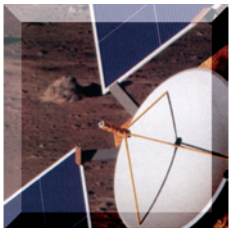

NEAR Shoemaker Spacecraft Mission Operations

Mark E. Holdridge

On 12 February 2001, Near Earth Asteroid Rendezvous (NEAR) Shoemaker became the first spacecraft to land on a small body, 433 Eros. Prior to that historic event, NEAR was the first-ever orbital mission about an asteroid. The mission presented general challenges associated with other planetary space missions as well as challenges unique to an inaugural mission around a small body. The NEAR team performed this operations feat with processes and tools developed during the 4-year-long cruise to Eros. Adding to the success of this historic mission was the cooperation among the NEAR science, navigation, guidance and control, mission design, and software teams. With clearly defined team roles, overlaps in responsibilities were minimized, as were the associated costs. This article discusses the processes and systems developed at APL that enabled the success of NEAR mission operations.

MISSION OPERATIONS OVERVIEW

The Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft was to rendezvous with a near-Earth asteroid, achieve orbit around the asteroid, and conduct the first systematic scientific exploration of such a body. On 14 February 2000, after a busy 4-year cruise, NEAR Shoemaker became the first spacecraft to orbit a small body, asteroid 433 Eros. The intensive yearlong orbital mission that ensued included numerous orbit changes and instrument operations designed to maximize the science return.

During the cruise to Eros, the mission operations (MOps) team carried out several important events including the flyby of main-belt asteroid 253 Mathilde, a deep space maneuver (DSM), and an Earth flyby. Lessons learned from these early events helped shape the tools used by the well-integrated MOps team that carried out the first-ever orbital science mission around, and down to the surface of, a small body.

Mission Operations Timeline

Figure 1 depicts the overall operations timeline for the NEAR mission starting with the launch on 17 February 1996. Many flight activities took place during the cruise to Eros, including numerous trajectory correction maneuvers (TCMs) that steered the craft to its final destination. As the figure shows, the majority of the mission was spent "getting there," with only 1 year of the 5-year mission dedicated to the close-up observation of Eros.

The cruise phase of the mission is shown in Fig. 2, a Sun-centered depiction of the orbit starting with launch. After launch in February 1996, NEAR began the first leg of its journey, which culminated in the asteroid 253 Mathilde flyby and the DSM. The Mathilde flyby produced the first scientific data return of the mission (first close-up observation of a C-class asteroid). Figure 3 is one of many images taken during NEAR's encounter with Mathilde.

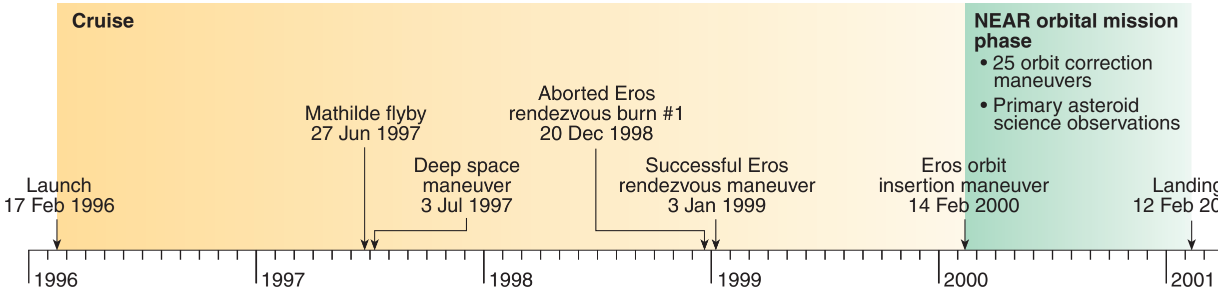

Figure 1. NEAR MOps timeline.

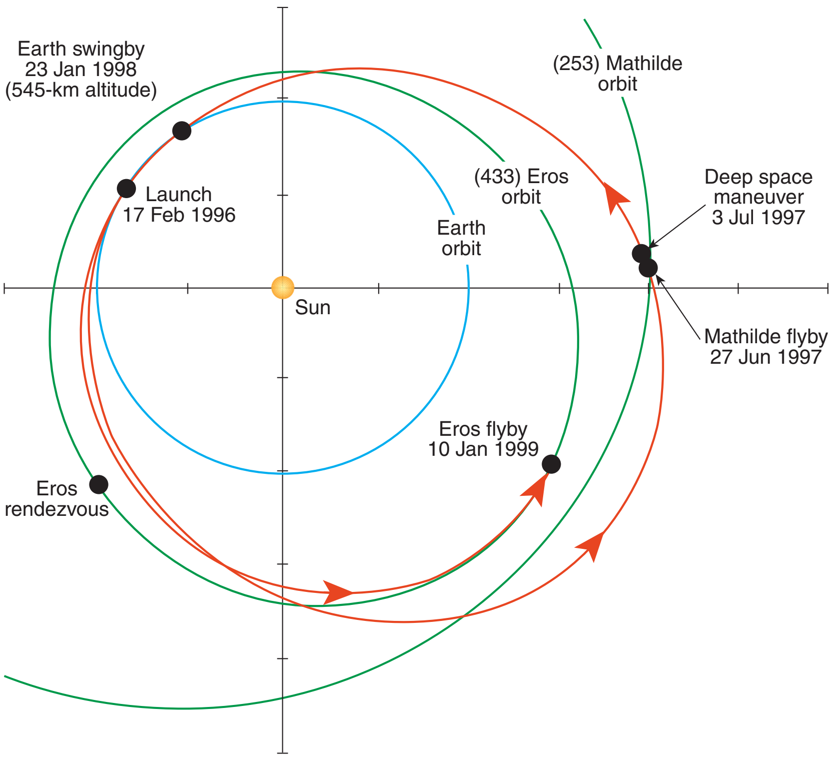

Figure 2. NEAR's Sun-centered trajectory.

Following the Mathilde encounter, NEAR's orbit was altered with a DSM to set up its trajectory for an Earth swingby. The DSM was the first firing of NEAR's 100-lbf bipropellant rocket engine and went without difficulties. Figure 4 is one of a series of images taken of Antarctica as NEAR later swooped over the Earth's Southern Hemisphere in January 1998.

Not obvious from the timelines are the lessons learned along the way and the comprehensive overhauls the APL Mission Operations Center (MOC) required to address these lessons and improve the overall state of the operation. An aborted first attempt to rendezvous with Eros on 20 December 1998 led to an unexpected Eros flyby[1] on 23 December and a yearlong return trajectory. During this extension to the cruise phase, mission operations implemented many more improvements to the command planning and validation process that would later prove beneficial to the subsequent orbital attempt. When the spacecraft returned to Eros in 2000 the team and the associated MOC ground support systems were ready to meet the challenges that lay ahead, planned and not planned, for what turned out to be a highly successful orbital mission at Eros followed by a soft landing on its surface.

Figure 3. Asteroid 253 Mathilde.

Mission Objectives

The NEAR Shoemaker spacecraft was to rendezvous with a near-Earth asteroid, achieve orbit around it, and conduct the first systematic scientific exploration of the body.[2,3] In summary, the primary mission objectives were to

- Determine the morphological and textural characteristics of the asteroid's surface

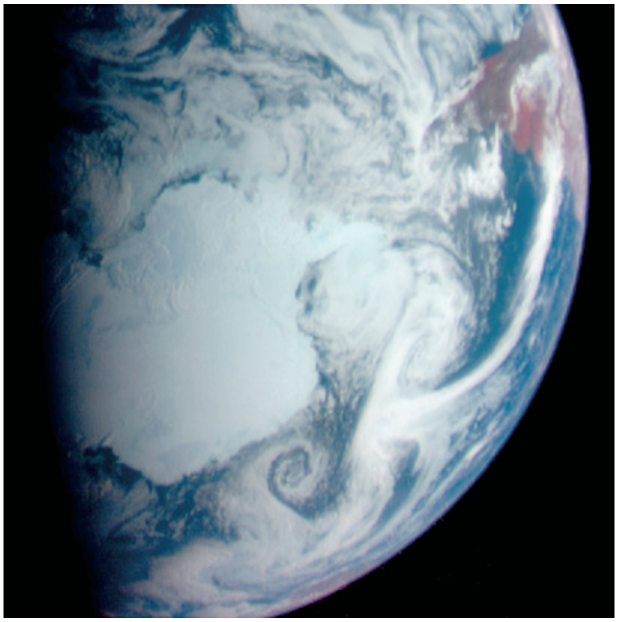

Figure 4. Image of Antarctica taken by NEAR.

- Determine the asteroid's elemental and mineralogical composition
- Determine whether the asteroid was a solid object or a rubble pile
- Determine whether the precursor body was primitive or differentiated
- Measure what, if any, magnetic field was present
- Determine if the asteroid had any satellites

A secondary objective, to fly by a C-class asteroid, was added to the science objectives just prior to launch. The highly successful flyby of Mathilde[4,5] was conducted on 27 June 1997.

The 14 February 2000 orbit insertion was the culmination of much tedious preparation and testing. The ensuing Eros orbital operations portion of the NEAR mission was the "prime science phase," when the major portion of the science objectives would be reached. This mission phase answered many scientific questions through 25 orbital correction maneuvers (OCMs) (Table 1) while in the process of determining Eros' gravity. The successful systematic nature of the orbital operation can only be attributed to the preparations made during the cruise phase and the perseverance of the entire team.

Mission objectives had to be translated into many operational objectives that included

- Spacecraft activities conducted reliably and on time
- Resolution of contention for spacecraft and ground system resources for science and supporting activities
- Implementation of numerous orbital and attitude maneuvers to the support trajectory profile
- Regular monitoring of all spacecraft systems for anomalous conditions

Table 1. NEAR OCMs and resulting orbits.

OCM	Date	Resulting orbit (km)
1	24 Feb 2000	365 × 204
2	03 Mar 2000	203 × 206
3	02 Apr 2000	210 × 100
4	11 Apr 2000	101 × 99
5	22 Apr 2000	101 × 50
6	30 Apr 2000	51 × 49
7	07 Jul 2000	50 × 35
8	14 Jul 2000	39 × 35
9	24 Jul 2000	50 × 37
10	31 Jul 2000	51 × 49
11	08 Aug 2000	52 × 50
12	26 Aug 2000	49 × 102
13	05 Sep 2000	100 × 103
14	13 Oct 2000	98 × 50
15	20 Oct 2000	52 × 50
16	25 Oct 2000	51 × 19
17	26 Oct 2000	67 × 198
18	03 Nov 2000	198 × 195
19	07 Dec 2000	196 × 35
20	13 Dec 2000	36 × 34
21	24 Jan 2001	35 × 22
22	28 Jan 2001	37 × 19
23	28 Jan 2001	36 × 35
24	02 Feb 2001	36 × 36
25	06 Feb 2001	36 × 36

- Reliable recording of and transmission back to Earth of science and engineering data (Some science data sets were deemed "critical" to the mission and hence required additional precautions to ensure data recovery.)

Summary of Operational Challenges

The NEAR mission, being the first in NASA's series of low-cost (but ambitious) Discovery-class missions, had more than its fair share of operational challenges. These can be thought of in two groups. The first group includes challenges common to most planetary exploration missions, but even so they were very significant in the context of low-cost mission operations, e.g.,

- Reliable, error-free execution of mission-critical spacecraft and instrument activities
- Simultaneous multi-instrument operations
- Long latency (round-trip-light-time) in commanding and command verification
- Tenuous nature of planetary distance communications

- Balancing science and housekeeping activities with competing spacecraft resource utilization
- Spacecraft and ground system complexity

Owing to the nature of the mission, NEAR also presented many operational challenges unique to space mission operations. Eros, like other asteroids and comets, is a small body, with physical properties only partially characterized. Eros' spin rate was known from Earth observations, but estimates for its shape, size, and mass were highly uncertain. Furthermore, challenges were linked to the low-cost nature of the mission, which limited overall team size and resource availability. These unique operational challenges included

- Small (Discovery Mission–class) MOps team
- First spacecraft navigation about a small body
- A science planning process highly dependent on unpredictable spacecraft trajectories
- Numerous orbit changes (Table 1) with rapid turnaround between maneuvers
- Operations in close proximity of the asteroid surface

The success of the orbital mission depended on the team overcoming all of these challenges. A discussion of the practices used on the NEAR mission to successfully overcome them appears later in the article.

NEAR MISSION OPERATIONS TEAM

Organization

The core NEAR MOps team, located at APL's main facility in Laurel, Maryland, was relatively small. Team members were responsible for planning and conducting day-to-day mission activities through all mission phases. Participants on other teams worked very closely with the core team to form the broader, extended group that included the Deep Space Network (DSN), navigation team, mission design team, science instrument teams, spacecraft engineering support, and the Science Data Center.

Over time, the core team's composition became a real-time flight operations team augmented by a small "off-line" team of multidisciplinary mission analysts. NEAR real-time and off-line operations personnel carried out the activities detailed in Table 2. For most off-line functions there was a corresponding real-time function and vice versa.

Staffing

Core MOps team staffing levels starting in October 1997 are shown in Fig. 5. From launch in 1996 to October 1997 the core team size averaged about six. The undeveloped state of the operations tools early in the mission sometimes made the job of such a small team daunting. To address these immediate operational concerns, the staffing plan was revisited and a plan was adopted to redistribute manpower from the "out" years (during the asteroid orbital mission) and apply it earlier to accelerate preparations.

With personnel increasing to 10 engineers by late 1997, the MOps team was able to make some headway on a major MOC rework concurrent with ongoing operations that included the highly successful flyby of Mathilde. The Mathilde flyby was a defining moment for the operation as it was a dramatic signal to those traditionally involved with planetary missions that APL was up to the task. The vision of NASA's chief administrator—"faster, better, cheaper" deep space

Table 2. Operations functions.

Real-time operations	Off-line mission analysis functions
Real-time pass operations planning	Mission planning
Shift scheduling and DSN track planning	Operations management and administrative functions
MOC ground system operations and trouble reporting	Ground system enhancement and upkeep
Interface with DSN networks, ground stations, voice systems, and data systems	Interface and coordination with navigation, guidance and control, mission design, and science teams
Real-time spacecraft status monitoring	Detailed spacecraft performance assesement
Spacecraft commanding	Spacecraft command sequence creation and validation, data management, spacecraft timekeeping, maneuver planning
Real-time mission simulation participation	Mission simulation planning
Anomaly recognition and contingency procedure execution	Contingency response, fault diagnosis, and recovery planning
Flight software loading	Flight software load preparation and testing
Software requirements definition and real-time system testing	Software requirements definition and off-line systems testing

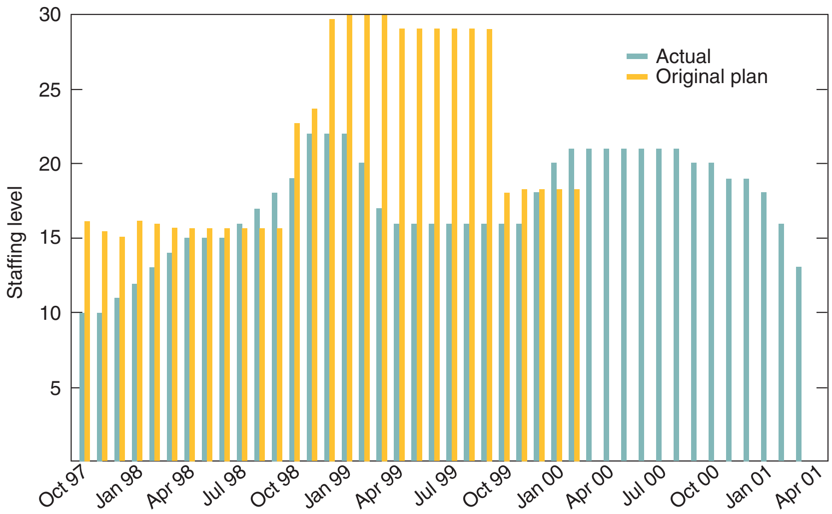

Figure 5. MOps team staffing levels.

operations—was now deeply entrenched at APL. Members of the team began to specialize in various aspects of the mission that required much attention and to refine operational processes and tools. The tremendous success of the Mathilde flyby provided a much needed source of adrenalin to a team that was truly on the leading edge of discovery.

The team continued to change in composition and size over the course of the cruise to Eros. Throughout the mission, the equivalent of three full-time engineers was available to offer spacecraft engineering backing. This valuable engineering support was provided by engineers that designed and built the spacecraft at APL. Their dedication to the mission, through all phases, significantly enhanced the operation and the MOps team's ability to respond to contingencies while also providing a stable knowledge base to a team that had suffered much turnover. The close-knit manner in which the core operations team and the specialized engineering support interacted was an enabling feature that produced many operations feats. In addition, dedicated navigation and DSN engineers located at the Jet Propulsion Laboratory (JPL) in Pasadena, California, rounded out this support with much needed engineering expertise.

Because of the aborted Eros rendezvous burn on 20 December 1998, the core team size was temporarily decreased during the extra year it took (February 1999 to February 2000) to return to Eros and achieve orbit. This resulted in some additional staffing turnover, but several new real-time team members were subsequently added and trained in the final months before the February 2000 orbit insertion. As the ground system and operational processes evolved and were made more automated during the orbital mission, the size of the operations team later decreased without adversely affecting the overall operation.

Broader Team Roles and Responsibilities

The broader operations effort for NEAR included the organizations shown in Fig. 6. Mission operations benefited from a highly cooperative relationship among the NEAR science, navigation, guidance and control (G&C), mission design, and software teams. Clear definition and adherence to operational interfaces, lines of responsibility, and rules for mission conduct were maintained. The close proximity of mission design, spacecraft and ground system engineering, and mission operations at APL significantly contributed to improved communications and increased awareness and involvement of engineering team members with mission operations. Science and operations team members regularly participated in constructive one-on-one discussions to resolve operational issues. This process

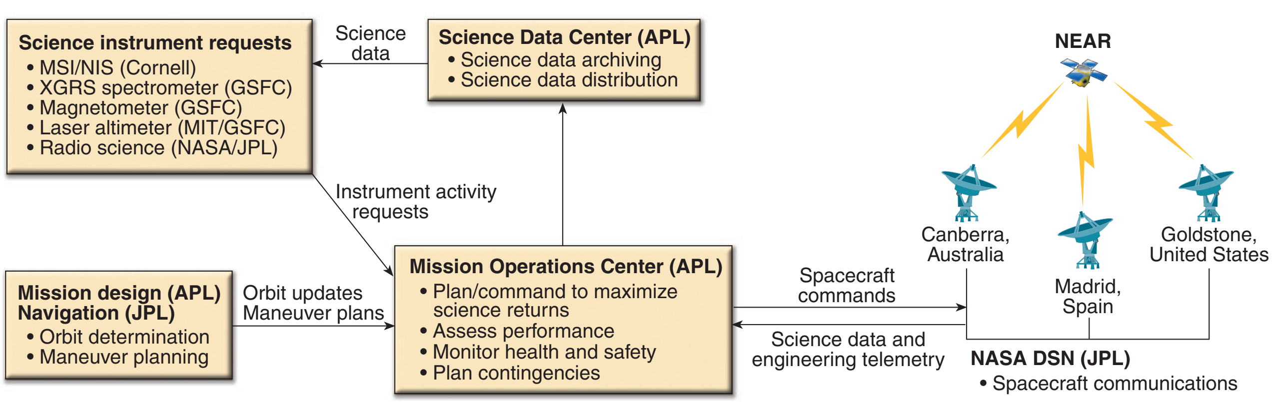

Figure 6. Operational roles and responsibilities.

led to improved communications and increased trust among the teams—the perfect environment for making decisions that would lead to maximum science return. The division of responsibilities among teams permitted all teams to do what they did best with minimal overlap in responsibilities (and associated costs).

Mission Operations Center

The MOC at APL, home to the core MOps team, provided a central facility to plan and conduct the operation with supporting engineering elements that included mission design, spacecraft engineering, software development and maintenance, and ground system maintenance. The core team carried out the real-time and off-line activities described earlier as well as the planning required to coordinate all team members for major events. The spacecraft engineers were responsible for detailed analysis and support for systems engineering, G&C, power, RF communications, and science instrument operations.

The mission design engineers were responsible for planning and verifying each orbital maneuver (OCMs and TCMs) with the navigation team to confirm that each maneuver was consistent with the mission design and the mission goals. Trade-offs were often needed to optimize a maneuver to stay within allowable spacecraft operating limitations.

The software development team was responsible for interacting with the MOps team to define requirements for improved software and for turning those requirements into usable tools. Because of the short spacecraft development schedule, many tools were developed in a less than ideal environment postlaunch, but the effort was a success. The software team viewed the operations team as the customer and made every attempt to provide the tools necessary, with turnaround times much shorter than those achieved with formal requirements definition. Emphasis was placed on working closely with MOps team members to understand what was needed and rapidly iterating on the correct solution with minimal time and bureaucracy.

With so much change taking place concurrent with flight operations, difficulties could not be avoided at times, but in the end, the combined teams managed to safely overhaul the entire MOC architecture (networks, security, workstation upgrades, application software, etc.) while minimizing impact on flight operations. This team effort should serve as a model for future rapid, cost-capped, software development efforts.

Navigation Team

The NEAR navigation team was responsible for spacecraft and planetary orbit determination as well as maneuver planning. This was accomplished by processing raw DSN spacecraft tracking data including spacecraft range and Doppler measurements taken during real-time spacecraft contacts with each of the three DSN sites (Fig. 6).

To support asteroid operations, the navigation team incorporated optical navigation (OpNav) techniques into the orbit determination process. Members of the navigation team, working closely with mission design engineers, were responsible for the design of each TCM during cruise and OCM during the orbital mission. Ultimately, the navigation team was responsible for designing the series of orbital maneuvers that landed NEAR on the surface of Eros.

The physical distances between the APL MOC in Maryland and the JPL navigation team in California did pose challenges in coordinating and conducting joint operations. However, the benefits of using experienced navigation engineers at JPL far outweighed the challenges associated with the long distance operations.

Science Data Center

Also located at APL, the NEAR Science Data Center was responsible for the retrieval (from the MOC) of all instrument data, science data merging and archiving, and data distribution to science team members. In addition, the center coordinated the recovery of mission science data with the science instrument teams and the MOps team.

Science Instrument Teams

Science instrument teams were responsible for the planning of all instrument operations (opportunity analysis). This work involved studying the geometrical relationships of the spacecraft's trajectory with respect to targets observed and using that information to create plans for pointing instruments to maximize science return.

Instrument teams at APL, Goddard Space Flight Center (GSFC), the Massachusetts Institute of Technology (MIT), and Cornell University developed the command sequence to operate their respective instruments and orient NEAR for best viewing while not violating the pointing constraints required to power the spacecraft and communicate with the Earth. All activities were closely coordinated by APL mission operations to ease problems integrating instrument activities and housekeeping operations while ensuring that flight rules were not violated. The instrument teams were also responsible for verifying that all instrument commands were safe for the instrument's operation.

NASA Deep Space Network

The DSN is composed of three Deep Space Communications Complexes, equally spaced around the Earth to virtually guarantee that one of the three sites will always be in view of a given spacecraft as the Earth rotates. These sites, connected by a worldwide network, are located in Madrid, Spain, Canberra, Australia, and

Goldstone, United States. The DSN is controlled from the Network Operations Control Center at JPL.

All spacecraft operations were conducted from the NEAR MOC at APL in real time. Each contact used the 34- or 70-m large-aperture antennas of NASA's DSN to conduct activities including command loads and data playbacks.

Primary Operational Interfaces and Data Flow

Figure 6 shows the primary operational interfaces between operations participants. Science and engineering data were transmitted by NEAR to the DSN at data rates ranging from 9.9 bps to 26.5 kbps. The DSN would forward all data from the spacecraft to the MOC in real time. Also forwarded were DSN data containing the status of the DSN systems used in isolating faults in ground data flow. All spacecraft commands flowed in the reverse direction. Spacecraft-to-Earth distances varied over the course of the mission, with maximum spacecraft Earth distance ≈474 million km (3.1 AU) in February 1997. The resulting one-way light-time delay in communicating with NEAR reached over 26 min during this time, i.e., it took nearly an hour to receive confirmation of a command sent to the spacecraft.

All NEAR science data transmitted to the MOC were forwarded to the Science Data Center for archiving and distribution to science team members. With spacecraft data recorded at several points in the ground data flow, the space-to-ground link proved most tenuous operationally. This link could be affected by such factors as local winds, cloud/rain, ground system configuration, and problems with the sensitive receiver assemblies used at the DSN antenna complexes. Despite the long-distance communications involved and the complexities, end-to-end network reliability for uplink and downlink averaged 98% success for the mission.

Science instrument requests were generated by respective instrument teams located at Cornell, APL, and GSFC. Figure 7 depicts the general flow of instrument requests from each science team.

NEAR's Multi-Spectral Imager (MSI) instrument operation was unique in that it had two users, the science imaging team and the navigation team. The navigation team used the MSI for OpNav and landmarking. For simplicity, all navigation requests were coordinated by the science imaging team at Cornell University so efficiencies could be realized with dual use of images for science and OpNav. This approach to coordinating science use of an instrument with navigation use should be considered for future missions as it proved both efficient and effective.

NEAR FLIGHT OPERATIONS EFFORTS

Cruise Phase Operations and Command Sequencing

The majority of misison operations were conducted during the cruise phase. Two-way communications with the spacecraft during this phase were usually conducted three times per week. Each spacecraft "contact" was typically 8 h long. During these routine supports, commands for the next period of operations were uploaded to the spacecraft and stored for later automatic execution. The flight recorders were routinely played back to retrieve spacecraft engineering data collected between contacts. These contacts were also critical to monitoring NEAR's status in real time, as spacecraft contingencies were always a possibility.

Each mission event was also conducted with complex command sequences developed in advance, transmitted to the spacecraft, and stored onboard for execution at predetermined times. These so-called "time

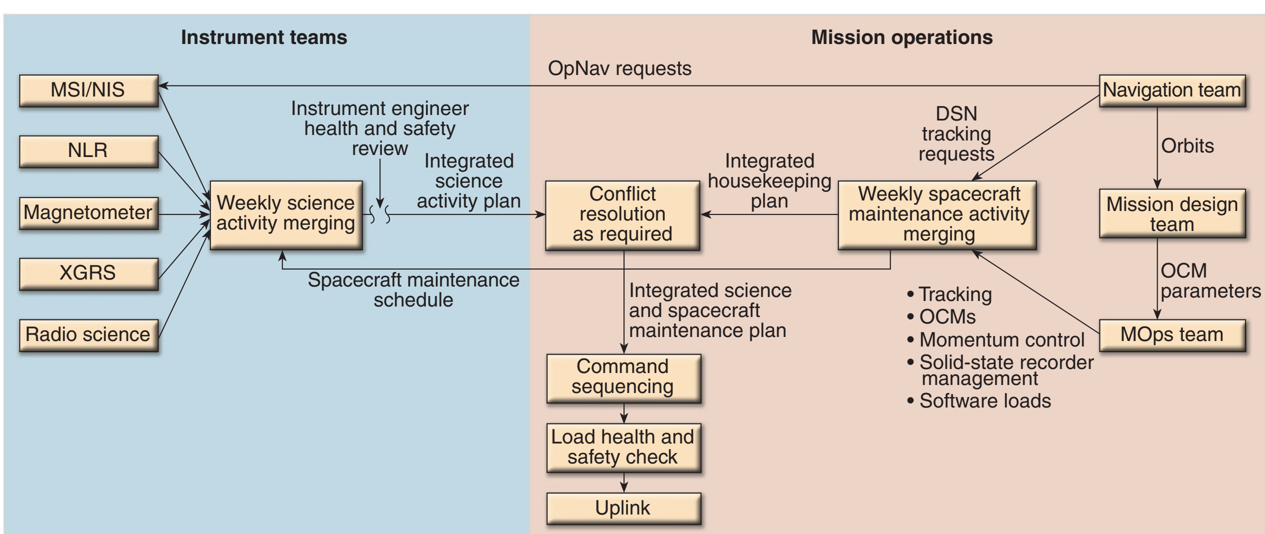

Figure 7. Instrument planning flow.

tagged" command sequences were generated manually for early operations. This approach proved very time-consuming and troublesome for a small operations team. Management of memory used onboard the spacecraft had to be accounted for via manual bookkeeping. The Mathilde encounter required approximately 6 months of development and testing of the critical flyby science sequence.

The Earth swingby was a similar effort. It was recognized that this ratio of effort to science payback had to be improved if we were to operate the spacecraft in the manner planned during Eros orbital operations. Since error-free commanding was essential to meeting mission objectives and manpower was limited in a climate of low-cost mission operations, a more reliable and automated approach was required.

To address this concern, concepts for a mission planning and command sequencing system were developed in 1997 and 1998. The resulting sequencing system enabled the MOps team to transition from manually creating and validating complex command sequences to using command blocks that would be individually tested and then used in flight over and over again. The complex system that evolved included designing, building, and testing reusable command blocks and incorporating flight rules and other logic into a command sequencing system. It also involved development of a software simulator that would later test every command load before transmission to the spacecraft. This unique implementation of a faster-than-real-time spacecraft simulator in the command path ensured that tens of thousands of commands were all carefully synchronized with each other and associated flight systems.

In July 1998, the first command sequences generated using this sequencing system were created. From that point forward, each of NEAR's command loads was created using the new system. This single system, and the operational practices used, did more to improve operation efficiency and reliability than any other procedural or software addition. Other MOC improvements and tools that were developed during the cruise phase included

- Spacecraft performance assessment system
- Spacecraft memory load, dump, and "compare" tools
- MOC security firewall
- Automated spacecraft timekeeping
- Critical OpNav production system
- Numerous improvements to the real-time command system

A major overhaul of the NEAR MOC and operational processes ensued during the cruise phase to improve our ability to conduct intensive operations with a small team in a reliable manner. In parallel with these activities numerous flight software loads were made to the spacecraft to enhance the performance of several onboard processors including G&C and several instrument processors.

The cruise period proved to be one of the most demanding times for NEAR operations, but the hands-on training and the ground system architecture ultimately obtained had tremendous long-term benefits beyond the mission. Both CONTOUR and MESSENGER missions plan to reuse many of the concepts and systems developed for NEAR. Although developing the system concurrent with ongoing operations was a demanding exercise, there were tremendous advantages to having the full operations team and software development teams working together on the design and implementation.

Asteroid Orbital Phase Operations

The 433 Eros orbital operation began on 14 February 2000 with a successful orbit insertion maneuver.[6,7] It went beyond merely placing the spacecraft into a single orbit; rather, it was an ambitious plan to observe Eros close up over a yearlong period from many different orbits designed to study the asteroid from all angles.

The orbital plan adopted,[6,7] which included the 25 OCMs shown in Table 1, was extremely challenging and had never before been attempted. The orbital history included two sets of low-altitude surface flyovers. The first was conducted in October 2000 (≈5.4 km minimum altitude) and a second set in January 2001 (≈2.7 km minimum altitude). The orbital mission phase ended with a controlled descent of NEAR Shoemaker to the surface of Eros on 12 February 2001.[6,7,8]

A Day in the Life of the Orbital Operation

The process of planning for the orbital operation began 2 years before orbit insertion and included working out a typical day in the life of the spacecraft's orbital operation. Time was allotted to many tasks that would be repeated onboard daily, with reusable command blocks tested once and used many times. A typical day in Eros orbit is shown in Fig. 8.

DSN antenna tracking was near-continuous with round-the-clock support from DSN and MOC personnel during the first 30 days and 20 h/day thereafter. The DSN's 34-m antenna subnetwork was used to communicate with NEAR Shoemaker and provide radiometric tracking services including range and two-way coherent Doppler measurements. The 34-m support was augmented with daily 70-m DSN contacts that were typically 8 h long.

The increased aperture of the 70-m antennas permitted daily downlink of science and engineering data, stored onboard NEAR Shoemaker's solid-state recorders (SSRs), to be quadrupled to rates ranging from 17.7 to 26.5 kbps. Total data return from the asteroid over the orbital mission was approximately 28.4 Gbytes, with imaging

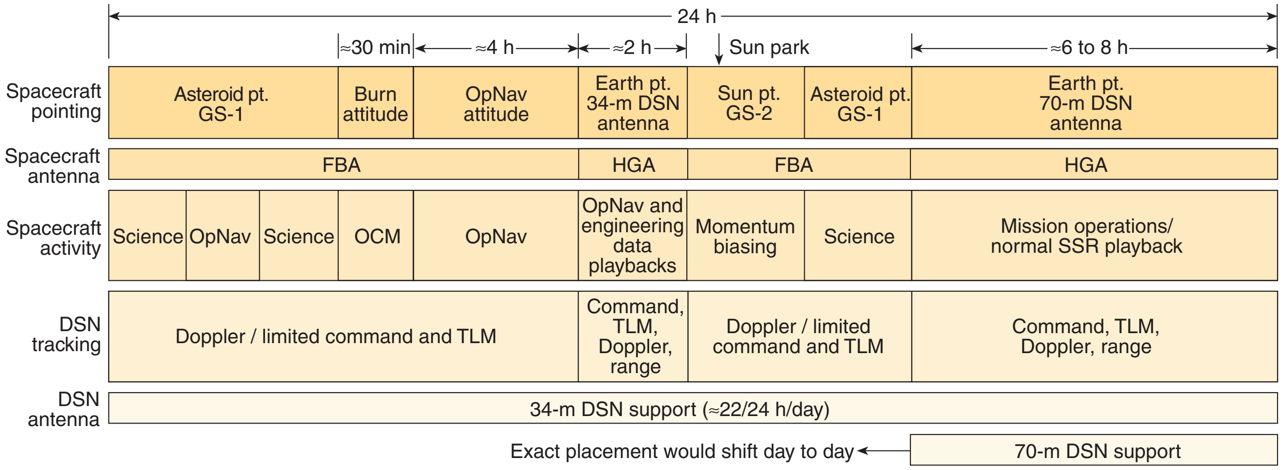

Figure 8. A day in the life of NEAR in Eros orbit.

science data contributing to the majority of the data return. This was a magnificent achievement for a probe orbiting an asteroid some 300 million km from Earth.

Spacecraft Momentum Management

Spacecraft angular momentum buildup from solar radiation pressure had to be regularly controlled during the orbital phase to prevent the attitude control mechanisms (spacecraft momentum wheels) from reaching saturation speeds. Momentum wheel speeds were periodically reduced via a propulsive event, concurrent with each OCM (shown as "Spacecraft activity" in Fig. 8), to prevent spacecraft reaction wheel saturation. During weeks when no OCM was planned, a separate momentum control maneuver (MCM) was planned solely for the purpose of momentum adjustment.

A model for predicting momentum buildup based on planned spacecraft operations was used by mission operations for planning MCMs. Additionally, during periods when no science or housekeeping operations were being performed, the spacecraft would be placed in a Sun park mode. In this mode, NEAR's G&C software would point it to reduce momentum buildup from solar ration pressure. Both of these techniques were used to minimize the total number of MCMs required for momentum control and hence to minimize the number of interruptions to science operations (several hours for each MCM) and maximize total science return over the mission.

Spacecraft Attitude

As seen in Fig. 8, the spacecraft's pointing varied over the course of a day with instruments (all co-aligned) nominally asteroid nadir pointed. The flexible design of NEAR's three-axis G&C system permitted the remaining degree of pointing freedom to place the spacecraft's medium-gain antenna (fanbeam antenna [FBA]) on the Earth by rotating the spacecraft about the instrument boresight. This permitted MOC real-time monitoring of the science operations while in progress at telemetry [TLM] bit rates between 9.9 and 39.4 bps. Even more importantly, the real-time monitoring permitted radiometric tracking of the spacecraft, which supplied the navigation team with near-continuous tracking data that expedited the orbit determination process and hence safe orbital operations.

Science data gathering was interrupted roughly once per day to point the spacecraft's high-gain antenna (HGA) toward Earth to play back science data recorded since the previous day. This process normally lasted 8 h/day, including the time required to reorient the spacecraft before and after data playback. To maximize data rates and hence total science data return, science data playbacks were planned coincident with the 70-m DSN. It was also during these supports that regular spacecraft command uploads were normally performed.

Finally, orbit control required vehicle pointing to be reoriented to support OCMs. OpNav and landmarking were performed before the maneuver to aid in the premaneuver orbit determination process and refinement of maneuver parameters. The spacecraft attitude was slewed to the maneuver attitude before the maneuver was performed. OpNav images were also taken immediately after each maneuver to provide an early means of detecting significant errors in maneuver performance that could jeopardize the mission (impact to Eros surface). This was a particular concern during the close flybys performed in October 2000 and January 2001.

Onboard Data Management Strategy

The MOps team presented the science teams with two proposals for onboard management of science data. The first option involved reserving two opportunities for retrieving the data to better guarantee Earth receipt of the data. The second was to record twice as much science data but provide only one opportunity for data playback. The science team opted to use both options depending on data criticality. Option one was used for so-called "critical data sets." These were special one-time science data gathering opportunities such as a close flyby of the surface. Option two was used for the majority of the orbital mission. This strategy was supported because the spacecraft remained in a given orbit for several revolutions. A science data retrieval opportunity missed for one orbit could be acquired from observations made on the following orbit. Given that end-to-end data capture averaged 98% for the mission, this approach proved to result in far higher overall levels of science data capture.

OVERCOMING CHALLENGES

General Challenges Associated with Planetary Space Missions

Reliable, error-free mission operations are key to any space mission. An important primary mission objective for such a mission is to minimize the number of unplanned activities. Error-free command loads go a long way to ensuring this objective. An unplanned activity could be anything from a sudden and unexpected entry to a spacecraft safemode to unexpected loss of spacecraft communications. The NEAR mission operation implemented many safeguards to minimize unplanned events. Some of these general approaches are common to many other planetary missions.

To ensure the reliable flow of commands in a timely manner, the majority of onboard activities were conducted using spacecraft commands prepared, tested, and stored onboard for later execution (stored commands). The stored command sequencing system's design and operation were therefore key to the successful commanding of NEAR and reliable operations.[9] Storing commands onboard prior to execution time addresses the light-time latency issue associated with commanding deep space missions, with all commands loaded in advance and executed when the time associated with each command has passed. To further accommodate the tenuous nature of the long-distance link to the spacecraft, multiple DSN uplink opportunities were designated (minimum of two) for each command load to better guarantee spacecraft receipt prior to the associated command execution times.

While this approach guaranteed delivery and timely execution of spacecraft commands, it did not guarantee error-free command sequencing. To accomplish this an elaborate three-step command sequence validation process was implemented.[10] Reuse of validated command sequences and effective use of simulators were key to an efficient orbital operation that included intensive, multiple instrument operations.

Challenges Unique to a First Mission Around a Small Body

The orbital mission was conducted with a MOps team numbering 21 at its peak. This is a significant reduction; typical planetary mission opertaions sometimes entail hundreds of personnel in the operations phases. The ability to successfully conduct this orbital mission with this level of efficiency was attributed to several factors[10,11] including

- Highly skilled and experienced MOps team members
- Minimal turnover of key personnel in the 2 years prior to orbit insertion
- Simple but capable NEAR Shoemaker spacecraft design and operations interfaces[2,3,12]
- Simplified operational interface with the science teams (as discussed earlier)
- Refined ground system design and operations team training during the 4-year cruise phase

The composition of the NEAR MOps team evolved over the course of the cruise period to meet the demands of the mission. Team members gained valuable experience through hands-on training, and personnel with additional experience to share were added to the team.

As overall team experience levels increased, so did the maturity of operations concepts and the systems required to carry them out. And as the list of mission accomplishments grew, including the asteroid Mathilde flyby and subsequent Earth swingby, team stability improved. Consequently, plans for NEAR operations became increasingly ambitious, as best demonstrated by the close flybys and the landing exercise on 12 February 2001.[7,8,13]

The 4-year cruise phase of the mission included a modest ground system upgrade effort. The MOps team was highly experienced and trained in the use of the new tool set by the start of the most demanding portion of the mission—Eros orbital operations. Furthermore, all team members were experienced in working with each other to design and implement complex operations. The cooperative manner in which all NEAR team members worked toward a common goal, sometimes under tremendous time pressures, was key to overall mission success.

The remaining unique challenges of the NEAR orbital mission were navigation related. The entire conduct of the science operation was highly dependent on properly navigating an asteroid,[7,12,14] a feat never before performed. Furthermore, planning and implementation of each orbital maneuver were dependent on preceding maneuvers, as well as the evolving characterization of Eros' gravity potential, which continued to show new traits each time NEAR's orbit was lowered closer to the surface.[13,15]

Science observation planning required an accurately predicted spacecraft trajectory to support geometrically related aspects of the science planning process. The predicted spacecraft trajectory had several sources of error. One source was due to the uncertainty in the asteroid's gravity potential early in the orbit phase. This uncertainty directly affected the accuracy of the predicted spacecraft trajectory over time. A second source of error came from each orbital maneuver's performance as measured in millimeters per second. Even errors on this order could translate into significant (from the science operations and OpNav perspective) spacecraft position errors days later. Finally, command sequence timing had to be maintained to ± 1 s. Also, landmark imaging posed a 20-ms time accuracy in reconstructing imaging times. Specialized processes were implemented in the MOC to track onboard clock drift with respect to ground time.

The interdependency of mission operations and navigation was foreseen. Consequently, operations processes relating to navigation, science, and housekeeping were designed to mitigate errors in predicted spacecraft navigation. Most of the science observations were conducted in an asteroid-centered reference frame in the spacecraft's G&C system, as were trajectory computations onboard. Each spacecraft trajectory uplink tended to "re-center" the spacecraft and instrument pointing without the need for command sequence updates.

Planning for future OCMs also depended on past OCM performance and trajectory uncertainties. Optimum times to perform OCMs were often tied to orbital node crossing times. Because OCMs had to be planned 4 weeks in advance along with science and housekeeping activities, estimates had to be used for the placement of OCMs on the mission timeline to avoid scheduling conflicts with other activities. The navigation team estimated an "OCM window" based on a no-earlier/no-later-than time for nodal crossings. Early in the orbital phase this window was typically on the order of several hours. As the asteroid gravity model improved and the performance of the propulsion system was better characterized, the width of the time window was reduced to less than 1 h.

The MOps team designed its preloaded OCM sequences to be stored and later executed in a way that would allow an update to the maneuver vector and its execution time as late as several hours before OCM execution. This approach was successfully used many times in Eros orbit. Figure 9 shows the typical OCM timeline, with final maneuver parameters (including exact time of maneuver) delivered to the MOC 48 h before the OCM. "Critical OpNavs" were scheduled before each OCM to provide the final optical inputs into the orbit determination process.

A DSN track was scheduled to follow each OCM to downlink post-OCM OpNavs and engineering data, conduct radiometric tracking, and provide for contingency orbit uploads in case a maneuver was aborted. Fortunately no orbital maneuver ever aborted, so the contingency orbit upload capability never had to be used. This plan for rapid data capture and postmaneuver assessment was a practical precaution for orbiting in close proximity to an asteroid.

Combined, these special provisions for handling navigation uncertainties and validating command loads permitted the orbital mission to be conducted in a highly flexible manner. All 25 OCMs were executed successfully and on time, allowing for a continuous flow of science and engineering data from the asteroid; interruptions to data occurred on only 2 out of 363 days of orbital operations.

FUTURE MISSION PLANS

The NEAR mission operation developed a working model for successfully conducting a Discovery-class planetary mission while producing a significant amount of highly unique science data. This was a "proof of concept" mission to rendezvous with and study an asteroid up close. The NEAR mission has demonstrated APL's ability to design, develop, and operate ambitious end-to-end deep space missions. More importantly, APL personnel now have hands-on experience in conducting planetary mission operations.

The models developed and used for this highly successful mission have been instrumental in APL's successful bids for the CONTOUR,[10] MESSENGER, and now New Horizons (Pluto) deep space missions. These future APL missions will present new and interesting

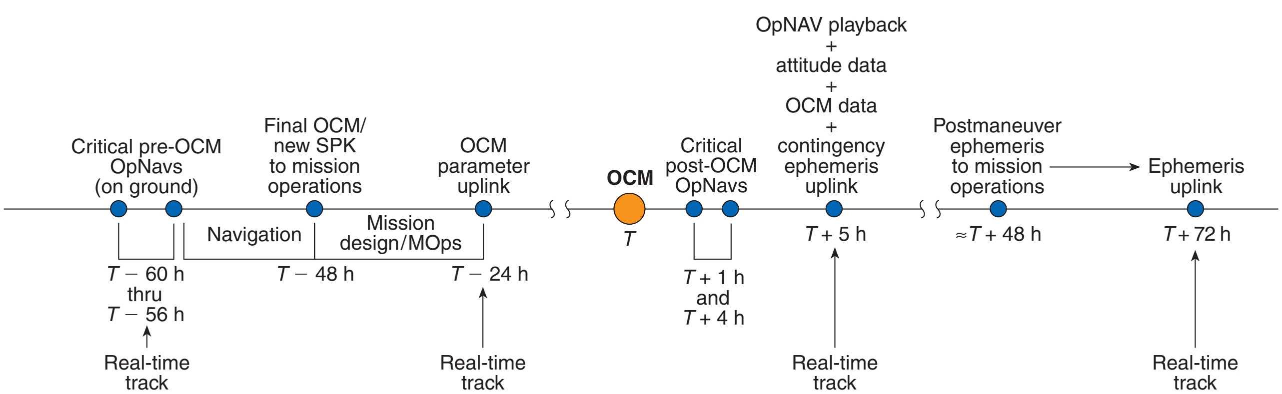

Figure 9. A typical OCM timeline (not drawn to scale). (SPK = SPICE format spacecraft ephemeris files.)

challenges to investigating unexplained portions of the solar system at low cost. CONTOUR and New Horizons will both adopt a concept of spacecraft and ground system hibernation to reduce operational costs and risk during long cruise periods. The MESSENGER spacecraft will carry out a yearlong science investigation of Mercury while protecting itself in relatively close proximity to the Sun.

APL now has a permanent foothold in planetary mission operations. Many of those responsible were members of the successful NEAR MOps team shown in the team photo (Fig. 10).

Figure 10. Members of the MOps team: (from left to right) Owen Dudley, Robert Dickey, TJ Mulich, Karl Whittenburg, Lisa Segal, Richard Shelton, Mark Holdridge, Carolyn Chura, Robert Nelson, Nickalaus Pinkine, John Rubinfeld, Pat Hamilton, Roland Riehn, Charlie Kowal, Dina Tady, and Charlie Hall.

REFERENCES

[1]Farquhar, R., Dunham, D., and Williams, B., "Second Coming of NEAR," *The Planetary Report*, 1–18 (Nov–Dec 1999).

[2]The NEAR Mission, *Johns Hopkins APL Tech. Dig.* **19**(2), T. B. Coughlin (guest ed.) (Apr–Jun 1998).

[3]Special issue on the NEAR Mission, *J. Astronaut. Sci.* **43**(4) (Oct–Dec 1995).

[4]Williams, B. G., Helfrich, C., Miller, J., Owen, W., Scheeres, D. J., et al., "Preliminary Plans for a Close Encounter with 253 Mathilde," paper AAS 97-177, *AAS/AIAA Space Flight Mechanics Mtg.* (10–12 Feb 1997).

[5]Harch, A., and Heyler, G. A., "Design and Execution of the Asteroid Mathilde Flyby," paper IAA-L98-0501, in *Proc. 3rd IAA Int. Conf. on Low-Cost Planetary Missions* (27 Apr–1 May 1998).

[6]Farquhar, R. W., Dunham, D. W., and McAdams, J. V., "NEAR Shoemaker at Eros: Rendezvous, Orbital Operations, and a Soft Landing," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-370, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[7]Williams, B. F., Antreasian, P. G., Bordi, J. J., Carranza, E., Chesley, S. R., et al., "Navigation for NEAR Shoemaker: The First Mission to Orbit an Asteroid," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-371, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[8]Nelson, R. L., Whittenburg, K. E., and Holdridge, M. E., "433 Eros Landing—Development of NEAR Shoemaker's Controlled Descent Sequence," *AIAA/USU Conf. on Small Satellites* (Aug 2001).

[9]LaVallee, D. B., and Whittenburg, K., "Design and Implementation of the NEAR Command Load Generation Process," in *Proc. IEEE Aerospace Conf.* (Mar 2001).

[10]Holdridge, M. E., "Applying Successful Mission Operations Approaches to CONTOUR Mission Operations," *4th IAA Int. Conf. on Low-Cost Planetary Missions*, IAA-L-0802 (May 2000).

[11]Holdridge, M. E., Nelson, R. L., and Whittenburg, K. E., "433 Eros Oribtal Mission Operations—Implementing the First Orbital Operations Around a Small Body," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-375, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[12]Santo, A. G., Lee, S. C., and Gold, R. E., "NEAR Spacecraft and Instrumentation," *J. Astronaut. Sci.* **43**, 373–397 (1995).

[13]Heyler, A., Ray, J. C., Harch, A., and Carcich, B., "Modeling and Performance of NEAR's G&C System During the Eros Orbital Phase and Controlled Descent," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-374, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[14]Scheeres, D. J., Miller, J. K., and Yeomans, D. K., "The Orbital Dynamics Environment of 433 Eros," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-373, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

[15]Antreasian, P. G., Chesley, S. R., Miller, J. K., Bordi, J. J., and Williams, B. G., "The Design and Navigation of the NEAR Shoemaker Landing on Eros," *AAS/AIAA Astrodynamics Specialists Conf.*, AAS-01-372, Quebec City, Quebec, Canada (30 Jul–2 Aug 2001).

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