

OSIRIS-REx Proximity Operations and Navigation Performance at (101955) Bennu

Peter G. Antreasian^{*}, Coralie D. Adam[†], Jeroen Geeraert[‡], Jason M. Leonard[§], Erik Lessac-Chenen[¶], Andrew Levine^{||},
Jim McAdams^{||}, Leilah K. McCarthy[¶], Derek Nelson[¶], Brian Page[‡], John Y. Pelgrift[¶], Eric Sahr[¶], Daniel Wibben^{**},
Bobby Williams^{††}, and Kenneth Williams^{‡‡}

*KinetX Aerospace, Space Navigation and Flight Dynamics (SNAFD) Practice, 21 W Easy Street, Simi Valley, CA,
93065, USA*

Kevin Berry^{§§}, Kenny Getzandanner^{¶¶}, Michael Moreau^{***}, Samantha Rieger^{||}, Benjamin W. Ashman^{†††}
NASA/GSFC, 8800 Greenbelt Road, Greenbelt, MD, USA

Dolan E. Highsmith^{‡‡‡}
Aerospace Corporation, 14745 Lee Road, Chantilly, VA, 20151, USA

Dante Lauretta^{§§§}
University of Arizona, Lunar and Planetary Laboratory, 1415 N 6th Ave, Tucson, AZ 85705, USA

The NASA Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft began close proximity operations at the small (500-m diameter) B-type asteroid (101955) Bennu in December 2018 and concluded in May 2021. Hundreds of grams of pristine surface regolith were collected on October 20, 2020, when the OSIRIS-REx spacecraft successfully executed the Touch and Go (TAG) sample collection sequence. The spacecraft touched down within 1 meter of the targeted site on the surface of Bennu. TAG was the culmination of over 2 years of navigation performance refinement as a result of extraordinary interagency teamwork between the Flight Dynamics System (FDS), science and spacecraft teams while in close proximity to Bennu. This paper will discuss the navigation processes, planning and performance during the proximity operations at Bennu.

I. Introduction

The NASA Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) spacecraft (S/C) began close proximity operations (ProxOps) at the small (500-m diameter) B-type asteroid (101955) Bennu in December 2018 and completed them in May 2021. The prime objective of the OSIRIS-REx mission is to collect at least 60-g of pristine sample of the asteroid and return it to Earth in 2023. The first half of that objective was accomplished on October 20, 2020 when the S/C successfully completed the sample collection sequence referred to as Touch and Go (TAG) [1, 2]. During TAG, the spacecraft touched down on the surface of Bennu within 1 meter of the targeted site. The samples are currently en route back to Earth safely within the Sample Return Capsule (SRC). The SRC will be jettisoned from the spacecraft and land in the Utah Test and Training Range (UTTR) on September 24,

^{*} OSIRIS-REx Navigation Team Chief

[†] OSIRIS-REx Optical Navigation Lead & TAG Navigation Manager

[‡] OSIRIS-REx Orbit Determination Engineer

[§] OSIRIS-REx Orbit Determination Lead

[¶] OSIRIS-REx Optical Navigation Engineer

^{||} OSIRIS-REx Mission Design & Maneuver Engineer

^{**} OSIRIS-REx Mission Design & Maneuver Team Lead

^{††} KinetX SNAFD Director

^{‡‡} KinetX SNAFD Flight Director

^{§§} OSIRIS-REx FDS TAG Lead

^{¶¶} OSIRIS-REx FDS Lead

^{***} OSIRIS-REx Deputy Project Manager

^{†††} OSIRIS-REx IV&V Lead

^{‡‡‡} OSIRIS-REx IV&V Engineer

^{§§§} OSIRIS-REx Principal Investigator

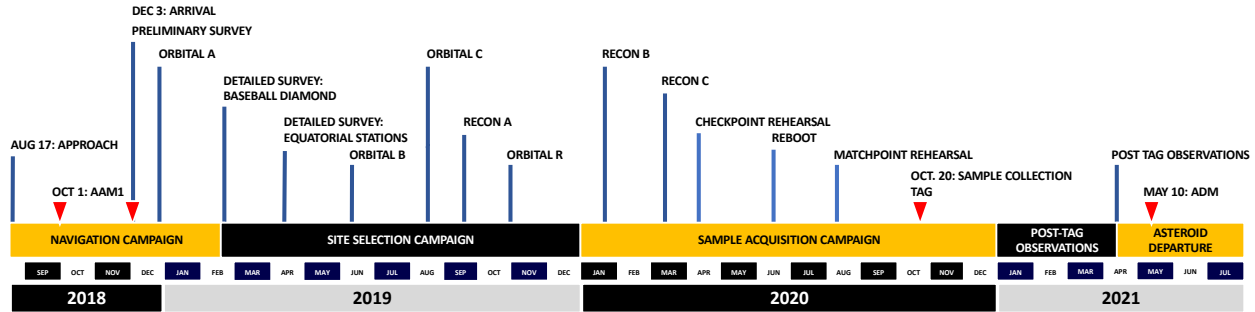


Fig. 1 Proximity Operations through Asteroid Departure, August 2018–May 2021.

2023 [2, 3]. TAG was the culmination of over 2 years of navigation performance refinement as a result of extraordinary interagency teamwork of the OSIRIS-REx the Flight Dynamics Systems (FDS), science and spacecraft teams while in close proximity to Bennu. Mission operations proceeded through progressively challenging campaigns culminating with the successful sample collection event. These campaigns included Navigation (*to learn to fly in the dynamical environment surrounding Bennu*), Site Selection (*to determine where to go*), and Sample Acquisition (*to collect the sample and stow it safely*). The ProxOps schedule is shown in Figure 1.

Mission operations during the Navigation Campaign were devoted to improving our navigation accuracy, both definitive and predictive, by gaining knowledge of Bennu’s geophysical and dynamical properties and transitioning to the more accurate landmark tracking data. This campaign also was key in the development of the high resolution digital terrain maps (DTMs) and shape model of Bennu, which was required to achieve the precision orbit determination (OD) accuracy required in subsequent campaigns. This campaign consisted of the Approach phase, beginning with the first optical navigation (OpNav) image in late August 2018; the Preliminary Survey phase, after the spacecraft arrived at Bennu in December 2018; and the Orbital A phase, spanning January-February 2019. Once the objectives of the Navigation campaign were satisfied, mission operations shifted focus to the Site Selection campaign. The goal of this campaign was to collect science observations and images at various solar longitudes, altitudes, phase and emission angles to further refine the Bennu DTMs. It included the Detailed Survey phase from late February to June 2019, the Orbital B phase from June to August 2019, Orbital C from August to late September 2019, the Reconnaissance (Recon) A phase during the entire month of October 2019, and, finally, Orbital R spanning November 2019 through the end of the 2019. Once all science requirements associated with these phases had been met and the primary and backup sample sites were selected, the Sample Acquisition Campaign commenced in January 2020. This campaign progressed through the Recon B, Recon C, Checkpoint Rehearsal (CP/R), Matchpoint Rehearsal (MP/R), and TAG sample collection phases from January through October 2020.

We designed the various OSIRIS-REx trajectories to achieve the navigation and science objectives of each campaign while satisfying spacecraft thermal, power and tracking constraints, as well as considering human factors. Trajectory types included hyperbolic flybys, near-surface reconnaissance flyovers and orbital arcs. During ProxOps, the spacecraft entered orbit 10 times with semi-major axes ranging from 820 to 1900 m, completed 21 science flybys and 8 reconnaissance flyovers supporting 31 observations at altitudes of 7 km down to 250 m, and performed two sample collection rehearsals and one TAG sample collection event. After stowing the sample shortly following TAG and drifting away for nearly three months, the OSIRIS-REx S/C performed a series of maneuvers to return to Bennu on April 7, 2021 to observe the disturbance of the TAG site from the impact on the surface by the TAG Sample Acquisition Mechanism (TAGSAM) and the four-thruster-plume impingements from the Attitude and Control System (ACS) thrusters during the back away burn.

The fourth mission in NASA’s New Frontiers program, the OSIRIS-REx spacecraft launched on September 8, 2016 aboard a United Launch Alliance (ULA) Atlas V 411 launch vehicle from Launch Complex 41 at Cape Canaveral Air Force Station, beginning the 2-year journey to Bennu. A year after launch, the spacecraft flew by Earth on September 22, 2017 for a gravity assist to alter its outgoing inclination by approximately 6° to match Bennu’s orbit [4]. A brief description of the S/C, propulsion system, telecom and instruments is provided in Antreasian et al. [4]. OSIRIS-REx is managed by NASA Goddard Space Flight Center (GSFC) in Greenbelt, MD. The spacecraft was built and is operated by the Lockheed Martin Space Systems Company (LM) in Denver, CO. The mission navigation was provided by the Flight Dynamics System (FDS) team which is managed by the FDS lead at GSFC and was comprised of the Navigation (Nav) team from KinetX Aerospace. FDS operations support and Independent Verification and Validation (IV&V) was also provided by GSFC and the Aerospace Corporation. All operational navigation products are provided by the KinetX Nav team. The Science Operations Working Group at the Science Processing and Operations Center (SPOC) located within

OSIRIS-REx FDS Organization (ProxOps)

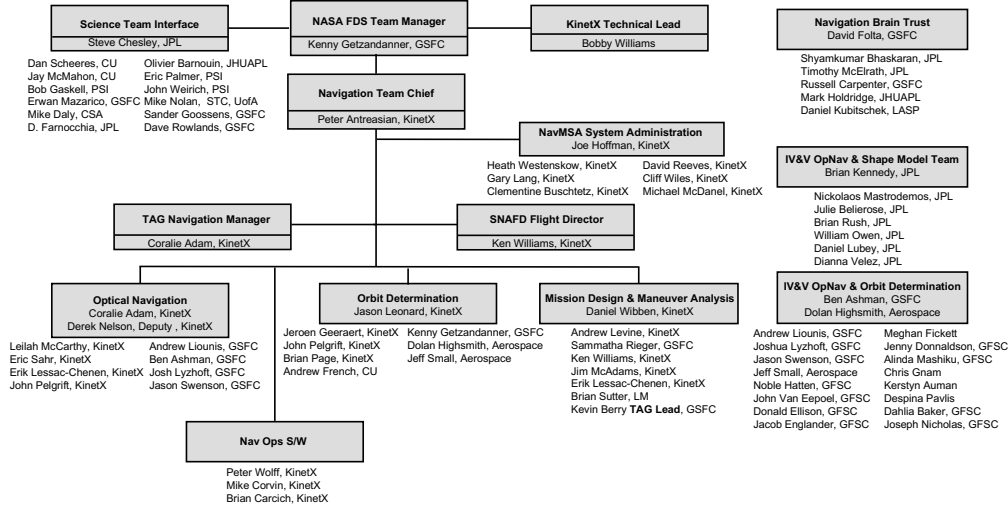


Fig. 2 OSIRIS-REx FDS Organizational chart during proximity operations.

the University of Arizona Lunar and Planetary Laboratory (UALPL) were responsible for planning then implementing science and OpNav sequences and processing the science telemetry and OpNav images for operations. The project is led by Principal Investigator (PI) Dr. Dante Lauretta from UALPL and Project Manager Richard Burns of GSFC's Space Science Mission Operations (SSMO) group.

In this paper, we will review the OSIRIS-REx navigation concept of operations and performance throughout the 2-year proximity operations at Bennu, including the Navigation, Site Selection and Sample Collection campaigns. First, we discuss the roles and responsibilities of the OSIRIS-REx Flight Dynamics Systems (FDS) team. Then we will cover processes involved in planning each phase including the mission design, OD covariance and maneuver Monte Carlo (MC) studies, and OpNav image planning. These processes usually required iteration with the science and/or spacecraft teams or internally within the Nav team to improve the science observation conditions or navigation accuracies. Next, we will discuss the details of how these phases were implemented, including placement of OD data cutoffs (DCOs), desaturation maneuvers (desats), High Gain Antenna (HGA) tracking passes, etc. Finally, we will show how our navigation performance met mission objectives and ultimately led to the historic TAG sample collection event.

II. Flight Dynamics Systems and Navigation

A. FDS Organization and Function

The Flight Dynamics team, shown in Figure 2, included engineers from GSFC, LM, KinetX and Aerospace Corporation. FDS was led from development Phase D through the middle of ProxOps by M. Moreau of GSFC. Moreau, who took over as Deputy Project manager, was succeeded by K. Getzandanner of GSFC through remainder of proximity operations and return cruise. P. Antreasian (KinetX) directed the KinetX Nav team as the Navigation Team Chief (NTC), which was comprised of the following teams: OpNav (led by C. Adam), OD (led by J. Leonard), Mission Design and Maneuver Analysis (MDMA, led by D. Wibben), and IT (led by J. Hoffman). B. Williams, the Director of KinetX Space Navigation & Flight Dynamics (SNAFD), and K. Williams, KinetX SNAFD Flight Director, provided technical direction to the FDS and Nav leads.

B. Roles & Responsibilities

1. Science Team Interface

FDS interacts with the science team through the Science Team Interface with scientists from University of Arizona (UA), GSFC, Jet Propulsion Laboratory (JPL), Johns Hopkins University Applied Physics Laboratory, (JHUAPL), University of Colorado (CU), Planetary Science Institute (PSI) and the Canadian Space Agency (CSA). This group included the Altimetry Working Group (ALTWG), led by O. Barnouin of JHUAPL, who was responsible for the timely Bennu shape model and Digital Terrain Maps (DTMs) used in our navigation solutions [5, 6], the Radio Science Working Group (RSWG), led by D. Scheeres of CU, who was responsible for the gravity science investigation at Bennu [7]. We

interacted with the JPL Solar System Dynamics team (JPLSSDT), led by S. Chesley, who, along with D. Farnocchia, were responsible for Bennu ephemeris improvements and the associated Yarkovsky acceleration characterization [8]. We also worked with JPL, UA, CU and GSFC on building the particle event database[9], event mappings[10], and initial orbit and gravity determination[11, 12]. We coordinated our deliveries to the science team with M. Nolan, the Science Team Chief at UALPL. We also worked with M. Nolan to finalize the Bennu orientation and spin models at various stages throughout ProxOps.

2. Mission Design & Maneuver Analysis Team

The MDMA team was responsible for providing the trajectory designs for each phase given science requirements and spacecraft constraints. During operations, they supported planning, designing and monitoring of all propulsive maneuvers. In planning each phase, the MDMA team ran Monte Carlo analyses to determine our navigational capabilities assuming the latest tracking, OpNav, desat schedules, OD DCOs and maneuver errors. They were responsible for coordination of these designs with the science planning team and to iterate if necessary to achieve the best science observation coverage given the expected navigation dispersions.

They provided the designs for every maneuver and for verifying their implementation. After monitoring each maneuver, they sent out a quicklook report of the burn performance to the project. For each phase development, they produced the maneuver playbook which described specifics about the maneuvers in that phase (discussed below). B. Sutter of LM initially designed the approach and proxops trajectories. This was the basis of our plans for operations at Bennu[13]. The KinetX Nav team took over the ProxOps mission design task approximately 1 year from encounter, as the mission design was revised to incorporate new or modified observation requirements, and ‘ventilate’ some aspects of the early approach and encounter period.

3. Orbit Determination Team

The OD team was responsible for determining the S/C and Bennu operational ephemerides using a combination of radio and optical data. They were responsible for performing covariance analyses on each mission phase and coordinating with science planning team on the expected trajectory dispersions for knowledge updates, which were documented in a Trajectory State Error (TSE) file. The TSE file, which was a product of these covariance studies, included predictions of the $1\text{-}\sigma$ S/C state errors in the Radial-Transverse-Normal (RTN) orbit-fixed frame from the DCO for days into the future at hourly intervals. The OD team was responsible for trending trajectory prediction performance as well as dynamical events such as desats, maneuvers, solar radiation pressure (SRP), etc. They were also responsible for the estimation of Bennu geophysical parameters (GM, gravity coefficients, spin state, etc.) and coordination of these parameters and their post-fit uncertainties with the science and LM Guidance, Navigation, & Control (GNC) and Natural Feature Tracking (NFT) teams. They generated reconstructed trajectories for final science data processing. Maneuver and desat reconstructions from the OD solutions were shared with the LM GNC and Propulsion teams for their trending analysis and developing in-flight maneuver execution error model improvements. The team also kept the DSN antenna pointing and frequency current with timely trajectory deliveries during cruise, but for operations at Bennu, a simplification was possible since the spacecraft was near the vicinity of the asteroid and its relative velocities were small. We delivered the latest Bennu ephemeris, marked with the S/C ID, for the purpose of generating DSN antenna pointing and frequency predicts, thereby eliminating routine ephemeris deliveries for the DSN. This Bennu ephemeris was used to track OSIRIS-REx for 2 years, from Nov 14, 2018 to November 9, 2020. Figure 3 shows the Doppler frequency ‘pseudo’ residual of the S/C as tracked by the DSN never exceeded ± 12 Hz throughout ProxOps.

The OD team worked with the LM thermal engineer, C. May, to develop the S/C thermal radiation pressure model using predicted surface temperatures at various attitudes (tuned from flight telemetry). The OD team also worked with University of Colorado PhD student, P. Kenneally, to develop the high precision ray-traced OSIRIS-REx solar radiation pressure model [14, 15] and Leonard et al. [16] describe our high fidelity modeling of

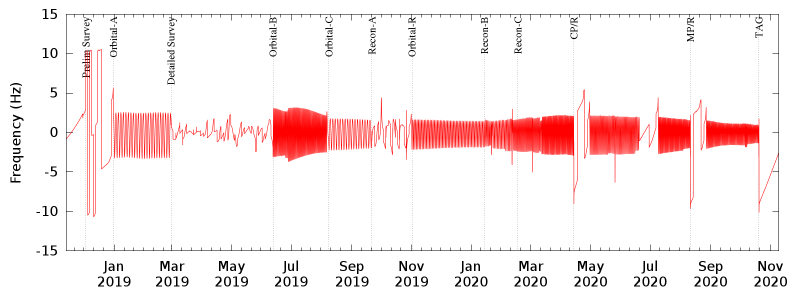


Fig. 3 The pseudo-Doppler residuals of the S/C as received from the DSN

the small forces affecting the S/C motion around Bennu and how these improvements enabled precision OD. Leonard et al. [16] explain the use of alternate measurements such as direct altimetry, altimetric cross-overs and image constraints for verifying reconstructed trajectories throughout orbital phase to be consistent to 10's of centimeters. The OD team exchanged results with the Science Team Chief and ALTWG on the Bennu orientation and spin determination, shape model scale and center-of-figure to center-of-mass offset [17], RSWG on Bennu GM and gravity harmonics [7, 12] and with the JPLSSDT on Bennu ephemeris improvements throughout ProxOps [8]. They also worked with the GNC-NFT team to verify their TAG trajectory modeling, helped tune the onboard navigation filter to account for the bounding errors on the gravity accelerations during the descent trajectory to the TAG site, and provided updated MLN feature locations. When the particle ejection phenomenon was discovered shortly after Orbital-A insertion in January 2019 [18], the OD and OpNav teams coordinated with GSFC, UALPL and JPLSSDT to perform track association, initial orbit determination of multiple particle orbits or ballistic arcs [11]. The multi-satellite arc OD filter including particle tracks enabled the determination of Bennu gravity harmonics to degree and order 9 [9], whereas the S/C orbit determination could only reliably estimate Bennu gravity to degree and order 3.

4. Optical Navigation Team

The OpNav team was responsible for planning OpNav observations and processing their observables for use in the OD operational solutions [19]. The last NavCam OpNav they processed for the TAG OD delivery, OD292, is shown in Figure 4. The landmark locations are marked with red labels and a measure of their pre-fit residuals are shown as yellow vectors on the surface of the asteroid.

Adam et al. [20] describe the OpNav concept of operations as implemented during ProxOps. They were responsible for overseeing calibration activities for the NavCam imagers and the creation of calibration products for these imagers [21]. In the strategic phase planning stages as Adam et al. [20] explain, they evaluated the pointing, exposure settings and the possibility of stray light for each of the OpNav imagers, including NavCam, MapCam and PolyCam, to ensure proper imagery of the asteroid in the shorter exposed images and desired star magnitudes in the longer exposed images. As a crucial element to the overall success of our navigation, they developed the OpNav narrative for each phase Technical Change Request (TCR) as explained below to ensure adequate coverage and quality of OpNavs with the appropriate imagers.

They worked with the Science Planning (SPT) and S/C teams to develop the daily sequence templates and schedule the OpNav images close to the nominal 2-hr cadence as much as possible outside of HGA passes, maneuvers, science observations, Δ DORs and S/C thermal cooldown periods. In general, they always tried to schedule the last OpNav image prior to the HGA downlink pass to decrease the DCO time relative to the maneuver or science observations to minimize down-track state errors. Whenever possible, they negotiated with the SPT to schedule OpNavs during science observations. For time critical OpNav downlinks, they assigned criticality levels for same-pass re-transmits as described below.

We had a number of NavCam issues beginning in late Approach, including spurious repeating 8x1 pixel patterns, incorrect Data Number values or image data, bad headers, images not transferred to the Digital Video Recorder (DVR) or periodic NavCam safing presumed to be due to radiation-induced upsets. Fortunately, through the diligence of the team, these issues were understood and generally occurred infrequently so as not to impact operations. However, to mitigate the possible loss of NavCam images prior to critical deliveries, we chose to schedule MapCams for backup. The OpNav team scheduled these in tandem to NavCams for critical late update maneuver or science deliveries.

The OpNav team evaluated the likelihood of the asteroid being captured in the FOV of the required imagers for a given phase using the S/C-Bennu state errors from either a MC or OD in the TSE format. The MC TSEs represented the control errors, the resultant errors after a series of maneuvers while the OD TSEs represented the predicted errors of knowledge updates with no future maneuvers except possibly desats. Part of the analysis was determining when, due to the S/C down-track errors, the asteroid would be out of the FOV. This analysis helped to determine the required ephemeris upload schedule, and whether or not mosaics were required after maneuvers to cover the errors from their

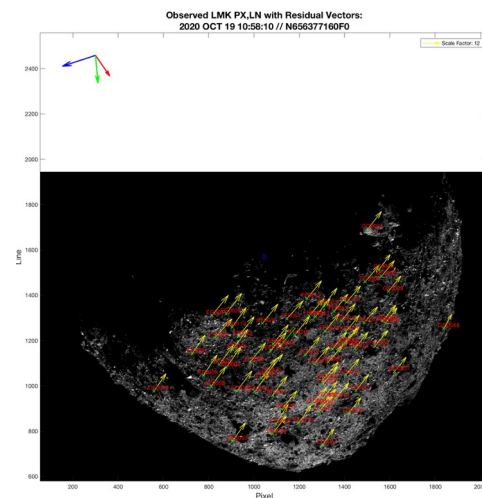


Fig. 4 Last NavCam image used in OD292 solution for the late update TAG design

dispersions.

The planning process for OpNav and science observations followed an integrated 8-week process as described below. At 7 weeks from sequence execution, the team delivered an OpNav request that detailed all the OpNavs desired by the FDS team for that week; the OpNav team ensured the OpNav images were scheduled as close to the plan developed in the phase TCR as possible. These requests specified the imager type, epoch windows, exposure settings, timing constraints, pointing specifications, settling times, re-transmit criticality, and imager sequence command block. The SPOC incorporated these imaging requests into the observation plans and, at 5 weeks before sequence execution, they delivered the OpNav checklist and report which were reviewed at the OpNav reconciliation meeting. If necessary, the OpNav team iterated with the SPOC to finalize imaging plan before implemented into the weekly sequence at 3 weeks before execution [20].

5. Independent Navigation

An external navigation review board headed by D. Folta of GSFC with flight dynamic principals from JPL, JHUAPL and CU's Laboratory for Atmospheric and Space Physics (LASP) reviewed our plans and concept of operations before proximity operations began. An independent OpNav and OD team at GSFC, led by B. Ashman, helped our team compare OpNav observables using their Goddard Image Analysis & Navigation (GIANT) image processing software [22], OD solutions using GSFC GEODYN and JPL MONTE navigation software [23], and an alternative approach to SPC for landmark identification in surface feature-base navigation [24]. Because of their experience and to buy down risk, an independent OpNav and Shape model team was formed by JPL navigators led by B. Kennedy. We periodically ran our OpNav and OD solutions with their shape models and compared these results with our operational solutions which used the ALTWG shape models; these were compared by Leonard et al. [17].

C. FDS TAG Leads

K. Berry of GSFC, the FDS Lead on TAG, was responsible for TAG trajectory design and MC error analysis and worked closely with the LM team on the original concept for the TAG navigation update utilizing Lidar measurements [2]. He developed the TAG MC to model all known errors in the propagation of the TAG trajectory after the Orbit Departure Maneuver (ODM) through the Checkpoint (CP) and Matchpoint (MP) burns, to the surface and, finally, the back-away maneuver. The CP burn started the S/C on descent toward the surface. The MP burn decreased the descent rate and targeted the final position and surface contact velocity at TAG. These maneuvers were ACS Vector burns consisting of three components each fired in sequence along each S/C body axes: X-Y-Z for CP and Z-Y-X for MP.

The TAG FDS Lead interacted closely with the S/C GNC, NFT and Propulsion teams to ensure the updated flight dynamics and maneuver parameters were verified between the teams. He was responsible for delivering the late update ODM, CP and MP burn parameters for implementation by the S/C team.

After NFT was baselined for TAG, an interagency (KinetX-GSFC-JHUAPL-PSI-CSA-UA-JPL) development effort was required to iterate on the Bennu orientation and feature landmarks used by the LM onboard NFT filter. We appointed C. Adam, the Optical Navigation lead, as the TAG Navigation Manager to manage this interagency effort and keep track of various deliverables to ensure the inputs to the NFT system were validated and synchronized across the navigation and altimetry subsystems.

D. Navigation Software

The KinetX Nav team used the navigation software, Multiple Interferometric Ranging Analysis for GPS Ensemble (MIRAGE), for Mission design, OD, and maneuver targeting. The Analytical Graphics, Inc System Tool Kit (STK) was used to target the specific phase, incidence and emission angles during the hyperbolic flybys in Detailed Survey and the reconnaissance flyovers in Recon A, B and C. The KinetX-developed Monte-Carlo Operational Navigation Simulation for Trajectory Evaluation and Research (MONSTER) tool was used to run Monte Carlo multi-maneuver phases in MIRAGE. The KinetX OpNav team used KinetX Image Processing software (KXIMP) for star-based Bennu center-finding, or centroiding, OpNavs and for determining camera pointing. Stereophotoclinometry (SPC) software, developed by B. Gaskell of PSI and managed by UA, was used to correlate the OpNav landmark images with the current shape model. The KinetX Fly-Point-Shoot (FPS) visualization software was used to verify OpNav imaging plans and compute pointing offsets for mosaics.

E. Co-location

Members of the FDS organization lived across the United States, including the KinetX SNAFD site in Simi Valley, CA, KinetX headquarters in Tempe, AZ, GSFC in Greenbelt, MD, Aerospace Corp. in Chantilly, VA and LM in Denver,

CO. Because of the challenges posed by this mission, a core Nav team consisting of five KinetX and two NASA team members were co-located with the LM Spacecraft team in the LM Space Systems Building at the Waterton Canyon campus near Denver, CO. The Nav team worked in the Navigation Mission Support Area (NavMSA) on the same floor as the S/C team MSA. As ProxOps were underway, an increased level of co-located staffing were maintained from remote members who traveled frequently to meet the demands of the schedule. On average, the co-located FDS-Nav team consisted of 1 NTC, 1 FDS lead, 2–4 OpNav, 2–3 OD, 3–4 MDMA and 1 IV&V members totaling 10–14 individuals.

This colocation enabled the FDS team to work closely with the LM GNC team led by R. Olds of LM, who was also responsible for the LM-developed NFT onboard navigation system. Fortunately, the nearly 6 years of co-development paid off, when the COVID-19 pandemic caused our teams to work remotely for most of 2020 during the most challenging period of our mission: the Sample Collection Campaign. Only a limited number of people were allowed on-site at LM during the height of the pandemic. By this time, however, the inter-team communications and interactions were well versed and everyone knew their responsibilities.

LM housed our primary server rack consisting of a primary and backup servers running Linux virtual machines (VMs) in a temperature-controlled server room and supported by backup generators. The NavMSA contained twelve workstations consisting of ten iMac workstations, three of which were devoted to OpNav processing with KXIMP and SPC, and two Microsoft Windows machines specifically for running STK. The NavMSA also included an Advanced Spacecraft Integration and System Test (ASIST) terminal directly connected to the JPL Flight LAN for viewing or querying real-time telemetry. For on-console support during critical events, we also had a workspace among the other sub-systems in the S/C team MSA consisting of a Windows, OpNav iMac and an ASIST machine. A block diagram of the NavMSA and its direct and remote connections is shown in Getzandanner et al. [25]. The GSFC IV&V team, as described by Getzandanner et al. [25], also had a separate support area and operational environment within the virtual Multi-Mission Operations Center (vMMOC) located at GSFC.

III. Mission Planning

A. Strategic Planning

The mission planning for ProxOps initially began pre-launch with the following references: the Baseline Reference Mission (BRM), the Design Reference Mission (DRM) and the Design Reference Asteroid (DRA). Produced by LM, the BRM detailed the concept of operations for all phases. The DRM provided a first cut of the required High Gain Antenna (HGA) tracking passes for sequence/commanding/ephemeris uplinks and science/engineering downlink for every day of each ProxOps phase. All significant geophysical and morphological data gathered on Bennu before encounter were recorded in the DRA. These included initial determination of models, parameters (and uncertainties) such as Bennu shape, orientation, spin state, gravity (GM), Yarkosky, albedo, etc., that were informed telescopically and from Deep Space Station Goldstone and Arecibo Observatory radar measurements from past Bennu-Earth close approaches (1999–2011) [26]. These models formed the basis of our trajectory designs and OD filter strategy.

Strategic planning for the first three mission phases began several months before Bennu approach. Each phase was planned with inputs from the S/C, Science Planning and FDS teams as phase TCRs. Then, as these first phases were underway and more information on Bennu was gathered, the project kicked off strategic planning TCRs for the remaining phases three months before their execution. The FDS team was responsible for delivering the reference trajectory, Maneuver Playbook, and OpNav Narrative corresponding to each phase. The SPT delivered the Science Phase Plan which included instrument observation plans to meet science requirements and achieve the objectives of the phase. With these inputs from FDS and Science, the S/C team built and delivered daily sequence templates for planning the onboard activities on a 15-minute to hourly basis.

The OSIRIS-REx Project Navigation Plan [27] formed the basis of the FDS concept of operations at Bennu. Williams et al. [13] summarizes this concept of operations with the mission design and navigation analyses for each of the ProxOps phases. The initial reference trajectories were based on a Bennu GM of $5.2 \text{ m}^3/\text{s}^2$, and the initial OD and MC trajectory analyses considered the 3σ error of $\pm 1.8 \text{ m}^3/\text{s}^2$. Updated reference trajectories were a prerequisite to each Phase TCR. We re-designed reference trajectories for each phase as more information on Bennu, such as gravity and orientation, was determined and science requirements and plans were further developed. The mission design process, with interactions and iteration between the teams for producing Phase TCR inputs, is illustrated in Figure 5. The process began with the mission and science requirements and other governing documents plus updated inputs and Bennu geophysical parameters for OpNav, MDMA and OD processes. The MDMA team designed the trajectory to meet the science requirements and S/C constraints. The OD team then assumed a baseline tracking, desat and late update (DCO) schedule, and ran a covariance analysis to determine the S/C state knowledge errors mapped from the

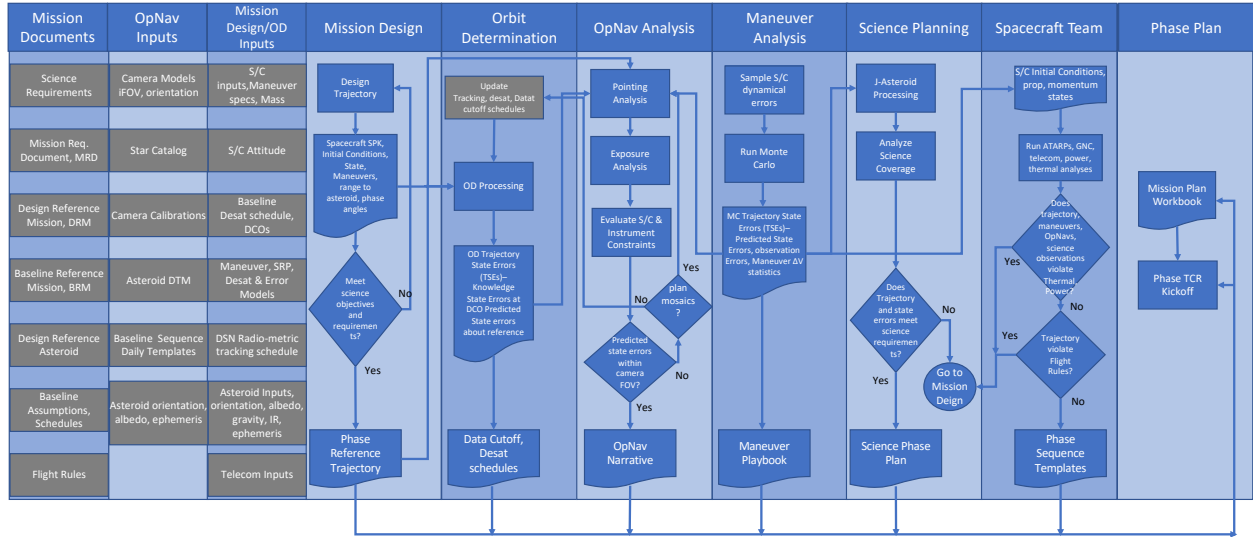


Fig. 5 The Mission design process for Phase TCR inputs

DCOs to time of maneuvers or science observations. Based on those results, they produced and delivered the TSE file of predicted state errors. The OpNav team evaluated those errors against the NavCam, MapCam and Polycam camera FOVs, assuming the initial late update schedule and when an updated ephemeris would be uplinked and become active onboard, to confirm capture. Also, the OD state errors at the maneuver epochs were inputs into the maneuver Monte Carlo analysis which also produced a TSE file. Those files represented the delivery errors assuming multiple maneuvers and OD DCOs. Both the OD and MC TSEs and the reference trajectory were delivered to the OpNav, Science and S/C teams for their analyses. Typically, for orbit insertions, the OpNav team found that it was necessary to plan for 2×1 or 3×1 NavCam mosaics to cover the expected post-burn dispersions. Sometimes, the team discovered that an OD DCO or desat had to be moved to ensure better down-track prediction performance. Occasionally, the SPT requested trajectories that bounded the 2 or 3 σ dispersions over the science observations to adjust their observation schedules. If the S/C or science team found issues, they would feed back this information to the MDMA team, who would iterate on the trajectory design until all teams were satisfied. Figure 6 shows the phase TCR development relative to the phase execution. Also shown are the deliveries of reference trajectories (refODs) supporting the development of those TCRs.

1. Maneuver Playbook

The MDMA team specified several attributes of the planned maneuvers for each phase in the Maneuver Playbook to help the S/C team prepare sequences. For each maneuver, the playbook showed the required maneuver thruster suite, the 99-percentile ΔV , and whether or not a late update design and/or time shift were needed. In this playbook, the MDMA team specified if the preliminary maneuver design is valid, that is, if it could be uploaded to the S/C and executed in the event the late update design or uplink is missed for whatever reason. This was important because missing a late update would almost guarantee science observations would be missed, but executing the preliminary burn kept the S/C on the mission schedule; however, in many cases the preliminary design would be dangerous to execute. These preliminary designs were typically designed in the week before execution, usually as set of burns that cover the phase or week. The playbook would also indicate the likelihood of needing to decompose each maneuver into two burns that would avoid the S/C Keep-out-zone (KOZ) (nominally a 45° cone about the S/C +Z axis). Only maneuvers for orbital insertion, the 2nd burn of orbit trim pairs and the ODM and Orbit Recapture Maneuver (ORM) for Recon B & C required time shifts in order to place them in the correct location for the next burn to be effective [28].

Just prior to Preliminary Survey, the project implemented a sunward burn option that would keep the S/C safe in the event of a missed maneuver or safe-mode by executing a pre-canned maneuver to move the spacecraft in the sun direction to prevent the S/C from going behind the asteroid. Such a scenario would have been dangerous or complicate recovery. Through the maneuver playbook, we identified how the S/C should respond in the event of a missed maneuver: if this contingency is potentially dangerous, put the S/C into safe mode, thereby executing the sunward burn; or if it is benign, skip the sunward burn. Fortunately for us and the project, this scenario never occurred and the S/C never missed a maneuver. If it had, it would have delayed our schedule by at least a few weeks to determine the cause, recover the S/C

from safe mode, re-design and analyze the trajectory for the current and upcoming phase, and build new sequences.

2. *OpNav Narrative*

The OpNav team produced the OpNav Narrative which described the planning, scheduling, pointing and exposures of OpNav imaging during the next phase. The TSEs from MC and OD analyses were used to verify the imaging plans relative to late update S/C ephemeris running onboard. If the errors exceeded the camera FOV, then either two-frame mosaics were planned or the weekly schedule of OD DCOs was adjusted to keep the asteroid in the FOV of the camera. The narrative includes reference plots of solar phase angles, range, camera resolutions and size of Bennu in the FOV. The narrative described scheduling OpNavs on a 2-hr cadence in the daily sequence templates where it could avoid other S/C activities. The narrative also evaluated stray light. Adam et al. [20] give more details of the OpNav Narrative.

B. Deep Space Network Tracking

The S/C was tracked via the NASA Deep Space Network (DSN) with ground stations in Goldstone, CA, Madrid, Spain and Canberra, Australia. Long-term planning for OSIRIS-REx began pre-launch with the submission of the User Loading Profile (ULP) document which specifies the project's desired number of tracking passes per week of a specified length, nominally 8 hrs, and the reference trajectory for the entire mission. This ULP was updated periodically during the mission as the mission plans changed. The ULP, along with the Navigation tracking requirements, are submitted to the OSIRIS-REx DSN scheduler who negotiates with other missions to meet these requirements as closely as possible. These tracking allocations began approximately 6–8 months in advance of real time with the submission of the project tracking requirements. At 4 months, the schedulers built the mission schedules and then participated in negotiations approximately 3 months out through execution. The project and FDS leaders met weekly with the DSN scheduler to ensure the daily, first-shift HGA tracks were scheduled while accommodating DSN maintenance and/or downtimes. The Navigation requirements included the need for at least 8 hrs of tracking per day plus near-continuous coverage of maneuvers and desats with at least 15 minutes of tracking before and after execution. The HGA tracks were required for downlinking the Science and OpNav observations, sequence commanding and ephemeris or maneuver uplinks. However, S/C thermal constraints limited the heating on S/C -X and -Z faces to 5–7 hrs when the S/C slews to point the HGA (S/C +X face) to Earth. Due to the signal strength, 2-way ranging was only available through the HGA after the S/C–Earth distance was more than 1 AU (beginning in July 2019 through end of ProxOps), which limited ranging to the 5–7 hrs per day of HGA contact. Maneuvers generally required the S/C to slew to a burn attitude thereby losing lock with the tracking station, so the S/C team would ensure these tracking requirements were met by accounting for additional tracking data before and after the slews to/from burn attitude. We also acquired up to four North-South (N-S) and East-West (E-W) Δ DOR baseline observations per week over multiple weeks each quarter throughout ProxOps to help maintain the Bennu ephemeris. These measurements were also acquired before and after orbit insertions and deep space maneuvers, including the Asteroid Departure Maneuver (ADM) on May 10, 2021.

C. Tactical Planning

As the Phase TCRs were developed, the DRM was eventually turned into the Mission Planning Workbook which tallied all important information, such as science data downlink volumes, rates, trajectory information, tracking passes, number of optical navigation images (OpNavs), etc., for each day of the phase. All pertinent data, including the Maneuver playbook, reference trajectory design description, sequence templates, and OpNav Requests, etc., were recorded and stored within LM's Redmine project management database within each phase TCR. Phase TCRs were approved before the start of the tactical weekly operations and sequence development that began 8 weeks from execution (E-8). Each weekly sequence was kicked-off by the Science Operations Planning Group (SOPG) by delivering and reviewing the science observation plan details for that week. At E-7 weeks, the OpNav team delivered the OpNav Request as described above. The SOPG would merge these OpNavs into the weekly science plan and return the OpNav checklist to the OpNav team for review and reconciliation at E-5 weeks. If necessary, a final OpNav Request would be delivered at E-3 weeks. Details of this planning process relative to OpNav and science planning are discussed by Adam et al. [20] and Lauretta et al. [3]. At E-6 weeks, the MDMA team had the opportunity to update the reference trajectory for the week of execution. The following week (E-5 weeks) the MDMA team documented the maneuver implementation details via the maneuver TCR inputs. All inputs from the S/C team, FDS and SOPG detailing the daily ground and S/C activities were gathered and any issues impacted and resolved in the weekly TCRs before being approved on Tuesday during week E-4. At E-3 weeks, the S/C team then reviewed with the project the status of the current sequence build process relative to each of other concurrently active weekly sequence builds in development. The sequence implementation was kicked-off that same week. Preliminary maneuver designs were delivered at E-1

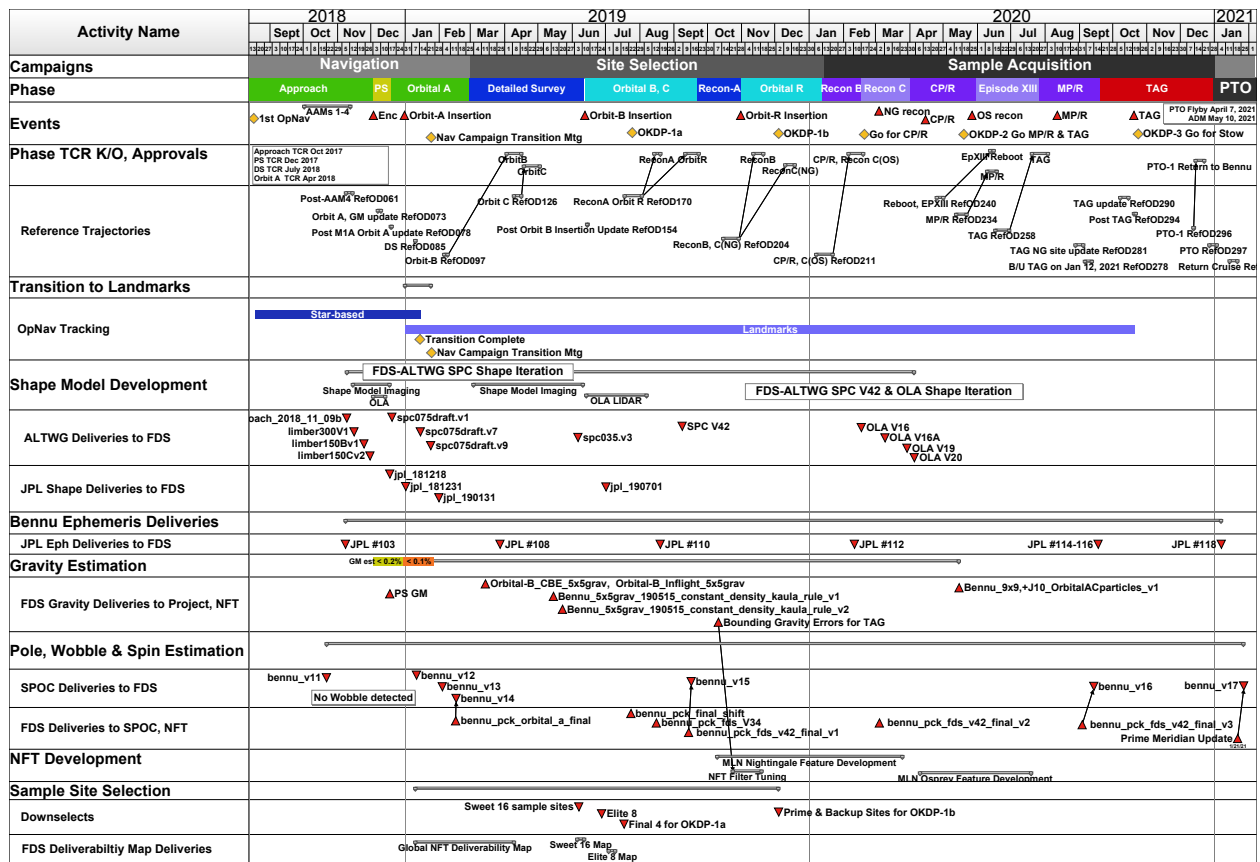


Fig. 6 Schedule of activities for Benu shape model, orientation, and gravity field development.

week. With no more science observation planned after CP/R through TAG, the weekly sequence development timeline was reduced to a 6-week build process, beginning with the OpNav Request. Sequence builds for the 3 weeks before and including MP/R or TAG were built together starting 6 weeks out. Immediately after TAG, the S/C no longer required the Benu-relative ephemeris onboard, so it was disabled. Later, however, the onboard ephemerides were once again required to capture OpNav images and safely navigate the S/C back to Benu during the Post-TAG-Observation (PTO) phase.

1. Downlink and Uplink criticality

FDS assigned criticality levels for the downlink of OpNav data and uplink of ephemeris and maneuver commands during HGA passes, depending on the impact to mission. Levels on a scale from 1–5 were assigned based on mission risk: 1 for potential loss of mission, 2 for large schedule impact and/or loss of critical science, 3 for loss of science data with no near-term impact (but may require future re-planning), 4 for loss or degraded science with no impact to schedule and 5 for no impact due to loss of uplink or downlink or no activities planned [20]. Criticality level 1 was never assigned during ProxOps due to the robustness in the mission design trajectories and the contingencies planned. Critical OpNav downlinks were assigned 2 or 3 to ensure same-pass retransmits were performed to recover missing frames or entire OpNavs provided the current HGA pass was still viable. For OpNav downlinks, level 2 required on-site support, while level 3 required on-call support with a response time of 1 hour or less. Late update uplinks for orbit insertion burns, orbit departure maneuvers or the 2nd burn of a orbit trim pair were assigned level 2 because of the immediate safety to the S/C in the event of the missed maneuver. Other maneuvers were assigned either level 3 or 4 depending on the phase and/or the availability of redundant uplink passes. Likewise for ephemeris uplinks, depending on the down-track state errors due to maneuver dispersions (e.g., after orbit insertions), criticality level 2's were assigned to uplink passes to ensure the onboard ephemeris was updated and prevent the loss of OpNavs. Criticality levels 2 and 3 required DSN level 3 (L3) support. DSN L3 support required a DSN mission review to assess operational readiness for supporting a critical mission event and on-console support during pass. Though missing a late update maneuver uplink in ProxOps could disrupt the mission

schedule, it was not feasible to designate all uplink passes as DSN L3 support. Because the HGA tracks were negotiated well in advance of execution, the inflexible schedule of activities made it difficult to schedule passes for contingencies.

D. Geometry

For reference, the distances between Bennu and the Sun and Earth, as well as the Sun-Earth-Probe (SEP) and Sun-Probe-Earth (SPE) angles, are illustrated in Figures 7(a) and 7(b), respectively. The Bennu-Earth distance primarily increased after April 2019, towards the latter stages of ProxOps. The S/C was in close proximity to Bennu for approximately two full Bennu orbits around the sun with period of 1.2 years. The range of solar phase angles experienced by the spacecraft is shown in Figure 7(c). The spacecraft distance to Bennu center and the Bennu-relative velocity throughout ProxOps are displayed in Figures 8(a) and 8(b), respectively. A majority of ProxOps was spent at distances below 2 km from Bennu. The Bennu-relative velocity magnitudes ranged from a few millimeters per second to under 10 cm/s.

E. Nav Team Processing Times

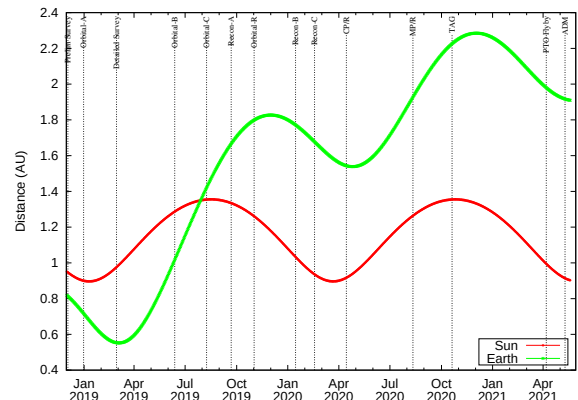
The processing times of the Navigation team during the late updates throughout ProxOps, shown in Figure 9, was closely monitored to ensure timely deliveries to the S/C team. The S/C team normally worked during the 2nd shift to build and test the maneuver commands or ephemeris update in order to have them ready for uplink by the next morning's HGA pass. We would regularly communicate our progress to the S/C team, especially if we projected the delivery to be significantly earlier or later than planned. The processing times for the OpNav and OD teams averaged 1.9 ± 0.7 hrs and 2.0 ± 0.9 hours, respectively. The MDMA team averaged 2.7 ± 1.1 hours for late update maneuver deliveries. In absence of maneuvers, the MDMA team processed and delivered the late update S/C ephemerides within 1.7 ± 0.8 hours. The Nav team was allotted 8 hours for the late update processing the Nav solutions and delivery of maneuver design and/or ephemeris to the project. Our total processing times for maneuver designs averaged 6.5 ± 1.1 hours with the quickest time just under 3 hours and longest at 10 hours. The team averaged 5.4 ± 1.1 hrs for the ephemeris-only deliveries.

IV. Proximity Operations at Bennu

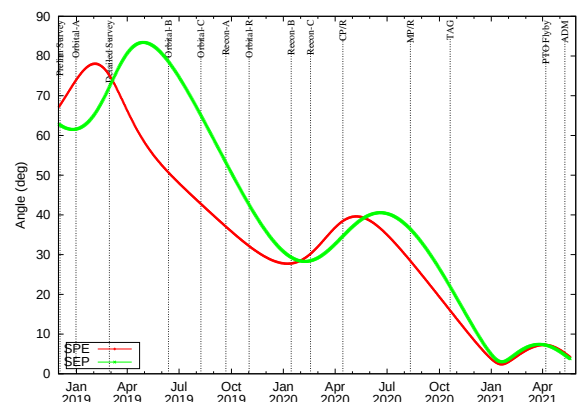
A. Navigation Campaign

1. Approach, August 17–December 2, 2018

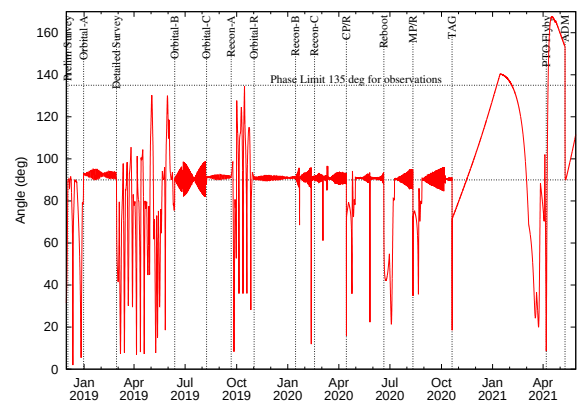
Starting in October 2018, we began slowing down the OSIRIS-REx spacecraft velocity relative to Bennu, first with two large maneuvers on the four 190-N main engines, AAM-1 on October 1 and AAM-2 on October 15, 2018. We then carefully navigated OSIRIS-REx through a specific spacecraft-to-Bennu solar-phase angle and range corridor required for science observations, using strategically placed maneuvers with progressively decreasing levels of thrust: one maneuver (AAM-3) with the six 22-N Trajectory Correction Maneuver (TCM) thrusters in late October, and three maneuvers, AAM-3a, AAM-4, MOP on the eight 4.5-N Attitude Control System thrusters (ACS) in November as finer control was needed at close range (< 200 km)



(a) Distance from Sun and Earth



(b) Sun-Probe-Earth and Sun-Earth-Probe Angles



(c) S/C–Bennu Phase Angles

Fig. 7 OSIRIS-REx Sun, Earth Geometries during Proxops

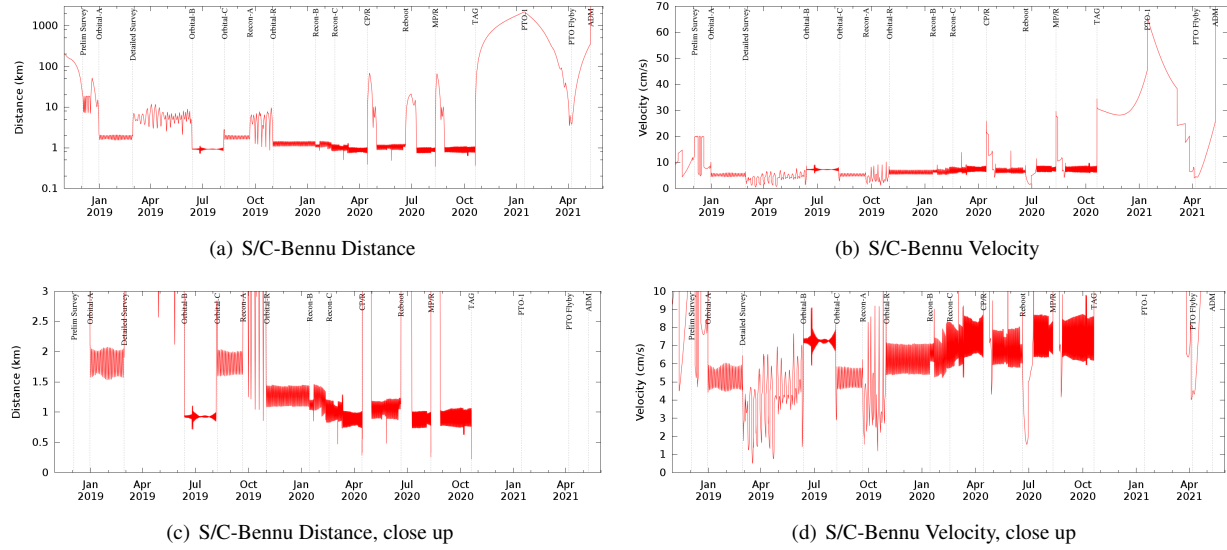


Fig. 8 Distance, velocity of spacecraft relative to Benu center during ProxOps to ADM

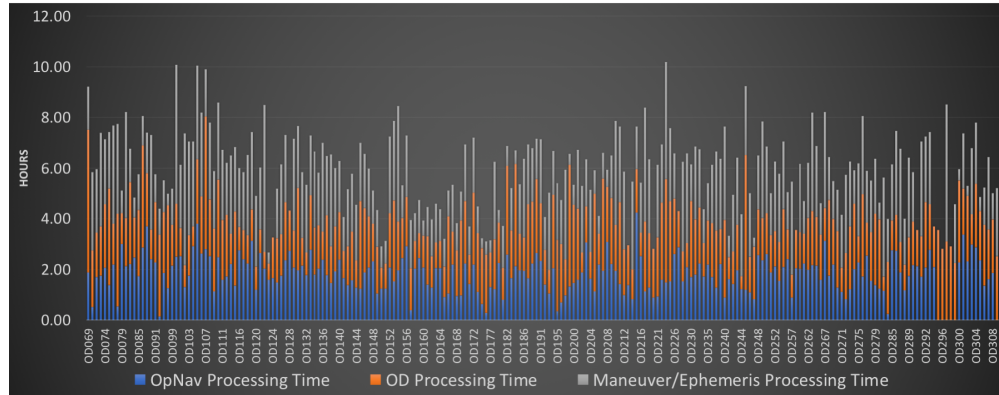


Fig. 9 The processing times of the Navigation team during operations.

to the asteroid. From the Approach design described in [13] we ventilated the schedule by adding two weeks before rendezvous with Benu at start of the Preliminary Survey. This was for allowing time for the project to review the results of the natural satellite search and determine operational key decision point 1 of whether it was safe to proceed or brake with the last scheduled burn before Preliminary Survey, MOP (December 1, 2018). This time also allowed for additional full PolyCam rotation imaging to support shape model creation and ‘relatively quiet’ time for the teams before the very challenging next phase. Wibben et al. [29] describe the asteroid-approach trajectory design for meeting the science requirements on Approach phase and Antreasian et al. [30] report on the navigation performance during this phase.

At the beginning of Approach when the spacecraft was far from Benu, we processed images of Benu as a point source against a background of known stars measured with respect to its predicted location in the camera frame (referred to as star-based OpNav) to create tracking observables. These tracking data were used in the OD process which determined the Benu-relative spacecraft state and Benu heliocentric ephemeris used in the maneuver designs and instrument pointing. As the apparent diameter of Benu grew in the camera frame the closer to the asteroid the spacecraft became, the star-based OpNav tracking observable transitioned to rely on the precise centroiding or center-finding of the asteroid center of mass using the visible asteroid limb relative to that projected from an accurate shape model in the camera frame [19]. Once the spacecraft arrived at the asteroid on December 3, 2018, we embarked on the next phase of the Navigation Campaign, to measure the central-body gravity (GM) of Benu. First, however, from the high resolution PolyCam images during Approach, the project was faced with a challenge when Benu was found to be much rockier than expected from Earth-based thermal inertia measurements that indicated abundant small particle regions with grains less than 2 cm that allowed for TAG delivery errors to be within a 25-m radius of the TAG site [3]. However, the project later found only a small number of areas with areas 5–20 m across [3].

2. Preliminary Survey, December 3–18, 2018

During the Preliminary Survey, we used these star-based centroiding OpNavs as the primary tracking data to navigate the S/C through five 7-km hyperbolic flybys, three over the northern region, and once each over the equatorial and southern regions of Bennu. To support this phase, we designed and executed seven maneuvers spaced 48 hours apart over two weeks. Each maneuver required a ‘24-hr’ late-update design from tracking data cutoff to execution. The objectives of the Preliminary Survey (PS) were to determine the mass/GM of Bennu to the 2% level, survey the Northern, Equatorial and Southern regions of Bennu, and complete the imaging for creating the 75-cm resolution shape model (with global ground sample distance resolution of 75 cm). Wibben et al. [29] describe the mission design of the flown trajectory and maneuver performance in this phase. They describe the changes in the trajectory from the pre-launch design [13] of one flyby over the Northern region to three, thereby increasing the maneuvers from five to seven and adding 4 extra days to this phase. This was due to our latest MC analysis prior to supporting the PS phase TCR that indicated that the incoming residual S/C radial errors relative to Bennu in addition to the dispersion of the first PS maneuver, M1P, (December 3, 2018) were too large to support the science observations over the first Northern flyover. Following the 3rd maneuver M3P on December 7, 2018, the S/C-Bennu state errors were improved significantly to meet the science observations over the third Northern pass. Leonard et al. [31] show how we determined the Bennu GM to below the objective level by estimating the Bennu GM at the end of PS to be $4.890 \pm 0.007 \text{ m}^3/\text{s}^2$ ($<0.2\%$). From Nov 26 to December 16, 2018 the Nav team delivered 12 OD solutions over an every other day schedule to update the onboard ephemeris in order to point the instruments at the asteroid. Eight of these updates include late update maneuver designs. The maneuver ΔV ’s in this phase ranged from 20–40 cm/s.

3. Orbital-A, December 19, 2018–February 27, 2019

After the last M7P maneuver on December 15, 2018, the S/C flew over the Southern pole of Bennu and drifted away from the asteroid to a distance of 52 km before the M1A burn (27 cm/s) on December 19, 2018 brought the S/C back to Bennu for a slow return and low activity period over the 2018 December Christmas holidays. Before this time, however, the project performed a successful ACS vector burn calibration on December 17 with a pre-built sequence to test the type of maneuvers required for the sample collection and rehearsals CP and MP maneuvers. These maneuvers required combinations of single axis maneuver directions in a fixed attitude to vector the combined burn direction rather than the nominal turn to burn attitude and thrust. The calibration showed nominal performance.

The Orbital A design changed over the pre-launch where instead of entering the S/C into a 2×1 km elliptical orbit then circularizing into a 1.5 km orbit, we chose to enter directly into 2.1×1.5 km elliptical frozen orbit. In addition to slowing the approach back to Bennu with M1A, this trajectory was designed to fly across in front of Bennu relative to the Sun before reaching the M2A location on December 29, 2018. Leonard et al. [31] mention that acquiring OpNavs before and after this flyby helped reduce the incoming S/C-Bennu state errors significantly before executing M2A (15 cm/s). After a 5-day break during the 2018 Christmas holidays, the team was preparing for the first orbit insertion around Bennu, and had produced and delivered a late update OD ephemeris on December 26 to update the onboard ephemeris on the December 27 morning HGA pass. This was required to ensure S/C pointing would capture Bennu in the camera FOV for OpNav images shuttered after that December 27 pass and downlinked on December 28 for use in the late update design of M2A burn which was to be uplinked and executed on the December 29 HGA pass. This burn would target the S/C near the sun terminator 2 km over Bennu North pole for the orbit insertion burn, M3A, on December 31, 2018. If the M2A late update was missed the S/C state errors for the Orbital A insertion burn, M3A, could not ensure a stable orbit with the preliminary burn design which was not uplinked and instead if the late update design configuration files were not uplinked the S/C would declare safe mode and execute the sunward burn. This prevents the S/C to travel into high solar phase regions which would challenge OpNav imaging for safe return navigation. This contingency would cause a multi-week schedule hit to redesign the Orbital A orbit insertion trajectory, replan, and update the sequence of the three burns to return, aim and insert into the delayed Orbital A. But when the LM S/C team were preparing to uplink the S/C ephemeris, the internet service provider, Century Link, which provided the network connecting LM to the JPL flight LAN, experienced a widespread outage and backup uplink methods were not fully functional at the time. Fortunately, a LM S/C team member who was in the Los Angeles area was able, with quick NASA-JPL-LM cooperation, to uplink the ephemeris one day later to the DSN from JPL in time to correct S/C pointing before the M2A burn which help to reconstruct this burn for the M3A design one day afterwards. Fortunately, we captured Bennu in the field of view with the stale onboard ephemeris and the internet connection was restored in time for the M2A uplink and execution on the morning of the December 29 pass. On New Year’s Eve of 2019 (December 31, 2018, 19:44 UTC), the Navigation Campaign progressed into Orbital A, when the 6-cm/s M3A maneuver fired to

place the spacecraft into a 2.1×1.5 km Sun-terminator ‘frozen’ orbit. The orbit conditions were ‘frozen’ in that the orbital-averaged energy of the solar pressure effect on the spacecraft motion was balanced by the gravitational force of Bennu, thereby constraining the orbit to remain in the Sun terminator plane (plane perpendicular to the Sun-Bennu vector). Wibben et al. [32] reported on design of this frozen orbit and the navigation performance of achieving it.

During the first two weeks of this orbit, we transitioned from using the star-based OpNav tracking to the more accurate OpNav technique, referred to as landmark tracking, as the primary data used in our OD solutions. These landmark observables were formed using the stereophotoclinometry (SPC) technique, which was dependent upon correlating natural features (craters, rocks, unique terrain, albedo variations, etc.) in images to those on a DTM of the asteroid shape [33]. This shape model was developed by ALTWG using the high-resolution imagery collected during Approach and Preliminary Survey [19]. These data enabled the precise determination of the pole, spin and prime meridian in the OD filter, comprising the Bennu-fixed coordinate frame orientation in the International Celestial Reference Frame (ICRF). The orientation of Bennu was a prerequisite for navigation and science evaluation in the following Site Selection campaign. Leonard et al. [31] discuss the transition to the landmark tracking during the first two weeks of Orbital A after demonstrating the improvements of the landmark-based OD solutions over the OD solutions based on star-based OpNav. The success criteria included improved trajectory reconstructions and predictions, landmark residual converged to levels consistent with shape model resolution, Bennu orientation parameters have converged and finally predicted state error meet the required accuracy for the next phase Detailed Survey. In addition to the landmark transition, Leonard et al. [31] describe the improvements in the various dynamical models governing the S/C motion such as SRP, thermal radiation pressure, antenna pressure, Bennu gravity and thermal re-radiation.

Parallel to the landmark transition, we also iterated shape model and Bennu orientation parameters with the ALTWG and the Science Team Chief. Leonard et al. [17] discuss the results of this process on the Bennu pole, prime meridian and spin determination and shape model scale and center-of-figure to center-of-mass offset.

Shortly after orbit insertion, on January 6, 2019, Hergenrother et al. [18] reported seeing hundreds of streaks in the long exposure NavCam images that bracket and were used to determine the camera pointing during the shorter exposure image of Bennu used for landmark registration in the SPC process. The streaks were later determined to be large amount of small particles which appeared to be ejected from the Southern region of Bennu. However, this became a major concern for the project; could these particles jeopardize the safety of the S/C? Would a particle impact harm the S/C or instrument? Do we need to implement the sunward burn and move the S/C to a safer location? Analysis confirmed that these were small particles less than 6 cm and found to be moving at rates from a few centimeter per second to a few meters per second. Further analysis determined that these particles posed no threat to the S/C and the project decided to proceed with Orbital A [34]. Several more particle ejections events were found in later long exposure NavCam images. In an effort to determine the origination areas on the Bennu surface where these ejections were occurring, the FDS and science teams coordinated on building a particle imaging database to perform track association of the same particles in multiple images. This led to quickly reconstructing these ejection events as described by Pelgrift et al. [10] with as little as two observations and assuming simple kinematics. Once a few of the particle tracks could be associated through several long-exposure images, Leonard et al. [11] determined their ballistic, hyperbolic or orbital trajectories using initial OD methods. As more particles were identified in multiple images, we combined these data into a combined multi-arc filter solution to determine their orbital arcs and the spherical gravity harmonics to degree and order 9 [9].

During this phase, the S/C made 23 orbits with orbital period of 60–62 hrs. We delivered 26 late update ephemerides and 3 late update maneuver designs for uplink. Because we didn’t know how well we could enter orbit, we schedule weekly orbit trim pairs in case we entered into an unstable or incorrect orbit. None of these were exercised.

B. Site Selection Campaign

1. Detailed Survey, February 28–June 7, 2019

At the beginning of the Site Selection Campaign from late February through beginning of June 2019, Detailed Survey was devoted to obtaining high-resolution imagery and spectral observations through 14 mostly south-to-north targeted hyperbolic flybys of Bennu at distances ranging from 3 to 5 km and different solar longitudes. These data would provide important information to the ALTWG for creating the higher-resolution DTMs for navigation and site selection in subsequent phases. Wibben et al. [35] report on the trajectory design and navigation performance during this phase. The first portion of the Detailed Survey (DS), referred to as the ‘Baseball Diamond’ (BD), underwent a major redesign after launch as a result of the interaction between FDS and the science team to better understand and iterate the science requirements for this phase. As such, the DS length increased from 56 to 100 days with the number of maneuvers increasing from 18 to 29. The number of hyperbolic flybys increased from 9 to 14 and science observation

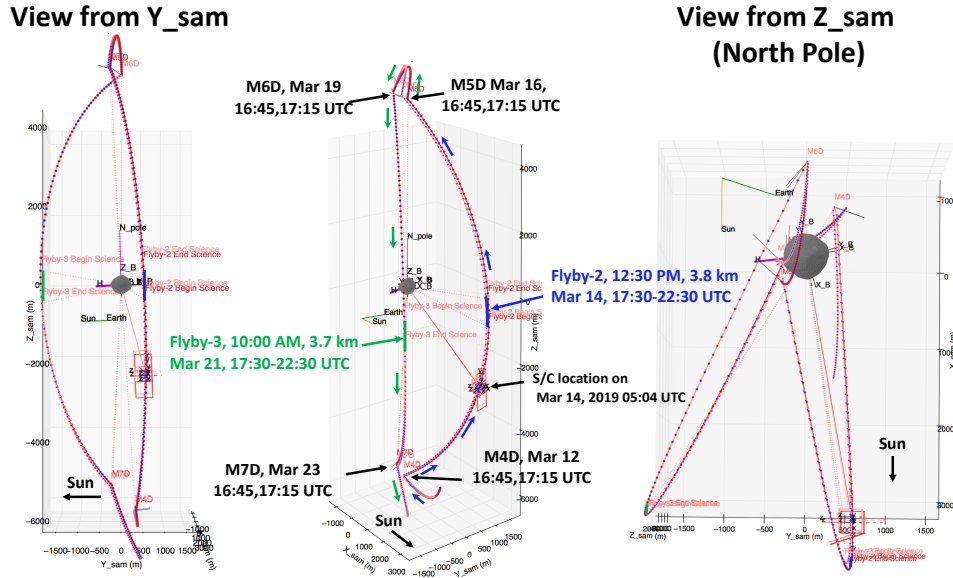


Fig. 10 Trajectory spanning the 2nd & 3rd Detailed Survey Flybys (FB-2, FB-3) from M4D on March 12 to M7D on March 23, 2019. (Note, M4D–M7D are decomposed burns with 2 components.)

windows changed from 11 to 18. The Equatorial survey (ES) portion of the DS didn't change much except for the order the flybys were done, but the BD portion changed the flybys to run North-South instead of East-West. The original plan included 4 science observation periods at Bennu-S/C ranges of 3.8 km in the $\pm 40^\circ$ latitudes at the $\pm 30^\circ$ East and West solar longitudes. The new plan included flybys at ranges of 3–5 km at solar longitudes of 10:00 AM and 12:30 PM. The operations schedule of the science observations, maneuvers and late updates for this phase is given by Getzandanner et al. [25].

During this phase, we delivered 47 OD solutions for 29 late update maneuver designs and 18 late knowledge updates supporting the 18 science observations during the 14 flybys. The maneuver ΔV magnitudes during the BD portion of the DS phase (M0D–M15D) ranged 3–8 cm/s. The BD flybys required 12 of these to be decomposed into two components to avoid the S/C KOZ constraint. The maneuver ΔV magnitudes of ES portion (M16D–M28D) ranged from 4–10 cm/s with only M16D being decomposed.

In addition to the knowledge updates for correcting the S/C onboard ephemeris, we also determined the timing error in the latitude crossing from when the science observations should begin to that from the knowledge update. Timing updates complicated the late update build process for the Science and S/C teams and added a small amount of risk, so it was only done if necessary. We missed a late knowledge update for one out of 18 science observations, due to a 'bomb-cyclone' blizzard that struck the Denver and LM area March 13, 2019, on the morning of the update for the 2nd DS (BD) flyby (3.8 km, 12:30 PM solar longitude). The conditions were rapidly deteriorating at the LM campus and LM officially closed at noon. As a result, the Mission Operations Manager (MOM) A. Calloway, made the "difficult but correct call to waive off the OD-1 (OD knowledge ephemeris) build and time shift for Flyby #2." Because of this missed update, the observations missed the southern half of the asteroid. Later, during the TAG site selection process of finding a safe site with sampleable regolith, the site selection board found it difficult to evaluate the possible sites without a complete data set. Therefore, per the project's direction, we designed and performed a successful re-flight of this second DS flyby on Sept. 26, 2019 at the beginning of the Reconnaissance A phase. Figure 10 shows the trajectory spanning the FB-2, 2019 and FB-3 (3.7 km, 10:00 AM solar longitude) flybys, respectively, on March 14 and March 21, 2019. The trajectories span from the FB-2 targeting maneuver, M4D, on March 12 to the M7D burn (March 23, 2019) which initiated the transfer to the FB-4-targeting burn, M8D (March 26, 2019). This and other trajectory plots below are plotted in the Bennu-orbit-fixed Sun-Anti-Momentum (SAM) frame as described in [28].

2. Orbital B, June 8–August 6, 2019

After the previously intensive 4-month activity, we navigated the spacecraft into a 925-m near-circular polar orbit referred to as Orbital B for gathering global imaging, various science observations, and mapping with the high-resolution OSIRIS-REx Laser Altimeter (OLA). This phase ended after the first week of August 2019 once the global coverage of

the asteroid was obtained by the OLA instrument. The orbit was designed to be as close to circular as possible which meant that the orbit plane was not frozen to the sun terminator as in Orbital A, but would precess about Bennu orbit angular momentum. To maintain adequate power from the S/C solar panels, the angle of the orbit plane from the sun terminator plane was required not to exceed $\pm 15^\circ$. The Orbit B phase began with the M1B (8 cm/s) on June 8, 2019, 17:00 UTC at the end of the trajectory from the last DS flyby. This burn targeted the M2B maneuver on June 10, 2019, 17:00 UTC in a similar fashion to the orbit insertion sequence of maneuvers for Orbit A. M2B (6 cm/s) targeted the orbit insertion burn, M3B, (6.5 cm/s) on June 12, 2019, 17:00 UTC, which then placed the S/C into the circular orbit with its orbit plane in the sun terminator [28]. Then after two weeks the orbit plane reaches 6° and the orbit is reset to endure a longer period of orbit plane evolution with trim maneuvers M4B (1.6 cm/s) and M5B (1.9 cm/s) on June 25, 2019, 17:00 UTC and 27, 2019, 23:00 UTC respectively. The M5B places the S/C into an orbit which slightly exceeds the circular orbit condition and orbit plane 10° from the terminator plane but evolves midway through circular orbit condition in terminator plane. See Getzandanner et al. [25] for the mission operations schedule for Orbit B insertion to the M5B maneuver. The S/C completed a total of 59.5 orbits with orbital periods averaging 22 hours in this orbit included 2.5 orbits during the trim. The orbital periods ranged from 21.2–22.6 hrs. During this 8-week phase, we made 22 late update deliveries including 4 late update maneuver designs.

3. *Orbital-C, August 6–September 16, 2019*

Following the conclusion of Orbital-B observations, we then performed two small maneuvers, M1C (2.3 cm/s, August 6, 2019, 17:00 UTC) and M2C (3.1 cm/s, August 8, 2019, 23:37 UTC) to transfer the S/C into a frozen Sun-terminator orbit in Orbital C. These orbits shared the same 1.8-km semi-major axis as Orbital-A, but the apoapsis and periapsis radii were slightly different: 2.1×1.5 km for Orbital A and 1.9×1.6 km for Orbital C. A lower cadence of operations was planned for Orbital C, including reduced navigation and science activities. However, this phase included additional long-exposure NavCam images for tracking particle activity when Bennu was near aphelion to see if there was a correlation between the level of particle ejection activity and solar distance. This phase, which covered August through mid-September 2019, was intended to provide a much-needed break for the operations team and time for the science team to evaluate the Orbital B data. However, it was still a busy time for the maneuver team as the planning for the reconnaissance phases was occurring during this timeframe.

The S/C orbited 18 times in this orbit with orbital periods ranging from 60–61.4 hrs. We made 8 late update ephemeris deliveries with 2 late update maneuver designs.

4. *Detailed Survey-Flyby 2 Re-flight and Reconnaissance-A, September 16-October 30, 2019*

As previously mentioned, at the beginning of the Recon A phase, we performed a re-flight of the second flyby of DS to collect observations that were missed due to the blizzard in March 2019. This re-flight occurred on September 26, 2019 and this time successfully obtained the science observations. During October 2019, we flew the spacecraft at ranges of 1-1.25 km over each of the final four sites (discussed in "Site Selection" below) while meeting specific science requirements to further explore the finer details of these sites. These flyovers produced imagery at resolutions down to 2 cm/px for creating higher-resolution DTMs for the onboard guidance NFT algorithm. The NFT algorithm was used to navigate the TAG trajectory after our ground-based navigation process determined the ODM and its location. Because the TAGSAM was designed to ingest rocks of 2 cm or less in size, these images provided clues for determining the sampleability of each site, and thus the data was important for the final selection of the primary TAG site. These flybys began with the Sandpiper site on October 5, Osprey on October 12, Kingfisher on October 19 and finally Nightingale on October 26, 2019. We will discuss the Recon A trajectory designs to meet the challenging science requirements and maneuver performance in a future paper.

On the morning of the late update activity for observations of the Osprey site and the post-observation M5R maneuver, an outage at the DSN Madrid tracking complex meant that the downlink session to start the late update process was missed. This meant there were no OpNav images available to update the trajectory for the observations of Osprey. Because the Osprey site was rated as a top site, the loss of these observations would have meant a certain delay to sample site selection and TAG. Thus the S/C, SPOC and FDS teams developed a plan to deliver a 'Super Late Update' the following day. During the 4 hour HGA contact, the FDS team quickly processed the first few OpNav images to reach the ground. The FDS team performed the OD then verified and delivered the trajectory to the S/C team who quickly processed the ephemeris for uplink within the same HGA pass, in time for science observations 2 hours later. There was, however, no time to update the preliminary design of the post-flyby maneuver, M5R (October 12, 2019) which was already onboard. As such, Figure 11 shows how the post-M5R trajectory (red) leading to the 1-km Kingfisher flyover

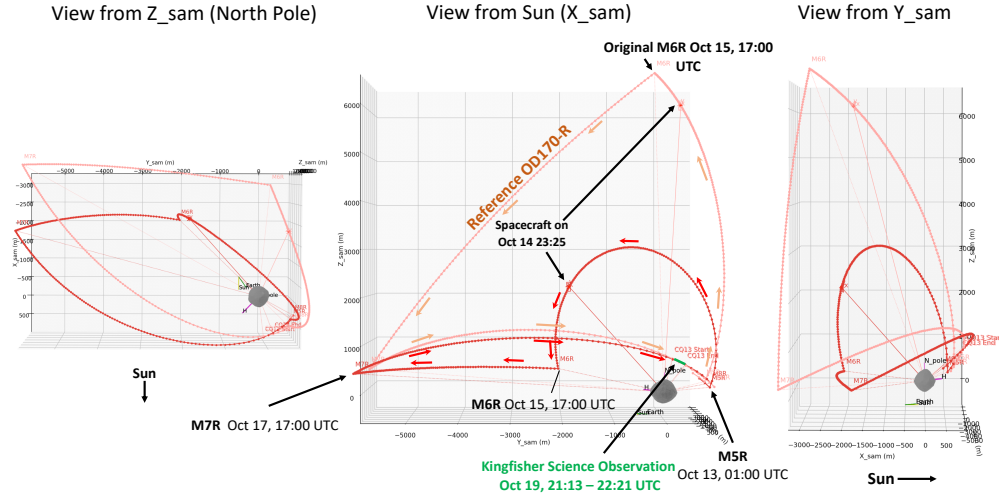


Fig. 11 Comparing the post-Osprey transfer trajectory to the Kingfisher Recon A flyover to the reference.

took a different path than the planned reference trajectory, refOD170 (orange). The reference trajectory was designed to have M5R target M6R on October 15, 2019 7 km above Bennu to form a triangular trajectory after reaching the starting point of the next flyby, Kingfisher, on October 17 for the M7R burn. Instead, the M5R burn was not retargeted based on the post M4R dispersions and so the path formed a partial orbit to a different M6R location on October 15. The trajectory leading to the next flyby was rectified by a targeting M6R back to the M7R reference location. This was within the realm of possibilities of our MC analyses, but shows how sensitive to trajectory errors and why late updates were necessary for just about every maneuver in ProxOps. The state error at the M5R burn time from the Recon A phase reference, refOD170, was 225 m in range and 1.2 cm/s in velocity. This great team effort salvaged the hi-resolution data of the Osprey site for site selection evaluation and kept the team on track for TAG.

During this phase, we delivered 17 late update ephemeris deliveries including 14 late update maneuver designs. Three late update deliveries per week were required to support maneuvers and science observations during the re-flight of DS FB-2 and each of the reconnaissance flyovers of the four sites. The maneuver ΔV magnitudes in this phase (M30D–M32D for re-flight of DS-RB2 and M1R–M11R for Recon A) ranged from 3–15 cm/s.

5. *Orbital-R, October 28, 2019–January 13, 2020*

The next phase provided some ease with ongoing operations, especially in light of the 2019 Thanksgiving and Christmas holidays. We chose to enter into an 1.1×1.4 km frozen orbit with orbital period averaging near 35 hrs, that would be a prerequisite to performing the closer Reconnaissance B flybys, thus the name Orbit R, R for reconnaissance. The orbit shown in Figure 12 began when the M12R burn (6 cm/s) on October 29, 2019 targeted orbit insertion with the M13R burn (4 cm/s) on October 31, 2020 and continued to the DCO for the 1st phasing burn of Recon B of Nightingale on January 13, 2020. During this time, the S/C orbited 50.5 times and we made weekly late update ephemeris deliveries totaling 14, two for late update maneuver designs.

6. *Site Selection*

The OLA measurements from Orbital B were used to create global and site-specific DTMs down to 5-cm resolution. The other Orbital B science data were used with data from DS to select from the abundantly rocky surface the best sites for TAG, considering navigation deliverability, safety, sampleability, and science value. Eventually, with the latest TAG deliverability and safety analyses using the information provided in the OLA DTMs, four sites, deemed ‘the Final Four’, were downselected in the summer of 2019 as candidate TAG sites. These were Sandpiper (lat,long: -47.17° , 321.31°), Nightingale (lat,long: 56.05° , 42.05°), Osprey (lat,long: 11.62° , 88.62°) and Kingfisher (lat,long: 11.41° , 55.59°). These sites were downselected from a set of 16 candidate sites identified earlier in the summer of 2019. The 16 sites had previously been downselected from over 50 candidate sites originally suggested from members of the project, crowd-sourced or picked from machine learning algorithm; ultimately many of these original candidates were determined to be infeasible for sample collection. The site selection process rated each site for deliverability, safety, sampleability and science value in global thematic maps. Deliverability was a measure of how well FDS and the NFT

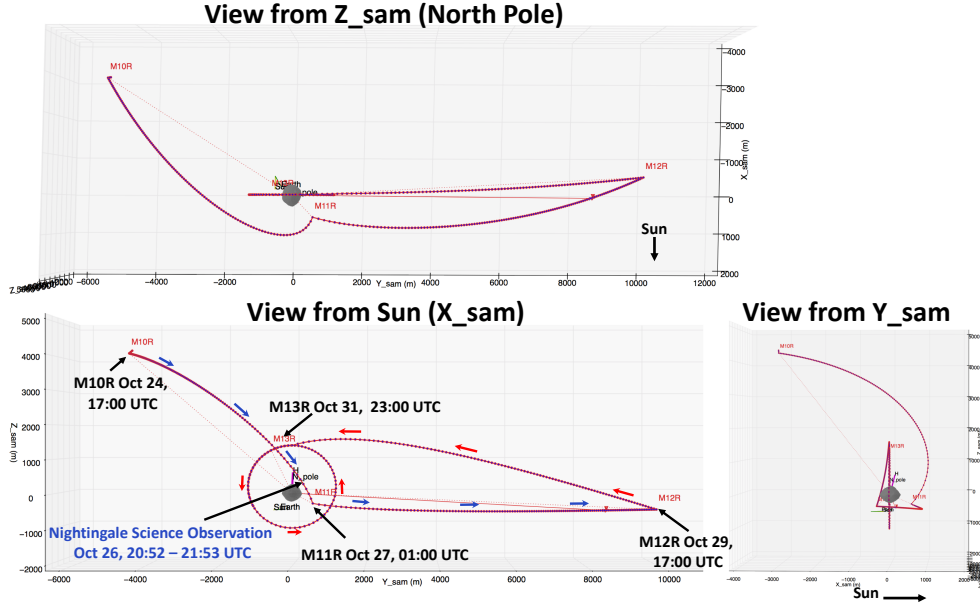


Fig. 12 Completing the last 1-km Recon A pass with flyby over Nightingale, then inserting into Orbit R.

system could deliver the S/C to the site. MC analyses of the TAG trajectory targeting each site were used to assess the probability of successful touchdown [2]. As Enos et al. [36], stated, "only a small number of sites of hazard-free regions, 5–8 m in radius were identified." Safety was a measure of how hazardous the site was when touching the surface and when backing away. A hazard avoidance algorithm was added to the NFT onboard software which checks the S/C state estimate of the NFT filter solution mapped to the surface against a hazard map of the site and signals an abort to fire the back away burn. Sampleability was a measure of how easily ingestible the regolith looked to be. The TAGSAM collector was designed to collect particles less than 2 cm. Science value provided a measure of how important the site was to achieving science objectives. The site selection activities are shown relative to the various Bennu models being developed in Figure 6.

C. Sample Acquisition Campaign

1. Reconnaissance B & C, January 14–March 29, 2020

Once a primary (Nightingale) and back-up site (Osprey) were chosen, the third campaign, Sample Acquisition, began in January 2020 to further explore these two sites, rehearse the TAG sequence, and finally perform the TAG sample-collection sequence. This campaign included two more reconnaissance phases (Recon B and C) to further image these sites at ranges of 625 m and 250 m, respectively, from January through March 2020 and after Checkpoint Rehearsal in April 2020. These flybys would provide the necessary imagery for finalizing the MLN feature catalogs for NFT and determining the sampleability of each site. During the 250-m flyovers, the PolyCam images acquired resolutions less than 1 cm per pixel thereby giving clues to the sampleability of rocks less than 2 cm in length. These reconnaissance flybys were redesigned to account for the change in the TAG design which now used NFT rather than LIDAR for the checkpoint and matchpoint maneuver updates, and to favor viewing geometries for constructing the final NFT features. Levine et al. [37] describe the mission design and navigation performance for these reconnaissance flybys. Wibben et al. [28] discuss the adjustments made to phase the orbits using the LTR thruster leading up to the ODM for each recon flyover. Levine et al. [37] explain how challenging it was to design these flybys to meet specific science requirements in terms of range to site, solar incident, phase and emission angles during the 42–57-min observation windows near close approach to site. These flybys required the late update delivery to include the maneuver designs for both the ODM and the post-flyby ORM. The ORMs for the post-Recon C flyovers were designed to capture into a clockwise orbit (opposite of the pre-departure orbit) which was necessary for the ODMs for both rehearsals and TAG [37]. Lauretta et al. [3] explain how the failure of the OLA Low Energy Laser Transmitter (LELT) during the Recon B flyover of the Osprey site was mitigated for in later flyovers for focusing PolyCam at close range with the use of the OLA High Energy Laser Transmitter (HELT) instead. There were 13 late update deliveries with 6 of these for maneuvers. Two scheduled phasing and two orbit trim pair maneuvers were canceled.

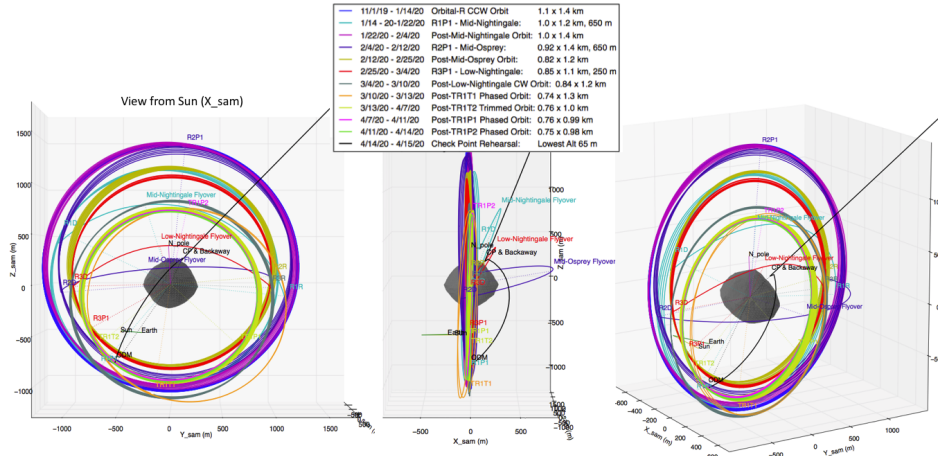


Fig. 13 The various orbits, flyovers from beginning of the Orbital-R phase though Checkpoint Rehearsal.

2. Checkpoint Rehearsal, March 30–May 31, 2020

The orbit leading up to the CP/R required a set of trim maneuvers, TR1T1 and TR1T2, on March 10 and 12, 2020, respectively, to correct the orbit plane and reduce orbit size by 150 m. In the week prior to the rehearsal, two phasing burns were executed to place the S/C at the correct orbital position for the ODM burn on Apr 14, 2020. Wibben et al. [28] explain how the execution errors of the first phasing maneuver, TR1P1, on Apr 7, 2020 with the LTR thruster placed the S/C just beyond the $-56.04^\circ \pm 6^\circ$ latitude requirement, so a second one, TR1P2, on Apr 11, 2020 was performed. This phasing of the orbit would require the smallest to be performed on the LTR thruster with a ΔV of 0.10 mm/s, however, the maneuver execution errors were expected to be fairly large at this small level so as Wibben et al. [28] explain, we chose to perform a smaller burn of 0.09 mm/s to ensure the relatively large execution errors would not move the spacecraft beyond the latitude requirement window. This strategy worked as we were within 2.24° of the targeted latitude at the time of the ODM. On Apr 13, 2020, we performed the late update design for the ODM and CP maneuvers. This delivery included passing our state and covariance at ODM to the GNC-NFT team to initialize their onboard NFT navigation filter. Because of the COVID-19 pandemic protocols only a small number of the team were allowed to be on-site for the CP/R event. As such only the Nav Team Chief and the TAG FDS lead, and a small number of the S/C team were on-console in the MSA to monitor the CP/R activities while the rest of the project monitored through remote connections. The ODM (TR1D) maneuver executed with a ΔV of 8 cm/s on Apr 14, 2020 to begin the CP/R trajectory. The MLN features in the post-ODM NavCam2 (NFT camera) images were successfully registered and filtered in the onboard NFT algorithm to update the S/C state and the CP vector maneuvers. These individual burns imparted 8 cm/s, 8 cm/s and 13 cm/s along each of the S/C X, Y and Z axes. The S/C descended to 60 m before the 40 cm/s back-away burn drove the S/C away from the asteroid.

Afterwards, the S/C returned to an 0.9×1.2 -km counter-clockwise orbit in the sun terminator plane within 2 weeks with the orbit insertion burn, TR1R4 (5 cm/s), on Apr 30, 2020. Once again this orbit required two phasing, R4P1 (1.4 mm/s May 19, 2020) and R4P2 (4 mm/s, May 23, 2020) maneuvers on the LTR thruster to target the ODM location (R4D, 14 cm/s) for the Recon C flyover of the Osprey site on May 26, 2020.

Figure 13 shows the various orbits, and flyover trajectories spanning the end of the Site Selection campaign with Orbital-R through the CP/R in the Sample Acquisition Campaign. Twenty late update deliveries were made during this phase with 10 of these for maneuver designs.

3. Episode XIII, Reboot, June 1–July 26, 2020

After the successful completion of the CP/R and the low reconnaissance flyover of the Osprey site, the S/C team wanted to reboot the S/C as a way to clear out anything stuck in memory that could potentially jeopardize the MP/R. The reboot sequence required dedicated time for the system to reboot while the S/C team was on-console and ready to diagnose any anomalies. This activity could impart a small unknown amount of ΔV and would preclude OpNav imaging so the project was wary to perform this activity while in orbit. It was then decided to dedicate an 8-week phase to depart the S/C from orbit, perform the reboot sequence, then return back into orbit for MP/R. This new phase was named Episode XIII as the 13th phase of the mission since launch, and the corresponding maneuvers were affectionately named after Star Wars droids. With the maneuver R2D2 (12 cm/s) on June 20, 2020, the S/C departed orbit to perform the

reboot during the week of June 22, 2020, before returning to the 0.8×1.0-km clockwise orbit with the BB8 orbit insertion maneuver on July 9, 2020 to set up the conditions for MP/R. This phase also provided the team with additional time to plan the MP/R and TAG events. We delivered 13 late update ODs during this phase; 7 of these were for maneuvers.

4. Matchpoint Rehearsal, July 27–August 20, 2020

The MP/R phase as Wibben et al. [28] explains only required one LTR phasing burn, TR2P1, on August 4, 2020 to place the S/C within 2.2° of the departure latitude for the ODM, TR2D, on August 11, 2020 to execute the MP/R sequence. This resulted in a close match to the ODM location as that for CP/R. The FDS team delivered the late update ODM (8 cm/s), and nominal CP and MP maneuver designs on August 10, 2020. Also delivered were the S/C state and covariance at ODM to initialize the onboard NFT filter. There were still restrictions on the number of team members who could be in the LM MSA to monitor the MP/R activities because of COVID-19, however four FDS team members were allowed this time to be onsite. After ODM, the S/C successfully flew the MP trajectory with state and CP and MP vector maneuver updates successfully performed by the NFT algorithm. The S/C descended to approximately 40 m over the TAG site before executing the back-away burn which moved the S/C away from the asteroid to a distance of 66 km before the TR2R1 maneuver on August 14, 2020, which returned the S/C back to Bennu to stage for orbit insertion into the pre-TAG orbit. The week between this burn and the TR2R2 maneuver on August 22, 2020, which initiated the 3 burn orbit insertion sequence, was used to once again reboot the S/C prior to TAG. The CP burns were similar to those in CP/R (8 cm/s, 8 cm/s, 14 cm/s). The MP Z, Y, X burns were, respectively, 7 cm/s, 9 mm/s and 6 mm/s. We performed 13 late update deliveries during this phase with 7 used for maneuver designs.

5. Touch And Go, August 21–November 22, 2020

The TR2R3 burn on August 25 targeted the orbit insertion location for the orbit insertion burn, TR2R4, on August 27, 2020, which then subsequently placed the S/C into the final orbit leading up to TAG. As Wibben et al. [28] explain, a set of trim maneuvers, T1T3 and T1T4, on October 6 and 8, 2020, respectively, were executed to correct the orbit then two phasing burns on T1P1 and T1P2 on October 13 and 17, 2020, respectively, were performed to successively place the S/C at the location for the ODM burn, T1D, on October 20, 2020 within the required errors. The second phasing burn, T1P2, was biased in order to target the same location of ODM that occurred for both the CP and MP rehearsals instead of the nominal ODM target. This method successfully phased the orbit such that the S/C departed orbit for TAG from a latitude within 0.1° of the desired location. The TAG trajectory and MC analyses were updated by Berry [38] to account for the rougher surface conditions than originally planned. For this big event, the project prepared to have a larger number of staff onsite with COVID-19 protocols in place such as a mask mandate and for people to be socially distanced by six feet. Detailed plans for team members were carefully laid out on a daily schedule beginning 1 week prior to TAG and continuing for 1–2 weeks afterward. These included daily seating or room assignments for team members in the LM SSB building and the NavMSA and S/C team MSA areas. This allowed for the attendance of most of the FDS team members during this event. On October 19, 2020, we delivered the late update TAG design that included the ODM (T1D), and CP and MP vector burns as well as the S/C state and covariance at the time of ODM to initialize the NFT filter.

It took approximately 1 second after the TAGSAM collector contacted the asteroid surface as shown in Figure 14 before the deceleration was detected by the onboard sensor which then expelled the nitrogen gas from the pressurized bottle attached to the arm to fluidize and guide the asteroid samples into the collector [39]. Five seconds later as planned, the back-away burn executed to move the S/C quickly away from the asteroid. With the NavCam2, MapCam and SamCam images on the TAG approach and descent trajectory and the backaway movie plus S/C telemetry, we estimated



Fig. 14 The TAGSAM collector makes contact with the surface.

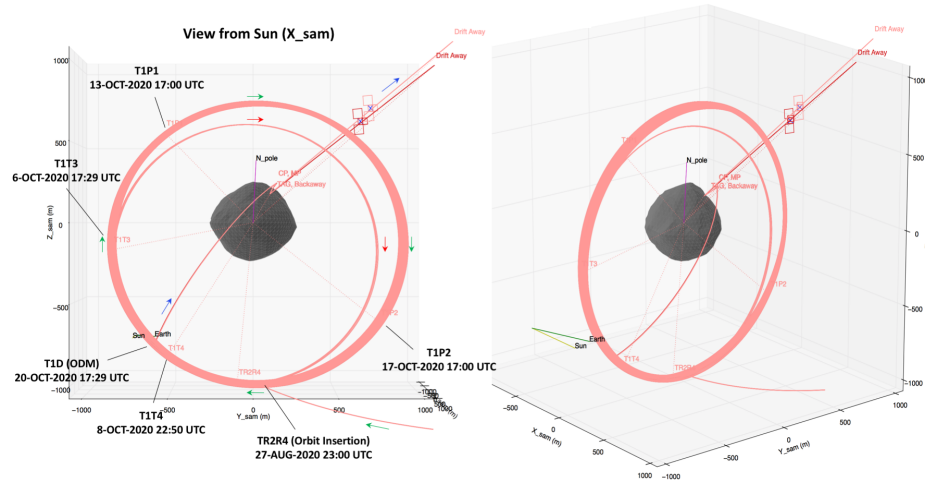


Fig. 15 Pre-TAG orbits from Orbit Insertion (TR2R4 August 27, 2020 23:00 UTC) to ODM (T1D, October 19, 2020 17:29 UTC), TAG trajectory on October 20 and post-TAG drift away (with late update TAG trajectory in orange compared to reconstruction in red).

the S/C was still moving downward at a velocity of 4 cm/s when the back-away burn fired; we also estimated an upward velocity impulse from gas firing and surface contact of approximately 6 cm/s, which was evident when reconstructing the back-away trajectory. The TAGSAM arm was estimated to have sunk to a depth of approximately 50 cm before the back-away burn reversed the spacecraft velocity [39]. Berry et al. [2] compares the as-flown-late-update TAG design to prelaunch and preliminary designs. The reconstructed contact location by the OD team is compared to the onboard estimate from NFT and the last state propagated to the surface in [2]. Our initial trajectory reconstruction was 98 cm off from the target, but NFT (onboard prediction from last image) computed 74 cm off. The Image Processing Working Group (IPWG) has confirmed it to be closer to 70 cm off. We know there's approximate 20-cm discrepancy between the shape model and reality. We are currently evaluating the final OLA shape model (V21) from ALTWG and hope to improve this error.

Two days after TAG, the TAGSAM collector head was imaged at various tilts to the sun. To our surprise, the images showed a multitude of particles escaping from the collector head. Each tilt of the wrist propelled particles from the head, similar to a salt shaker, and it became evident to the PI and project that we needed to speed up the Stow decision process to minimize further mass loss. Analysis of the likely volume of sample inside the TAGSAM from post TAG images suggested a high likelihood that we collected much more material than the 60 g minimum requirement [39]. With their tools built to analyse the particle ejections from Bennu, the OpNav team were able to help with a quick assessment of the mass and rate of particles escaping the TAGSAM head, ultimately estimated to be on the order of 10's of grams [40].

Figure 15 shows the 60 pre-TAG orbits from August 27 to October 19, 2020, after the orbit insertion burn, TR2R4, on August 27, 2020 23:00 UTC through the TAG trajectory beginning with the T1D (ODM) burn on October 20,

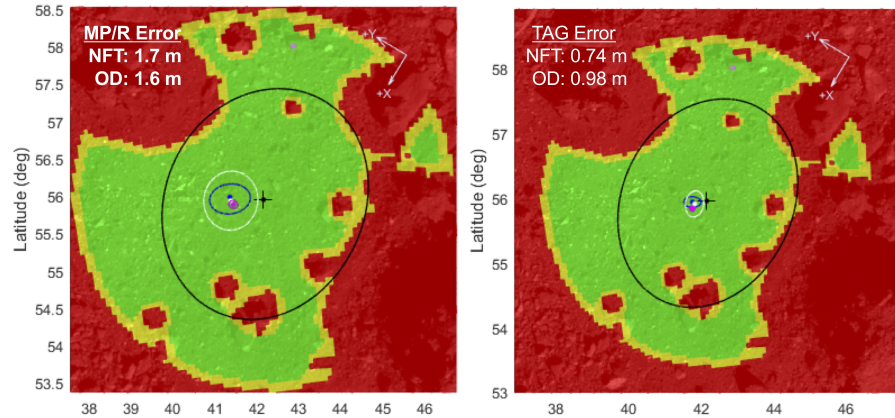


Fig. 16 Predicted and Reconstructed TAG Location: MP/R versus TAG.

17:29 UTC to the time of surface contact at 21:49:50 UTC and after the back-away burn 5 seconds later to October 20, 23:00 UTC. This Figure compares the late update (orange) to the reconstructed TAG trajectory (red). Figure 16 shows representations of the delivery errors for MP/R (left) and TAG (right). This Figure shows the Nightingale site with the $3\text{-}\sigma$ TAG error ellipse from the late update TAG MC in black overlaid with the hazard map in red and yellow [2]. For MP/R (left) the points and ellipses correspond to predicted contact point and uncertainties propagated from just following the MP burn, from an altitude of approximately 40 meters above the surface. For TAG (right) the points and uncertainties are from reconstruction of data from the TAG event. The pink dot (and tiny ellipse) represent the reconstructed OD from the navigation team using all available data. The white ellipses are the last onboard NFT state estimate propagated to the surface; this represents the navigation uncertainty onboard the S/C during the flight activity. Blue ellipses are from a navigation MC analysis using the final NFT state and covariance as initial conditions, which bounds the region we should have expected to touch based on the latest information available from the onboard system. Following the reconstruction of MP/R, the consistent delivery location from both CP and MP rehearsals suggested there may be a systematic bias in the maneuver execution errors for the family of trajectories we were flying. The LM Prop engineer, C. Parish, examined the modeling behind the vector burns and proposed to tweak a few propulsion parameters. It appears by comparing the MP/R and TAG reconstructed locations, this tweak may have helped move the actual TAG point closer to the target location, thus the rehearsals were useful in helping to ensure contact in a favorable location within the Nightingale region. During this phase, we delivered 11 late update OD solutions with five of these supporting late update maneuver designs.

D. Post TAG

1. Post-TAG Observations, January 4–April 9 22, 2020.

After TAG, the spacecraft drifted away from Bennu at a rate of approximately 43 cm/s, no more late updates were required to maintain the S/C trajectory. However, there grew interest in the science community to observe the aftermath of the TAG site, so at the request of the PI, we designed a trajectory to return the S/C to Bennu for a 3-km DS FB-2-like flyby. The project eventually decided to approve this new ProxOps phase but required that the first maneuver could not be implemented until after the 2020-2021 Christmas and New Year holidays. By the time of the first maneuver, PTO1, to execute on January 14, 2021, the S/C had drifted further away from Bennu to a distance of 2200 km, thereby complicating the return. The Post-TAG-Observation (PTO) trajectory was designed with five maneuvers with the first burn, PTO1, on January 14, 2021, to stop the drift and return back to Bennu needing to be performed as a decomposed maneuver on the TCM thrusters with total ΔV of 1.1 m/s, thereby adding more than normal dispersions to the return trajectory. Further complicating the PTO trajectory was the high phase angles that precluded OpNav imaging until 1 month after PTO1. There was a desire to execute the post TAG observations on a more relaxed cadence than previous mission phases to reduce the burden on the operations team, so late update maneuver designs or ephemeris updates were relaxed to 48 hours or more except for the final late science knowledge update. The S/C on Apr 7, 2021 successfully flew over the TAG site on Apr 7, 2021, and obtained imagery to compare to pre-TAG images from the DS FB-2 images. Figure 17 shows this last flyby trajectory of Bennu from the PTO targeting maneuver, PTO5 (11 cm/s), on Apr 4, 2021, 20:00 through Apr 13, 2021 20:00 UTC. The last OpNav NavCam image was shuttered on Apr 9, 2021 14:25 UTC at a distance of 6 km. We made 13 deliveries with 4 of these for the 48-hour maneuver designs. Because of the TCM maneuver, PTO 1 had a DCO 1.5 weeks ahead of its execution similar to cruise phase maneuver designs.

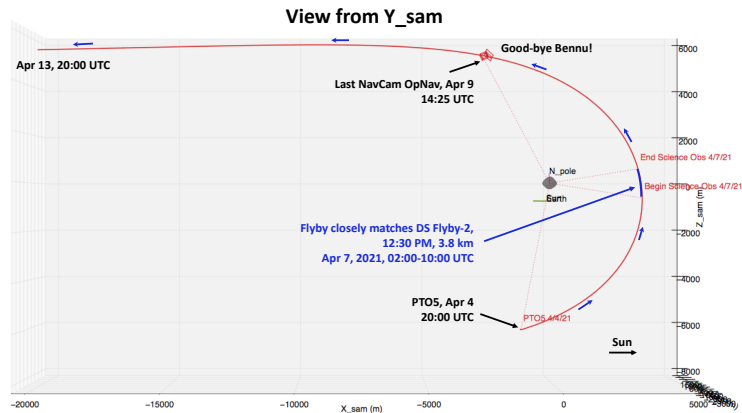


Fig. 17 The Post-TAG-Observation flyby, Apr 4 to Apr 13, 2021.

2. Asteroid Departure Maneuver, May 10, 2021

At a distance of 359.5 km from Bennu and moving at a Bennu-relative speed of 25.3 cm/s, the S/C departed the asteroid with the ADM which executed on May 10, 2021 20:00 UTC using the ME. The TCM thrusters were used to

settle the fuel before the start of the ME 30 seconds later, contributing 2.6 m/s to the total burn magnitude of ΔV of 266 m/s. This maneuver started the S/C on a 2.4-year trajectory back to Earth, targeting the release and landing of the SRC with the samples from Bennu at the Utah Test and Training Range early on the morning of September 24, 2023.

E. Bennu Ephemeris, Geophysics & Shape Model Development

As mentioned beforehand, we worked with the Science Team to produce the ephemeris and geophysical models of Bennu, including its shape, pole, prime meridian and spin, GM, and spherical harmonic gravity coefficients. Figure 6 illustrates all the Bennu products which were delivered from SPOC, JPL, and FDS. During Orbital A, we were simultaneously evaluating the ALTWG 75-cm SPC shape models while also completing the transition to using landmarks operationally for navigation.

1. Bennu Shape Model Development

Leonard et al. [17] discuss how the FDS iterated on the shape models delivered from ALTWG. Development of the final shape model required navigation to feedback estimates of Bennu's orientation, spin rate, prime meridian, scale and center-of-figure to center-of-mass offset to ALTWG so they could iterate their solutions for landmarks incorporating these updated parameters. Leonard et al. [17] also discuss the processes whereby we assess the quality and compare the ALTWG and JPL shape models to certify them for use in operations.

2. Bennu Ephemeris Improvements

Operationally in our OD solutions during Approach, we began using JPL Bennu solution #76 from JPL SSDT which fit Bennu's orbit to Earth-based optical, radar delays, and Doppler observations through 2011. Once we began receiving optical data, we then routinely estimated the Bennu ephemeris as changes in the Brouwer and Clemens Set III orbit parameters [41], along with the S/C in our OD filter. As such, we determined the ephemeris down to the meter level, but these estimates were only viable on short time scales, weeks to months and could not be reliably used to predict the Bennu ephemeris over longer terms. A few times through ProxOps, Bennu ephemeris file updates were delivered to the project from JPL SSDT who found that to fit the meter-level OSIRIS-REx range data with the historical observations, they needed to model the point-mass gravitational perturbations from up to 343 small bodies [8]. We would baseline these updates after verifying their improvements by comparing them to our current internally updated ephemerides. We received Bennu solution updates #103 in November 2018, #108 in March 2019, #110 in August 2019, #112 in February 2020, and #114–116 in September 2020 for testing before releasing the final Bennu ephemeris, #118, in January 2021. In the 2nd week of March 2019, we noticed a sinusoidal signature in our range pass biases and Doppler residuals, but could not determine the cause. We noticed this issue went away with the #108 ephemeris. After differencing this ephemeris with the #103 we noticed what looked like a poor fitting polynomial in the #103 ephemeris. For the #108 ephemeris, Farnocchia [42] increased the integration precision from double to quadruple precision, tightened down the Chebyshev fit due to smaller state uncertainties and began estimating the thermal inertia. According to Farnocchia [42], it was holding the thermal inertia value to the pre-encounter value that caused the sinusoidal pattern in the range data; and by estimating it from the OSIRIS-REx orbital data, it removed this signature and produced a value that was in line with the thermal inertia measured from in situ thermal observations. Figure 18 shows the pass-through 2-way range residuals and standard deviation of our OD solutions with our internally updated Bennu ephemeris covering each phase to the same OD but replacing Bennu with the #110 ephemeris delivered in August 2019 and the final solution, #118. These differences represent the Earth-Bennu error of these ephemerides from our internal Bennu ephemerides, which in Figure 18 remained within 2.1 m of difference from #118 for each phase. Not shown are the pass-throughs of the ΔDOR measurements which show no significant differences of these ephemerides in the Earth plane-of-sky.

Farnocchia et al. [8] report on the refinement of the hazard assessment of Bennu for future close Earth encounters which is one of the prime objectives of the mission (i.e., "Security," part of the mission name). With the OSIRIS-REx

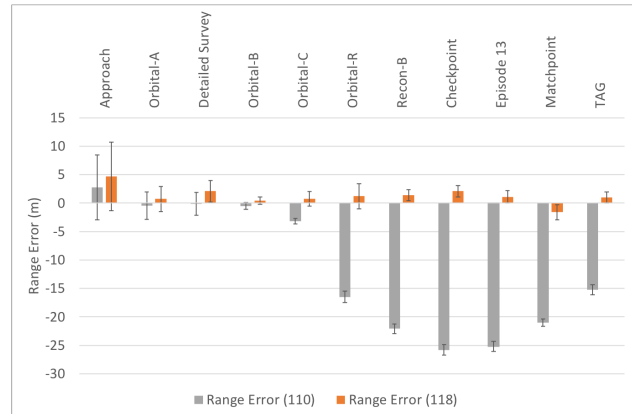


Fig. 18 Pass-through of 2-way range residuals of delivered OD solutions using Bennu #110 and #118 to compare internal Bennu solutions

range data spanning Jan 2019 to Oct 2020, Farnocchia et al. [8] accurately determined the Yarkovsky effect on the predicted Bennu ephemeris thereby drastically reducing the likelihood of an Earth impact in 2136, but increasing it in 2182. Overall, the cumulative impact probability through year 2300 was increased over their pre-encounter assessment. They estimated semimajor axis of Bennu to change at a rate of -284.6 ± 0.2 m/yr. According to Farnocchia et al. [8], "(b)oth Bennu and (29075) 1950 DA have a Palermo scale value of -1.42 and share the distinction as the currently most hazardous object in the asteroid catalog."

F. Gravity

The RSWG planned a dedicated 9-day radio science experiment to determine Bennu gravity in the original 1-km Orbital B before encounter with Bennu [43]. The objective of the RSWG as stated in the mission requirements document (MRD-134) was to "determine the spherical harmonic coefficients of Bennu's gravity field to degree and order 4" while the S/C remained in quiescent operations [43]. During these nine days, the S/C would be tracked by near-continuous radio-metric Doppler and range data while the S/C remained in a fixed Sun-pointing attitude and OpNavs were to be collected from NavCam when Bennu was in FOV of camera. However, OD covariance studies determined that only degree and order 3 could be detected; it would not be possible to reliably determine the field to degree 4 in the 1 km orbit, or even in the re-designed 925-m orbit. The original requirement could be accomplished from orbits 700–800 m in radius. The FDS team worked with the RSWG to finalize this plan targeted for the orbital-B time frame, but unfortunately this dedicated experiment was eventually removed from the ProxOps schedule after the durations of the earlier phases were lengthened and the project became concerned with completing all the necessary tasks for the prime objective to collect a sample. Serendipitously, the discovery and subsequent tracking of small particles ejecting from the surface and sometimes orbiting Bennu at very low altitudes provided a fantastic data set for estimating the gravity field, allowing the original objective to be met.

Leonard et al. [31] describes our initial point-mass GM of Bennu estimates during PS. Shortly after PS, we made four Bennu gravity field deliveries to the project. Since our OD solutions in Orbital A did not produce reliable estimates, we chose to deliver gravity fields based on the current shape model assuming constant density.

The first 3 deliveries were made before Orbital B. These include Bennu GM and normalized spherical gravity harmonic coefficients to degree and order 5. Gravity coefficient values were based on the officially delivered 75-cm ALTWG shape model, v20, assuming constant density with reference radius of 290 m and the Bennu pole state in `bennu_v14.tpc` (pole vector, prime meridian and rotation rate). The covariance for the gravity coefficients was based on the RSWG's modified Kaula rule for Bennu [43].

Our final Bennu gravity field was estimated from in-orbit NavCam observations of seven particle orbitals. This included four particle orbits in the Orbital A and three in Orbital C phases. This file contained the Bennu GM and normalized spherical gravity harmonic coefficients up to degree and order 9 plus J10. These values were estimated from multi-arc OD filter of the seven particle orbits with a reference radius of 290 m and with the Bennu pole/spin state defined in `bennu_v15.tpc`. These values were similar to those reported by Scheeres et al. [12] who explain that these data offered an unique advantage of measuring the internal mass distribution within a small asteroid. Comparisons of the 9x9 field with one based on the asteroid shape assuming constant density revealed heterogeneous mass distributions within such as a lower density center and equatorial bulge [12].

V. Results

Each of these campaigns provided unique challenges for navigation. Because the science observations were dependent on accurate pointing of the instruments, which in turn was dependent on the onboard S/C-Bennu relative ephemeris, our primary challenge was to consistently provide the best predicted trajectory over the sequenced science observations. In order to meet the requirements for critical science observations and maneuver designs, late update OD deliveries were routinely scheduled to include the latest landmark tracking data up to 28-33 hours before the start of the science observation or maneuver window. Note that we aimed to have the DCO to be 24 hours before the start, but when realities of scheduling sequence events, S/C constraints and human factoring became involved, the predict durations for most late update deliveries usually fell within 28-33 hours. Also, note that when we refer to DCO, we mean the time of the shuttering of the last OpNav instead of the last radio-metric data which usually could meet the 24-hour DCO. The inclusion of the radio-metric data after the OpNav didn't significantly improve the prediction performance. Figure 19 exhibits our late update OD trajectory prediction performance of 75 of our last OD solutions (OD199-OD292) used for late update maneuvers and ephemeris uploads from Orbital R through TAG. These only included OD solutions for orbital predictions and did not include out-of-orbit solutions such as after rehearsals or during Episode XIII. These predictions also did not include desats within the 28-hr prediction span. Shown in Figure 19 are the differences of these

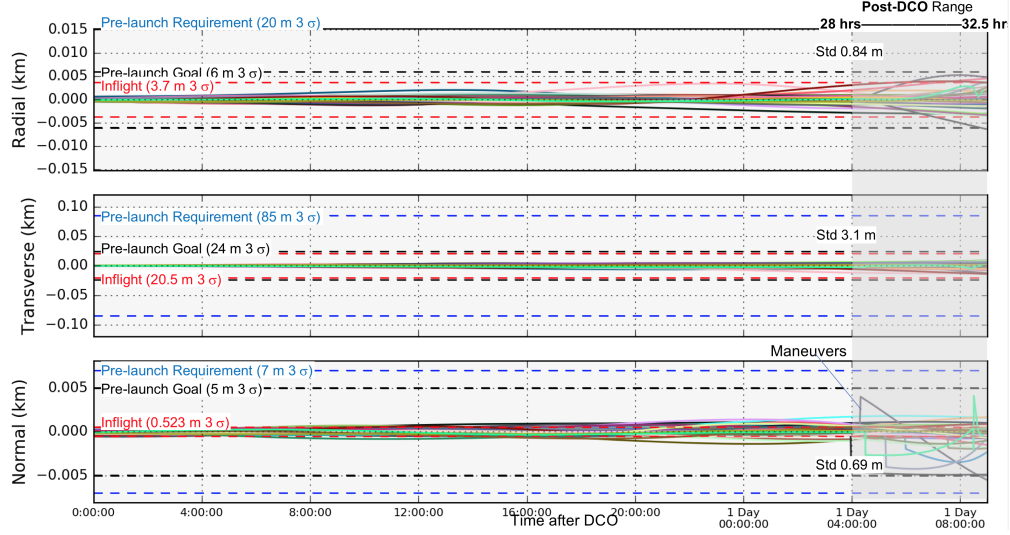


Fig. 19 Orbital R, Recon B, C, CP/R, MP/R, TAG OD 28-hr Prediction, OD199–292 (Nov 1, 2019—Oct 20, 2020, 75 Orbital OD predicts compared).

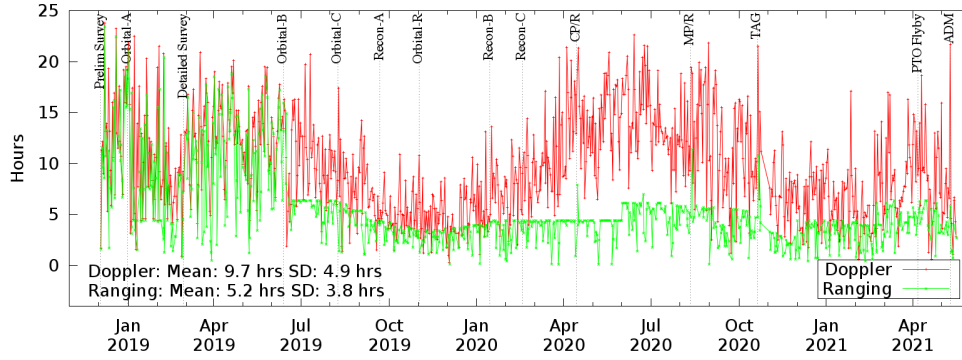


Fig. 20 Daily tracking pass durations for 2-Doppler and range.

OD solutions from the reconstructed trajectories over the late update prediction period in the Radial, Transverse, and Normal components of the Bennu-centered orbit-fixed frame. Note that these reconstructed trajectories had *a posteriori* 1- σ errors less than 10 cm for each component during these spans. After the DCO, these predictions are shown in Figure 19 to have 1- σ errors of 0.84 m, 3.1 m, and 0.69 m, respectively, in the Radial, Transverse, and Normal directions after 28 hours. The maximum RTN errors were respectively 3.4 m, 11.8 m and 4.5 m. The errors are compared to the pre-launch requirements and goals and to ‘inflight’ values which represented updated covariance analysis with updated inflight models. The pre-launch requirements were developed for the state error required at ODM to meet the original 25-m TAG accuracy requirement [38]. Leonard et al. [44] discuss more details of the predictive performance during the different phases.

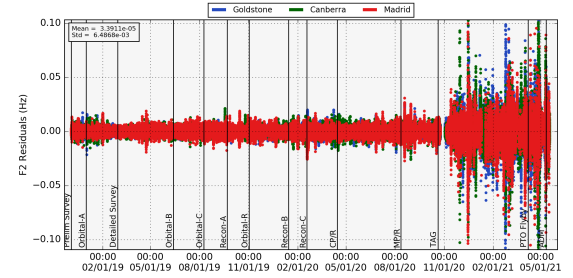
A. Tracking data performance

1. Radio-metric Tracking

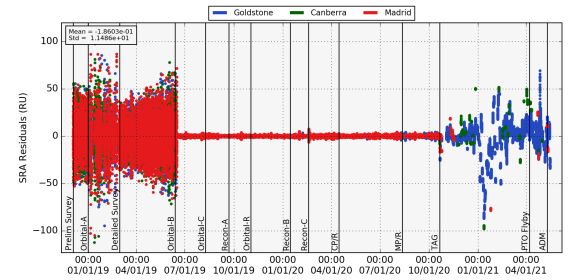
Once in close range to Bennu, the OpNav data became the primary tracking data type; however, it was prudent to cover as much as the S/C motion as possible and supplement this with radio-metric data. Figure 20 show the DSN 2-way Doppler and ranging tracking pass durations during ProxOps. On average the project acquired 9.7 hours of Doppler and 5.2 hours of ranging per day from Preliminary Survey through ADM. Data was downlinked over the HGA on the S/C X-face (see ref [4] for brief description of the spacecraft). The post-fit 2-way Doppler residuals throughout the ProxOps from Preliminary Survey to Asteroid Departure Maneuver are shown in Figure 21(a). Figure 21(b) shows the post-fit range residuals. The noisier early data were ranging data acquired via the LGA antenna to supplement the HGA data when

Bennu was in range of Earth for sufficient link. After Bennu-Earth distance was greater 1 au, the LGA could not support ranging, but we acquired 5–7 hours of ranging data per day on the HGA. In addition to critical events like orbit insertions, we scheduled Δ DOR measurements quarterly throughout ProxOps primarily for keeping check on the Bennu ephemeris. When possible, we would schedule two pairs of N-S and E-W baselines, but due to low declination, only N-S baselines were available in summer of 2020. Shortly after TAG, S/C operations continued through a long extended solar conjunction period from November 23, 2020 to November 10, 2021 where the SEP angle remained below 10° . The noise caused by the extended travel of the radio signal through the solar plasma is shown towards the end of ProxOps through ADM in Figure 22(a) for Doppler and 22(b) for ranging residuals. Likewise for the per-pass range biases shown in Figure 22(c) which nominally averaged near zero with standard deviation less than 1 m, but increased to 1.2 ± 3.7 m during the solar conjunction period. The range delays during the solar conjunction period were augmented by the DSN solar plasma model.

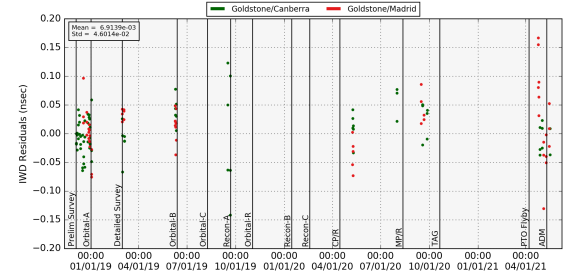
The greatest S/C-Earth distance during ProxOps was 2.3 AU just after TAG at the end of the year 2020. With a nominal Δ DOR performance of 0.06 nsec (2.25 nrad), the spacecraft state in the Earth Plane of Sky (POS) ranged from 180 to 770 m in Figure 21(c). Though these data were not more accurate than the OpNav data, they provided a check on the S/C (and Bennu) Earth POS motion. We scheduled the last OpNav closest to the start of the HGA downlink pass, which would begin early in morning. The downlink of the OpNavs would begin the start of the navigation process. Getzandanner et al. [25] discuss how these tracks were primarily scheduled over the Madrid DSN complex. Generally, the 2-way Doppler were weighted 3 times per-pass for the noise displayed in Figure 22(a). Likewise, the range data were weighted 3 times the noise shown in Figure 22(b). The Doppler noise was well under our pre-launch assumption of 0.1 mm/s for the duration of ProxOps through TAG, then the noise quickly rose afterwards as the S/C-Earth enters the extended solar conjunction period.



(a) 2-way X-band Doppler, 1 Hz = 17.748 mm/s



(b) 2-way X-band range, 1 RU = 0.143 m



(c) Δ DOR residuals mapped to Earth POS

Fig. 21 Radio-metric Tracking residuals

2. Optical Navigation Tracking

The OpNav landmark residuals are shown in Figures 23(a) and 23(c) respectively, for the NavCam, MapCam and PolyCam cameras. Figure 23(e) shows the star-based centroiding OpNav residuals. The performance of these landmarks relative to the data weights used in OD solution deliveries in phases spanning Orbital B through Recon C are discussed by McCarthy et al. [45]. Figures 23(b), 23(d) and 23(f) compare the NavCam2 (NFT camera) residuals respectively during the CP/R, MP/R and TAG post-ODM trajectories from our OD reconstructions of these events.

The OD solution pointing estimates are shown in Figure 24(b) for OpNavs that were not bracketed by long-exposure star images. Sahr et al. [46] discuss the OpNav imagers pointing performance for the OpNav images throughout ProxOps. Sahr et al. [46] compare the various pointing sources such as the predicted and reconstructed attitude c-kernels, pointing solutions from long-exposure star images using KXIMP, pointing estimates from the OD solutions and pointing estimation generated in the SPC process for OpNav deliveries.

B. Trending of Forces, Desats, SRP, maneuvers, data quality

1. Forces on OSIRIS-REx during ProxOps

The forces that affected the S/C motion while in close range to Bennu are shown in Figure 25. The Bennu point mass gravity, was largest force, with SRP the second largest at 1–2 magnitude lower except in Orbital B, Recon C, rehearsals and the pre-TAG orbits through TAG when Bennu oblateness became the secondary force in the range of 10–150 nm/s². This force reaches its max when the S/C touches the surface during TAG at 36000 nm/s². The SRP ranged from 30–83 nm/s². One magnitude below this was the S/C thermal infrared radiation pressure in the 4–10 nm/s² range. Below this force, the stochastic forces represented mis-modeled forces with accelerations less than 2 nm/s². Figure 24(a) shows these accelerations in the each of the S/C body-fixed axis. Down-track errors were predominantly caused by mis-modeling of forces along the S/C Y-body-fixed axis which, as shown in figure 24(a), had 1- σ errors less than 0.08 nm/s². The 1- σ errors along the X-axis which faced the sun most of ProxOps and the Z axis, which was mostly Bennu-nadir pointing, both had 1- σ errors of 0.5 nm/s². The force due to Bennu albedo had a slightly larger effect at 0.3–0.6 nm/s² than the force due to Bennu infrared emission at 0.05–0.55 nm/s². The influence of Bennu distance to the sun is evident in the cyclic nature of most of these forces in Figure 25, except the Bennu point mass and oblateness forces. When the S/C drifted away after TAG, the sun became the dominate force until the return to Bennu for the PTO flyby.

2. ACS, LTR performance

From launch to the time of the ADM maneuver, we designed and executed a total of 125 maneuvers including 151 individual components. There were a total of 114 maneuvers from start of ProxOps on Dec 3, 2018 with M1P through ADM in May 2021. Two thruster sets were used for the majority of ProxOps: The ACS-TBT thrusters set was utilized for maneuvers greater than 1 cm/s and generally up to 50 cm/s. The LTR thrusters were used for very small maneuvers, between 0.09 to 20 mm/s. The overlapping performance regime provided some flexibility when planning maneuvers that fell within the 1–2 cm/s range. There were 15 LTR maneuvers performed during proximity operations and executed within LM's required LTR burn errors for both magnitude and pointing. The ACS-TBT and LTR maneuver ΔV magnitude errors as function of burn magnitude are shown in Figures 26(a) and 26(b), respectively. These errors as the number of standard deviation from the *a priori* maneuver execution errors are displayed in Figure 26(c) and 26(d). The maneuver pointing as function of maneuver magnitude are shown in Figure 26(e) and 26(f) for the ACS-TBT and LTR maneuvers respectively. Most of the ACS-TBT errors were under 1% of burn magnitude, under 1 σ from their *a priori* errors, and less than 0.3 deg in pointing error except for the smallest burns. LTR maneuvers with ΔV 's greater than 1.4 mm/s had burn errors less than 2% and less than 1 σ from their *a priori* execution errors. All the LTR had pointing errors less than 1.2° except the smallest burn, TR1P2, which had pointing error of 4°. Note, the 2 trim burns, T1T3, T1T4, and 2 phasing burns, T1P1 and T1P2, that corrected the pre-TAG orbit are labeled in green on the LTR performance plots in Figures 26(b), 26(d) and 26(f).

The reaction wheel momentum desaturation maneuvers involved firing thruster couples about each S/C axis to drive the momentum to zero or to a biased amount. The desat requirement was 2 mm/s: pre-flight analysis showed that the expected ΔV magnitudes of the desats could be around 0.5 mm/sec (1 σ) for the 3-day frequency and up to 2.0 mm/sec (1 σ) for the 7–10-day frequency [44]. Figure 27 shows the magnitude and post-fit error for each of the 189 desats from September 1, 2018 to May 10, 2021. This plot demonstrates the strength of the optical data at resolving the desat ΔV s, i.e., small error bars. From start of Orbital A, the imparted ΔV remain small due to the fact that two desats were scheduled per week to keep momentum growth low. Lower momentum state allowed for faster slews to science observation attitudes. Weekly biased and 'masked' desats were scheduled just before and through PS then two per week

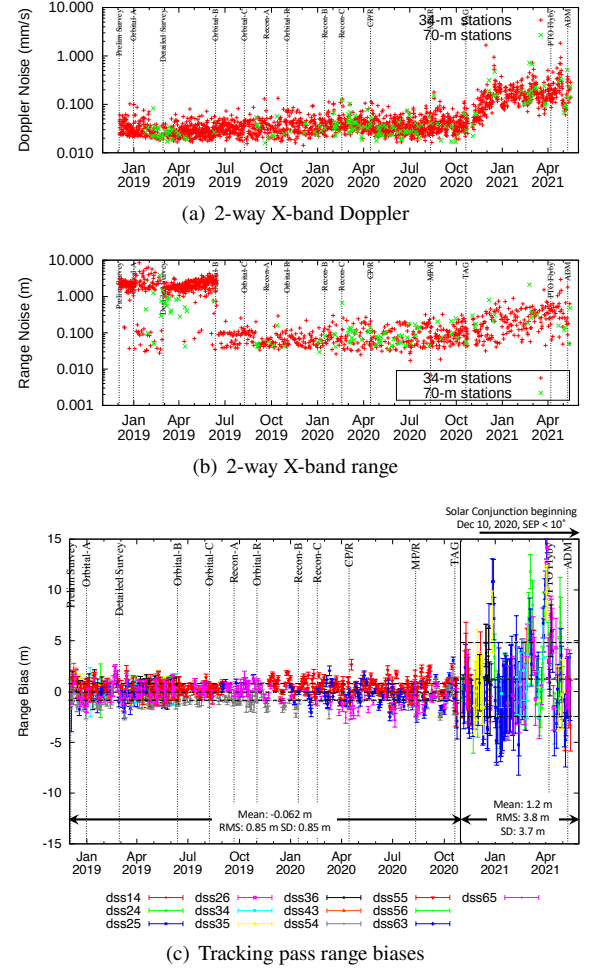


Fig. 22 Radio-metric tracking noise

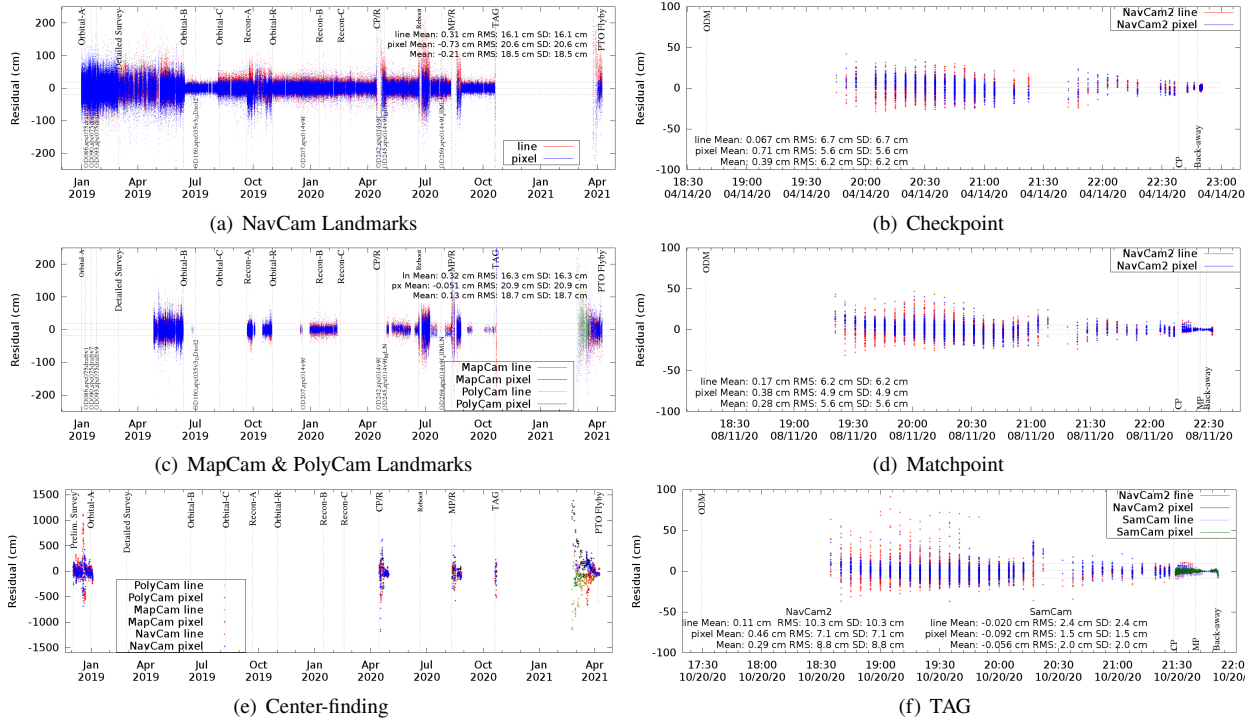


Fig. 23 Optical Navigation Residuals throughout ProxOps.

were scheduled through end of DS. Masked desats involved suppressing the momentum desaturation about 1 of the S/C axis to effectively lower the total ΔV . In general, one desat per week were scheduled per week beginning with Orbital B through end of ProxOps. These desats performed well within the requirements with weighted mean and standard deviation of 0.21 ± 0.20 mm/s.

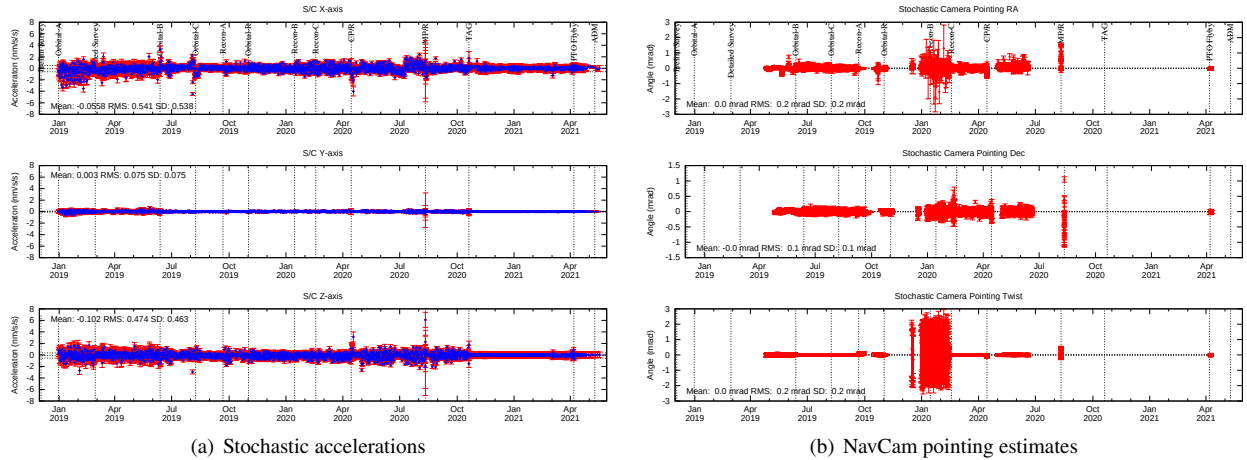


Fig. 24 Stochastic accelerations and pointing throughout ProxOps.

C. Notable Statistics

Over the 2.5 years (December 2, 2018–May 10, 2021) in close proximity to Bennu we:

- Delivered 244 Orbit Determination solutions
- Delivered 24 Reference Trajectories (plus 7 contingencies)
- Delivered > 490 OpNav solutions supporting OD deliveries and shape model analyses
- Delivered 100 ‘24-hr’ late update maneuver designs
- Delivered 143 late update ephemeris-only onboard trajectories

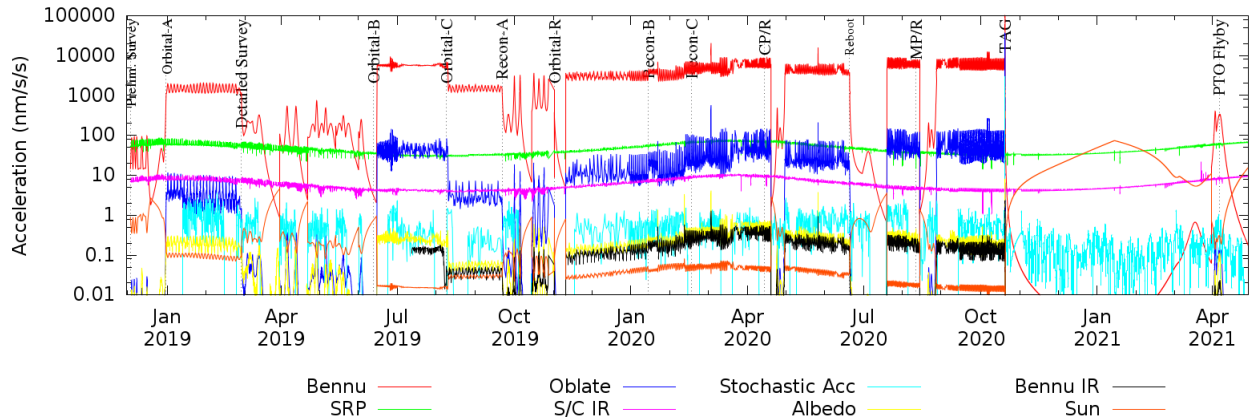
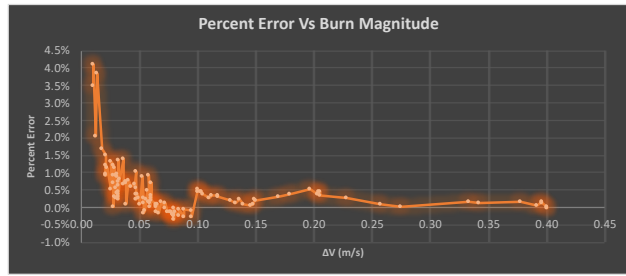


Fig. 25 Major Forces acting on spacecraft during Proxops.

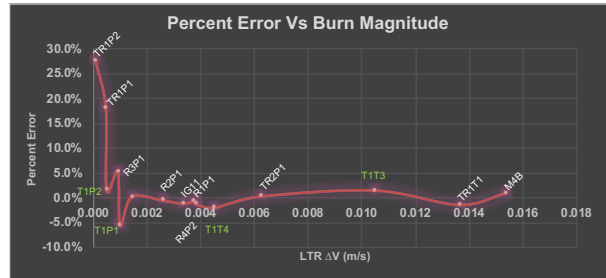
- Processed 37,592 optical navigation images (23628 long, 13964 short exposures)
- Performed 114 maneuvers with 140 individual burn components (103 ACS-TBT, 15 LTR, 15 ACS-Vector, 1 ME and 3 TCM, 3 Back-away burns, 15 decomposed)
- Executed the smallest maneuver of the mission: 0.09 mm/s (Second phasing burn for CP/R, TR1P2)
- Completed approximately 363 orbits around Benu
- Performed 10 separate orbit insertions (including ORMs)
- Completed 29 Science Flybys (21 hyperbolic flybys, 8 reconnaissance flyovers) supporting 31 observations (with flyby altitudes ranging from 240 m to 7 km)
- Flew the first application of frozen orbits about a small body
- Earned Two Guinness World Records:
 - Smallest object ever orbited
 - Closest orbit of a planetary body (1.6x2.1 km orbit of Orbital A) **clarify w/note about 870 m orbit below**
- Flew the lowest captured orbit: SMA 870 m (pre-Matchpoint)
- Matched the orbit departure latitude 3 times within 2° for rehearsals and TAG
- And finally delivered the spacecraft to the surface within 1 meter of the desired TAG site!

VI. Conclusions

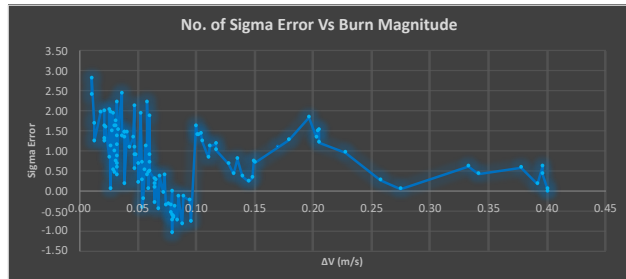
When the S/C arrived at Benu, we found an asteroid much different than expected. Benu's rocky surface and dearth of safe sample collection sites meant that many aspects of the proximity operations plan had to be revised or re-invented, including the entire sample site selection process. Benu's small size made all of the routine aspects of planetary mission navigation much more challenging, but the tighter TAG requirements due the rockier surface meant that we had to improve the models governing the OD trajectory predictions, such as Benu's gravity, SRP, and S/C thermal radiation pressure to levels much better than what had been predicted or analyzed prior to launch. The mission benefited greatly from the fact that many aspects of S/C performance such as pointing alignment errors, maneuver execution errors and perturbations from desats were much smaller than expected. The successful TAG event was due to the extraordinary inter-agency teamwork of the FDS, Science and S/C teams over the 2 years in close proximity to Benu. We worked together with the Science Team Chief, and the science working groups in the Science Team Interface to ensure that the Benu gravity, shape model and DTMs, pole, prime meridian, spin state, scale, and center-of-figure to center-of-mass offset met the required accuracies for a successful sample collection. The high cadence of activities, challenging navigation, and dependency of precise inter-agency developed Benu models makes OSIRIS-REx one of the most complex NASA missions yet. It is important to review our lessons learned from our implementation as reported by Getzandanner et al. [25] to be better prepared and more efficient for future asteroid sample return missions.



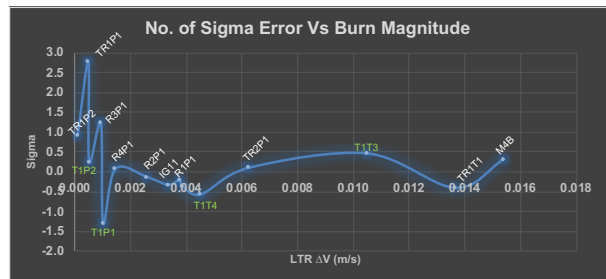
(a) ACS-TBT Percent Magnitude Error



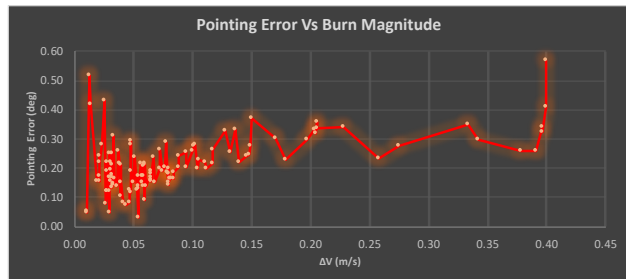
(b) LTR Percent Magnitude Error



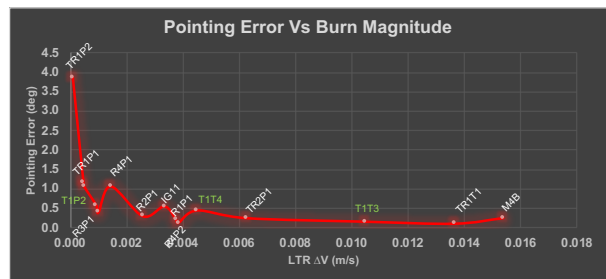
(c) ACS-TBT Magnitude Sigma Error



(d) LTR Percent Magnitude Sigma Error



(e) ACS-TBT Pointing Error



(f) LTR Pointing Error

Fig. 26 Proximity Operations maneuver errors versus ΔV magnitude, respectively for ACS-TBT and LTR maneuvers: (a, b) Percent magnitude error (c, d) Number of CBE Sigma magnitude error (e, f) Pointing errors

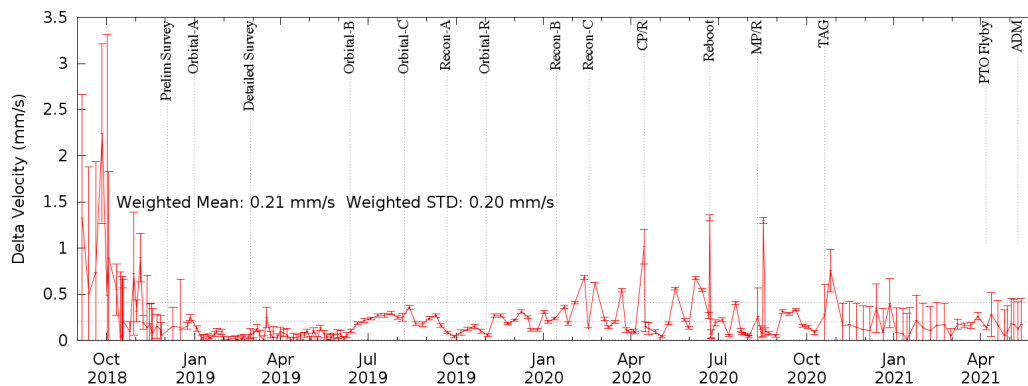


Fig. 27 The magnitude of the ΔV imparted from momentum desaturations spanning Approach through ADM

Acknowledgments

The authors acknowledge the significant contributions from members of the OSIRIS-REx team including the Lockheed-Martin flight operations team, the University of Arizona science planning and operation teams, ALTWG, RSWG and SSDT. We also wish to thank Peter Kroger of JPL for his service in supporting our Δ DORs and for his timely deliveries. This material is based upon work supported by NASA under Contracts NNM10AA11C and NNG13FC02C. OSIRIS-REx is the third mission in NASA's New Frontiers Program. Dante Lauretta of the University of Arizona, Tucson, is the principal investigator, and the University of Arizona also leads the science team and the science observation planning and data processing. Lockheed Martin Space Systems in Denver built the spacecraft and is providing flight operations. Goddard Space Flight Center and KinetX Aerospace are responsible for navigating the OSIRIS-REx spacecraft.

References

- [1] Lauretta, D. S., Balram-Knutson, S. S., Beshore, E., Boynton, W. V., Drouet d'Aubigny, C., DellaGiustina, D. N., Enos, H. L., Golish, D. R., Hergenrother, C. W., Howell, E. S., et al., "OSIRIS-REx: Sample Return from Asteroid (101955) Benu," *Space Science Reviews*, Vol. 212, No. 1, 2017, pp. 925–984. <https://doi.org/10.1007/s11214-017-0405-1>.
- [2] Berry, K., Getzandanner, K., Moreau, M., Rieger, S., Antreasian, P., Adam, C., Wibben, D., Leonard, J., Levine, A., Geeraert, J., et al., "Contact with Benu! Flight Performance Versus Prediction of OSIRIS-REx "TAG" Sample Collection," *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA*, 2022.
- [3] Lauretta, D. S., Enos, H. L., Polit, A. T., Roper, H. L., and Wolner, C. W., "Chapter 8 - OSIRIS-REx at Benu: Overcoming Challenges to Collect a Sample of the Early Solar System," *Sample Return Missions*, edited by A. Longobardo, Elsevier, 2021, pp. 163–194. <https://doi.org/10.1016/B978-0-12-818330-4.00008-2>.
- [4] Antreasian, P., Leonard, J., McAdams, J., Moreau, M., Page, B., Wibben, D., and Williams, K., "OSIRIS-REx Navigation Performance During First Leg of Outbound Cruise," *41st Annual AAS Guidance, Navigation and Control Conference*, 2018. AAS 18-062.
- [5] Barnouin, O. S., Daly, M. G., Palmer, E. E., Gaskell, R. W., Weirich, J. R., Johnson, C. L., Asad, M. M. A., Roberts, J. H., Perry, M. E., Susorney, H. C. M., et al., "Shape of (101955) Benu Indicative of a Rubble Pile with Internal Stiffness," *Nature geoscience*, Vol. 12, No. 4, 2019, pp. 247–252. <https://doi.org/10.1038/s41561-019-0330-x>.
- [6] Barnouin, O., Daly, M., Palmer, E., Johnson, C., Gaskell, R., Al Asad, M., Bierhaus, E., Craft, K., Ernst, C., Espiritu, R., et al., "Digital Terrain Mapping by the OSIRIS-REx Mission," *Planetary and Space Science*, Vol. 180, 2020, p. 104764. <https://doi.org/10.1016/j.pss.2019.104764>.
- [7] Scheeres, D. J., McMahon, J. W., French, A. S., Brack, D. N., Chesley, S. R., Farnocchia, D., Takahashi, Y., Leonard, J. M., Geeraert, J., Page, B., et al., "The Dynamic Geophysical Environment of (101955) Benu Based on OSIRIS-REx Measurements," *Nature Astronomy*, Vol. 3, No. 4, 2019, pp. 352–361. <https://doi.org/10.1038/s41550-019-0721-3>.
- [8] Farnocchia, D., Chesley, S. R., Takahashi, Y., Rozitis, B., Vokrouhlický, D., Rush, B. P., Mastrodemos, N., Kennedy, B. M., Park, R. S., Bellerose, J., et al., "Ephemeris and Hazard Assessment for Near-Earth Asteroid (101955) Benu Based on OSIRIS-REx Data," *Icarus*, Vol. 369, 2021, p. 114594. <https://doi.org/10.1016/j.icarus.2021.114594>.
- [9] Chesley, S. R., French, A. S., Davis, A. B., Jacobson, R. A., Brozović, M., Farnocchia, D., Selznick, S., Liounis, A. J., Hergenrother, C. W., Moreau, M. C., et al., "Trajectory Estimation for Particles Observed in the Vicinity of (101955) Benu," *Journal of Geophysical Research: Planets*, Vol. 125, No. 9, 2020. <https://doi.org/10.1029/2019JE006363>.
- [10] Pelgrift, J. Y., Lessac-Chenen, E. J., Adam, C. D., Leonard, J. M., Nelson, D. S., McCarthy, L., Sahr, E. M., Liounis, A., Moreau, M., Bos, B. J., et al., "Reconstruction of Benu Particle Events From Sparse Data," *Earth and Space Science*, Vol. 7, No. 8, 2020. <https://doi.org/10.1029/2019EA000938>.
- [11] Leonard, J. M., Adam, C. D., Pelgrift, J. Y., Lessac-Chenen, E. J., Nelson, D. S., Antreasian, P. G., Liounis, A. J., Moreau, M. C., Hergenrother, C. W., Chesley, S. R., et al., "Initial Orbit Determination and Event Reconstruction From Estimation of Particle Trajectories About (101955) Benu," *Earth and Space Science*, Vol. 7, No. 9, 2020. <https://doi.org/10.1029/2019EA000937>.
- [12] Scheeres, D., French, A., Tricarico, P., Chesley, S., Takahashi, Y., Farnocchia, D., McMahon, J., Brack, D. N., Davis, A., Ballouz, R., et al., "Heterogeneous mass distribution of the rubble-pile asteroid (101955) Benu," *Science Advances*, Vol. 6, No. 41, 2021. <https://doi.org/10.1126/sciadv.abc3350>.

- [13] Williams, B., Antreasian, P., Carranza, E., Jackman, C., Leonard, J., Nelson, D., Page, B., Stanbridge, D., Wibben, D., Williams, K., et al., "OSIRIS-REx Flight Dynamics and Navigation Design," *Space Science Reviews*, Vol. 214, No. 4, 2018, p. 69.
- [14] Kenneally, P., "Faster than Real-Time GPGPU Radiation Pressure Modeling Methods," Ph.D. thesis, University of Colorado, Boulder, 2019.
- [15] Geeraert, J., Leonard, J., Kenneally, P., Antreasian, P., Moreau, M., and Lauretta, D., "OSIRIS-REx Navigation Small Force Models," *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference*, American Astronautical Society, 2019, AAS 19-717.
- [16] Leonard, J. M., Geeraert, J. L., Page, B. R., French, A. S., Antreasian, P. G., Adam, C. D., Wibben, D. R., Moreau, M. C., and Lauretta, D. S., "OSIRIS-REx Precision Orbit Determination," *AGU 100, AGU Fall Meeting, San Francisco, CA, 9-13 December*, 2019.
- [17] Leonard, J. M., Geeraert, J. L., Page, B. R., French, A. S., Ashman, B. W., Antreasian, P. G., Adam, C., Lessac-Chenen, E., McCarthy, L., Nelson, D., et al., "OSIRIS-REx Shape Model Performance During the Navigation Campaign," *43rd Annual AAS GNC Conference*, 2020, AAS 20-153.
- [18] Hergenrother, C. W., Adam, C. D., Chesley, S. R., and Lauretta, D. S., "Introduction to the Special Issue: Exploration of the Activity of Asteroid (101955) Bennu," *Journal of Geophysical Research: Planets*, Vol. 125, No. 9, 2020. <https://doi.org/10.1029/2020JE006549>.
- [19] Jackman, C. D., Nelson, D. S., McCarthy, L. K., Finley, T. J., Liounis, A. J., Getzandanner, K. M., Antreasian, P. G., and Moreau, M. C., "Optical Navigation Concept of Operations for the OSIRIS-REx Mission," *Proceedings of the AAS/AIAA Space Flight Mechanics Meeting*, 2017, AAS 17-489.
- [20] Adam, C. D., Knutson, S., Billett, O., Moreau, M. C., Antreasian, P. G., Bos, B. J., Calloway, A., Castro, N., Cavaluzzi, J., Carcich, B. T., et al., "Concept of Operations for OSIRIS-REx Optical Navigation Image Planning," *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA, 2022*.
- [21] Pelgrift, J. Y., Sahr, E. M., Nelson, D. S., Jackman, C. D., Benhacine, L., Bos, B. J., Rizk, B., d'Aubigny, C. Y. D., Golish, D. R., DellaGiustina, D. N., et al., "In-Flight Calibration of the OSIRIS-REx Optical Navigation Imagers," 2018.
- [22] Liounis, A. J., Swenson, J. C., Small, J., Lyzhoft, J. R., Ashman, B. W., Getzandanner, K. M., Highsmith, D. E., Moreau, M. C., Adam, C. D., Antreasian, P. G., et al., "Independent Optical Navigation Processing for the OSIRIS-REx Mission Using the Goddard Image Analysis and Navigation Tool," *2nd RPI Space Imaging Workshop, Saratoga Springs, NY, 28-30 October*, 2019.
- [23] Highsmith, D. E., Swenson, J. C., Ashman, B. W., and Andrew J. Liounis, J. L. S., y, K. M. G., Lyzhoft, J., and David D. Rowlands, J. E. D., Mazarico, E. M., Moreau, M. C., Leonard, J. M., et al., "NASA Goddard Independent Navigation Results for OSIRIS-REx Initial Encounter at Bennu," *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference*, American Astronautical Society, 2019, AAS 19-819.
- [24] Gnam, C., Liounis, A. J., Ashman, B. W., Getzandanner, K. M., Lyzhoft, J. R., Small, J., Highsmith, D. E., Adam, C. D., Leonard, J. M., Antreasian, P. G., et al., "A Novel Surface Feature Navigation Algorithm Using Ray Tracing," *2nd RPI Space Imaging Workshop, Saratoga Springs, NY, 28-30 October*, 2019.
- [25] Getzandanner, K. M., Berry, K. E., Antreasian, P. G., Leonard, J. M., Adam, C. D., Wibben, D. R., Moreau, M. C., Highsmith, D. E., and Lauretta, D. S., "Small-Body Proximity Operations & TAG: Navigation Experiences & Lessons Learned from the OSIRIS-REx Mission," *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA, 2022*.
- [26] Nolan, M. C., Magri, C., Howell, E. S., Benner, L. A., Giorgini, J. D., Hergenrother, C. W., Hudson, R. S., Lauretta, D. S., Margot, J.-L., Ostro, S. J., et al., "Shape Model and Surface Properties of the OSIRIS-REx Target Asteroid (101955) Bennu from Radar and Lightcurve Observations," *Icarus*, Vol. 226, No. 1, 2013, pp. 629-640.
- [27] "OSIRIS-REx Project Navigation Plan, OSIRIS-REx-PLAN-0066, Rev A," NASA Goddard Space Flight Center, August 29, 2016.
- [28] Wibben, D. R., Levine, A., McAdams, J. V., Antreasian, P. G., Rieger, S., Getzandanner, K. M., Moreau, M. C., and Lauretta, D. S., "OSIRIS-REx Orbit Trim Strategy," *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA, 2022*.
- [29] Wibben, D., Levine, A., Rieger, S., McAdams, J., Antreasian, P., Leonard, J., Moreau, M., and Lauretta, D., "OSIRIS-REx Navigation Campaign Trajectory Design and Maneuver Performance," *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference*, American Astronautical Society, 2019.

- [30] Antreasian, P., Moreau, M., Jackman, C., Williams, K., Page, B., and Leonard, J., “Early Navigation Performance of the OSIRIS-REx Approach to Bennu,” *42nd AAS Guidance, Navigation and Control Conference, Breckenridge, CO*, 2019, AAS 19-035.
- [31] Leonard, J. M., Geeraert, J., Page, B., French, A. S., Antreasian, P., Adam, C. D., Wibben, D., Moreau, M., and Lauretta, D., “OSIRIS-REx Orbit Determination Performance during the Navigation Campaign,” *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference*, American Astronautical Society, 2019, AAS 19-714.
- [32] Wibben, D., Levine, A., Rieger, S., McAdams, J., Antreasian, P., Leonard, J., , Moreau, M., and Lauretta, D., “OSIRIS-REx Frozen Orbit Design and Flight Experience,” *Proceedings of the 2019 AAS/AIAA Astrodynamics Specialist Conference*, American Astronautical Society, 2019, AAS 19-677.
- [33] Gaskell, R. W., “Optical Navigation Near Small Bodies,” *Spaceflight Mechanics*, Vol. 140, 2011.
- [34] Lauretta, D., Hergenrother, C., Chesley, S., Leonard, J., Pelgrift, J., Adam, C., Al Asad, M., Antreasian, P., Ballouz, R.-L., Becker, K., et al., “Episodes of Particle Ejection from the Surface of the Active Asteroid (101955) Bennu,” *Science*, Vol. 366, No. 6470, 2019, p. eaay3544. <https://doi.org/10.1126/science.aay3544>.
- [35] Wibben, D. R., Levine, A., Rieger, S., McAdams, J. V., Getzandanner, K. M., Antreasian, P. G., Leonard, J. M., Moreau, M. C., and Lauretta, D. S., “Trajectory Design and Maneuver Performance of the OSIRIS-REx Detailed Survey of Bennu,” *43rd Annual AAS GNC Conference*, 2020, AAS 20-151.
- [36] Enos, H. L., Polit, A. T., Lauretta, D., Antreasian, P., Bennett, C., Berry, K., Bierhaus, E. B., Burns, R., H. C. Connolly, J., Clark, B., et al., “OSIRIS-REx’s Search for a Sample Site: Selecting the Prime (Nightingale) and Backup (Osprey) Sites on Asteroid (101955) Bennu,” *51st Lunar and Planetary Science Conference*, 2020.
- [37] Levine, A., Wibben, D. R., Rieger, S., McAdams, J. V., Antreasian, P., Leonard, J. M., Moreau, M. C., and Lauretta, D. S., “Trajectory Design and Maneuver Performance of the OSIRIS-REx Low Altitude Reconnaissance of Bennu,” *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA*, 2022.
- [38] Berry, K., Getzandanner, K., Moreau, M., Antreasian, P., Polit, A., Nolan, M., Enos, H., and Lauretta, D., “Revisiting OSIRIS-REx Touch-And-Go (TAG) Performance Given the Realities of Asteroid Bennu,” *43rd Guidance and Control Conference*, American Astronautical Society, 2020, AAS-20-088.
- [39] Lauretta, D., and Team, T. O.-R., “THE OSIRIS-REx Touch-And-Go Sample Acquisition Event and Implications for the Nature of the Returned Sample,” *52nd Lunar and Planetary Science Conference*, 2021.
- [40] Adam, C. D., Nelson, D. S., Pelgrift, J. Y., Erik, Hergenrother, C. W., Sahr, E. M., McCarthy, L. K., d’Aubigny, C. Y. D., and Lauretta, D. S., “Imaging-Based 3D Reconstruction of Sample Mass Lost from the OSIRIS-REx Spacecraft,” *AGU Fall Meeting, New Orleans, LA, 13-17 December*, 2021.
- [41] BROUWER, D., and CLEMENCE, G. M., *Methods of Celestial Mechanics*, Academic Press, 1961.
- [42] Farnocchia, D., “Re: New Bennu ephemeris,” , April 2019.
- [43] McMahon, J. W., Scheeres, D. J., Hesar, S. G., Farnocchia, D., Chesley, S., and Lauretta, D., “The OSIRIS-REx Radio Science Experiment at Bennu,” *Space Science Reviews*, Vol. 214, No. 1, 2018, p. 43. <https://doi.org/10.1007/s11214-018-0480-y>.
- [44] Leonard, J. M., Geeraert, J. L., Pelgrift, J. Y., Antreasian, P. G., Adam, C. D., Wibben, D. R., Getzandanner, K. M., Ashman, B. W., and Lauretta, D. S., “Navigation Prediction Performance During OSIRIS-REx Proximity Operations at (101955) Bennu,” *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA*, 2022.
- [45] McCarthy, L. K., Adam, C. D., Nelson, D. S., Sahr, E. M., Pelgrift, J. Y., Lessac-Chenen, E., and Lauretta, D. S., “OSIRIS-REx Landmark Optical Navigation Performance During Orbital and Close Proximity Operations at Asteroid Bennu,” *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA*, 2022.
- [46] Sahr, E. M., Pelgrift, J. Y., Nelson, D., Adam, C. D., McCarthy, L. K., and Lauretta, D. S., “OSIRIS-REx Pointing Performance and Comparisons,” *The 32nd AIAA/AAS Space Flight Mechanics Meeting, San Diego, CA*, 2022.