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# MANEUVER STRATEGY FOR OSIRIS-REX PROXIMITY OPERATIONS

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## ABSTRACT

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) asteroid sample return mission will study and observe asteroid (101955) Bennu (previously known as 1999 RQ36) and subsequently collect and return a sample from the asteroid to Earth for further detailed analysis. After a successful launch in September 2016, the spacecraft will be in cruise phase for two years until arrival at asteroid Bennu in late 2018. At that time, a series of critical maneuvers will provide an initial characterization of Bennu and the dynamical environment surrounding it, ultimately concluding with a successful capture into orbit about the small asteroid. This paper discusses some of the unique navigation challenges presented by these early operational phases in close proximity to Bennu and shares key observations and results from operational tests that have prepared the operations team and help mitigate the risks posed by these challenges.

## 1 INTRODUCTION

NASA's Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission will travel to asteroid Bennu in order to acquire a sample of the asteroid's regolith and return it to Earth. [1] The asteroid is both the most accessible carbonaceous asteroid and one of the most potentially hazardous asteroids known. Knowledge of its nature is fundamental to understanding planet formation and the origin of life, and improved knowledge of its future trajectory will allow us to better protect Earth from potential asteroid impacts. In order to gain this knowledge, the detailed chemical composition of an asteroid sample must be understood. Thus, the primary goal of the mission is to successfully collect a sample from the surface of Bennu and return it to Earth such that scientists can perform the detailed analysis necessary in order to answer these questions. [2]

Successfully launched in September, 2016, the OSIRIS-REx spacecraft will travel for over two years on its journey to rendezvous with Bennu in late 2018. The cruise phase of the mission can be divided into two sub-phases, separated by the Earth Gravity Assist (EGA) in September 2017. During the first year of cruise, there are one planned Deep Space Maneuver (DSM) and several potential Trajectory Correction Maneuvers (TCMs) that keep the spacecraft on the desired trajectory and target the spacecraft to the B-plane geometry necessary for a successful Earth flyby. Following EGA, two additional maneuvers are planned prior to the beginning of the Bennu Approach mission phase and arrival at the asteroid. The Bennu Approach, which formally begins with execution of the first Asteroid Approach Maneuver (AAM) in October of 2018, leads to the start of proximity operations. This entails an extensive science campaign to fully characterize target asteroid Bennu and culminates in the Touch-And-Go (TAG) maneuver in order to collect a sample of asteroid regolith from the surface. This time spent close to the asteroid, which spans nearly two years, has been divided into several different mission phases, each with its own unique goals and objectives. A high level summary of the duration of each phase and their primary science goals can be seen in Fig 1.

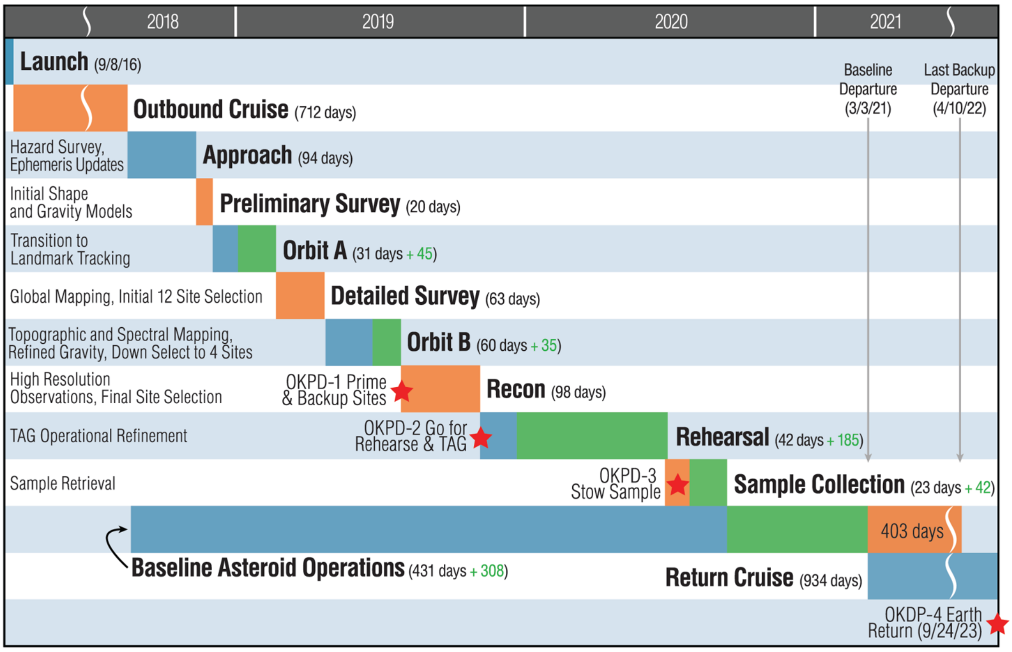



Figure 1: Timeline of the OSIRIS-REx mission from Launch in 2016 through Sample Return in 2023. Green segments represent schedule margin.

The proximity operations portion of the timeline, from Approach until the beginning of Return Cruise, can be split into three smaller campaigns. The first of these campaigns, which consists of the Approach, Preliminary Survey, and Orbital A mission phases, has been designated as the Navigation campaign due to the navigation-focused characterization of the asteroid. These first three mission phases will emphasize gaining knowledge of the asteroid's ephemeris, gravity field, and preliminary shape model that will support the transition from star-based to landmark-based optical navigation (OpNav) during the Orbital A phase, which ends at the start of the Science campaign. These phases have been designed to provide an initial characterization of Bennu and its dynamical environment in order to successfully insert the spacecraft into an orbit about the small near-Earth asteroid. However, the mission design required to achieve these goals is operationally complex, and will present several early challenges to the OSIRIS-REx Navigation team. A summary of the maneuvers planned in each of these phases is shown in Table 1. In order to mitigate these risks, the team has designed and scheduled to complete before Bennu several Navigation Training Exercises (NTEs) and operational tests that simulate these early Bennu orbit phases. Currently, the first two of these test have been completed. The first, NTE-1, focused on the Approach phase challenges including star-based

OpNav and asteroid Approach phase maneuver design. The second, NTE-2, practiced the maneuvers and activities leading up to and following the initial orbit insertion during the Orbital A phase. This paper will discuss the unique navigational challenges that will be faced during these early phases that comprise the Navigation campaign at Bennu. The results and key observations from the NTE-1 and NTE-2 activities, as well as associated analyses, will also be discussed.

Table 1: OSIRIS-REx Navigation Campaign Maneuver Strategy

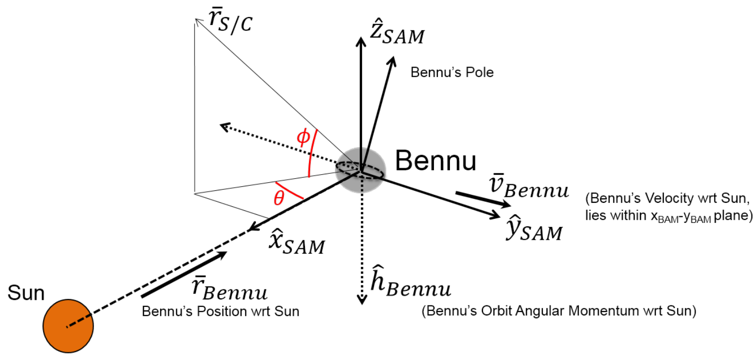
| *Phase* | *Maneuver* | *Placement* | *Purpose* | *Thruster Type* |
|---|---|---|---|---|
| | | | ***Bennu Arrival, 1-Sep-2018*** | |
| Approach | AAM1 | 1-Oct-2018 | Deterministic burn to begin Bennu arrival | Main Engine |
| | AAM2 | 15-Oct-2018 | Deterministic burn to continue Bennu approach and cleanup AAM1 execution errors. Targets 0 deg phase | Main Engine |
| | AAM2a | 22-Oct-2018 | Statistical burn to cleanup AAM2 execution errors | TCM |
| | AAM3 | 29-Oct-2018 | Deterministic burn to continue Bennu approach. Targets -20 deg solar latitude | TCM |
| | AAM3a | 5-Nov-2018 | Statistical burn to cleanup AAM3 execution errors | ACSTBT |
| | AAM4 | 12-Nov-2018 | Deterministic burn to continue Bennu approach and target start of Preliminary Survey | ACSTBT |
| | M0P | 30-Nov-2018 | Statistical burn to cleanup AAM4 execution errors | ACSTBT/LTR |
| Prelim Survey | M1P | 3-Dec-2018 | Initiate 1st North Pole flyover | ACSTBT |
| | M2P | 5-Dec-2018 | Initiate 2nd North Pole flyover | ACSTBT |
| | M3P | 7-Dec-2018 | Initiate 3rd North Pole flyover | ACSTBT |
| | M4P | 9-Dec-2018 | Complete North Pole flyover | ACSTBT |
| | M5P | 11-Dec-2018 | Initiate Equatorial flyover | ACSTBT |
| | M6P | 13-Dec-2018 | Complete Equatorial flyover | ACSTBT |
| | M7P | 15-Dec-2018 | Initiate South Pole flyover | ACSTBT |
| Orbit A | M1A | 22-Dec-2018 | Target staging point, 'Reverse Drift' | ACSTBT |
| | M2A | 29-Dec-2018 | Target 2km orbit insertion point | ACSTBT |
| | M3A | 31-Dec-2018 | Insert to initial Nav orbit | ACSTBT |
| | M4A | 7-Jan-2019 | Nav Orbit cleanup/Insert to circular orbit | ACSTBT |

The remainder of the paper continues with an overview of the Approach, Preliminary Survey, and Orbital A mission phases, including key objectives and the unique, first-time challenges that will be encountered. Next, the scenario covered by NTE-1: Approach Optical Navigation, Orbit Determination, and Maneuver Design will be discussed along with the results and key observations that were learned following test execution with emphasis on the maneuver design portion. Finally, the details of NTE-2: Orbit Insertion will be presented and discussed with focus on the trajectory and maneuver design of each leg of the test leading up to the initial orbit insertion.

## 2 OVERVIEW OF NAVIGATION CAMPAIGN MISSION PHASES

### 2.1 Asteroid Approach

The first phase of the Bennu navigation campaign, the Approach phase, is divided into four deterministic maneuvers: AAM-1 through AAM-4. The approach was designed to be robust in that it provides a single set of arrival circumstances for all Launch opportunities compatible with the spacecraft operational design, including favorable illumination conditions of the asteroid for key science observations. The AAM sequence was designed in order to create a gradual approach to Bennu with adequate time both to optically acquire that asteroid using the spacecraft's onboard cameras and also to survey the vicinity of the asteroid for any natural satellites. The AAM sequence is designed to enable graceful recovery to the Bennu approach sequence if AAM-1 is not executed, which provides additional robustness. Neither AAM-1 nor AAM-2 will target the Bennu B-Plane, but will instead target the next maneuver in the asteroid approach sequence. These first two maneuvers of the approach sequence are among the largest expected to be performed throughout the mission and are key to slowing down the spacecraft's Bennu-relative velocity. AAM-3 also will not target the Bennu B-Plane, but will instead target the spacecraft to specific illumination conditions in support of science observations. The final maneuver, AAM-4, will target the desired Bennu B-Plane conditions necessary for the start of the Preliminary Survey Phase, which will begin three weeks after AAM-4. OpNav observations will begin as early as several months prior to AAM-1 such that the full OpNav process has been exercised well before the first AAM. During the initial approach, the navigation team will utilize star-based OpNav images in addition to radiometric tracking data to solve for an accurate spacecraft state.




Longitude → $\theta = tan^{-1}\left(\frac{r_{s/c\,y_{SAM}}}{r_{s/c\,x_{SAM}}}\right)$

Latitude → $\phi = tan^{-1}\left(\frac{r_{s/c\,z_{SAM}}}{\sqrt{r^2_{s/c\,x_{SAM}} + r^2_{s/c\,y_{SAM}}}}\right)$

$$\hat{x}_{SAM} = -\hat{r}_{Bennu}$$
$$\hat{y}_{SAM} = \hat{z}_{SAM} \times \hat{x}_{SAM}$$
$$\hat{z}_{SAM} = -(\widehat{\bar{r}_{Bennu} \times \bar{v}_{Bennu}})$$

Figure 2: OSIRIS-REx Sun Anti-Momentum Coordinate Frame Definition

The Approach trajectory was carefully designed to satisfy science observation requirements on the variations in solar longitude, solar latitude, and range to Bennu over the span of planned observations. At this early stage of the mission, Bennu's shape and surface geometry will not yet be fully known, thus it was vital that the project use a consistent Bennu-centric coordinate frame that is independent of these features in order to design and analyze the incoming trajectory. The chosen coordinate frame, named the Sun Anti-Momentum (SAM) frame, is defined solely based on Bennu's orbit, as depicted in Fig. 2. The coordinate system has its origin at Bennu's center of mass, and the $x$-axis points along the Bennu-Sun line. The $z$-axis is in the opposite direction of Bennu's heliocentric orbital angular momentum vector, and the $y$-axis completes the right-handed frame. Representing the spacecraft position in this frame in spherical coordinates defines the values of solar longitude and solar latitude ($\theta$ and $\phi$ in Fig. 2, respectively), that are used as reference for maneuver targets and science observation constraints during this phase.

The nominal approach trajectory profile will place the spacecraft across a wide variety of solar latitudes and longitudes in order to provide opportunities for science observations at various illumination conditions, as seen with the solid lines in Fig. 3. An important navigation consideration are the several planned opportunities for imaging at four different solar longitude stations following AAM-3 that are vital for the first generation of a 3-D shape model of Bennu. This science product is among the most important for the navigation team because an accurate shape model allows for a faster, smoother transition to landmark-based OpNav and more accurate navigation solutions in the Orbital A phase. However, to obtain the images at the necessary conditions, strict requirements on the possible range of solar longitude and latitude are necessary. These requirements pose a unique, early challenge on the navigation team because they require precise knowledge of the spacecraft position and accurate maneuver designs while the approaching spacecraft remains several hundreds of kilometers away from the small asteroid. This fact, along with the relatively large size of the early AAMs, led to the introduction of statistical cleanup maneuvers into the nominal schedule to better control the approach trajectory of the spacecraft.

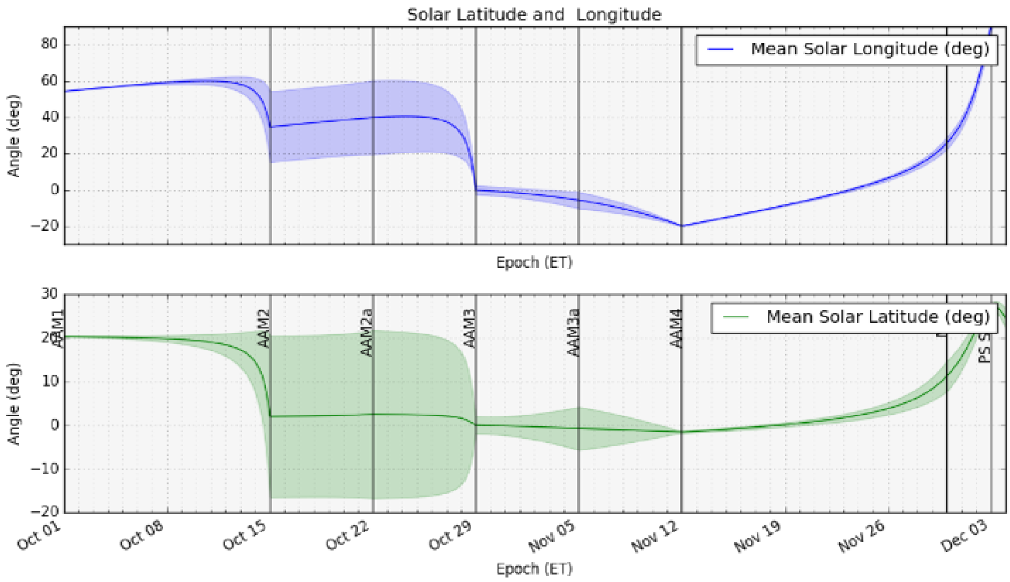



Figure 3: OSIRIS-REx Approach Phase Solar Longitude and Latitude Profile $\pm 1\sigma$

The first Approach cleanup maneuver, AAM-2a, was added to correct for maneuver execution errors from the previous burns. AAM-1 and AAM-2 will be performed using the main engines and are among the largest maneuvers of the entire mission, thus their relative size also increases the expected errors following completion of the maneuver. The AAM-2a burn also helps constrain the location of AAM-3, which will immediately proceed critical science observations. The second cleanup burn, AAM-3a, was added due to the high importance of science data being taken at that time. Particularly, this is when both spectrometers will provide an initial, disc integrated solution of the composition of asteroid Bennu. Both spectrometers, one of which will observe the thermal emission spectrum and the other will observe the visible and infrared, have small fields of view and thus are greatly affected by uncertainties in the spacecraft's trajectory. In addition, this is when initial imaging of the asteroid that will be used to help determine the initial asteroid shape model is being performed. Finally, the last identified cleanup maneuver, labeled M0P, will be a staging burn to constrain the location of the beginning of the next phase, Preliminary Survey. This is placed two days prior to the beginning of Preliminary Survey and is needed due to the long period of time without any maneuvers following AAM-4. The final weeks of the Approach phase also include numerous scientific observations of Bennu that levy demanding requirements on trajectory control and orbit determination (OD) uncertainties, including imaging with PolyCam, the spacecraft narrow field-of-view camera, in order to obtain the highest resolution images possible for building the first asteroid shape model. Fig. 3 shows the $\pm 1\sigma$ trajectory dispersions possible in the shaded areas surrounding the nominal Approach trajectory profile with these additional statistical maneuvers in place.

### 2.2 Preliminary Survey

The Preliminary Survey phase will begin with the M1P maneuver immediately following the end of the Approach mission phase. At this point the spacecraft will be approximately 18 km from Bennu and will initiate the first asteroid flyby with a closest approach distance of 7 km over Bennu's north pole. The spacecraft will first perform three separate flybys over the north pole, with each subsequent pass helping to gather information on the asteroid's gravity and to reduce uncertainties in the spacecraft trajectory such that science can reliably be acquired during the final flyover. Afterwards the spacecraft will perform 7 km flybys over Bennu's equator and south pole, resulting in five flybys in total.

As can be seen in Table 1, in order to keep each of these flyover passes as identical as possible, all maneuvers in this phase are spaced exactly 48 hours apart, imposing several operational challenges to the navigation team. In order to ensure that the maneuvers deliver the spacecraft along the flyby trajectory as accurately as possible, the team has devised a "Late Update" schedule where the team will acquire the latest OpNav images, update the spacecraft ephemeris knowledge, generate a final maneuver design, and upload the final design to the spacecraft all within 24 hours of burn execution. This schedule has necessitated careful planning of all activities and will require significant effort from the team in order to ensure on-time completion of each task. While Preliminary Survey is the first phase in which this schedule will be executed, this schedule will also be used in all subsequent phases of proximity operations at the asteroid. The Preliminary Survey phase is the subject of a test planned for execution in Fall 2017.

### 2.3 Orbital A

The primary goal of the Orbital A phase is to place the spacecraft into orbit about Bennu for the first time. Following the end of the Preliminary Survey phase, the spacecraft will be drifting away from Bennu. The M1A, or 'Reverse Drift', burn set to occur approximately 100 km from the asteroid, will initiate the orbit insertion sequence. The Orbital A phase will officially begin with the execution of the M2A burn to target the spacecraft to the location of orbit insertion approximately 2 km from Bennu. The orbit insertion burn will be executed two days later. Due to the expected low gravitational acceleration of Bennu (nominal GM of $5.2 \pm 0.6\ \mathrm{m}^3/\mathrm{s}^2(1\sigma)$ [3]), orbits about Bennu can be tenuous, especially at higher altitudes, and orbit velocities will be low - less than 10 cm/s. This causes any perturbing acceleration such as solar radiation pressure (SRP) or reaction wheel desaturation events (on the order of 0.5 mm/s) to play a significant role in Bennu's dynamical environment and the orbit design. In addition, while the close flybys of the Preliminary Survey phase will help reduce uncertainty in the asteroid's GM, Bennu's gravity field will still be known to only $1-2\%$ at the time of initial orbit insertion. These factors, along with the desire to guarantee spacecraft safety for over 21 days while in orbit, necessitate a design that is robust and stable in this uncertain and challenging dynamical environment.

Due to the significant impact of SRP and Bennu's low GM, orbits that are typically stable will instead show oscillating orbital elements over time. For example, an initially circular orbit with a semi-major axis of 1.5 km, will within 15 days have an eccentricity value of 0.142 with a closest approach altitude of 1.04 km from the asteroid's surface. [4, 5] To help provide stability against solar pressure and limit these orbit oscillations, the initial orbit has instead been chosen to be a Sun-Terminator frozen orbit. The frozen orbit represents an equilibrium solution of the secular equations of motion for orbits reacting to perturbations from SRP such that the orbital elements will remain constant on average. [4, 5] This orbit is designed to reside in the terminator plane, equivalent to the $y-z$ plane in Bennu SAM coordinate frame in order to provide stability relative to SRP. For any given insertion point and desired orbit size, the orbital elements of the frozen are determined by:

$$e = \cos\Lambda \tag{1}$$

$$i = 90^\circ \tag{2}$$

$$\Omega = \pm 90^\circ \tag{3}$$

$$\omega = \mp 90^\circ \tag{4}$$

where $\Lambda$ is a parameter resulting from the secular dynamical equations that relates the accelerations due to the asteroid's gravity and SRP:

$$\tan\Lambda = \frac{3(1+\rho)P_0}{2B}\sqrt{\frac{a}{\mu\mu_S A(1-E^2)}} \tag{5}$$

where $\rho$ is the spacecraft reflectance, $P_0$ is the solar flux, $B$ is the spacecraft mass to area ratio, $a$ is the desired spacecraft-asteroid semi-major axis, $\mu$ is the asteroid's gravitational parameter, $\mu_S$ is the solar gravitational parameter, $A$ is asteroid-sun semi-major axis, and $E$ is the asteroid-sun orbit eccentricity. With these orbital elements, a stable orbit can be designed with specified size and relatively little oscillation in orbital elements. Fig. 4 shows a comparison of the evolution of an initially circular orbit with semi-major axis of 1.5 km with a frozen orbit with a semi-major axis of 1.75 km (orbit insertion at apoapse at 2 km) over the entire Orbital A mission phase. Clearly, the initially circular orbit evolves considerably more while the frozen orbit remains nearly constant over the time period. The attractive nature of the frozen orbit stability led to the selection of this orbit as the baseline to provide a stable, safe initial orbit.

## 3 NTE-1: STAR-BASED OPTICAL NAVIGATION AND ASTEROID APPROACH MANEUVER DESIGN

The first NTE performed by the team focused on some of the challenges identified in the Approach mission phase. Specifically, NTE-1 exercised routine OD, OpNav, and maneuver design cycles and associated internal FDS interfaces in tandem for the first time, as will happen during the actual asteroid approach.

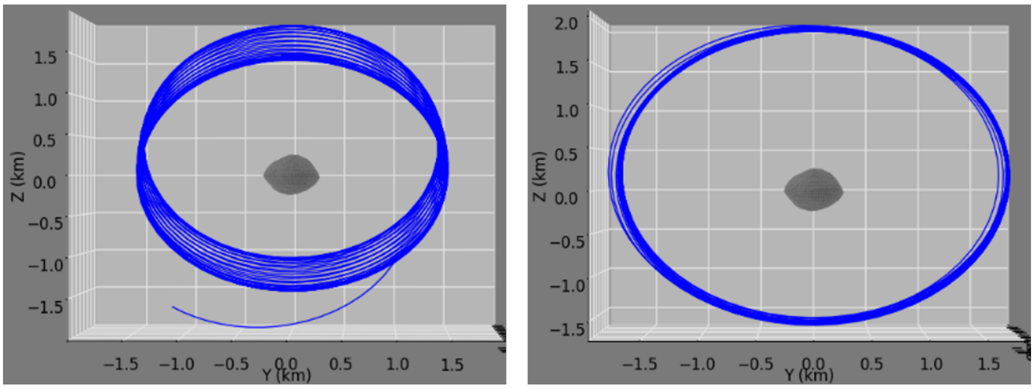



Figure 4: Comparison of Sun-Terminator Orbits: Insertion into initially circular with a semi-major axis of 1.5 km(left) and frozen orbit with semi-major axis of 1.75 km (right)

### 3.1 Test Scenario

The NTE-1 scenario was chosen to cover 16 days in the middle of the Approach phase, beginning with a reconstruction of AAM-1 on October 9, 2018, 6 days prior to the execution of AAM-2. For this test it was assumed that AAM-2 was designed prior to the start of this test. The test would continue through the decision point on the need for the statistical AAM-2a burn and then end with the generation of the design of the AAM-3 burn, which will happen 5 days prior to the October 29, 2018 AAM-3 burn execution. The test was set to execute during the week of March 6, 2017. The maneuver design team needed to generate an initial design of the AAM-2a burn and provide a recommendation on whether or not it would be required to clean up the post-AAM2 trajectory. If it was deemed necessary, the team would generate a final AAM-2a design and provide all the necessary operational products for its execution. Afterwards, the team would generate a design for the AAM-3 burn to complete the test.

The test simulation featured several perturbations from the nominal trajectory, including perturbations to the Bennu ephemeris, SRP and small force accelerations and execution errors in the AAM-1 and AAM-2 burns. The trajectory also included several reaction wheel desaturation events that were perturbed and unknown to the team executing the test. The simulation included simulated range and Doppler data and OpNav images consistent with the test scenario, and an attitude profile consistent with expected spacecraft slewing during this phase.

### 3.2 Test Execution and Results

The maneuver team's tasks for NTE-1 began on the third day of test execution. By this time, the OpNav and OD teams had processed data up to AAM-2 + 2 days, which corresponds with the design of the AAM-2a maneuver. Further information on the execution and results of the OD and OpNav portions of the test can be found in [6].

Using the latest OD solution of the spacecraft trajectory, the maneuver team was able to produce a design of the AAM-2a maneuver. As described previously, the Approach maneuver sequence was designed to fly the spacecraft through specific regions of space surrounding Bennu, thus the targets of each burn in the sequence are the Bennu SAM frame coordinates of the next maneuver. For AAM-2a, which ideally is not required, the goal is to target the spacecraft back to the reference trajectory at AAM-3. However, the current estimated trajectory suggested that the AAM-2 maneuver execution errors would have resulted in an error in the AAM-3 target location of over 300 km and in order to correct for this error, the AAM-2a burn would require a delta-v of 59 cm/s. Since this value is significantly higher than the limit set to recommend waiving the burn, it was quickly decided to make execution of AAM-2a to be mandatory. With the operations schedule allowing for just one loop through the maneuver design cycle for AAM-2a design, no further updates were made and the design was completed and delivered. Table 2 presents details on the AAM-2a design and compares it to the nominal AAM-2a design, the mean value resulting from Monte Carlo analysis, the truth design of the burn generated for this test, and the value that was reconstructed during the test by the OD team following maneuver execution.

Table 2: Comparison of NTE-1 AAM-2a design

| Maneuver | Date | Case | DV (m/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| **AAM-2a** | 22-Oct-2018 | NTE-1 Design | 0.5897 | 73.142 | 55.490 |
| | | NTE-1 Truth | 0.5939 | 73.877 | 55.356 |
| | | Monte Carlo Mean (1000 cases) | 2.060 | - | - |

Clearly the designed maneuver value is very close to the truth maneuver value, demonstrating that this portion of the test was successful. In addition, the delta-v values seen in the test are significantly below the mean seen from Monte Carlo analyses performed by the team, indicating that the AAM-2 burn prior to test performed reasonably well.

Following the completed design of the AAM-2a burn, the maneuver team's next task was to generate a design for AAM-3, the last step of the test. The team essentially repeated the same steps as the design of AAM-2a, except AAM-3 is a deterministic burn and will always be performed. Prior to the last OD delivery, the preliminary design of the burn initially indicated that it violated a key constraint of the OSIRIS-REx spacecraft. The design of any maneuver must not allow the instrument deck to be pointed within a certain angle of the spacecraft-Sun line in order to maintain safety of the on-board instruments. If the nominal maneuver design necessitates a violation of this constraint, specific procedures must be invoked in order to generate a new design that splits the burn in to multiple segments that will result in the same trajectory change effect as the original, single delta-V design without violating the keep-out zone constraint. The team was required to invoke the procedures necessary to decompose the burn for the preliminary design, and delivered the burn in two separate segments. Fortunately, the final design as reported in Table 3 did not require decomposition and was able to proceed without issue.

Table 3 presents a comparison between design and truth values of the AAM-3 burn for the test, as well as the mean values from the most recent Monte Carlo analyses. Clearly the design closely matches the truth once again, signaling a successful completion of NTE-1 for the maneuver team.

Table 3: Comparison of NTE-1 AAM-3 design

| Maneuver | Date | Case | DV (m/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| **AAM-3** | 29-Oct-2018 | NTE-1 Design | 4.875 | 124.437 | 23.639 |
| | | NTE-1 Truth | 4.876 | 124.444 | 23.620 |
| | | Monte Carlo Mean (1000 cases) | 5.848 | 152.518 | 23.469 |

## 4 NTE-2: ORBIT-A INSERTION AND MANEUVER LATE UPDATE

The second NTE performed by the team focused on the challenges associated with the Orbital A phase. The scenario for NTE-2 differs from that of NTE-1 in that the team would alternate between operational and simulation portions of the test. This allowed each subsequent leg of the simulation to be responsive to the characteristics of the Orbit Determination and Maneuver Design solutions from the previous leg, providing a higher degree of realism for the test. The focus of the test was to exercise the OD, OpNav, and Late-Update Maneuver design cycles for Orbital A Bennu orbit insertion.

### 4.1 Test Scenario

The NTE-2 scenario was chosen to cover the span of the first 3 weeks of the Orbital A phase, beginning with the first OD delivery following M7P, which initiates the final flyby of Preliminary Survey. At this point the spacecraft is drifting away from the asteroid for approximately a week after the last flyby of Preliminary Survey until the execution of the M1A burn around 100 km from Bennu. The maneuver team designed maneuvers M1A through M4A, with the test ending following the design of M4A. In order to evaluate performance of the final Orbital A orbit, this M4A design was implemented and the result propagated for several weeks until the end of the Orbital-A mission phase to assess the stability of the final orbit. A timeline for NTE-2 specifying each individual simulation leg is shown in Fig. 5.

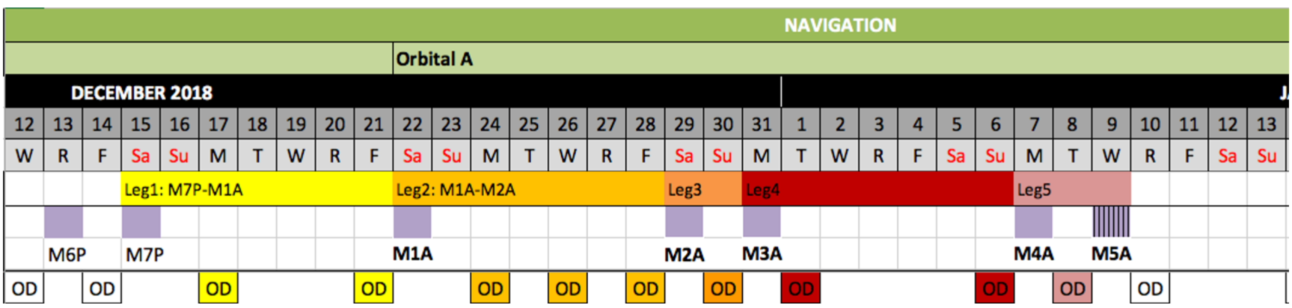



Figure 5: NTE-2 Timeline

The test simulation once again featured several perturbations from the nominal trajectory, including perturbations to the Bennu ephemeris, SRP, small force accelerations, execution errors for all included maneuvers, and spacecraft attitude errors. The simulation also includes several reaction wheel desaturation events approximately every 3-4 days during the test. The test included simulated range and Doppler data and OpNav images consistent with the test scenario.

### 4.2 Test Execution and Results

During the execution of the test, with each Orbit Determination solution as shown in Fig. 5 a maneuver design was performed. While the nominal schedule has identified a placeholder for a 24-hour late update of each maneuver design, it is preferred to only exercise them if necessary due to the operational complexity and possibility of error, so the trending of maneuver parameters across several designs provided valuable insight to the team. Notably the Orbital A trajectory was designed to prevent any maneuver from requiring decomposition in order to satisfy spacecraft constraints due to the high accuracy of each maneuver required in order to capture into the desired orbit successfully.

The first leg of the test focused on the design of M1A and featured both preliminary and late update designs. The goal of M1A is to bring the spacecraft to a staging point at M2A approximately 3 km in front of the Bennu-Sun terminator plane, after which M2A would target the orbit insertion point below Bennu's south pole. With each M1A design, the team also provided a design of M2A. A summary of these designs is reported in Table 4 with the preliminary design corresponding to the OD from December 17, with the late update scheduled on December 21 exactly 24 hours prior to M1A execution. Due to the test being simulated in separate legs, the 'Truth' value listed was not available prior to delivery of the final design. Instead, this is the perturbed maneuver that was implemented for use in the next leg of the test based on expected maneuver execution errors. While the shift in parameters for M1A is small between the two designs, the changes all represent a shift greater than $1\sigma$ based on expected maneuver execution errors. The team therefore agreed to deliver and use the late update solution for M1A.

Table 4: Comparison of NTE-2 M1A Designs

| Maneuver | Date | Case | DV (cm/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| **M1A** | 22-Dec-2018 | Preliminary (T-5 days) | 33.76 | 141.00 | 18.33 |
| | | Late Update (T-1 day) | 33.92 | 141.53 | 17.69 |
| | | Truth | 33.94 | 141.82 | 17.76 |
| **M2A** | 29-Dec-2018 | Preliminary (T-12 days) | 7.38 | 282.54 | -23.92 |
| | | Late Update (T-8 days) | 7.20 | 290.02 | -22.10 |

Following the delivery of the late update of M1A, the first leg of NTE-2 was complete. The second leg, focused on the design of M2A, also spanned approximately one week but included updates to the maneuvers designs on 3 separate days, on December 24, 26, and 28, the last of which is the late update for the burn. Similar to the process used with M1A, a new M2A design was generated with each OD solution, along with a new design of M3A. The details of each design are reported in Table 5. The M2A maneuver will target the orbit insertion point, set at 2 km range from Bennu's south pole, which is also apoapse of the targeted frozen orbit following M3A. The orbit insertion burn M3A is planned to occur as the spacecraft crosses the Bennu-Sun terminator plane, and is one of the few maneuvers of the mission planned to shift in time with each design. However, prior to execution of M2A the maneuver epoch remains at the nominal time with an associated timing uncertainty. The M3A maneuver is targeted to insert the spacecraft into a 2 X 1.5 km frozen orbit about Bennu in the terminator plane. The design of the frozen orbit is as described in Eq. (1)-(5) with a desired semi-major axis of 1.75 km. Assuming apoapse at 2 km, the resulting frozen orbit eccentricity from Eq. (1) is found to be 0.1469 with an orbit period of nearly 63 hours. Notably, the angular momentum vector of the designed orbit is orthogonal to the terminator plane, but pointed away from the Sun, i.e., the orbit will appear to be retrograde and rotating clockwise when viewed from the Sun. The M3A delta-V is seen to be nearly double that of M2A due to the combination of the incoming hyperbolic trajectory and the desired retrograde frozen orbit. The angle between the pre- and post-M3A velocity vectors of greater than 150 deg such that M3A will almost reverse the direction of the spacecraft's velocity in order to enter into the desired orbit. A plot of the trajectory associated with the late update M2A and M3A designs in Table 5 is shown in Fig. 6.

Table 5: Comparison of NTE-2 M2A Designs

| Maneuver | Date | Case | DV (cm/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| **M2A** | 29-Dec-2018 | M1A Late Update (T-8 days) | 7.20 | 290.02 | -22.10 |
| | | 12/24 Preliminary (T-5 days) | 6.87 | 299.67 | -24.13 |
| | | 12/26 Preliminary (T-3 days) | 6.88 | 300.20 | -22.31 |
| | | Late Update (T-1 day) | 7.05 | 300.27 | -22.51 |
| | | Truth | 7.16 | 300.17 | -22.37 |
| **M3A** | 31-Dec-2018 | 12/24 Preliminary (T-7 days) | 14.35 | 310.01 | -13.83 |
| | | 12/26 Preliminary (T-5 days) | 14.28 | 309.69 | -13.69 |
| | | Late Update (T-3 days) | 14.17 | 309.72 | -13.61 |

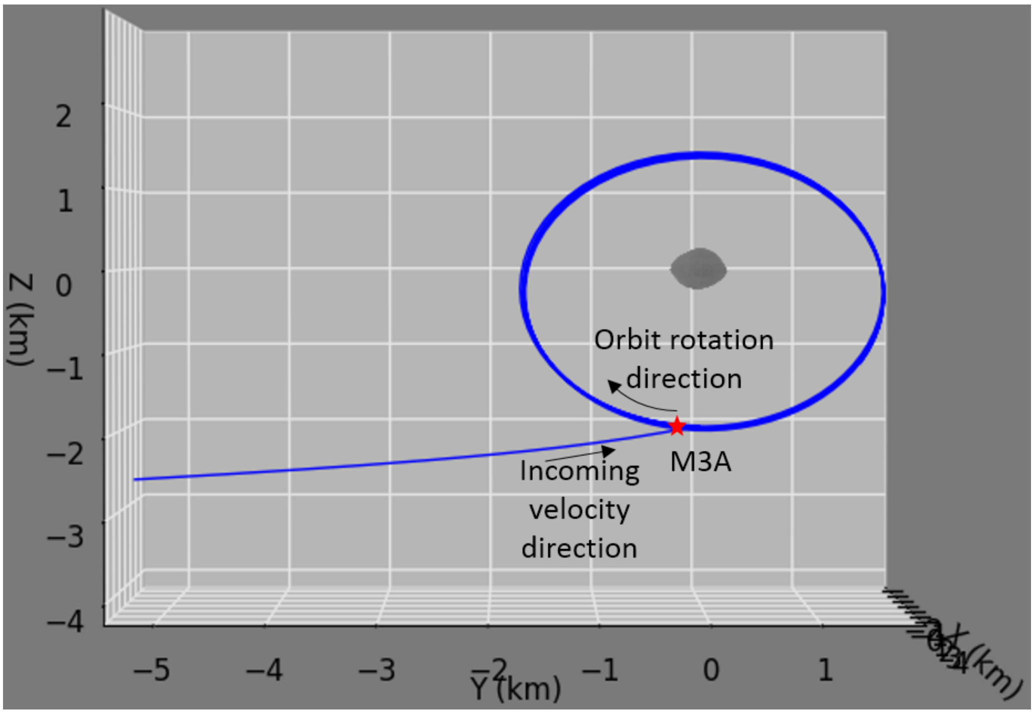



Figure 6: View from the Sun of orbit design at M2A late update, Bennu-centered SAM frame

In order to target the orbit insertion point as accurately as possible, the late update design of M2A was delivered completing the second leg of NTE-2. The small errors seen between the truth M1A and the late update M1A design can be seen in the relatively small changes between the pre- and post-M1A designs of M2A. As the team performed the late update design of M3A on the next leg of the test, it was quickly seen that the incoming trajectory following M2A was not as expected. While it was unknown during the test, the difference between the delivered M2A and the perturbed truth M2A delta-V values represent a nearly $3\sigma$ event, which indicated that there will likely be a considerable shift in the M3A late update design. An analysis of the incoming trajectory showed that the periapse range following M2A was 2.12 km, and never reached the range necessary to insert into orbit at the originally planned 2 km range. In addition, the time of periapse was nearly two hours after the nominal M3A execution epoch, and was reached several degrees in solar phase angle behind the terminator plane. It was observed that spacecraft crossed the terminator plane 55 minutes after the nominal burn time, with a radius of 2.14 km. Because the terminator crossing occurred an hour earlier than periapse with the ranges to Bennu between the two points being similar, M3A was placed at the point where the spacecraft was predicted to cross the terminator plane.

Due to the trajectory not reaching the planned 2 km insertion point, the frozen orbit targeted with the M3A maneuver had to be redesigned. Assuming insertion at an apoapse of 2.14 km, it was no longer possible to design a frozen orbit with a semi-major axis of 1.75 km, because the eccentricity of the orbit is set based on the gravitational and SRP accelerations. By iterating on the design of the frozen orbit, the desired orbit eccentricity and semi-major axis values can be found. In this case, the semi-major axis was 1.85 km with an eccentricity of 0.129. Using this new orbit design, the M3A late update design was generated and delivered. This M3A late update design is summarized in Table 6. The parameters relative to the pre-M2A design show the large changes between the two M3A designs caused by the $3\sigma$ execution of M2A, despite the fact that the solutions were generated just 48 hours apart.

Table 6: Comparison of NTE-2 M3A Designs

| Maneuver | Date | Case | DV (cm/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| | | M2A Late Update (T-3 days) | 14.17 | 309.72 | -13.61 |
| | | Late Update (T-1 day) | 13.99 | 308.12 | -12.29 |
| **M3A** | 31-Dec-2018 | Truth | 14.17 | 308.57 | -11.97 |

Analyzing the first OD solutions following the execution of M3A, it was clear that the achieved orbit was considerably different than the targeted orbit. Once again, the differences between the late update and truth values of M3A as reported in Table 6 show a roughly $3\sigma$ burn execution error. Figure 7 shows a view of the targeted and achieved orbits along the terminator plane when propagated until the end of the Orbital A phase. Clearly, the achieved orbit does not exhibit the desired frozen orbit behavior. However, in spite of the large maneuver execution errors in both M2A and M3A, the test demonstrated that it was possible to insert into an orbit that was safe and would meet all of the subsequent orbit operations requirements. The final leg of the test involved designing an M4A maneuver approximately one week following orbit insertion to place the spacecraft in a circular orbit about Bennu. While initially circular orbits will evolve significantly due to SRP and other perturbing factors as previously discussed, they will exhibit periodic behavior resulting in several desirable traits from a science perspective. Initial analysis of the achieved orbit revealed that a periapse crossing would occur on January 9, 2019 with a spacecraft-asteroid range near 1.75 km. At this epoch the spacecraft was also predicted to be close to the terminator plane which would be beneficial to place the initial orbit inclination in the terminator plane after being circularized. Therefore this epoch was fixed for the next maneuver, and remained fixed despite changes to the orbit with each subsequent solution. The summary of the M4A designs corresponding with each OD solution throughout the week leading up to the late update for the maneuver appear in Table 7. Clearly, there are significant changes across the various solutions, demonstrating that any maneuver to change or trim the orbit during this phase will require a late update of the maneuver design. After completion of the test, it was found that these changes, specifically those between January 5 and January 8, were caused by reaction wheel desaturation events. In particular, one of these events January 7 had a delta-V of approximately 1 mm/s, and was observed to change the orbit significantly. Therefore, caution must be practiced with the size and placement in orbit of the desaturation events during actual operations.

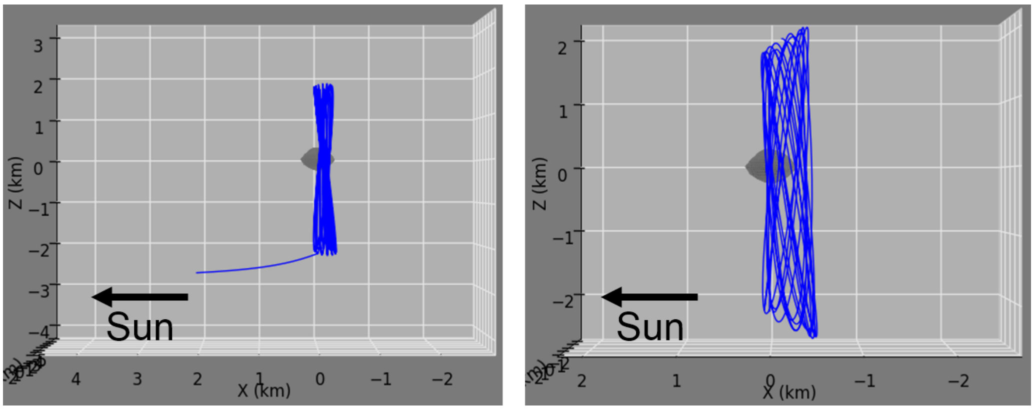



Figure 7: Comparison of the targeted (left) and achieved (right) initial orbit about Bennu looking along the terminator plane in the SAM frame

Table 7: Comparison of NTE-2 M4A Designs

| Maneuver | Date | Case | DV (cm/s) | RA (deg) | Dec (deg) |
|---|---|---|---|---|---|
| **M4A** | 9-Jan-2019 | January 1 Preliminary (T-8 days) | 0.599 | 3.00 | 13.44 |
| | | January 3 Preliminary (T-6 days) | 0.356 | 314.79 | 17.48 |
| | | January 5 Preliminary (T-4 days) | 0.378 | 313.89 | 19.11 |
| | | January 8 Late Update (T-1 day) | 0.817 | 10.92 | 19.09 |

## 5 CONCLUSIONS

The NASA OSIRIS-REx asteroid sample return mission, set to arrive at asteroid Bennu in late 2018, successfully launched on September 8, 2016. Following the launch, the navigation team has been preparing for the challenges of proximity operations at the asteroid. Thus far, the team has completed the first two of several Navigation Training Exercises that focus on the early phases of the mission at Bennu. The first exercise, which focused on the early maneuvers as the spacecraft initially approaches the asteroid helped train the team on tools that will be used, and also allowed the team to exercise the process of decomposing a maneuver into components for the first time. The second exercise focused on the many activities leading up to and immediately following the initial Bennu orbit insertion, and exposed the team to some variations and perturbations that could be encountered during this phase. The team was able to successfully place the spacecraft in a safe orbit about Bennu despite off-nominal maneuver executions and unexpected perturbations. Due to the variability of orbit characteristics and limitations in controlling these in the presence of various error sources, it was determined that the goal of placing the spacecraft in a relatively stable orbit with M3A was sufficient to meet the objective of performing the OpNav transition. The M4A maneuver, intended to place the spacecraft in a circular orbit, will be deferred until after the OpNav transition is completed, to enhance Science observations and help characterize the effectiveness of orbit adjustments required in later mission phases. This proved to be a valuable and insightful experience for the team to better understand the driving error sources and helped to identify further challenges that need to be discussed with the broader flight team prior to arrival at Bennu.

## 6 ACKNOWLEDGEMENTS

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