OSIRIS-REx Orbit Determination Covariance Studies at Bennu

AAS 16-101
February 9, 2016

39th Annual AAS Guidance & Control Conference
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**Origins Spectral Interpretation Resource Identification Security Regolith Explorer Mission**

**Institutional Partners**
- **Principal Investigator** UA
- **Project management** — GSFC
- **Spacecraft contractor/Mission Ops** — LMSSC
- **Instrument providers** — UA, ASU, GSFC, CSA, MIT
- **Navigation** — KinetX / GSFC
- **Science ops & science data center** — UA SPOC

**Mission Facts (7.1 year mission)**
- **Launch** (ATLAS V–411), September 3rd, 2016 (39 day launch window)
- **Earth Fly-By**, September 2017
- **Asteroid Approach Maneuver**, October 2018
- **Touch-And-Go (TAG) Sample Collection**, August 2019
- **Asteroid Departure Maneuver**, March 2021
- **Sample Return Capsule (SRC) Release**, September 24, 2023
- **3-axis-stabilized spacecraft**, with gimbaled solar arrays
- **5 Payloads & Touch-And-Go Sample-Acq-Mechanism (TAGSAM)**
Asteroid Bennu Overview

- Bennu (formally 1999 RQ36) is a primitive B-class, Near-Earth, carbonaceous (volatile-rich) asteroid, a class of object never before visited by a spacecraft.
- Its size, shape, and rotation state are known from extensive characterization by the Arecibo Planetary Radar System.
  - About 500 m diameter, 4.3 hr rotation period, 436.6 day orbit of Sun, 350 K maximum surface temperature, 3% geometric albedo, micro-gravity environment.
- Study of this Potentially Hazardous Asteroid is strategically important to NASA and Congress.
Asteroid Bennu – One of the Smallest Small Bodies Ever Visited

- Bennu is one of the smallest objects ever visited:
  - Mean Diameter = 492 ± 20 meters (1-sigma uncertainty)
  - \( M = (7.8 \pm 0.9) \times 10^{10} \) kg
    (1-sigma uncertainty)
  - \( GM = \mu = 5.2 \) (3-sigma uncertainty 3.4 to 7.0 m\(^3\)/s\(^2\))
- OSIRIS-REx is operating in very close proximity to Bennu, to include contact with the surface:
  - Safe “home” orbit has 1 km radius
- Large *a priori* uncertainty in mass, shape/features, spin axis/rate/pole, albedo and surface properties

Bennu

Itokawa

\[ 535 \times 294 \times 209 \text{ m} \]
\[ (3.51\pm0.105)\times10^{10} \text{ kg} \]

Bennu

\[ 492 \text{ m} \]
\[ (7.8 \pm 0.9) \times 10^{10} \text{ kg} \]

Comet 67P

\[ 4.1 \times 4.5 \text{ km}, (1.0\pm0.1)\times10^{13} \text{ kg} \]
Telecom: fixed HGA provides high data rates without gimbaled HGA complexity (& MGA/LGAs)

MGA for TAG Coverage and long-range-cruise safe mode (not shown)

Flight-Proven Stardust-Heritage Sample Return Capsule (SRC)

2-axis gimbaled Solar Arrays

-X LGA for inner cruise (SPE*>90°)
+X LGA Farside (not shown) (SPE*<90°)
* SPE = Sun-Probe-Earth Angle

Single plane of motion TAGSAM w/potentiometers provides simple & reliable positioning

Science Deck
**NAVIGATION SENSORS**

- **NavCam (MSSS)**
  - Primary wide-angle navigation camera

- **GN&C Flash Lidar (ASC)**

- **PolyCam (University of Arizona)**
  - POLYCAM acquires Bennu from 2M km range and refines its ephemeris, performs hi-res survey
  - Primary camera for imaging asteroid and field stars on approach

- **MapCam (University of Arizona)**
  - MAPCAM performs filter photometry and maps the surface
  - Primary camera for landmark tracking during survey

- **OLA Science Lidar (MDA)**
**Optical Navigation Phases: Star-based to Landmarks**

- Optical Navigation images are needed to determine spacecraft state errors to the required level of accuracy.
- Differences between observed and modeled positions of target objects are used to update the spacecraft position & camera pointing.

**Approach**

Target body is unresolved and appears against a background of stars.

**Transition**

Target body is partially/fully resolved, stars are still visible.

**Proximity Ops**

Target body surface fills the entire FOV, no stars or limbs visible.
CHALLENGES FOR SMALL BODY NAVIGATION

• Small perturbations result in large predictive errors in the S/C trajectory down-track position over relatively short periods
  • Small non-gravitational forces 1–10 nm/s²
    • From solar radiation pressure mis-modeling, S/C thermal radiation, asteroid IR and albedo
  • Small ΔV’s momentum desaturation maneuvers are a significant orbital perturbation
    • FDS analysis assumes residual ΔV from a desat is:
      • < 0.5 mm/s (1σ) every 3 days (CBE < 0.1 mm/s (1σ) )
      • or < 2 mm/s (1σ) every 10 days

• Science observations, maneuver designs require 10’s of meters position accuracy
  • Navigation prediction errors are large relative to orbital radius
  • Requires precise characterization of the small forces to levels less than past planetary or small body missions
  • Also requires frequent late-update OD deliveries to support the rapid pace of maneuvers and observations

• TAG sequence requires down-track errors < 30 m (1σ)
  • This requires non-grav forces to be determined ≤ 3 nm/s²
    • Assuming a late-update OD with a data cutoff of 24 hrs before Orbit departure
### ProxOps Timeline at Bennu and Science Team Deliveries to FDS

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Sept 18</th>
<th>Oct 18</th>
<th>Nov 18</th>
<th>Dec 18</th>
<th>Jan 19</th>
<th>Feb 19</th>
<th>Mar 19</th>
<th>Apr 19</th>
<th>May 19</th>
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<th>Oct 19</th>
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<td>Navigation Campaign</td>
<td>Site Selection</td>
<td>Collect &amp; Stow</td>
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<td>ProxOps Phase</td>
<td>Approach</td>
<td>PS</td>
<td>Orb-A</td>
<td>Detailed Survey</td>
<td>Orbital-B, Safe Home, Sorties</td>
<td>TAG</td>
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</table>

#### Events:
- AAMs 1-4
- Enc
- Orbit-A Insertion 12/17/18
- Radio Science Gravity Experiment 3/26/19
- 255-m, 625-m Recon Passes 5/13/19
- Rehearsal 10/12/19
- TAG 10/12/19

#### Deliveries:
- SPOC Deliveries to FDS
- Down select & site Final Site Selection 8/21/19

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MAJOR FORCES IN 1-KM ORBIT

Major Forces acting on Orex during Orbit-B

Accelerations (km/s²)

16-Feb-19 00:00 - 30-Mar-19 00:00

- Total central body
- S/C IR
- Sun 3rd body
- Earth 3rd body
- Jupiter 3rd body
- Infrared albedo
- 4x4 gravity

Legend:
- Albedo
- Pluto
- Venus
- Infrared
- Moon
- Solar
- Earth
- Central
- Relativity
- Oblate
- Saturn
- Mars
- Total
- Mercury
- Neptune
- Uranus
- Sun
THERMAL MODEL ORBITAL POSITIONS

HGA-to-Earth Attitude
SPE = 72.5°

Eq. X Sunrise
Position 4
194733 sec
Bennu North

Eq. X Sunset
Position 2
146125 sec

Orbital B
0.93 AU on
03/01/2019

Bennu South
Position 3
170479 sec

X_SC out of page
Y_SC
Z_SC
# Spacecraft IR Forces

![Spacecraft IR Forces Diagram](image)

### Thermal Model

<table>
<thead>
<tr>
<th>Thermal Model</th>
<th>Solar Dist (AU)</th>
<th>Attitude</th>
<th>Along Each S/C Axis (Face only)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td>X (nm/s²)</td>
<td>Y (nm/s²)</td>
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<tr>
<td>Model 1</td>
<td>1.35</td>
<td>Nadir</td>
<td>-2.58</td>
<td>-0.04</td>
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<td></td>
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<td>HGA</td>
<td>-1.46</td>
<td>-0.03</td>
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<tr>
<td>Model 2</td>
<td>0.93</td>
<td>Nadir</td>
<td>-6.47</td>
<td>-0.05</td>
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<td>HGA</td>
<td>-2.33</td>
<td>-0.03</td>
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</table>

<table>
<thead>
<tr>
<th>SRP @ AU (nm/s²)</th>
<th>X/SRP</th>
<th>Z/SRP</th>
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<tr>
<td>28</td>
<td>12%</td>
<td>2.9%</td>
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<tr>
<td>7.0%</td>
<td>7.6%</td>
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<tr>
<td>65</td>
<td>13%</td>
<td>3%</td>
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<tr>
<td>7.7%</td>
<td>7.7%</td>
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</tbody>
</table>

* HGA Attitude: HGA (+X) at Earth, Sun in X-Z plane
**PROXOPS FILTER STRATEGY**

- Significant Filter Estimated Parameters
  - S/C epoch state
  - Solar Pressure
  - Bennu ephemeris, pole, prime meridian, spin, GM, 4x4 gravity field
  - 3-axis Stochastic non-grav. acceleration to account for small forces
    - (S/C IR, asteroid IR, albedo, SRP)(1-day batches, white noise)
  - Stochastic image pointing errors
    - (batched per image, white noise)
  - Maneuvers (direction, ΔV magnitude)
  - Desat ΔV’s (every 3–10 days)

- Measurements
  - X-band Radio-metric Tracking:
    - 2-way Doppler 8 hrs / day
    - 2-way Range 4 hrs / day
  - Star-based, Landmark OpNavs
    - Star-based: up to 1 / day during Approach through Orbital-A
    - Landmark-based: 8-12 images / day, 1 image every 3–2 hrs
      - Total Landmarks placed equidistant (40 baseline / 100 CBE)

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BENNU GM IMPROVEMENTS

GM Errors (1-sigma)

Priori GM error: 100%

2.0 km Orbit Insertion
1.5 km Orbit Insertion

Preliminary Survey
Orbital-A
Baseball Diamond

< 2% after South Pole Flyby
< 1% after M3A, (2 km Orbit Insertion)
DETAILED SURVEY – MID-LATITUDE OBSERVATIONS

26 Dec 2018 00:20:15.220

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Detailed Survey – Predicted S/C State Errors During Mid-Latitude Observations

2σ Latitudinal Errors

Position (km)

00:00:00 12-Jan-2019
00:00:00 13-Jan-2019
00:00:00 14-Jan-2019
00:00:00 15-Jan-2019
00:00:00 16-Jan-2019

Velocity (km/sec)

50–70 m

~100 m

HGA  LGA  OpNav
**Detailed Survey – Predicted S/C State Errors During Mid-Latitude Observations**

![Graph](image)

**2σ Longitudinal Errors**

- Position (km)
- Velocity (km/sec)

- 80–100 m
- ~110 m

- MNVR
- DCO
- DESAT

12-Jan-2019 to 16-Jan-2019

HGA, LGA, OpNav
DETAILED SURVEY – EQUATORIAL OBSERVATIONS
Detailed Survey – Predicted S/C State Errors During Equatorial Observations

2σ Latitudinal Errors

Observation period

Position (km)

Days from Observation

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DETAILED SURVEY – PREDICTED S/C STATE ERRORS DURING EQUATORIAL OBSERVATIONS

2σ Longitudinal Errors

- Observation period
- 25 m
- 50 m
- Equatorial Observations
- 2nd Observations During high phase legs (Plume survey)
**Orbital-B**

**Orbit Insertion**

- M0B
- M1B
- M2B
- M3B

**Terminator Orbit**

- 1 km

**Maneuver Description**

<table>
<thead>
<tr>
<th>Maneuver Description</th>
<th>Date</th>
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<tbody>
<tr>
<td>29_Target Orbit A Maneuver M0B</td>
<td>2/8/2019</td>
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<tr>
<td>29_Inset Orbit A Maneuver M1B</td>
<td>2/10/2019</td>
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<tr>
<td>30_Target Orbit B Maneuver M2B</td>
<td>2/16/2019</td>
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<tr>
<td>30_Inset Orbit B Maneuver M3B</td>
<td>2/18/2019</td>
</tr>
</tbody>
</table>

**OSIRIS_R_Mag (km):** 1.164601
**OSIRIS_Decimal (deg):** 55.719
**OSIRIS_Right_Asc (deg):** -89.320
ORBITAL-B – PREDICTED S/C TRANSVERSE ERRORS

Transverse Orbit Errors (1-sigma) in Orbit-B

Req. for State at ODM/TAG: 0.028 km 1σ

Filtered

Predicted

- Baseline no desats
- CBE no desats
- Baseline with desats
- CBE with desats

Position Error (km)

1e-01
1e-02
1e-03
1e-04
1e-05

Velocity Error (km/s)

1e-06
1e-07
1e-08

10/06/19 10/07/19 10/08/19 10/09/19 10/10/19 10/11/19 10/12/19 10/13/19 10/14/19

65 m
44 m
19 m
8 m
ORBITAL-B – PREDICTED S/C STATE ERRORS† (1σ)  
NO DESATS

No Desat Errors in Predictions

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<tr>
<th>Case</th>
<th>Desats in predict</th>
<th>Map Time</th>
<th>R (m)</th>
<th>T (m)</th>
<th>N (m)</th>
<th>DR (mm/s)</th>
<th>DT (mm/s)</th>
<th>DN (mm/s)</th>
<th>Downtrack Timing Error</th>
<th>Downtrack Pt Error (deg)</th>
<th>Crosstrack Pt Error (deg)</th>
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<td><strong>At DCO</strong></td>
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<td>.1 min</td>
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<td>11-Oct-19 12:00</td>
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<tr>
<td>Baseline</td>
<td>None</td>
<td>7-Nov-19 12:00</td>
<td>335.41</td>
<td>6775.91</td>
<td>15.86</td>
<td>600.60</td>
<td>1.37</td>
<td>3.85</td>
<td>26.1 hr</td>
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<td>7-Nov-19 12:00</td>
<td>112.52</td>
<td>2267.19</td>
<td>2.96</td>
<td>201.00</td>
<td>0.64</td>
<td>1.45</td>
<td>8.73 hr</td>
<td>129.9</td>
<td>0.2</td>
</tr>
</tbody>
</table>

†Assumes T error maps directly into down-track timing, true anomaly or pointing error of circular orbit
### Orbital-B – Predicted S/C State Errors \( ^\dagger \) (1\( \sigma \)) With 3-Day Desats

<table>
<thead>
<tr>
<th>Case</th>
<th>Desats in predict</th>
<th>Map Time</th>
<th>R (m)</th>
<th>T (m)</th>
<th>N (m)</th>
<th>DR (mm/s)</th>
<th>DT (mm/s)</th>
<th>DN (mm/s)</th>
<th>Downtrack Timing Error</th>
<th>Downtrack Pt Error (deg)</th>
<th>Crosstrack Pt Error (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>At DCO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>using mean motion*time</td>
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<tr>
<td>Baseline</td>
<td>Desats</td>
<td>10-Oct-19 12:00</td>
<td>0.64</td>
<td>0.55</td>
<td>0.38</td>
<td>0.06</td>
<td>0.09</td>
<td>0.04</td>
<td>.1 min</td>
<td>0.0</td>
<td>0.0</td>
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<td>Desats</td>
<td>10-Oct-19 12:00</td>
<td>0.46</td>
<td>0.29</td>
<td>0.31</td>
<td>0.03</td>
<td>0.08</td>
<td>0.03</td>
<td>.1 min</td>
<td>0.0</td>
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<tr>
<td><strong>Predict 1 day</strong></td>
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<tr>
<td>Baseline</td>
<td>Desats</td>
<td>11-Oct-19 12:00</td>
<td>7.14</td>
<td>65.34</td>
<td>1.92</td>
<td>4.50</td>
<td>0.24</td>
<td>0.02</td>
<td>15.1 min</td>
<td>3.7</td>
<td>0.1</td>
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<td>2.92</td>
<td>0.13</td>
<td>0.02</td>
<td>10.1 min</td>
<td>2.5</td>
<td>0.2</td>
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<tr>
<td><strong>Predict 2 days</strong></td>
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<td></td>
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<tr>
<td>Baseline</td>
<td>Desats</td>
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<td>9.87</td>
<td>156.30</td>
<td>1.77</td>
<td>10.95</td>
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<td>36.1 min</td>
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<tr>
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<td>Desats</td>
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<td>6.65</td>
<td>0.14</td>
<td>0.03</td>
<td>22.5 min</td>
<td>5.6</td>
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<tr>
<td><strong>Predict 1 week</strong></td>
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<tr>
<td>Baseline</td>
<td>Desats</td>
<td>17-Oct-19 12:00</td>
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<td>1082.00</td>
<td>7.99</td>
<td>77.13</td>
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<td>0.83</td>
<td>4.17 hr</td>
<td>62.0</td>
<td>0.5</td>
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<tr>
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<td>813.00</td>
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<td>57.50</td>
<td>0.83</td>
<td>0.75</td>
<td>3.13 hr</td>
<td>46.6</td>
<td>0.4</td>
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<td><strong>Predict 2 weeks</strong></td>
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<tr>
<td>Baseline</td>
<td>Desats</td>
<td>24-Oct-19 12:00</td>
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<td>2973.00</td>
<td>18.78</td>
<td>218.90</td>
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<td>1.78</td>
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<td>24-Oct-19 12:00</td>
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<td>2204.00</td>
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<td>8.49 hr</td>
<td>126.3</td>
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</tr>
<tr>
<td>Baseline</td>
<td>Desats</td>
<td>7-Nov-19 12:00</td>
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<td>8984.00</td>
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<td>7-Nov-19 12:00</td>
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<td>5.39</td>
<td>6.73</td>
<td>23.51 hr</td>
<td>349.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>

\( ^\dagger \) Assumes T error maps directly into down-track timing, true anomaly or pointing error of circular orbit.
DCO+ 1 DAY
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO+ 2 DAYS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO + 3 DAYS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO + 4 DAYS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO + 5 DAYS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO + 6 DAYS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO+1 WEEK
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
DCO+2 WEEKS
No Desats

Orbital-B
1-km Orbit
Orbit Period: ~ 24 hrs
OSIRIS-REx mission requires unprecedented levels of navigation performance during Bennu Proximity Operations.

- Science Observations, Orbit insertion, Recon and TAG require predicted state errors to be on the order of 10’s of meters.
  - This in turn requires late OD deliveries for updating the planned maneuver or Science observation with OpNav images shuttered ~24 hrs before the event.
- Successful TAG requires the non-gravitational forces to be characterized ≤ 3 nm/s² level.
- Rapid cadence of maneuvers and observation plans are required to meet Mission & Science Objectives.
Backup
OSIRIS-REx

**Defined**

- **Origins**
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **Spectral Interpretation**
  - Provide ground truth for telescopic data of the entire asteroid population
- **Resource Identification**
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **Security**
  - Measure the Yarkovsky effect on a potentially hazardous asteroid
- **Regolith Explorer**
  - Document the regolith at the sampling site at scales down to the sub-cm

**Mission Success**

- **Rendezvous** with asteroid Bennu
- **Contact** the asteroid surface with TAGSAM and collect a sample
- Safely return asteroid sample to Earth and deliver them to the curatorial facility at the NASA Johnson Space Center
- Provide for the initial analysis and plan for the long-term curation of the returned sample
- Ensure a sample allocation process is in place to conduct early science return studies as well as long-term general studies
TWO-YEAR CRUISE

Launch: Sep 4, 2016
EGA: Sep 22, 2017
Bennu Encounter: Nov 19, 2018

DSM-1: Jan 6, 2017
DSM-2: Dec 2, 2017
OREX: 2-yr Outbound Cruise

Earth
Sun
Bennu