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ORBIT DETERMINATION STRATEGY AND SIMULATION PERFORMANCE FOR OSIRIS-REX PROXIMITY OPERATIONS

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ABSTRACT

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) is a NASA New Frontiers mission to the near-earth asteroid Bennu that will rendezvous in 2018, create a comprehensive and detailed set of observations over several years, collect a regolith sample, and return the sample to Earth in 2023. The Orbit Determination (OD) team is a sub-section of the Flight Dynamics System responsible for generating precise reconstructions and predictions of the spacecraft trajectory. The OD team processes radiometric data, LIDAR, as well as center-finding and landmark-based Optical Navigation images throughout the proximity operations phase to estimate and predict the spacecraft location within several meters. Stringent knowledge requirements stress the OD team's concept of operations and procedures to produce verified and consistent high quality solutions for observation planning, maneuver planning, and onboard sequencing. This paper will provide insight into the OD concept of operations and summarize the OD performance expected during the approach and early proximity operation phases, based on our pre-encounter knowledge of Bennu. Strategies and methods used to compare and evaluate predicted and reconstructed solutions are detailed. The use of high fidelity operational tests during early 2017 will stress the teams concept of operations and ability to produce precise OD solutions with minimal turn-around delay.

1 INTRODUCTION

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) is a NASA New Frontiers mission to the near-earth asteroid Bennu (101955) that will rendezvous in 2018, create a comprehensive and detailed set of observations over several years, collect a regolith sample, and return the sample to Earth in 2023. The Orbit Determination (OD) team is a sub-section of the Flight Dynamics System (FDS) responsible for generating precise reconstructions and predictions of the spacecraft trajectory. The OD team processes radiometric data, LIDAR, as well as center-finding and landmark-based Optical Navigation (OpNav) images throughout the proximity operations phase to estimate and predict the spacecraft location within several meters. Stringent knowledge requirements stress the OD team's concept of operations and procedures to produce verified and consistent high quality solutions for observation planning, maneuver planning, and onboard sequencing.

The beginning of proximity operations (ProxOps) is comprised of a multiple phase Navigation Campaign allowing for early characterization of the asteroid Bennu. During the first three ProxOps phases, OSIRIS-REx approaches Bennu from interplanetary cruise, conducts multiple polar and equatorial flybys during Preliminary Survey, and then transitions to the first orbital phase known as Orbital-A. During the Approach phase, PolyCam is used to acquire Bennu as a point source when the spacecraft is over 2 million km away from Bennu. These early images combined with 2-way X-band Doppler, range tracking and Delta-Differential One-way Range (DDOR) acquired from the Deep Space Network (DSN) allow for the determination of the spacecraft state relative to Bennu and refine the Bennu ephemeris. The second ProxOps phase, Preliminary Survey, consists of multiple 7-km hyperbolic flybys over the Northern, Equatorial and Southern regions of Bennu allowing for the mass of Bennu to be determined to within 2%. After the completion of Preliminary Survey, the OD team will prepare for orbit insertion and begin the transition to Landmark-based OpNav.[1]

The transition from star-based OpNavs during Approach and Preliminary Survey as the primary navigation observations to the landmark OpNav images using the powerful Stereophotoclinometry (SPC) [2, 3] technique will take place during this orbital mission phase, referred to as Orbital-A. The primary focus of this phase is for the Navigation Team to successfully transition to landmark navigation and focus on refining the Bennu shape model developed with Approach and Preliminary Survey imaging. During the two-week transition period, the OD team will be focused on determining Bennu's rotational state, center-of-figure to center-of-mass offsets induced by approach imaging, any scaling issues with the shape model, and quantifying the quality and location of landmarks generated by the SPC software. After extensive definitive and predictive trajectory comparisons between SPC landmark based solutions and center-finding OpNav solutions, ProxOps continues into a site selection-focused ConOps: a more detailed sequence of survey flybys; a lower 1 km radius Orbital-B; and several 500 and 225 m Reconnaissance sorties. Once the prime and backup sample sites are selected, the mission proceeds to rehearsing and performing the Touch-and-Go (TAG) surface sampling event.[4]

This paper examines the OD strategies during the Approach and Orbital-A insertion timeframes. A brief overview of the OD process is provided to show the complex nature of the early transition periods during ProxOps. Detailed high-fidelity tests were produced within the Navigation Team to exercise the teams ability to respond to the critical phases of Approach and early characterization of center-finding OpNavs as well as the Orbital-A insertion.

2 NAVIGATION TRAINING EXERCISES

Several Navigation Training Exercises (NTEs) are planned during the 2-yr outbound cruise phase to Bennu. These tests are planned to prepare and train the FDS team through several key first-time-events, navigation techniques, and unique processes required for close proximity operations. The FDS team recently completed two of these tests covering: the Approach and Orbital-A insertion Phases.

An overall project testing program has been developed to train Flight Team members and validate ground system processes, tools, procedures, and interfaces for OSIRIS-REx key activities required to achieve mission success. These NTE tests are an integral part of this program. The test products from these NTEs in most cases feed into the project's Operations Proficiency Integrated Exercises (OPIEs) or Operation Readiness Tests (ORTs) which are planned to demonstrate the flight team's readiness for these key activities.

The objectives of the NTEs are to train the Team covering all FDS functions required for proximity operations:

- Mission design, contingency planning
- Center-finding OpNav processing
- Landmark OpNav processing
- Orbit Determination with radio, DDOR and OpNavs
- Bennu ephemeris, gravity and spin-state determination
- Small force characterization
- Preliminary and final (late update) maneuver design

All these functions except landmark processing and Bennu spin-state determination are required for the Approach and Orbital-A insertion phases. The objectives of the Approach and Orbital-A NTEs included the development of a more refined concept of operations for these phases, orbit characterization, team decision making, and procedure updates.

3 OPTICAL NAVIGATION OVERVIEW

OpNav, a sub-function of FDS, uses information extracted from spacecraft images to assist in the OD of the spacecraft.[5, 6] While radiometric data are needed for OD throughout the entire mission, these data are most useful in determination of spacecraft position relative to Earth, and their use in establishing the spacecraft state relative to other bodies is highly dependent on the ephemeris knowledge of those other bodies. When such knowledge is limited, or uncertainties are relatively large when compared to the scale of the body (as is the case for most missions to small bodies), use of Earth-based radiometric data types is insufficient to meet mission objectives and ensure spacecraft safety. Therefore, processing of OpNav images near small bodies like Bennu is essential to ensure precise determination of the spacecraft ephemeris relative to the asteroid.

OpNav for the OSIRIS-REx mission uses both star fields and asteroid landmarks for navigation with a suite of imagers given in Table 1.[7, 8] Star-based OpNav is utilized in early mission phases, before global imaging data and digital terrain maps (DTMs) are available for landmark navigation. The objective of star-based OpNav is to determine the position of the target body center relative to inertial star positions. The camera pointing is estimated by minimizing the differences between imaged background star locations and the cataloged star positions, in order to correct for errors in the spacecraft derived pointing solution. Accurate inertial camera pointing determined from this process allows for precise calculation of the predicted location of the Bennu center of mass (CM). The observed location of the Bennu CM is derived using a variety of algorithms available in the KinetX Star-Based Image Processing Suite, KXIMP.[9] The OD estimation filter minimizes the difference between observed and computed (pixel, line) body centers, along with other radiometric tracking data measurements.

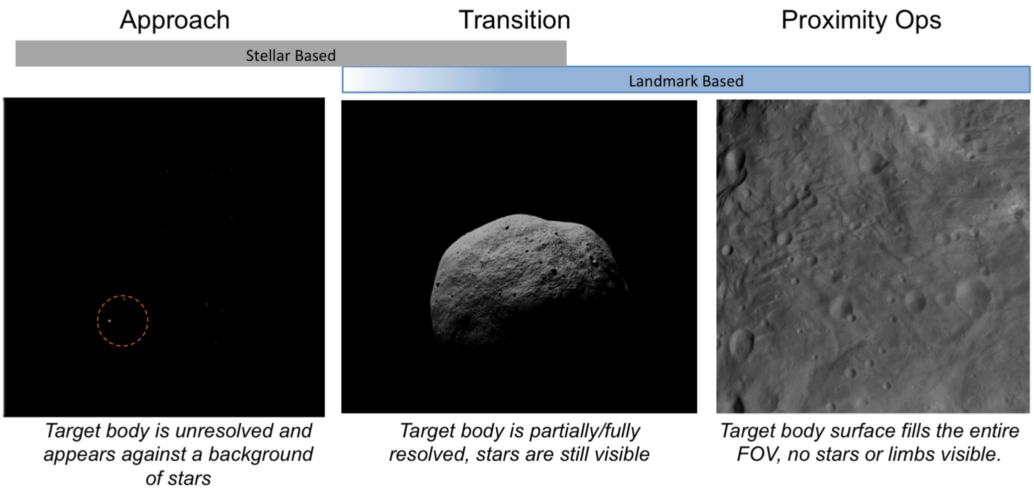


Figure 1: Transition from star-based to landmark navigation.

Table 1: OpNav Imager Optical and Radiometric Properties

	PolyCam (at ∞)	MapCam (PAN)	SamCam	NavCams 1 & 2
IFOV (μrad/px)	13.5	68	254	280
Detector size (px)	1024x1024	1024x1024	1024x1024	2592x1944
Aperture (mm)	175	38	4.3	2.28
Focal length (mm)	630	125	24	7.6
Pixel size (microns)	8.5x8.5	8.5x8.5	8.5x8.5	2.2x2.2

4 ORBIT DETERMINATION OVERVIEW

Orbit Determination (OD) is the process of estimating the spacecraft state (position and velocity) by minimizing in a least squares sense the residuals of tracking data observable and computed observables. The computed observables are based on a dynamical model of the spacecraft's equations of motion due to gravity, solar radiation pressure (SRP), maneuvers and momentum desaturation events (desats), and other small non-gravitational forces.

During flight operations, OD is geared towards the generation and delivery of certain data products used by the project. The OD team produces the following products throughout the mission:

- Trajectory Predicts for Maneuver Designs: Prior to a planned maneuver, an estimated trajectory and its uncertainty is predicted forward to the maneuver epoch in order to design the maneuver.
- Knowledge Updates: Prior to a planned mission phase, an estimated trajectory and its uncertainty is predicted forward for use in generating or updating the sequence aboard the spacecraft.
- Trajectory Reconstructions: At specific times, the data arc is terminated and used to provide an improved estimate of the trajectory and associated uncertainties at points interior to the data arc to assist in science data reduction.
- Maneuver Reconstructions: Data before and after a TCM are used to estimate maneuver parameters with the objective to improve their future designs.

- Tracking Prediction Updates: Trajectory updates given to the DSN for antenna pointing predictions and for proper up-link and down-link tracking of radio frequencies.

4.1 Filter Strategies

During early ProxOps the OD team will be processing and characterizing the center-finding OpNav measurements for the first time. Extending off of the current cruise OD strategy, there will be a baseline OD filter that every team member maintains. In addition to the baseline filter strategy, multiple other filtering setups will be maintained by a subset of the team in order to verify consistency between solutions. These non-baseline filter strategies will employ variations in the estimated parameters and associated uncertainties, different measurement weighting schemes, and a variety of measurement types and pairs. Each of these solutions will be compared to each other to determine consistency between their reconstructed and predicted states, variations in the non-dynamic bias parameters estimates, and contribution of consider covariance inflation to certain estimated parameters.[10]

Filter Estimated Parameters

- S/C epoch state
- SRP scale factor
- 3-axis 0.5 mm/sec Desats (3-day campaign)
- RA, DEC, DV Finite Burns
- 3-axis Stochastic acceleration (3e-12 km/s^2) to account for small forces (S/C IR, asteroid IR, albedo, SRP)

Consider Parameters

- Earth ephemeris errors
- DSN station locations (correlated cov, from 2016 survey)
- Media errors (Ionosphere Day, Night, Troposphere Wet, Dry)
- Polar motion, UT1 errors

X-Band Radiometric Tracking

- 2-way Doppler (weighted at 0.1 mm/sec)
- 2-way Range (weighted at 3 m)
- DDOR (weighted at 0.06 nanoseconds)

NavCam Centerfinding OpNavs

- Scheduled 8 images per day, 1 image every 2-3 hours

Radiometric data are typically weighted at the standard deviation of the noise level computed the residuals on a per-pass basis. The weights applied for the Center-Finding OpNavs is determined by

$$W = (W_{min}^2 + (C * d)^2)^{1/2} \tag{1}$$

where W_{min} is the minimum weight (1.0 pixel), C is the apparent diameter scale factor (1% of the diameter), and d is the apparent diameter of the asteroid in pixels. The apparent diameter of the asteroid in pixels can be computed by:

$$d = d_a/(r * iFOV) \tag{2}$$

where d_a is the diameter of the asteroid (nominally 512 m for Bennu), r is the range to the asteroid surface, and $iFOV$ is the angular resolution of the detector (rad/pix).

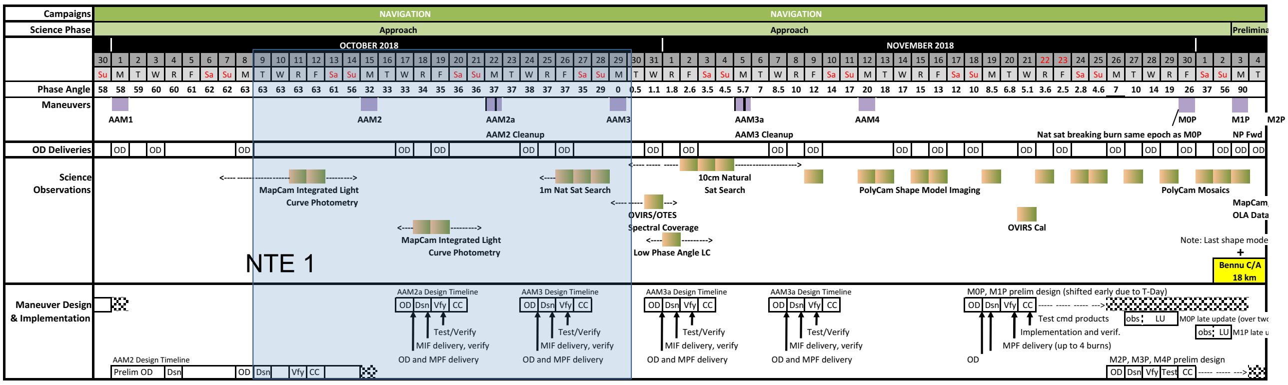


Figure 2: Approach Timeline.

5 APPROACH NAVIGATION AND TESTING

5.1 Phase Overview

The approach phase of the OSIRIS-REx mission begins in August of 2018 with the initial attempt to optically acquire Bennu at 60 days prior to rendezvous with the asteroid. The timeline in Figure 2 indicates the activities (maneuvers, science observations) occurring in the last two months before rendezvous with Bennu. This figure shows when OD solutions are delivered to design the approach maneuvers. The narrow-angle $0.8°$ field-of-view (FOV) PolyCam camera is used during this phase to acquire Bennu when the spacecraft is more than 2 million km out from Bennu. When the spacecraft reaches within 136 km, the $4°$ FOV MapCam is used to ensure the entire limb of the asteroid with background stars as faint as 4th magnitude can be imaged. Finally, at ranges of 20 km or less, center-finding OpNav images are shuttered with the wide 40° FOV NavCam. During this timeframe, DSN tracking passes are increased from three to seven 8-hr passes per week to near-continuous coverage while being augmented with two DDOR baselines per week. These early PolyCam images are used with the star-based OpNav technique and the DSN's radiometric tracking data to determine the spacecraft's state relative to Bennu and refine the ephemeris of Bennu.

The first two Asteroid Approach Maneuvers (AAM-1, AAM-2) slow the approach rate to approximately 5.2 m/s. At a distance of approximately 150 km from Bennu, the AAM-3 burn further slows the approach rate to 10 cm/s. In order to satisfy science observation requirements, the AAM-3 burn targets a specific range of solar longitude and latitude relative to Bennu in the Sun Anti-Momentum (SAM) frame described in Ref [11]. To meet these requirements after AAM-3, a statistical maneuver, AAM-2A, is needed to clean up execution errors from the relatively large 150 m/s AAM-2 maneuver. AAM-4 is used to perform final targeting to Bennu at 18.5 km to begin the Preliminary Survey. Finally, at encounter minus three days, the M0P, is a final contingency maneuver scheduled to retarget the trajectory to the M1P maneuver location if necessary which begins the next phase, Preliminary Survey. The AAM maneuver design-implementation-verify-approval-uplink cycles indicated in Figure 2 are seven days for the first two AAMs and five days for the subsequent approach burns. More details of this final asteroid approach sequence is described in Ref [11].

5.2 Test Framework

The FDS team created a detailed test (NTE-01) to exercise the team's ability to ingest star-based optical navigation with an unresolved and resolved object and incorporate this data with radiometric Range, Doppler, and DDOR. The test also exercised the maneuver design cycle for the Approach phase. The test spanned AAM-2 -1 day through AAM-2a +2 days and allowed for an AAM-2 and AAM-2a reconstruction as well as AAM-2a and AAM-3 maneuver design and verification activities. A perturbed truth spacecraft trajectory was simulated with AAM-2/AAM-2a maneuver execution errors, desaturation maneuvers, perturbed Bennu ephemeris, and errors in the SRP modeling and external accelerations. Range, Doppler, and DDOR data was simulated over the duration of the trajectory span with center-finding OpNav images on a daily basis per the current mission imaging plan.

The truth trajectory was formed from a random draw of spacecraft state, Bennu state, maneuver errors and key dynamic parameters using an OD covariance based on accumulation of data mapped the test epoch. Desaturation events with random errors on the order of 2 mm/s or less were scheduled every seven days up to AAM-3. Stochastic three-axis accelerations were also modeled every seven days with errors of 1-8 nm/s^2. The attitude profile modeled during this phase consisted of the nominal Sun-pointed (+X to Sun) orientation. Daily 5-hr HGA (+X) to Earth attitudes are included as well as the 20-min Bennu pointing attitude for OpNavs every 3 hours. Realistic images of Bennu and stars were simulated at these epochs by members of the FDS team at NASA's Goddard Space Flight Center using their high resolution Freespace image-rendering software. These OpNavs were simulated as long + short exposure pairs that we expect to acquire in operations. The long exposures are used to image background stars, while the short exposures are used to calculate the centroid of Bennu. Radiometric data and DDORs were also simulated assuming expected range of noise for these datatype.

5.3 Covariance Analysis

The approach maneuvers, AAM-1, AAM-2 are not targeted to the Bennu B-plane; AAM-1 is targeted to AAM-2's Cartesian coordinates relative to Bennu, and AAM-2 and AAM-2a are targeted to AAM-3's Cartesian coordinates. To monitor navigation performance during these maneuvers, the spacecraft state errors are mapped into a a RTN (radial, transverse, and normal) and VNC (velocity, normal, co-normal) frame instead of a B-plane. Since the relative v-infinity vector is constantly changing due to the approach maneuvers, the B-plane is not a consistent metric to use as a comparison between multiple approach maneuvers.

The 1-sigma spacecraft state errors without DDOR data are compared in the Bennu-relative RTN frame during the approach phase to Bennu (Sep–Nov, 2018) to a case without including the consider parameters in the filter in Figure 3. The no-DDOR case is compared to the baseline case with DDOR in Figure 3. The addition of DDOR measurements reduced the expected navigation uncertainties during Approach, however, the measurement has significant sensitivity to the uncertainties in the consider parameters, namely the Earth ephemeris, station locations, media and UT1. Figure 3 also compares the DDOR case without the consider parameters in the filter. The DDOR measurements are shown to improve the radial errors relative to Bennu. They also improve the Transverse, Normal errors during the last half of September to the first half of October 2018.

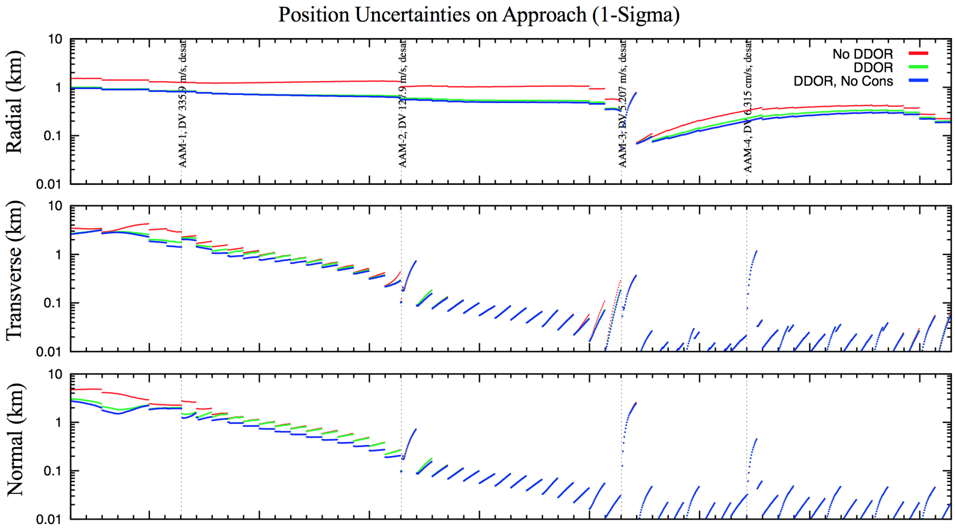


Figure 3: Approach current state RTN state uncertainties.

5.4 Test Results

The main objective of NTE-01 was to focus on the navigation challenges not yet tested in operations that were identified during the Approach mission phase. NTE-01 exercised routine OD, OpNav, and maneuver design cycles and associated internal FDS interfaces in tandem for the first time, as will be the case during the actual asteroid approach. The OD team delivered three official OD solutions during the test: OD001 (10/17/19 data cutoff (DCO)) was the initial reconstruction of AAM2 and was used for the final design of AAM-2A; OD002 (10/20/19 DCO) was used for a late update design of AAM-2a; and OD003 (10/24/19 DCO) was used for the reconstruction of AAM-2a and the final design of AAM-3.

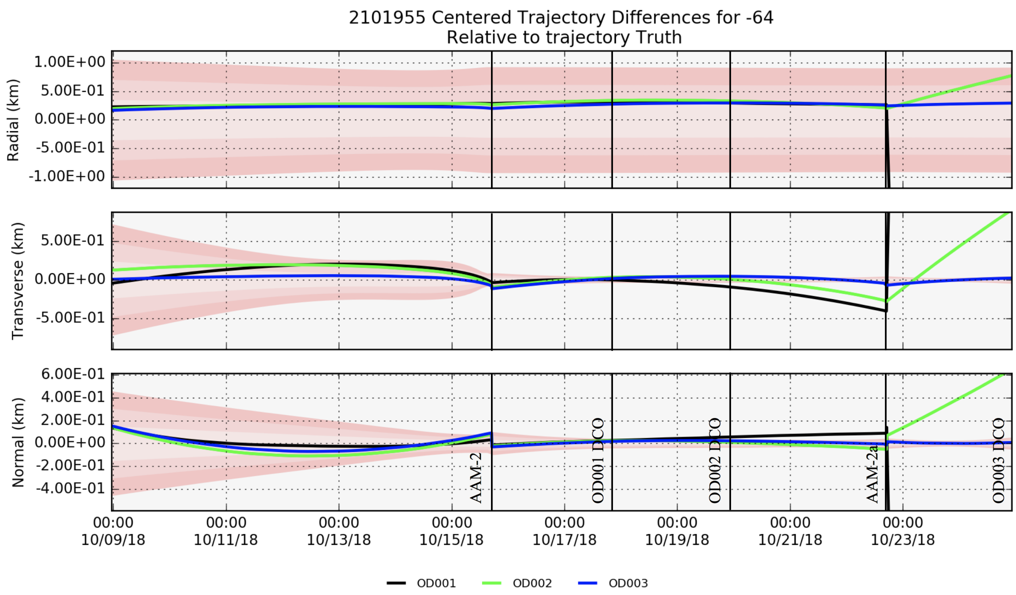


Figure 4: Approach reconstructed RTN state uncertainties for OREx.

Figure 4 shows the reconstructed OD solutions during the test timeframe with DCOs for each OD noted. The uncertainty bounds are 1-, 2-, and 3-sigma reconstructed smoothed uncertainties. OD001

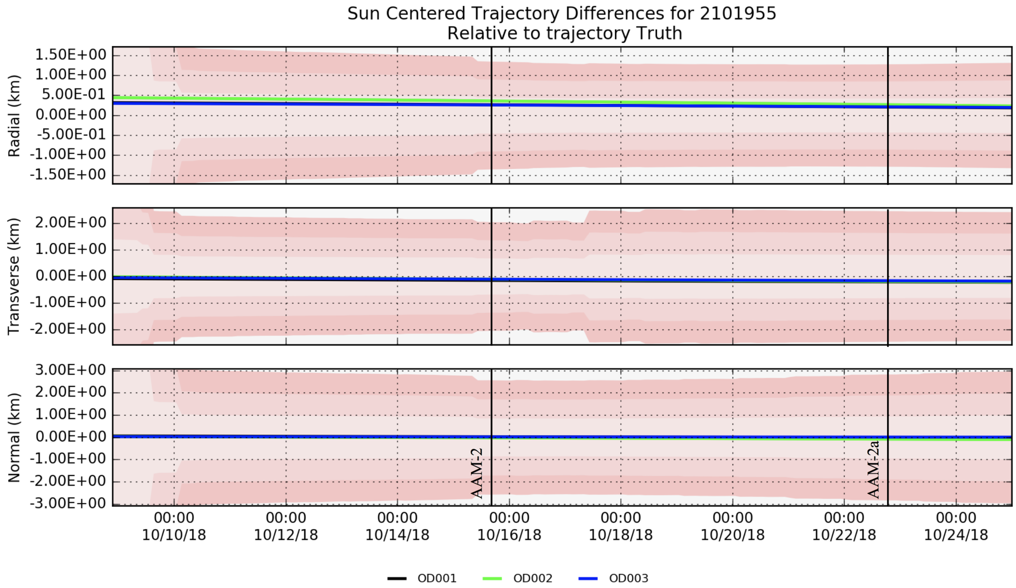


Figure 5: Approach current state RTN state uncertainties for Bennu's ephemeris.

and OD002 wander off after their respective DCOs due to improper predictions of small forces when compared to truth; these solutions also did not include the AAM-2a maneuver design, which is the reason they diverge after AAM-2a. Figure 5 gives the trajectory errors for Bennu relative to the Sun in the Bennu-Sun RTN frame with 1-, 2-, and 3-sigma current state uncertainties. During the Approach phase, the Bennu ephemeris had a radial bias when compared to the true trajectory. This radial bias can also been seen in Figure 4 for the S/C-Bennu RTN frame. The OpNav images on approach give strong information in the out-of-plane directions, however they do not provide any strong distance information when the spacecraft is considerably far away.

Table 2 compares the reconstruction of the AAM-2 and AAM-2A maneuvers (magnitude, direction) to the Truth. These comparisons use the post-fit uncertainties associated with the last OD solution delivered in the NTE-01 test (OD003) to determine the difference in terms of the number of standard deviations this solution lies from Truth. The reconstructed maneuver parameters for both burns are shown to be close to 1σ from the Truth.

Table 2: The reconstructed maneuvers of NTE-01 compared to Truth

Maneuver	Parameter	Truth	Reconstruct	Post-fit Uncertainty (1σ)	Difference of Truth/Postfit sigma
AAM-2	ΔV (m/s)	136.56717	136.56705	0.00008	1.3
	Right Ascension (deg)	83.8678	83.8687	0.0008	1.1
	Declination (deg)	7.4563	7.4560	0.0004	0.77
AAM-2A	ΔV (m/s)	0.6056	0.6049	0.0011	0.66
	Right Ascension (deg)	72.44	72.73	0.29	0.99
	Declination (deg)	54.18	54.22	0.17	0.21

6 ORBITAL-A NAVIGATION AND TESTING

6.1 Phase Overview

The initial characterization of Bennu originates from data obtained on Approach and through the Preliminary Survey hyperbolic flyby phases. Once the Preliminary Survey phase is completed with the final south-pole flyby, the spacecraft drifts away from the asteroid to a maximum distance of about 100 km. The timeline of maneuvers and OD deliveries supporting the preliminary and final (late update) maneuver designs which lead up to insertion into the initial 2.1 X 1.5 km orbit and final 1.5-km orbit of the Orbital-A phase is illustrated in Figure 6. With a maneuver ΔV magnitude of approximately 34 cm/s, the M1A burn stops the drift from Bennu and targets the M2A staging point. The M2A burn (7 cm/s) targets the location of the orbit insertion burn, M3A (14 cm/s), for the initial orbit near the terminator plane at approximately 2.1 km. The subsequent burn, M4A (0.8 cm/s), is used to circularize the orbit at 1.5 km. Finally, the M5A, burn is available to clean up the orbit. The ΔV values indicated above represent the maneuver magnitudes designed in the NTE-02 test described below.

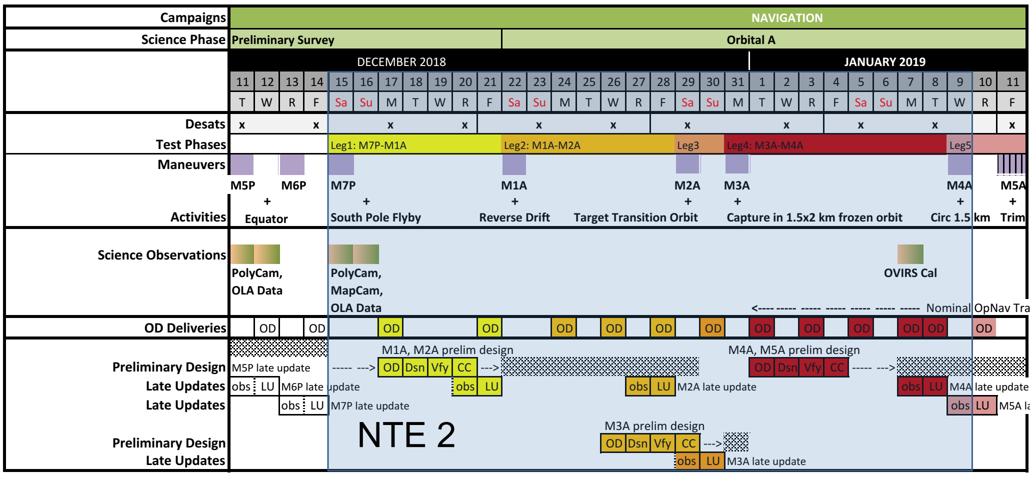


Figure 6: Orbital-A Insertion Timeline.

The major objective of the Orbital-A Phase is to allow the Navigation Team to transition from the star-based center-finding optical navigation to feature-based (landmark) navigation before the more demanding higher precision activities in subsequent mission phases. The initial transition work and qualification of landmarks will begin as early as the Preliminary Survey phase, however, the current baseline is to maintain the use of center-finding OpNavs during the Orbital-A insertion phase. To accomplish the transition to landmark navigation, the spacecraft will be placed into a roughly 1.5 to 2.0 km-radius terminator orbit for at least two weeks. The Navigation Team required that there would be no extra Project OD deliveries or responsibilities outside of navigation during this time to support Science Observations. The Team will maintain the OD solutions for late maneuver updates and periodic on-board ephemeris to keep the OpNav images centered on Bennu. The Science Team may use these solutions to design observations, but no special deliveries for these observations will be made.

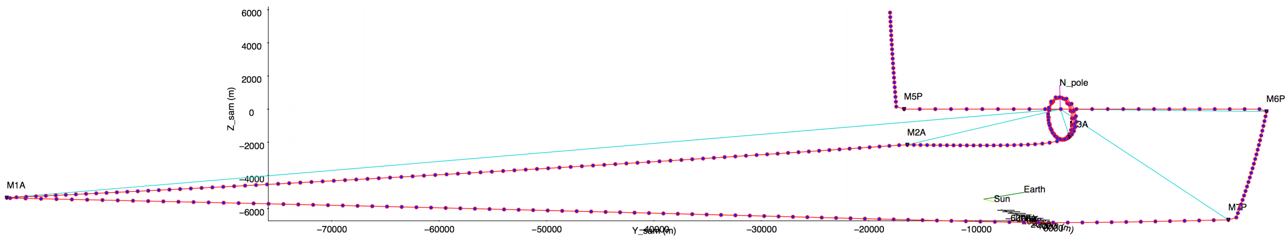


Figure 7: Orbital-A Trajectory as viewed from the Sun.

6.2 Test Framework

The second Navigation Test Exercise (NTE-02) was designed to test the FDS team's ability to insert into the first orbit around Bennu. The test was designed to span from the maneuver, M7P, that targets the last 7-km flyby (South Pole) of the Preliminary Survey phase through the drift away from the asteroid and return approach through Orbital-A insertion with maneuvers M1A through M4A. Similar to NTE-01, the Navigation Team used radiometric Range, Doppler, and DDOR as well as star-based optical navigation of Bennu as a resolved object. The long-short exposure OpNav pairs were increased from a set every three hours to every two hours after orbit insertion. Random 3-axis desat ΔV of 1 mm/s or less were sampled every three days during this phase. Stochastic 3-axis accelerations of 0.1-3 nm/s^2 were applied every seven days up to M3A, then these were applied every 35 hours (roughly half of orbital period). The attitude profile was similar to NTE-01, except the nominal attitude changed to Bennu Nadir point (+Z to Bennu, +X to Sun) once orbit was achieved.

Unlike previous tests, this exercise had simulated data that was responsive to the decisions made by the FDS team. Nominally, readiness tests are designed with a few members generating the true trajectories and maneuvers through an entire timeframe. NTE-02 began with a true trajectory created in a similar method described for NTE-01 and simulated data that spanned from the post Preliminary Survey state until the DCO for M1A. The OD team would generate their best estimate of the predicted trajectory for the maneuver team to design M1A. The design was fed back into the simulation and perturbed by the team simulating the data. A new set of data was generated for the true trajectory based on a perturbed M1A design through M2A. The process was then repeated for M2A through M5A producing a more realistic scenario than previous simulations. This simulation style was chosen in order to examine, in detail, the ability of the FDS team to insert into orbit around Bennu, one of the most critical periods of the mission.

6.3 Covariance Analysis

Significant uncertainty analyses have been conducted for each of the mission phases for OSIRIS-REx. While each mission phase has their own unique set of requirements and challenges, the Orbital-A phase is unique in that it is solely designed to insert into a stable orbit. The current design poses many challenges after the completion of Preliminary Survey. One of the most notable is the increased radial uncertainty as shown in Figure 8 after the spacecraft drifts away from the asteroid following M7P. After M1A when the spacecraft initiates its approach back to Bennu, the radial uncertainty still grows due to a lack in parallax between the OpNav images. It isn't until close approach and M3A (orbit insertion) when the radial uncertainty begins to drop. It was found that DDOR measurements can help reduce these errors significantly. Because the orbit insertion is a critical event, in addition to scheduling DDORs, the FDS Team is currently looking at trajectory options to help keep the state errors bounded during this time. Position uncertainties after orbit insertion are about 10 m as shown in Figure 8.

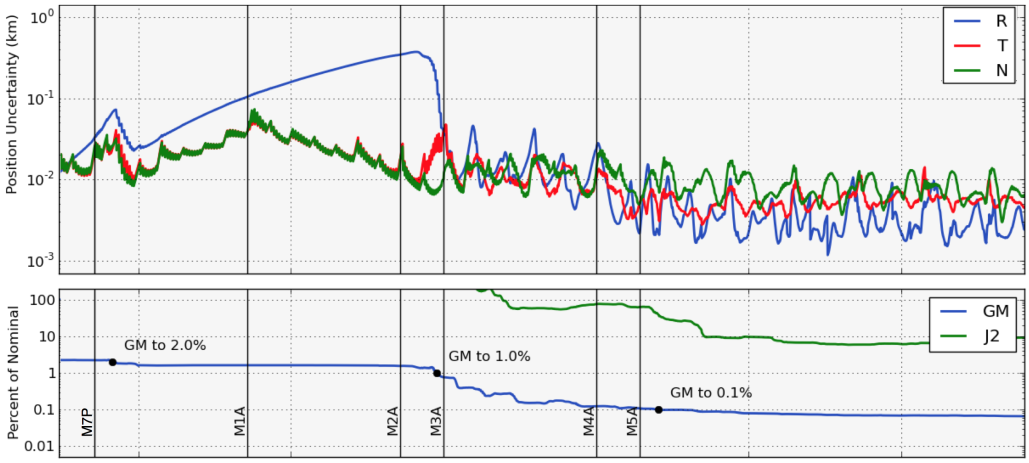


Figure 8: OD knowledge errors and expected improvement of Bennu's GM and J2. Shown are the 1-sigma errors and these errors as a percentage of nominal GM.

Figure 9 shows the 2-sigma OD knowledge and control errors of the M3A maneuver, which inserts the S/C into the initial orbit. These errors are expressed in the Radial-Transverse-Normal directions. Notice the "saw-tooth" steps in the radial and transverse components. This shows how the OpNav data improves the spacecraft state, while errors of the small non-gravitational forces of 3 nm/s^2 or less continue to degrade the state after each measurement.

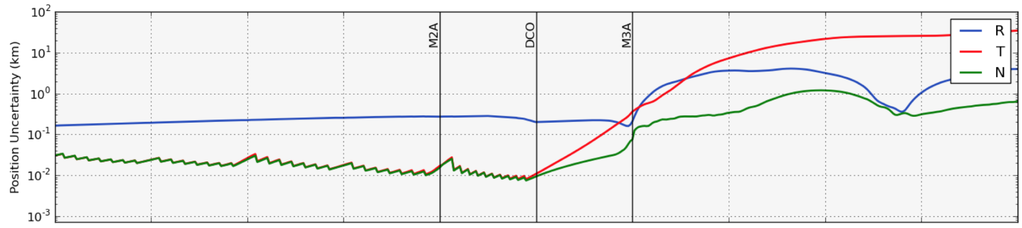


Figure 9: OD knowledge and predicted uncertainties for the M3A DCO.

6.4 Test Results

Figure 10 shows the postfit center-finding OpNav residuals from just after M7P through Orbital-A insertion. The growth in the residuals around 17-DEC-2018 are due to the closest approach flyby of the southern pole of Bennu on the last leg of the Preliminary Survey phase. The postfit residuals then reach a noise floor as the spacecraft range increases rapidly relative to Bennu. The growth in the residuals after 31-DEC-2018 are due to the range during Orbital-A insertion in which the spacecraft is < 2 km from the surface. Figure 10 also shows the postfit residuals normalized by the weighting scheme given by Eq. 1. This weighting scheme results in normalized standard deviation of the post-fit residuals of 0.3 sigma indicating that Eq. 1 is underweighting the center-finding OpNav residuals. Regardless, it may be prudent to de-weight the OpNavs due to possible systematic errors in their processing. For instance, it was found that there was a 0.7 pixel bias in the OpNav line observables, which may have been caused by the bright limb of the asteroid in the images.

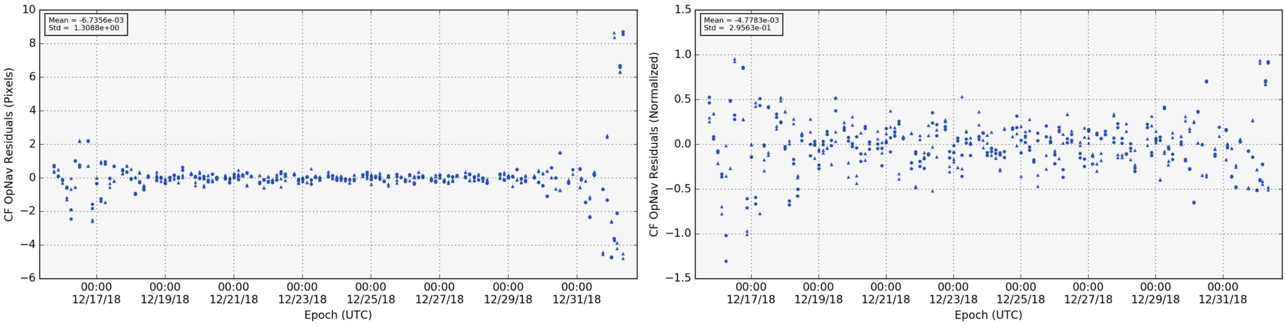


Figure 10: NTE-2 Orbital-A center-finding OpNav residuals: postfit (left) and normalized (right).

Figure 11 gives the reconstructed 1-sigma B-Plane estimates and uncertainties at the time of the orbital insertion maneuver M3A. The left diagram in this Figure shows the M2A target and the post-M2A OD (OD006, 12/30/18 16:00 DCO) relative to Bennu's diameter; the middle diagram shows the post-orbit insertion OD solutions compared to OD006, which was used to design M3A; finally, the right diagram shows the final reconstructed solution, OD012, with the 01/08/19 00:00 DCO to be approximately 1-sigma from the truth.

OD007 was the first post-M3A solution with approximately 1 day of OpNav after M3A (1/1/19 16:00 DCO). OD007b only included radiometric data after M3A. The OpNavs used in OD007 were suspect due to processing with the predicted trajectory after M3A, which was in error from the 2.6-σ over burn of M3A. The post-M3A radio-only solution (OD007b) was used to reprocess these OpNavs in OD008. This produced a better OD solution against the Truth as compared to OD007 in Figure 11. The M3A over burn resulted in an orbit that was more circular at first than the designed 2.2 X 1.6-km orbit. The desaturation events on Jan 3 and Jan 5 were on the order of 1 mm/s, thus perturbing the

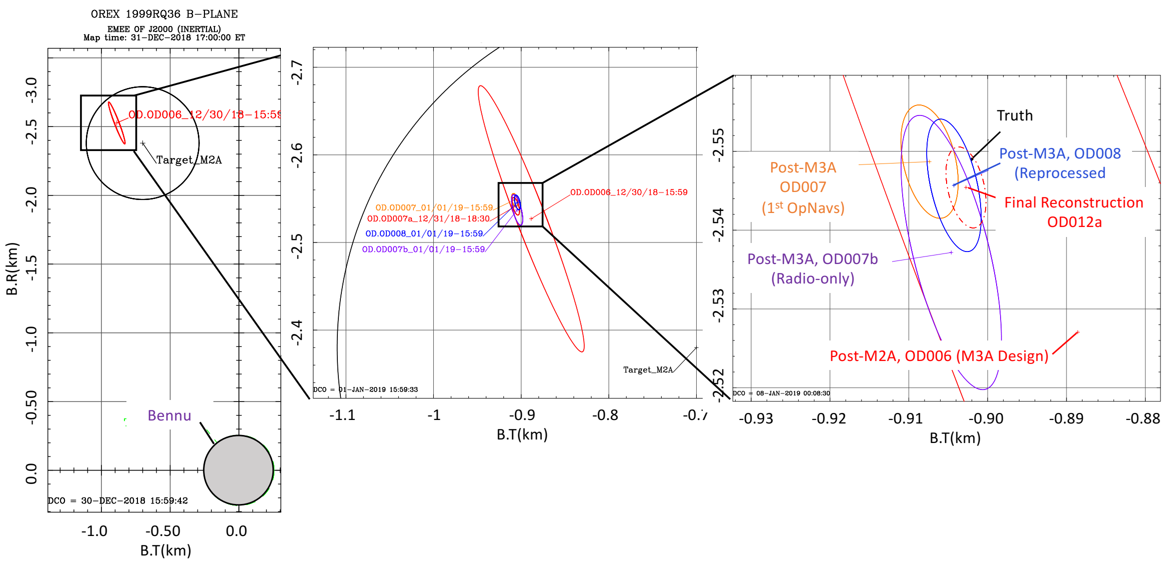


Figure 11: Orbital-A Insertion B-plane (EME-J2000) showing the M2A target, the late-update solution for M3A, OD006, initial post-M3A solutions, OD007-OD008 and final reconstruction OD012.

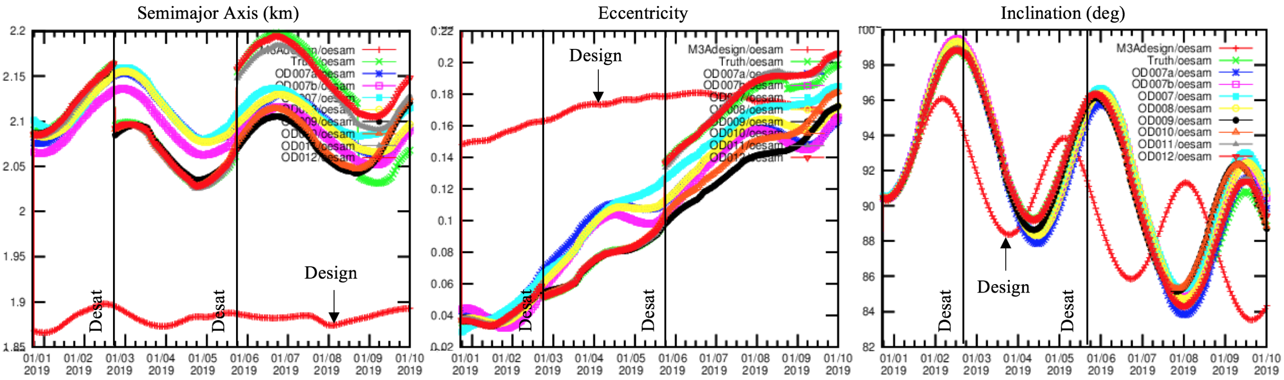


Figure 12: Comparison of Orbital-A post-insertion solutions for the orbit.

orbit as seen in Figure 12. The final reconstructed OD012 solution matched the Truth until the last desat on Jan 8 which was not in the data arc. Figure 13 shows the reconstructed portion of the trajectory prior to M3A and the smoothed uncertainties from OD012. All of the post orbit insertion OD deliveries were consistent in their reconstruction of the events prior to insertion to less than 1-sigma showing that the solutions only slightly varied based on the estimated desats.

Figure 14 compare the OD solution parameters: maneuver ΔV, Bennu GM, SRP scale factor and stochastic non-gravitational acceleration estimates to the Truth. The M1A ΔV estimates and the GM estimates showed good agreement to the Truth. M2A ΔV estimates were biased over 2-σ while the final M3A estimate was over 1-σ from the Truth. Once the spacecraft entered orbit, some of SRP scale factor estimates departed from the truth, but eventually came back with the last OD (OD012).

One of the largest contributing factors for the necessity of OD solutions every few days during the Orbital-A timeframe arise from the large predicted state uncertainties immediately after a DCO. Figure 15 gives the predicted uncertainties after several OD DCOs after orbit insertion in down-track

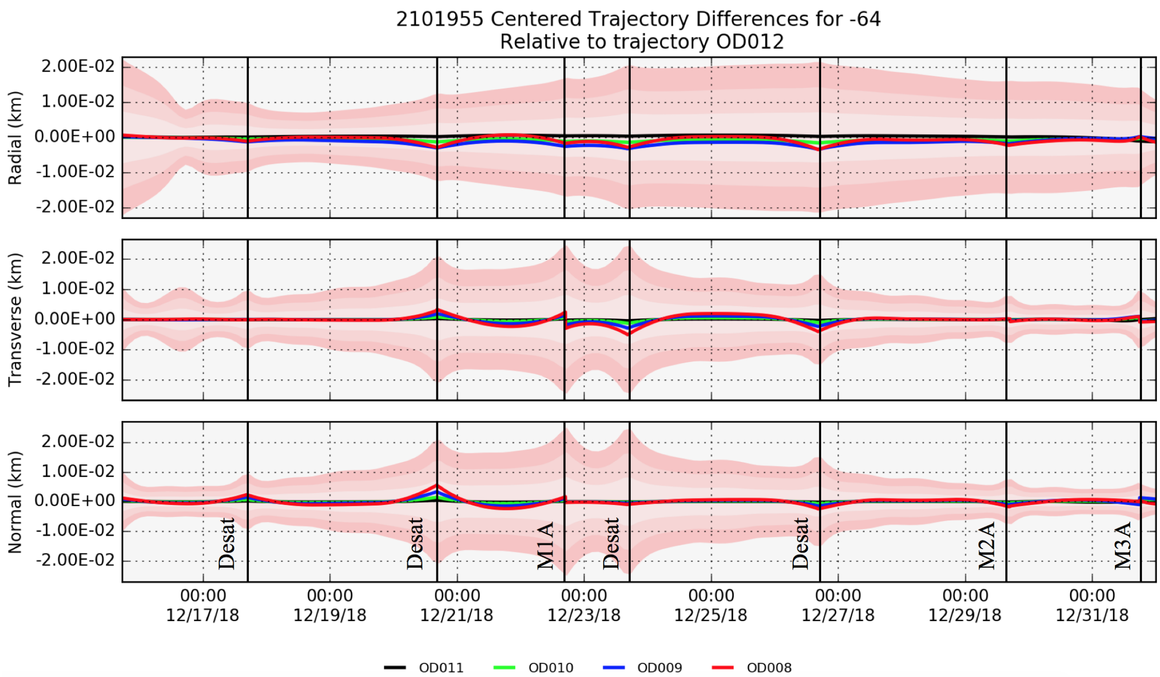
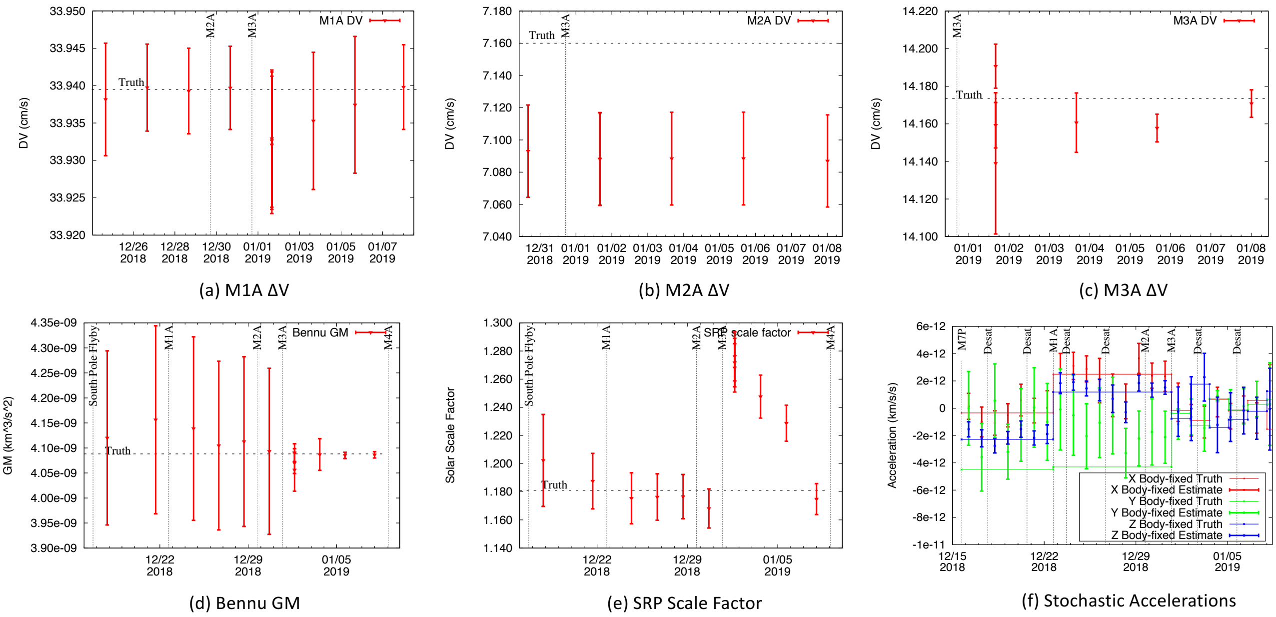


Figure 13: Reconstruction of Orbit A prior to Insertion at M3A.



(a) M1A ΔV
(b) M2A ΔV
(c) M3A ΔV
(d) Bennu GM
(e) SRP Scale Factor
(f) Stochastic Accelerations

Figure 14: Parameter estimates compared to Truth: a) M1A ΔV, b) M2A ΔV, c) M3A ΔV, d) Bennu GM, e) SRP scale factor and f) Stochastic accelerations.

timing and true-anomaly. The main contributors to the uncertainty growth are desats and stochastic acceleration uncertainties. True anomaly uncertainties can reach 180 degrees within a few days of the DCO resulting in the image plan to not have Bennu in the center of the FOV and inducing a ranging issue in the OpNav process as previously described.

In order to accurately assess the Bennu ephemeris estimation in JPL's SETIII parameters [12], a variance-covariance and correlation corner plot was created to express the amount of shift in the estimates from solution to solution. While Figure 5 provides an immediate view of the corrections applied to the Bennu-Sun RTN frame, the initial covariance provided by JPL with its correlations are provided in the SETIII parameter space. In order to determine the amount and direction of the shift and understand the correlation between parameters throughout Orbital-A, Figure 16 was created for several post insertion OD deliveries. The *a priori* covariance has large correlations in several parameters. As extra tracking data is processed, the correlations begin to shift and decrease. OD012 significantly reduces the uncertainty in the parameters DMW, DE, and EDW (see Reference [12] for

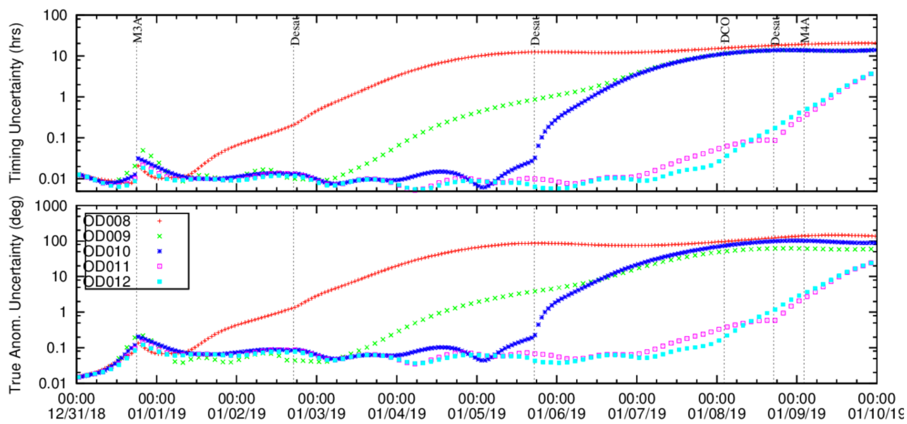


Figure 15: Timing and True Anomaly uncertainties predicted out post-M3A orbit insertion.

a detailed explanation of the parameters). Figure 16 shows that the estimated parameters generally shifted << 1-sigma and that there were no unreasonable shifts within the *a priori* uncertainty.

7 CONCLUSION

These tests illustrated how easily small forces and small maneuvers can change the trajectory of the spacecraft in close proximity to the asteroid. A ΔV of 1 mm/s or less imparted from the thruster imbalance during a desat can possibly change the orbit semi-major axis by 100 m and shift periapsis location by 6 hrs. The NTE-2 test focused on Bennu having a significantly lower GM than the nominal value used in most of the FDS analyses. The lower GM caused unique challenges to our small-body orbit insertion operation concept. This scenario helped the Team to better understand how to adapt to the expected range of GMs that we may encounter.

The NTE exercises provided the Team with valuable experience. The tests, especially the NTE2,

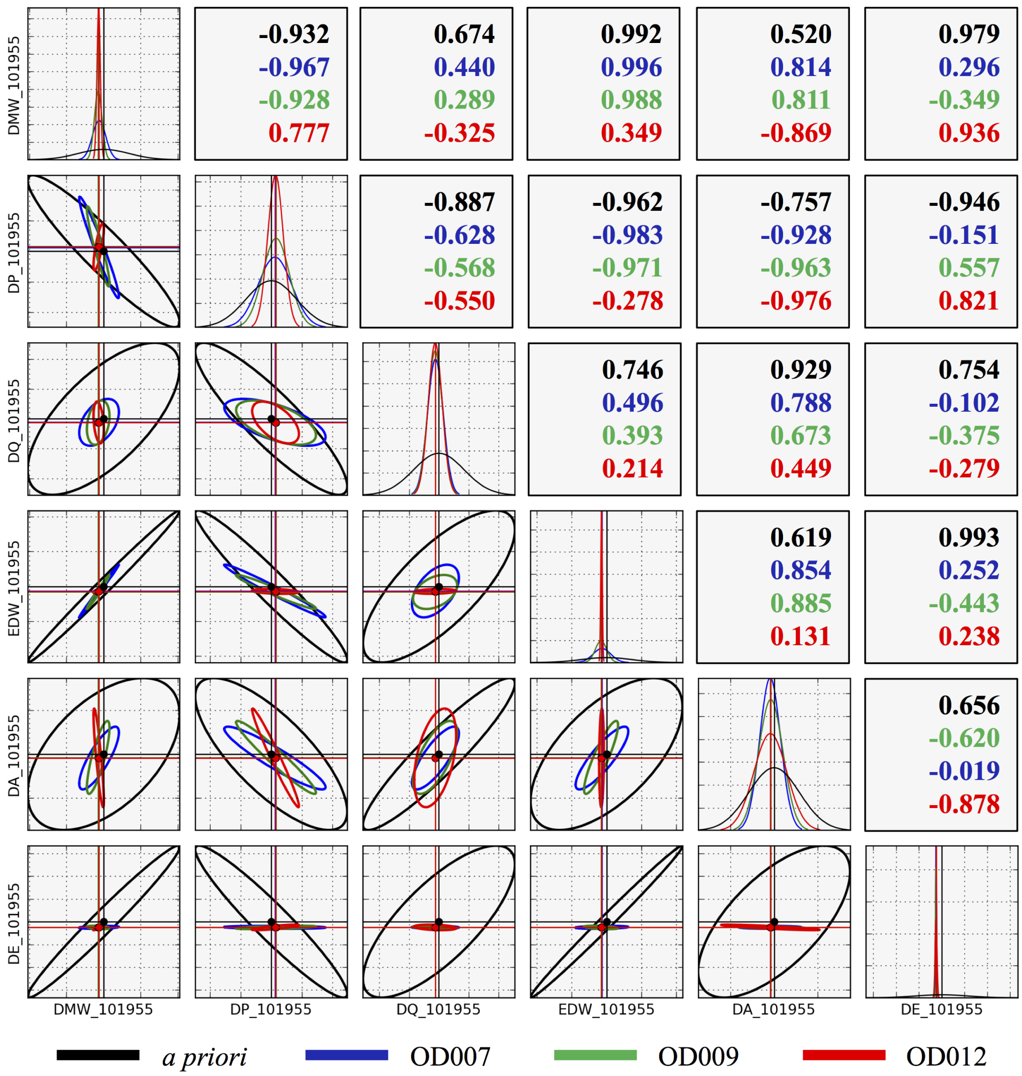


Figure 16: Bennu SETIII Parameter Estimates and 3-sigma Covariance with the correlation coefficients in the upper diagonal.

emphasized critical situations and decision making with respect to the orbit insertion about a small body. Several lessons learned were gained from these tests. The FDS Team will apply these in the coming months to update procedures and further refine the concept of operations with the Flight Team during these phases. These lessons will be used to develop the Project OPIE and ORT tests.

8 ACKNOWLEDGMENTS

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