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OSIRIS-REx Touch-And-Go (TAG) Navigation Performance

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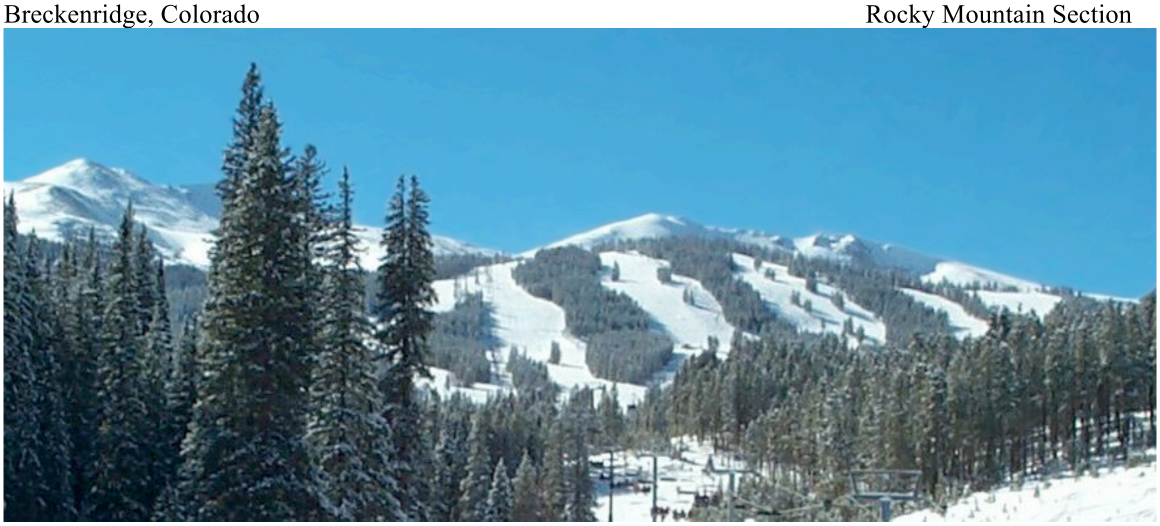

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OSIRIS-REX TOUCH-AND-GO (TAG) NAVIGATION PERFORMANCE

Kevin Berry,* Peter Antreasian,† Michael C. Moreau,‡ Alex May,§ Brian Sutter¶

The Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) mission is a NASA New Frontiers mission launching in 2016 to rendezvous with the near-Earth asteroid (101955) Bennu in late 2018. Following an extensive campaign of proximity operations activities to characterize the properties of Bennu and select a suitable sample site, OSIRIS-REx will fly a Touch-And-Go (TAG) trajectory to the asteroid's surface to obtain a regolith sample. The paper summarizes the mission design of the TAG sequence, the propulsive maneuvers required to achieve the trajectory, and the sequence of events leading up to the TAG event. The paper also summarizes the Monte-Carlo simulation of the TAG sequence and presents analysis results that demonstrate the ability to conduct the TAG within 25 meters of the selected sample site and ± 2 cm/s of the targeted contact velocity. The paper describes some of the challenges associated with conducting precision navigation operations and ultimately contacting a very small asteroid.

INTRODUCTION

Origins Spectral Interpretation Resource Identification Security Regolith Explorer (OSIRIS-REx) is the third mission selected as part of NASA's New Frontiers Program. OSIRIS-REx will travel to a near-Earth carbonaceous asteroid (101955) Bennu, study it in detail, and return to Earth with a regolith sample. This sample will provide insight into the initial states of planet formation and the origin of life. The data collected at the asteroid will also improve our understanding of asteroids that can impact Earth.[1,2]

Upon arriving at the asteroid, the spacecraft will spend five months in various orbits collecting surface images, Laser Imaging Detection and Ranging (LIDAR) data, and radiometric tracking data. The various data sets will be used to develop a detailed topographic surface map, a spin state model, and a gravity model, all of which will be used to select four candidate sampling sites on the asteroid's surface. The spacecraft will then spend three months conducting reconnaissance of the candidate sample sites at lower altitudes. The various maps and models will be refined for the regions surrounding the candidate sites, and the single best site will be selected for sampling.

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The sample will be obtained during the TAG (Touch-And-Go) sequence, a series of maneuvers designed to approach Bennu and "tag" the surface with the sample collection mechanism. The sample collection will be performed after a series of incremental TAG rehearsals are completed during a six week period leading up to the actual TAG. Three TAG attempts have been accounted for in the schedule and propellant budget in case the first attempt is deemed unsuccessful. Figure 1 is an illustration of the OSIRIS-REx spacecraft with the sample-arm deployed.

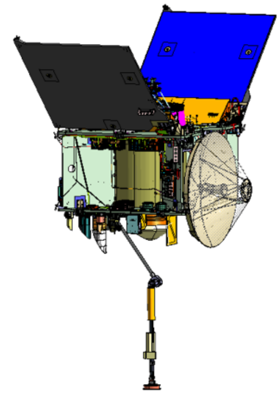

Figure 1. OSIRIS-REx

Designing and implementing a TAG trajectory sequence to bring the spacecraft down to the surface of asteroid Bennu accurately and safely for successful regolith sample collection will be one of the most challenging tasks of the OSIRIS-REx mission. After preliminary analysis demonstrated that TAG requirements could not be met by simply applying pre-computed maneuvers based on nominal state information, the OSIRIS-REx Flight Dynamics Team developed a simple, yet elegant, closed-loop on-board guidance scheme that utilizes a two-dimensional polynomial relationship between the Cartesian spacecraft state (position and velocity) predictions and LIDAR measurements. The array of coefficients for this polynomial representation can be calibrated in a straightforward fashion and uploaded to the spacecraft, and the simple linear maneuver correction calculations based on the polynomial model are easily performed and applied on-board in real-time. This technique requires only a limited amount of spacecraft autonomy but allows all requirements to be met. This paper describes the tools created to design the TAG trajectories and presents results of analysis of TAG performance for a range of possible TAG sites given the best current understanding of Bennu characteristics.

DESCRIPTION OF THE TAG SEQUENCE AND TIMELINE

The overall timeline leading up to the TAG event is summarized in Table 1. The TAG sequence consists of a burn to depart orbit, two burns to target the TAG site and TAG velocity, the actual TAG event, followed by the back-away burn. The TAG sequence targeting methodology is detailed in the 2013 paper by Berry et al.[3] The spacecraft will begin the TAG sequence in the "Safe Home Orbit," which is a circular solar terminator plane orbit with a radius of 1 km. The orbit departure latitude is chosen to be the negative of the TAG site latitude. When the spacecraft crosses the orbit departure latitude on the morning side of the asteroid, the de-orbit burn (referred to as the Orbit Departure Maneuver (ODM)) will be performed with the goal of arriving at the 125 m altitude Checkpoint position four hours later. The trajectory sequence following the ODM is depicted in Figure 2.

At 24 hours before executing the TAG sequence, the last OpNav image used to design ODM and TAG parameters will be shuttered and subsequently downloaded. The ODM will be a turn-burn-turn maneuver, meaning that the spacecraft will slew to point the main thrusters in the burn direction, fire the thrusters, then slew back. Before and after the de-orbit burn, the spacecraft attitude is set to point the solar arrays at the sun. One hour after de-orbit, the spacecraft will slew into the inertially fixed OpNav attitude where it will collect images of the asteroid surface to be used by the navigation team for trajectory reconstruction following TAG.

At 85 minutes prior to TAG, the spacecraft will slew into the inertially fixed "Look-Ahead" attitude, which is defined by taking the TAG attitude and rotating it by 30 degrees about the negative orbit normal vector. This attitude points the LIDAR closer to nadir, or further forward than the TAG

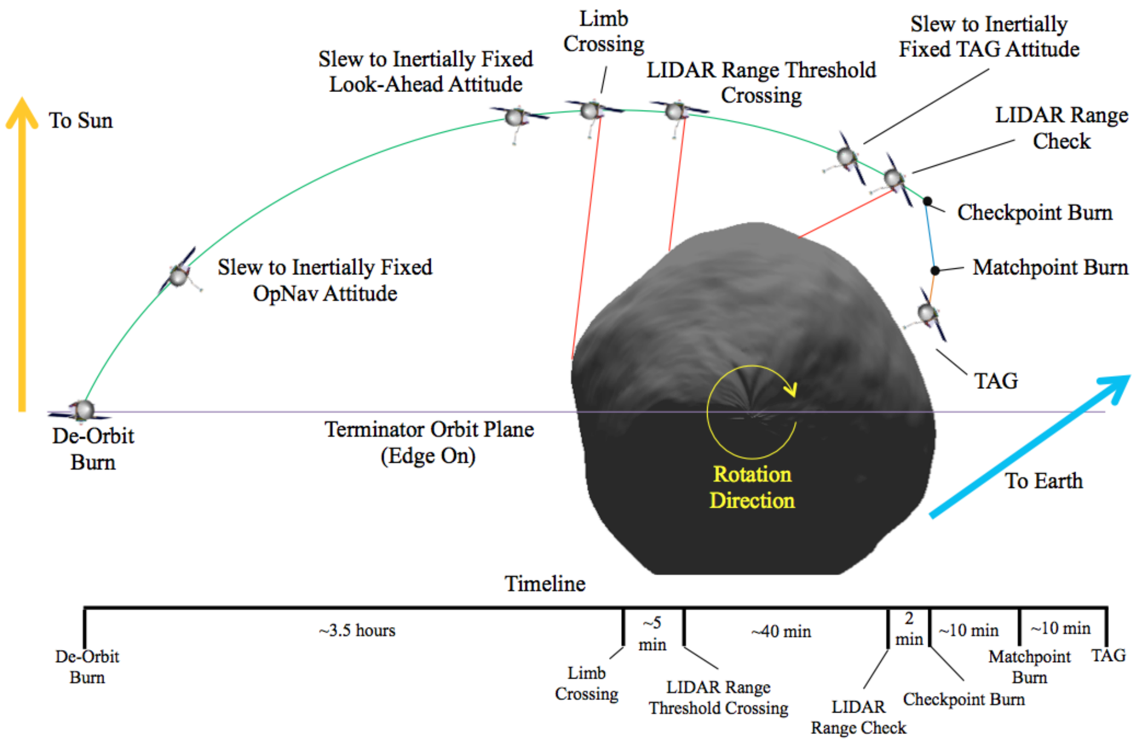

Figure 2. TAG Trajectory Sequence Following the De-Orbit Maneuver

attitude, hence the name "Look-Ahead," to get earlier range measurements from the surface. The LIDAR will be powered on when it is still pointed off into space and will begin receiving measurements when the beam crosses the limb of the asteroid. The nominal trajectory is used to define a nominal LIDAR Range Threshold based on an optimal incidence angle with the surface, and the spacecraft records the time that the LIDAR Range Threshold is actually crossed. Differencing the actual threshold crossing time with the nominal gives a measurement of in-track trajectory errors; this is one of two measurements subsequently used in the guidance algorithm.[3]

At 31 minutes prior to TAG, the spacecraft will slew into the inertially fixed TAG attitude. The TAG attitude is determined by calculating the average surface normal vector of the TAG site in the inertial frame at the nominal TAG time and aligning the Touch-And-Go Sample Acquisition Mechanism (TAGSAM) arm with that normal vector while pointing the high gain antenna as close to Earth as possible. This attitude is maintained for the remainder of the TAG sequence.

A couple of minutes before the nominal Checkpoint time, another LIDAR range measurement is recorded. This "LIDAR Range Check" value is differenced with the nominal to give a measurement of the radial trajectory errors for the guidance algorithm, which is then used to predict the actual Checkpoint state and update the remaining burns.

When the Checkpoint position is reached, the Checkpoint maneuver will be performed to cancel out the majority of the surface-relative lateral velocity and begin descending towards the surface. The Checkpoint maneuver is a set of three burns in the body frame occurring sequentially. This maneuver mode allows the spacecraft to maintain its inertially-fixed attitude.

After ten minutes, the spacecraft will reach the Matchpoint at an altitude of 55 m. The Matchpoint maneuver reduces the rate of descent sufficiently to achieve a vertical velocity of 10 cm/s at TAG. Note that the Checkpoint and Matchpoint maneuvers are targeted together to achieve the ideal TAG conditions. TAG occurs approximately 10 minutes after the Matchpoint maneuver.

Measurements made during the approach to the surface and used to reconstruct the TAG trajectory include images of the surface recorded by optical navigation cameras, measurements of range to the surface recorded by a LIDAR, and radiometric Doppler tracking data. Measurements from the LIDAR are also used to update the onboard estimate of spacecraft position prior to Checkpoint and for onboard corridor monitoring after Checkpoint.[3]

Table 1. Timeline Leading up to TAG

Time	Activity
TAG-21 days	Safe Home Orbit insertion maneuver, subsequent orbit trim burns
TAG-10 days	Spacecraft performs final reaction wheel desat maneuver prior to sample collection
TAG-5 days	Preliminary design of TAG trajectory, phasing maneuver design
TAG-4 days	Orbit phasing maneuver to setup ODM conditions
TAG-29 hours	Data cutoff (time of last OpNav) for final ODM design and TAG parameters
TAG-6 hours	Final parameter upload
TAG-270 minutes (4.5 hrs)	Orbit Departure Maneuver
TAG-228 minutes	Slew to Sun-point w/Comm attitude
TAG-180 minutes	Slew to OpNav imaging attitude
T-85 minutes	Slew to TAG look-ahead attitude
T-60$\pm$20 minutes	LIDAR Range Threshold time measurement
T-31 minutes	Slew to TAG attitude
T-22 minutes	LIDAR Range measurement and Guided TAG update
T-20 minutes	Checkpoint maneuver
T-10 minutes	Matchpoint maneuver

DRIVING REQUIREMENTS ON TAG

The TAG performance requirements allocated to the Flight Dynamics System are described in the following paragraphs.

TAG Position Error $\leq$ 25 m

The Flight Dynamics System has a requirement to deliver the spacecraft to within 25 m of a given TAG site with a Confidence Interval (CI) of 98.3%, which is approximately 2.85σ for a two-dimensional Gaussian distribution. The 98.3% CI is an allocation of the overall mission-level requirement on the probability of successfully acquiring a sample of at least 60 grams with a single TAG attempt.

Horizontal Velocity Error $\leq$ 2 cm/s

The spacecraft has a maximum tip-over angle of 45°, which if exceeded could cause the spacecraft to land on its side on the asteroid's surface. If the TAG site has a high surface friction, a high horizontal velocity during TAG can result in excessive tipping. The maximum horizontal velocity was chosen to be 2 cm/s to meet the maximum tip-over requirement with margin.

To prevent the spacecraft from tipping over during TAG, the attitude control system will be actively controlling the spacecraft attitude with reaction wheels. If the attitude rates exceed the capability of the wheels, thrusters will be engaged to provide the necessary control authority to protect the spacecraft.

Vertical Velocity 10±2 cm/s

Another potential cause of excessive tipping is if the spacecraft experiences high vertical velocity combined with a high TAG angle. The maximum vertical velocity has been set to 12 cm/s to meet the tip-over requirement. The vertical velocity must be greater than 8 cm/s to provide sufficient contact time between the TAGSAM head and the asteroid surface for sample collection. Combining the minimum and maximum allowable vertical velocity, TAG is targeted to occur with 10 cm/s of vertical velocity and is required to have no more than ±2 cm/s of vertical velocity error.

Trajectory Timing-Based Attitude Error ≤ 4.4°

As described previously, the inertially-fixed spacecraft attitude at TAG will be selected to align with the normal vector at the TAG site, at the time of TAG. Since Bennu is rotating, deviations in the time of TAG due to trajectory dispersions will result in an angular offset between the surface normal and the spacecraft TAG attitude. The TAGSAM head is hinged to allow up to 15° of tilt during TAG. If this angle is exceeded, the TAGSAM head will not be able to lay flat on the surface and the sample acquisition may be unsuccessful. In order to avoid exceeding this 15° limit, 14° have been allocated to local surface variations within 25 m of the TAG site, 3° have been allocated to spacecraft attitude control errors, and 4.4° have been allocated to trajectory timing-based attitude errors. The Root-Sum-Square (RSS) of the allocated angles is 14.98°.

MONTE CARLO ANALYSIS AND TAG SIMULATION

A thorough Monte Carlo analysis is required to verify the ability of the TAG methodology to meet requirements. Multiple Monte Carlo simulation cases are performed to span the range of uncertainty in Bennu physical characteristics and possible TAG sites. The simulation is designed to first determine the unique sequence of nominal orbit departure, Checkpoint, and Matchpoint maneuvers to deliver the spacecraft to the selected TAG site. Then, a Monte Carlo analysis is performed to understand the expected trajectory dispersions associated with this case. The Trajectory design and targeting in this analysis is performed with STK (Systems Tool Kit) by Analytical Graphics, Inc. MATLAB (by MathWorks, Inc.) is used to drive the Monte Carlo analysis by automating the inputs to the STK scenario and applying the various perturbations to the nominal trajectory.

Modeling assumptions for the TAG Monte Carlo simulation are summarized in Table 2. TAG sites corresponding to three different latitudes are simulated: at the equator, $-45°$, and $75°$ latitude. The asteroid spin axis is set to 180° away from the ecliptic normal, which is the best estimate provided by radio astronomers. The nominal asteroid gravitational parameter (GM) value is 5.2 m^3/s^2, but current uncertainty in the estimates of asteroid density and size yield bounding GM values of 3.4 m^3/s^2 "low" and 7.0 m^3/s^2 "high." Uncertainty in the rotation state of Bennu is modeled assuming a 0.2° 3σ offset in right ascension and declination, and a 0.1 sec/rev 3σ offset in the Bennu rotation rate.

The asteroid surface is modeled using the 2012 radar shape model from Nolan et al.[4] The resolution of the shape model is 25 m (i.e. 25 m between facets), and the uncertainty in body radius is approximately 10 m at the equator and 50 m at the poles.[5,6] Range measurements from the LIDAR are simulated by determining the intersection of the LIDAR bore site with the modeled Bennu shape, accounting for spacecraft pointing errors, with additional variations applied to account for small-scale surface features. Surface variations from the mean Bennu shape are modeled for two different assumed surfaces: 3.3 m 3σ for expected Bennu roughness and 7.8 m 3σ for a worst-case roughness based on asteroid 25143 Itokawa (1998 SF_{36}).[3]

The simulation also includes navigation uncertainties associated with the spacecraft state at the time of the orbit departure maneuver and maneuver execution errors associated with the orbit departure, Checkpoint, and Matchpoint burns. Each maneuver will be performed with the ACS thrusters and will impart a change in velocity ($\Delta\vec{v}$) between 1 cm/s and 20 cm/s in magnitude. The small magnitudes of these maneuvers drive the proportional errors to be larger than typical maneuver execution errors. The 3σ maneuver execution errors modeled for turn-burn-turn and vector burns are specified separately in Table 2.

Table 2. Summary of Models and Errors in TAG Simulation

Parameter	Current Model or Uncertainty (3σ)
Initial state errors	42-84 m in-track (see next section)
Maneuver execution errors:	
ACS turn-burn-turn (Orbit Departure)	Magnitude Error: RSS of 0.3 mm/s with 1.5% of $\Delta\vec{v}$ magnitude
	Transverse Error: 0.3 mm/s + 2.5% of total $\Delta\vec{v}$ magnitude
Vector burn (CP and MP):	
$\pm X$ and $\pm Y$ spacecraft body directions:	Magnitude Error: RSS of 1.5 mm/s with 5% of $\Delta\vec{v}$ magnitude
	Transverse Error: 1.5 mm/s + 10% of total $\Delta\vec{v}$ magnitude
$\pm Z$ spacecraft body directions:	Magnitude Error: RSS of 1.5 mm/s with 5% of $\Delta\vec{v}$ magnitude
	Transverse Error: 1.5 mm/s + 2.5% of total $\Delta\vec{v}$ magnitude
GM	3.4, 5.2, 7.0 m^3/s^2
Shape model	2012 Nolan Model
Surface variation errors	3.3 m for Bennu
	7.8 m for Itokawa
LIDAR measurement errors	noise: 10 cm + 1% of range
	bias: 10 cm + 1% of range
LIDAR pointing errors	13.2 mrad per axis
GM error	0.15%
Spherical Harmonic Coefficient error	30% on each value independently
SRP error	10%
Bennu spin rate error	0.1 sec/rev beginning at OD cutoff
Bennu spin axis error	0.2 deg in Right Ascension and Declination independently
S/C wet mass	1182 kg

NAVIGATION UNCERTAINTY

Initial orbit uncertainty for the Monte Carlo analyses is provided through an Orbit Determination (OD) covariance analysis. Simulated radiometric range and Doppler measurements are combined with simulated optical navigation based on asteroid surface landmark tracking to generate state covariance information for each of the aforementioned three GM values. Included error sources are measurement noise, ground station location knowledge errors, optical navigation pointing uncertainty, maneuver execution errors from previous burns, asteroid ephemeris errors, and errors in force modeling for asteroid gravity and solar radiation pressure (SRP). This section describes the assumptions behind the navigation uncertainties used in the TAG Monte Carlo analysis and presents sensitivity to the potential range of Bennu GM values. A more complete discussion of the full range of OD analyses will be provided in an upcoming paper.

The challenge for performing the TAG event is to determine the spacecraft state given the available optical and radiometric data and accurately predict the state relative to Bennu at the time of the ODM one day later. A requirement is levied on Flight Dynamics that 24-hour predictions of the spacecraft state shall have in-track position errors less than 85 m 3σ. The relatively short 24-hour time span from the data cutoff (DCO) to ODM execution is necessary to perform the OD, determine ODM and TAG parameters, sequence, test, verify, review and uplink before the ODM and TAG sequence execution. In order to determine the pre-ODM spacecraft state within the requirements, all the forces affecting the spacecraft's motion must be well calibrated. Of particular importance is the calibration of small non-gravitational forces (< 100 nm/s^2) such as SRP, Bennu albedo and Infrared (IR) radiation pressure and the force imparted from the thermal energy imbalance across each axis of the spacecraft bus and solar arrays. Detailed finite-difference thermal models of the spacecraft in Orbital-B have been provided by the Spacecraft Team at Lockheed-Martin to determine the magnitudes and directions of this force by summing the thermal energy being emitted from each exterior surface along the orbit. This force can be as large as 20% of SRP and is expected from the covariance analysis to be calibrated to less than 8% of SRP (<3 nm/s^2) at the time of TAG in October 2019.

The navigation strategy for performing the TAG sequence is to establish a quiescent orbital attitude and momentum management plan beginning ten days prior to ODM. This quiescent attitude would allow better determination of the non-gravitational forces. Once the day of TAG is known, the safe-home orbit conditions begin ten days beforehand by performing the last momentum desaturation maneuver before TAG. The spacecraft's orientation is placed into the "nadir-point" attitude, which consists of pointing the spacecraft's Z-axis (instrument deck) to nadir and X-axis to the Sun. No desats or slews for science observations are allowed during this ten-day period. A Phasing maneuver to place the spacecraft at the desired orbital latitude for ODM is scheduled to execute four days before ODM. The nominal attitude plan also includes pointing the High Gain Antenna (HGA) (X-axis) towards the Earth to downlink OpNavs and spacecraft telemetry while keeping the Sun in the spacecraft X-Z plane once per day for approximately five hours. The nadir-pointing, wide-field-of-view NavCam will shutter OpNavs every two hours except during the HGA passes. Each OpNav image is assumed to contain as many as 40 landmarks. Note the Low Gain Antenna (LGA) is also used to support the two-way Doppler tracking during the nadir-pointing attitude when the LGA geometry relative to Earth is favorable. The radiometric tracking schedule during this time assumes daily eight-hour passes of two-way X-band Doppler and five hours of ranging.

The data arc for determining the state at the time of the ODM begins four days prior to the ODM. The arc was assumed to be established after the Phasing maneuver and extends to the last OpNav image shuttered 24 hours before ODM executes. In addition to the spacecraft's state at epoch, the OD filter includes the estimation of the spacecraft solar pressure scale factor, Bennu's GM, 4x4 spherical harmonics, pole direction, rotation rate and ephemeris. A white-noise three-axis stochastic acceleration model is estimated to account for un-modeled non-gravitational forces described above. The process noise for this model is set to 3 nm/s^2 along each spacecraft axis. Since the orbital period for the nominal GM is nearly 24 hours, this stochastic model consists of

24-hr batches uncorrelated in time. Errors due to DSN station locations, ionospheric, tropospheric calibrations, Earth ephemeris, polar motion and UT1 are considered in the filter. The resulting 3σ navigation state uncertainties at time of ODM are presented in Table 3 for the nominal, low and high values of Bennu's GM. Values are given in the orbital radius, in-track (transverse) and cross-track (normal) directions. The uncertainties specified in Table 3 are used to initialize the ephemeris uncertainty for the TAG Monte Carlo analyses. Figure 3 shows the 3σ radial, transverse, normal state errors during the data arc and mapped to the time of the ODM, 24 hours after the data cutoff.

Table 3. 3σ Navigation Spacecraft State Uncertainty at time of ODM

	Position Uncertainty			Velocity Uncertainty		
	Radial (m)	In-Track (m)	Cross-Track (m)	Radial (mm/s)	In-Track (mm/s)	Cross-Track (mm/s)
Low GM	18.108	83.826	5.264	4.816	0.592	0.108
Nominal GM	12.483	52.619	3.795	3.922	0.506	0.031
High GM	11.599	41.612	2.687	3.652	0.572	0.059

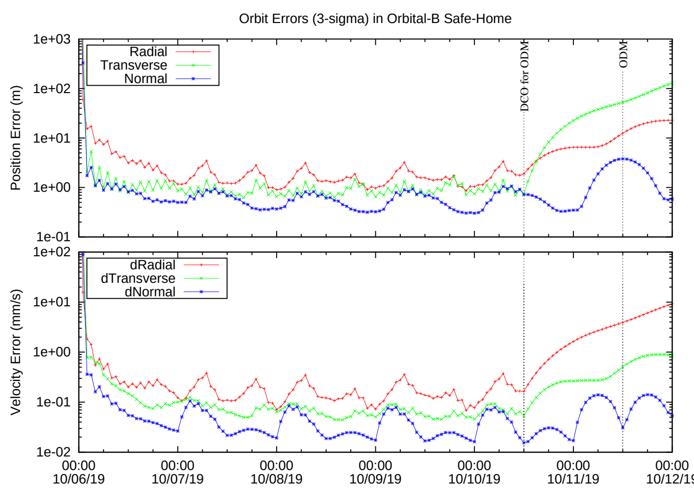

Figure 3. 3σ state errors before and after data cutoff in Safe-home orbit. State errors at the time of ODM are indicated in the plots.

TAG DELIVERY RESULTS

Table 4 presents the results of the Checkpoint prediction algorithm with all of the error sources included. There is no explicit requirement on the Checkpoint navigation state accuracy, but these errors represent the uncertainty in the onboard state estimate at the time of Checkpoint after incorporating information from the LIDAR range threshold crossing and range check measurements. The first three columns are the 3σ prediction errors in the radial, in-track, and cross-track directions using the expected Bennu surface variation model. The last three columns show the prediction errors using the worst-case Itokawa-based surface variation model.

Continuing down to the surface of the asteroid, Table 5 presents all of the TAG results. The first column is the 98.3% CI TAG error* obtained from Monte Carlo runs using the expected Bennu

*"TAG error" refers to the point along the 98.3% CI ellipse that is furthest from the target site. The 98.3% CI ellipse is fit to the dispersion of simulated points of spacecraft contact on the asteroid's surface. The center of this ellipse is

Table 4. Checkpoint Prediction Algorithm Results

	Expected Bennu Surface Model Errors 3σ (m) Radial	Expected Bennu Surface Model Errors 3σ (m) In-Track	Expected Bennu Surface Model Errors 3σ (m) Cross-Track	Itokawa-Based Surface Model Errors 3σ (m) Radial	Itokawa-Based Surface Model Errors 3σ (m) In-Track	Itokawa-Based Surface Model Errors 3σ (m) Cross-Track
0° Latitude, Low GM	5.56	10.55	8.73	8.58	11.64	8.74
0° Latitude, Nominal GM	5.43	9.69	8.19	8.36	11.73	8.19
0° Latitude, High GM	6.23	9.29	7.76	9.03	11.45	7.76
−45° Latitude, Low GM	6.05	7.79	7.75	9.25	11.46	7.76
−45° Latitude, Nominal GM	4.91	4.84	7.81	8.11	6.92	7.81
−45° Latitude, High GM	5.37	5.29	7.38	8.53	7.55	7.38
75° Latitude, Low GM	9.16	15.50	5.32	13.51	21.25	5.40
75° Latitude, Nominal GM	6.22	7.42	4.99	10.34	12.41	5.15
75° Latitude, High GM	5.76	5.27	4.41	9.11	8.06	4.56

surface variation model, followed by the results from the Itokawa-based surface variation model. The middle two columns show the 3σ TAG horizontal velocity errors, and the last two columns show the 3σ TAG vertical velocity errors, all relative to the spacecraft body frame. A representative set of position and velocity errors is shown in Figure 4, illustrating that the statistical performance clearly falls within the position requirement of 25 m and the velocity requirements of 2 cm/s.

Table 5. TAG Results for Expected Bennu and Itokawa-Based Surface Models

	98.3% CI TAG Error Expected Bennu Surface (m)	98.3% CI TAG Error Itokawa-Based Surface (m)	3σ Body-Relative Hor Velocity Expected Bennu Surface (cm/s)	3σ Body-Relative Hor Velocity Itokawa-Based Surface (cm/s)	3σ Body-Relative Ver Velocity Expected Bennu Surface (cm/s)	3σ Body-Relative Ver Velocity Itokawa-Based Surface (cm/s)
Requirement	25	25	2	2	2	2
0° Latitude, Low GM	15.61	15.79	1.62	1.62	1.30	1.31
0° Latitude, Nominal GM	15.03	15.30	1.46	1.47	1.15	1.17
0° Latitude, High GM	14.51	15.20	1.59	1.61	1.17	1.19
−45° Latitude, Low GM	15.18	15.37	1.64	1.72	1.01	1.03
−45° Latitude, Nominal GM	16.17	16.44	1.64	1.66	0.94	0.97
−45° Latitude, High GM	18.33	18.84	1.78	1.80	1.08	1.15
75° Latitude, Low GM	17.18	21.71	1.77	1.98	0.98	1.06
75° Latitude, Nominal GM	16.63	17.90	1.73	1.86	0.84	0.95
75° Latitude, High GM	20.42	20.72	1.91	1.97	1.01	1.15

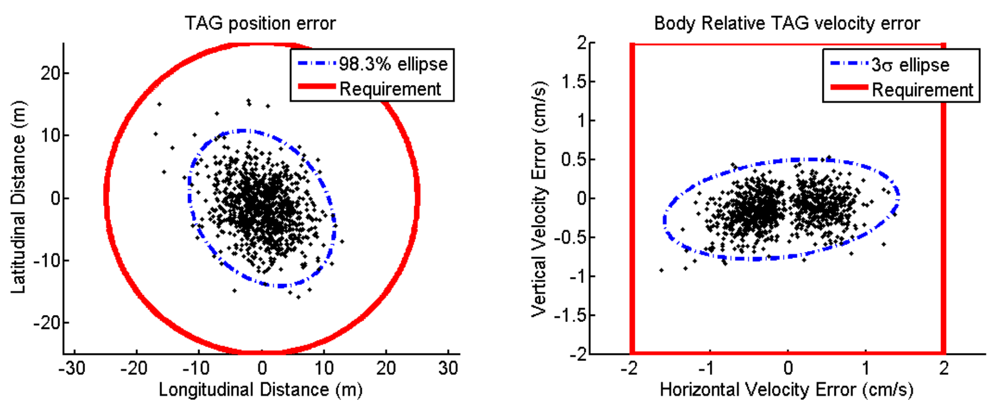

Figure 4. Representative TAG Position and Velocity Errors

generally near the desired point of contact, but the results being presented includes any bias in the dispersions.

The navigation uncertainties result in a large range of initial conditions leading up to the orbit departure maneuver, as was shown previously. If the resulting TAG trajectory deviates far enough from the nominal, the onboard system will detect and trigger an abort to maneuver the spacecraft away from the asteroid. The Monte Carlo simulation produced a small number of cases that resulted in aborts prior to Checkpoint: aborts are due to the LIDAR range threshold not being crossed (due to a high altitude in the trajectory) or the asteroid surface being outside of the field of view of the LIDAR for the entire trajectory (due to large in-track errors). Some abort cases also resulted due to large errors in TAG timing causing the attitude error to exceed the 4.4 degree requirement. Table 6 shows the total percent of aborts for each case.

Table 6. Percent of Aborts

	Expected Bennu Surface Model Pre-Checkpoint Aborts (%)	Itokawa-Based Surface Model Pre-Checkpoint Aborts (%)	Expected Bennu Surface Model TAG Timing Aborts (%)	Itokawa-Based Surface Model TAG Timing Aborts (%)	Expected Bennu Surface Model Total Aborts (%)	Itokawa-Based Surface Model Total Aborts (%)
0° Latitude, Low GM	0.4	0.4	0.5	0.7	0.9	1.1
0° Latitude, Nominal GM	0.0	0.0	0.6	0.6	0.6	0.6
0° Latitude, High GM	0.9	0.9	1.1	1.2	2.0	2.1
$-45°$ Latitude, Low GM	0.0	0.0	0.2	0.2	0.2	0.2
$-45°$ Latitude, Nominal GM	0.0	0.0	0.3	0.5	0.3	0.5
$-45°$ Latitude, High GM	0.0	0.0	0.7	0.8	0.7	0.8
75° Latitude, Low GM	4.6	4.7	0.0	0.1	4.6	4.8
75° Latitude, Nominal GM	0.0	0.0	0.0	0.0	0.0	0.0
75° Latitude, High GM	0.0	0.0	0.0	0.0	0.0	0.0

Sensitivity analysis was performed to assess the relative contributions of the various error sources to the TAG performance. Maneuver execution error (ODM and Checkpoint/Matchpoint) and navigation uncertainties are roughly equal as dominant error sources. The results described above represent a conservative estimate of the navigation performance that can be expected on orbit, as described in the *Navigation Uncertainty* section, assuming process noise set to 3 nm/s^2 in each spacecraft body axis. Additional Monte Carlo cases were performed using initial navigation states that assumed small forces in the directions perpendicular to the Sun vector can be characterized more precisely; in these cases process noise was set to 1 nm/s^2 in the body axes perpendicular to the Sun vector. Better initial navigation states resulted in improvements in the TAG accuracy by up to 26% and a reduction in the TAG velocity error by up to 25% while the percent of TAG aborts dropped to 0.5% for the worst case. While the baseline analyses use conservative assumptions to show the required performance in the presence of large uncertainties in the characteristics of Bennu, this sensitivity analysis illustrates the potential for improved performance with improved knowledge of key parameters.

CONCLUSIONS AND FUTURE WORK

An integrated trajectory design and Monte Carlo simulation capability has been developed for the OSIRIS-REx sample return mission to the Near Earth Asteroid Bennu. A sample collection sequence, referred to as TAG, has been baselined that involves a ground based design of the end-to-end TAG trajectory finalized in the 24 hours prior to the TAG event, utilizing a simplified, onboard guidance update based on LIDAR measurements made during the approach to the surface. Flight dynamics tools autonomously design a sequence of maneuvers to conduct the TAG event anywhere on the surface of Bennu, and perform Monte Carlo analysis for each example TAG site in consideration of the expected uncertainty in Bennu physical parameters, dynamical errors, and spacecraft performance. This analysis has demonstrated TAG can be successfully conducted using a single baseline TAG design, meeting performance requirements for position, velocity, and timing/attitude for nearly all locations on Bennu.

Navigation uncertainties at the time of orbit departure are a dominant error source in the TAG performance. A covariance analysis has been performed to examine the sensitivities to various small forces acting on the spacecraft and the corresponding ability to predict the spacecraft state for periods of 24 hours, the predictive interval applicable at the time the TAG design is finalized. Due to Bennu's small mass, SRP and accelerations imparted due to thermal imbalances across spacecraft surfaces on different axes (as large as 20% of SRP) are significant orbital perturbations impacting the ability to achieve required predictive accuracies after 24 hours. The TAG performance presented in this paper corresponds to somewhat conservative assumptions for how well some of the small forces can be characterized during the mission.

The LIDAR-based onboard navigation update is expected to result in onboard knowledge of the Checkpoint state to better than 10 meters in each component in most cases, and never worse than 22 meters. TAG position errors are typically less than 18 meters and range from 15-22 meters (relative to a requirement of 25 meters). TAG horizontal velocity errors are typically less than 1.8 cm/s, and vertical velocity errors less than 1.2 cm/s with all cases below the required 2 cm/s.

Some TAG sites result in a small number of trajectories that would result in abort criteria being triggered at the time of the Checkpoint maneuver; however, subsequent analysis has indicated instances of aborts are reduced or eliminated completely for cases that assume reduced navigation uncertainties or better maneuver execution error performance. Moreover, modifications to certain parameters of the TAG design, such as the LIDAR look-ahead angle can reduce instances of aborts by optimizing the timeline for a specific site and ground track leading to that site.

The analysis tools described in this paper will be utilized over the next year to examine TAG performance and spacecraft safety in the presence of various failure scenarios, such as an unknown failed thruster occurring during the TAG sequence. An integrated verification and validation activity intended to certify all of the flight software, ground simulation, and analysis tools that are part of the TAG design will be conducted. Finally, the Flight System team at Lockheed Martin is leading the development of an onboard optical navigation system referred to as Natural Feature Tracking (NFT) that is intended to serve as a backup to the LIDAR-based guidance inputs described in this paper. This activity is described in another paper presented as part of this session.[7]

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