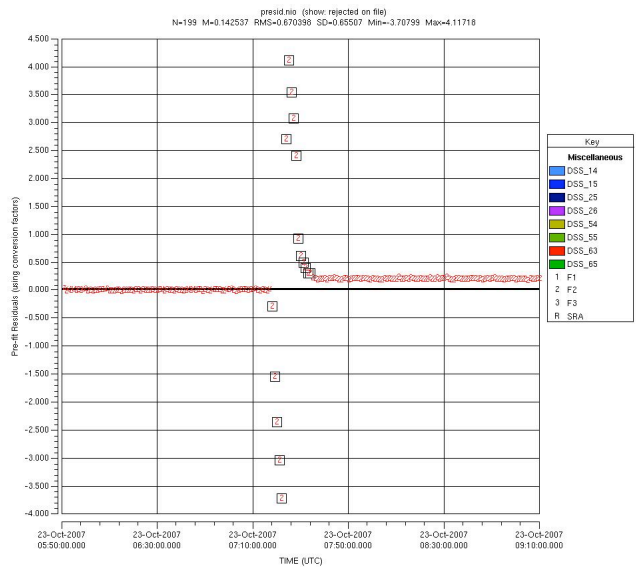

Figure 3. Pre-fit Doppler residuals during RWA bias

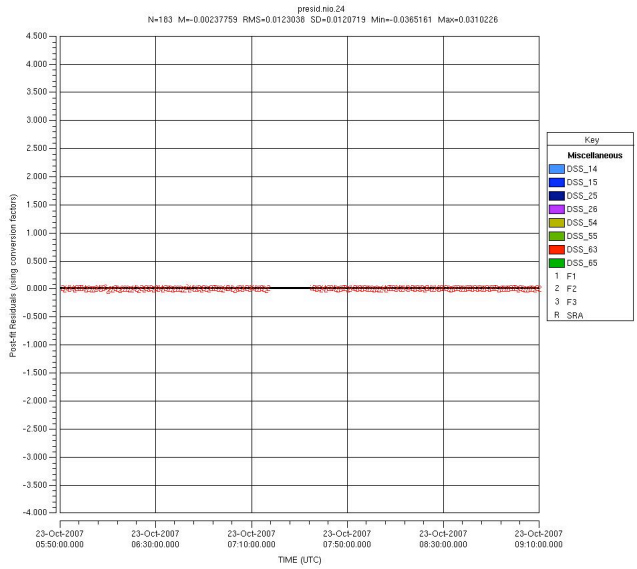

Figure 4. Post-fit Doppler residuals during RWA bias

thrusting must be deleted. Figure 3 displays the data before the model has been able to be fitted by the OD software. Figure 4 shows the data after the Doppler during RCS thrusting has been removed, as denoted by the gap in the middle of the data, and the data has been fitted to the dynamic models. Notice that Doppler data before and after the gap are along the zero-line. This indicates that the impulsive model has estimated the ΔV for this RWA bias.

For circumstances where there is only one small force event occurring within a time span of a few hours, it is fairly easy to visually determine where thrusting is taking place and edit those points out. However, it becomes difficult to make the same visual determination when there are consecutive small force events within a short span of time. This is the case with RWA friction tests.

Figure 5 shows the Doppler residuals during a RWA friction test. RWA friction tests are characterized by five distinct events that result in RCS thrusting. These five events take place over a span of about 4 hours. The five events are: 1) RWA spin-up from its initial rate to a high clockwise rate; 2) RWA coast down to zero; 3) RWA spin-up from the zero rate to a high counter-clockwise rate; 4) RWA coast down to zero; 5) RWA rate bias in preparation for the next set of science slews. The location of the impulsive maneuver model for the five respective events are clearly indicated by the spikes in the Doppler residuals. However, as is the case with the RWA bias, simply knowing where the small force is modeled is insufficient. Identification of periods of quiescent thrusting is required in order to properly edit out the Doppler data.

As is the nature of RWA friction tests, the RCS thrusters are firing on a fairly regular bias in order to counteract the disturbance torques induced by the RWA. However, the pulse width of most of the thruster firings approach the minimum duration Propulsion Module Subsystem (PMS) produces. This poses a unique challenge to removing Doppler data, as it is very difficult visually to distinguish between periods of very low thrusting and periods of no thrusting. Figure 6 displays the thruster firing profile (calculated from thruster on-time telemetry) and the five events for the RWA friction test shown in Figure 5.

It may seem at first thought that if the thrusting is so low that it cannot not be detected visually in the Doppler residuals, then why not keep it in the data set and let the OD software process it. Experience has revealed that the non-modeled thrusting, no matter how slight, adds uncertainty to the solution and degrades the ΔV estimation.

Based on the information from Figure 6, Figure 7 shows periods of no thrusting within the Doppler residuals. Figure 8 shows the effect of removing the Doppler data during the five friction test events. And

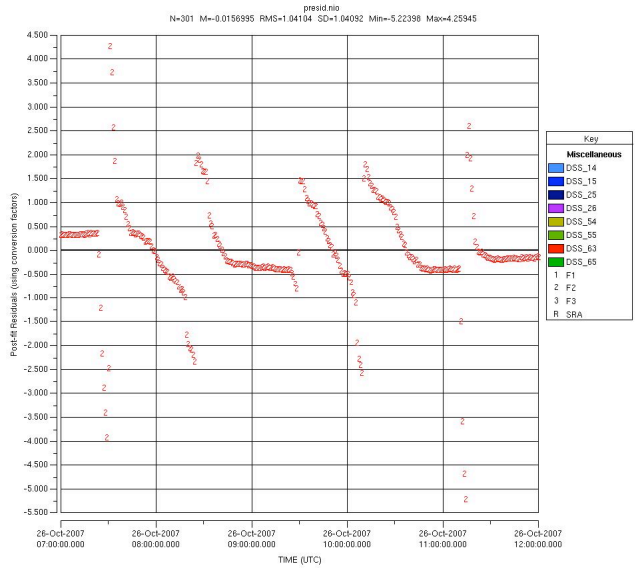

Figure 5. Doppler residuals during RWA friction test

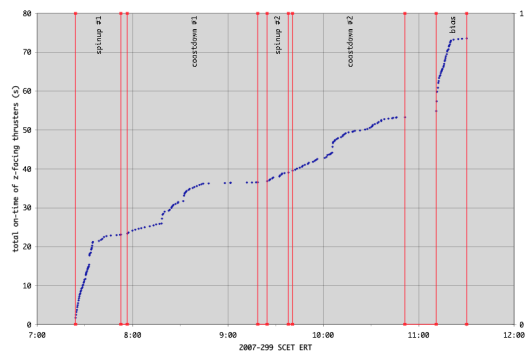

Figure 6. Thruster firings during RWA friction test

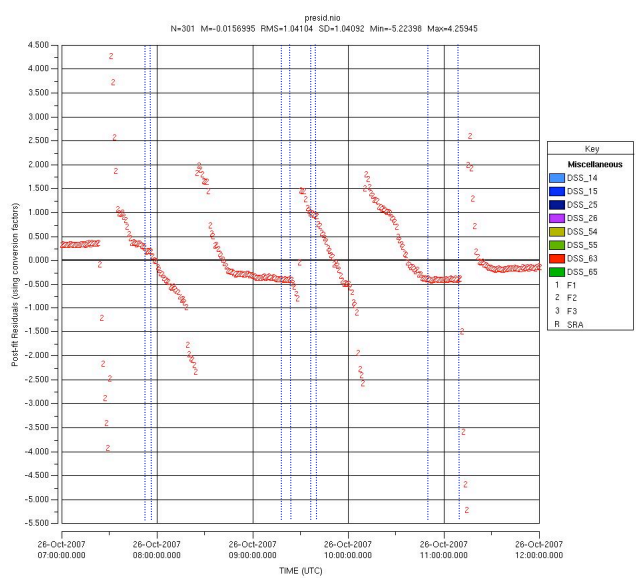

Figure 7. Doppler residuals during RWA friction test with quiescent periods indicated by blue lines

Figure 9 shows how well the Doppler data eventually fits the impulsive maneuver model.

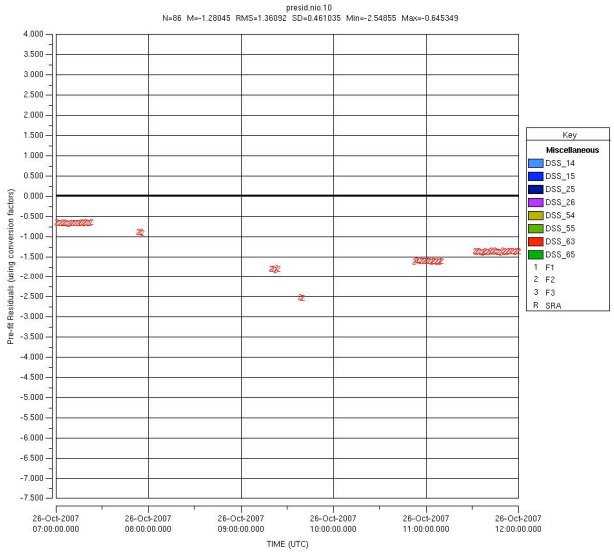

Figure 8. Doppler residuals during RWA friction test with thruster data removed

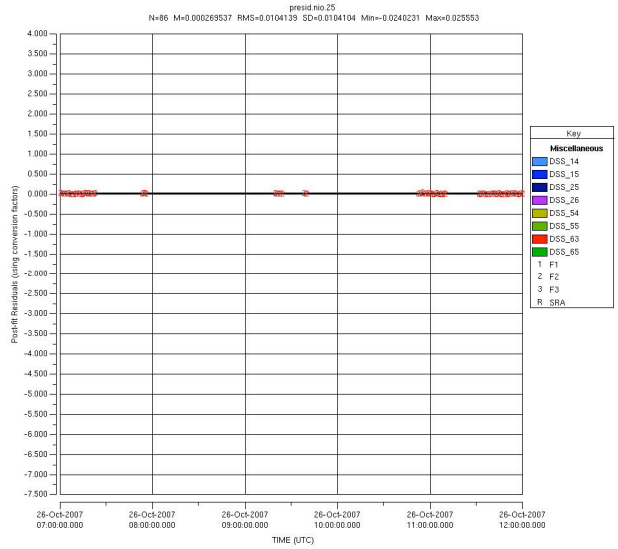

Figure 9. Fitted Doppler residuals from RWA friction test

The RWA friction test is the most stressing case where utilizing AACS thruster on-time telemetry is used. In general, this technique has not been necessary for RWA biases, as demonstrated earlier. This methodology has also been applied to ME-OTMs and RPWS data collection periods where it has been important to distinguish between thrusting due to attitude control deadbanding and RWA spin-down/spin-up events.

There have been two main benefits from using the AACS thruster on-time telemetry: 1) it has removed all ambiguity from determining when the spacecraft is and is not quiescent from small forces; and 2) it has provided for more accurate estimation of the ΔV of the small force events.

Navigation's estimate of ΔV has been fed back to SCO and AACS as another means for them to monitor and assess the spacecraft's performance and to evaluate the ability to predict the impact of the small force events. Prior to the execution of these small force ΔV events, AACS provides predictions to Navigation so that the ΔV of the event and its uncertainty can be properly modeled. Navigation relies on accurate ΔV predictions for mapping the spacecraft trajectory to encounters for future maneuver designs.

One manner in which the feedback of Navigation ΔV estimate has been used by SCO to improve spacecraft operations has been with estimating the thrust magnitude of the RCS.

B. Estimating RCS Thrust

The Propulsion Module Subsystem team's responsibility within SCO is to monitor the performance and maintaining the health and safety of the Main Engine and RCS thrusters. Key elements to their duties include tracking propellant consumables and estimating the thrust of the ME and RCS. Close tracking of propellant consumables is vital so that the spacecraft's mass properties are always up to date. Also, since the RCS utilize the single blowdown propellant tank, close tracking of the RCS monopropellant is required for their models to provide an accurate estimate of thrust.

An accurate estimate of spacecraft mass and the RCS thrust is important because RCS-OTMs, unlike ME-OTMs, do not use an accelerometer to terminate the OTM. Rather, the AACS FSW uses a timer to specify cutoff based on Newton's 2nd Law of Motion (Eq. 1).

$$\Delta t_{calculated} = \Delta V_{commanded} \frac{s/c_mass_{FSW}}{F_{FSW}} \tag{1}$$

where $\Delta V_{commanded}$ = requested ΔV from the OTM sequence
s/c_mass_{FSW} = PMS-determined spacecraft mass loaded in AACS FSW
F_{FSW} = PMS determined RCS thrust loaded in AACS FSW
$\Delta t_{calculated}$ = required duration of all four z-facing thrusters

Another critical reason for accurate estimates of RCS thrust is for periods when small force ΔVs occur while Cassini is not over a tracking pass. When radiometric data is unavailable for Navigation to use to resolve the small force ΔV, Navigation must rely on the AACS telemetry estimate of ΔV.

To a first order, AACS FSW again utilizes Newton's 2nd Law of Motion for its on-board calculation of ΔV (Eq. 2). Thruster tailoff performance is also taken into account by the AACS FSW, but it tends to be a higher order effect.

$$\Delta V_{AACS_tlm} = \frac{F_{FSW}\Delta t_{AACS_tlm}}{s/c_mass_{FSW}} \tag{2}$$

Here F_{FSW} and s/c_mass_{FSW} are the same as in Eq (1). The difference is now ΔV_{AACS_tlm} is calculated based on RCS thruster on-times, Δt_{AACS_tlm}. This is the same thruster on-time telemetry that was referenced for the purposes of editing Doppler residuals.

Using a simple relationship that thrust and ΔV are directly proportional assuming that spacecraft mass and thruster on-time are constant, Navigation is able to estimate RCS thrust based on its estimate of ΔV (Eq. 3).

$$F_{Nav_est} = F_{FSW}\frac{\Delta V_{Nav_est}}{\Delta V_{AACS_tlm}} \tag{3}$$

Since the accuracy of Navigation's estimate of ΔV is well below 0.1 mm/s, the Navigation estimate of thrust is believed to be accurate to about 0.01 N. However, Navigation does observe variations in its thrust estimate from event to event. It is suspected that these variations are due to factors such as varying thruster duty cycles, the temperature increases of the thruster cluster during ΔV events greater than 10 mm/s, variations in propellant tank temperature due to bus heater switches, and freshness of catbed material.♦ Given all these sources of uncertainty, Navigation has been able to consistently report thrust estimates within 5% of the estimate from PMS. Figure 10 compares the estimate of the Propulsion and Navigation estimates for thrust over the past year for RWA biases.

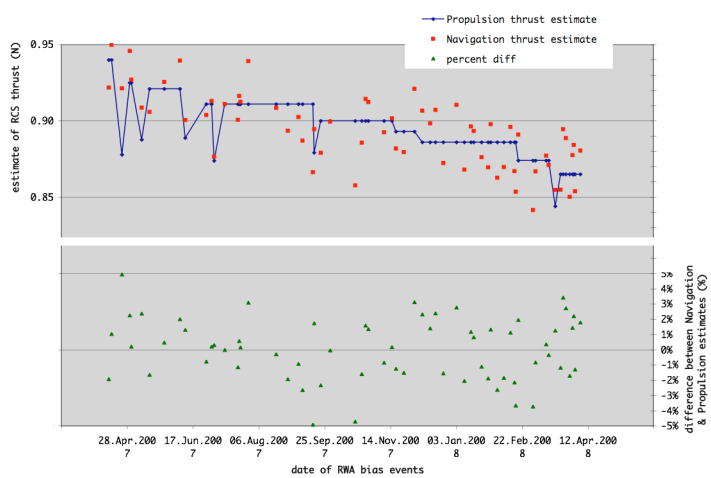

Figure 10. Comparison of Propulsion and Navigation estimates of RCS thrust for RWA biases

Frankly, it is not Navigation's intent to supplant the expertise of the PMS team. Rather, by using Doppler to estimate thrust, Navigation serves as an independent validation of their estimate of RCS thrust. Feedback from Navigation has already served to improve the PMS modeling of RCS thrust. Also, Navigation data was the first indication that the AACS estimate for the RCS thruster tailoff time needed to be updated. More details of this study and update can be found in Bates, et al[9].

C. Modeling ΔV Events when Radiometric Data is Not Available

The vast majority of the targeted encounters are associated with low altitude Titan flybys while the spacecraft is oriented in order to collect valuable science data. Cassini will have completed 45 targeted Titan encounters during the 4-year prime mission (July 2004-July 2008)[10] and is scheduled to make another 26 close flybys with Titan in the 2-year extended mission (July 2008-July 2010)[11].

As mentioned previously, the science instruments and HGA are fix-mounted on the spacecraft. Except for the rare circumstance where the radio science gravity experiment is the prime instrument during the flyby, no tracking data are acquired during targeted encounters. For most other flybys, the spacecraft is slewing frequently in order to point the science instruments at the targets of interest. In the case of low altitude Titan flybys, the spacecraft

♦ Personal communication, T.J. Barber, Lead Engineer, Propulsion Module Subsystem, 2007

transitions from RWA to RCS control. Thus all the slewing during this period is done via the eight RCS thrusters. The coupled y-thrusters slew the spacecraft about its z-axis, and the uncoupled z-thrusters slew the spacecraft about the x and y-axes (see Figure 11).

A great advantage to using the RCS for slewing is that they are able to turn the spacecraft at a much faster rate than the RWA. Observation time is at a premium during targeted encounters, and as a result it is necessary to slew the spacecraft as quickly as possible from one target to the next. Occasionally even if the spacecraft encounters Titan at an altitude that is too high to be affected by Titan's atmosphere, the science community requests that slews be executed by the RCS.

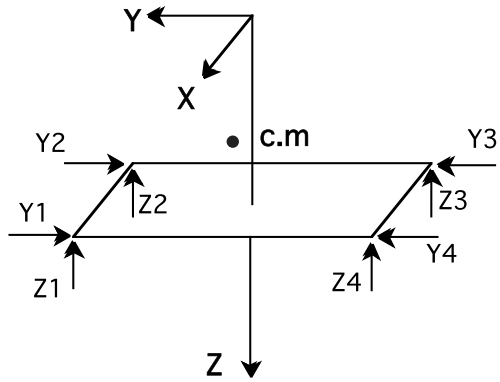

Figure 11. RCS Thruster Locations and Directions of Reaction Thrust

As indicated previously, the primary reason for RCS control during low altitude Titan flybys is for maintaining attitude control in the presence of Titan's dense atmosphere. During Titan flybys, atmospheric drag provides the third largest perturbation to Cassini's trajectory (Saturn and Titan's gravity are the first and second, respectively).[2] As a result, drag needs to be modeled in order to get an accurate OD solution. Figure 12 shows the AACS ΔV telemetry for the RCS thrusting, slews and the effect of atmospheric drag, in the EME2000 inertial coordinate system. The telemetry is plotted against a predictive model also provided by AACS.

There are two important results in Figure 12. AACS is able to predict the ΔV from slewing accurately. And the greatest source of uncertainty in the AACS model is the density of Titan's atmosphere, as seen by the deviation between the predict curves and the telemetry points around Titan closest approach (~14:30 in Figure 12).

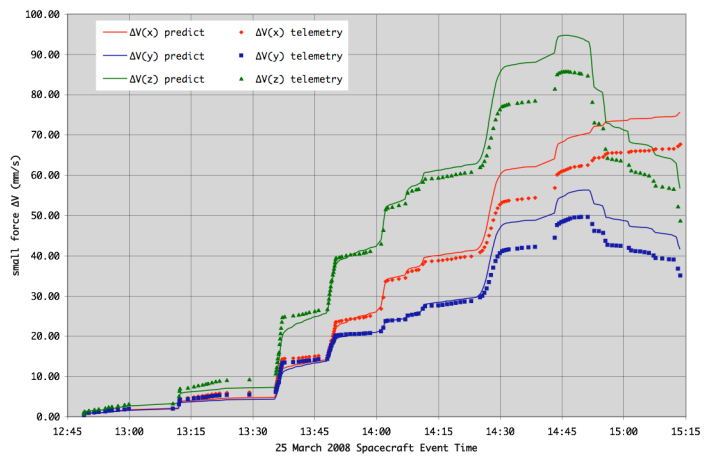

Figure 12. RCS ΔV accumulated during a typical Titan flyby (mm/s, EME-J2000)

With only a couple of tracking passes between the flyby and cleanup-OTM, the OD team is under time pressure following a low altitude Titan flyby. They need to determine the flyby prediction errors, correct for any satellite orbit errors, and the effects of the RCS thrusting and the drag forces during the encounter. The trajectory, as it is mapped to the next targeted encounter has been observed to be very sensitive to small changes in the drag estimate. Because of Navigation's ability to validate the RCS thrust estimate, the AACS ΔV telemetry is trusted to about 5%. Since there are only a couple of tracking passes between flyby & cleanup-OTM, the use of AACS ΔV telemetry allows Navigation to get the best possible solution in the shortest amount of time.

More detail about the atmospheric drag model used by OD during low altitude Titan flybys can be found in Pelletier, et al.[12]

D. Estimating Spacecraft Pointing During OTMs

Most of the ΔV experienced during an OTM occurs while the spacecraft is at an off-Earth burn attitude. Due to the fixed mount of Cassini's High Gain Antenna, no tracking data are acquired during OTMs.

Whereas an impulsive maneuver model is employed for small force ΔV events, including those events associated with an OTM, a finite burn 'rocket equation' is used to model off-Earth portion of OTMs. The OD team estimates the magnitude, right ascension, and declination of the ΔV vector. The *a priori* values from which the OD team bases its estimate come from the maneuver design. Maneuver execution errors are modeled using the Gates model. The Gates error model determines *a priori* uncertainties for fixed and proportional errors of magnitude and pointing.[13]

After the OTM has executed, AACS telemetry has been found to be a better source for the "*a priori* value" of the pointing used to seed the OD process than the true *a priori* value from the original maneuver design. Figure 13 is a slide from the AACS "quick-look" analysis presentation following OTM-149.[14] This slide displays the ΔV, as reported by AACS telemetry, for every event within this ME-OTM. The events in red correspond to ΔV that occurred while the spacecraft was off of Earth-point. The line in blue indicates the ΔV delivered by the Main Engine. At the bottom of the slide, AACS also provides its estimate of spacecraft pointing during OTM-149. Updated uncertainties are derived from comparisons of the telemetry to the reconstructed maneuver pointing. Details of this telemetry-based uncertainty model can be found in Roth, et al.[15]

JPL

Estimated ΔV from telemetry

- **ΔV vectors (mm/s) are in J2000 coordinate frame:**

0.04 mm/s telemetry resolution

EVENT	x-axis (mm/s)	y-axis (mm/s)	z-axis (mm/s)	mag (mm/s)	KPT (mm/s)
RWA Spin Down...	4.36	-1.92	-1	4.87	5.34
deadbanding....	0.04	-0.04	0	0.06	
YAW Turn.....	0.32	-0.92	2.36	2.55	2.85
deadbanding....	-0.28	-0.08	-0.16	0.33	
0.9deg Offset...	-1.84	0.6	1.04	2.2	2.689
deadbanding....	-0.44	0.16	0.28	0.55	
BURN.....	**-2438.9**	**584.01**	**1109.69**	**2742.3**	
	-1.56	0.68	1.12	2.04	
0.9deg Un-Offset a	-2.08	0.68	1.16	2.48	2.688
deadbanding	-0.08	0	0.04	0.09	
Un-YAW Turn.....	-0.08	-0.8	2.48	2.61	2.85
deadbanding....	0.84	-0.4	-0.2	0.95	
RWA Spin Up.....	3.28	-1.44	-0.76	3.66	3.53
Total Off Earth.	**-2444.84**	**584.49**	**1118.33**	**2751.28**	
Pointing Directions	ra (deg)	dec (deg)			
	166.555	23.984			

*KPT does not model deadbanding or burn DV

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Figure 13. AACS estimate of ΔV during OTM-149

OTM-149 is chosen as an example because there were only four tracking passes until the final design for the next maneuver, OTM-150. OTM-149 is the cleanup-OTM from the Enceladus-3 encounter, and OTM-150 is the apoapsis-OTM that targets the Titan-42 encounter 19 days later. A fast transfer between targeted encounters forces the Navigation team under time pressure to resolve the previous OTM's effect on the trajectory in preparation for the next OTM.

Figure 14 shows the B-plane plot of the OD solutions leading up to OTM-150 with radiometric data cutoffs for each solution listed in the label. The center of the ellipse on the B-plane represents the spacecraft's predicted position relative to the target satellite at the time of closest approach. The ellipse is the 1-σ dispersion due to trajectory errors and uncertainties in the modeling of future events. The blue ellipses represent solutions based on the OTM-149 maneuver design for spacecraft pointing during the OTM with the Gates model for the uncertainty. The green ellipses represent solutions using the AACS telemetry estimate for spacecraft pointing as the *a priori* value and using uncertainties consistent with Roth's telemetry-based uncertainty model. Both sets of solutions map the spacecraft trajectory forward to the next Titan encounter.

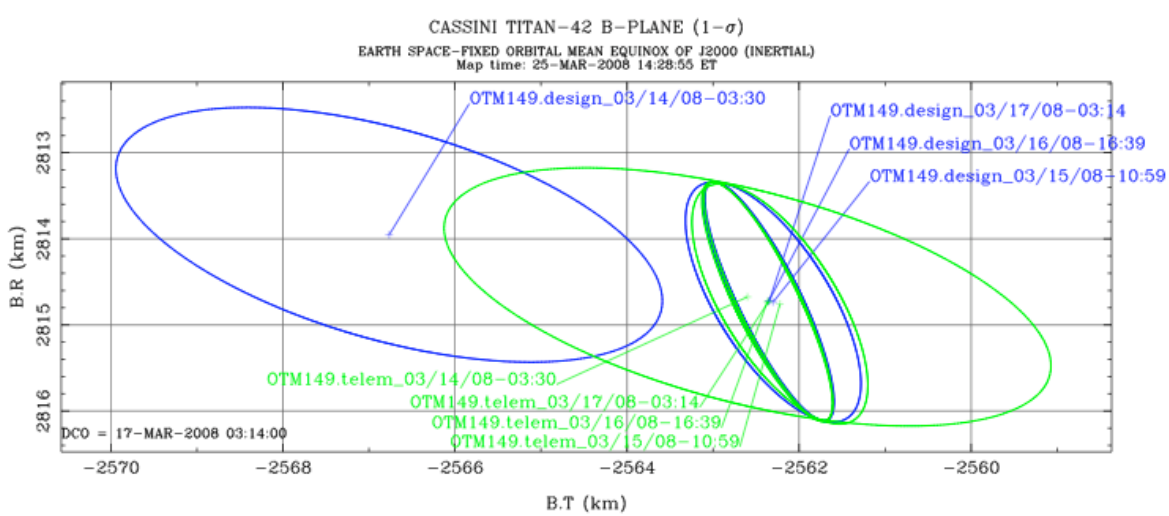

Figure 14. B-plane solutions between OTMs 149 and 150

Figure 14 shows that the estimate of the spacecraft's trajectory improves as more data is added. This is indicated by the decreasing size in the 1-σ dispersion ellipse. However, when estimates shift substantially, as was the case with the "design-based" solution between 14 and 15 March, additional investigation is required to ensure that the change is valid and that the OD software is estimating other modeled parameters properly. Notice however that the "telemetry-based" solution hardly shifted (i.e., the 14 March solution is more consistent with subsequent solutions).

Further investigation revealed the details behind the shift in the "design-based" solution and the consistency in the "telemetry-based" solution. Figure 15 shows the evolution of the spacecraft pointing during OTM-149. Plotted are the estimates for right ascension and declination with their respective uncertainties. Also displayed are the *a priori* values for right ascension and declination used to seed the OD process.

The data in Figure 15 shows that the spacecraft performance during OTM-149 resulted in an OD estimate for spacecraft pointing that is much closer to the AACS telemetry estimate than it is the original maneuver design. It is also interesting to note that the OD estimate for pointing based on the maneuver design did shift by more than 1-σ between the 14th and 15th of March.

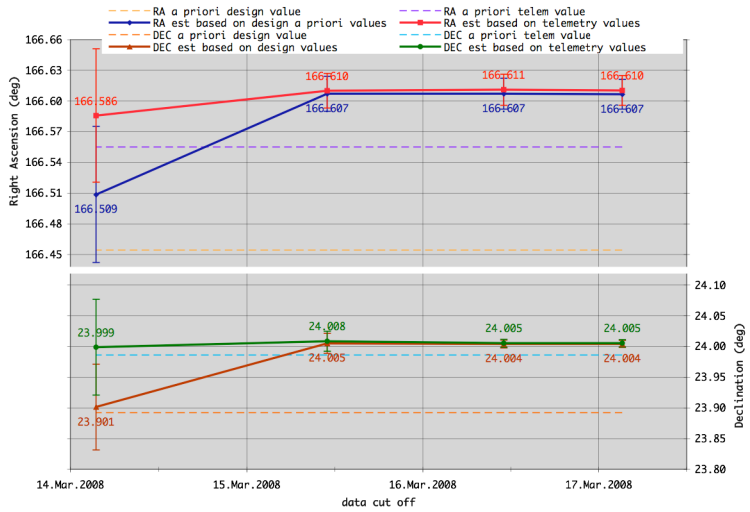

Figure 15. Estimates of Right Ascension and Declination for OTM-149, with uncertainties and a priori values

The use of AACS telemetry for estimating spacecraft pointing during OTMs has allowed for more reliable OD solutions, with greater precision in a short amount of time. The benefits gained from using AACS telemetry give the Navigation team additional confidence when preparing for future OTMs and when deciding whether or not to cancel OTMs.

E. Spacecraft Attitude Telemetry

This paper has only discussed the impact of propulsive forces on Navigation operations, however there are other small forces acting upon the spacecraft that are taken into consideration. Acceleration due to thermal radiation pressure from Cassini's radioisotope thermoelectric generators (RTG) is also estimated by the OD team. Since the RTGs are fixed on board the spacecraft, the spacecraft attitude must be accounted for when estimating the effect of their resulting acceleration.

AACS regularly provides a prediction of the spacecraft attitude. Nominally the OD team uses this predicted attitude information. An attempt has been made to use attitude telemetry to refine the effect of the thermal radiation acceleration. In order for the thermal radiation acceleration model to be effective, continuous knowledge of the spacecraft attitude is required. However gaps in attitude telemetry are quite common due to tracking station issues. These gaps would have to be patched with prediction data. An easy to use software tool has not been developed yet to assist the OD team in incorporating the predicted attitude data with the telemetry data. The current process to fill in the gaps in telemetry is non-trivial and cumbersome.

The AACS prediction for spacecraft attitude has proven to be very accurate, as confirmed by the pointing of a dozen science instruments. For the periods where spacecraft attitude telemetry has been used, little appreciable improvement has been noticed in either the OD solutions or the estimates of the thermal radiation pressure. It has been concluded that for Cassini, the small benefit gained from using attitude telemetry was not worth the large amount of work required to use it. However that may not be the case for other missions where these small accelerations have a larger effect.

V. Considerations for Future Missions

Other missions have utilized spacecraft telemetry, namely ΔV telemetry, to enhance their navigation process.[16] However, Cassini has used a broader range of spacecraft telemetry in a manner that is more extensive. As a flagship mission, Cassini was able to adapt its process into its prime mission because of ability to draw upon a diverse group

of people with expertise in multiple areas and the project is flexible enough when an improvement to an existing process is identified.

Many future missions are limited in their resources to the extent that they do not have the benefit of a large flight team to implement the changes similar to the ones that Cassini required. Consequently. it would be beneficial if future missions were able to take the lessons learned from Cassini and tailor them to meet their needs.

Of course designing a "nav-friendly" spacecraft with only coupled balanced thrusters is most desirable. But an engineering compromise typically made by the spacecraft design team is to have thrusters that are uncoupled.

Whether the spacecraft has coupled or uncoupled thrusters, early identification of engineering and science activities that can impact navigation needs to be made. This will allow the Navigation team to have a greater input on the scheduling of the activities. Navigation benefited greatly from the exercise in 2005 to take the responsibility to work with the spacecraft and science teams to reschedule all the RWA friction tests in the middle of the prime mission. Navigation was able to take the experience gained and apply it early on in the planning for Cassini's extended mission just as the downlink schedule was being negotiated.

Once the activities that impact Navigation have been identified, Navigation can then place requirements on the spacecraft team to properly configure telemetry to meet their needs prior to launch. Since the primary use of spacecraft telemetry is to monitor the health and performance of the spacecraft (especially during test, launch, and initial checkout phases of mission operations), the spacecraft might not be able to launch with the telemetry configuration that is best suited for Navigation. The Cassini Navigation Team was very fortunate that AACS was able to identify measurements that were of lower priority to free up bandwidth for newly identified higher priority telemetry. If Navigation establishes their telemetry requirements as early as possible during spacecraft development, then the spacecraft team can ensure that the telemetry system will be flexible enough to be reconfigured at a more appropriate time.

It is far preferable to have the proper telemetry configuration established for Navigation pre-launch rather than hoping for a reconfiguration post-launch. For missions with a short cruise phase, such as those to Mars, there really is no time to reconfigure telemetry.

It would be fair to say that ΔV telemetry is paramount to characterizing any propulsive event. This becomes even more important if the mission expects many such ΔV events to occur without any tracking station coverage. Ideally, the resolution of ΔV telemetry should be at least the same order of magnitude, if not better, that the uncertainty in the Doppler measurements. The Cassini Orbit Determination team is able to estimate the ΔV via Doppler to about 0.010 mm/s for RWA biases and less than 0.10 mm/s for RWA friction tests and other small force events; the resolution of the AACS ΔV telemetry is 0.04 mm/s.

The accuracy of the ΔV telemetry depends on how the flight software calculates it. The spacecraft team's ability to accurately estimate spacecraft mass and thruster output is critical to the ΔV telemetry. Therefore, as many small force events as possible must be scheduled over tracking coverage. Precise estimation of ΔV via radiometric tracking data is required for the Navigation team to independently validate the ΔV telemetry and the propulsion estimate of thrust. This is the only way to gain confidence in the accuracy of telemetry for when tracking data is not available.

When small force propulsive events do occur over tracking coverage, thruster on-time telemetry should be required. Knowing thruster on-times removes any ambiguity in distinguishing between Doppler points that have shifted due to thrusting and points that are noisy.

The sampling rate of thruster on-time depends on the nature of the spacecraft's attitude control system. For example, the more frequently the spacecraft is expected to deadband, the greater the telemetry sampling rate needs to be. Also, the telemetry sampling rate should be less than the Doppler count time. When the Cassini thruster on-times were being sampled every 512 seconds, processing 60-second Doppler data from RWA friction test was challenging. It was nearly impossible to clearly correlate which Doppler points displayed thrusting. Increasing the frequency of the thruster on-time telemetry to every 16 seconds makes processing the Doppler during RWA friction test faster and more reliable.

Science teams already require that spacecraft attitude telemetry as a high priority. For missions where small body-fixed accelerations have a significant impact on Navigation, be sure that the software is created to easily fill in any telemetry gaps with predicted attitude data.

The last requirement for future missions is to have at least one member of their team act as the "Navigation Systems Engineer." The spacecraft team typically has a number of systems engineers who understand enough about the spacecraft subsystems that they can make sure that all the pieces of the spacecraft are working well together. That role is lacking in general with most other Navigation teams.

It is very important to have members of the Navigation team who understand the relationship between the spacecraft engineering operations and navigation. It should be a level of understanding that goes beyond the

rudimentary knowledge of what the spacecraft engineering team is doing. Rather, a Navigation Systems Engineer should understand the fundamental needs of both sides such that they can effectively and positively influence operations on both sides of the fence. It would be most beneficial to have members of the Navigation team and members of the Spacecraft team cross-train in order to gain that understanding.

VI. Conclusion

The use of spacecraft telemetry has greatly improved how the Cassini Navigation Team operates. The Orbit Determination process is more refined, especially during small force events. More accurate estimations of ΔV have led to improvement in the modeling for the RCS thrusters. Improved calibrations of RCS thrust give confidence to the accuracy of the ΔV telemetry during periods when tracking data is not available. And accurate ΔV telemetry has made it possible for OD solutions with reduced uncertainties to be generated quicker than before. The higher precision OD solutions have provided greater confidence when under tight time constraints to design a maneuver and to the decisions whether to cancel or execute maneuvers.

The success of the Cassini Navigation Team to expand the use of telemetry will hopefully serve as a call to future missions.

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