Small-Body Proximity Operations & TAG: Navigation Experiences & Lessons Learned from the OSIRIS-REx Mission

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On October 20th, 2020, the nearly two-year proximity operations campaign for the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission at the near-Earth asteroid (101955) Bennu culminated in a successful Touch-and-Go (TAG) sample collection event. Navigation performance was a significant driver for flight activities at Bennu, which consisted of multiple phases geared towards characterizing the asteroid, selecting a sample site, and safely guiding the spacecraft to and from the surface in order to collect at least 60 g of pristine regolith. The entire operations team gained a tremendous amount of experience operating in the challenging small body environment and overcame many challenges. In this paper, we summarize navigation-focused experiences and lessons learned from OSIRIS-REx proximity operations at Bennu that are applicable to future missions to small asteroids, comets, and planetary moons. Areas of focus include staffing and organization, ground system infrastructure, mission phase planning, navigation operations, and spacecraft and payload considerations.

I. Introduction

In August 2018, the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft [1] captured its first image of the near-Earth asteroid (101955) Bennu. The mission team spent the next two years characterizing the target body and associated dynamical environment in order to select a safe and scientifically-interesting sample site [2]. The high-cadence operations consisted of several unique mission phases with over 130 propulsive maneuvers and over 300 navigation ephemeris updates. The optical navigation (OpNav) team processed almost 38,000 images to produce Bennu-relative observables for spacecraft orbit determination (OD) and trajectory prediction. In October of 2020, proximity operations culminated in the Touch-and-Go (TAG) sample acquisition event that resulted in successful collection of hundreds of grams of pristine regolith from the surface of Bennu [3, 4]. Post-TAG trajectory reconstruction indicated that the spacecraft touched down within 1 m of the desired

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location on the surface of Bennu. The success of the TAG event was largely enabled by the navigation performance throughout proximity operations, which far exceeded expectations prior to Bennu arrival [5, 6].

The OSIRIS-REx navigation concept of operations built upon the experience and lessons learned from previous missions to small solar system bodies, including the NASA's Near-Earth Asteroid Rendezvous (NEAR) [7] and Dawn [8] missions, the European Space Agency's (ESA) Rosetta mission [9–11], and Japan Aerospace Exploration Agency's (JAXA) Hayabusa and Hayabusa2 missions [12, 13]. Navigating and operating a spacecraft in the vicinity of a small body presents unique challenges. The relatively small size of the objects means non-conservative and perturbing forces acting on the spacecraft, including solar radiation pressure (SRP) and spacecraft thermal re-radiation, are a significant contributor to the overall dynamics and trajectory propagation, often equivalent or within a few orders of magnitude of the acceleration due to the target body's gravity [14]. Navigation performance and limited onboard autonomy was a significant driver for OSIRIS-REx observation planning and maneuver execution and led to the "24-Hour Late Update" ephemeris and maneuver update operations concept used throughout proximity operations. Maneuvers required to adjust the spacecraft's orbit or change its path entirely are correspondingly small (tens of centimeters down to a few millimeters per second on OSIRIS-REx), requiring precise execution while providing significant control authority and flexibility in the trajectory design.

Another challenging aspect of operations for OSIRIS-REx and other small body missions is the requirement to characterize the target object and its dynamical environment using in situ observations while simultaneously navigating the spacecraft. A significant portion of Bennu proximity operations were dedicated to geophysical parameter estimation and mapping. Developing the detailed shape models and topographic maps used for terrain-relative OpNav [15], site selection, and scientific analysis depended upon iterations between the navigation team and the Altimetry Working Group [16–18]. Observation requirements and constraints for the images used to construct the models drove trajectory and phase planning. Bennu geophysical parameters, including the gravitational parameter (GM), spin pole and rate, and shape scale were estimated along with the spacecraft trajectory in the OD solution [19]. Many of these parameters were tightly coupled and hard to estimate independently of one another, particularly GM, spacecraft orbit radius, and shape scale. The implementation of stable, "frozen" terminator orbits for the orbital campaigns was ideal from an operations standpoint [20], but further complicated geophysical parameter estimation. The navigation team spent a significant amount of effort in estimating and separating these parameters, employing multi-arc solutions, altimetry data, and differenced measurement types [21, 22].

Successful navigation at Bennu was attributed to multiple factors, including the skill and experience of the navigation team, ample resources and staffing, and effective communication and coordination between subsystems: navigation, spacecraft operations, science, and science planning. Detailed planning for each mission phase began more than 12 weeks in advance and required coordination between the navigation and science planning teams to fully understand observation requirements and constraints. The high cadence of operations and length of the planning schedule meant multiple phases were developed in parallel, each at a different stage of the development cycle: planning, implementation/testing, and execution. Adequate staffing was critical to allow dedicated navigators from each sub-element (OpNav, OD, and trajectory design/maneuver planning) to focus on individual phases from design through operations.

Detailed technical descriptions of OSIRIS-REx trajectory design and navigation performance are presented in multiple publications by members of the OSIRIS-REx Flight Dynamics System (FDS). In this paper, we summarize the high-level experiences and lessons learned observed and compiled by FDS throughout OSIRIS-REx development, planning, and proximity operations that may be applicable to future missions to small solar system bodies: asteroids, comets, and planetary moons. Areas of focus include:

- Defining observation requirements and spacecraft constraints
- Accurately characterizing expected navigation performance
- Navigation team staffing and resource planning
- Interfaces and coordination between the navigation, spacecraft operations, and science planning teams
- Considering operations concepts, cadence, and human factors early in the design cycle
- Trajectory, maneuver, and observation planning process and timeline
- Trajectory/orbit design and guidance strategies, including TAG
- Incorporating onboard autonomy to reduce operations complexity
- Navigation sensors and performance, including cameras and altimeters/LiDARs

For each topic, we will describe the specific OSIRIS-REx implementation, discuss the pros and cons with the approach, and provide recommendations on improvements and alternative strategies for future small body missions.

II. Flight Dynamics Team Organization & Staffing

The OSIRIS-REx FDS consisted of navigation personnel primarily from Goddard Space Flight Center's (GSFC) Navigation and Mission Design Branch (NMDB) and the Space Flight Dynamics Practice (SNAFD) at KinetX, Inc. KinetX provided primary operational navigation services and was responsible for all official deliveries throughout the mission. GSFC was responsible for overall FDS management and provided analysis and surge support to the primary operations team. GSFC also provided Independent Verification & Validation (IVV) support for navigation deliveries using independent tools and techniques. Other organizations supporting FDS included Lockheed Martin (reference mission design), Aerospace Corporation (navigation subject matter expertise and project support), the Jet Propulsion Laboratory (JPL) (independent shape model development), and GSFC's Geodesy & Geophysics and Planetary Geodynamics Laboratories (geodesy, geophysical parameter estimation, and tracking data evaluation).

Given the complexity and surprises encountered at Bennu, having adequate FDS staffing and resources were critical to successful navigation operations and TAG. During the time frame of the the FDS critical design review (CDR) (about two years prior to launch) it became apparent that the scope of the navigation effort would need to be much larger than originally planned. The mission concept envisioned a small navigation team during operations, comparable in size to a Mars orbiting mission. In reality, the OSIRIS-REx mission concept would require pushing the capabilities of deep space navigation well beyond that of a planetary orbiter, and following the mission CDR, significant additional resources were allocated commensurate with the challenge. The additional staff proved essential to complete the necessary analysis to validate the mission concept prior to launch, and support the planning and execution of multiple mission phases in parallel during operations. A timeline of each OSIRIS-REx mission phase and the corresponding duration is provided in Fig. 1. Detailed descriptions of the individual mission phases and navigation considerations can be found in [5, 6, 23–28], among others.

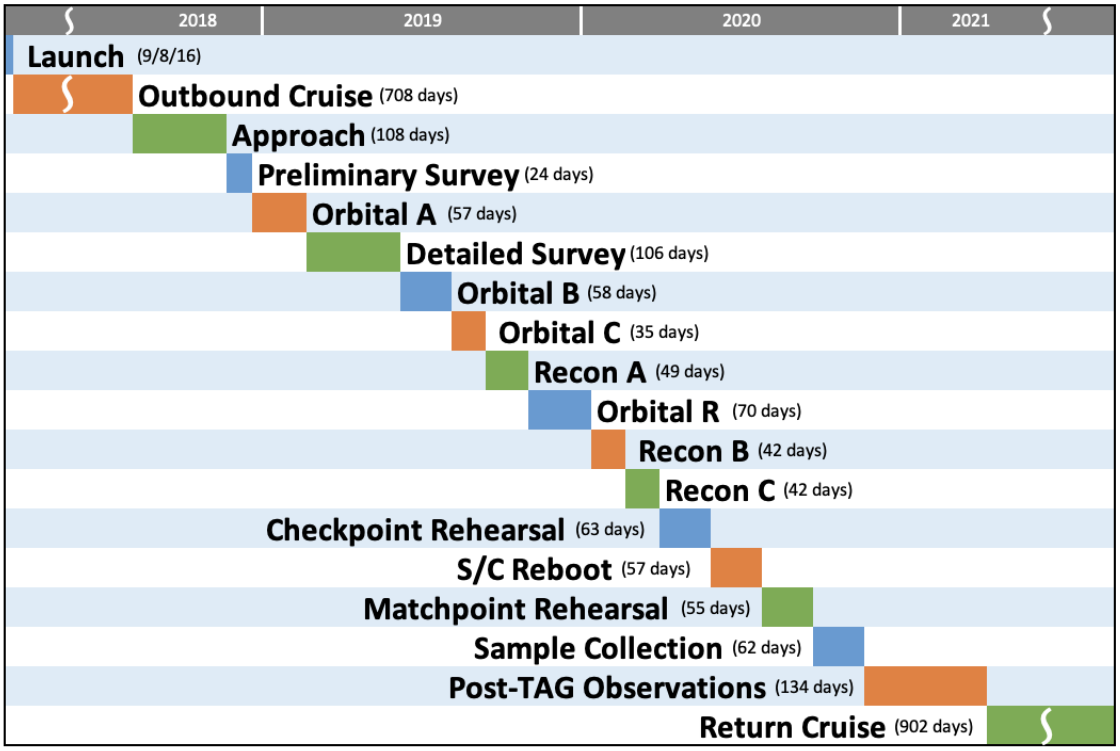

Fig. 1 Overview of each OSIRIS-REx mission phase and corresponding duration.

Each mission phase had unique science and operational objectives and presented additional operational challenges. Because of the tight operational timeline at Bennu, multiple phases were planned in parallel. In general, each core navigation function (OD, OpNav, and Trajectory Design/Maneuver Planning) each had at least three or more analysts that could each focus on different aspect of planning and operations for an individual phase. Although most navigation personnel provided some level of support for all phases, at least one analyst from each discipline was assigned primary responsibility for each individual phase. For each phase, navigation personnel participated in:

- Phase planning, development, design, and analysis
- Flight implementation and execution
- Post-phase reconstruction, analysis, and model/process improvement

During the flight implementation stage, there was at least one prime and back-up analyst from each element supporting critical navigation deliveries. For OpNav deliveries that featured both centroid and landmark image processing, at least one analyst was assigned to each technique. Furthermore, the OD team often employed one or two additional analysts running various alternate filter cases for comparison with the baseline solution prior to delivery. Similarly, maneuver design updates typically utilized additional analysts investigating alternate designs and running Monte Carlo error analyses.

Analysts were also able to engage in deep-dive analysis and development efforts to tune and improve operational models, develop new operations and analysis tools, streamline procedures, and investigate anomalies. These activities were critical given the various surprises and challenges encountered at Bennu up to and including TAG. The team and mission benefited greatly from having adequate FDS surge staffing following the discovery of particle ejection events from the surface of Bennu [29]. Navigation personnel were able to quickly assess the operational impacts of the events and determine there was no risk to the spacecraft. OpNav engineers developed tools and techniques to manually and automatically identify and track particles in OpNav images, ultimately contributing to the automated image processing pipeline [30–32]. OD team members developed methods to use particle observations as measurement data for high-fidelity gravity field reconstruction. FDS personnel also supported various contingency planning and analysis efforts throughout proximity operations. The total FDS staffing profile through proximity operations is provided in Fig. 2 and reflects core FDS support from KinetX, GSFC, and Aerospace Corporation. Note that the values are expressed as full-time equivalents (FTEs) and reflect the fact that some individuals worked more than full-time during certain periods. The maximum staffing level of over 35 FTEs occurred following the discovery of particle ejection events in February 2019 to support tracking and pipeline development.

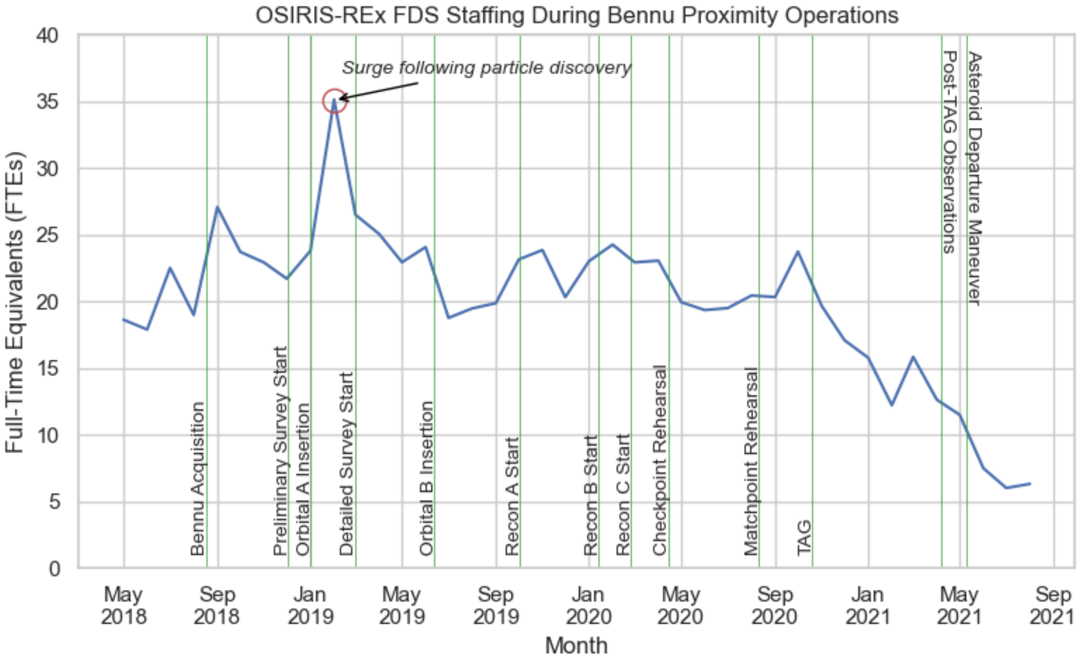

Fig. 2 Total FDS monthly staffing during Bennu proximity operations. Values are expressed as FTEs and include analysts, management, and support personnel from KinetX, GSFC, and Aerospace Corporation.

The original intent of the GSFC-based IVV team was to serve as a completely independent entity that could cross-check operational deliveries as a risk-reduction activity [33]. However, the team realized early in proximity operations that it was more beneficial for prime and IVV personnel to work together as an integrated team by comparing and improving models, discussing solution differences, investigating potential anomalies, and resolving discrepancies.

Having access to independent tools and a diverse experience base was extremely valuable; however, a rigorous and completely independent verification of each official delivery was not necessary given the prime team's operations procedure and internal quality assurance checks.

In summary, FDS benefited greatly from a large team with diverse experience and tools and proved essential for success of complex, small body mission that featured multiple challenges and surprises [3].

III. Navigation Operations Environment

Primary navigation operations were performed on a dedicated network infrastructure developed and implemented by FDS. The Navigation Mission Support Area (NavMSA) consisted of a virtual network environment and a physical facility hosting personnel, ground hardware, and workstations. The physical component of the NavMSA was co-located with the OSIRIS-REx spacecraft operations team at the Lockheed Martin Mission Support Area (MSA) in Littleton, Colorado. A decision was made to co-locate the navigation operations team with the spacecraft operations team in consideration of the fast pace of operations and time critical product deliveries between the teams required to execute late updates. A core contingent of FDS team members were permanently stationed at the NavMSA, while other team members participated both in person by regularly travelling to the Lockheed facility, or from their remote location.

NavMSA network architecture consisted of multi-processor servers, shared data storage with automatic back-ups, and individual workstations. NavMSA computational resources allowed for multiple users to run processor- and memory-demanding applications, e.g., parallelized Monte Carlo error analyses, multi-arc OD runs with large datasets, etc., simultaneously. The large volume of input data (images, altimetry data, etc.) and analysis results were substantially larger than the estimates used to develop the original NavMSA storage requirements. Moreover, network drive space was not easily expanded due to the design of the NavMSA storage architecture, requiring constant data management and manual archiving by the analysts. Having an accurate estimate of overall system storage requirements in the development phase (especially missions employing OpNav and/or altimetry), as well as enabling easy network drive space expansion, are both lessons learned for future FDS ground system development.

The NavMSA also featured direct interfaces with the spacecraft flight data repository (hosted by the MSA) and the Deep Space Network (DSN) tracking data servers. These connections enabled FDS to implement and deploy automation for data download, synchronization, and product delivery, which facilitated efficient and fast navigation product delivery schedules. A high-level summary of the overall FDS network connectivity is shown in Fig. 3.

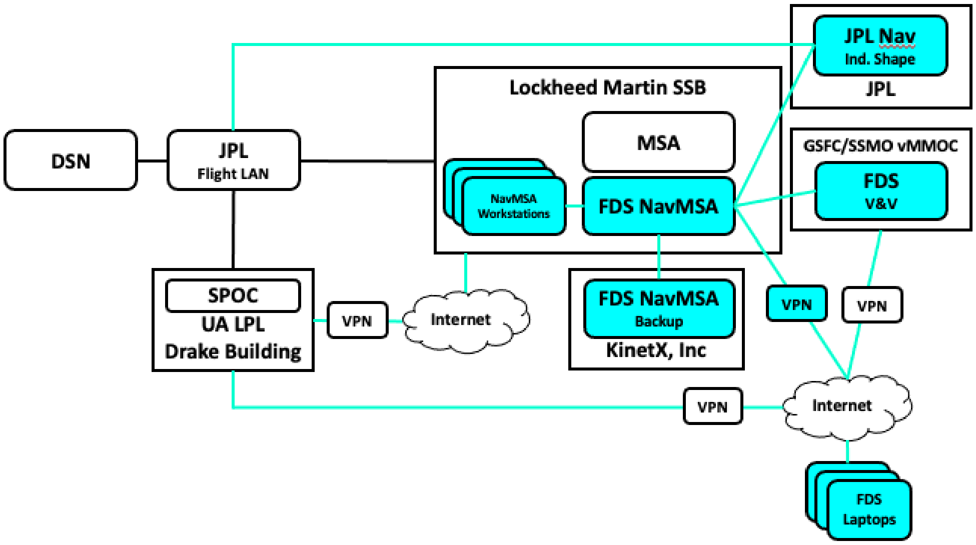

Fig. 3 High-level overview of the FDS physical locations and network connectivity. FDS network elements are highlighted in teal.

The NavMSA architecture also allowed for secure remote access of all operational systems and data. FDS personnel could initiate a Virtual Private Network (VPN) connection to the NavMSA from anywhere using their company- or government-issued laptop. This capability not only enabled work across a geographically-distributed team, but was also critical for operational support and deliveries during poor weather and other unexpected events, including two historic snowstorms that hit the Denver area in the early spring of 2019.

The GSFC IVV team had a separate operational environment deployed as part of the GSFC Space Science Mission Operations's (SSMO) virtual Multi-Mission Operations Center (vMMOC) architecture [34]. The IVV navigation operations environment is described in detail in Ref. [35]. Similar to the NavMSA, the IVV implementation supported remote access via VPN, as well as direct connectivity to the DSN and MSA through NASA's IONet. The IVV's virtual implementation also allowed for dynamic allocation of processors, memory, and storage space as the computational needs of the IVV team evolved throughout operations.

Managing a distributed, diverse, and multi-organizational team presented its own challenges. Team members were located across the country, primarily in Washington, D.C.; Denver, Colorado; Simi Valley, California; and Tempe, Arizona. FDS management relied heavily on collaboration and communication tools, including instant messaging platforms, wikis, and configuration management systems, throughout development and operations.

Although the distributed team had demonstrated an ability to work effectively together during mission development, co-location of a critical mass of navigation team members together, and co-locating the navigation team with the spacecraft operations team was a critically important factor in overall mission success. It allowed for efficient and effective communication and transfer of information between the navigation and spacecraft personnel. Having some team members located in the same place was also extremely beneficial during first-time activities and when encountering surprises. The more direct, timely, and honest communication allowed the two teams to resolve issues quickly. "Hallway conversations" augmented official project meetings and helped build a rapport between the two groups. This interaction was absolutely essential given the tight coupling between navigation and spacecraft operations while at Bennu. A few specific examples include:

- Iterating on trajectory designs to ensure spacecraft constraints are met
- Coupling between onboard ephemeris updates and observation pointing accuracy
- Inter-dependency between FDS and the Guidance, Navigation, & Control (GNC) subsystem
- Maneuver execution performance and trending
- Fault detection and responses to contingencies

The third element of the operations team, the Science Processing Operations Center (SPOC) for OSIRIS-REx, was hosted at the University of Arizona in Tucson, Arizona. This provided an opportunity to contrast interfacing across teams in person with interfacing remotely, which was particularly challenging when working through new concepts or procedures. In retrospect it would have been advantageous for some members of the SPOC team to co-locate with MSA and FDS team members periodically, particularly early in the operations phase of the mission. When the team was forced to move to fully-remote operations for a period of time in March 2020 due to the emergence of the COVID-19 pandemic, the foundation of significant time spent working together in person was critical to weathering this period successfully. Thus, a major lesson-learned from OSIRIS-REx is the importance of allocating sufficient funds for co-location travel, particularly early in the mission. For large, similarly complex and highly-integrated missions, serious consideration should be given to at least some level of co-location of the primary navigation operations area with the primary mission operations facility and personnel. In cases in which tight integration is needed between science planning, trajectory design, and spacecraft constraint tracking, consideration should be given to co-location of science planning team members as well.

Building the strong relationships among the operations teams early and enabling remote operations were beneficial throughout proximity operations, especially when operations were impacted by the COVID-19 pandemic. Beginning in March 2020, all activities at the MSA, NavMSA, and SPOC were transitioned to remote operations, except for activities that required in-person action (e.g., spacecraft command generation and uplink). Most meetings were made virtual and travel was significantly restricted. Fortunately, FDS was already well-versed in remote operations concepts by that point. Limited in-person attendance was allowed for rehearsals and TAG which required special coordination and logistics to maintain social-distancing and safety protocols. Despite the additional challenges, the pandemic did not affect the operation team's ability to meet mission objectives and successfully execute TAG.

IV. Mission Phase Planning

The OSIRIS-REx mission phase planning process is described in detail in [3, 23, 36] and summarized here for reference. The planning cycle for each phase is separated into two parts: strategic and tactical. The strategic planning cycle began 12 weeks prior to the start of the phase and usually began with an initial reference trajectory delivery from FDS. Development and refinement of the reference trajectory required frequent iterations between FDS, MSA, and SPOC to ensure science observation requirements were met while complying with all spacecraft constraints.

Prior to launch, the mission development team developed and documented a proximity operations concept and spacecraft trajectory design known as the Design Reference Mission (DRM). The DRM was refined and referenced throughout development and provided confidence that the as-built spacecraft was capable of meeting mission objectives. However, when proximity operations planning was revisited during outbound cruise, the team realized that the original observation requirements and constraints used to develop the DRM were not sufficient to meet operational and science objectives. One specific example included the required set of imagery needed to build the detailed topographic maps required for terrain-relative OpNav. Construction of the maps using stereophotoclinometry (SPC) requires multiple images under specific viewing geometries and lighting conditions at an appropriate resolution for the desired map ground sample distance (GSD) [37–42]. One of the main objectives of the Detailed Survey (DS) phase was to collect the imagery necessary to build a global set of topographic maps at 35 cm GSD. Prior to arrival at Bennu, FDS personnel worked with the Altimetry Working Group (AltWG) to re-design DS trajectory and imaging plan to ensure accurate map construction using SPC [25]. Later in proximity operations, the sample site reconnaissance campaign was re-designed to enable high-fidelity, sub-mm map construction around candidate sites for use by the onboard Natural Feature Tracking (NFT) image processing and navigation system during TAG [43, 44]. The re-design resulted in three separate phases with flybys at 1 km (Recon A), 620 m (Recon B), and 250 m (Recon C) [27]. Recon A flybys were performed on the final four candidate sites: Sandpiper, Osprey, Kingfisher, and Nightingale. Recon B and C flybys were executed for the primary and back-up sites: Nightingale and Osprey, respectively. In general, having an accurate understanding of science observation requirements early in the mission design cycle is key for proximity operations planning and design prior to arrival; however, flexibility is still required to respond and adapt to information gathered and surprises encountered *in situ*.

Iterations between FDS, MSA, and SPOC during the strategic planning cycle typically occurred in stages. Scientists and the SPOC would provide FDS with a target trajectory “window” that defined the acceptable range of spacecraft locations during observation collection. For example, a “window” for image observations may consist of acceptable altitude, solar latitude, and phase angle ranges. FDS would generate candidate trajectory designs that satisfied the observation window requirements while adhering to relevant spacecraft and operational constraints. SPOC personnel would then analyze the trajectories and develop candidate observation plans. In parallel, the MSA would assess the trajectory and observation plans to ensure spacecraft constraints were satisfied. The three elements would continue to iterate until the design closed. While this process ultimately resulted in successful completion of all proximity operations objectives, there are potential opportunities to make the process better and more efficient. One possible improvement for future missions is to incorporate more of the science observation planning and spacecraft constraint checking directly in the trajectory design and optimization software and processes. That would allow for much more efficient and faster iteration on the design with fewer intermediate deliveries among the various elements, potentially leading to a shorter overall design timeline and more globally-optimal solutions.

Another important aspect of the planning cycle was taking into account navigation prediction uncertainty and trajectory dispersions in the observation planning and operations concept. This aspect of planning was particularly challenging for OSIRIS-REx because of the small size and mass of Bennu; very small orbit prediction errors were nevertheless very large relative to the orbital radius of the spacecraft magnifying the affects of position errors when mapped to observation constraints. Observation plans and spacecraft sequences were designed based on the nominal or as-designed spacecraft trajectory. Science instrument observations and OpNav image exposures were designed relative to an onboard spacecraft ephemeris which was uploaded prior to each activity. The spacecraft trajectory used to build the onboard ephemeris products was a result of combining DSN radiometric tracking data and OpNav observables in a high-precision OD solution, which was propagated forward using frequently-updated dynamical models. The onboard ephemeris update process is discussed more in Section V. Maneuver execution and dynamical modeling errors led to a range of possible spacecraft positions at the time of a particular science observation sequence. It was the responsibility of FDS to assess our ability to “deliver” the spacecraft to the desired location at the time of the observation. It was also necessary to know the expected accuracy of the onboard ephemeris at the time of the observation. The expected trajectory prediction performance was used to determine observation mosaic sizes and how much “over-scanning” was required to ensure global or site-specific observations achieved the desired surface coverage. The relative magnitude of the perturbing forces compared to gravity, as well as the relatively low altitudes leading to large angular errors for corresponding translational errors, were two major influences on navigation performance unique to the small body environment. Therefore, overall navigation performance was a significant driver in overall operations complexity.

Over-estimating navigation performance could lead to missed or degraded observations, while too much conservatism could lead to unnecessarily complex implementations. FDS worked with the rest of the project to develop pre-launch requirements on trajectory delivery and prediction performance for each proximity operations phase. However, FDS continuously re-assessed and improved modeling and prediction performance throughout operations in an effort to be as accurate as possible [14, 21, 28]. Therefore, for each mission phase, FDS generated updated prediction and delivery statistics using linear covariance and Monte Carlo error analysis. FDS developed an interface based around Trajectory State Error (TSE) files to communicate expected prediction and delivery performance to the SPOC and MSA. Because observations were planned relative to the onboard ephemeris, the team had to check spacecraft constraint compliance across the range of possible trajectories to ensure there were no violations with the final update prior to execution. This is another aspect of mission planning that would benefit from more tightly integrated trajectory design, observation planning, and spacecraft constraint checking processes.

At the end of the strategic planning cycle, technical and implementation details for the phase were documented in a project Technical Change Request (TCR). Attached to the TCR were various documents that served as useful references throughout phase planning, review, and operations. In addition to the final reference trajectory, FDS was also responsible for delivering a Maneuver Playbook and OpNav Narrative. The Maneuver Playbook contained information on each planned maneuver, including the execution time, Δv range, thruster suite, chance of decomposition due to spacecraft keep-out zone (KOZ) violation, and the spacecraft's response to a missed maneuver late-update. Information documented in the Maneuver Playbook was generated through extensive Monte Carlo error analyses of the baseline phase trajectory design.

The missed late-update response was particularly important given the spacecraft safety and overall schedule considerations. If the operations team failed to uplink the final late-update maneuver design for whatever reason (DSN outage, product build/test failure, weather event, etc.), the spacecraft could respond in one of three ways:

- Execute the previously-uploaded preliminary design,
- Skip the maneuver and continue on the current orbit/trajectory, or
- Enter safemode and initiate a pre-programmed burn towards the Sun and away from Bennu

A summary of the missed-maneuver response decision strategy is shown in Fig. 4. In general, it was preferable to execute the preliminary design with potential degradation to subsequent science observations if it was safe to do so, or to skip the maneuver entirely. A safemode response and corresponding Sun-ward burn was reserved for instances where the spacecraft executing the preliminary design or not executing the maneuver at all resulted in a potential impact trajectory. Such a scenario would result in an extended delay of up to eight weeks given the nominal planning cycle. Therefore, it was critical for FDS to have an accurate understanding of missed late-update maneuver performance in order to select the appropriate response without risking spacecraft safety or unnecessary delays. Fortunately, the Sun-ward maneuver safemode response was not exercised during Bennu proximity operations.

The processes associated with OpNav planning are described in detail in [36]. The OpNav Narrative summarized the plan for OpNav image acquisition and the corresponding analyses to determine the image collection schedule and cadence, the number of images collected, which camera(s) were used, and the corresponding exposure times. The narrative also indicated and described the use of multi-image mosaics (e.g., 2×2, 3×1, 3×3, etc.) used to ensure a sufficient fraction of Bennu fell into the camera field-of-view when taking into account expected onboard ephemeris errors. Mosaics were employed when necessary given analysis of the ephemeris uncertainties. OpNav image sequences were implemented in flight using Asteroid Target Files (ATFs). ATFs were planned relative to the nadir vector according to the onboard ephemeris and could be easily shifted in time. As a result, ATFs could be re-used inside and across multiple phases if the OpNav conops was similar, thereby reducing complexity and effort. The onboard capability to target observations based on a nadir-relative plan developed on the ground was actually implemented as a flight software path post-launch, in response to the realization that updating science sequences as part of every late update process would be infeasible.

The team also developed Daily Planning Templates that allocated windows for science activities, high gain passes, OpNav visits, and spacecraft activities. Defining a set of templates for each mission phase allowed the spacecraft team to analyze power, thermal, and communications constraints for a finite set of scenarios for each mission phase, and provided science and navigation planners with windows of time during which they could perform their activities and not exceed any spacecraft constraints. This simplified planning by limiting the number of unique observation scenarios that needed to be analyzed by the spacecraft team. For example, templates balanced nadir-pointed periods for science observations and OpNav images, DSN data downlink windows on the high gain antenna (HGA), maneuver execution opportunities, and spacecraft thermal cool-down periods in sun-point attitude. In general, templates were designed as repeatable as possible for human factors considerations. Daily, 6-hour HGA passes were scheduled to start early in

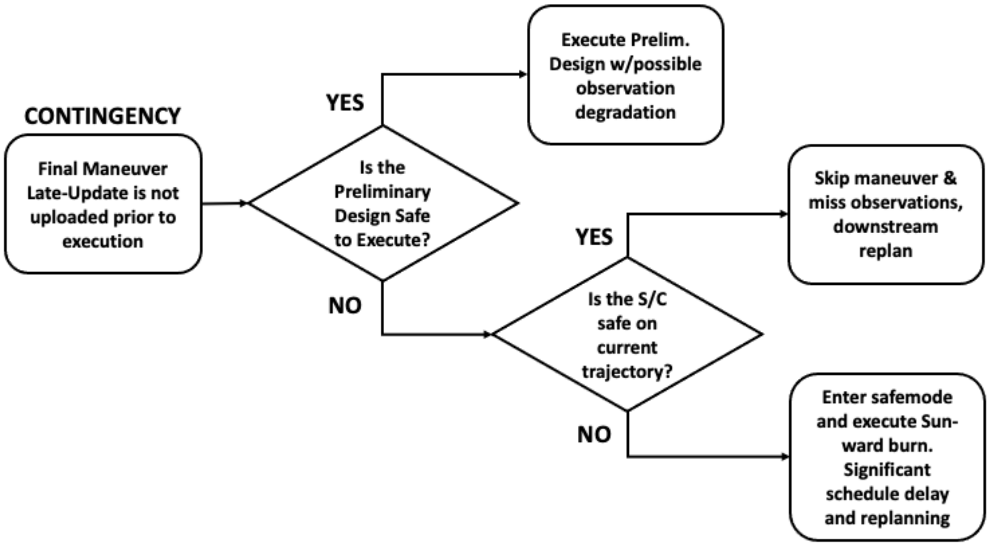

Fig. 4 Outline of missed-maneuver late-update contingency response. If a maneuver late-update is not uploaded, the spacecraft can respond by (a) executing the previously-uploaded preliminary design, (b) skip the maneuver entirely, or (c) enter safemode and execute a pre-canned Sun-ward maneuver to drift away from Bennu.

the morning mountain time (MT) to allow for real-time support by operators at the MSA. It also kept FDS and MSA personnel supporting time-critical 24-hour late-updates on first and second shifts, respectively. As detailed plans were finalized for each mission phase, the project maintained a schedule with hourly resolution to show the actual scheduled HGA contacts and science and OpNav activities relative to the basic templates. These schedules were cumbersome to maintain using Excel workbooks, but were essential to tracking details important to assess DSN coverage changes. A future mission of this complexity would benefit from more automated tools that integrate all of these critical schedule details in a flexible, graphical format.

While repeatable templates were convenient, they also led to a heavy reliance on a single DSN complex for critical support. The early morning MT HGA windows mostly fell when the spacecraft was in view of the Madrid DSN complex during a significant portion of proximity operations, including reconnaissance, rehearsals, and TAG. As a result, operations were especially sensitive to Madrid complex availability and scheduling. Complex availability at Madrid became a significant risk during the height of the COVID-19 pandemic when that region of Spain was heavily impacted by the virus. Per direction from NASA and the DSN, the project carefully assessed the impacts of potential Madrid complex outages and planned back-up contacts, as necessary. Fortunately, throughout the entirety of proximity operations, including during the COVID period, nearly all of the most time critical DSN supports occurred as planned enabling the mission to stay on track for TAG in 2020.

FDS also provided inputs to the phase Mission Plan Workbook, which documented overall daily activities and statistics including science observations and data volume, number of OpNav images collected and down-linked, DSN contacts and uplink/downlink criticality, and navigation deliveries. For each OD update, FDS defined the necessary update timeline (usually 24-hours, but occasionally 48) in order to meet navigation performance requirements. DSN criticality designations were important to ensure adequate DSN support and redundancy for pre-late update OpNav image downlinks and product uploads. Missing either the downlink or uplink opportunity for a 24-hour late update would jeopardize the following operational activity (science observation, maneuver, etc.) and possibly lead to a significant schedule delay and re-plan.

Official approval of the phase TCR marked the transition between the strategic and tactical planning cycles. The 8-week tactical cycle consisted of flight product development, implementation, testing, review, and execution. Development and implementation were tracked via weekly TCRs and corresponding Flight Activity plans. Flight product development was tracked and reviewed on a weekly basis starting three weeks prior to execution (E-3) and continued through execution week (E-0). It was important for FDS to review plans for each week to ensure they contained the correct OD delivery schedules, OpNav cadences, DSN tracking schedules and criticalities, and maneuver implementation details. FDS and MSA also used these status meetings to coordinate on trajectory file deliveries, naming conventions, and contents (e.g., which future maneuvers are included in the propagation). They also coordinated contingency file deliveries and onboard ephemeris updates in the event of a missed-maneuver or a similar off-nominal operational event.

Overall, the rigorous 12-week planning cycle was employed successfully without issue throughout OSIRIS-REx proximity operations at Bennu. However, the extended planning process did have drawbacks. Major changes to phase plans, including trajectory designs, maneuver placements, and observation sequences and schedules, could not be implemented easily without a significant amount of work, extended re-planning periods, and schedule delays. Although never realized, unexpected contingencies could have potentially caused significant delays leading up to TAG. As a result, certain contingency scenarios were discussed and developed in detail, including trajectory designs and maneuver plans by FDS. In some cases, the tactical planning cycle included two parallel paths to account for high-impact or higher-likelihood contingencies, requiring double the effort by the operations team. A more flexible and agile planning and implementation process may have provided additional robustness to surprises and contingencies. However, future projects will have to weigh the benefits of a streamlined process versus a more rigorous and risk-averse strategy.

V. Navigation Operations at Bennu

OSIRIS-REx proximity operations at Bennu was organized in three separate campaigns:

1) Navigation Campaign
2) Sample Site Selection Campaign
3) Rehearsals & Sample Acquisition

The overall proximity operations timeline is shown in Fig. 5.

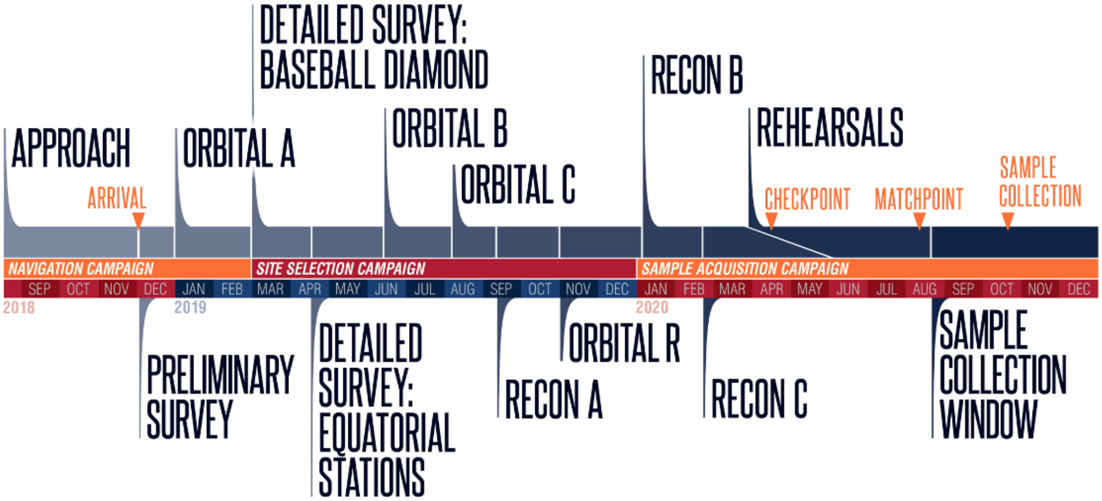

Fig. 5 Timeline for OSIRIS-REx proximity operations at Bennu.

The Navigation Campaign consisted of the Approach, Preliminary Survey, and Orbit A phases and was dedicated to FDS's efforts to prepare for and begin precision navigation around the asteroid. Allocating a specific campaign to navigation early in proximity operations was valuable, and allowed FDS to systematically approach Bennu, begin relative navigation using OpNav, characterize Bennu's mass to sufficient accuracy to enter into orbit, and transition from centroid-based to landmark OpNav image processing. All these objectives were completed successfully, allowing the OSIRIS-REx spacecraft to enter orbit about Bennu on December 31, 2018. Trajectory design and navigation performance for the Navigation Campaign are described in detail in Refs. [5, 6, 24], among others.

The original design of the Preliminary Survey phase included three sequential flybys with a close approach distance of 7 km: one over Bennu's north pole, one over the equator on the sunward-side, and one over the south pole. During the planning stages, FDS added two more flybys over the north pole (three total). The additional flybys were required to estimate Bennu's GM and reduce navigation prediction uncertainties in order to plan and collect science observations on the third and final north pole pass. One potential improvement to the Navigation Campaign trajectory design and conops is to modify Preliminary Survey or add a dedicated phase near the end of Approach that provides optimized viewing geometries for shape model and map construction using SPC, similar to the "triangular" approach geometry employed during the Rosetta mission's rendezvous with the comet 67P/Churyumov-Gerasimenko [9]. Aligning the initial flyby geometry along the Earth line-of-sight would also improve mass and gravity field recovery. Both techniques were incorporated in "Triangular Survey" and "Gravity Survey" phases, respectively, in the reference design for the proposed OSIRIS-REx extended mission (see Fig. 6). The extended mission, if approved, will rendezvous with the near-Earth asteroid (99942) Apophis in April 2029 [45].

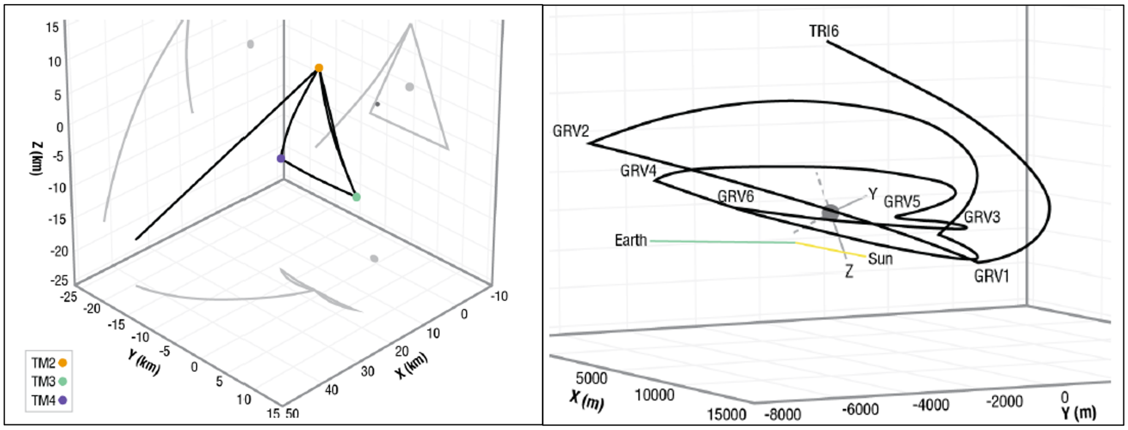

Fig. 6 Notional Triangular Survey (left) and Gravity Survey (right) designs for the proposed extended mission Apophis rendezvous concept. Both are examples for potential improvements to the OSIRIS-REx initial shape and gravity surveys.

The Bennu orbit insertion and orbit design strategies are detailed in Refs. [20, 24]. Initial covariance analysis of the orbit insertion sequence indicated a sensitivity to trajectory knowledge in the radial direction, which is difficult to measure directly with OpNav data, particularly when relying on centroid-based observables. To improve the radial position knowledge, FDS included a transfer leg prior to orbit insertion that directed the spacecraft across the sunward-side of Bennu to provide parallax for the OpNav observables. Inclusion of the additional transfer showed significant navigation performance improvement in both analysis and flight versus a straight-on, radial approach. FDS also requested additional sets of DSN Delta-Differenced One-Way Range (DDOR) baselines to further improve the radial trajectory knowledge.

The first orbital phase, 1.85 km semi-major axis (SMA) Orbital A, served as the transition point between centroid-based and landmark OpNav image processing. In preparing for the transition, FDS and AltWG worked together to develop the first official set of 70 cm GSD global landmarks using Approach and Preliminary Survey data. Building the maps was an iterative process, which began with FDS providing an initial reconstructed trajectory to AltWG. AltWG used the trajectory and image data to build an initial set of maps and corresponding map coordinates in the Bennu body-fixed frame. FDS used the maps and map coordinates to update the trajectory solution while also estimating the map locations, overall scale, orientation, and the geometric offset between the shape model center and the asteroid's center of mass. FDS delivered the updated trajectory and solution parameters back to AltWG, and the process was repeated until the solutions converged. The process resulted in successful generation of the 70 cm global maps and transition to landmark OpNav image processing. A similar process was used to construct the global 35 cm models, as well as the NFT Maps for Landmark Navigations (MLNs) utilized during TAG [43, 44]. However, the teams did recognize that the external interface and iterations between FDS and AltWG could have benefited from a more tightly-coupled and more direct iteration process between SPC map construction and FDS OD solution updates. For future missions, we recommend incorporating operational shape model construction responsibilities within the FDS and integrating it with the OD and OpNav image processing subsystems, as employed on previous small-body missions [46, 47] and the JPL independent shape modeling effort on OSIRIS-REx [48].

The driver for early transition to landmark-based OpNav image processing came primarily from reviewer feedback during the development cycle, which questioned the accuracy of center-finding techniques for extended objects when they fill a significant fraction of the camera field-of-view (FOV). In-flight center-finding performance, however, was much better than pre-launch expectations. The improved perfomance was mainly attributed to the use of 2D cross-correlation for registration of preliminary shape model deliveries from AltWG. Utilizing similar image processing techniques on future missions could potentially reduce the urgency of the landmark transition thereby simplifying operations early in the mission. Missions that have less-demanding navigation performance requirements, e.g., lower-budget missions that focus primarily on *in situ* observations without sample acquisition, may be able to avoid landmark construction entirely and rely solely on centroid-based OpNav with a preliminary shape model derived from alternate techniques.

All of the orbital phases at Bennu except Orbital B utilized a "frozen" orbit configuration in the asteroid-sun terminator plane. Frozen orbits are designed to balance perturbations due to SRP and third-body gravity from the sun in order to minimize variations in eccentricity and angular deviations from the terminator plane [49–52]. OSIRIS-REx was the first mission to utilize frozen orbits about a small body, and it proved immensely valuable [20]. Each orbital phase contained placeholders for optional two-burn trim sequences to correct deviations from the desired orbit. In practice, insertion performance and frozen orbit stability was such that no orbit adjustments were required for any orbital phase and all optional trim maneuvers were ultimately waived (except immediately following orbit re-insertion for the Recon C flyby of Nightingale and following orbit insertion after Matchpoint Rehearsal).

While the application of frozen orbits were optimal from an orbit stability and maintenance standpoint, there were also impacts on Bennu characterization and geophysical parameter estimation. Because frozen orbits are designed to balance perturbations, it also makes it difficult to differentiate and estimate contributions from various forces in the OD solution, notably gravity, SRP, and stochastic accelerations. Incorporating additional orbital phases with non-frozen configurations, including inclined/non-terminator orbits would likely improve the characterization of spacecraft non-gravitational forces and the dynamical environment around Bennu.

A significant amount of effort was dedicated by FDS to improve spacecraft dynamical modeling and trajectory prediction, as outlined in Refs. [14, 28]. Calibration and model improvement efforts began during cruise and continued throughout proximity operations. Efforts focused on multiple areas, including SRP, spacecraft thermal re-radiation pressure, and residual Δv from momentum desaturations. The team also analyzed and estimated Bennu geophysical parameters that affected trajectory propagation, including Bennu's geophysical parameter and non-spherical gravity field, as well as the asteroid's spin state. FDS developed and tested models and tools to estimate and model non-principal axis rotation; however, it was not observed in flight. The extensive analysis enabled FDS to accurately model accelerations below the expected noise level of 3e-12 $\mathrm{km}^3/\mathrm{s}^2$, confirmed by frequent definitive-predictive overlap comparisons. The additional effort and performance paid dividends throughout Bennu operations, especially given the tighter TAG accuracy requirements related to Bennu's surprisingly rough surface.

Another important aspect of navigation prediction performance was spacecraft attitude modeling. As discussed in Ref. [28], an appreciable amount of effort was made by FDS to accurately model the spacecraft attitude for non-gravitational force modeling in the predicted trajectory span. The main complication was that the attitude profile was defined relative to the reference trajectory; however, the reference trajectory propagation was dependent on the attitude profile. Close coordination and iterations between the FDS and GNC subsystems was required in order to resolve the coupling between trajectory and attitude. Although the modeling performance met the requirements of Bennu proximity operations, there was still room for improvement and streamlining the process. One possible improvement would be to incorporate more of GNC's attitude modeling capabilities directly in the FDS trajectory modeling and propagation tools. Another suggestion, employed in the latter stages of proximity operations at Bennu, is to have a more rigorous documentation of which attitude products should be used at any given stage of planning and incorporate additional attitude product updates prior to key operational events, e.g., phasing for TAG.

One particularly difficult aspect of Bennu geophysical characterization was the coupling and ambiguity between shape model scale, orbit radius, and Bennu GM. As described in [22], there is no unique solution for all three parameters in a single orbit configuration using direct OpNav measurements alone. This was discovered during proximity operations when comparing shape models and corresponding scales derived from images and OSIRIS-REx Laser Altimeter (OLA) returns. Compounding the problem further was an apparent bias in the reported OLA mirror scanning platform angles, as well as the range returns from the OLA High-Intensity Laser Transmitter (HELT), which was used during Preliminary Survey and Orbital A. The Low-Intensity Laser Transmitter (LELT) did not appear to exhibit an appreciable bias and was used primarily in the Orbital B phase. In order to reconcile the discrepancies, FDS utilized differenced data types, including image constraints and altimetric crossovers, as well as multi-arc solutions that combined tracking data from multiple orbital phases. FDS also successfully proposed dedicated off-nadir OLA observations during the Orbital R phase, which are able to more directly differentiate scale and orbit radius. As a result, FDS produced scale estimates on the order of 10 cm confidence.

Navigation prediction and delivery requirements for observations drove the onboard ephemeris and maneuver updates throughout proximity operations. In a highly-perturbed small body environment, prediction accuracy quickly degrades as the propagation time progresses further away from the OD tracking data cutoff (DCO). This led the operations team to compress the late-update timeline as short as possible. The most common late-update timeline was 24-hours and aptly named the "24-hour Late Update." The day before the maneuver or observation, the latest OpNav images were downlinked during the regular morning MT HGA pass. FDS then had approximately eight hours to receive the images, perform OpNav image processing and generate observables, construct an updated OD solution, update any maneuver designs, and propagate the trajectory forward past the time of the next planned update. FDS would then deliver the updated trajectory and maneuver products to the MSA, who would build, test, and upload the corresponding spacecraft commands during the next day's HGA pass. The activity (maneuver or science observation) would typically occur within a few hours after uplink, for a total duration from the last OpNav image exposure time (DCO) to execution of roughly 36 hours. FDS typically finished well within the 8-hour allocation (see Ref. [23] for full delivery time statistics). In addition to updating onboard ephemeris and maneuver products, the operations team also had the option of applying an observation time shift. Time shifts were utilized during DS to account for in-track delivery errors and ensure observations were collected within the required solar latitude range [25]. For all late-update products, FDS and the project had the option to waive the update if analysis indicated it was not necessary to meet requirements; although, it was almost always performed. The team exercised 24-hour Late Updates usually at least one or more times per week throughout proximity operations, leading to hundreds to successful uplinks.

Maneuver designs and updates were often carried out in a two-step process. FDS delivered a preliminary maneuver design one or more weeks in advance of the execution epoch. The preliminary design allowed the MSA to build and test notional spacecraft commands and help identify any possible issues. The preliminary design was also the last opportunity for FDS to modify the thruster suite used to execute the maneuver, which was dependent on the desired Δv. During the late-update, FDS delivered a final design to the MSA which usually represented only a slight change from the preliminary design products. The preliminary/final design process was a useful strategy employed throughout proximity operations.

While the late-update process was a successful strategy for OSIRIS-REx proximity operations, the high-cadence activities had significant human factors impacts throughout the nearly two years at Bennu. The timeline of events, maneuvers, and late-updates for DS, one of the more intense operational phases, is shown in Fig. 7. The operations team supported three to four late-updates per week over a 16-week period including Orbital B insertion. An important lesson learned for future missions is to incorporate onboard autonomy to alleviate the need for frequent, time-sensitive ephemeris and/or maneuver updates and reduce the overall ground operations cadence. For example, incorporating even a limited set of onboard image-processing and navigation capabilities to autonomously update the onboard ephemeris or observation pointing would eliminate the need for ground-based late-updates. It would also allow for more frequent updates and shorter propagation times between the DCO and activity, leading to more accurate performance and potentially more ambitious science data collection opportunities. Onboard updates would also simplify the onboard ephemeris management strategy, which had to be closely coordinated on OSIRIS-REx to ensure the spacecraft had an accurate and representative trajectory to capture OpNav images and avoid costly safemode entries. The successful use of NFT during TAG provided a flight demonstration of an image-based onboard navigation system, and similar techniques and technologies could be expanded and applied on future missions.

Prior to the first sample acquisition attempt, OSIRIS-REx executed a pair of TAG rehearsals on April 14 and August 11, 2020. The first rehearsal, Checkpoint Rehearsal, exercised the pre-departure phasing maneuvers, the departure maneuver, and the checkpoint maneuver sending the spacecraft roughly 60 m above the surface of the target TAG site, Nightingale. Checkpoint Rehearsal also exercised the NFT-based update of the checkpoint maneuver. The rehearsal ended with execution of the 40 cm/s back-away burn (BAB) sending the spacecraft on a controlled drift away from Bennu. The rehearsal executed without issue and post-rehearsal analysis indicated that the predicted TAG performance was well within the expected range. In the original plan, the MSA was scheduled to perform a spacecraft processor reset during the drift-away before returning to Bennu and re-inserting into orbit. The goal of the reset was to clear post-rehearsal caches and return the processor memory to a predictable state that could be replicated on the flight hardware simulator. However, the project decided to delay the processor reset because it required significant in-person support from operations personnel that was not possible given COVID-19 occupancy restrictions at the MSA during that time. The spacecraft re-inserted to orbit about Bennu on April 30, 2020 without the requisite reboot. The actual reboot occurred in late June around the same time as the originally-scheduled Matchpoint Rehearsal. The reboot required the spacecraft to leave and re-enter orbit over a 4-week period.

The project was then faced with a decision: forgo the Matchpoint Rehearsal and go straight to TAG during the originally-scheduled first attempt in August, or execute Matchpoint Rehearsal in August and delay the first TAG attempt until October. Strong arguments were made on both sides. The successful execution of Checkpoint Rehearsal provided confidence that going straight to TAG would result in successful sample acquisition. It was also argued that since the spacecraft already descends roughly 40 m during Matchpoint Rehearsal, that it was best to continue on to the surface and

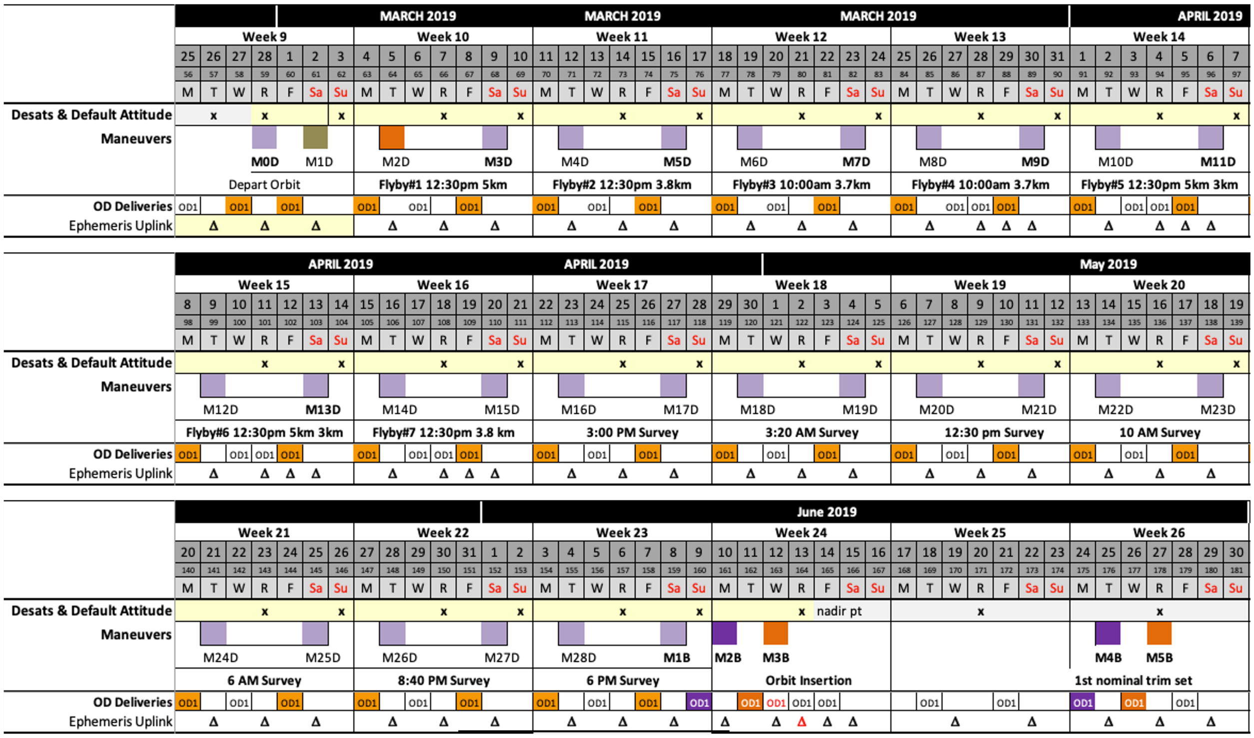

Fig. 7 Timeline of maneuvers and late-updates during the 15-week Detailed Survey mission phase and subsequent Orbital B insertion.

rely on an automated abort as a back-up. On the other hand, aborting a TAG attempt at 5 m would potentially disturb the primary sample site with the BAB thruster plumes and forcing the team to switch to the back-up site. Performing Matchpoint Rehearsal would provide additional confidence and data prior to executing the first TAG attempt, but it meant a significant schedule delay and an additional flight activity that carried its own risks. Ultimately, OSIRIS-REx project leadership elected to perform the Matchpoint Rehearsal in August and delay the primary TAG attempt. Nonetheless, it is worthwhile for future missions to consider the relative value of multiple rehearsals and the approach and objectives for each.

The TAG trajectory design and guidance strategy is described in detail in Refs. [53–56]. Given the predicted and achieved performance, the approach proved to be an efficient and effective method to deliver the spacecraft safely to the surface for TAG sample acquisition. The linear guidance scheme for onboard maneuver updates was more than adequate for the Bennu dynamical environment and guided OSIRIS-REx to within 1 m of the desired surface contact location. The decision to baseline NFT over the previous approach was made early in proximity operations when it became obvious that the initial 25 m TAG accuracy requirement was not sufficient to safely touch the rough surface of Bennu. The original concept utilized two discrete measurements from the GNC light detection and ranging (LiDAR) and a polynomial derived from simulated measurements generated via Monte Carlo runs. Switching to NFT also allowed the flight team to develop and implement a hazard map patch. The patch enabled an onboard abort initiated at 5 m above the surface in the event NFT predicted touchdown on a hazard with a probability above a pre-defined threshold. The hazard map was developed on the ground and uplinked to the spacecraft prior to TAG. Fortunately, NFT estimated a 0% probability of unsafe contact and a hazard map-based abort was never realized. Regardless, both NFT and the hazard map patch were essential to successful TAG at Nightingale on October 20, 2020.

Due to processor limitations, the OSIRIS-REx flight system was not able to run both NFT and the GNC LiDAR simultaneously. The GNC LiDAR data required an onboard pre-processing algorithm that would have exceeded processor limits if run at the same time as NFT. Therefore, NFT had to rely entirely on terrain-relative image processing for navigation observables. High resolution MLNs, on the order of mm-scale, were required to utilize NFT near the surface primarily for time-of-touch predictions. Data requirements for MLN construction drove trajectory designs and observation plans for the reconnaissance flybys. Incorporating active ranging data from the LiDAR in the NFT solution, however, could have potentially reduced or eliminated the need for mm-scale MLNs, thereby simplifying pre-TAG operations. Additionally, LiDAR data complement terrain-relative optical observables by providing a direct measurement of range, which is only inferred in optical-only solutions. In general, future small-body missions that employ onboard autonomous guidance for TAG should incorporate both terrain-relative image and LiDAR datatypes as part of the navigation solution.

VI. Spacecraft & Payload Considerations

The OSIRIS-REx spacecraft proved to be a high-performing vehicle that was more than capable of completing all operational objectives at Bennu, including TAG. A graphical depiction of the OSIRIS-REx spacecraft including labels for key components and instruments is shown in Fig. 8, for reference. Working with and navigating the spacecraft through nearly two years of proximity operations yielded experiences and perspectives that could inform spacecraft and payload design for future missions to small bodies.

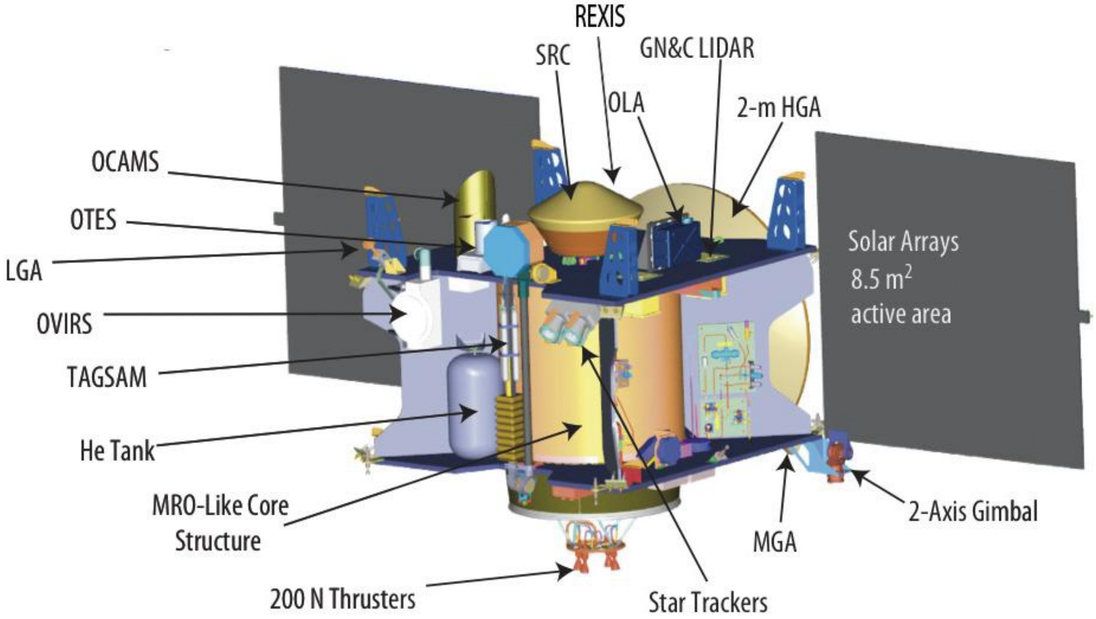

Fig. 8 Graphical depiction of the OSIRIS-REx spacecraft. Key components and instruments are labeled.

The ability to perform OpNav with various onboard imagers was an enabling capability for precision navigation relative to Bennu. The OCAMS camera suite [57] was part of the original OSIRIS-REx design consisted of PolyCam (0.8° FOV), MapCam (4° FOV), and SamCam (20.8° FOV). All three cameras utilized a 1024×1024 CCD detectors. The TAGCAMS camera suite [58, 59] was added to the OSIRIS-REx payload just before CDR. TAGCAMS consisted of two nearly identical navigation-focused cameras, NavCam and NFTCam, and a third camera, StowCam, to view the sample stow sequence and Sample Return Capsule (SRC) closure. All three cameras had a 44°× 32° FOV and a 2592×1944 complementary metal oxide semiconductor (CMOS) detector and were mounted on the +Z side of the spacecraft. The navigation cameras were added to provide the navigation images for NFT, the onboard navigation capability added as a back-up guidance system for TAG. NFT required a wide FOV imager to perform near-surface, terrain-relative image processing. NFTCam was the primary NFT imager and canted -14° about the spacecraft Y-axis in order to keep the TAGSAM sample collection arm out of the field of view during TAG descent. NavCam was the back-up imager for NFT, but its orientation was optimized for routine OpNav acquisition. NavCam had a cant angle of only +6° toward the illuminated side of the asteroid during normal nadir-pointed attitude. The original OpNav concept utilized the SamCam and MapCam for optical navigation imaging; however, the addition of a dedicated, wide FOV imager was immensely useful for OpNav since it provided landmark data across a wide portion of the surface of Bennu at varying distances in a single image, which helps distinguish between pointing and translational errors in the OD solution [39]. NavCam's wide FOV was also important to help maintain Bennu within the frame of the camera for longer periods following ephemeris updates, and the wide FOV enabled centroid-based OpNav image processing at shorter distances from Bennu and during the orbital phases. Similarly, the wide FOV allowed for the use of long-short image pairs for improved attitude estimation beyond the approach phase, which is discussed further below. It was also instrumental in the discovery and subsequent tracking of particle ejection events from the surface. Detailed analysis and assessment of landmark OpNav image processing and pointing performance is presented in Refs. [60] and [61], respectively.

Having multiple imagers with a range of FOVs, from narrow to wide, was also convenient from an OpNav and shape model construction perspective early in proximity operations. Map construction requires surface imagery at a similar GSD as the desired map under construction. Similarly, map registration for OpNav image processing works best when the image GSD is close to the map GSD. During OSIRIS-REx proximity operations, images captured using PolyCam and MapCam at higher resolution were used to construct maps for OpNav image processing with the wider FOV NavCam in subsequent phases when the spacecraft was at closer ranges. This technique could be easily be applied to future missions given an equivalently-diverse set of cameras.

Accurate OD processing using OpNav observables requires precise and accurate knowledge of the camera frame orientation at the time of the image exposure. Typically the orientation is expressed as two separate rotations: the rotation between the spacecraft body-fixed and inertial frames, as determined by the GNC subsystem, and the nominally-fixed offset between the camera and spacecraft frames. The OSIRIS-REx spacecraft did not employ a stable optical platform or "bench" for the imagers, LiDARs, and star-trackers. Instead, the instruments and sensors were mounted directly to the spacecraft deck. As a result, knowledge of the orientation between the camera frames and the spacecraft body-fixed frame, as defined by the star-trackers, was sensitive to thermal distortions of the spacecraft deck itself. Pre-launch analysis suggested camera pointing errors due to thermal distortions would be a large factor in the OpNav error budget. Consequently, this contributed to the requirement for a wide FOV navigation camera, and required the development of techniques to utilize long/short image pairs to correct for camera pointing using background stars at each OpNav visit. Luckily, the camera-to-star-tracker alignments were very stable, greatly exceeding pre-launch predictions, which made it possible to use attitude solutions directly from the spacecraft attitude reference in many instances. If thermal distortion had been at predicted levels, it would have complicated OpNav processing and likely would have negatively impacted the level of navigation performance achieved. In retrospect, the pointing requirements for the navigation imagers should have been more stringent, and future missions should carefully consider whether to employ a stable and thermally-isolated optical platform for the instruments, sensors, and star-trackers to reduce thermal variations in the camera-spacecraft alignment.

During the approach phase when Bennu was un-resolved or partially-resolved, the OpNav team used background stars in OpNav images to directly compute the camera orientation at the time of the exposure. This technique, however, was not possible once the asteroid became fully resolved in NavCam and stars were no longer visible due to shorter exposure times required to not over-saturate Bennu. Instead, the OpNav team used a strategy to capture alternating long-short-long exposure NavCam images for each OpNav opportunity. The long exposure images over-saturated Bennu but contained background stars that could be used for attitude estimation. The OpNav team would then interpolate the attitude of the long-exposure images to the time of the short exposure, which featured an appropriately-saturated Bennu for observable generation. The long-short-long exposure strategy was utilized throughout proximity operations and had a significant impact on overall OD solution quality. The strategy also led to the serendipitous discovery of particle ejection events from the surface of Bennu, which were first detected and confirmed in the long exposure NavCam OpNav images [29, 32, 62].

The OSIRIS-REx spacecraft featured a passive thermal management which imposed constraints on the total duration the spacecraft remained in particular attitudes before returning to sun-point for cool-down. The thermal limits were a driver for daily template designs and observation planning. While an active thermal management system would mean a more complex spacecraft design with mass and power considerations, it could also simplify operations concepts for missions to near-Earth asteroids (NEAs). Future mission architects should weight the spacecraft design and operations considerations of an active thermal management system.

As discussed in Ref. [28], FDS worked with thermal engineers at the MSA to develop a temperature model of various spacecraft surfaces. The model, which was a function of heliocentric distance and the sun angle off of the spacecraft +Z deck, allowed FDS to accurately calculate forces induced by thermal imbalances across the spacecraft. The thermal engineers relied on high-fidelity thermal simulations informed by flight data from spacecraft thermal sensors to produce the temperature data. The ability to accurately model temperatures of specific spacecraft components and surfaces was essential to modeling radiation pressure forces and key to achieving the level of navigation prediction performance realized at Bennu. Thus, robust temperature monitoring and modeling capabilities are a key requirement to achieving the levels of navigation performance realized on OSIRIS-REx.

Similarly, FDS utilized 3D models of the OSIRIS-REx spacecraft to calculate high-fidelity SRP models using ray-tracing [14, 63]. Having access to spacecraft models for non-gravitational force modeling is important for high-precision navigation modeling and performance. Including surface material optical reflectance and emissivity properties within the model itself, which is possible in most common modeling formats, would also allow for more accurate modeling and further improved navigation performance.

To date, the OSIRIS-REx spacecraft has executed over 130 propulsive maneuvers with a wide range of Δv magnitudes. The largest maneuver, Deep Space Maneuver 1 (DSM-1) on December 28, 2016, had a Δv magnitude of approximately 430 m/s. In contrast, the first phasing burn for Checkpoint Rehearsal occurred on April 7, 2020 with a mere 0.09 mm/s Δv. In order to accommodate the full range of required Δv control authority, OSIRIS-REx employed four sets of thrusters, summarized in Table 1.

Table 1 Summary of the OSIRIS-REx spacecraft thruster suites and Δv ranges.

Thruster Suite	Thrust	# of Thrusters	Min. Δv	Max. Δv
Main Engine (ME)	200 N	4	50 m/s	N/A
Trajectory Control Maneuver (TCM)	22 N	6	50 cm/s	50 m/s
Attitude Control System (ACS)	4.5 N	16	1 cm/s	60 cm/s
Low-Thrust Reaction Assembly (LTR)	0.9 N	2	0.08 mm/s	3 cm/s

The majority of maneuvers performed during Bennu proximity operations utilized the Attitude Control System (ACS) thruster suite in Turn-Burn-Turn (TBT) mode. The Low-Thrust Reaction Assembly (LTR) thruster was added to the spacecraft design primarily for execution of precise phasing maneuvers while in orbit. Bennu's relatively low gravity meant that small propulsive maneuvers translated into relatively large changes in orbital period and consequently spacecraft phasing. The need for the LTR thruster was first identified by FDS during TAG design and error analysis. Phasing maneuvers on the order of a few mm/s or less executed 3 to 7 days out were required to ensure the spacecraft was within ± 6° (3σ) of the desired departure latitude. Constraints on the departure location for TAG was mainly driven by the NFT feature catalog development, i.e., ensuring that the uploaded MLNs fell within the as-flown NFTCam ground track. More information on phasing maneuver requirements, strategies, and performance is provided in Ref. [26].

There was a small amount of overlap in the Δv ranges for the Trajectory Control Maneuver (TCM) and ACS thrusters, as well as the ACS and LTR thrusters. This modest amount of overlap was occasionally useful when the Δv requirements for a statistical maneuver fell near the boundary between thruster sets. Even more overlap, however, may have further alleviated occasional issues with thruster selection during strategic planning and Maneuver Playbook development.

The OSIRIS-REx spacecraft carried three active ranging devices: a pair of redundant GNC LiDARs and OLA. The 3D flash GNC LiDARs, built by Advanced Scientific Concepts (ASC), featured a 128×128 full array with a maximum measurement frequency of 30 frames per second. Since NFT was the primary guidance system for TAG, the GNC LiDARs were not utilized operationally outside of a cruise calibration checkout and a limb-crossing checkout at the beginning of Orbital B at an altitude of approximately 700 m. Both sensors performed as expected and within requirements. Detailed information on GNC LiDAR performance is provide in Refs. [64, 65]. It is unfortunate that the Bennu proximity operations schedule did not allow for a more thorough GNC LiDAR checkout and data collection in order to provide additional flight performance information for flash LiDARs and inform future navigation applications. An effort by the FDS team to compare and cross-calibrate OLA and GNC LiDAR measurements is in work. Both GNC LiDARs are still fully-functional and available to support the proposed extended mission and associated proximity operations campaign at Apophis.

The OLA instrument, contributed by the Canadian Space Agency (CSA), is a scanning LiDAR with an effective FOV of 13.4°× 11.8°and a maximum measurement rate of 10 kHz. OLA is described in detail in Ref. [66]. The instrument featured two independent laser transmitters: a HELT for longer ranges and a LELT for shorter ranges. Utilizing both the HELT and LELT provided a relatively large total operational range of 36 m to 9 km from the surface of Bennu, which is desirable for small-body missions.

As emphasized in Section V, active ranging data from OLA complimented optical data types in the OD solutions and improved both spacecraft navigation and Bennu geophysical parameter estimation. OLA data was also used by

AltWG to build shape models and detailed topographic maps and was critical to the sample site selection process [16, 17, 67, 68]. OLA data collected during the Orbital B phase provided the highest resolution global topographic information during the down-selection to four candidate sample sites. The advantage of LiDAR-derived shape models is that they do not require multiple data collection opportunities at prescribed viewing geometries and lighting conditions. As a result, they are typically available sooner in operations than equivalent models constructed from optical data, albeit at potentially lower resolution. Therefore, the two shape model products are also complimentary, as was the case for OLA- and SPC-derived shape and topography products at Bennu. FDS also demonstrated the successful use of OLA-derived topographic maps for terrain-relative OpNav image processing [69].

In general, future missions to small bodies should include a capable 3D active ranging device to support both navigation and target body characterization. Comprehensive ground and in-flight calibration is also critical, as evident by the discovery of the scan mirror scale and HELT range biases. Accurate calibration also applies to all other instruments, and includes cross-calibration and relative alignment between different sensors.

VII. Conclusions

The extensive and high-cadence Bennu proximity operations campaign enabled unprecedented characterization of the target body and ultimately led to successful TAG sample acquisition, in spite of Bennu's surprising rocky surface and lack of suitable sites for navigating the spacecraft to the surface. During TAG the spacecraft contacted the surface within 1 m of the desired location, whereas the original TAG delivery performance was specified as 25 meters. FDS and the rest of the OSIRIS-REx team gained a significant amount of experience operating a spacecraft in the vicinity of a small solar system object. They responded to Bennu's many surprises by continuously re-evaluating tools, techniques, models and processes to improve navigation and maneuver execution performance and greatly exceed pre-launch requirements as Bennu operations progressed. Planning and flight implementation required close coordination and communication across FDS, MSA, and SPOC. The mission also benefited greatly from project leadership's willingness to invest early in new capabilities and risk-reduction activities. This applied to both technology, e.g., NFT, the hazard map patch, etc., as well as improvements to ground tools and techniques.

The navigation-focused descriptions, lessons learned, and recommendations provided in this paper are informed by the nearly two-year expedition at Bennu. All spacecraft missions have unique requirements and challenges, and many of the experiences described in this paper stem from Bennu's extremely small size and the complicated, close proximity operations required to execute the science phase of the mission. While the lesson's learned would be most relevant to another mission to very small body, any future mission to a small asteroid, comet, or planetary moon could benefit from consideration of the OSIRIS-REx experiences.

Above all, the most significant factor in successful execution of navigation operations at Bennu were the contributions of the individual engineers and navigators that comprised the FDS team. The OSIRIS-REx navigation team was comprised of engineers with widely ranging backgrounds and levels of experience, but everyone shared an incredible dedication to mission success. Team members frequently went above and beyond the call of duty, and worked diligently with their colleagues to overcome challenges. The great dynamic was a major strength throughout development and operations and enabled by the drive, determination, and common goals of the individuals supporting FDS activities.

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