Managing Momentum on the Dawn Low Thrust Mission

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Abstract—Dawn is low-thrust interplanetary spacecraft en-route to the asteroids Vesta and Ceres in an effort to better understand the early creation of the solar system. After launch in September 2007, the spacecraft will flyby Mars in February 2009 before arriving at Vesta in summer of 2011 and Ceres in early 2015. Three solar electric ion-propulsion engines are used to provide the primary thrust for the Dawn spacecraft. Ion engines produce a very small but very efficient force, and therefore must be thrusting almost continuously to realize the necessary change in velocity to reach Vesta and Ceres.

Momentum must be carefully managed to ensure the spacecraft has enough control authority to perform necessary turns and hold a fixed inertial attitude against external torques. Along with torques from solar pressure and gravity-gradients, ion-propulsion engines produce a torque about the thrust axis that must also be countered by the four reaction wheel assemblies (RWA). New constraints were placed on the 8-year mission shortly prior to launch that required Dawn to minimize time spent in the sub-Elasto-Hydro-Dynamic (sub-EHD) region and minimize the total revolutions of all four RWAs. Accurate prediction of wheel speeds is the first step in developing a strategy to minimize both wheel speeds and total revolutions. Due to schedule and staffing constraints, the ground tools needed to accomplish this momentum management process were developed post launch, in parallel with the missions initial checkout phase.

This paper discusses the momentum management issues of ion-propulsion missions and specifically the Dawn spacecraft. The discussion includes the tools and strategies developed to manage the spacecraft momentum with the goal of preserving RWA health.

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1. INTRODUCTION

Dawn is NASA’s ninth Discovery class mission on a journey to orbit two asteroids in the region between Mars and Jupiter. Scientists believe the asteroid belt provides similar conditions as those found during the formation of Earth. Dawn will investigate Vesta and Ceres, which are two of the larger objects in the region, and each provides a unique view into the formation of planet like objects. The Dawn mission is also unique as it will be the first spacecraft to orbit two extraterrestrial planetary bodies [1].

Launching on September 27, 2007, the Dawn spacecraft began its 8-year journey. After a flyby of Mars it will begin mapping Vesta in 2011 and then Ceres in 2015. Built by Orbital Sciences Corporation and operated by the Jet Propulsion Laboratory, the spacecraft has design heritage from both organizations. The mission is made possible by ion propulsion technology, successfully demonstrated by NASA’s Deep Space 1 (DS1) mission. Using an ion propulsion system on Dawn provides a mission opportunity that would be too costly or massive with conventional propulsion, however a long trajectory is required to reach the asteroids.
the delta-V per unit of propellant for an object of given mass. Dawn will be able to provide about 11 km/s of delta-V by the end of mission using less than 450 kg of propellant. For missions like Dawn this efficiency allows for a smaller and less expensive spacecraft to be built and launched.

Low thrust missions also provide unique complexities. Although a large total delta-V can be achieved, it is realized in small amounts over long periods of time. Conventional mission design composed of a ballistic cruise phase gives way to a new design that requires nearly constant thrusting to reach the desired targets. Continuous thrusting means any spacecraft anomalies must be solved quickly with a focus on a safely returning to thrusting as soon as possible. Margin must be carried throughout the mission to accommodate a small amount of lost thrusting time while still reaching the targeted asteroids. Thrusting constantly reshapes the trajectory and requires continuous re-optimization of the thrust attitudes. Heavy involvement by the navigation team and spacecraft operations team is needed during the entire cruise phase of the mission.

An additional unique consideration with the use of ion propulsion systems is the duration and magnitude of rotational torques that exist. The ion engines are used for days at a time continuously producing a rotational, “swirl” torque even when using thrust vector control. When using reaction wheels for attitude control the momentum accumulation from this external torque is significant. Given that the reaction wheel assemblies (RWA) have a limited momentum capacity, the RWA momentum must be offloaded using hydrazine thrusters. Momentum cannot be offloaded before and after thrusting but must be managed throughout the duration that the ion engine is in use. In addition to the usual solar and gravity gradient torques, swirl torque, which is a function of IPS engine throttle level, adds complexity to the RWA momentum management.

Most RWAs are known to wear down faster with the amount of time spent in low speed regions where lubricant does not spread well and metal to metal friction begins to occur. This low speed region is known as the subelasto-hydrodynamic (subEHD) region. The subEHD region for the reaction wheels on Dawn is thought to be below 20 rad/s. Shortly before launch, the project identified a risk item associated with total revolutions accumulated on each RWA. An additional constraint was levied on the operations team right before launch to reduce the accumulated revolutions, in effect reducing the desired average speed.

The need for a tool that could predict the wheel speeds and momentum state for upcoming activities was readily apparent. Due to schedule and budget constraints, a tool to provide this capability was not developed prior to launch. Being developed out of necessity, a momentum management tool slowly began to take shape during initial checkout to meet the immediate basic needs. Eventually ground software tools were refined to accommodate a wide range of momentum management issues. The Dawn momentum management tools provide wheel speed and momentum predictions, design capabilities to reduce subEHD and total revolutions, and provide verification methods to compare results with flight data.

This paper discusses momentum management issues of ion-propulsion missions and specifically the Dawn spacecraft. The discussion includes the tools and strategies developed to manage the spacecraft momentum with the goal of preserving RWA health.

2. SPACECRAFT CONFIGURATION

The Dawn spacecraft has significant heritage from other Orbital and JPL projects. Dawn is an adaptation of Orbital’s STAR-2 spacecraft bus with avionics from the LEGOStar-2 series. JPL provided the ion propulsion system (IPS), based on the DSI mission[2].

![Dawn Spacecraft](image)

**Figure 2.** Dawn Spacecraft.

The dominant feature of the Dawn spacecraft is the large solar arrays, which extend to a length of 20 meters. Such large solar arrays are necessary to provide the power to the ion engines beyond 2AU. The figure shows the large solar panels mounted along the $y$-axis, and the high-gain antenna mounted on the $+x$ face of the spacecraft. Some of the attitude determination hardware is also mounted on the $+z$ deck including the two star trackers, and the inertial reference units (IRU’s).

**Attitude Control Subsystem (ACS) Hardware**

The Attitude control system has three actuator sets that can be used both to control the spacecraft and to overcome external torques. These three systems are IPS engines, reaction wheel assemblies (RWAs), and hydrazine thrusters.

The three IPS engines are aligned in the $xz$ plane with the center engine mounted on the $z$ face and aligned with the $z$-axis. The other two IPS engines are canted approximately 50 deg from $z$ towards the $x$-axis. All three IPS engines are gimbaled and have thrust vector control (TVC) to maintain
attitude about the two axes perpendicular to the thrust vector. Only one IPS engine can be used at a time due to power constraints. Since TVC can only control attitude about two axes, either RCS or RWA must be used to control the spacecraft about the thrust axis.

Four RWAs are mounted in a pyramid orientation and can be seen in Figure 3. RWAs are the primary actuator for attitude control when not using IPS. When under IPS thrust, the wheels provide control about the thrust vector, with TVC providing control perpendicular to the thrust line. Controlling spacecraft attitude with RWAs is based on the principle of conservation of angular momentum. Altering the wheel speed of one RWA changes the momentum of that RWA. The spacecraft rotates to counteract this change in wheel speed. At least three RWAs are necessary for controlling all three independent spacecraft axes. Over prolonged times external forces can add more momentum to the system than the reaction wheels can accommodate. Hydrazine thrusters must be used periodically to remove this momentum.

![Figure 3. RWA Configuration.](image)

The hydrazine thruster system consists of two redundant sets of 6 thrusters that can be used for attitude control, or to adjust the momentum of the RWAs. Not all of the hydrazine thrusters are coupled, and multiple thrusters must be fired to produce a torque about any axis other than the z-axis. Every time the uncoupled thrusters are fired a small delta-V is imparted to the spacecraft.

ACS Operational Modes

The Dawn spacecraft operates under several hardware configurations based on the task. When not thrusting with the IPS engines, the attitude may be controlled either by RWA’s or the hydrazine thrusters. Because they provide better pointing stability, RWA’s are used as the primary actuator while not thrusting. All four RWA’s can be used with a speed bias, to keep the zero momentum state out of the sub-EHD region. Although the four wheel configuration allows flexibility in momentum management it is generally not used. The Dawn project has chosen to operate in the three-wheel configuration to reduce the overall use of each wheel. Every six months the active wheel set is changed allowing a different wheel to be turned off.

Hydrazine thrusters provide a large control authority in comparison to the RWA’s. For this reason they would be used as the fall back controller in safe mode or if multiple RWA’s failed. Conserving hydrazine for use in desaturating the RWAs is another reason thrusters are not used as the default controller.

Most of the mission is spent thrusting with the IPS engines, which can be operated in 4 configurations: RWA control (with IPS seen as an external torque), hydrazine thruster control (with IPS seen as an external torque), TVC-RWA, TVC-JET (i.e. with hydrazine thrusters for control about the thrust axis). The first two configurations are rarely used as anything other than a transition to one of the TVC configurations, because momentum grows fast without TVC. TVC actively aligns the thrust axis through the center of mass (c.m.): when TVC is not on, any torques from the engine misalignment must be compensated for by another system. TVC-RWA is the preferred operational mode primarily for the pointing accuracy but also to conserve hydrazine and to minimize undesirable delta-V. Although TVC is controlling two axes, external torques still build momentum about the third axis.

3. EXTERNAL TORQUES

There are three significant sources of external torque that the Dawn spacecraft encounters: solar pressure, gravity gradient, and IPS swirl torque. Solar pressure is inversely proportional to the square of the solar range, if the center of pressure (c.p.) is offset from the center of mass (c.m.) a torque is produced. Since the solar panels are always kept normal to the sun, the spacecraft is relatively symmetric about the c.p., however Figure 2 shows location of the large high gain antenna which causes the c.p. to move away from the c.m.

Gravity gradient torque is the torque created on the spacecraft by nearby bodies of mass. This torque is inversely proportional to the cube of the distance between the body and the spacecraft. During cruise this distance is insignificant and thus gravity gradient torque isn’t considered. However, gravity gradient torque will be a factor during certain phases of the mission, most importantly during Mars flyby and at Ceres and Vesta.

The ion engines produce a rotational torque about the thrust axis called swirl torque, the most significant torque measured on Dawn. See Brophy et al. for more on swirl torque [3] (referred to as roll torque). Charged ions pass through two plates with a grid of holes while exiting the engine. Very small rotational misalignments of these plates is thought to produce the swirl torque observed on Dawn and DS1. Gimbal actuators which can also translationally move the thrust vector may contribute as well. Components of torque in the yaw and pitch axis of the IPS engine can be removed by TVC, but the remaining component results in roll/swirl torque. The
magnitude of the swirl torque is a function of the ion engine throttle level, and for Dawn this swirl torque is generally an order of magnitude larger than solar pressure torque.

4. DAWN MOMENTUM MANAGEMENT TOOL
Constraints on the momentum and wheel speed made accurate and efficient prediction a necessity for activity development early on in the mission. Dawn’s momentum management tool grew from a simple script that used rotations to predict wheel speeds at desired attitudes. Some of the initial ideas and concepts were drawn from wheel management tools on other missions but the specifics of Dawn necessitated a different approach and new capabilities[4]. The tool incorporated new capabilities and functions, as they were needed in flight operations, growing with each new sequence. The Dawn tool named MomProf (short for Momentum Profiler), is now a broad program that interfaces with other ground simulation and planning tools to provide wheel speed and momentum predictions, external torque modeling, RWA desaturation planning, and flight data analysis.

Managing Momentum
Five main issues must be taken into account for momentum management on Dawn, each imposing unique limitations. These issues are: low wheel speed (subEHD region), total revolutions, maximum speed, momentum error, and limitations in the command system.

- **Low wheel speeds (sub-EHD region)**
  Extensive research has been done on mechanical ball bearings used in RWA’s. A known problem is lubrication in the vacuum of the space environment. When the RWA’s spin faster than some minimum speed, the lubricant is able to provide an appropriate layer between the bearings and the race. This minimum speed defines the elastohydrodynamic (EHD) region. Whenever the speed is below the minimum, undesirable metal-to-metal friction can occur. The subEHD region for the Dawn reaction wheels is considered to be anything slower than 20 rad/s. An allocation for the total subEHD time of each RWA has been defined by the vendor to preserve the health of the wheels, requiring the operations team to actively avoid RWA speeds in this region.

- **Maximum speed**
  Dawn’s RWA’s have a wheel speed limit of 534 rad/s enforced by FSW, limiting the control authority and storable momentum of the RWA’s. The software limit protects against mechanical damage to the RWA’s that can be caused by exceeding the designed speed. This upper limit must be monitored through spacecraft turns to ensure a slew will not be commanded that demands more control authority than is available. In the event that this limit is exceeded a swap of RWA’s occurs, further overspeed violations lead to a transition to RCS control to provide the control authority to perform the turn. Unexpected transitions to RCS control results in an expense of hydrazine, and unintended delta-V which is not desired.

- **Total revolutions**
  Just prior to launch a new constraint was placed on the total revolutions for each RWA. A failure scenario was identified that was associated with total revolutions of the RWA. Dawn has taken the conservative approach, constraining the total revolutions to prevent any RWA from exceeding the new limit before the end of the mission. Since the mission and spacecraft were not designed with this constraint, the result has a significant impact on the operations team. Now even with a max speed capacity of 535 rad/s, the desired average speed during cruise is 50 rad/s. Keeping wheel speeds above 20 rad/s and attempting to average 50 rad/s greatly reduces the usable range of the momentum capacity. RWA desaturations must be designed more frequently and with fewer options to maintain the average wheel speed.

- **Momentum error**
  Onboard fault protection (FP) monitors the error between the current estimated momentum state and the last commanded momentum target. This fault monitor helps protect against excessive momentum accumulation before the RWAs run out of control authority. When a flight limit is exceeded an autonomous momentum adjustment (auto-desat) is commanded, returning the momentum state to the previous commanded momentum target. Since the momentum is commanded in the body frame an auto-desat may result in undesirable wheel speeds, if the auto-desat occurs at any attitude other than the attitude of the previous desat. Auto-desats can result in violating the three previous criteria discussed and are disabled, relying on the next level of FP if necessary. The operations team is responsible for accurately predicting and managing the momentum to avoid an FP response.

- **Commanding Limitations**
  There is a limitation on how accurately the spacecraft can realize a commanded momentum. This is a result of both non-coupled hydrazine thrusters and control algorithm limitations. In an effort to reduce hydrazine use during momentum adjustments, the flight software terminates a momentum adjust when the momentum error of each spacecraft body axis is within 0.2 Nms of the commanded values. A momentum error up to 0.2 Nms in one axis can translate to a wheel speed error in the range of 0 to 6 rad/s. Variations in final momentum error of all three axes can produce a wheel speed error ranging from 0 to 12 rad/s; however 3 to 7 rad/s is the generally observed range. With the previously defined constraints on wheel speeds the 0.2 Nms is a factor in the planning process.

Coordinate Frames and Momentum Background
For the Dawn spacecraft the J2000 coordinate frame is used as the inertial fixed frame. As the spacecraft orientation changes, the S/C body frame rotates with respect to J2000. Angular momentum is conserved when looking at the S/C as a system, thus the momentum vector is fixed in the J2000 coordinate frame. In order to manage the momentum the inertial vector must be translated to the spacecraft body frame. Figure 4 shows the J2000 frame, and the inertial vector \( \mathbf{h} \). The second set of axis shows the body frame rotated with respect to J2000. It is clear that the total momentum vector is identical.
in both coordinate frames, however the decomposition for the total momentum into components along the axes is dependent on the rotation of the spacecraft. Given \( \mathbf{h} \) and an orientation \( (q) \), \( h_x, h_y, h_z \) can be calculated in the body frame and used to compute \( \mathbf{h} \) at any other \( q \).

![Diagram showing Vector in J2000 and S/C body Frame.](image)

**Figure 4.** Momentum Vector in J2000 and S/C body Frame.

To effect a change in attitude, the spacecraft uses the reaction wheels to change the components of \( \mathbf{h} \) in the body frame. A rotation matrix between the RWA coordinate frame and the S/C body frame allows for easy conversion between individual wheel speeds and momentum in the S/C body frame. The problem is reversible. Given an initial \( \mathbf{h} \) and \( q \) one can determine wheel speeds. A unique solution exists for three wheels, however four wheel configurations have an infinite number of solutions. A bias setting for the wheels by the flight software provides the constraint to determine a unique solution.

**Tool Fundamentals**

MomProf was developed to operate in the MATLAB environment which provides an easy to use, common user interface. All data is loaded into MATLAB as a structure to provide easy, consistent access to all inputs by individual functions within the tool. A configuration file provides infrequently changed parameters such as RWA inertia, S/C inertia, and the rotation matrix defining the alignment of the each RWA in the Body frame. A tab delimited input file contains time, attitude, s/c rate, and mode information. This input file is an output of the kinematics pointing and constraint verification tool used to simulate sequence activities. Used in its most basic application, the Dawn momentum tool uses the basic principle of angular momentum computing momentum in the body frame, and RWA wheel speeds, for all given orientations in the input file.

From the wheel speeds calculated, the tool then summarizes time spent in sub-EHD, total revolutions, maximum wheel speed, maximum momentum error, and average wheel speed. A warning message is also generated providing the times that either momentum error or wheel speeds exceed thresholds, signaling that the momentum profile will result in a fault response if not altered. This information, along with a time history plot of wheel speeds and momentum allows quick analysis of planned activities. Various initial momentum states can be analyzed to find the solution that best meets the momentum management requirements. Representative outputs of the data summary and plots are shown in Figure 5.

![Momentum Tool Outputs](image)

**Figure 5.** Momentum Tool Outputs

**Adding External Torques and Derivatives**

Propagating momentum in the body frame and calculating wheel speeds is a relatively basic process in a system where angular momentum is perfectly conserved. However, in our real system we must consider external torques which add to the total momentum, and the desaturation procedures necessary to keep the momentum in an acceptable range. Incorporating significant external torques adds complexity since there are various external torques that act in different conditions. Figure 6 represents the data flow through MomProf.

![Flow diagram of tool](image)

**Figure 6.** Flow diagram of tool.
Adding external torque modeling and desat modeling turns the Dawn momentum tool into an indispensable visualization and planning tool.

Examples of this increased complexity is that solar torque generally acts about the y axis, while thrusting on IPS3 swirl torque acts about the z-axis, and IPS1 and IPS2 produce torques about a vector canted 50 deg from the z-axis. External torque models for the Dawn momentum management tool are generally based on curve fits of measured flight data and updated regularly to improve future predictions. The MomProf input file includes ACS mode information and selected actuator state, which allows MomProf to apply the appropriate external torque models during timeframes they are to be expected. Since these external torques are acting in the body frame, one extra step is required in the tool. For each orientation in the input file the initial momentum vector is translated to the body frame and the momentum is calculated. Then the external torques are added to this momentum in the body frame. Finally the new momentum vector is calculated in the inertial frame. This new vector will be used for the next orientation.

External swirl torque from the IPS engine increases the momentum enough to require a desat at least once a day, while targeting an average wheel speed of 50 rad/sec. In an effort to help reduce average wheel speed and simplify sequencing, desats are commonly done every 12 hours while thrusting with the IPS engines. With a desat every 12 hours commanding a new momentum state, it is not practical to split the input file up and individually analyze the data between each desat. Providing an easy method to incorporate multiple desats made the analysis of entire sequences practical. A file containing desat time and the same parameters used for flight commands is read by MomProf inserting the commanded momentum targets at the desired times.

The flight software performs two kinds of desats, one is a normal desat done while in RW A control, and the other only removes momentum about the roll axis of the currently used IPS engine when using TVC. This second type is commonly referred to as a TVC-desat. Specific IPS engine and RWA combinations can result in swirl torque only affecting the speeds of two wheels. If the thrust axis only produces momentum affecting only two wheels, then the TVC-desat acting about the same axis has no control over the third wheel. Once entering TVC this third wheel will stay fixed at its current speed until the transitioning back to pure RWA control. This wheel must be carefully controlled, inadvertently allowing one wheel to get stuck in the sub-EHD region for up to 7 days could have significant impact to the health of that RWA. These conditions and the behavior of TVC-desats require extra care when selecting the normal desat prior to entering TVC control, to ensure reasonable wheel speeds at the time of the desat as well as at the time entering TVC.

**Momentum Target Selection**

One aspect of commanding momentum in the body frame is that specific wheel speeds may be desired at an attitude different from the attitude at which the desat is done. This scenario is the standard case during thrusting sequences. The spacecraft turns from the downlink attitude to the thrust attitude for a week before returning to the downlink attitude. Desats are often done during the downlink to provide Doppler visibility for the navigation team but we want to specify wheel speeds for the weeklong thrust attitude. Normal Dawn configuration uses only three wheels at a time, in this configuration there is only one set of corresponding wheel speeds between two attitudes. MomProf added functionality that takes desired speeds for any two wheels and provides the pre-turn and post-turn wheel speeds for all variations of the third wheel.

The purpose of the MomProf is to provide accurate predictions of S/C momentum and wheel speeds. Analyzing the ac-
Figure 8. Example output of predict comparison with flight data.

accuracy of the tool requires comparison with flight data. Flight telemetry can be loaded and plotted on top of the prediction. Figure 8 shows the difference between predicts and actual wheel speeds. This quick and easy comparison allows for insight into the accuracy of external torque models.

The top graph in Figure 8 shows an overlay of flight data on the prediction, while the bottom graph shows the per-axis error between predict and flight. Upside-down pyramids indicate where desats occur on the prediction error graph. The figure shows some of the difficulties in predicting momentum on the Dawn spacecraft. On the far left a desat is performed just prior to day of year 253 followed by a turn to thrust attitude. During the turn and prior to the start of thrusting the IPS engines are in diode mode where xenon flows out of the engine during this warm up mode. The external torque from this free flowing xenon is difficult to model and shows up in the errors early on day 253. The first desat, indicated by the triangle, shows the effect of the desat cutting off when the momentum error falls below the 0.2 Nms threshold. Errors remain relatively constant between desats representing a good model of the swirl torque caused by the IPS engine. Additional errors from using uncoupled thrusters for desats, commanded versus actual IPS thrust axis, and other details that show up in flight telemetry analysis are not discussed in this paper.

5. CONCLUSIONS

Momentum management is and will be an important issue on the Dawn spacecraft. This paper outlined some of the unique and challenging issues facing the operations team. The external torque generated by the IPS engines is a significant factor that must be well thought out on any ion-propulsion mission using RWA for attitude control. Constraints on wheel speeds and how those affect the workable operating range of the RWA must also be understood with any RWA mission, but is even more important on a mission like Dawn that must handle such large external torques. Last minute operational constraints, MomProf, was discussed, showing design and analysis capabilities used for sequence development. The MomProf tool allows the operations team to use some specific management methods and techniques to meet the needs of the Dawn’s spacecraft. The momentum management tool will grow with the mission to meet future needs and is expected to be an integral player in planning Vesta and Ceres operations.
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BIOGRAPHY

Brett A. Smith received his B.S. degree in Control Systems Engineering from Montana Tech of the University of Montana in 2000 and a M.S. in Mechanical and Aerospace Engineering from the George Washington University in 2004. From 2001 to 2002 worked as a systems engineer with Honeywell Defense Avionics designing flight software requirements for the KC-10 and C-5 aircraft. Starting in 2004 he joined the Jet Propulsion Laboratory as an attitude control engineer on the Cassini spacecraft. He is currently an attitude control engineer on both the EPOXI and Dawn missions.

Charles A. Vanelli Tony Vanelli is a Senior Engineer with the Jet Propulsion Laboratory, in the Guidance and Control Systems Engineering Group. He received his BSEE from the University of Texas at Austin, and his MSME and Engineer’s degree from the California Institute of Technology. His work at Caltech concerned control systems and autonomous motion planning for various vehicles, including spacecraft. Upon joining JPL in 1997 he worked on the design, implementation, and operations of the attitude control system for NASA’s Deep Space One spacecraft, which successfully made the first deep space use of ion thrust to fly by Asteroid Braille in 1999. After a mission recovery effort following the loss of DS-1’s sole star tracker, and a successful flyby of Comet Borrelly in September 2001, he went on to lead the development of the Mars Exploration Rover’s attitude determination and pointing system used for Mars-surface operations. He is now the lead ACS engineer for the Dawn mission. His outside interests include history and soccer.

Edward R. Swenka received his B.S. degree in Aerospace Engineering from the University of California Los Angeles in 1996 and a M.S. in Aerospace Engineering from the University of Southern California in 2001. He joined the Jet Propulsion Laboratory in 1995 and has worked on various missions including the Mars Exploration Rovers, Deep Impact, and Dawn as a guidance and control systems engineer. He was the Avionics Project Element Manager on the Dawn missions and is currently supporting the GRAIL project.