Enhanced Gravity Tractor Derived from the Asteroid Redirect Mission for Deflecting Hypothetical Asteroid 2017 PDC

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Asteroid Redirect Mission: Three Main Segments

**IDENTIFY**

Ground- and space-based assets detect and characterize potential target asteroids

- Pan-STARRS
- NEOWISE
- Goldstone
- Arecibo
- Infrared Telescope Facility

**REDIRECT**

Solar electric propulsion (SEP) based system redirects asteroid boulder to cis-lunar space.

**EXPLORE**

Crew launches aboard SLS rocket, travels to cis-lunar space in Orion spacecraft to rendezvous with returned boulder, studies and returns samples to Earth
Asteroid Redirect Mission (ARM) Robotic Segment Overview

1) Launch on Delta IV Heavy, Falcon Heavy or Space Launch System (SLS)

2) Non-Critical Deployments and Checkouts

3) Outbound Cruise

4) Asteroid Operations (230 days)

5) Inbound Cruise

6) Transfer to ARCM Destination Orbit

7) Crew Operations

8) Transfer to Long-Term Stable Orbit

Near-Earth Asteroid (NEA)

LDRO Moon

Approach and Characterization

Boulder Collection

Planetary Defense Demonstration

100 days 50 days 50 days 30 days

Margin
Halo vs. In-line EGT Operations

**Halo EGT**

- **Strengths**
  - Higher time efficacy and mass efficiency for optimal collected masses
  - Higher thrust efficiency – nominally, no SEP engine gimballing required (except for low collected/asteroid mass)
  - Mass efficiency can be roughly twice as good as in-line for high collected masses

- **Weaknesses**
  - Lower time efficacy and mass efficiency for low collected masses
  - More complex GN&C architecture
  - Requires more collected mass to reach full potential

**In-line EGT**

- **Strengths**
  - Simplifies CN&C architecture
  - Time efficacy and mass efficiency can be roughly twice as good as halo for low collected masses

- **Weaknesses**
  - High gimbal angles lead to low thrust efficiency
  - Lower mass efficiency for high collected masses
  - Requires large thruster gimbal range (60+ deg)

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**Efficacy/Efficiency**

<table>
<thead>
<tr>
<th><strong>Definition</strong></th>
<th><strong>Efficacy/Efficiency</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Determines the stay time to reach a detectable deflection</td>
<td>Time efficacy (ΔV/time)</td>
</tr>
<tr>
<td>How much applied thrust is projected along the desired inertial direction</td>
<td>Thrust efficiency</td>
</tr>
<tr>
<td>Determines how much propellant is needed to reach a detectable deflection</td>
<td>Mass efficiency (ΔV/propellant)</td>
</tr>
</tbody>
</table>

*Note: asteroid and spacecraft/collected mass are not to scale.*
Enhanced Gravity Tractor – The Power of Multiplication

- The gravitational attraction force of the traditional gravity tractor is limited by the mass of the spacecraft and deflection efforts can take many decades.

- As long as the spacecraft has sufficient thrust and propellant capability, the EGT force is only limited by the amount of in-situ mass collected and greatly reduces deflection time.

\[
F = \frac{G \cdot M_{\text{Asteroid}} \cdot M_{\text{Spacecraft + Acquired}}}{r^2}
\]

For example:

- 1,000,000 ton asteroid & 10 ton spacecraft: \( F = \frac{G \cdot 1,000,000 \cdot 10}{r^2} \propto 10 \text{ million tons}^2 \)

- If 990 tons of material is acquired: \( F = \frac{G \cdot 999,010 \cdot 1,000}{r^2} \propto 1 \text{ billion tons}^2 \)
  - provides two orders of magnitude more force!
Pros and Cons of Enhanced Gravity Tractor

Standard Gravity Tractor (GT)

• Pros
  – Can choose the direction of the deflection
  – Ephemeris (and impact point) is constantly updated to high precision
  – Deflection is independent of surface topography, composition, structure, and momentum multiplication factor
  – Very low forces imparted on asteroid is not a disruption concern

• Cons
  – Low thrust leads to long deflection times

Enhanced Gravity Tractor (EGT)

• Pros beyond standard GT
  – Augments mass of the spacecraft to maximize thrust capability of the SEP
  – Can make use of higher thrust EP systems
  – Can shorten GT deflection times by order(s) of magnitude
  – Allows operational flexibility by trading augmentation mass and distance from the asteroid

• Cons
  – Requires collection of mass from target asteroid
2017 PDC Overview

- **Hypothetical** asteroid for 2017 Planetary Defense Conference

- Diameter 100-250 m

- Density Unknown

- Most likely hypothetical impact date: July 21, 2027

- Highly eccentric orbit extends from 0.88 to 3.60 au

- Orbital period: 3.35 years

- Inclination: 6.3 degrees to Earth’s orbit
EGT Deflection Assumptions

- Asteroids 100-250 m diameter with bulk densities of 2 and 4 g/cm³ (in backup)
- SEP Specific Impulse ($I_{sp}$) = 7000 s (higher than ARM robotic spacecraft)
- SEP power level refers to the total power available to the thrusters at 1 AU.
  - 40 kW = 0.82 N @ 1 AU (lower thrust than ARM robotic spacecraft with 40 kW)
  - 150 kW = 3.06 N @ 1 AU
  - 300 kW = 6.12 N @ 1 AU
- The system is assumed to be designed to be able to use the higher power available at solar ranges less than 1 AU.
- SEP System Efficiency = 0.70
- Available power and resulting thrust varies as $1/r^2$.
- EGT operation uses the halo method and full thrust capability to deflect the asteroid.

<table>
<thead>
<tr>
<th>Asteroid Diam. (m)</th>
<th>40 kW System</th>
<th>150 kW System</th>
<th>300 kW System</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>37.6</td>
<td>141.1</td>
<td>282.2</td>
</tr>
<tr>
<td>150</td>
<td>25.1</td>
<td>94.1</td>
<td>188.2</td>
</tr>
<tr>
<td>200</td>
<td>18.8</td>
<td>70.6</td>
<td>141.1</td>
</tr>
<tr>
<td>250</td>
<td>15.1</td>
<td>56.4</td>
<td>112.9</td>
</tr>
</tbody>
</table>

- Utilized 2017 PDC ephemeris and Opik $b$-plane data inputs provided by Paul Chodas – Manager, Center for Near Earth Object Studies (CNEOS).
40-kW Total System Power (at 1 AU)

$I_{sp} = 7000$ s

**40-kW system can deflect 2017 PDC sizes up to 100-m diameter at 2 g/cm³ in ≤ ~3.5 years and up to 150-m diameter in ≤ ~7 years (Zeta deflection > 1).**

**ARM-class spacecraft can 2017 PDC sizes up to 150-m size range.**
150-kW Total System Power (at 1 AU)

\[ I_{sp} = 7000 \text{ s} \]

- 150-kW system can deflect 2017 PDC sizes up to 200-m diameter at 2 g/cm³ in \( \leq 6 \) years.
• **300-kW system can deflect 2017 PDC sizes up to 250-m diameter at 2 g/cm³ in ≤ ~6 years.**
Total Propellant Used During EGT – $I_{sp} = 7000$ s

- The high $I_{sp}$ (7000 s) results in reasonable propellant quantities.
- This does not include the propellant required to transport the EGT system to the asteroid (added in following trajectory analysis).
Transit Trajectory Analysis Assumptions

- Trajectory analysis utilized NASA’s Copernicus Trajectory Design and Optimization System.

- SEP used during the transit and asteroid rendezvous with additional 5% tankage for propellant consumed during transit.

- Transit trajectory assumed EGT propellant estimate for maximum of 7 years of EGT operations to allow time for transit, characterization, and mass collection (optimization for shorter EGT operations not performed).

<table>
<thead>
<tr>
<th>System</th>
<th>Dry Mass (kg)</th>
<th>7-year EGT Prop (kg)</th>
<th>EGT Wet Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-kW system</td>
<td>5,500</td>
<td>690</td>
<td>6,190</td>
</tr>
<tr>
<td>150-kW system</td>
<td>7,500</td>
<td>2,580</td>
<td>10,080</td>
</tr>
<tr>
<td>300-kW system</td>
<td>11,000</td>
<td>5,160</td>
<td>16,160</td>
</tr>
</tbody>
</table>

- Chemical departure stage modeled using:
  - Propellant Mass Fraction (PMF) = 0.85
  - $I_{sp} = 450$ s
  - Low-Earth Orbit (LEO) departure altitude = 400 km circular
  - High-Earth Orbit (HEO) departure altitude = 400 km x 393,622 km
# 40-kW System Transit Trajectory Results

<table>
<thead>
<tr>
<th>Earth Departure Date (EDD)</th>
<th>Asteroid Arrival Date (AAD)</th>
<th>EGT System Initial Mass (kg)</th>
<th>EGT System Propellant for Transit (kg)</th>
<th>Dep $V_{\infty}$ (km/s)</th>
<th>$\Delta V$ LEO (km/s)</th>
<th>Total IMLEO (kg)</th>
<th>$\Delta V$ HEO (km/s)</th>
<th>Total IMHEO (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/11/2017</td>
<td>7/19/2020</td>
<td>6,422</td>
<td>221</td>
<td>7.6</td>
<td>5.574</td>
<td>41,117</td>
<td>2.489</td>
<td>13,029</td>
</tr>
<tr>
<td>6/11/2018</td>
<td>12/20/2020</td>
<td>6,598</td>
<td>388</td>
<td>6</td>
<td>4.726</td>
<td>29,100</td>
<td>1.640</td>
<td>10,393</td>
</tr>
</tbody>
</table>

- Delivery of 40-kW EGT system requires Initial Mass in Low-Earth Orbit (IMLEO) of ~29-41 t or Initial Mass in High-Earth Orbit (IMHEO) of ~10-13 t.
  - ~23-35 t departure stage from LEO
  - ~4-7 t departure stage from HEO
- Trajectory diagrams provided in backup.
# 150-kW System Transit Trajectory Results

<table>
<thead>
<tr>
<th>Earth Departure Date (EDD)</th>
<th>Asteroid Arrival Date (AAD)</th>
<th>EGT System Initial Mass (kg)</th>
<th>EGT System Propellant for Transit (kg)</th>
<th>Dep $V_{\text{inf}}$ (km/s)</th>
<th>$\Delta V$ LEO (km/s)</th>
<th>Total IMLEO (kg)</th>
<th>$\Delta V$ HEO (km/s)</th>
<th>Total IMHEO (kg)</th>
</tr>
</thead>
</table>

- Delivery of 150-kW EGT system requires Initial Mass in Low-Earth Orbit (IMLEO) of ~47 t or Initial Mass in High-Earth Orbit (IMHEO) of ~17 t.
  - ~37 t departure stage from LEO
  - ~6 t departure stage from HEO
- Trajectory diagrams provided in backup.
### 300-kW System Transit Trajectory Results

<table>
<thead>
<tr>
<th>Earth Departure Date (EDD)</th>
<th>Asteroid Arrival Date (AAD)</th>
<th>EGT System Initial Mass (kg)</th>
<th>EGT System Propellant for Transit (kg)</th>
<th>Dep $V_{\text{inf}}$ (km/s)</th>
<th>$\Delta V$ LEO (km/s)</th>
<th>Total IMLEO (kg)</th>
<th>$\Delta V$ HEO (km/s)</th>
<th>Total IMHEO (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/2/2017</td>
<td>7/10/2019</td>
<td>17,345</td>
<td>1128</td>
<td>6.0</td>
<td>4.726</td>
<td>76,498</td>
<td>1.640</td>
<td>27,321</td>
</tr>
<tr>
<td>6/21/2018</td>
<td>10/17/2020</td>
<td>17,356</td>
<td>1,139</td>
<td>6.0</td>
<td>4.726</td>
<td>76,547</td>
<td>1.640</td>
<td>27,338</td>
</tr>
<tr>
<td>5/22/2020</td>
<td>7/27/2023</td>
<td>17,179</td>
<td>971</td>
<td>6.0</td>
<td>4.726</td>
<td>75,766</td>
<td>1.640</td>
<td>27,059</td>
</tr>
</tbody>
</table>

- Delivery of 300-kW EGT system requires Initial Mass in Low-Earth Orbit (IMLEO) of ~77 t or Initial Mass in High-Earth Orbit (IMHEO) of ~27 t.
  - ~60 t departure stage from LEO
  - ~10 t departure stage from HEO
- Trajectory diagrams provided in backup.
Summary

• As demonstrated by this case study of the hypothetical asteroid 2017 PDC, the EGT can effectively deflect hazardous asteroids in years rather than the decades typically needed for the standard GT.
  
  – With reasonable SEP systems like those derived from the proposed ARM system, EGT can deflect hazardous-sized asteroids.
  
  • 40-kW system can deflect 2017 PDC sizes up to 100-m diameter at 2 g/cm³ in ≤ ~3.5 years and up to 150-m diameter in ≤ ~7 years.
  
  • 150-kW system can deflect 2017 PDC sizes up to 200-m diameter at 2 g/cm³ in ≤ 6 years.
  
  • 300-kW system can deflect 2017 PDC sizes up to 250-m diameter at 2 g/cm³ in ≤ ~6 years.
  
  – Deflection capability is a direct function of the power level (at a fixed $I_{sp}$).

• Initial trajectory analyses show that these systems can be delivered in a timely manner to the target asteroid utilizing reasonably-sized chemical propulsion departure stages along with solar electric propulsion for transit.
Closing Remarks

• Multiple techniques should be considered in a system of systems approach (e.g., we typically bring multiple tools to fix something).
  – Rendezvous spacecraft provides the best orbit determination (pre- and post-deflection) and physical characterization of the asteroid and can improve the effectiveness of a kinetic impactor – get the spacecraft as soon as possible.
  – EGT technique is most practical against smaller asteroids where kinetic impactor could cause disruption if sized for a wide range of asteroid masses – real-time decision.
  – EGT could provide significant trim maneuver capability after a kinetic impact.

• On-orbit resources and expertise in interacting with asteroids are critical to responding in a timely manner (eliminate development and launch).
  – Decreases time from detection to EGT ready date as much as possible.
  – Repurpose assets to support a deflection campaign (e.g., re-fueling existing vehicles).
  – Planetary defense and asteroid mining are very closely linked.
    • PD community should work closely with the asteroid mining community as it develops.
    • The ability to capture and manipulate significant mass from an asteroid will be developed by the asteroid mining community and is enabling for the EGT option allowing it to become viable for PD missions with rendezvous opportunities and years, not decades, of warning time.
Thank you for your time and attention.
Questions?
• Utilized 2017 PDC data inputs provided by Paul Chodas – Manager, Center for Near Earth Object Studies (CNEOS).

• The ephemeris (“eph”) file gives the position of the asteroid as a function of time before impact.
  ✓ Used this to get the solar range as a function of time before impact.

• The $b$-plane (“$b00$”) file gives the partials of $x_i$ and $zeta$, respectively, as a function of time before impact. The partials are with respect to velocity in the ACN frame, where $A$ is along-track (parallel to velocity vector), $C$ is cross-track and $N$ is normal.
  ✓ Used the partial of $zeta$ w.r.t. $dv_A$ (further optimization of deflection is possible using other derivatives).
  ✓ Calculated the thrust as a function of solar range for a given power at 1 AU (assuming a $1/r^2$ variation).
  ✓ Broke the deflection up into 1-day increments of EGT thrusting and then integrated to get the total $zeta$ deflection in the 2017 PDC $b$-plane.
## Required Collected Mass (t) for 4 g/cm³ Bulk Density Asteroids

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<td>28.9</td>
<td>108.6</td>
<td>217.1</td>
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<tr>
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<td>21.7</td>
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</tr>
<tr>
<td>250</td>
<td>17.4</td>
<td>65.1</td>
<td>130.3</td>
</tr>
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</table>
40-kW Total System Power (at 1 AU)

\[ I_{sp} = 7000 \text{ s} \]

- **40-kW system** can deflect 2017 PDC sizes up to 100-m diameter at 4 g/cm³ in \( \leq \sim 5 \text{ years} \).

- **ARM-class spacecraft** can deflect 2017 PDC sizes up to 100-m size range.
150-kW Total System Power (at 1 AU) – $I_{sp} = 7000$ s

$I_{sp} = 7000$ s

- 150-kW System can deflect 2017 PDC sizes up to 200-m diameter at 4 g/cm$^3$ in ≤ 7 years.
300-kW Total System Power (at 1 AU)

\( I_{sp} = 7000 \text{ s} \)

- 300-kW system can deflect 2017 PDC sizes up to 250-m diameter at 4 g/cm\(^3\) in \(\leq 7\) years.
40-kW Total System Power (at 1 AU)

$I_{sp} = 2600 \text{ s}$

- 40-kW, 2600 s $I_{SP}$ system can deflect 2017 PDC sizes up to 200-m diameter at 2 g/cm³ in ≤ 7 years compared to 150-m capability for the 40-kW, 7000-s $I_{sp}$ system.
• 150-kW, 2600 s $I_{sp}$ system can deflect 2017 PDC sizes up to 250-m diameter at 2 g/cm$^3$ in ≤ 4 years compared to <200-m capability for the 150-kW, 7000-s $I_{sp}$ system.
300-kW Total System Power (at 1 AU)

\[ \text{\( I_{sp} = 2600 \, \text{s} \)} \]

- 300-kW, 2600 s ISP system can deflect 2017 PDC sizes up to 250-m diameter at 2 g/cm\(^3\) in \( \leq 3.5 \) years compared to 150-m capability for the 300-kW, 7000-s \( I_{sp} \) system.
• The lower $I_{sp}$ of the current ARM robotic spacecraft results in high propellant quantities for higher powers.

• These propellant quantities lead to unreasonable IMLEO masses for the outbound trajectories, leading to the assessment of a higher $I_{sp}$, lower thrust system.
40-kW System Transit Trajectory Results

40 kW, Isp = 7000 s, EDD = June 2017
40-kW System Transit Trajectory Results

40 kW, Isp = 7000 s, EDD = June 2018

Earth Orbit

2017 PDC Orbit

AAD: 12/20/2020

EDD: 6/11/2018
150-kW System Transit Trajectory Results

150 kW, Isp = 7000 s, EDD = May 2017, ADD = Nov 2019
150-kW System Transit Trajectory Results

150 kW, $I_{sp} = 7000$ s, EDD = June 2018

[Diagram showing Earth Orbit and PDC Orbit with dates and trajectory details]
150-kW System Transit Trajectory Results

150 kW, $I_{sp} = 7000$ s, EDD = May 2020

AAD: 7/27/2023

EDD: 5/18/2020

Earth Orbit

2017 PDC Orbit
300-kW System Transit Trajectory Results

300 kW, Isp = 7000 s, EDD = June 2017, AAD = July 2019
300-kW System Transit Trajectory Results

300 kW, $I_{sp} = 7000$ s, EDD = June 2018

EDD: 6/21/2018

AAD: 10/17/2020

2017 PDC Orbit

Earth Orbit

AAD: 10/17/2020

EDD: 6/21/2018
300-kW System Transit Trajectory Results

300 kW, $I_{sp} = 7000$ s, EDD = May 2020

AAD: 7/27/2023

EDD: 5/22/2020