BILLIARDS:
Baseline Instrumented Lithology Lander, Inspector and Asteroid
Redirection Demonstration System

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Introduction

BILLIARDS

- Baseline Instrumented Lithology Lander, Inspector, and Asteroid Redirection Demonstration System
- Proposed demonstration mission for “Billiard-Ball” concept
- Select asteroid pair with natural close approach to minimize cost and complexity

Primary Objectives

- Rendezvous with a small (<10m), near Earth (alpha) asteroid
- Maneuver the alpha asteroid to a collision with a ∼100m (beta) asteroid
- Produce a detectable deflection or disruption of the beta asteroid

Secondary objectives

- Contribute knowledge of asteroid composition and characteristics
- Contribute knowledge of small-body formation
- Opportunity for international collaboration
Concept of Operations
Physical properties

- Absolute magnitude: 28.0
- Diameter range: $6_{-2}^{+4}$ m
- Density range: $1.1_{-0.5}^{+0.7}$ g/cm³

Orbital properties

- Inclination: 2.58°
- Semimajor Axis: 1.06 AU
- Eccentricity: 0.0416
- Orbit classification: Apollo
Beta Asteroid Selection

Final Beta Asteroid Selection
- Collision must occur with radio line of sight to Earth
- Must be visible from space based observatories
- Ideally visible from ground based observatories
- Select minimum close approach distance to alpha asteroid without violating other constraints

- 2010 PR10
- 24 have a close approach with 2011 MD after 2024
- 250 with diameters of 100 to 500 meters
- 2,000 with OCC = 0
- 6,500 are not PHAs
- 11,500 near Earth asteroids
Beta Asteroid - 2010 PR_{10}

- Physical properties
  - Absolute magnitude: 21.7
  - Diameter range: 80-356 m
  - Expected diameter: 160 m

- Orbital properties
  - Minimum natural close approach: 9.329e-3 AU
  - Inclination: 9.2°
  - Semimajor Axis: 1.2 AU
  - Eccentricity: 0.18
  - Orbit classification: Amor

- Close approach
  - Five close approaches prior to impact
  - Impact date: Jan 26, 2029
  - Impact velocity: 6.6 km/s
  - Expected Q/Q*: 9.0
    - Most likely disrupted by impact
Spacecraft Design

- **Instrumentation Module**
  - Houses most spacecraft systems
  - Provides high Isp propulsion for alpha asteroid rendezvous and redirection
  - Includes imagers for navigation and scientific data collection

- **Terminal Guidance Module**
  - Houses asteroid capture mechanism and internal sample instruments
  - Conducts final asteroid guidance maneuvers shortly before collision
  - High thrust propulsion for autonomous correction maneuvers
## Δv Budget

<table>
<thead>
<tr>
<th>Maneuver Type</th>
<th>Maneuver</th>
<th>Start Date</th>
<th>Δv</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Launch</strong></td>
<td>Launch</td>
<td>July 4, 2021</td>
<td>$C_3 = 5.225 \text{ km}^2/\text{s}^2$</td>
</tr>
<tr>
<td>Falcon 9 v1.1</td>
<td></td>
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<tr>
<td>Instrumentation Module</td>
<td>Terminal Guidance Module</td>
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<tr>
<td><strong>Low-thrust</strong></td>
<td>Alpha Rendezvous</td>
<td>July 11, 2021 (L+7d)</td>
<td>1.6 km/s</td>
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<tr>
<td>Instrumentation Module</td>
<td>Terminal Guidance Module</td>
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<td></td>
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<tr>
<td><strong>Low-thrust</strong></td>
<td>Alpha Redirect</td>
<td>August 12, 2025</td>
<td>12 m/s</td>
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<tr>
<td>Instrumentation Module</td>
<td>Midcourse Corrections</td>
<td></td>
<td>19.2 m/s</td>
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<tr>
<td><strong>High-thrust</strong></td>
<td>Terminal Guidance Maneuvers</td>
<td>January 25, 2029 (I-24h)</td>
<td>8 m/s</td>
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<tr>
<td>Terminal Guidance Module</td>
<td>Alpha Asteroid</td>
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<tr>
<td>Alpha Asteroid</td>
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</table>
Alpha asteroid rotating about the position vector between the two asteroids with period $T$ (3 min).

Note: $v_z \gg v_{drift}$
## Spacecraft Mass Estimates

### Instrumentation Module

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
</tr>
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<tbody>
<tr>
<td>Structural</td>
<td>240</td>
</tr>
<tr>
<td>Propulsion (dry)</td>
<td>120</td>
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<tr>
<td>SEP Propellant</td>
<td>750</td>
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<tr>
<td>RCS Propellant</td>
<td>50</td>
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<tr>
<td>Power System</td>
<td>401</td>
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<tr>
<td>Thermal</td>
<td>44</td>
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<tr>
<td>Data Processing</td>
<td>61</td>
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<tr>
<td>Attitude Control</td>
<td>64</td>
</tr>
<tr>
<td>Science Instrumentation</td>
<td>70</td>
</tr>
<tr>
<td><strong>Total Dry</strong></td>
<td><strong>1000</strong></td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1800</strong></td>
</tr>
</tbody>
</table>

### Terminal Guidance Module

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
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</thead>
<tbody>
<tr>
<td>Structural</td>
<td>240</td>
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<tr>
<td>Propulsion (dry)</td>
<td>26</td>
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<tr>
<td>Bi-propellant</td>
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<tr>
<td>Power System</td>
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<tr>
<td>Thermal</td>
<td>32</td>
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<tr>
<td>Data Processing</td>
<td>16</td>
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<tr>
<td>Science Instrumentation</td>
<td>70</td>
</tr>
<tr>
<td>Capture Mechanism</td>
<td>310</td>
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<tr>
<td><strong>Total Dry</strong></td>
<td><strong>687</strong></td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>1287</strong></td>
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## FY2014 Cost Estimate

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
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<tr>
<td>IM P&amp;D Cost</td>
<td>$518M</td>
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<tr>
<td>TGM P&amp;D Cost</td>
<td>$334M</td>
</tr>
<tr>
<td>Capture Mechanism Cost</td>
<td>$64M</td>
</tr>
<tr>
<td>Launch Vehicle Cost (Falcon 9 v1.1)</td>
<td>$85M</td>
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<tr>
<td>Total Mission Cost</td>
<td>$1001M</td>
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</tbody>
</table>
Conclusion

- **2011 MD (alpha asteroid)**
  - Density: \(1.1 \text{ g/cm}^3\)
  - Diameter: 6 m
- **2010 PR_{10}**
  - Diameter: 160 m
- **Timeline**
  - Earth Departure: July 4, 2021
  - Rendezvous with Alpha asteroid: July 11, 2021 - December 31, 2024
  - Impact velocity: 6.6 km/s
  - Collision: January 27, 2029
- **Budget**
  - $1001M (FY 2014)
- **Mission Objectives**
  - Produce an “artificial” collision between two near-earth asteroids, testing an option for future planetary defense missions
  - Observe and confirm collision
  - Gather knowledge of asteroid physical properties
  - Gather knowledge of asteroid disruption dynamics
References

- “HORIZONS Web-Interface”, NASA Jet Propulsion Laboratory.
- “JPL Small-Body Database Browser”, NASA Jet Propulsion Laboratory.
References (cont.)

- “National Space Science Data Center: Stardust/NExT”, NASA.
Backup Slides
Alpha to Beta Asteroid
Multi-Revolution Lambert Solver
Beta Asteroid Distance to Earth
Disruption vs. Deflection

**Assumptions**

Minimum detectible $\Delta v_\beta = 1 \frac{cm}{s}$

$m_\alpha = 130,000 \ kg$

$\rho_\beta = 1400 \frac{kg}{m^2}$

**Deflection**

$m_\alpha v_{rel} = m_\beta \Delta v_\beta$

$r_\beta = \left( \frac{m_\alpha v_{rel}}{\frac{1}{2} \pi \rho_\beta \Delta v_{min}} \right)^{\frac{1}{3}}$

**Disruption**

$Q = \frac{E_\alpha}{m_\beta} = Q^*_d$

$r_\beta = \left( \frac{\frac{1}{2} m_\alpha v_{rel}^2}{Q^*_d \frac{1}{2} \pi \rho_\beta} \right)^{\frac{1}{3}}$
Earth to Alpha Asteroid Trajectory

Designed with EMTG.
Alpha Asteroid Apparent Magnitude
Beta Asteroid Apparent Magnitude