HYDRAZINE CONSERVATION FOR THE DAWN SPACECRAFT OPERATIONS AT THE DWARF PLANET CERES[*]

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Dawn is a low-thrust interplanetary spacecraft currently orbiting the dwarf planet Ceres. After successfully completing its Vesta and Ceres prime missions, Dawn is now in its extended mission, continuously exploring Ceres. After losing the second reaction wheel assembly at the end of the Vesta mission, the feasibility of the Ceres mission was at risk due to the potentially significant increase in hydrazine consumption from using only the reaction control system thrusters. This paper summarizes the intense, collaborative efforts undertaken by the project to conserve hydrazine prior to Vesta departure, during cruise to Ceres, and throughout the Ceres mission. The project's efforts in minimizing the number of turns are discussed. A special emphasis is given to describing various efforts taken by the Attitude Control Subsystem team in an attempt to reduce hydrazine consumption. These efforts include: changing default slew rates, control gain tuning, changing nadir pointing strategy with Ahead Cross Nadir pointing, hybrid control implementation using hydrazine based thrusters and two remaining reaction wheels, optimal science turn location analysis, and reaction wheel angular momentum management strategies for reducing the number of momentum unloadings. In addition to the Attitude Control Subsystem team's efforts, the Mission Design and Navigation team's efforts taken in designing hydrazine friendly orbit transfers are discussed. The trade study performed collaboratively by the Attitude Control Subsystem team and the Science Operations Support Team in choosing hydrazine friendly off-nadir targets is also discussed. Various simulation results are presented and compared against actual flight data obtained. Lastly, remaining hydrazine status at the end of the prime Ceres mission and the hydrazine management planning for the extended mission are discussed.

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INTRODUCTION

Dawn is the ninth project in the National Aeronautics and Space Administration's (NASA's) Discovery Program, with the mission objective of exploring the two most massive protoplanets in the main asteroid belt, Vesta and Ceres. Launched in September 2007, Dawn arrived at Vesta in July 2011 and explored the primitive body for approximately one year before departing in September 2012. After a 2.5 year cruise, Dawn arrived at Ceres in March 2015, making it the first interplanetary spacecraft to orbit two extraterrestrial (and nonsolar) bodies.[1] Dawn has completed its Ceres prime mission successfully in June 2016 after acquiring very rich scientific data in the Ceres Low Altitude Mapping Orbit (LAMO). With another series of exciting science campaigns scheduled in the ongoing extended mission, the value derived from Dawn will continue to be discussed in scientific circles for years to come.

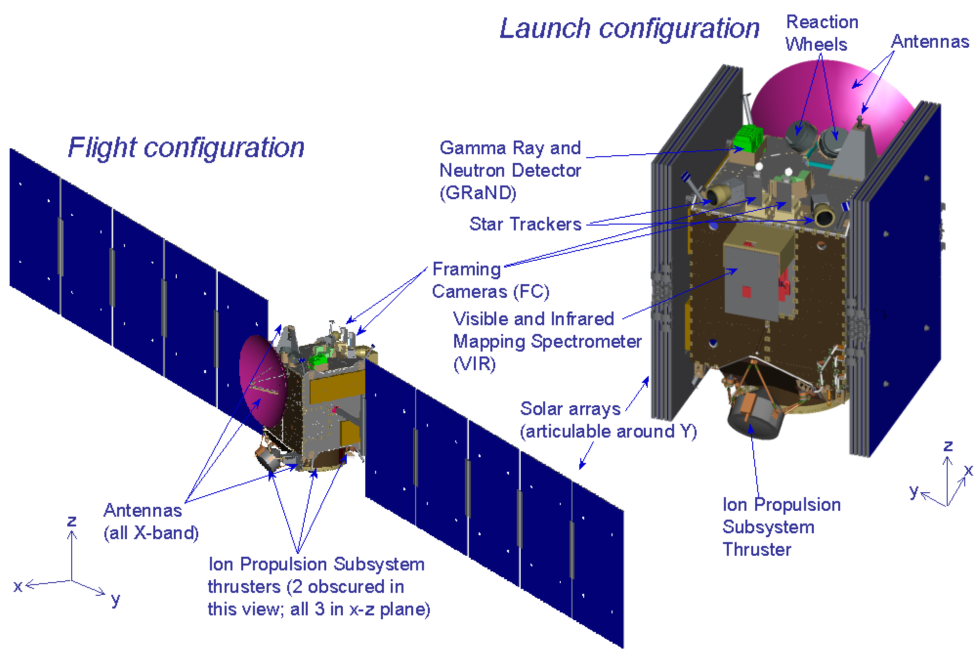

Figure 1. Dawn Spacecraft

Dawn's Attitude Control Subsystem (ACS) provides 3-axis attitude control using both reaction wheel assemblies (RWA) and a monopropellant hydrazine reaction control system (RCS). Although equipped with both RWA and RCS actuators, for the vast majority of the mission, Dawn uses continuous vectored thrust to maintain attitude. Thrust is provided by one of the three xenon ion propulsion engines. A thrust vector control (TVC) system provides 2-axis attitude control perpendicular to the line-of-thrust using a two degree-of-freedom gimbal mounted on each ion propulsion engine. Either RWA or RCS system provides attitude control about the remaining axis along the line-of-thrust. These control modes are respectively known as "TVC+RWA" or "TVC+RCS" control.[2] RWAs were designed to be the primary system for attitude control, and "TVC+RWA" was the default control mode while thrusting. However, a series of high friction RWA anomalies resulted in the loss of the first reaction wheel in 2010 prior to the Vesta operations, and the loss of the second reaction wheel during the departure from Vesta in 2012. With two of the four reaction wheel assemblies decommissioned, 3-axis attitude control using only RWAs was no longer a possibility. This meant a potentially significant increase in hydrazine consumption from using the RCS thrusters for attitude control. Immediately following the completion of the Vesta mission, the project had to undertake a rapid redesign effort to determine the feasibility of a Ceres mission using only the RCS thrusters for attitude control. Planning for efficient use of hydrazine became the primary focus of the mission planning for cruise to Ceres as well as operations at Ceres.

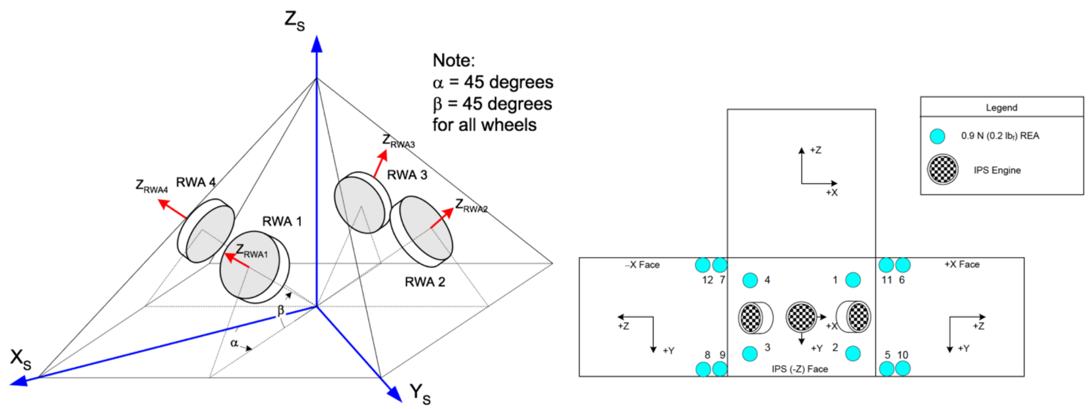

Figure 2. Dawn RWA and RCS Actuator Configurations

HYDRAZINE CONSERVATION

The first RWA fault with RWA4 was a premature failure after accumulating only ~25% of the expected lifetime of 2 billion revolutions (which was a very conservative limit compared to the original RWA lifetime limit of 8 billion revolutions). This unexpected RWA fault and the uncertainty on the lifetimes of the remaining three RWAs led the project to promptly undertake a campaign to conserve hydrazine. This section describes various efforts undertaken by the Dawn operations team to conserve hydrazine.

Hydrazine Conservation Efforts Prior to Second RWA fault during Vesta Departure

The first RWA fault with RWA4 occurred in June 2010, approximately one year before the start of the prime Vesta mission. In order to preserve the lifetimes of the RWAs for use in orbit at Vesta and Ceres, the project decided to power off the three remaining RWAs in August 2010. Immediately following the RWA failure, the project undertook an effort to conserve hydrazine.

In November 2010, new control gains were implemented in the attitude control subsystem to reduce hydrazine consumption in all-RCS control. These new control gains effectively loosened deadbands in roll around the axis that contained the High Gain Antenna (HGA), thus causing less frequent RCS thruster firings.[3] Also at the same time, the spacecraft slew rate was reduced from 0.1°/s to 0.05 °/s. With the slower slew rate, hydrazine cost for each spacecraft turn became roughly half of the nominal rate.

To prepare for the contingency case of yet another RWA fault, the project also undertook an effort to develop a hybrid attitude control capability which uses only two RWAs in combination with hydrazine based RCS thrusters to provide 3-axis attitude control.[4] Since two of the three axes are controlled by reaction wheels and only the third axis is controlled by RCS thrusters, hybrid control consumes significantly less hydrazine than all-RCS control. The software for this hybrid control system was installed in the spacecraft in April 2011 in case it was needed for Vesta operations. The remaining three RWAs were powered on again in May 2011 for the Vesta operations and they performed well throughout the Vesta mission. During the Vesta departure phase in August 2012, the second RWA fault with RWA3 occurred. System fault protection powered off all RWAs. All-RCS control and "TVC+RCS" control became the default control modes for "Cruise to Ceres" phase.

Dawn launched with 42.7 kg of usable hydrazine. When the second RWA faulted, there were 29.6 kg of remaining hydrazine. If no changes were made to the mission operations plan, Dawn would have arrived at Ceres with 18 kg of remaining hydrazine assuming no further anomalies. Although it was still too early to quantify the hydrazine cost for the Ceres science campaign at the time as the Ceres science plan was still under development, the expectation was that 18 kg was not enough to have a successful Ceres science campaign. This meant that the project had to find new ways to save even more hydrazine.

Hydrazine Conservation Efforts During Cruise to Ceres

With two of the four RWAs decommissioned, full RWA 3-axis attitude control was no longer a possibility. The feasibility of the Ceres mission was now at risk due to the potentially significant increase in hydrazine consumption from using RCS thrusters. Hydrazine consumption became a significant metric in most decisions about mission operations. The project had to undertake a more dramatic campaign as quickly as possible to conserve as much hydrazine as possible.

One of the most hydrazine-costly activities is turning. The Dawn spacecraft has to turn to point the High Gain Antenna (HGA) to Earth for each high-rate Deep Space Network (DSN) communication session. For the "Cruise to Ceres" mission phase, the project decided to have one HGA session every four weeks rather than every week. Also, in order to save still more hydrazine, the slew rate was reduced even further from 0.05 °/s to 0.025°/s.

Following the two RWA faults, the lifetimes of the remaining reaction wheels were uncertain and their reliability was questionable. The Science Operations Support Team (SOST) put efforts in re-architecting the Ceres science plan that would meet all science requirements even without any further use of the two remaining reaction wheels. Unlike the Vesta science plan which had frequent communication pass turns to Earth when the spacecraft was traversing the dark side of Vesta, the Ceres science plan included turns only when they were absolutely needed: when onboard data storage was full or when it was necessary to conduct other engineering activities. Also, turns to off-nadir angles were planned to be commanded directly rather than first turning to nadir and then performing a small off-nadir turn, further reducing the number of turns. Overall, the re-architected Ceres science plan had a factor of five less planned turns at Ceres than Vesta for a roughly equivalent mission duration.[5]

With all the hydrazine saving efforts combined, the available hydrazine upon Ceres arrival was 27.8 kg, which was significantly larger than the 18 kg we would have had if none of the hydrazine saving efforts were implemented during the "Cruise to Ceres" phase. The Dawn operations team delivered a Ceres science plan that would require ~17 kg of hydrazine expenditure even without using reaction wheels in hybrid control mode. Now the project had enough available hydrazine with adequate margin to carry out a successful Ceres science campaign.

Hydrazine Conservation Efforts During Operations at Ceres

Dawn began its Ceres prime mission in December 2014 shortly before being captured into orbit around Ceres in March 2015. There are four main science orbits at Ceres: Rotational Characterization orbit 3 (RC3) orbit at 13,520 km, Survey orbit at 4,424 km, High Altitude Mapping Orbit (HAMO) at 1,474 km, and Low Altitude Mapping Orbit (LAMO) at 374 km.

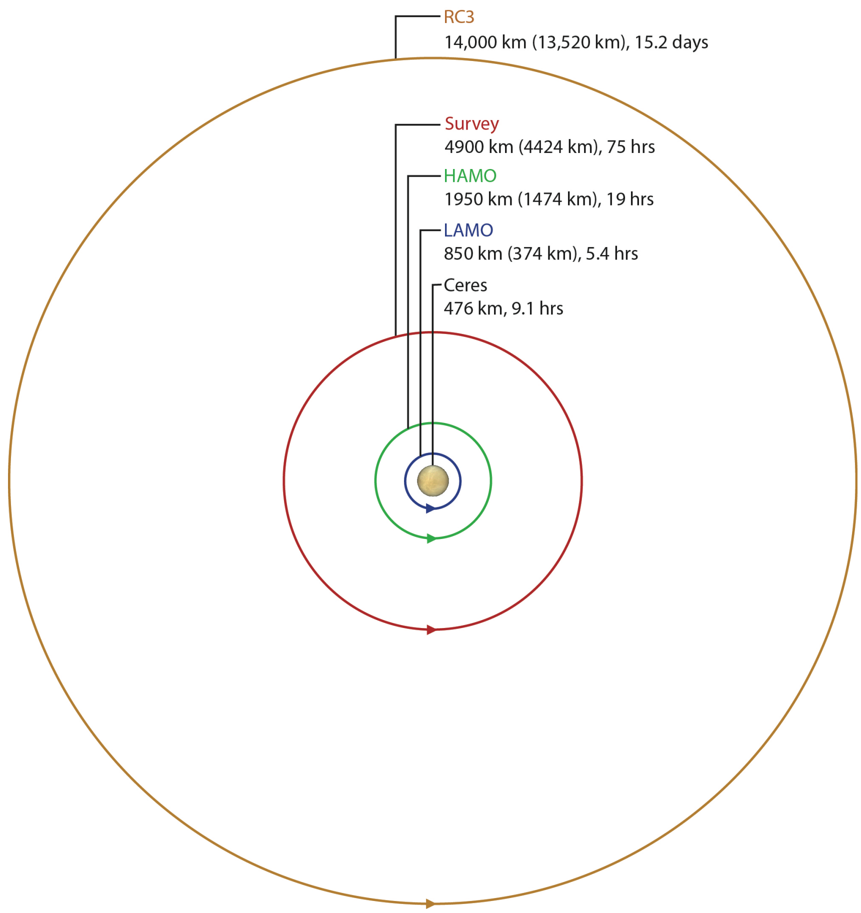

Figure 3. Ceres Science Orbits (Orbit Radius and Orbit Altitude) [6]

Even though enough hydrazine (with margin allocated for contingencies) was available for the entire Ceres mission planned, the Dawn operations team continued to put efforts into conserving hydrazine at every possible opportunity. The hydrazine consumption was tracked on a weekly basis and compared to the simulation predictions. Simulation models were updated with flight experience to produce more accurate predictions. Figure 4 shows the predicted and the actual hydrazine consumptions for the entire Ceres prime mission.

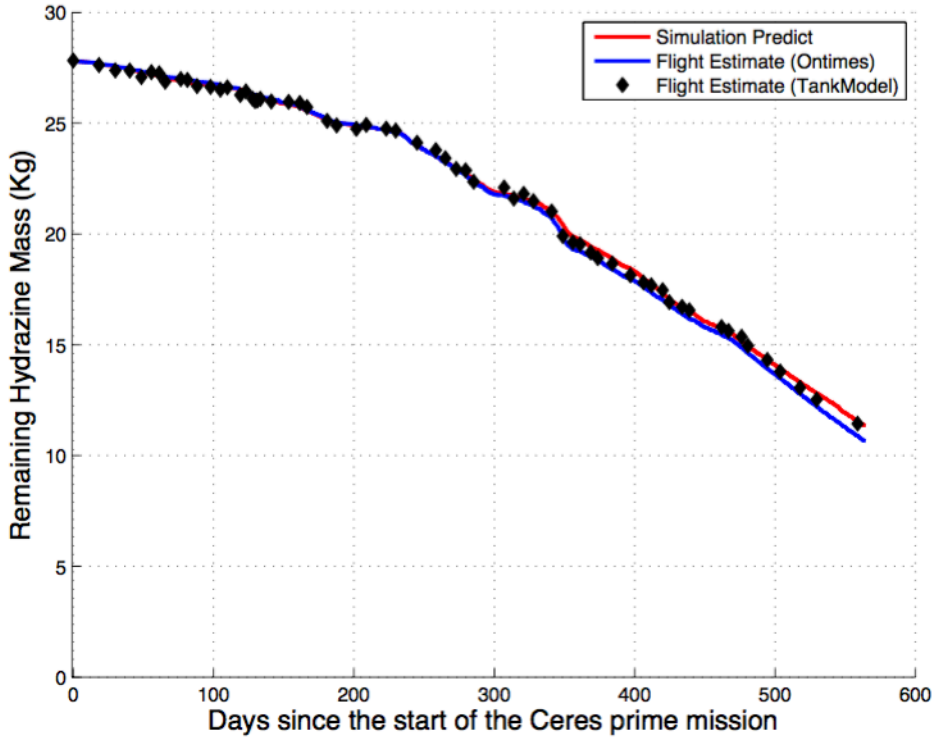

Figure 4. Hydrazine Consumption for the Entire Ceres Prime Mission

When designing orbit transfers from one science orbit to another, the Mission Design and Navigation (MDNAV) team put efforts into minimizing the amount of forced coasting. When coasting, Ion Propulsion System (IPS) thrusting is stopped and attitude is held fixed at an inertial target. Since hydrazine-based RCS thrusters are used to control attitude during coasting, coasting uses more hydrazine than IPS thrusting. When designing the reference trajectories, any unnecessary coast for margin was removed. Hydrazine savings from continuously thrusting instead of coasting ranged from 0.3 g/hr to 0.6 g/hr. Each transfer cycle had coast margin of around one day, and the MDNAV team eliminated most of the coasting to save hydrazine.[7]

Another decision that the project had to make was when to start using hybrid control for Ceres operations. Hybrid control, although not as efficient as full RWA control, produces a significant hydrazine savings over all-RCS control. However, the amount of hydrazine saving is not equivalent among the different phases of Ceres operations. Figure 5 illustrates this case by showing the average hydrazine cost of both science pointing and HGA pointing for all-RCS and hybrid control, as a function of orbit radius.

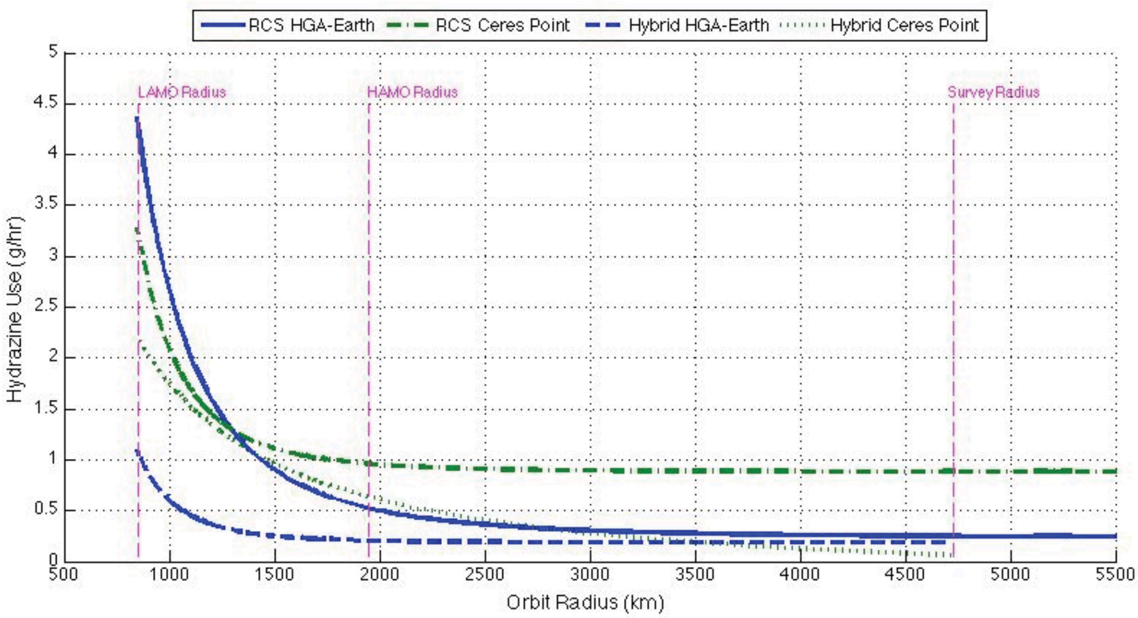

Figure 5. Hydrazine Cost vs. Orbit Radius[8]

Although the two remaining RWAs had not displayed any anomalous behaviors, the confidence in their remaining lifetimes was low. (The two RWAs that had filed had not displayed anomalous behaviors prior to their failures.) The project decided to wait until the Low Altitude Mapping Orbit (LAMO) to use hybrid control, where what may be a very limited remaining reaction wheel lifetime would yield the greatest hydrazine savings when compared to all-RCS control. Hybrid control became the default control mode starting from the LAMO phase. The two remaining RWAs have been performing flawlessly without any signs of problem.

Working collaboratively with the MDNAV team and the SOST, the Attitude Control Subsystem (ACS) team put significant efforts in conserving hydrazine. When the MDNAV team delivered science orbit reference trajectories, the ACS team performed optimal turn location analyses by simulating hundreds of turns at various locations on the orbit. Both the turns to Ceres nadir pointing and the turns to Earth for DSN communication were simulated. One such analysis performed for the LAMO phase is shown in Figure 6.

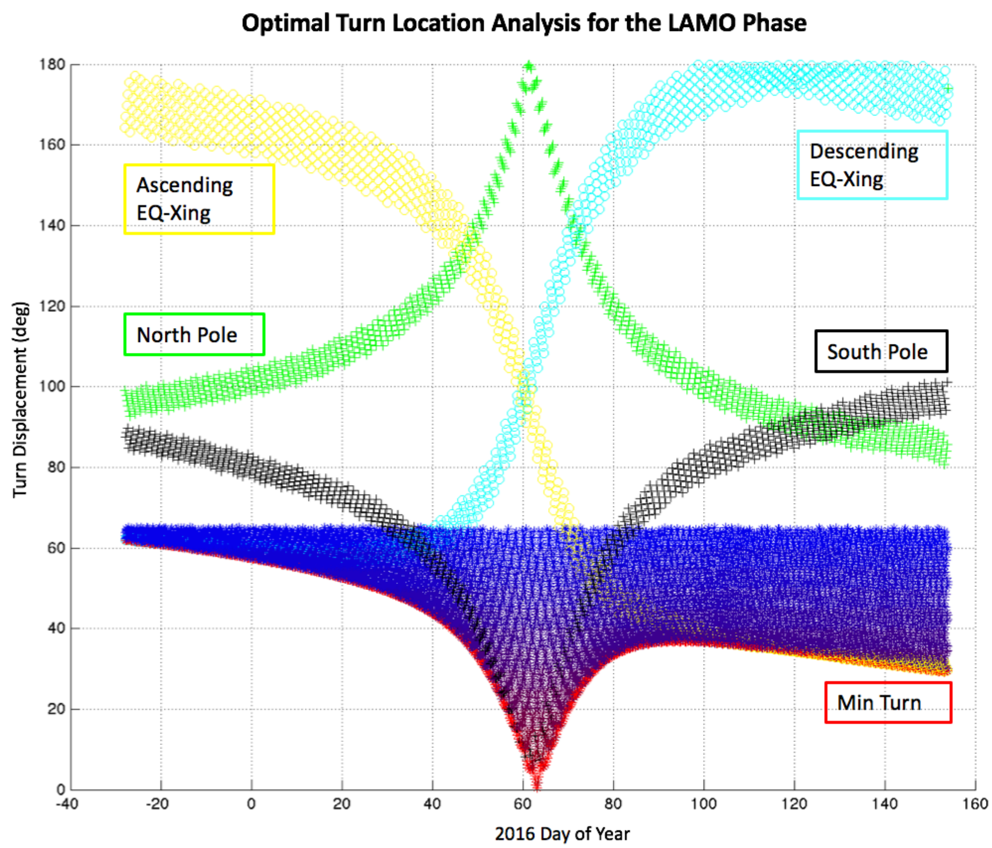

Figure 6. Optimal Turn Locations

The total angular displacements for turns along various points on the reference trajectory are plotted in blue (only the ones with less than 65 deg angular displacement are shown for clarity purposes). From all the available turns (shown in blue), the turns that start at four different orbit geometric features (North Pole, South Pole, Ascending Equator Crossing, and Descending Equator Crossing) were examined. Based on this analysis, the ACS team recommended the SOST to initiate turns where angular displacement can be minimized, thus conserving hydrazine. For example, the ACS team recommended the following for the LAMO phase:

- Before 2016-040: Start Turns at Descending Equator Crossing
- Between 2016-040 and 2016-075: Start Turns at South Pole
- After 2016-075: Start Turns at Ascending Equator Crossing

The prime LAMO mission had a total of nine science design cycles. The SOST placed all the turns at optimal locations for the first six cycles. For the last three cycles, most of the turns were placed at optimal locations except for few turns that had to be moved because of the DSN coverage.

Another change the ACS team implemented was to stay in the "TargetInertial" mode and use the Ahead Cross Nadir (ACN) pointing for nadir pointing, rather than switching to the "AsteroidNadirPointing" mode for nadir pointing. The ACN pointing is a pointing strategy developed by the ACS team after launch and implemented in a new software load in 2010 to conveniently command nadir and off-nadir pointing. "Ahead" direction is defined by the direction of the velocity vector. Nadir direction information is computed continuously by the onboard spacecraft computer based on the ephemeris information. "Cross" direction completes the right-hand orthonormal coordinate frame. Off-nadir pointing can be easily achieved by issuing ACN target in the form of [offset amount in the Ahead direction, offset amount in the Cross direction]. The ACN pointing with [0, 0] target means zero degree offsets in both Ahead and Cross directions, and this achieves same pointing as nadir pointing in "AsteroidNadirPointing" mode. The hydrazine saving comes from the special filtering algorithm that is used to reduce excessive thruster firings in the all-RCS "TargetInertial mode". Since RWAs were always assumed in use for nadir pointing when the spacecraft was originally designed, the "AsteroidNadirPointing" mode does not have this special filtering algorithm and thus ends up using extra thruster firings. The HAMO phase had total of six science design cycles, and all the nadir and off-nadir turns in the HAMO phase were implemented using the ACN pointing in the "TargetInertial" mode. The hydrazine savings averaged more than 100 grams for each of the six science design cycles, resulting in total hydrazine saving of more than 600 grams for the entire HAMO phase. The hydrazine cost comparison for the first HAMO cycle, da700 sequence, is shown below.

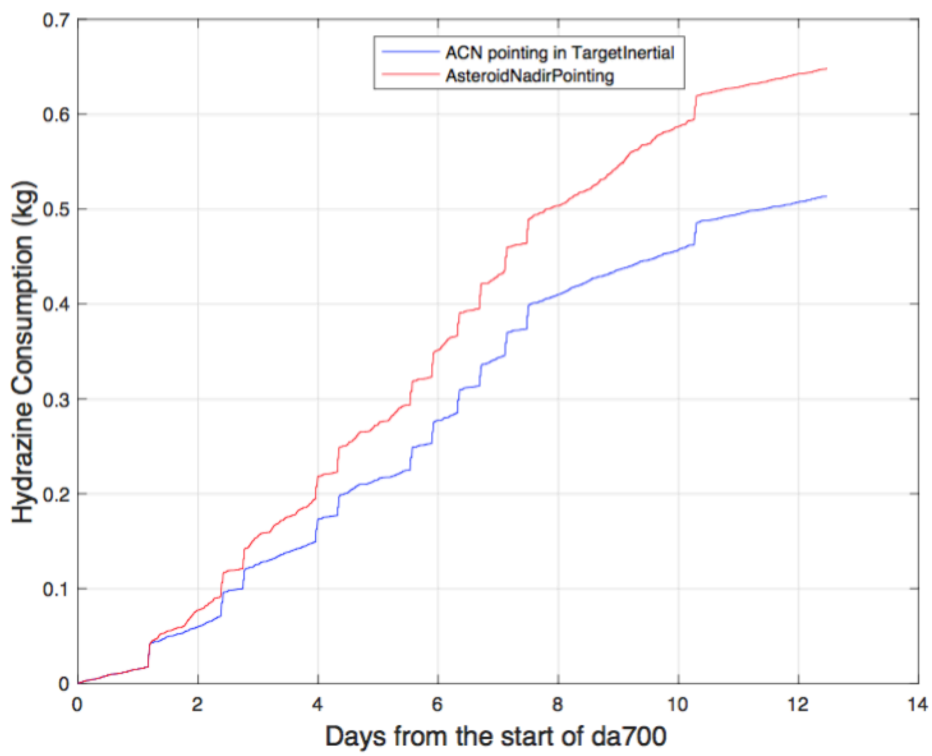

Figure 7. Hydrazine Cost Comparison for da700: ACN pointing vs. AsteroidNadirPointing

When the remaining two reaction wheels were powered on for hybrid control in LAMO, the ACS team put efforts into optimizing a few reaction wheel related parameters for hydrazine efficiency. For each sequence or even for different activities within a sequence, the polarity of the spacecraft angular momentum adjust target, either [0.0, 0.81, 1.15] Nms or [0.0, -0.81, -1.15] Nms, was carefully chosen such that the number of momentum unloadings is minimized. During a momentum unloading, RCS thrusters produce torque in the counter direction to cancel the resulting RWA torque on the body. Fewer momentum unloadings translates into conserving more hydrazine. Figure 8 illustrates that a significant hydrazine saving of ~500 g could be achieved by using the positive momentum target instead of the negative momentum target in da909, the last LAMO sequence of the Ceres prime mission.

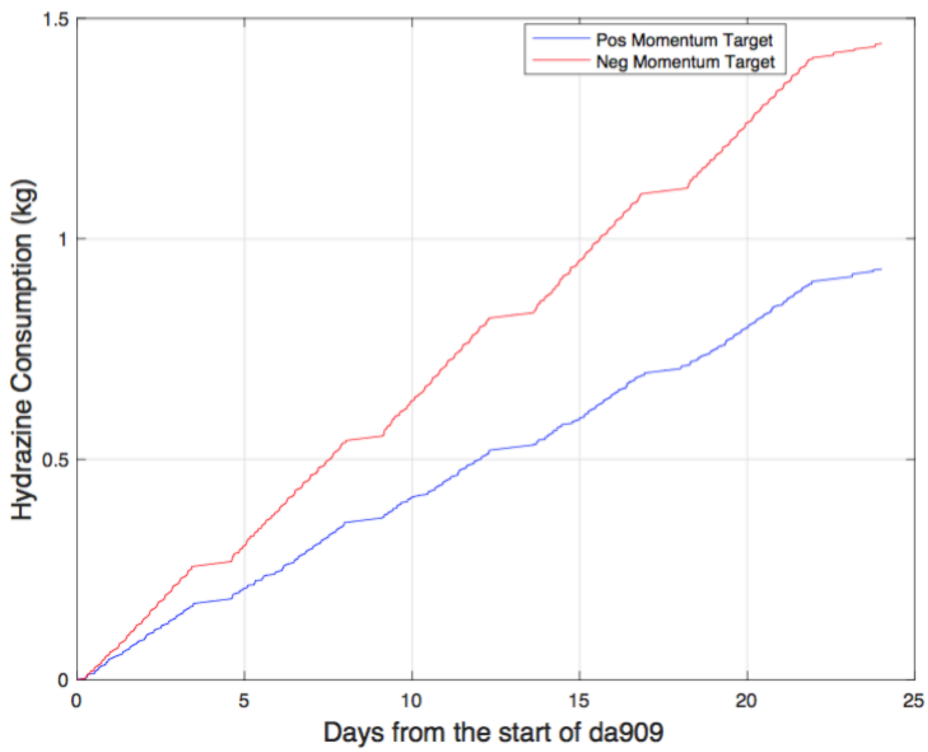

Figure 8. Hydrazine Cost Comparison for da909: Positive Momentum Target vs. Negative Momentum Target

The values for the three-axis momentum error high threshold were chosen to be [2.0, 2.0, 2.0] Nms for nominal science operations. When the difference between the spacecraft momentum and the momentum adjust target grows larger than the momentum error high threshold, a momentum unloading gets issued. By using a small momentum error high threshold of [2.0, 2.0, 2.0] Nms instead of using a larger threshold on the order of [10.0, 10.0, 10.0] Nms, the momentum stored in each reaction wheel is minimized. This in turn minimizes the RWA gyroscopic stiffness that the RCS thruster controlled axis has to overcome, thus minimizing the propellant usage. Figure 9 illustrates that over 1 kg of hydrazine could be saved for da900, the first LAMO cycle, by using momentum error high threshold of [2.0, 2.0, 2.0] Nms instead of [10.0, 10.0, 10.0] Nms.

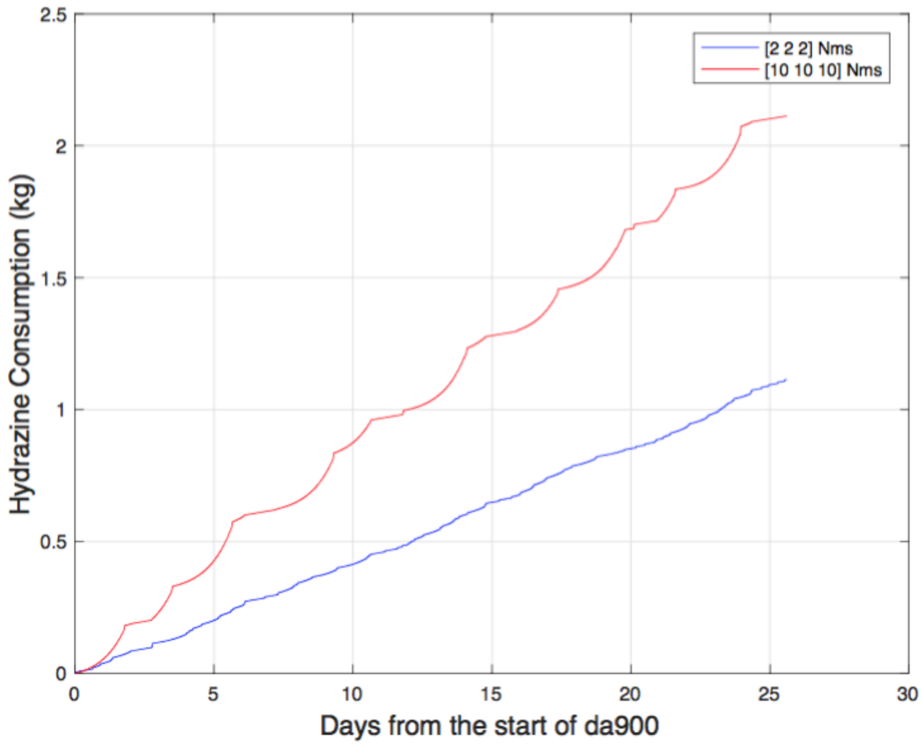

Figure 9. Hydrazine Cost Comparison for da900: [2 2 2] Nms momentum error high threshold vs [10 10 10] Nms momentum error high threshold

A slightly larger value of [5.0, 5.0, 5.0] Nms was chosen for the momentum error high threshold for the orbit maintenance maneuvers (OMMs) with the IPS thrusting. When performing an OMM with the IPS thrusting, hybrid control is used to control only one axis about the line of thrust. Typical OMM duration was 12 hours or less in the LAMO orbit. By carefully choosing an appropriate value for the momentum error high threshold, the Dawn operations team was able to completely eliminate the need for momentum unloading during OMMs throughout the entire LAMO phase, effectively eliminating the RCS thruster firings during OMMs.

After the successful completion of the full Ceres mapping during the first four science cycles in LAMO, SOST proposed a LAMO topography campaign which involved mapping Ceres with off-nadir pointing. The ACS team and the SOST collaboratively performed a trade study on various off-nadir angles that optimize hydrazine cost without sacrificing topography science results. One of the findings of the study was that there seemed to be some off-nadir configurations that favorably grow gravity gradient torque which would in turn cancel out the reaction wheel momentum growth, thus minimizing the number of momentum unloadings. For example, as shown in Figure 10, choosing an ACN target of [0, -5] deg reduces hydrazine consumption by more than a factor of five when compared to [-7, 7] deg ACN target. By carefully choosing off-nadir angles, a successful LAMO topography campaign could be carried out while minimizing hydrazine cost at the same time.

Cross Angle (deg) \ Ahead Angle (deg)	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
7	1773							1582							
6		1669						1502							
5			1552					1474					1628		
4								1453							
3	1619							1358							1680
2								1315							
1								1176							
0	1538	1561	1566	1432	1296	1209	1202	1146	1220	1282	1374	1455	1445	1557	1611
-1								1093							
-2								1037							
-3	1407							786							1439
-4								346							
-5			1043					342					1048		
-6								360							
-7	1158							386							1250

Figure 10. Hydrazine Cost (in grams) for Various Off-Nadir ACN Targets in the LAMO orbit

Ceres Extended Mission and Future Considerations

After the successful completion of the Ceres prime mission, Dawn is now in an extended mission continuously returning valuable scientific data at Ceres. There are three different science orbits planned for the Ceres extended mission. The first Extended Mission Orbit (XMO1) was dedicated to improve and wrap up science campaign at the 385 km LAMO orbit. After XMO1, the orbit was raised to the 1500 km XMO2 orbit where detailed observation of the Oxo and Juling craters were performed.

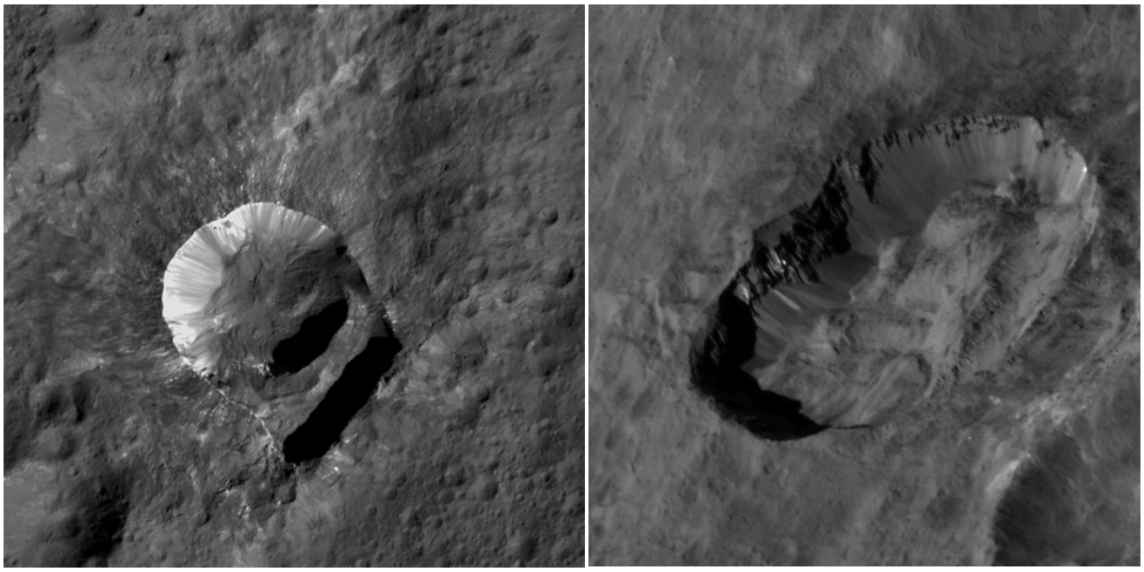

Figure 11. Oxo crater (left) and Juling crater (right)

After XMO2, the orbit was once again raised to the >7,200 km XMO3 orbit, where background spectra for the gamma ray and neutron detector (GRaND) instrument are being continuously obtained to improve the signal-to-noise radio of the elemental measurements collected at low-altitude. The Dawn extended mission operation is currently scheduled to end on June 30, 2017.

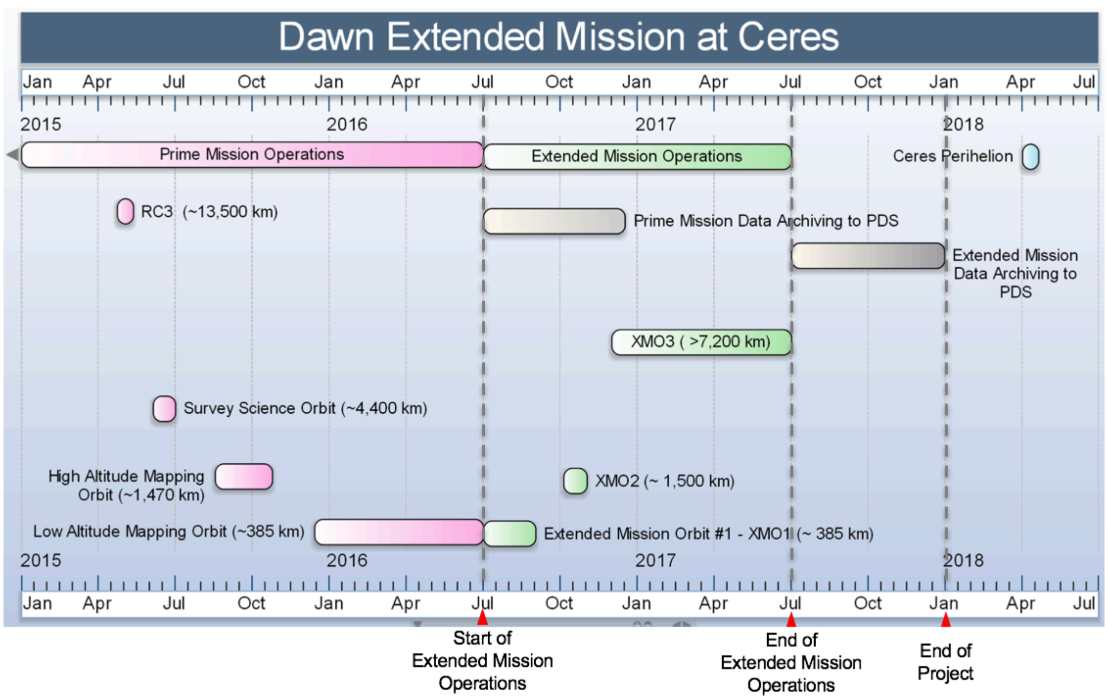

Figure 12. Ceres Extended Mission Timeline

Hybrid control has been working flawlessly without showing any signs of reaction wheel anomalies. If one or both of the remaining RWAs fault, then all-RCS control will have to take over, and the hydrazine cost will roughly be doubled. The current hydrazine estimates predict that there is adequate hydrazine remaining to successfully complete the current extended mission even with all-RCS control. The project has been continuously looking for ways to conserve hydrazine in all-RCS control at the higher Ceres orbit. Opening up deadbands further to the maximum allowable values while still maintaining acceptable HGA pointing would reduce hydrazine consumption. Also, the spacecraft slew rate, which was changed to 0.05 °/s for Ceres operations after completing the "Cruise to Ceres" phase at 0.025°/s, can be set back to 0.025°/s. This slower slew rate will reduce hydrazine consumption for each turn roughly by half. Dawn started the Ceres extended mission with 11.4 kg of remaining hydrazine. At the beginning of XMO3 in December 2016, there was 9.2 kg of remaining hydrazine.

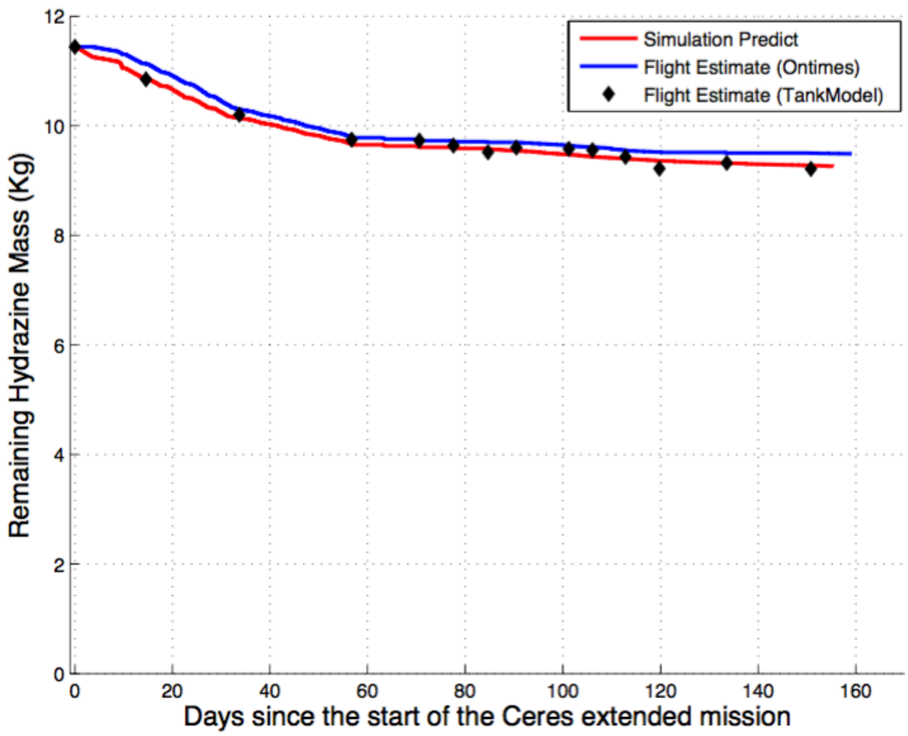

Figure 13. Ceres Extended Mission Hydrazine Consumption through the Start of XMO3

CONCLUSION

Dawn has successfully completed the Vesta and Ceres prime mission. All the prime mission objectives have been accomplished, and the quantity and quality of the science return has exceeded expectations. After a series of reaction wheel faults, the feasibility of a successful Ceres mission was at risk. The project had to promptly undertake a major campaign to conserve hydrazine. With the collaborative efforts on conserving hydrazine by each team member, the project was able to design and execute a highly successful Ceres prime mission without sacrificing any scientific return. Hybrid control has been working flawlessly, and produced a significant hydrazine saving throughout the entire LAMO phase. This hydrazine saving enabled the option for extended mission operations. The current extended mission is scheduled to be completed on June 30, 2017. Current estimates predict that there will still be significant hydrazine left at the end of the extended mission. The project continues to put efforts on conserving hydrazine. Should another extended mission be awarded, the project will have enough hydrazine available to make it an exciting mission.

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