BILLIARDS:

Baseline Instrumented Lithology Lander, Inspector and Asteroid Redirection Demonstration System

Matthew Marcus, Joshua Sloane, Oliver Ortiz, Brent Barbee

Department of Aerospace Engineering
The University of Maryland
IAA Planetary Defense Conference
13-17 April 2015
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

Nominal beta asteroid trajectory
Nominal alpha asteroid trajectory

Lauch  Asteroid rendezvous  Low thrust maneuver  Collision
Alpha Asteroid - 2011 MD

- **Physical properties**
  - Absolute magnitude: 28.0
  - Diameter range: $6^{+4}_{-2}$ m
  - Density range: $1.1^{+0.7}_{-0.5}$ g/cm$^3$

- **Orbital properties**
  - Inclination: 2.58°
  - Semimajor Axis: 1.06 AU
  - Eccentricity: 0.0416
  - Orbit classification: Apollo
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
<table>
<thead>
<tr>
<th>Maneuver Type</th>
<th>Maneuver</th>
<th>Start Date</th>
<th>$\Delta v$</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>
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<tr>
<td>Falcon 9 v1.1</td>
<td></td>
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<tr>
<td>Instrumentation Module</td>
<td></td>
<td></td>
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<tr>
<td>Terminal Guidance Module</td>
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<tr>
<td><strong>Low-thrust</strong></td>
<td>Alpha Rendezvous</td>
<td>July 11, 2021</td>
<td>1.6 km/s</td>
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<td>Instrumentation Module</td>
<td></td>
<td>(L+7d)</td>
<td></td>
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<td>Terminal Guidance Module</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 19.2 m/s</td>
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<td>Instrumentation Module</td>
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<td>Terminal Guidance Module</td>
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<tr>
<td>Alpha Asteroid</td>
<td>Midcourse Corrections</td>
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<td><strong>High-thrust</strong></td>
<td>Terminal Guidance</td>
<td>January 25, 2029</td>
<td>8 m/s</td>
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<td>Instrumentation Module</td>
<td>Maneuvers</td>
<td>(I-24h)</td>
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<tr>
<td>Alpha Asteroid</td>
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</table>
Terminal Guidance - CONOPS

Alpha asteroid rotating about the position vector between the two asteroids with period \( T \) (3 min).

Note: \( v_z \gg v_{\text{drift}} \)
## Spacecraft Mass Estimates

### Instrumentation Module

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>Structural</td>
<td>240</td>
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<tr>
<td>Propulsion (dry)</td>
<td>120</td>
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<td>SEP Propellant</td>
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<td>RCS Propellant</td>
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<tr>
<td>Power System</td>
<td>401</td>
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<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>
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<tr>
<td>Science Instrumentation</td>
<td>70</td>
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<tr>
<td>Total Dry</td>
<td>1000</td>
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<tr>
<td>Total</td>
<td>1800</td>
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</tbody>
</table>

### Terminal Guidance Module

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
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<tbody>
<tr>
<td>Structural</td>
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<td>Propulsion (dry)</td>
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<td>Bi-propellant</td>
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<td>Power System</td>
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<td>Thermal</td>
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<tr>
<td>Data Processing</td>
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<td>Science Instrumentation</td>
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<tr>
<td>Capture Mechanism</td>
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<td>Total Dry</td>
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<tr>
<td>Total</td>
<td>1287</td>
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<td>Cost Category</td>
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<tr>
<td>IM P&amp;D Cost</td>
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<td>TGM P&amp;D Cost</td>
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<td>Capture Mechanism Cost</td>
<td>$64M</td>
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<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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</table>
Conclusion

- **2011 MD (alpha asteroid)**
  - Density: 1.1 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.


“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 $\Delta v_\beta = 1 \frac{cm}{s}$
- $m_\alpha = 130,000 \text{ kg}$
- $\rho_\beta = 1400 \frac{kg}{m^3}$

**Deflection**

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

$$r_\beta = \left(\frac{m_\alpha v_{rel}}{\frac{4}{3} \pi \rho_\beta \Delta v_{min}}\right)^{\frac{1}{3}}$$

**Disruption**

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

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

![Graph showing disruption vs. deflection with Assumptions and formulas]

- max beta radius with $\Delta v >= 1 \text{ cm/s}$
- max beta radius that gets disrupted, $Q_\alpha^* = 10$
- max beta radius that gets disrupted, $Q_\alpha^* = 100$
- Estimated radius and relative velocity
Earth to Alpha Asteroid Trajectory

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