(Preprint) AAS 16-XXX

AN INDEPENDENT ORBIT DETERMINATION SIMULATION FOR THE OSIRIS-REX ASTEROID SAMPLE RETURN MISSION

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After arriving at the near-Earth asteroid (101955) Bennu in late 2018, the OSIRIS-REx spacecraft will execute a series of observation campaigns and orbit phases to accurately characterize Bennu and ultimately collect a sample of pristine regolith from it's surface. While in the vicinity of Bennu, the OSIRIS-REx navigation team will rely on a combination of ground-based radiometric tracking data and optical navigation (OpNav) images to generate and deliver precision orbit determination products. Long before arrival at Bennu, the navigation team is performing multiple orbit determination simulations and thread tests to verify navigation performance and ensure interfaces between multiple software suites function properly. In this paper, we summarize the results of an independent orbit determination simulation of the Orbit B phase of the mission performed to test the interface between the OpNav image processing and orbit determination software packages.

INTRODUCTION

In September of 2018, the Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx) spacecraft will rendezvous with the near-Earth asteroid (NEA) 101955 Bennu (1999 RQ_{36}). After performing multiple close-proximity flybys, OSIRIS-REx will perform a sequence of five maneuvers to insert into a 1.5 km radius stable, circular orbit in the asteroid's terminator plane (the plane perpendicular to the asteroid-Sun line). OSIRIS-REx will remain in the 1.5 km orbit, known as "Orbit A," for approximately three weeks before lowering into a 1 km orbit, also in the asteroid's terminator plane, known as "Orbit B." From Orbit B, the spacecraft will execute multiple near-surface reconnaissance passes and rehearsals in preparation for a Touch-and-Go (TAG) sequence to collect approximately 60 grams of pristine regolith from the surface of Bennu. After the TAG sequence is performed and sample collection is confirmed, OSIRIS-REx will depart Bennu and safely deliver the sample return capsule to the surface of Earth.[1]

The OSIRIS-REx mission presents similar navigation challenges to previous NEA rendezvous missions.[2] Although ground-based observations provide estimates for many of Bennu's physical and dynamical properties, those estimates must be verified or refined via in-situ observations during approach and proximity operations. Therefore, parameters such as Bennu's ephemeris, mass, non-spherical gravity, and spin state are included in the orbit determination (OD) solution and estimated using radiometric and optical navigation (OpNav) tracking data. While ground-based radiometric tracking data from the Deep Space Network (DSN) offers spacecraft position and velocity information with respect to the Earth-centered inertial frame, OpNav provides a direct measurement of the spacecraft's state relative to the asteroid.[3] Images of the asteroid are also used to develop global shape models and topographic maps and to refine estimates of the asteroid's rotation period, spin-axis, and any non-principal axis rotation that may be present.

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Orbit B marks an important phase in operational OD and navigation. The phase begins with a nine-day radio-science campaign where the spacecraft's orbit is allowed to evolve naturally without maneuvers or momentum desaturations. Near-continuous radiometric tracking, combined with OpNav and altimetry data, allow for precise characterization of the dynamic environment about Bennu, including the gravity field and spin state. During Orbit B, the the landmark-based OpNav technique is used exclusively as the asteroid fills a large portion of the primary navigation camera (NavCam) field-of-view and stars are no longer visible in the same image. Following the radioscience campaign and additional detailed surface observations, Orbit B serves as a "Safe Home" orbit for conducting reconnaissance passes, rehearsals, and TAG sample acquisition. In order to support these near-surface operations, the navigation team is required to predict the spacecraft's position in Orbit B, 24-hours after OD data cut-off, to within 20, 85, and 7 meters (3σ) in the radial, along-track, and cross-track (orbit normal) directions, respectively.

The task of successfully navigating OSIRIS-REx in the vicinity of Bennu falls to the OSIRIS-REx Flight Dynamics Subsystem (FDS). The FDS team is comprised of personnel from three organizations: NASA Goddard Space Flight Center (GSFC), Lockheed Martin, and KinetX Aerospace. KinetX is responsible for orbit determination and OpNav image processing for all phases of the OSIRIS-REx mission. Lockheed Martin and GSFC are responsible for trajectory design and optimization. GSFC personnel are also responsible for independent verification & validation (IV&V) of operational navigation products. Long before arrival at Bennu, the navigation team continues to perform multiple orbit determination simulations and thread tests to verify navigation performance and ensure interfaces between multiple software suites function properly. In July of 2015, KinetX led the last of three Orbit Determination Thread Tests (ODTT3) with the entire FDS team to test the interface between the OpNav image processing and orbit determination software packages, verify flight dynamics requirements, assess navigation performance, and ensure software packages used by various teams within FDS are consistent. The test focused on the Orbit B phase of the mission and included processing of simulated landmark-based OpNav, altimetric range, and radiometric tracking data.

This paper will present a nominal Orbit B trajectory propagated using estimates of Bennu's physical and dynamical properties. It will then summarize the procedure for processing simulated radiometric tracking, OpNav, and altimetric data. Finally, it will discuss the results from the independent OD solution and identify future work.

METHODOLOGY

The analysis presented in this paper was designed to simulate the end-to-end process of producing an OD solution during the Orbit B phase of the mission. Independent image processing and OD analysis was performed using two software packages that will be utilized for verification and validation.

During OSIRIS-REx operations, KinetX personnel will perform primary OD and generate operational navigation products using the flight-tested MIRAGE navigation software package. The GEODYN II precision OD and geodetic parameter estimation program,[4] developed and maintained by the Planetary Geodynamics Laboratory at GSFC, will be used for science data processing and as an independent tool for navigation solution comparisons. In this analysis, GEODYN II was employed to simulate direct altimetry data, process simulated radiometric and OpNav data, and generate OD solutions. Landmark-based OpNav measurement processing was recently added to GEODYN II to support OSIRIS-REx. An objective of this test was to ensure these models were implemented correctly and could be used to perform OD.

The Lithosphere software package will be used for OpNav image processing and landmark measurement construction during OSIRIS-REx operations at Bennu. Lithosphere was developed by Dr. Robert Gaskell and is currently maintained by the OSIRIS-REx Science Processing and Operations Center (SPOC). Lithosphere will also be used by the OSIRIS-REx science team to build global shape models and topographic maps using images of Bennu. Specific tools in the Lithosphere package were used in this analysis to process simulated images of Bennu and to produce OpNav landmark observables.

The interface between GEODYN II and Lithosphere consists of two file types: binary Spacecraft Position Kernels (SPKs) and REGRES data files. SPKs store position and velocity information for spacecraft and celestial objects and are part of the SPICE observation geometry system developed by NASA's Navigation and Ancillary Information Facility.[5] A spacecraft ephemeris generated in GEODYN II (either simulated or determined) can be converted to an SPK and read by Lithosphere. Lithosphere uses the SPK, along with other kernels that describe the spacecraft and asteroid geometry, to process the OpNav images and produce observables. The observables are then written to an ASCII text file, known as a REGRES file, along with additional information needed to model the OpNav measurement. GEODYN II is able to read the REGRES file and process the OpNav observables in the OD solution.

The simulation and OD analysis presented considered perturbations and errors in the dynamics models used to propagate spacecraft motion, including uncertainties in the gravity field, spin state, maneuver execution, solar radiation pressure (SRP) scale factor, and small force modeling. It also modeled and considered error sources that affect measurements, including errors in spacecraft attitude, OpNav landmark locations, and image noise. It did not model errors in DSN station locations, tropospheric or ionospheric delays, or camera distortions. The "truth" trajectory and radiometric tracking data were simulated by KinetX personnel using the MIRAGE navigation software package.

SIMULATION

The nominal spacecraft trajectory for the simulation was designed to match the planned OSIRIS-REx Orbit B mission phase. The physical properties of Bennu necessary to simulate the dynamical environment during proximity operations were modeled based on information provided by the OSIRIS-REx Science Team,[6] the Design Reference Asteroid document,[7] and the Trajectory Standards Document.[8] The nominal parameters are summarized in Table 1. Force models used in the propagation include a 15×15 spherical harmonic gravity model, 10-plate SRP, spacecraft thermal radiation, and third-body gravity from all major planets and the sun. A mass of 1196.98 kg and a scale factor of 1.0 was used for SRP modeling. Spacecraft plate properties used for SRP modeling are summarized in Table 2.

Table 1. Physical parameters for the asteroid (101995) Bennu.

Parameter	Nominal
Gravitational Parameter, μ (m^3/s^2)	5.2
Mean Radius (m)	245.9
IAU Spin State	
Right Ascension, α (deg)	86.639
Declination, δ (deg)	-65.108
Constant, ω_0 (deg)	89.646
Rate, ω (deg/day)	2010.489449

Table 2. Spacecraft N-plate properties used for SRP modeling.

Plate		Area (m^2)	Specular Coeff.	Diffuse Coeff.
Bus	+X	5.174	0.000	0.441
	-X	5.174	0.056	0.435
	+Y	5.175	0.076	0.411
	-Y	5.175	0.076	0.411
	+Z	6.471	0.000	0.474
	-Z	6.471	0.000	0.474
Array Front	(x2)	4.903	0.080	0.000
Array Back	(x2)	4.903	0.000	0.069

The nominal Orbit B trajectory is a 1.0 km radius circular orbit in the sun-asteroid terminator plane with a period of approximately 24 hours. The nominal trajectory was propagated for approximately 4 days beginning on October 7th, 2019 at 1:00PM. A small phasing maneuver ($\Delta V \approx 0.8$ mm/s) was applied on Oct 8, 2019 16:00 ET to target a specific TAG departure latitude and longitude approximately 5 days later.[9] This trajectory was considered the “truth” trajectory and used to simulate radiometric tracking data and OpNav images. A graphical representation of the orbit is shown in Figure 1.

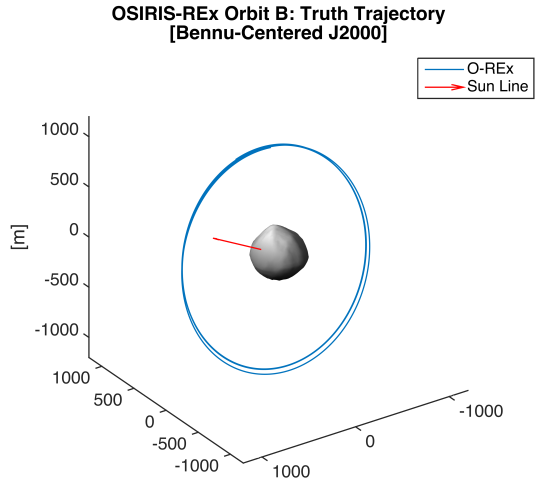

Figure 1. Nominal Orbit B trajectory in the Bennu-centered J2000 frame.

Simulated radiometric tracking data consisted of range and Doppler measurements from antennas located at two DSN complexes: Goldstone, California and Madrid, Spain. Tracking passes occurred daily, with low-gain antenna coverage from approximately 6:30am to 9:30am UTC, and high-gain passes from 9:30am until 2:30pm UTC. Zero-mean, Gaussian noise was added to the range and Doppler measurements with standard deviations of 3 meters and 0.1 mm/s, respectively.

OpNav images of Bennu’s surface, taken from NavCam, were also simulated for the test. A total of 54 images were simulated at two hour intervals starting at noon on October 7th and ending around 11 PM on October 12th, except during an image black-out period that occurred from 3:15pm until 8:45pm each day.* A nadir-pointed attitude profile was used for all images, with the instrument deck (+Z axis) of OSIRIS-REx pointed at the center of Bennu and the solar panels oriented toward the sun (+X axis). The NavCam camera frame is rotated +6 degrees about the spacecraft body-fixed Y-axis, and then -70 degrees about the spacecraft body-fixed +Z axis. Attitude errors were applied to the nominal NavCam pointing consistent with the current best estimate for spacecraft performance: 1.15 mrad boresight and 1.01 mrad roll, both 1σ. NavCam is a realization of the ECAM-M50 commercial imaging system developed by Malin Space Science Systems (MSSS). The optical and detector properties used to simulate the NavCam images were provided by MSSS and are shown in Table 3.

Table 3. NavCam optical and detector properties used for simulated images.

Parameter	Value
Field-of-View (deg)	44×33
Resolution (pixels)	2592×1944
IFOV (deg)	0.017
Focal Length (mm)	7.68
Depth of Focus (m)	5 to ∞
Spectral Range (nm)	400 to 700

The images were rendered using the geometry modeling tool Geomod and the physically-based stochastic

*Ideally, the image black-out period should align with the high-gain passes. However, there was a small disconnect in this test between the image simulation epochs and the simulated radiometric data.

ray tracer Phillum, both developed at GSFC as part of the Freespace Simulation Environment. For each image, a scene was constructed in Geomod using the simulated spacecraft trajectory and attitude information at the desired exposure time of the image. Ray tracing was performed backwards from the camera to the light source by following a large number of light rays from a pixelated detector grid, through a lens system, and into the scene. Pixel intensities for each image were calculated based on the results of the ray tracing and the camera detector properties. An example of a NavCam rendered image from October 5th, 2019 at 2PM is shown in Figure 2.

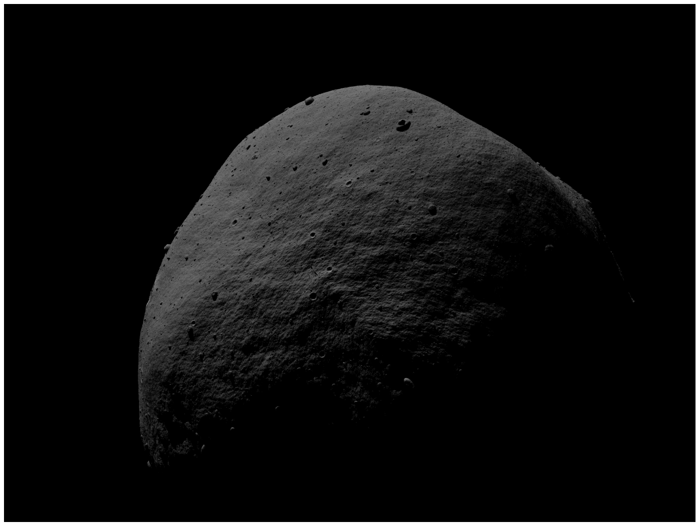

Figure 2. Simulated NavCam image using the simulated spacecraft and Bennu geometry from October 5th, 2019 at 2PM.

A set of 6142 topographic maps (known as "maplets") at 5cm resolution were used to model the shape and topography of Bennu. The maplets were provided by members of the OSIRIS-REx Science Team and incorporated the global shape of Bennu derived from ground-based radar observations,[10] as well as synthetic surface roughness, boulders, and craters added to achieve the desired 5cm resolution. Each maplet defined a local coordinate system, centered at a specified point on the surface, and a grid of local heights and relative albedos at 5 cm increments. Local topography and relative albedo information for a Bennu maplet located at 134.5 degrees longitude and 36.3 degrees latitude is shown in Figure 3.

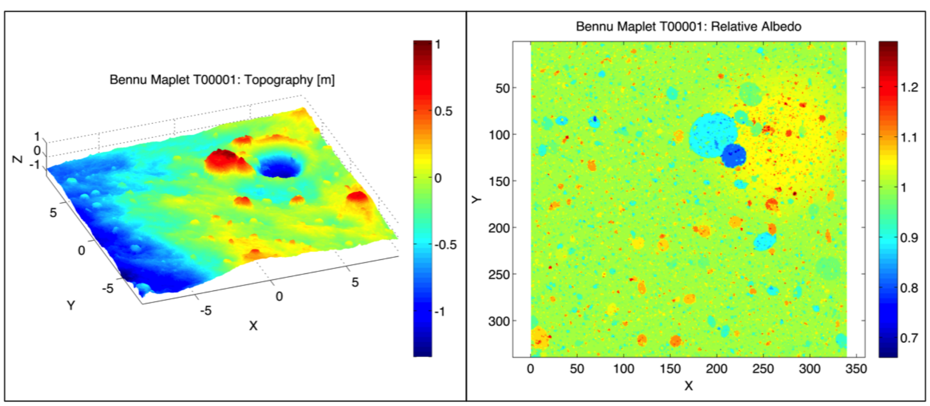

Figure 3. Local topography (left) and relative albedo (right) information for Bennu maplet T00001 (134.5 degrees longitude, 36.3 degrees latitude).

The independent version of the Orbit B thread test included the use of simulated OSIRIS-REx Laser Altimeter (OLA) data in the form of altimetric range measurements. Altimetric range measurements are defined as the slant range from the spacecraft to the surface along OLA's boresight. They are constructed via the round-trip light time of a laser pulse from the emitter, to the surface, and back to the detector. Digital Elevation Models (DEMs) of the surface of Bennu at 8 pixels per degree (PPD) and 1 PPD were constructed from the 5cm maplet data. Simulated OLA altimetry was generated in GEODYN using the 8 PPD DEM and the true spacecraft trajectory. In subsequent OD runs, the computed altimetry measurements used the 1 PPD DEM to capture differences between the true surface and the limited resolution modeled surface during Orbit B.

ANALYSIS

A Priori Trajectory

The test consisted of a trajectory arc spanning from October 7th, 2019 at 13:00 to October 11th, 2019 at 16:00 UTC. The *a priori* parameters used in the OD solution differed from the "truth" trajectory used to simulate measurements by an amount consistent with FDS covariance analyses and expected uncertainties during the Orbit B mission phase. Differences included the initial spacecraft state, Bennu gravitational parameter, Bennu spherical harmonic coefficients (up to degree/order 3), phasing maneuver ΔV, SRP scale factor, Bennu orientation, spacecraft attitude, and navigation landmark positions. The difference between the truth and *a priori* trajectories is shown in Figure 4.

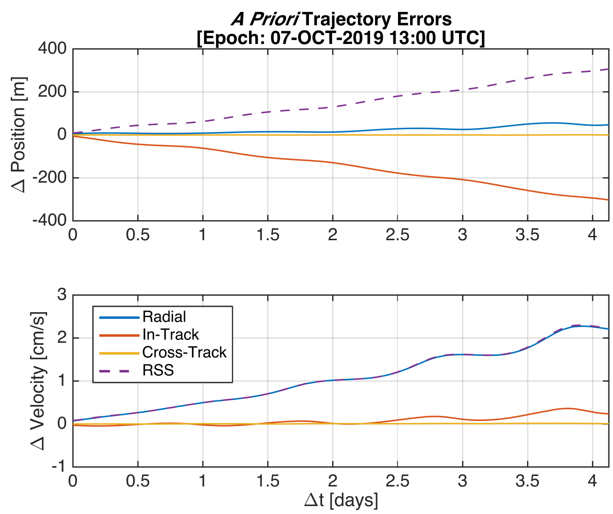

Figure 4. Position (top) and velocity (bottom) errors of the *a priori* trajectory with respect to the "truth" trajectory in Radial, In-Track, and Cross-Track coordinates.

Radio-Only Solution

The image processing software used to construct the landmark-based OpNav observables requires an initial estimate of the spacecraft's position at each image time. For this test, an OD solution using only the simulated radiometric tracking data provided an initial trajectory. The radiometric tracking data was processed using the GEODYN II precision OD program. GEODYN II uses an iterative weighted batch-least squares (WBLS) estimator to find the initial spacecraft state solution that results in the minimum residual variance for a given set of measurements. Solve-for parameters for the radio-only solution included the initial spacecraft state, SRP scale factor, phasing maneuver ΔV (magnitude and direction), constant acceleration bias, and a DSN range bias. Asteroid geodetic parameters were held fixed at the *a priori* values.

Attempting to solve for all of the parameters over the entire four-day arc caused the WBLS solution to diverge. Instead, the radio-only solution was broken up into two separate GEODYN runs. First, an OD solution was performed using data from the beginning of the arc up to (but not including) the phasing maneuver. The resulting solve-for parameters were used as *a priori* estimates for a second WBLS solution using data from the beginning of the arc through the second DSN pass after the phasing maneuver (October 9th 21:00:00 UTC). The initial WBLS solution also required *a priori* constraints on the initial spacecraft state on the order of 50 meters and 1 cm/s.

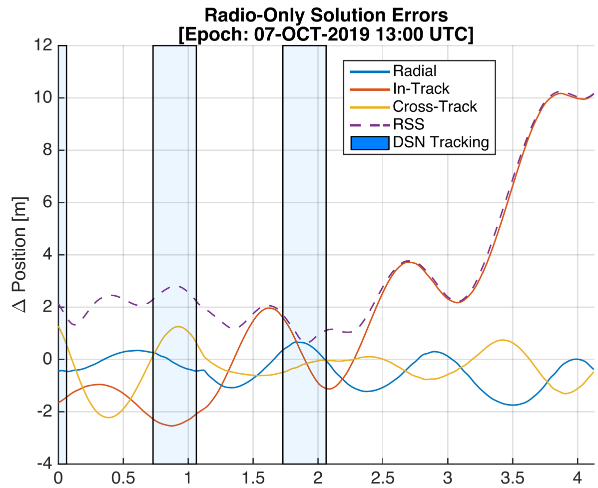

Figure 5. Position errors of the a radio-only trajectory solution with respect to the nominal "truth" trajectory in Radial, In-Track, and Cross-Track coordinates. Periods of DSN radiometric tracking (range and Doppler) used in the solution are shown in blue.

The radio-only solution converged with range and Doppler root-sum-square (RSS) residuals of 22.9 RU and 0.056 Hz, respectively. Actual position errors for the solution are shown in Figure 5. The accuracy of the radio-only solution was sufficient for automated processing of the OpNav images.

OpNav Image Processing

The goal of OpNav image processing is to uniquely identify and locate topographic surface features, known as landmarks, in an image. The sample and line pixel location of a landmark in the 2D image plane, combined with knowledge of the landmark's cartesian position on the surface, provides information of the spacecraft's relative position and orientation in the asteroid fixed frame. During proximity operations, the OSIRIS-REx navigation team will rely on a technique known as stereophotoclinometry (SPC),[11,12,13] implemented in the Lithosphere software package, to construct uniquely-identifiable landmarks and locate them in OpNav images. SPC uses the amount of reflected light from the surface, measured via extracted pixel brightness from multiple images, to build height and albedo maps similar to the one shown in Figure 3. The origin of the local coordinate frame that defines each maplet is used as a landmark in subsequent OpNav images.

In actual operations, SPC will be used to construct maplets for the entire asteroid at incrementally higher resolutions. Maplets at 75 cm resolution, generated from images taken during approach and preliminary survey, will be available during Orbit B. For this test, a set of 384 maplets at 75 cm resolution with a grid size of 99×99 points were generated by downsampling from the set of 5 cm maplets used to render the simulated images.

Each image was processed separately using the AUTOREGISTER program, part of the Lithosphere software package. The maplet registration procedure is summarized below.

First, sample and line locations of landmarks (i.e. maplet centers) in the 2D image plane are calculated using the estimated spacecraft geometry. Maplets are then filtered out based on parameters such as fractional visible width of the maplet in the image, percent of the maplet in shadow, maximum emission angle, and the ratio between image scale and maplet scale. The filter constraints used for this analysis are shown in Table 4.

Table 4. Constraints used to filter maplets from image registration.

Constraint	Value
Visible Width (%)	100
Max Emission Angle (deg)	75
Min Shadow (%)	25
Min Image/Maplet Scale	0
Max Image/Maplet Scale	3

The remaining maplets are illuminated based on the predicted incidence and emission angles and an appropriate reflectance function. Brightness values are extracted from the image using the spacecraft *a priori* position and pointing. For each maplet, 2D arrays of the extracted and predicted illumination values are cross-correlated and a maximum correlation coefficient is determined. The shift corresponding to the maximum correlation coefficient is used to calculate an updated sample and line location of the landmark in the 2D image plane. The updated sample and line location is recorded and available for use in the orbit determination solution. Predicted versus extracted maplet brightness for three maplets registered in a simulated image are shown in Figure 6.

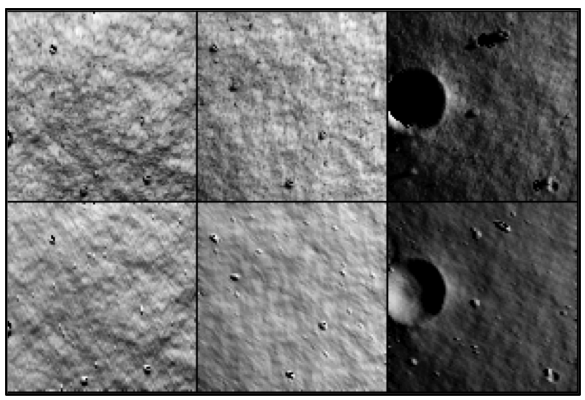

Figure 6. Extracted (top row) and predicted (bottom row) brightness for three maplets in the simulated image N623803681F1 (Epoch: October 8th, 2019 at 10:46:53 pm UTC).

GEODYN II uses a camera projection model to fit predicted sample and line locations of landmark with observed values in an image.[3] The relative position of the landmark with respect to the camera frame (R^c) is calculated using the a priori position and attitude of the spacecraft, as well as the orientation parameters for the target body. The relative landmark position is then projected into the camera's focal plane (x, y) using a gnomonic projection (Eq. 1). A six parameter model with four radial terms and two tip/tilt terms (δ_{1-6}) is used to correct the focal plane positions (x', y') for camera distortions and detector misalignment[14] (Eq. 2). Finally, the distorted focal plane positions are converted to sample and line locations (s, l) in the image plane using a linear transformation (Eq. 3). The camera transformation parameters used in this study are shown in Table 5. Distortion was not applied to the simulated images and all of the distortion coefficients were set to zero.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{f}{R_z^c} \begin{bmatrix} R_x^c \\ R_y^c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} -yr & xr^2 & -yr^3 & xr^4 & xy & x^2 \\ xr & yr^2 & xr^3 & yr^4 & y^2 & xy \end{bmatrix} \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ \delta_5 \\ \delta_6 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} s \\ l \end{bmatrix} = \begin{bmatrix} s_0 \\ l_0 \end{bmatrix} + \begin{bmatrix} K_{xx} & K_{xy} & K_{xxy} \\ K_{yx} & K_{yy} & K_{yxy} \end{bmatrix} \begin{bmatrix} x' \\ y' \\ x'y' \end{bmatrix} \quad (3)$$

Table 5. Parameters describing the projection of landmark positions into the image plane.

Parameter	Value
f (mm)	7.86
δ_{1-6}	0
s_0 (pix)	1296.5
l_0 (pix)	972.5
K_x (pix/mm)	454.54
K_y (pix/mm)	454.54
K_{xy}, K_{yx} (pix/mm)	0
K_{xxy}, K_{yxy} (pix/mm^2)	0

RESULTS

Radio + Landmark Solution

Registering the 96 maplets in the 54 simulated images resulted in 428 OpNav measurements for inclusion in the OD solution. The observed sample and line location of the 10 landmarks registered in the image N624034081F1 are shown in Table 6. The image processing resulted in landmark location shifts (Δs, Δl) on the order of 10's of pixels, which is consistent with the accuracy of the radio-only trajectory solution used as the initial estimate.

Table 6. Landmarks identified in the simulated image N624034081F1 (Epoch: October 11th, 2019 at 2:46:53am). The landmark longitude and latitude are the *a priori* values, which include a 1 meter error (1σ). The shifts (Δs, Δl) are based on the radio-only solution as the *a priori*.

Landmark ID	Longitude, deg	Latitude, deg	Observed s, pix	Observed l, pix	Δs	Δl
BM0022	-59.82	19.86	1988.070	196.050	-19.57	2.58
BM0023	-80.74	19.96	2286.890	172.220	-34.51	3.66
BM0024	-100.30	19.98	2605.340	280.520	-28.03	0.54
BM0038	-29.2 2	40.31	1593.090	585.970	-10.51	-3.77
BM0039	-60.30	39.83	1881.660	429.140	-25.51	7.24
BM0040	-90.28	40.34	2246.86	439.190	-23.25	-5.68
BM0041	-119.95	39.91	2605.660	697.620	-26.34	4.97
BM0050	-40.52	60.10	1650.420	777.230	-30.64	3.46
BM0051	-79.97	59.93	1958.520	728.760	-23.13	6.93
BM0052	-121.24	59.93	2275.710	934.070	-34.33	-6.14

The 428 OpNav measurements were processed with the radiometric data in GEODYN II to generate a final OD solution. The range, Doppler, and OpNav measurements were weighted at 24.5 RU, 0.0056 Hz, and 0.45 pixels, respectively. Two solutions were performed with the radiometric and OpNav data. The first GEODYN run solved for the spacecraft trajectory, phasing maneuver, camera pointing, landmark locations,

and an acceleration bias using the radio-only solution as an *a priori* while the asteroid's geodetic parameters were held fixed. The second run used the solution from the previous run as the *a priori* to solve for all of the parameters, including the geodetic parameters, and perform a final update on the spacecraft trajectory. The second solution converged with the residual statistics shown in Table 7. The sample and line residuals for the landmark OpNav measurements are shown in Figure 7. Compared to the "truth" trajectory used to simulate the data, the radio plus landmark solution had total errors of less than 5 m over the entire arc (Figure 8).

Table 7. Measurement residual statistics for the radio plus landmark OD solution.

Measurement	Number	Mean	RSS
Range (RU)	188	0.00	21.8898
Doppler (Hz)	1738	0.0003	0.0059
OpNav, Total (pix)	428	-0.0234	0.8398

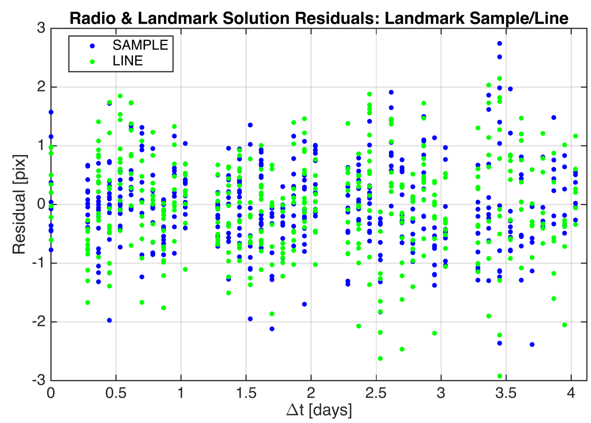

Figure 7. Post-fit landmark OpNav residuals for the radio plus landmark data OD solution.

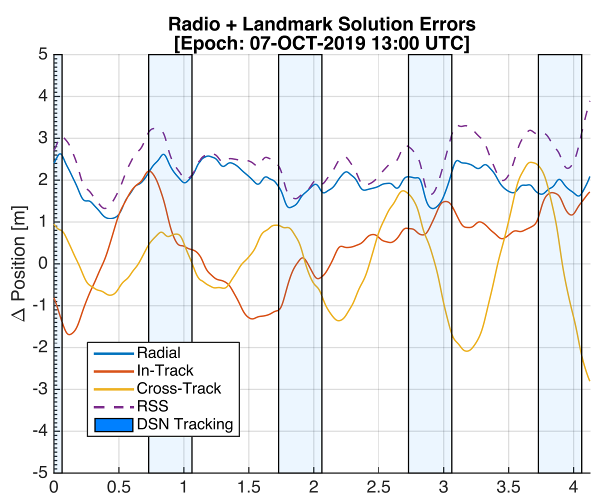

Figure 8. Position errors of the radio plus landmark trajectory solution with respect to the nominal "truth" trajectory in Radial, In-Track, and Cross-Track coordinates.

A summary of the solutions for Bennu geophysical parameters and gravity coefficients using radio and landmark data are shown in Table 8 and Figure 9, respectively. While the spacecraft trajectory errors are relatively low, the gravitational parameter and spin state solutions differ from the truth more than the formal uncertainty predicts. This is expected for a short-arc solution (four-day) with realistic perturbations to the dynamics, including maneuver execution errors on the phasing maneuver and unmodeled accelerations. The higher-order gravity model coefficients also have relatively high errors, which confirms the weak observability of the gravity field beyond degree and order 2. During OSIRIS-REx operations, information from the nine-day, uninterrupted radio-science campaign at the beginning of the Orbit B phase will be used to estimate and constrain Bennu's geophysical parameters for subsequent navigation solutions.

Table 8. Radio and landmark solution for Bennu geophysical parameters.

Parameter	Truth	*A Priori* Value	*A Posteriori* Value	Formal σ
Gravitational Parameter, μ (m^3/s^2)	5.1969	5.2000	5.1626	1.490e-03
IAU Spin State				
Right Ascension, α (deg)	86.6388	86.6088	86.5730	8.772e-03
Declination, δ (deg)	-65.1086	-65.1286	-65.1207	4.995e-03
Constant, ω_0 (deg)	89.6456	89.6456	89.6454	1.000e-02
Rate, ω (deg/day)	2010.489449	2010.489400	2010.489433	4.924e-11

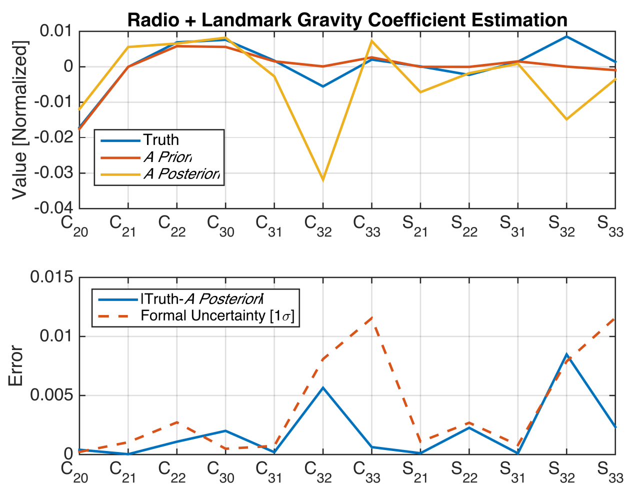

Figure 9. Truth, *A Priori*, and *A Posteriori* values for Bennu gravity coefficients (top) and associated errors and formal uncertainties (bottom) up to degree and order 3.

Radio + Landmark + Altimetric Range Solution

Altimeter range measurements from the OLA instrument were simulated and then added to the GEODYN solution to observe their impact on the solution accuracy. OLA is a scanning lidar that will collect data in 150 second scans. Each scan will survey an 80×80 meter patch of the asteroid. This 80×80 meter pattern was reproduced in the simulation. Since OLA produces data at a high rate (up to 10,000 Hz),[1] the measurements were down sampled to to 2667 ranges per 150 second scan. This was done to keep the number of measurements of each type on the same order of magnitude in the WBLS solution, as well as reduce processing time. The scans were simulated so that the center epoch of the scan was near the landmark observations.

It will be necessary to estimate pointing biases in roll and pitch angles for the OLA altimeter. Fortunately, the pointing for OLA should be stable over each 150 second scan, so it should be sufficient to estimate a mean pointing bias in roll and pitch for each scan. Also the observing geometry of each scan is favorable for pointing bias recovery. As the scan is traced out, the effective pointing changes slowly in roll and pitch.

This is essentially the same as a pointing calibration maneuver used in other laser altimeter missions, such as ICEsat.[15] Pointing biases were estimated in solutions that used altimeter ranges

The altimeter range measurements were weighted at 15 cm. The second solution converged with altimeter range residual statistics shown in Table 9. The residuals for the altimeter range measurements are shown in Figure 10. Adding the altimeter range data resulted in a trajectory solution that matched the "truth" to around 1 meter for the entire four-day arc (Figure 11), which was an improvement over the radio and landmark solution (Figure 8).

Table 9. Measurement residual statistics for the radio, landmark, and altimetric range OD solution.

Measurement	Number	Mean	RSS
Range (RU)	188	0.00	21.2771
Doppler (Hz)	1738	0.0014	0.0061
OpNav, Total (pix)	428	-0.0729	0.8361
Altimetric Range (cm)	2667	-0.85	29.50

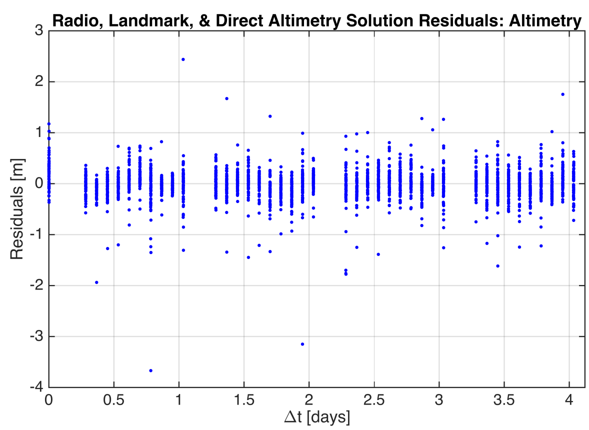

Figure 10. Post-fit altimetric range residuals for the radio, landmark, and altimetry data OD solution.

A summary of the solutions for Bennu geophysical parameters using radio, landmark, and altimetric range data is shown in Table 10. Similar to the trajectory solution, the accuracy of the gravitational parameter and spin state estimates improved with the addition of altimetry data. This suggests that the altimetry data improves the radial knowledge of the trajectory and helps to resolve issues of scale associated with the landmark observations and solving for the positions of the landmarks.[16] It also demonstrates the benefits of using large amounts of data when dealing with short arc solutions, and that altimetry and OpNav measurements are complimentary. The altimetry measurements did not significantly change the estimates of the gravity field coefficients compared to the radio and landmark solution, which is again consistent with a lack of sensitivity to those parameters.

While the results with altimetry look promising, it is important to note that the efficiency of the measurements depends on an accurate topographic map of Bennu's surface. This study considered the effects of lower resolution data products compared to the truth surface, but did not include realistic errors on the topographic model used to compute the predicted altimetry measurements. The OSIRIS-REx Altimetry Working Group is currently assessing the expected accuracy of topographic products generated during operations using SPC and altimetric data.

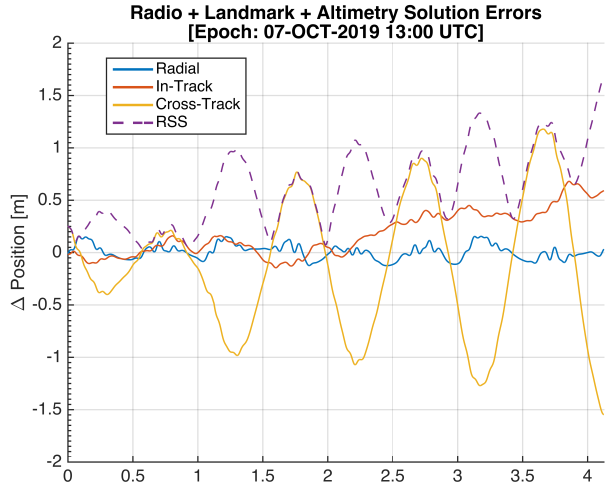

Figure 11. Position errors of the radio, landmark, and altimetric range trajectory solution with respect to the nominal "truth" trajectory in Radial, In-Track, and Cross-Track coordinates.

Table 10. Radio, landmark, and altimetric range solution for Bennu geophysical parameters.

Parameter	Truth	*A Priori* Value	*A Posteriori* Value	Formal σ
Gravitational Parameter, μ (m^3/s^2)	5.1969	5.2000	5.1954	1.059e-03
IAU Spin State				
Right Ascension, α (deg)	86.6388	86.6088	86.6205	7.8676e-04
Declination, δ (deg)	-65.1086	-65.1286	-65.1165	8.8772e-04
Constant, ω_0 (deg)	89.6456	89.6456	89.6453	1.000e-02
Rate, ω (deg/day)	2010.489449	2010.489400	2010.489404	1.6078e-11

CONCLUSION

The analysis and results presented in this paper demonstrated an independent, end-to-end simulation of the orbit determination process for the Orbit B phase of the OSIRIS-REx mission leading up to TAG. A "truth" trajectory was generated by KinetX personnel for the OSIRIS-REx spacecraft in Orbit B using current best estimates for asteroid physical parameters with expected perturbations. The truth trajectory was used to simulate radiometric tracking data, OpNav images, and altimetric range measurements. The OpNav images were processed to produce landmark measurements, which were combined with the radiometric data in a full orbit determination solution. A second solution was performed adding altimetric range measurements which improved the accuracy of the trajectory solution and geophysical parameter estimation. The accuracy of the final OD solution indicates that the interface between the OpNav image processing and OD software functioned properly and that all measurements were modeled correctly.

ACKNOWLEDGMENT

The authors would like to acknowledge the members of the OSIRIS-REx Flight Dynamics and Radioscience Teams, as well as the Science Processing Operations Center, for supporting and generating products for the Orbit B Thread Test. The authors would also like to thank developers in the GSFC Planetary Geodynamics Laboratory for GEODYN software development. This work is supported by the OSIRIS-REx Asteroid Sample Return Mission, selected in 2011 as the third mission in NASA's New Frontiers Program. OSIRIS-REx is managed for NASA by the Goddard Space Flight Center in Greenbelt, MD. The Principal Investigator is Dr. Dante Lauretta of the University of Arizona in Tucson. Lockheed Martin Space Systems

in Denver is building the spacecraft.

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