ORBIT STABILITY OF OSIRIS-REX IN THE VICINITY OF BENNU USING A HIGH-FIDELITY SOLAR RADIATION MODEL

OSIRIS-REX™
ASTEROID SAMPLE RETURN MISSION

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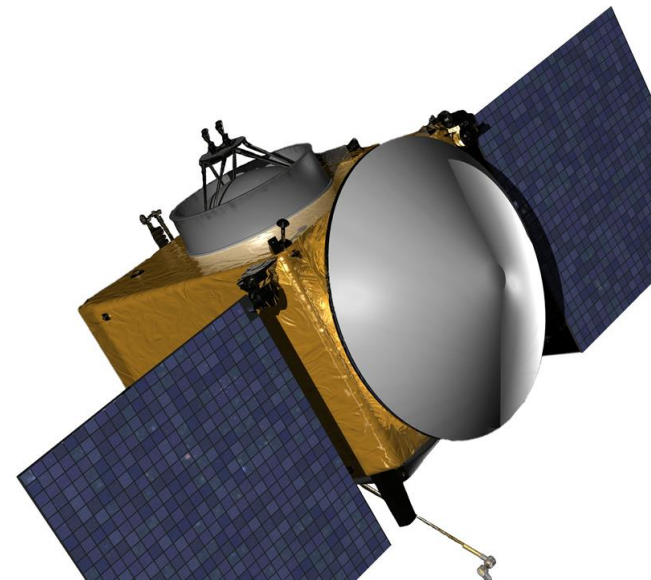ALINDA MASHIKU*
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THE UNIVERSITY OF ARIZONA – NASA GODDARD SPACE FLIGHT CENTER – LOCKHEED MARTIN - KINETX

AGENDA

- INTRODUCTION and PROBLEM STATEMENT
- SOLAR RADIATION PRESSURE MODELING
- STABILITY DESIGN – VARIATION OF PARAMETERS (VOP)
- RESULTING ORBIT DESIGNS
- CONCLUSIONS

MOTIVATION

- The OSIRIS-REx mission (Origins Spectral Interpretation Resource Identification Security Regolith EXplorer) is an asteroid sample return mission to Bennu (RQ36) that is scheduled to launch in 2016.
- The planned science operations precluding the sample retrieval involve operations in terminator orbits (orbit plane is perpendicular to the sun).
- Over longer durations the solar radiation pressure (SRP) perturbs the orbit causing it to preccess.

OUR WORK INVOLVES:

- Modeling high fidelity SRP model to capture the perturbations during attitude changes.
- Design a stable orbit from the high fidelity models to analyze the stability over time.

PROBLEM STATEMEMT

- Develop High-fidelity SRP model (using SPAD tool)
  - Considers absorption, specular reflection, and diffuse reflection
  - Uses ray-tracing method to model path of sunlight (on OSIRIS-REx spacecraft model)
  - Propagate Orbit B in GMAT using:
    - High-fidelity SRP force model (from SPAD)
    - 16th-order gravity model
    - 3rd body perturbations: Sun, Jupiter, Earth, and Moon
- Compare with cannonball model
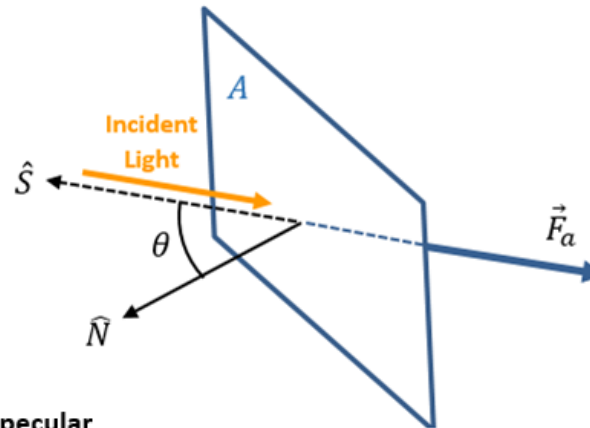- Design a stable orbit using Variation of parameters (VOP).
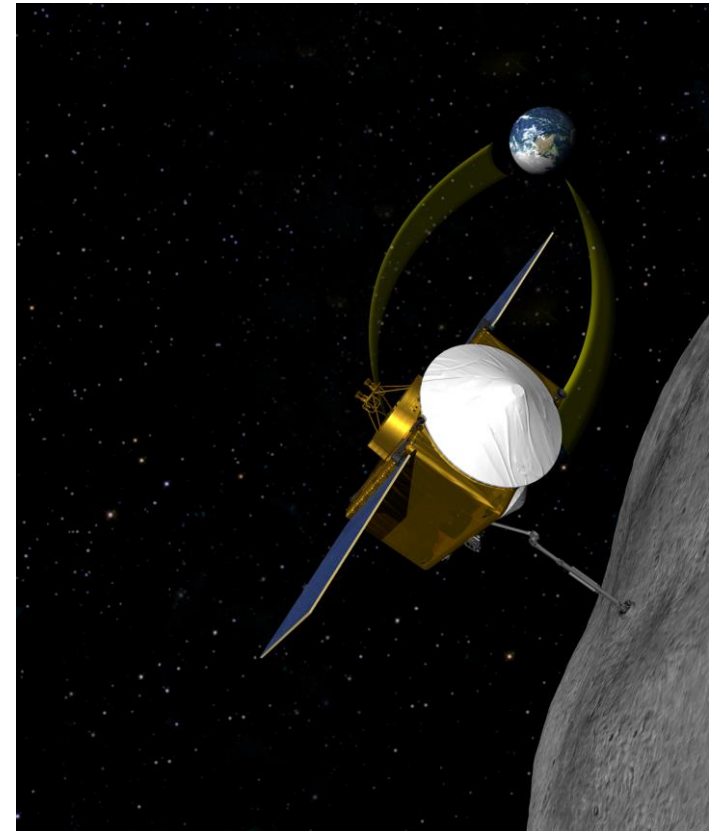
OSIRIS-REx's Orbit B

- What is Orbit B:
  - Circular 1 km orbit about Bennu (altitude of ~3 R_B)
  - Terminator orbit (orbit normal vector directed at Sun)
  - Key Activity: gather optical data for 12 TAG sites and map gravity field
- OSIRIS-REx orientation during Orbit B
  - Nominal: nadir pointing, with solar panels directed at Sun
  - HGA Pointing: Each (Earth) day, HGA pointed at Earth (for 8 hrs), with body-fixed z axis pointed at Sun (approximately)
  - Attitude changes cause change in SRP force on spacecraft—which needs to be modeled for a high-fidelity trajectory simulation
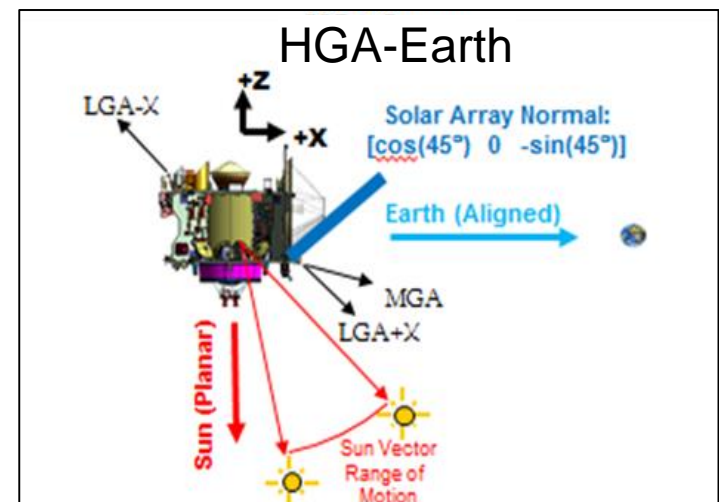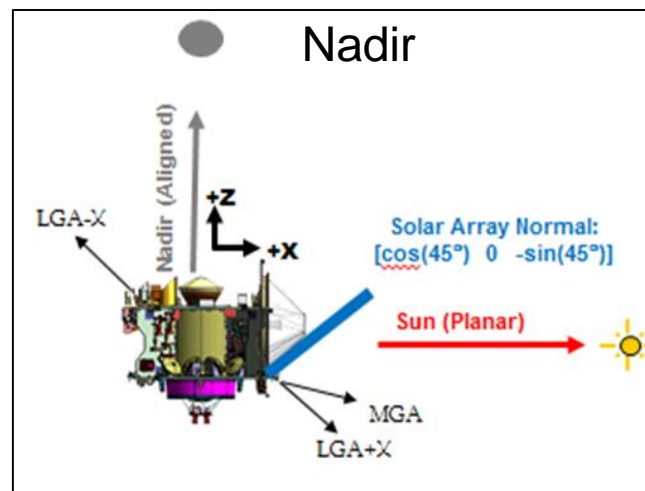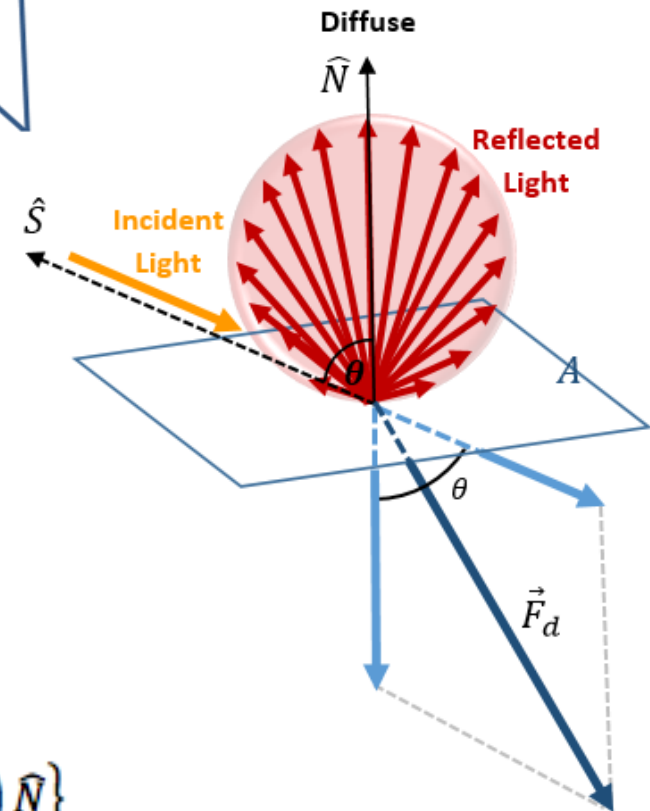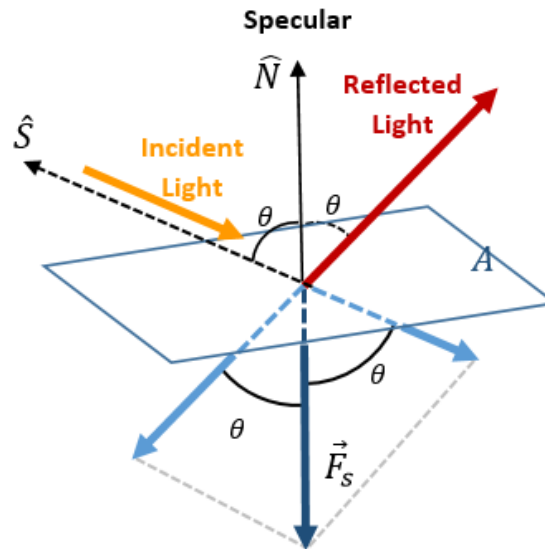
SOLAR RADIATION FORCE MODEL

Absorbed Light

Reflected Light

$$\vec{F}_{SRP} = \vec{F}_a + \vec{F}_s + \vec{F}_d$$

$$= -P_{SRP}A cos\theta \left\{ (1 - C_s)\hat{S} + 2 \left(C_s cos\theta + \frac{1}{3}C_d \right) \hat{N} \right\}$$

RAY TRACING

- Ray tracing is the process of following the path of a light ray as it absorbs and/or reflects off of various surfaces of an object.

- Used to model the SRP forces acting on the spacecraft in high fidelity

  - Create pixel array normal to Sun-spacecraft vector

  - Project points at each pixel center onto spacecraft surface

 - Compute SRP force at each surface contact point and find net force
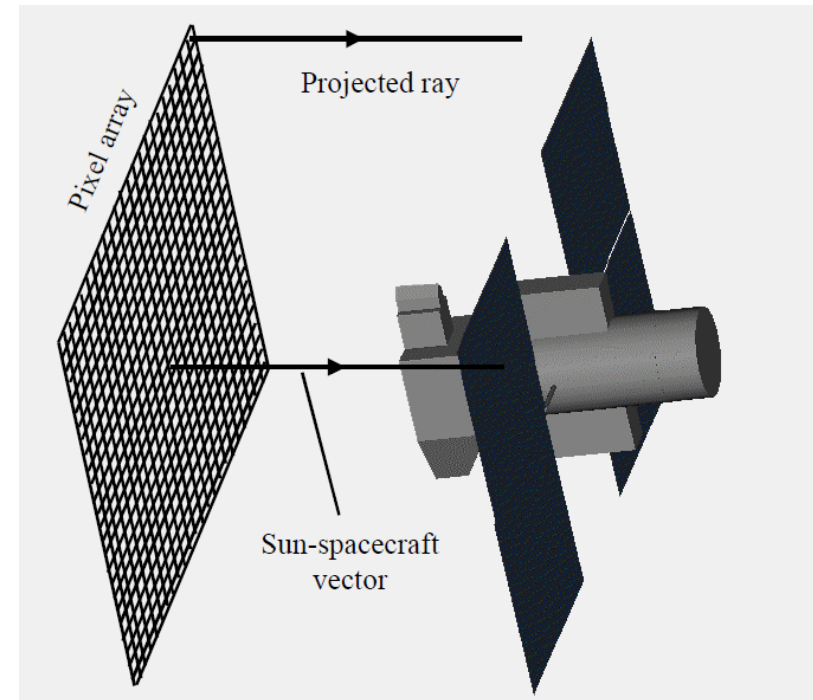
Ziebart, M., and Dare, P., "Analytical Solar Radiation Pressure Modeling for GLONASS using a Pixel Array", *Journal of Geodesy*, Vol. 75, 2001.

OSIRIS-REx CAD Model for SPAD Analysis

- Ray tracing modeled using the Solar Pressure and Aerodynamic Drag (SPAD) tool, developed at GSFC in Code 595, Navigation and Mission Design Branch

- The tool takes in inputs of:
  - Material properties (emissivity etc)
  - Dimensions (to generate CAD model)
  - Pixel size (for light-ray grid)
  - Azimuth and elevation (S/C model orientation)

- SPAD outputs the Force/SRP

- Trajectory propagation tool (GMAT) computes force on S/C using computed Sun-S/C distance, and specified S/C attitude.
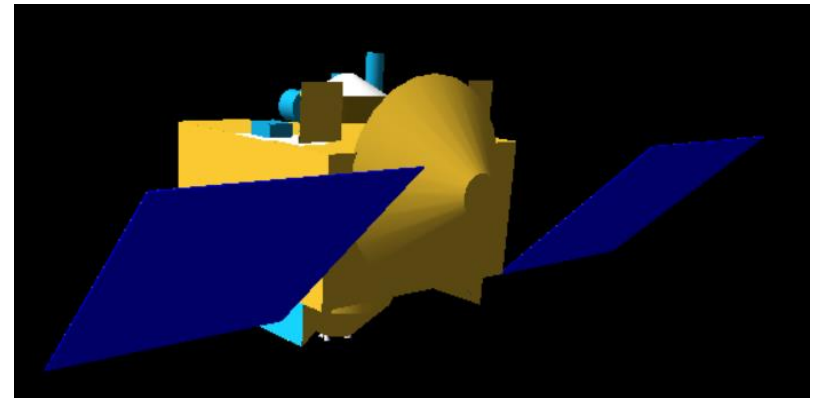
SPAD-generated OSIRIS-REx model

VARIATION OF PARAMETERS

Assumptions

- The following assumptions will be made for the purposes of this analysis.

- The orbit of the spacecraft about the asteroid is high enough that an inverse square law asteroid gravity model suffices. (For the case of OSIRIS-Rex Orbit B, the orbital radius is roughly equal to four asteroid radii, so this assumption is certainly valid.)

- The eccentricity of the spacecraft orbit about the asteroid is small enough that first-order modeling of eccentricity effects is valid.

- The spacecraft is in a near-terminator orbit about the asteroid.

- The spacecraft has a constant ratio of projected area to the Sun and mass, and behaves as a pure solar absorber.

- The changes in the spacecraft orbital elements that are caused by solar radiation pressure occur slowly enough that integration over a complete spacecraft orbit, using constant element values in the VOP equations across this range, is valid.

VOP EQUATIONS

$$\dot{a} = \frac{2}{n\sqrt{1-e^2}}\left\{e\sin n\, a_R + (1+e\cos n)a_S\right\}$$

$$\dot{e} = \frac{\sqrt{1-e^2}}{na}\left\{\sin n\, a_R + \frac{(e+2\cos n + e\cos^2 n)}{(1+e\cos n)}a_S\right\}$$

$$\dot{i} = \frac{r\cos(w+n)}{na^2\sqrt{1-e^2}}a_W$$

$$\dot{w} = \frac{r\sin(w+n)}{na^2\sqrt{1-e^2}\sin i}a_W$$

$$\dot{w} = \frac{\sqrt{1-e^2}}{nae}\left\{-\cos n\, a_R + \sin n\frac{(2+e\cos n)}{(1+e\cos n)}a_S - \frac{e\cot i\sin(w+n)}{(1+e\cos n)}a_W\right\}$$

AVERAGED PER-REV ELEMENT CHANGES

- The components of SRP perturbation acceleration in the spacecraft rotating RSW frame can be computed and put into the Gaussian VOP equations, giving the instantaneous variations in each orbital element
- Since the spacecraft orbit has $e << 1$, linearization of eccentricity effects is acceptable
- Integrating over a complete spacecraft rev gives the per-rev changes in the spacecraft orbital elements:

$$\Delta a \approx 0,$$

$$\Delta e \approx -3(\pi / m)(1 - e^2)^3 a^2 p_s (c_r A / m)\sin I \sin y,$$

$$\Delta i \approx 3(\pi / m)e(1 - e^2)^2 a^2 p_s (c_r A / m)\cos I \cos W,$$

$$\Delta W \approx 3(\pi / m)e(1 - e^2)^2 a^2 p_s (c_r A / m)\operatorname{cosec} i \cos I \sin W,$$

$$\Delta w \approx 3(\pi / m)e^{-1}(1 - e^2)^2 a^2 p_s (c_r A / m)\left\{\sin I \cos y - e^2 \cot i \cos I \sin W\right\}.$$

USE FOR STABLE TERMINATOR ORBIT DESIGN

- Desired geometry of spacecraft orbit about asteroid:
  - Angle λ either 0 (giving CCW spacecraft motion about asteroid as viewed from the Sun) or 180 deg (CW motion)
  - Inclination (relative to orbital plane of asteroid) 90 deg
  - All elements constant except for RAAN: this must precess at asteroid orbital rate, in order for orbit to remain on terminator
- The conditions on λ and i imply that the per-rev changes in e and ω will be zero, as desired
- Zero per-rev change in i is obtained by setting ω to either 90 deg (CCW motion case) or 270 deg (CW)
- Selecting the correct eccentricity value (see next slide for expression) can then be used to adjust the per-rev change in Ω to give the desired nodal regression rate
- Mechanism: if orbit is eccentric (here, mildly so), SRP gives a net out-of-plane Δv centered at apogee: this torques orbit, changing Ω (but not i, for ω as selected)

ORBIT B SCENARIO

SRP-Stable Orbit B

- A SRP-stable orbital eccentricity value of 0.139, using the following numerical values that correspond to OSIRIS-Rex Orbit B:
- Spacecraft
  - mass (during Orbit B): $m = 1{,}198$ kg
  - projected area: $A = 12\ m^2$
  - coefficient of reflectivity: $c_r = 1.4$
  - mean orbital speed: $v_{orb} = 0.06450$ m/s
- Bennu gravitational parameter: $\mu = 4.16$ km^3/s^2
- Spacecraft-orbit semi-major axis (about Bennu): $a = 1{,}000$ m (4 times asteroid radius of ~250 m)
- Bennu's mean motion (heliocentric): $n = 1.67 \times 10^{-7}$ rad/s
- Bennu's solar distance: 1.11 AU
- SRP: $p_s = 3.69 \times 10^{-6}$ N/m^2
- The corresponding spacecraft apoapse and periapse radii are 1,139 m, and 861 m, respectively.

CANNONBALL

A

B

- In this view, an un-perturbed terminator orbit would appear as a single circle or ellipse. The yellow arcs shown in the figures represent times when the spacecraft is in its nadir-pointing orientation (16 hrs per day), and the blue arcs represent times when the spacecraft is oriented with its HGA directed at Earth (8 hrs per day). For a spherical spacecraft however, the orientation changes make no impact on the SRP force or the trajectory.

- Figure A shows the propagated Orbit B trajectory using the nominal initial orbit conditions (with $e = 0$), and Figure B shows the Orbit B propagation with the redesigned orbit ($e = = 0.139$). Over the 60-day propagation, both trajectories exhibit perturbation; however, the redesigned trajectory in Figure B is clearly improved.
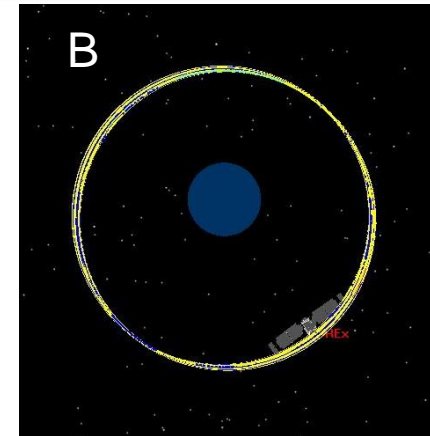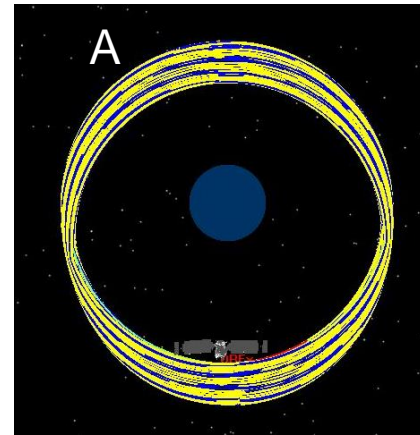
Orbit B Propagations: Cannonball SRP Model, A = 12 m^2

Legend: Nominal Orbit; $e = 0.139$, $\omega = 90^o$; $e = 0.125$, $\omega = 90^o$

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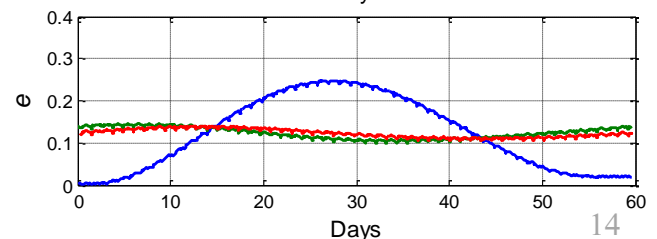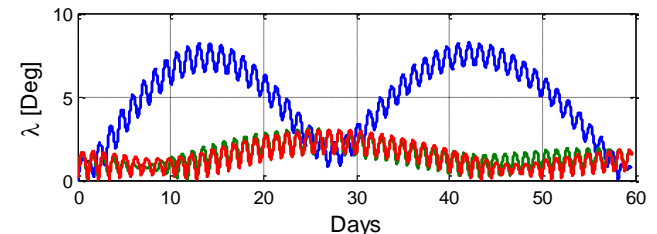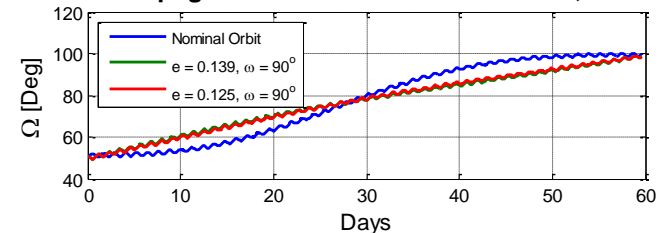
SPAD MODEL

The top figures show the trajectory in the Bennu-Sun rotating frame (similar to that of Figure 6), where the view is along the Bennu-Sun direction. The propagation of the Orbit B trajectory using the nominal initial orbit conditions (with $e = 0$) is shown in Figure A and the propagation of the stabilized Orbit B (with $e = = 0.139$) is shown in Figure B.
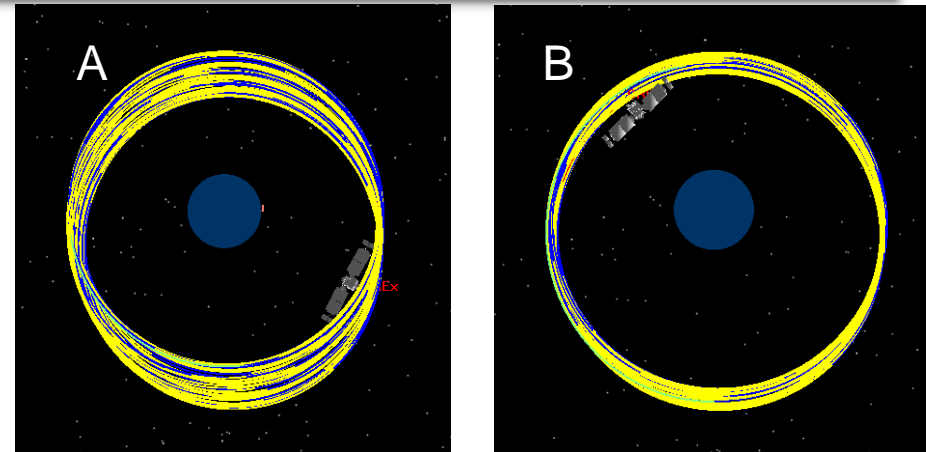
Both trajectories are clearly perturbed; however, the designed trajectory in Figure B exhibits less perturbation over the 60-day simulation. The yellow arcs shown in the figures represent times when the spacecraft is in its nadir-pointing orientation, and the blue arcs represent times when the spacecraft is oriented with its HGA directed at Earth. Unlike with the cannonball SRP model, however, the orientation changes do have an impact on the SRP force, and thus, the resulting propagation of Orbit B.

Orbit B Propagations: SPAD SRP Model

Legend:
- Nominal Orbit
- $e = 0.139,\ \omega = 90^\circ$
- $e = 0.114,\ \omega = 90^\circ$

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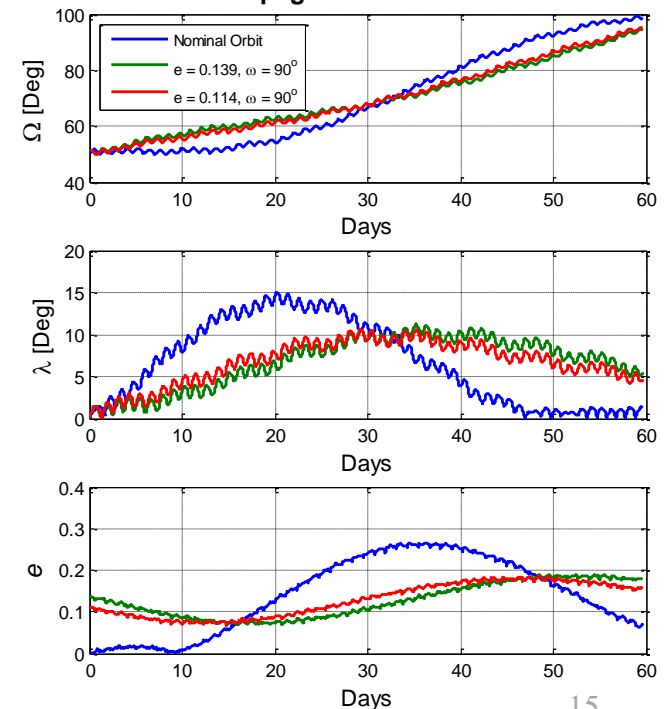
CONCLUSIONS

- SRP plays a significant role in maintaining the nominal terminator orbit about Bennu

- Significant differences in trajectories found between cannonball and SPAD SRP models

- Designed new SRP-stable terminator orbit using VOP equations, which requires an eccentricity of about 0.139

BACKUP SLIDES

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The results show that there are significant differences between the three trajectories investigated for this analysis—one key difference being the variation in eccentricity.

The SPAD and 12-m2 cannonball cases exhibit a lag in Ω precession (compared to the 20-m2 cannonball case). A key contributor to this precession lag seems to be the smaller amount of SRP force experienced by the SPAD and 12-m2 cannonball models (which is due to their smaller cross-sectional areas).

The lag in Ω precession increases the deviation between the orbit normal and the Sun direction, which is shown by the increase in the amplitude of β (the angle between the orbit normal vector and the Sun line).
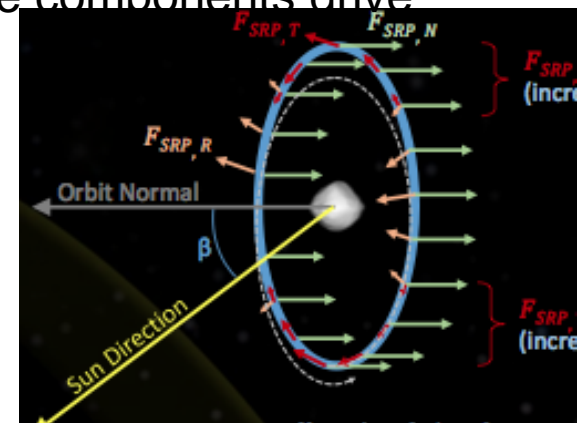
Larger values of β cause more of the SRP force to be directed in the orbit-relative radial and transverse directions. The transverse force components drive the change in eccentricity.

$F_{SRP,T}$

$F_{SRP,N}$

$F_{SRP,T}$ raises apoapsis (increasing e, increasing a)

$F_{SRP,T}$ lowers periapsis (increasing e, decreasing a)

INFLUENCE OF SRP ON OSIRIS-REx AT BENNU

- Acceleration due to gravity of Bennu and Sun: (in nominal Orbit B)

$$\ddot{\vec{r}}_{B/sc} = -\frac{GM_B + GM_{sc}}{r_{B/sc}^3}\vec{r}_{B/sc} + GM_\odot\left(\frac{\vec{r}_{sc/\odot}}{r_{sc/\odot}^3} - \frac{\vec{r}_{B/\odot}}{r_{B/\odot}^3}\right)$$

Accel due to Bennu's gravity ≈ 3.88 x 10^{-6} m/s^2

Accel due to Sun's gravity ≈ 3.93 x 10^{-11} m/s^2

Net Accel due to gravity ≈ 3.88 x 10^{-6} m/s^2

- Acceleration due to SRP (~1% the accel due to gravity)

Solar pressure at 1.015 AU, P_{SRP} = 4.49x10^{-6} m/s^2, mass of SC = 1198 kg

Cannonball (A=12m^2, C_R=1.4): a_{can} = $C_R A P_{SRP}/m$ ≈ 6.30 x 10^{-8} m/s^2

SPAD Model (Nadir): a_{Nadir} ≈ 5.29 x 10^{-8} m/s^2

SPAD Model (Earth-Pointing): $a_{Earth-Pointing}$ ≈ 5.1 x 10^{-8} m/s^2