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DAWN SPACECRAFT PERFORMANCE AT CERES: RESULTS OF HYBRID CONTROL FOR CERES MAPPING [*]

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Dawn is a low-thrust interplanetary spacecraft currently orbiting the dwarf planet Ceres, to better understand the early creation of the solar system. Launched in September 2007, Dawn arrived at Vesta in July 2011. After a 16-month successful science campaign at Vesta, Dawn departed for Ceres, arriving in early 2015. The Dawn spacecraft uses both reaction wheel assemblies (RWA) and a reaction control system (RCS) to provide 3-axis attitude control for the spacecraft. Reaction wheels were designed to be the primary system for attitude control, however two wheels have shown high friction anomalies and have been removed from service. The project has implemented a hybrid control algorithm using two reaction wheels and RCS thrusters. This hybrid control capability enabled Dawn to achieve very high science return, while significantly conserving remaining hydrazine propellant.

With only two remaining healthy RWA's, hybrid control became part of the baseline plan for Ceres science operations. The Dawn team developed specific operational approaches in which sequences were developed with careful consideration of science versus resource trades. Commanding and sequence planning also incorporated contingency planning, in the event that another reaction wheel may fail. Despite the differences in operational approach between Vesta and Ceres, both campaigns achieved very rich scientific data return.

This paper highlights Dawn's recent flight experience with hybrid attitude control during Ceres orbit operations. The discussion includes the approaches utilized by the Dawn team to address unique operational challenges presented by the hybrid approach, and reviews spacecraft performance under hybrid control in low orbit at Ceres. Additionally, methods used to optimize hydrazine use and thereby extend the science campaign will be presented. Finally, a preliminary assessment of an orbit

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transfer with two reaction wheels, during extended mission operations, is discussed.

INTRODUCTION

Dawn, NASA's ninth Discovery class mission, is finishing a journey that orbited Vesta and Ceres, two large protoplanets in the main asteroid belt between Mars and Jupiter. Investigation of Vesta and Ceres is providing insight into the formation of planet-like objects, as scientists believe they retain a record of the conditions and processes during that epoch of the solar system. The Dawn mission is also unique in that it is the first spacecraft to orbit two extraterrestrial planetary bodies.

Built by Orbital Sciences Corporation (now Orbital ATK) and operated by the Jet Propulsion Laboratory, the Dawn spacecraft began its 9-year journey on September 27, 2007. After a 3.5-year cruise phase, Dawn orbited Vesta in July of 2011 through September of 2012. The yearlong science campaign at Vesta was very successful, producing significant findings about the composition of Vesta and the early formation of the solar system.[1,2] After completing the Vesta campaign, Dawn had a 2.5-year cruise phase en-route to arrival at Ceres in March of 2015. Dawn successfully completed its prime mission in orbit around Ceres in June of 2016, and continues in orbit around Ceres at the time of publication.

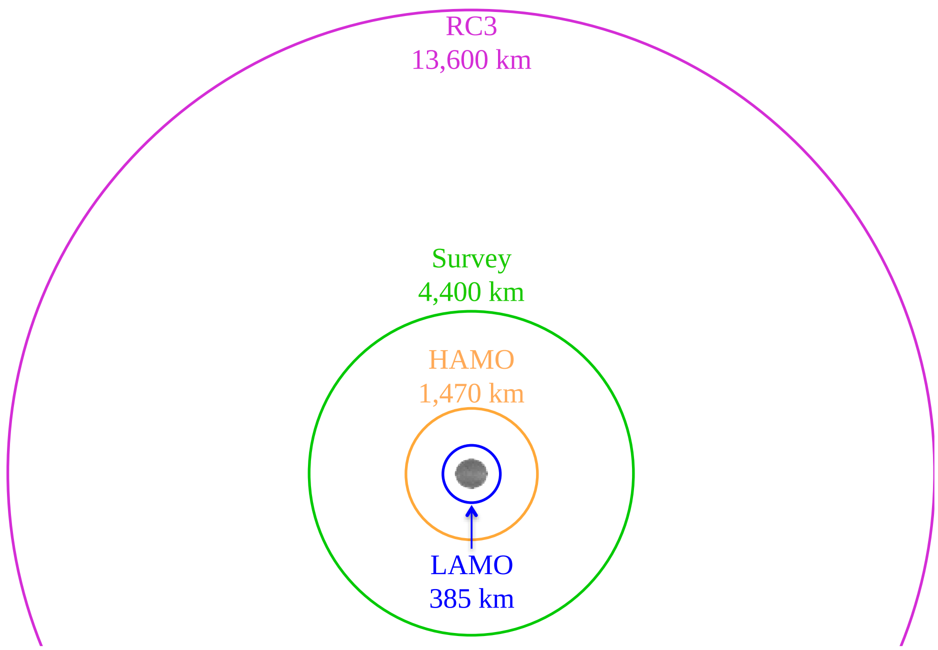

Figure 1. Ceres Science Orbits

Ceres science plans look very similar to what was done at Vesta. There are four main science orbits starting with the rotational characterization (RC3) orbit at a 13,600 km altitude followed by a 4,400 km altitude survey orbit. Dawn then transferred down to the third science orbit, a 1,470 km High-Altitude Mapping Orbit (HAMO) followed by the final, 385 km, Low Altitude Mapping Orbit (LAMO).

While the high level science plan and orbit structure are similar there are two main differences in the Ceres science plan compared to the Vesta science plan. One difference is the size and shape of Ceres, and the second is the reduced capabilities of the spacecraft due to the two faulted reaction wheel assemblies. Ceres' larger, more uniform gravitational field reduces demand on the attitude control system, and the Ceres LAMO orbit has a significantly longer period. Conversely, operating with a reduced set of reaction wheels adds complexity to the operational plans at Ceres.

Dawn's mission plan was to use reaction wheels for attitude control for all the science operations but that was no longer an option for Ceres. With two healthy RWAs remaining, there was a desire to take advantage of a capability to use a mixed actuator set, consisting of RWAs and reaction control system (RCS) thrusters for attitude control. While the Ceres mission can be accomplished in all-RCS, the hydrazine available is a finite resource. Hybrid control is more economical and can provide more science observation time before the end of the mission. However, this control mode had only been exercised on the flight system as an in-flight calibration.[3] Significant work was needed to incorporate hybrid control mode into the Ceres operations plan.

SPACECRAFT DETAILS

The Dawn spacecraft is based on Orbital Sciences Corporation's heritage commercial spacecraft designs, with modifications made for the interplanetary mission. Much of the ion propulsion system for the Dawn spacecraft was leveraged off the experiences of the earlier Deep Space 1 mission.

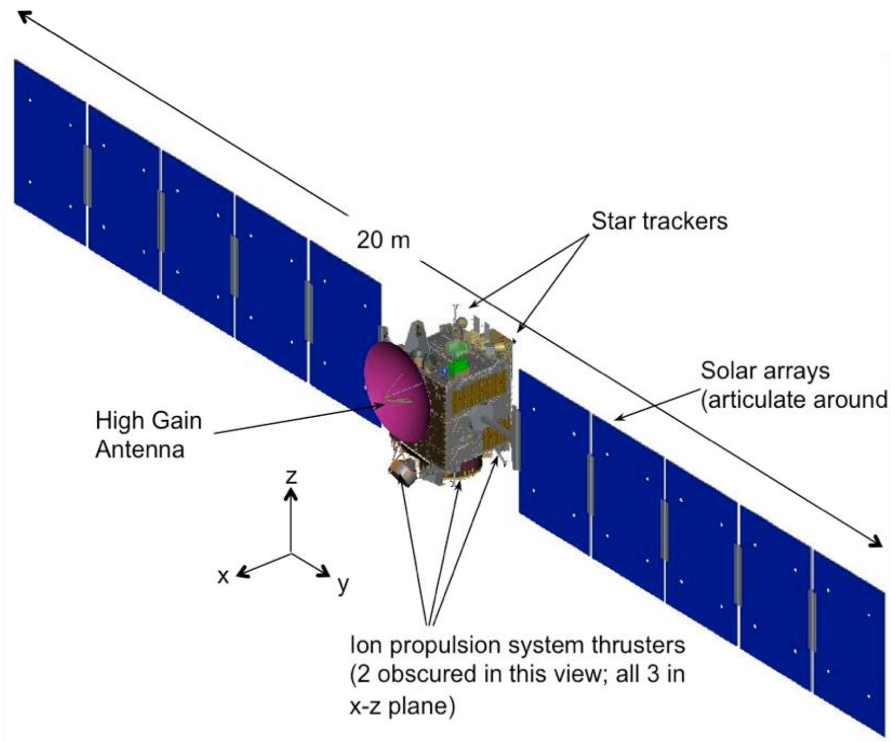

Figure 2. Dawn Spacecraft

The Dawn spacecraft is 3-axis controlled with two primary sets of control actuators, plus the gimbaled ion propulsion system. One of the two primary actuators was a set of four reaction wheel assemblies (RWA), arranged in a pyramid configuration (see **Figure 3**). The pyramid configuration allowed for redundancy since any three reaction wheels could be used to provide 3-axis attitude control. A hydrazine based reaction control system (RCS) consisting of two redundant sets of six 0.9 N thrusters is also used for 3-axis control. The RCS system was intended for unloading accumulated momentum in the wheels, and providing attitude control in safe-mode. Each ion propulsion system (IPS) engine is gimbaled to provide control about two axes during thrusting with the IPS, leaving one axis to be controlled by either the RWAs or the RCS. The gimbaled thrust-vector control (TVC) system is used whenever the IPS system is used. Science observations are conducted in either RWA control or RCS control, while the IPS engines are used for interplanetary cruise and orbit transfers.

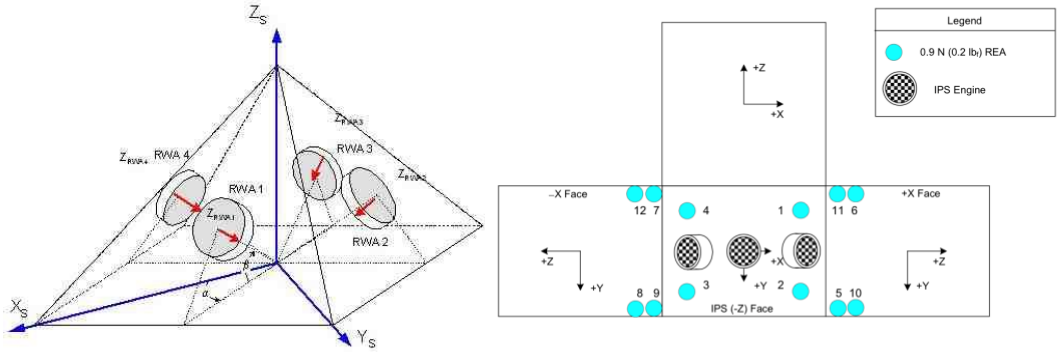

Figure 3. Dawn Actuator Configurations

RWA ANOMALIES AND DEVELOPMENT OF HYBRID CONTROL

Dawn was originally designed to use either RCS control or RWA control for attitude control. However, anomalies with the RWAs led to the development of a hybrid RCS-RWA capability. Prior to launch it was identified that the RWAs on Dawn were at higher risk for failure.[4] RWA #4 experienced a high friction anomaly in June 2010, after accumulation only ~0.5 billion revolutions, at the time of failure. This premature anomaly, along with similar anomalous behavior observed on other spacecraft, led the Dawn flight team to be concerned about the other three wheels having similar anomaly before the end of orbit operations.[5,6]

This first RWA fault in 2010 resulted in the rapid development of a hybrid control capability to operate the spacecraft with a combination of RWA and RCS actuators – hybrid mode. It was unclear at the time how much of the mission could be achieved with all-RCS operations if another wheel faulted. Algorithms for hybrid control were developed based on the experience from past missions that required operation with a reduced actuator set.[5,6] New Flight software was installed onboard the spacecraft in April of 2011, however, it was not executed in-flight until the second wheel failure. The basic premise of the hybrid controller is to distribute the control torque commands to the different actuators. Desired control torque is still computed by the FSW in the spacecraft body frame. The body frame torque vector is projected onto the RWA plane to determine the torque components to send to each RWA. Remaining torque, not distributed to the RWAs, is allocated to the RCS thrusters. Details of the hybrid control design are described in Bruno 2012 reference.[7]

A second RWA anomaly occurred as Dawn was wrapping up science operations at Vesta. RWAs 1-3 were used as the primary actuator set for all of the Vesta operations (May 2011 – Aug 2012). During the Vesta departure, RWA #3 experienced a high friction anomaly similar to what was seen on RWA #4. RWA #3 had accumulated approximately 1.1 billion revolutions before the anomaly, still well below the expected lifetime. Neither RWA #3 nor RWA #4 has been exercised since the second fault. Extensive review of the data from the anomalies has been performed. It was hoped that some early indications, like an earlier small friction spike or a period of moderately increased friction, would be able to provide early warning of a likely anomaly. Analysis of the anomalies has not generated a clear root cause, or any new methods that would reduce the likelihood of future RWA anomalies.

PLANNING FOR CERES OPERATIONS

With the loss of the second wheel, hydrazine was being used at a significantly higher rate than previously planned. This caused a shift in operations planning to more closely manage this limited resource such that it did not limit the overall science return.[8] A lot of work was done, both to find ways to conserve hydrazine, as well as to accommodate the science objectives at Ceres.[9] Significant reduction in hydrazine use was achieved during the cruise to Ceres, which allowed for a plan that could accomplish the nominal plan on RCS control. An all RCS control option had low propellant margin in the plan, so use of the hybrid control option was desired to conserve the hydrazine consumables. There were five primary factors that went into planning for Ceres operations with hybrid control: when to use hybrid, RCS consumable conservation, thruster on/off cycle management, science planning accommodation, and hybrid sequence commanding.

Determining when to use hybrid control

One major decision for the flight team going into the Ceres planning process was choosing when to take advantage of hybrid control. Significant savings of hydrazine could be realized with hybrid control, though the benefit was not uniform across the science plan. Given the wheel failures, the team pursued plans to optimize hybrid control use and did not assume that the wheels would survive for the duration of the Ceres campaign.

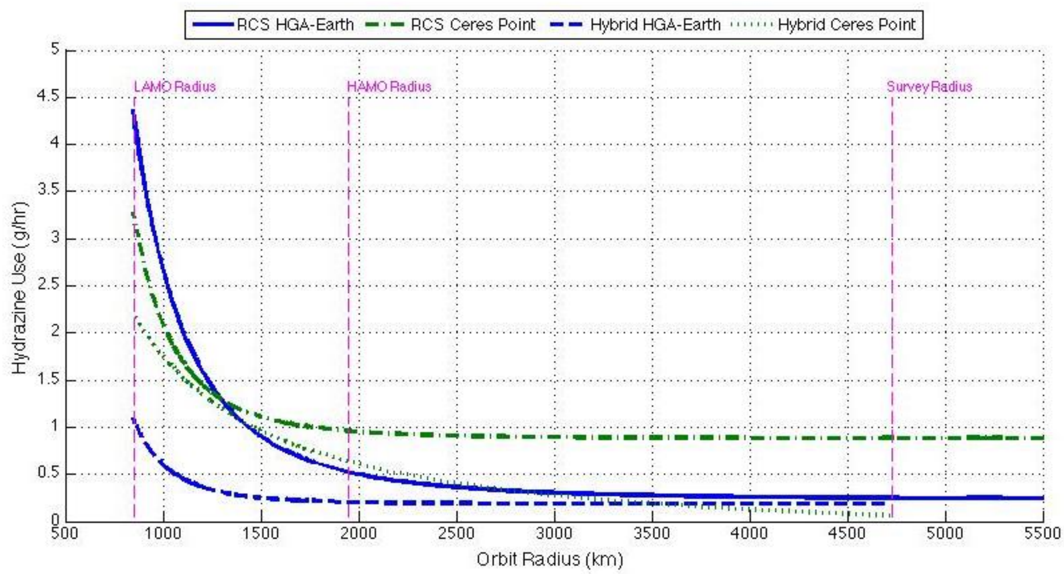

Figure 4. Hydrazine Use as a Function of Orbit Radius

The science objectives at Ceres resulted in an orbit profile similar to Vesta, with 4 primary science orbits. Each orbit had unique objectives, all with different propellant costs. **Figure 4** shows the average propellant cost as a function of orbits radius, with the science orbits identified at the appropriate radii. Propellant cost for both hybrid and RCS control are shown for the two primary attitudes: instruments pointed at nadir (Ceres Point), and in the downlink orientation (HGA-Earth). While high orbits still produced hydrazine savings, the most dramatic savings in the total propellant were achieved at low altitudes. A striking finding was the LAMO hydrazine savings of approximately 1 g/hr while nadir pointed, and ~3 g/hr savings while pointed HGA-to-Earth. It was found, that under RCS control, 90 days in the lowest orbit would use as much hydrazine as the planned 320 days to get to the LAMO orbit. With this realization the decision was made to save the use of hybrid control until LAMO. Since we could not guarantee that the wheels would survive more than 90 days, the decision was to use them where they provided the largest benefit.

Conserving propellant with hybrid control

There were a number of factors that would affect the amount of propellant savings under hybrid control, though the primary one, that could be controlled, was the amount of momentum stored in the two wheels in use. Once the RCS thrusters are used for partial control of the spacecraft, then momentum is no longer conserved in the system. When the spacecraft is rotated, such as pointing at Ceres nadir, the thrusters have to push the RWA momentum vector. Effectively the spinning RWAs produce a gyroscopic stiffness that the thruster controlled axis has to overcome. As expected, minimizing the wheel momentum helped to minimize the propellant usage. Limiting rotation would have also helped mitigate this issue, however this was not an available option, based on the pointing commanding capabilities.[10] The built-in solar array optimization algorithm restricts the available attitudes. The primary vector is all that can be defined and the algorithm computes the most power optimal orientation to completely define the 3-axis attitude.

There were downsides to keeping the wheel momentum vector small, such as increased sub-elastohydrodynamic (EHD) time and increased numbers of zero-crossings. Both of these are thought to reduce lifetime of the RWA, due to excessive metal-to-metal contacts. Increasing the average wheel speed significantly cut into the hydrazine savings to the point of nearly losing all the benefits of hybrid while nadir pointing at Ceres. Earlier in the mission, operational guidelines led us to actively plan the RWA use to avoid zero-crossings and low RPM ranges, those guidelines were disregarded for operations at Ceres. With the two previous RWA anomalies, the flight team determined that the risk to RWA health was greatly outweighed by the hydrazine saving potential.

RCS Thruster Pulse Management

One unexpected result of using hybrid control was the need to actively manage RCS thruster pulse duration. Simulations clearly showed that the lowest science orbit would be the most expensive on the hydrazine budget in all-RCS control. Simulations of all-RCS control showed an evenly distributed use of thrusters, however hybrid control relied heavily on only two thrusters. Due to the geometry of the healthy RWAs and thruster locations, hybrid control results in the thruster controlled axis aligned with just two RCS thrusters. Simulations of hybrid control showed that there would be a large number of minimum impulse firings on these two RCS thrusters, enough to exceed the specified maximum pulse count limit for the two thrusters in use. With thruster specifications in mind, we were able to increase the minimum thruster pulse duration without having to change the hybrid controller algorithm. Increasing the minimum pulse duration reduces pulse counts, but at the same time results in increased pointing error in the thruster controlled axis. This error was not significant for the science observations, however it would have detrimental effect on the telecom downlink performance. In the end, we were able to provide margin on the thruster pulse counts and still meet high gain antenna pointing requirements with a tailored approach. During science pointing sequences, the minimum pulse width was relaxed by a factor of 4, reducing pulse counts. During downlink periods, tighter pointing accuracy is required, so the minimum pulse width was restored to nominal. This provided the needed pulse count margins for the RCS thrusters without compromising either science data or telecom performance.

Science Planning Accommodations

Special accommodations in science planning at Ceres were needed both for portions that were under all-RCS control, and for those under hybrid control. It was important for the team to develop a single observation strategy that was adaptable for either control scenario. Tight all-RWA pointing at Vesta allowed very precise planning of camera image footprints. Under all-RCS control, looser pointing performance could result in significant gaps between images in the data set. A plan based on a reduced FOV could guarantee overlap even if adjacent images were be on opposite sides of the loose RCS control range. Under hybrid control the RCS controller is responsible for portions of the axes orthogonal to the camera boresight, therefore a reduced FOV was necessary for planning hybrid control sequences as well. **Figure 5** shows the control range under hybrid control. There was loose control about the spacecraft Y-axis and Z-axis, and tighter control about the X-axis. Optimization of solar array orientation prevented the tightly controlled axis from consistently aligning with the along track or cross track direction. To simplify the planning process, a common reduced FOV was used to ensure adequate image overlap with either all-RCS or hybrid control.

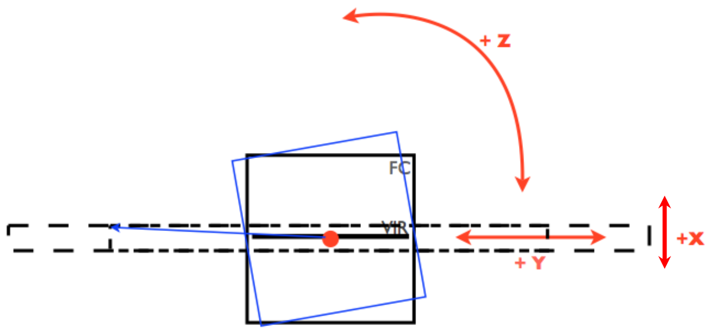

Figure 5. Hybrid (RWA 1-2) Control Pointing Performance

Hybrid Control Sequencing Commanding

This agnostic science plan allowed the operations team to build sequences robust to either all-RCS or hybrid operating conditions, so that in the event of a change of planned actuators, nominal science operations could be resumed quickly. In fact, the sequences were built with the unique commanding for both all-RCS and hybrid control. If operating under hybrid control, as planned, the all-RCS commands would be non-interactive. Similarly, if it were necessary to go to all-RCS, the sequence would still work and the unique hybrid commands would be non-interactive. This only worked with the help of the science team in making the plan robust to both scenarios and not making specific use of either control case. While this method took a bit more work upfront to work out it provided a much simpler and relaxed sequencing approach when the reliability of the remaining wheels was uncertain.

HYBRID CONTROL IN-FLIGHT PERFORMANCE

The final Ceres observations strategy resulted in using RCS-TVC for orbit transfers and all-RCS control for all science orbits except the LAMO orbit. RWA1 and 2 were powered on after the transfer down to the LAMO orbit and hybrid control was used for the 250 days of LAMO. Hybrid control performed very well and saved enough hydrazine to allow a longer LAMO phase and opportunities for an extended mission.

Hydrazine Use Prediction vs. Actual

While **Figure 4** showed relative differences in propellant usage it was based on steady state averages and not the detailed estimates based on any given plan. That data was used to make the high level decision of when to use RCS control and hybrid control. With the high level decisions made, the flight team then went through a planning process of developing integrated sequences for the entire baseline science plan; this was called the integrated sequence build (ISB) process. This ISB process allowed for detailed predictions of hydrazine use to ensure the plan would be achievable. **Figure 6** shows the ISB predictions as well as the as-flown sequence predictions and compares those to actual flight estimates of hydrazine usage.

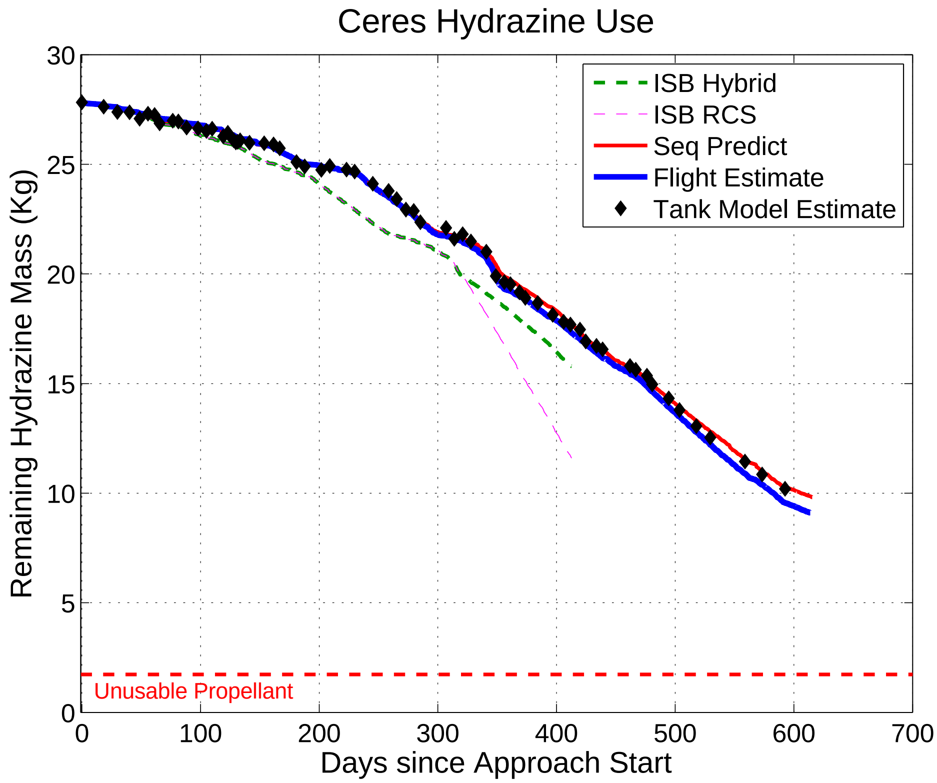

Figure 6. Ceres Hydrazine Use

Figure 7 shows the same data as **Figure 6**, although it is zoomed in to focus on the LAMO timeframe and the ISB data was shifted to the actual start of LAMO. The planned ISB sequence predictions can be seen based on the plan of using RCS control down to LAMO and then hybrid control for LAMO. The separation of the ISB predictions from the as-flown sequences and flight data was a result of modifications to the plan that kept Dawn at higher altitudes longer than in the initial ISB plan. The dashed magenta line shows that if another wheel failed and LAMO had to be executed on RCS control there would have been only ~200 days before all the usable propellant was used. The prime mission ended 180 days after our LAMO arrival so it is clear that under all-RCS control the plan had just enough hydrazine to operate until the end of the prime mission, with almost no margin for anomalies. The level 1 science objectives would have been met in the first ~42 days, but we wanted to ensure that we could gather additional data through the end of prime mission, and have more propellant margin. Under the basic plan, hybrid control cut the propellant use in half allowing for LAMO operations to last for twice as long, or have close to 10 kg of hydrazine margin at the end of the prime mission, as indicated by when green dashed line. Flight data in blue showed that hydrazine was able to be conserved even more than our intial plan ending the prime mission with 11.4 kg.

Identifiable in both the hydrazine use figures is that the flight estimates were very close to the sequence predictions, the blue flight estimate line is computed from thruster on-time telemetry while the black diamonds are hydrazine consumption estimates using tank pressure and temperature telemetry. The accuracy of both the ISB predictions as well as the final sequence predictions were very good. The accuracy of the predictions and the realized propellant savings allowed for planning and execution of a much better science data set. By the end of LAMO Dawn had acquired 99.9% imaging coverage and topography coverage of 94.9% of Ceres at the high resolution in LAMO. By contrast no imaging was required in LAMO for mission success.

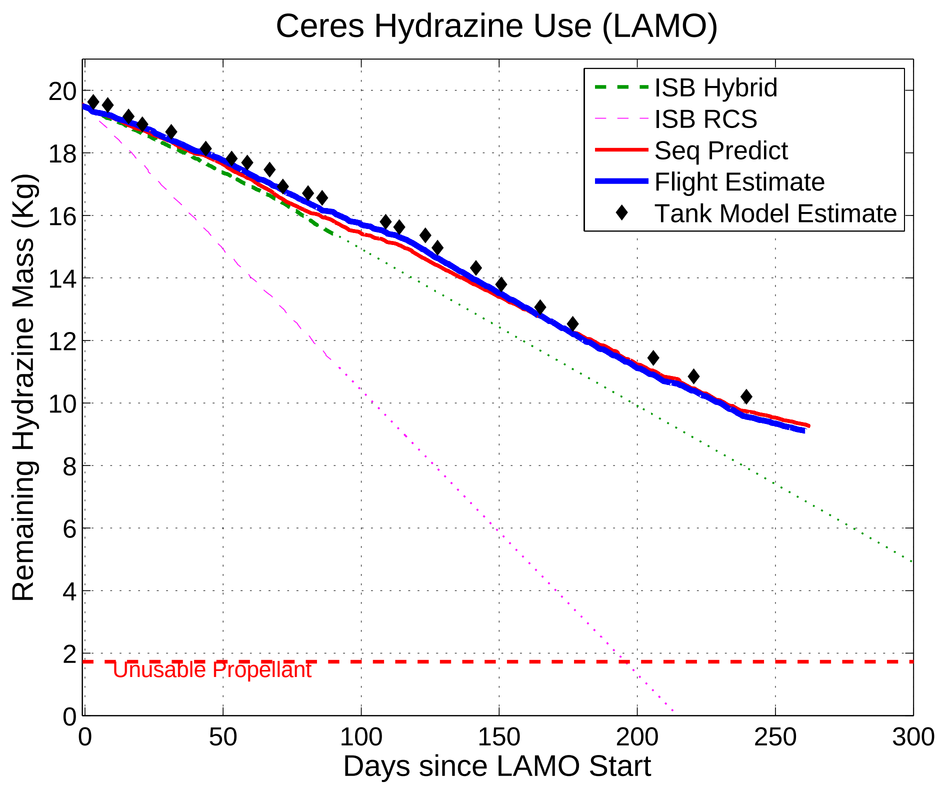

Figure 7. Ceres LAMO Hydrazine Use

Off-Nadir Pointed Hydrazine Savings

The initial 90 days of LAMO operations consisted of nadir pointed science observations. Once the initial mapping was done, it was desired to do off-nadir observations to build up a topography data set. Initially, it was expected that the off-nadir imaging would use more hydrazine since the non-symmetric orientation of the spacecraft would produce higher gravity gradient torques, which would need to be counteracted. While simulations of all-RCS cases showed modest increase in hydrazine cost for off-nadir angles of up to 8 degrees, hybrid simulation showed a different story. It was found that optimizing the momentum state of the wheels in accordance with the off-nadir angle could produce up to 60% savings of hydrazine compared to straight nadir pointing. Conversely, non-optimized momentum states could result in using 30% more hydrazine than nadir pointed observations. The ideal parameters were initial RWA momentum states that would decrease based on a combination of the gravity gradient profile and the natural rotation of the spacecraft. Some off-nadir angles provided a better rotation for exchange of momentum between the two RWAs in the hybrid controller.

The attitude that resulted in the local minimum in hydrazine use was not ideal for science topography data. However, we learned how to optimize the momentum target with the desired off-nadir angles to reduce the hydrazine use as much as possible. In the end, all the topography observations with various off-nadir look angles up to 8 degrees had hydrazine use that was comparable to nadir observations. Some of these benefits can be seen in Figure 7, where more optimal off-nadir angles were used and the slope shallows out for short periods, around 100 days since LAMO start.

Pointing Performance

The Dawn spacecraft had a wealth of experience in both all-RWA and all-RCS control throughout its long mission, resulting in fine tuned pointing simulation capabilities for those scenarios. With well-tuned parameters for both all-RCS and all-RWA pointing simulations, the hybrid control pointing performance was a combination of these two configurations. Pointing accuracy, under hybrid control, in the science pointing configurations was 4 mrad radial 99%. However, this accuracy is dominated by the RCS gain parameters in the Y-axis, with the RWA controlled X-axis approximately two orders of magnitude tighter. This resulted in 4 mrad 99% Y-axis accuracy, and 0.07 mrad 99% X-axis accuracy. The pointing stability also reflects dominant control mechanism for each axis, with the Y-axis performance at 0.12 mrad/s and the X-axis stability roughly two orders of magnitude lower. **Figure 8** details this pointing performance over a period of 100 hours, starting with a downlink session then turning to science pointing.

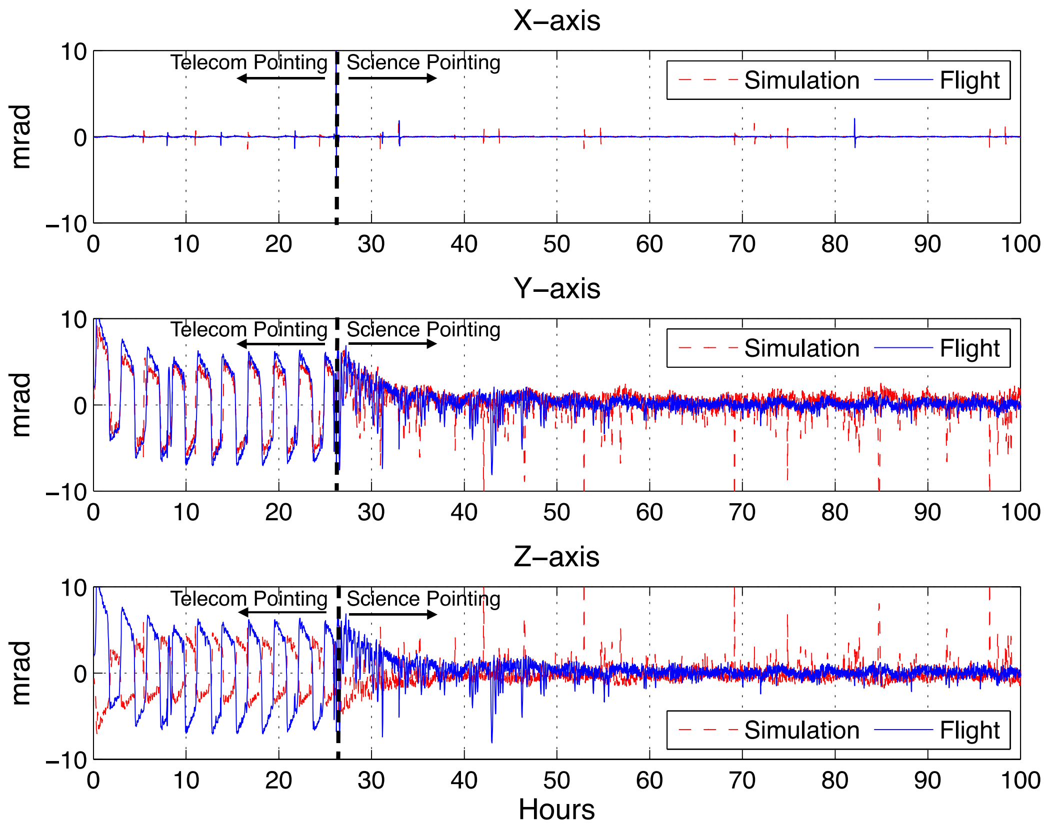

Figure 8. Hybrid Control Pointing Accuracy in LAMO

Wheel Health

Hybrid control while performing nadir science observations did not provide flexibility to manage momentum in a way favorable to the RWA hardware. Throughout the mission prior to the second wheel fault, efforts were made to avoid periods with the wheels operating in low speed ranges. This rpm management was done to avoid time in the sub-EHD range where increased wear on the bearings may occur. Achieving the fuel reductions, while collecting imaging, necessitated a low RWA momentum vector and thus low average wheel speeds. Earlier in the mission the distribution of wheel speeds looked bimodal with larger percentages of time spent just outside the sub-EHD range. **Figure 9** shows the distribution of wheel speeds that were observed while operating in hybrid control at Ceres. No rpm management to avoid sub-EHD was performed so that keeping low wheel speeds for fuel reductions and significant zero crossings resulted in a significant amount of time operating the RWA in the sub-EHD region.

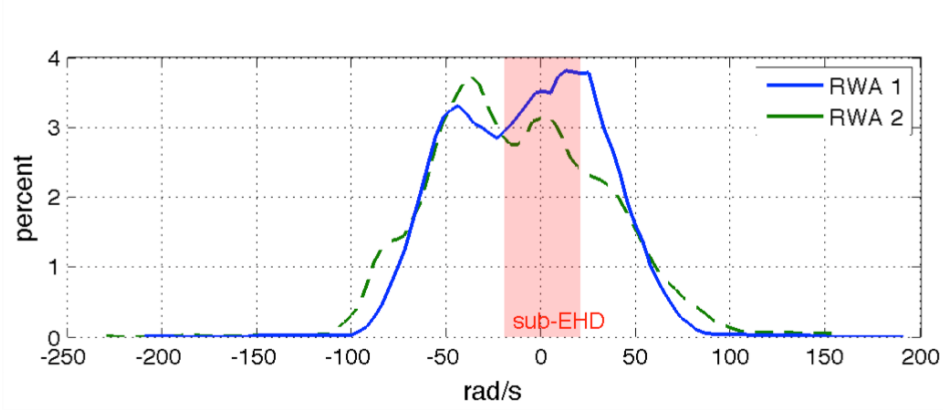

Figure 9 Reaction Wheel Speed Distribution (Ceres LAMO)

Despite removing any optimization of wheel speed use to improve long-term health, there have been no indications of any degradation in the performance of the two healthy wheels. While the type of anomaly seen in RWA-3 and RWA-4 provided no advanced indication, no new anomalies have occurred and no new indication of wear have been identified. No significant spikes or deviations in the estimated friction have been seen, and the data looks in line with friction estimates throughout the mission.

PRELIMINARY RESULTS FROM EXTENDED MISSION

Since finishing the prime mission in June of 2016, Dawn has continued in an extended mission, gathering additional science, thanks to the hydrazine savings provided by hybrid control. The spacecraft has since left the LAMO altitude, raising the orbit to two different extended mission orbits, to capture additional unique observations, under different viewing conditions. The RWAs have continued to operate well and hybrid control operations continue. The transfer to the higher orbits provided the opportunity for extended operations in the configuration of 2-RWAs plus the gimbaled ion engine for control. All aspects of attitude control have continued to work well through the orbit transfers and additional science orbits. As the spacecraft raised higher out of the Ceres gravity well, the propellant usage has been significantly reduced and with the hybrid control capability there is the opportunity for significant extended mission operations.

CONCLUSION

The Dawn mission had a very successful prime mission culminating in highly successful Ceres science campaign. Despite the setback of two RWA anomalies that removed them from service, the Dawn spacecraft was able to return a rich science data set at Ceres comparable to that returned from the Vesta campaign. The loss of the two reaction wheels led to a different operational mode at Ceres, which was outlined here, with a focus on the use of RCS-RWA hybrid control in the lowest science orbit, LAMO. A number of observation planning and sequencing accommodations were implemented to make the science observations work efficiently and ensure our more limited hydrazine resources are conserved. Some of the accommodations were to use RCS to preserve the wheel lifetime, tightly restrict momentum growth while in hybrid, plan for oversampling of observations to accommodate reduced pointing accuracy, and modify sequences to be compatible with both RCS and hybrid.

By planning the Ceres campaign as a whole, we were able to smartly apply the hybrid control to most effectively conserve hydrazine and provide more time for science observations in the lowest orbit. Flight performance matched predictions quite well and hybrid control in the LAMO orbit was able to provide realized savings of approximately 2x compared to all-RCS control. Additional reduction in hydrazine use was found by optimizing RWA momentum state with off-nadir pointing angles, while the optimal configuration was not ideal for science observation needs, this allowed us to match momentum states to minimize hydrazine use for desired off nadir angle observations.

Despite focusing efforts on propellant savings and not on optimal conditions for RWA operations, the RWA performed well and remained healthy. No indications of increased friction were seen even, with the significant number of zero crossings and time spent operating at low RPMs. The continued health of the wheels has resulted in significant hydrazine remaining after completing the nominal operations in the Ceres LAMO orbit. After completing more than what could have been achieved with RCS control, there was enough hydrazine to have a significant extended mission, which is currently ongoing.

Hybrid control operations worked very well for Dawn helping achieve a very successful Ceres campaign. The implementation of the hybrid control logic, and the time to plan for optimal use, allowed for the success that was seen. The Dawn solution was specific to the Dawn mission but shows that given flexibility and a fair amount of time to prepare we were able to get a full rich science data set.

ACKNOWLEDGEMENTS

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