Continuing Efforts at NASA MSFC Analyzing Options for Deflection of Near Earth Objects

Presentation to Asteroid Deflection Research Workshop
Arlington, VA
October 23-24, 2008

Robert B. Adams
Outline

• Review of 2003-4 study
  – Concepts considered
  – Trajectory models developed
  – Integrated analysis process
  – Consequences analysis
  – Results and Recommendations

• Review of 2007 study
  – Operational concept
  – Deflection concepts considered
  – Results and Recommendations

• New maneuver for the kinetic deflection option

• Current activities at MSFC

• Recommendations
Introduction to 2003-4 Study

• First foray by MSFC team into the field of Planetary Defense

• Emphasis was on
  – Considering as wide a number of options as possible
  – Developing an integrated design trade and evaluation process
  – Educating ourselves on the NEO threat literature

• Approach
  – Develop models for outbound propulsion systems, threat mitigation systems, outbound trajectory simulation, and inbound deflection simulation
  – Link models using a collaborative engineering environment
  – Evaluate performance of combinations of outbound and threat mitigation systems parametrically

• Documentation
  – NASA TP 2004-213089
Options Considered

• Outbound propulsion
  – Staged chemical
  – Nuclear Thermal Rocket
  – Nuclear Pulse
  – Solar Sail
  – Solar Collector

• Threat mitigation
  – Nuclear Fragmentation
  – Nuclear Deflection
  – Solar Sail
  – Solar Collector
  – Magnetic Flux Compression
  – Mass Driver
  – Kinetic Deflection
Trajectory Analysis

- **Outbound Trajectory**
  - Given an asteroid’s orbital elements, a departure date, and the desired outbound time of flight, $\Delta V$’s for both rendezvous and ballistic interception trajectories are generated.
  - The departure date defines Earth’s position at departure and therefore the vehicle’s initial position.
  - Similarly, the asteroid’s initial position is calculated and using the time of flight, it’s final position can be calculated. The asteroid’s final position is the same as the vehicle’s final position.
  - Using Gauss’ method, the 2 positions of the vehicle and a time of flight between them defines the vehicle’s trajectory.
Outbound Trajectory

Sample Results – Changing Flight Time

Required ΔV for Interception or Rendezvous with Asteroid Ejected from Main Asteroid Belt

- 100 days
- 150 days
- 200 days
- 250 days
- 300 days
Outbound Trajectory

- Sample Results – Changing Inclination
  - In this example, the asteroid’s inclination was varied. An outbound time of flight of 200 days was held constant

Required \( \Delta V \) for Interception or Rendezvous with Asteroid Ejected from Main Asteroid Belt (TOF=200d)

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Given the velocity vector of the planetary body at impact to be \((-40, 0, 0)^T\), what do the two-body and three-body orbits look like that will give this velocity at impact? ANS: 2.5 versus 5.0 AU!
Inbound Trajectory

Required Impulsive Delta-V for 35 km/s Velocity

\[ V = (-34.47, 0, 6.078)^T \]

Days Before Impact

Impulsive Delta-V (km/s)

INSIDE
OUTSIDE
UP
DOWN
ACCEL
DECEL

0 0.0002 0.0004 0.0006 0.0008 0.001 0.0012 0.0014 0.0016 0.0018 0.002

-1000 -900 -800 -700 -600 -500 -400 -300
Inbound Trajectory

- **Modified Asteroid 1999JT6**
  - 1999JT6 orbit was modified slightly to force Earth collision. It is this modified (hypothetical) asteroid that is being defended against in this study.

  Semimajor Axis (AU)  
  - 2.13

  Eccentricity  
  - 0.578

  Inclination  
  - 11.46

  Ascending Node (deg)  
  - 45.02

  Argument of Periapsis (deg)  
  - 41.83
Threat Assessment

- Modified version of existing Monte Carlo code used to estimate number of deaths caused by asteroid impact
- Given maximum size and energy of deflectable NEO’s calculates number of deaths prevented per century

Integrated Analysis
The Staged Chemical Vehicle

5 stage vehicle
Isp = 465 sec (LOx-LH₂)
Stage structural fraction based on historical data
ΔV split between stages is optimized
### Conclusions (2003-4 study)

<table>
<thead>
<tr>
<th>System</th>
<th>Maneuver</th>
<th>Time Before Impact (days)#/ Outbound Travel Time (days)</th>
<th>Total System Mass at SOI (mT) for Different Asteroid Diameters (meters)</th>
<th>Maximum Diameter of Asteroid (meters)/Total System Mass at Earth SOI (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Staged Chemical + Mass Driver</td>
<td>Rendezvous</td>
<td>2900/2400</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Interception</td>
<td>1509/599</td>
<td>0.847</td>
<td>8.27</td>
</tr>
<tr>
<td></td>
<td>Rendezvous</td>
<td>1075/943</td>
<td>5.62</td>
<td>568</td>
</tr>
<tr>
<td></td>
<td>Interception</td>
<td>1025/800</td>
<td>73.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Staged Chemical + Nuclear Deflection</td>
<td>Rendezvous</td>
<td>2170/970</td>
<td>29.7</td>
<td>41.8</td>
</tr>
<tr>
<td>Solar Collector</td>
<td>Rendezvous (~3 yr)</td>
<td>1076/1011**</td>
<td>0.637</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>Rendezvous (~10 yr)</td>
<td>3635/3520**</td>
<td>0.550</td>
<td>0.636</td>
</tr>
</tbody>
</table>

*maximum was constrained to a total system mass at Earth SOI of 1000 metric tons.

** times are for 100m chondrite. Outbound times must be shorter for larger asteroids, although total mission times change little.

§ the solar collector system is limited more by solar collector size than by total system mass.

# the time from launch of the vehicle to the expected date of impact of the unperturbed NEO.
Conclusions (2003-4 study)

- Baseline case is Nuclear Pulse outbound with Nuclear Deflection inbound
Introduction to the 2007 Study

• Premise was to evaluate the potential of the Constellation architecture (specifically the Ares I and V vehicles) to support NEO deflection

• Emphasis here was to consider operational difficulties in a near term deflection scenario
  – Address the premise that mitigation should be considered after a “real” threat is identified
  – Consider the interactions between characterization and mitigation phases of the mission
  – Develop an operation plan flexible to address a number of different scenarios in time before impact, asteroid size and asteroid composition/structure

• Threat mitigation concepts considered
  – Nuclear Deflection
  – Kinetic Deflection
  – Solar Collector
Exploration Vehicles

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 Exploration Vehicles
Groundrules and Assumptions

• Funding limited for research and development of planetary defense architecture
  – Technology Readiness Level of 5 or above
  – Use of planned exploration architecture advantageous

• Exploration Vehicles
  – Ares I available in 2014
  – Ares V available in 2020

• Other Operational Parameters
  – Assume potentially hazardous NEO detected after 2018
  – Planetary Defense architecture components standing ready
  – Architecture to use the full capabilities of the exploration vehicles.
  – Architecture to defeat as much of the threat posed by NEO’s as possible given above constraints.

• Only publicly available information to be used in this study.
### Operational Concept

**Timeline of events**

- **T-0**: Existing/Future Detection system locates NEO with high probability of collision with Earth.
- **T+3 months**: Observer rendezvous/fly-by of NEO, data transmitted to Earth.
- **T+1 1/4 years**: If a high likelihood of collision is confirmed, Ares I is pulled from rotation, fitted with an observer stack, and launched.
- **T+1 1/2 years**: Based on observer data, cradle is fitted with appropriate mitigation system. Ares V is pulled from rotation, fitted with an interceptor stack, and launched.
- **T+2 1/2 years**: NEO passes Earth with a miss distance of at least 3 Earth radii.
- **T+5-15 years**: Solar Collectors rendezvous with NEO, direct secondary collector beam on NEO; or Kinetic Interceptors impact on NEO at 1 hour intervals; or Cradle fly-by of NEO, nuclear interceptors detonate at 1 hour intervals. (Actual times will be based on particulars of threatening NEO.)

*(Operational Concept diagram with timelines and event markers.)*
Observer Stack

Trans-Asteroid Insertion Stage

Rendezvous Stage

Observer Satellite

NEO Lander

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fueled Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAI</td>
<td>23,316</td>
</tr>
<tr>
<td>Rendezvous</td>
<td>4,640</td>
</tr>
<tr>
<td>Observer/lander</td>
<td>1,500</td>
</tr>
<tr>
<td>Total</td>
<td>29,456</td>
</tr>
</tbody>
</table>

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Observer Stack

• Design
  – TAI stage
    • intended for Earth escape
  – Rendezvous stage
    • used to match orbit with NEO
    • can be used for additional DV for fly-by burn when rendezvous not possible
  – Observer satellite
    • Next generation *Deep Impact* probe
    • Solar panels replaced with RTG’s for operation past Mars orbit
    • Impactor from Deep Impact replaced with lander

• Performance

<table>
<thead>
<tr>
<th>Propulsion System</th>
<th>Thrust (lbf)/No. of Engines</th>
<th>Nominal Isp (seconds)</th>
<th>ΔV capability (m/s)</th>
<th>Propellant (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lox/LH2</td>
<td>24750/1</td>
<td>465.5</td>
<td>4150</td>
<td>13,860</td>
</tr>
<tr>
<td>Hydrazine/N2O4</td>
<td>1000/1</td>
<td>330</td>
<td>2000</td>
<td>2165</td>
</tr>
<tr>
<td>Hydrazine</td>
<td>5/16</td>
<td>234</td>
<td>60</td>
<td>107</td>
</tr>
</tbody>
</table>
Observer Stack

- Observer measurements and methodology
  - All measurements have redundant instruments
  - Operational plan
    - Lander separates from observer and approaches NEO
    - As lander prepares for landing it fires several weights around NEO
    - Observer tracks weights, calculates NEO mass from deflection angle of weights
    - Lander moors to NEO. Low thrust engine keeps lander pressed against NEO
    - Observer launches several explosive charges to impact NEO in different locations.
    - Lander measures seismic response and triangulates voids in NEO structure.
    - Other sensors on lander and observer makes continuous readings. Observer relays lander data to Earth
Observer Stack

- Observer measurements and methodology
  - Table of instruments and measurements on observer

<table>
<thead>
<tr>
<th>Category</th>
<th>Instruments</th>
<th>Planned measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>Laser Ranger</td>
<td>Orbital elements</td>
</tr>
<tr>
<td></td>
<td>Narrow Field CCD</td>
<td>surface mapping, geometry, dust environment</td>
</tr>
<tr>
<td></td>
<td>Wide Field CCD</td>
<td>Dust environment, geometry, potential satellites</td>
</tr>
<tr>
<td></td>
<td>Spectrometer</td>
<td>Composition, density</td>
</tr>
<tr>
<td>Radar</td>
<td>MARSIS radar sounder</td>
<td>Density, internal structure</td>
</tr>
<tr>
<td></td>
<td>Dual mode radar/data link</td>
<td>Internal structure</td>
</tr>
<tr>
<td>Other</td>
<td>Gravity sensor</td>
<td>Mass, gravitational field</td>
</tr>
</tbody>
</table>

- Instruments and measurements on lander

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Planned measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical analysis package</td>
<td>Composition</td>
</tr>
<tr>
<td>Seismic sensor</td>
<td>Internal structure</td>
</tr>
<tr>
<td>Fly-by balls</td>
<td>Mass, Gravitational field</td>
</tr>
</tbody>
</table>
**Observer Stack**

- **Decision tree (conjectural)**

Assumes political environment prefers kinetic interception, solar collector, nuclear interception in that order.

![Decision tree diagram](image)
Interceptor Stack

<table>
<thead>
<tr>
<th>Stage</th>
<th>Fueled Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kick</td>
<td>45,359</td>
</tr>
<tr>
<td>Cradle</td>
<td>2,005</td>
</tr>
<tr>
<td>Bullets (6)</td>
<td>9,000</td>
</tr>
<tr>
<td>Total</td>
<td>56,364</td>
</tr>
</tbody>
</table>

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Interceptor Stack

- Solar Arrays
- Thermal Radiators
- Generic Bullets
- LIDAR, WFOV Camera, NFOV Camera
Interceptor Stack

• Design and Performance
  – Ares V Earth Departure Stage (EDS)
    • Half full (approx.) of propellant at Low Earth Orbit. \( \Delta V - 3940 \text{ m/s} \)
  – Interceptor Kick-Stage
    • Lox/LH2 upper stage ignites immediately after EDS burnout and separation. \( \Delta V - 4650 \text{ m/s} \)
  – Cradle
    • Cradle carries six “bullets”, each bullet weighing 1500 kg
    • Cradle has sufficient power to maintain bullets until release
    • Cradle radar locates NEO to within 1 km (some redundancy with observer) communicates location to bullets
  – Bullets
    • Can be nuclear interceptor, kinetic interceptor, or solar collector
    • Handles terminal intercept when within 5000 km of NEO
Nuclear Interceptor

Main Engine

Hydrazine Tank

Divert Thrusters and Central Combustion Chamber

N2O4 Tank

B83 Nuclear Warhead

LIDAR, WFOV Camera, NFOV Camera

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Nuclear Interceptor

- Physics of Nuclear Deflection
  - Explosion at optimum standoff distance from NEO
  - Explosion to cover maximum surface that can be ablated
  - Only X-ray interaction with NEO considered here
  - Monte Carlo model of X-ray penetration and absorption
  - Spectral ejection of vaporized material

![Graphs showing Delta V increments and standoff relationships](image)
Prediction comparison against other models in literature

Comparison of Predictions

Delta V, cm/s

0 5 10 15 20 25 30 35

Woodcock, X-rays
Shafer, X-rays
Dearborn, neutrons
Dearborn, neutrons 20%
Dearborn, neutrons 40%
NASA "astro block 3%"
NASA "new astro block 30%"
NASA "Inbound Pulse"
Nuclear Interceptor

- **Terminal Intercept package**
  - Bipropellant system, turns on inside 5000 km from target
  - Main combustion chamber on constantly, propellant diverted to appropriate thruster
  - LIDAR, WFOV, NFOV cameras guide to target
  - $\Delta V$ requirements for terminal intercept shown below. Design assumes 200 m/s for terminal intercept operations
Nuclear Interceptor Effectiveness (single interceptor)

Estimated Nuclear Divert Performance
Density 1500 kg/m³, Yield 1 MT, Standoff 100m, X-rays

- Delta V, m/s against Asteroid Diameter, m (log scale)

- The graph shows the estimated nuclear divert performance for different asteroid diameters, with the delta V in m/s and the asteroid diameter in m on a log scale.
Kinetic Interceptor

Hall Thruster (3) – not shown

Solar arrays

Xenon Tank

Terminal Intercept System

Penetrator

Shunt Radiator

5.5 m

1.5 m
**Kinetic Interceptor**

- **Physics of Kinetic Interception**
  - Made estimate of maximum impact velocity without fracture
  - Assume inelastic collision of kinetic interceptor with NEO
  - Momentum from potential ejecta not included

![Graph showing craterization by 1500 kg bullet impact speed versus asteroid diameter.]
Kinetic Interceptor

- Kinetic Interceptor Effectiveness (single interceptor)
Comparative Analysis

- Baseline NEO was assumed to have an orbit similar to Apophis
- Orbit was modified to cause Apophis to impact Earth on April 22, 2029 12:10:10.73

<table>
<thead>
<tr>
<th>Orbital Element</th>
<th>Original</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis (m)</td>
<td>137986931.808626</td>
<td>137978976.28259</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.19114698829234</td>
<td>0.19091399221024</td>
</tr>
<tr>
<td>Inclination (deg)</td>
<td>3.34145210222811</td>
<td>3.333348213097</td>
</tr>
<tr>
<td>Right ascension of the ascending node (deg)</td>
<td>203.874080430574</td>
<td>212.35750466471</td>
</tr>
<tr>
<td>Argument of perigee (deg)</td>
<td>126.695719648246</td>
<td>127.46966492194</td>
</tr>
<tr>
<td>Mean anomaly (deg)</td>
<td>137.86541454524</td>
<td>127.25811549492</td>
</tr>
</tbody>
</table>
• Required $\Delta V$ for impulsive deflection using nuclear interceptors
Comparative Analysis

- Required $\Delta V$ for impulsive deflection using kinetic interceptor

![Graph showing required $\Delta V$ for M-Apophis Deflection](image)
Comparative Analysis

- Combined nuclear interceptor analysis against asteroid diameter
Combined Analysis

- Combined kinetic interceptor analysis against asteroid diameter
Conclusions

- Nuclear Interceptor option can deflect NEO’s of smaller size (100-500 m) with 2 years or more time before impact, and larger NEO’s with 5+ years warning.
- Kinetic Interceptors may be effective for deflection of asteroid up to 300-400 m but require 8-10 years warning time.
- Solar collectors show promise for deflection of NEO’s up to 1 km if issues pertaining to long operation time can be overcome.
- Ares I and Ares V vehicles show sufficient performance to enable development of a near term categorization and mitigation architecture.
New Maneuver for Kinetic Deflection

• Outproduct of my Dissertation Research
  – “Invented” it myself; then found it had been considered before

• History
  – Maneuver was suggested by Hermann Oberth, 1929, repeated by Willy Ley, 1951 and Robert Heinlein, 1952
  – Cursory derivation completed by Derek Lawden, 1953
  – Reviewed in two AIAA papers in the 1960’s, one by Edelbaum
  – No other reference found since, in textbooks, papers, etc.

• Number of applications
  – Deep space exploration
  – Crewed round trip missions to NEO’s, Mars
  – High speed Kinetic impactors
  – Rapid rendezvous by any NEO deflection system
Introduction to Oberth Maneuvers

- Oberth Two-Burn Escape Maneuver
  - Criteria
  \[ \Delta V_1 + \Delta V_3 > V_{c1} \]
  - For two body orbits only, multi-body systems should have a less restrictive criteria

- This maneuver appears to have been forgotten by the astrodynamics community
Introduction to Oberth Maneuvers

• Underlying physics
  – Vis-visa equation
    \[ \zeta = \frac{V^2}{2} - \frac{\mu}{r} \]
  – Imagine vehicle as payload attached to two masses with springs
    • First spring breaks, ejecting first mass (propellant from first burn) into higher orbit
    • Second spring breaks, ejecting payload to escape and second mass (propellant from second burn) into very tight orbit around central body
  – Oberth maneuver extracts more of the specific orbital energy (see Vis-visa equation) from the onboard propellant
Potential

- This maneuver can dramatically increase achievable escape velocity
Potential

- Using the two burn maneuver can raise orbit much faster than Hohmann transfers

Note that the dotted lines show ratios relative to Earth
Current MSFC Efforts

- In-house Collaborative Engineering Environment Developed
  - Answers communication issues between project engineers
  - Simplifies integration of complex multi-disciplinary models
  - Enables data tracking, storage and recollection
- Planned release of code through open source channels
- Impetus for development of this code in part because of difficulties experienced in previous NEO deflection studies
- Extensively documented, both user’s and programmer’s manuals
- In use for several years in Advanced Concepts Office
- Website: http:\\parsec.msfc.nasa.gov
- PARSEC: Preliminary Analysis of Revolutionary Space Exploration Concepts
In service since 2004
Over 25 studies performed
Current MSFC Efforts

• Embarking on crewed NEO mission survey
  – Still in early stages of development

• Objectives
  – Build on previous efforts in this area
  – Consider constellation architecture
  – Will consider Oberth maneuver
  – Other objectives still being determined

• I welcome input from anyone with suggestions on the course of this study
Recommendations

- **Mitigation Concepts**
  - Maintain trade space as open as possible as long as possible
  - Never know when a new concept, material or resource will make a previously marginal concept a winner

- **Integrated Analysis**
  - Crucial to enable communication between team members with as little overhead as possible
  - CEE’s can facilitate communication and realize orders of magnitude improvement in efficiency of creating designs

- **Synergy**
  - Resources are limited for this mission; exploring synergy with scientific research and crewed exploration objectives is indicated
  - Military expertise is strongly applicable to NEO deflection

- **Operational Analysis**
  - Understanding of NEO population drives operational possibilities
  - A number of deflection technologies may be needed to answer threat
  - Developing deflection system after threat is detected greatly limits operational response time
Acknowledgements

- Dr. Bong Wie and Iowa State
  - For organizing this symposium and having the foresight to start the Asteroid Deflection Research Center

- My Co-Authors on NASA TP-2004-213-089
  - Reginald Alexander, Joseph Bonometti, Jack Chapman, Matthew Devine, Sharon Fincher, Randall Hopkins, Tara Polsgrove; NASA-MSFC
  - Geoffrey Statham, Slade White; ERC, Inc.
  - Advice and Review from
    - Jonathan Campbell, Roy Young; NASA-MSFC
  - Our Colleagues from the RASC program
    - Pat Troutman, Dan Mazanek; NASA-LaRC
Acknowledgements

• My Co-Participants of the 2007 study
  – Jonathan W. Campbell, Randall C. Hopkins and W. Scott Smith, National Aeronautics and Space Administration, Marshall Space Flight Center
  – William Arnold; Jacob Sverdrup
  – Mike Baysinger and Tracie Crane; Qualis Corporation
  – Pete Capizzo and Steven Sutherlin; Raytheon Corporation
  – John Dankanich and Gordon Woodcock; Gray Research Inc.
  – George Edlin and Johnny Rushing; Alpha Technology, Inc.
  – Leo Fabisinski, David Jones, Steve McKamey and Scott Thomas; International Space Systems, Inc.
  – Claudio Maccone; Member of the International Academy of Astronautics
  – Greg Matloff; New York City College of Technology
  – John Remo; Harvard University

• MSFC New Business office for funding and management support
  – John Horack, Les Johnson and Mike LaPointe; NASA-MSFC

National Aeronautics and Space Administration
Marshall Space Flight Center
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Acknowledgements

• My doctoral committee chairs
  – Dr. Clark Hawk
  – Dr. Georgia Richardson

• My teammates on the PARSEC Development Project
  – Too many to name, many participated on one or more of the previous studies
Backup Charts
Background and History

Map of Madison County, Alabama with the damage template from the 1908 Tunguska event superimposed

Total population within damage area ~ 350,000
Pertinent Websites

- NASA Near-Earth Object Program
  http://neo.jpl.nasa.gov/
- Asteroid/Comet Impact Hazards
  http://impact.arc.nasa.gov/
- NEO Information Centre
  http://www.nearearthobjects.co.uk/
- NASA HQ Library on NEO’s
  http://www.hq.nasa.gov/office/hqlibrary/pathfinders/aster.htm
- Spaceguard Foundation Home Page
  http://spaceguard.iasf-roma.inaf.it/
- B612 Foundation Home Page
  http://www.b612foundation.org/
Threat Mitigation

- Solar Sail
  - Concept simplicity offset by operational difficulties for: rotating bodies, debris-rich environments, fragmented bodies

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- Thrust simply not sufficient for any but the smallest objects
• Solar Collector
  – Concept simplicity makes this an attractive option provided operational issues can be resolved
  – Could work well with rotating and fragmented bodies – even in a debris-rich environment

-100 m collector could concentrate enough energy to move up to 1 km objects

Threat Mitigation

• **Mass Driver**
  - Mechanically complex and massive system – requires extensive assembly and preparation work on target
  - Could work well as part of a long-term deflection campaign (i.e. with years before Earth-impact) provided mechanical reliability problems can be overcome

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Mass Driver Design – Main Components

Major Components of the Mass Driver System

- Power Management and Conditioning System
- Cable from Solar Panels
- Solar Panel
- Power Cable
- Coolant Line
- Mass Driver
- Bucket
- Bucket Return Rail
- Expellant Storage Facility
- Bucket Loading and Cooling Facility
- Cooling System
- Radiator Panel
- Solar Panel
- Power Cable
- Coolant Line
- Mass Driver
Solar Collector

- Inflatable Vanes
- Primary Collector
- Secondary Collector
- Tip Vanes/Avionics

Dimensions:
- 50 m
- 16.67 m
- 9.375 m
Solar Collector

• **Physics of Solar Collector**
  – Primary collector always faces sun
  – Estimate of performance assumes 1 AU distance from sun
  – Secondary collector located at focus
  – Beam from secondary directed on NEO
  – Beam penetration into crust vaporizing material
  – Ejecta transmits momentum to NEO
  – Secondary collector sized to
    • Handle aberration from non-uniformities in parabolic primary
    • Non-point source for sun
    • Secondary not perpendicular to focus plane from primary
  – Collector efficiency estimated at 50% incident on primary
Solar Collector

• Design
  – Primary collector
    • made of solar sail materials
    • Folded “parachute-like” to fit in allowable bullet volume
    • Inflated using vanes along major seams, nitrogen gas cures thin film laminate vanes after inflation
  – Secondary collector
    • Thin film of gold layered on beryllium plating
    • Niobium heat pipes with potassium working fluid mounted on back side of beryllium plating to radiate away heat
    • 0.5 m sun shield mounted 0.5 m away from secondary
  – Tip vanes
    • Solar arrays double as tip vanes for attitude control.
    • Redundant communications and avionics systems at all four tip vanes
Solar Collector

- Solar Collector Effectiveness (single collector)
Comparative Analysis

- Required acceleration for continuous deflection
Comparative Analysis

• Combined solar collector performance against asteroid diameter