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

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FDS Team consists of three organizations:

**KinetX Space Flight Dynamics Practice**
- Orbit Determination
- Optical Navigation (OpNav)
- Maneuver Planning

**Lockheed Martin Space Systems Company**
- Trajectory Design & Optimization

**Goddard Space Flight Center**
- FDS Management
- Launch Window Analysis
- IV&V of Navigation Products
**Orbit Determination Thread Test 3B**

- Realistic Orbit Determination & OpNav simulation of the Orbit B mission phase leading up to TAG

- Objectives:
  - Test interfaces between OD & OpNav Software
  - Verify flight dynamics requirements
  - Assess navigation performance
  - Ensure consistent results across FDS organizations

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**Pre-TAG Operations Timeline**


- Phasing Burn
- Phasing Burn
- TAG ODM DCO
- TAG ODM

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**ODTT3B**
ODTT3B SOFTWARE

• MIRAGE
  • Operational precision OD software
  • Developed by JPL/CalTech, licensed to KinetX

Independent evaluation of ODTT3B

• GEODYN
  • Precision OD and geodetic parameter estimation software
  • Radio-science and IV&V of navigation products
  • Weighted Batch Least Squares (WBLS) Estimator
  • Developed by the GSFC Planetary Geodynamics Laboratory

• SPC Toolkit/Lithosphere
  • Global shape model and topographic product development
  • OpNav image processing and landmark measurement generation
  • Developed by Dr. Robert Gaskell, maintained by the OSIRIS-REx SPOC at University of Arizona
• Nominal Orbit B: 1 km radius, circular orbit in the terminator plane

• Perturbations applied to “truth” trajectory propagation:
  • Initial Spacecraft State
  • Bennu Gravitational Parameter
  • Bennu Spherical Harmonic Coefficients (up to degree/order 3)
  • Bennu Orientation (RA/Dec/Rate)
  • Phasing Maneuver ΔV
  • SRP Scale Factor
  • Spacecraft Attitude
  • Spacecraft Thermal Accelerations

• Resulted in errors >300 meters after 4 days
A PRIORI ERRORS

A Priori Trajectory Errors
[Epoch: 07-OCT-2019 13:00 UTC]
SIMULATED DATA

• DSN Radiometric Data
  • Daily passes (6:30am to 2:30pm UTC)
  • Range & Doppler
  • Noise: 3 meters, 0.1 mm/s (1σ)

• NavCam OpNav Images
  • One image every 2 hours (54 total)
  • Blackout Period: 3:15pm to 8:45pm UTC
  • Attitude Errors: 1.15 mrad boresite, 1.01 mrad roll (1σ)
  • Read Noise and Dark Current Added

• Altimetric Range Measurements
  • Based on OSIRIS-REx Laser Altimeter (OLA)
  • Generated using a Digital Elevation Model (DEM) at 8 pixels per degree [PPD]
  • Raster Scan at 10,000 Hz
SYNTHETIC IMAGE RENDERING

- Synthetic surface model generated at 5cm resolution
  - Based on radar-derived shape model (20 meter resolution)

- Lens and detector model based on OSIRIS-REx NavCam

- Stochastic ray-tracing of terrain data using GSFC/Freespace
Radio-Only Solution (1/2)

- Performed an OD solution with radiometric data only
  - Provides a reasonable *a priori* estimate for automated image processing

- Solved in two arcs:
  - Up to (but not including) the phasing maneuver
  - Through the second DSN pass after the phasing maneuver

- Estimated Parameters:
  - Initial State
  - SRP Scale Factor
  - Phasing Maneuver $\Delta V$
  - Constant Acceleration Bias
  - DSN Range Bias

- Bennu geophysical parameters held fixed at *a priori* values

![Diagram showing DSN Tracking and Iteration #1 and #2 over the dates Oct 7 to Oct 12. The diagram indicates tracking and iteration activities with specific times and events.](attachment:image.png)
OpNav Image Processing

- Registered topographic maps (75 cm resolution) in the OpNav images
  - Derived from 5cm global data
  - Location of the map center (aka “landmark”) is used as an OD observable

- Processed 96 landmarks in 54 images
  - Resulted in 428 OpNav Observables
  - Average shifts of ~25 pixels

- Landmark location errors of 1 meter in each axis (1σ)
Re-calculated the OD solution with radiometric and landmark data

Solved in two arcs:
- Entire arc with geophysical parameters fixed
- Entire arc with geophysical parameters as solve-fors

Estimated Parameters:
- Initial State
- SRP Scale Factor
- Phasing Maneuver ΔV
- Constant Acceleration Bias
- DSN Range Bias
- Camera pointing at each image epoch
- Bennu-Fixed Landmark Locations
- Bennu Geophysical parameters

Final solution measurement residual statistics:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Weight</th>
<th>Number</th>
<th>Mean</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (RU)</td>
<td>24.5</td>
<td>188</td>
<td>0.00</td>
<td>21.89</td>
</tr>
<tr>
<td>Doppler (Hz)</td>
<td>0.0056</td>
<td>1738</td>
<td>0.0003</td>
<td>0.0059</td>
</tr>
<tr>
<td>OpNav, Total (pix)</td>
<td>0.45</td>
<td>428</td>
<td>-0.0234</td>
<td>0.8398</td>
</tr>
</tbody>
</table>
Radio & Landmark Solution Residuals: Landmark Sample/Line

- Sample
- Line

Residual [px] vs. Δt [days]
Radio + Landmark Solution Errors
[Epoch: 07-OCT-2019 13:00 UTC]
ADDING ALTIMETRY DATA (1/3)

- Re-calculated OD solution with radiometric, landmark, and altimetric range data

- Used a 1 PPD DEM to compute predicted measurements
  - 8 PPD used for “true” measurements

- Same solve-for parameters and filter strategy as before

- Showed a modest improvement in trajectory solution and improved geodetic parameter estimation (particularly Bennu GM)

Final solution measurement residual statistics:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Weight</th>
<th>Number</th>
<th>Mean</th>
<th>RSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (RU)</td>
<td>24.5</td>
<td>188</td>
<td>0.00</td>
<td>21.28</td>
</tr>
<tr>
<td>Doppler (Hz)</td>
<td>0.0056</td>
<td>1738</td>
<td>0.0014</td>
<td>0.0061</td>
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<tr>
<td>OpNav, Total (pix)</td>
<td>0.45</td>
<td>428</td>
<td>-0.0729</td>
<td>0.8361</td>
</tr>
<tr>
<td>Altimetric Range (cm)</td>
<td>15</td>
<td>2667</td>
<td>-0.85</td>
<td>29.5</td>
</tr>
</tbody>
</table>
Radio, Landmark, & Direct Altimetry Solution Residuals: Altimetry

Residuals [m] vs. \( \Delta t \) [days]
Radio + Landmark + Altimetry Solution Errors
[Epoch: 07-OCT-2019 13:00 UTC]

- Radial
- In-Track
- Cross-Track
- RSS
### Bennu Geophysical Parameter Estimation (1/2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Truth</th>
<th>Without Altimetry</th>
<th>With Altimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM, $\mu$ (m$^3$/s$^2$)</td>
<td>5.1969</td>
<td>5.1626</td>
<td>5.1954</td>
</tr>
<tr>
<td>RA, $\alpha$ (deg)</td>
<td>86.6388</td>
<td>86.5730</td>
<td>86.6205</td>
</tr>
<tr>
<td>Dec, $\delta$ (deg)</td>
<td>-65.1086</td>
<td>-65.1207</td>
<td>-65.1165</td>
</tr>
<tr>
<td>Constant, $\omega_0$ (deg)</td>
<td>89.6456</td>
<td>89.6454</td>
<td>89.6453</td>
</tr>
<tr>
<td>Rate, $\omega$ (deg/day)</td>
<td>2010.489449</td>
<td>2010.489433</td>
<td>2010.489404</td>
</tr>
</tbody>
</table>
Radio + Landmark + Altimetry Gravity Coefficient Estimation

Value [Normalized]

-0.06 -0.04 -0.02 0 0.02

C_{20} C_{21} C_{22} C_{30} C_{31} C_{32} C_{33} S_{21} S_{22} S_{31} S_{32} S_{33}

Truth
A Priori
A Posteriori

Error

0 0.005 0.01 0.015

C_{20} C_{21} C_{22} C_{30} C_{31} C_{32} C_{33} S_{21} S_{22} S_{31} S_{32} S_{33}

Truth - A Posteriori
Formal Uncertainty [1\sigma]
SUMMARY

- Successfully completed an independent OD and OpNav simulation of the Orbit B mission phase
  - Interfaces between OD and OpNav software worked properly
  - Refined procedures and solution strategies
  - Definitive solution accuracy of <4 meters
  - Consistent solutions across FDS software and organizations

- Verified that short-arc solutions are not favorable for geophysical parameter estimation, but trajectory still meets requirements
  - Expected for a four-day arc with realistic perturbations to the dynamics
  - Will rely on a nine-day, uninterrupted radio-science campaign at the beginning of Orbit B

- Incorporating altimetry data resulted in a modest improvement in solution accuracy, notably:
  - Radial component of the trajectory
  - Bennu geophysical parameters (specifically GM)