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

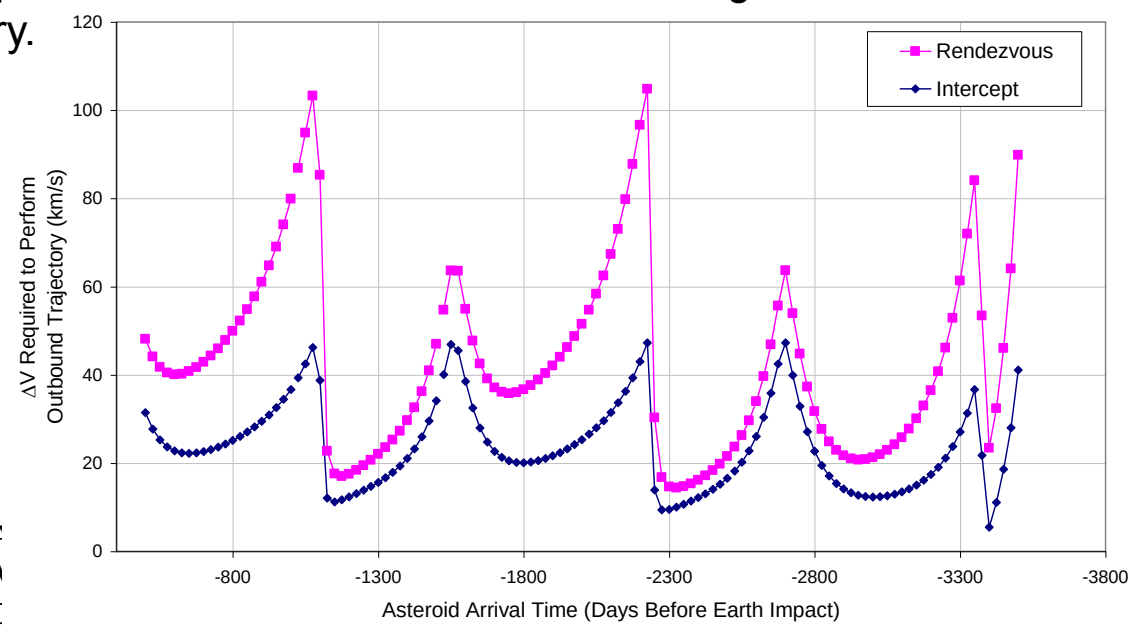
- First foray by MSFC team into the field of Planetary Defense
- Emphasis was on
  - Considering as wide a number of options as possible
  - Developing an integrated design trade and evaluation process
  - Educating ourselves on the NEO threat literature
- Approach
  - Develop models for outbound propulsion 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

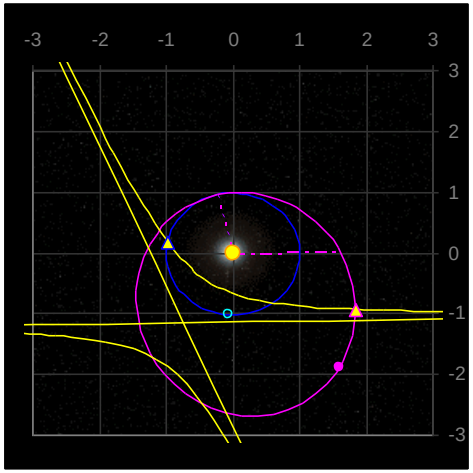
Trajectory Analysis

- Outbound Trajectory
  - Given an asteroid's orbital elements, a departure date, and the desired outbound time of flight, ΔV'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.

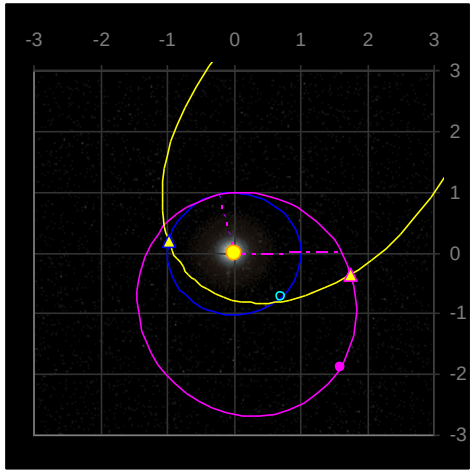


Outbound Trajectory

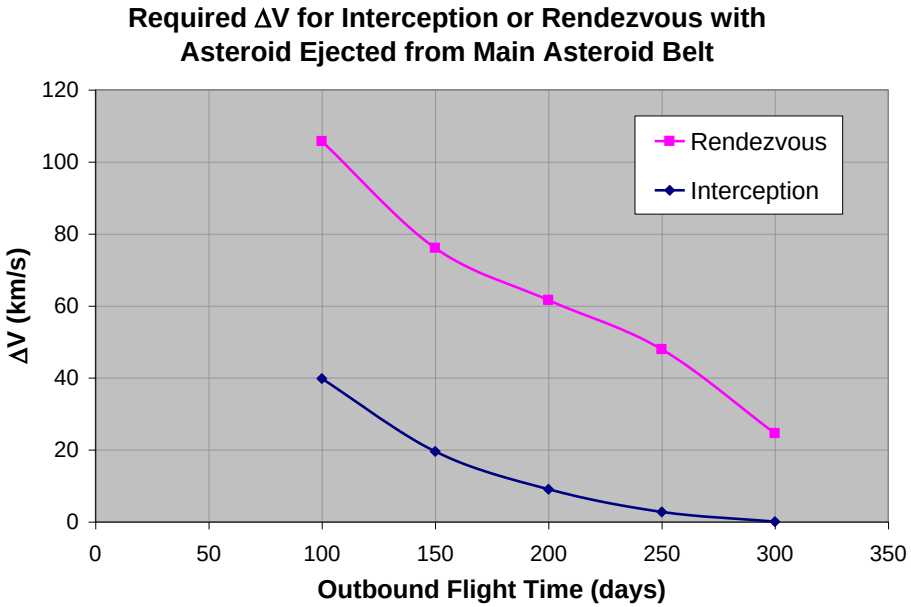
Sample Results – Changing Flight Time

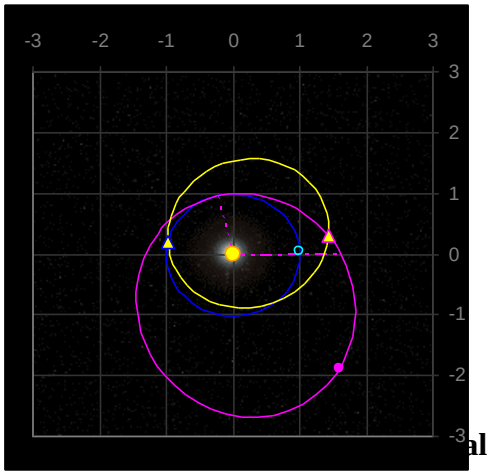


100 days

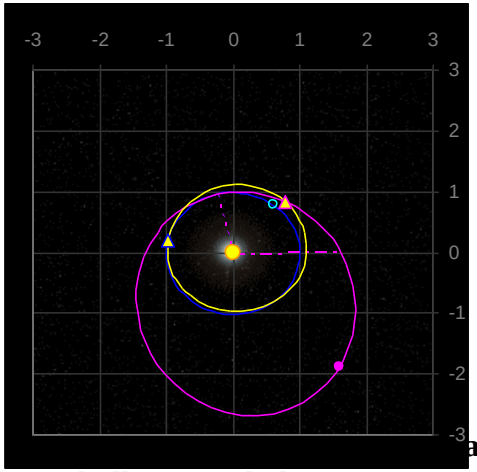


150 days

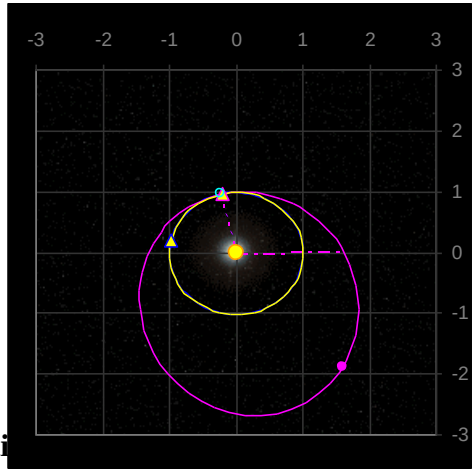




200 days



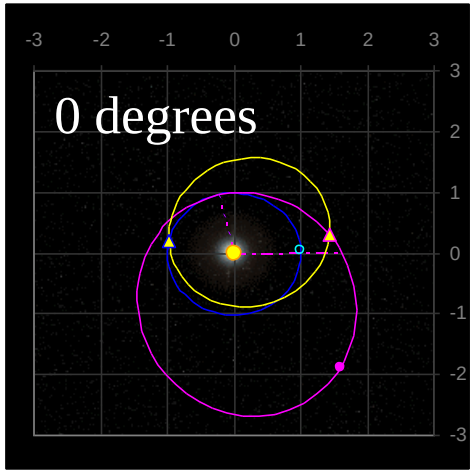
250 days

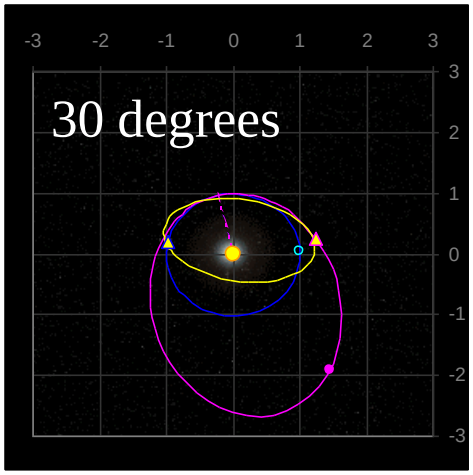


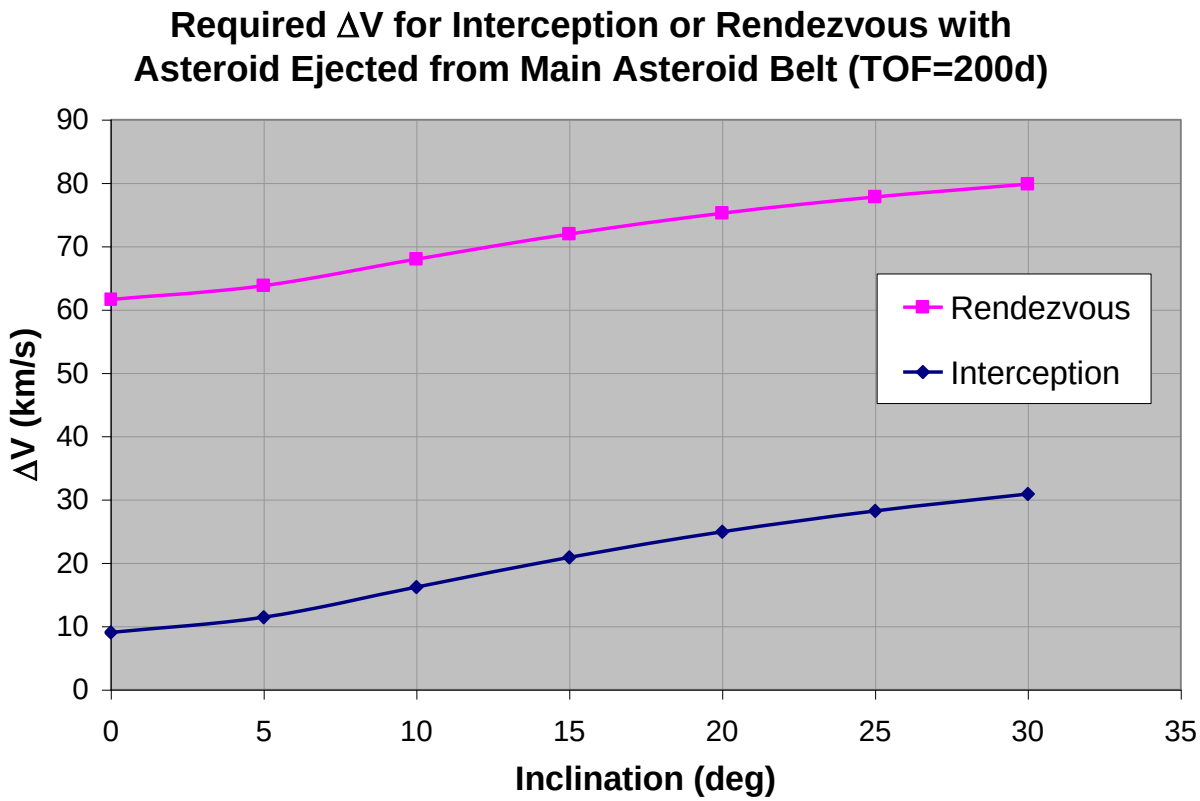
300 days

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

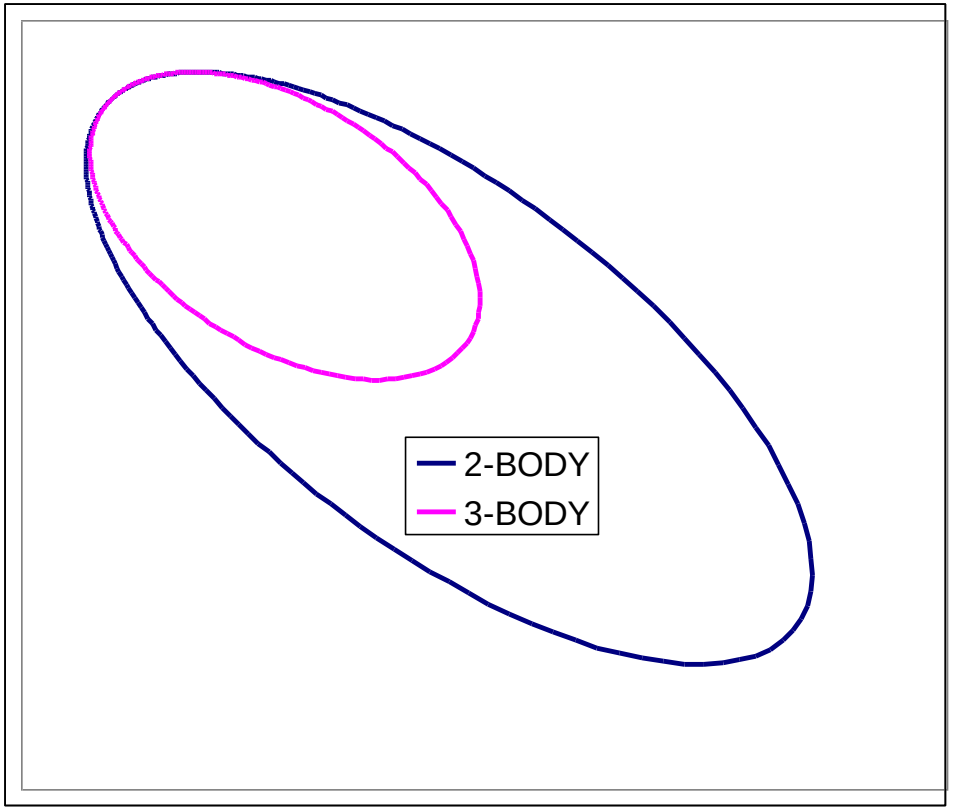




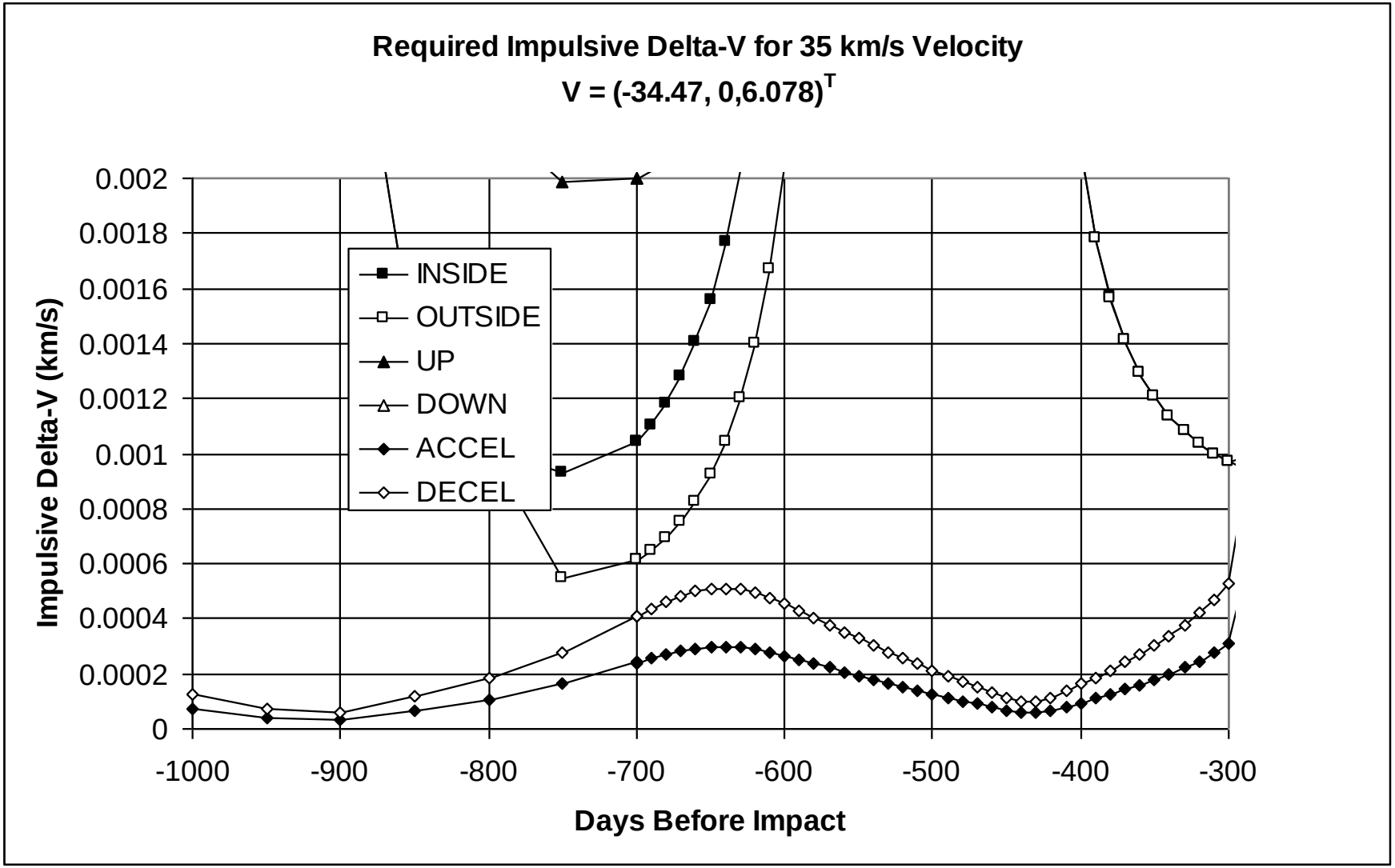


Inbound Trajectory

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!



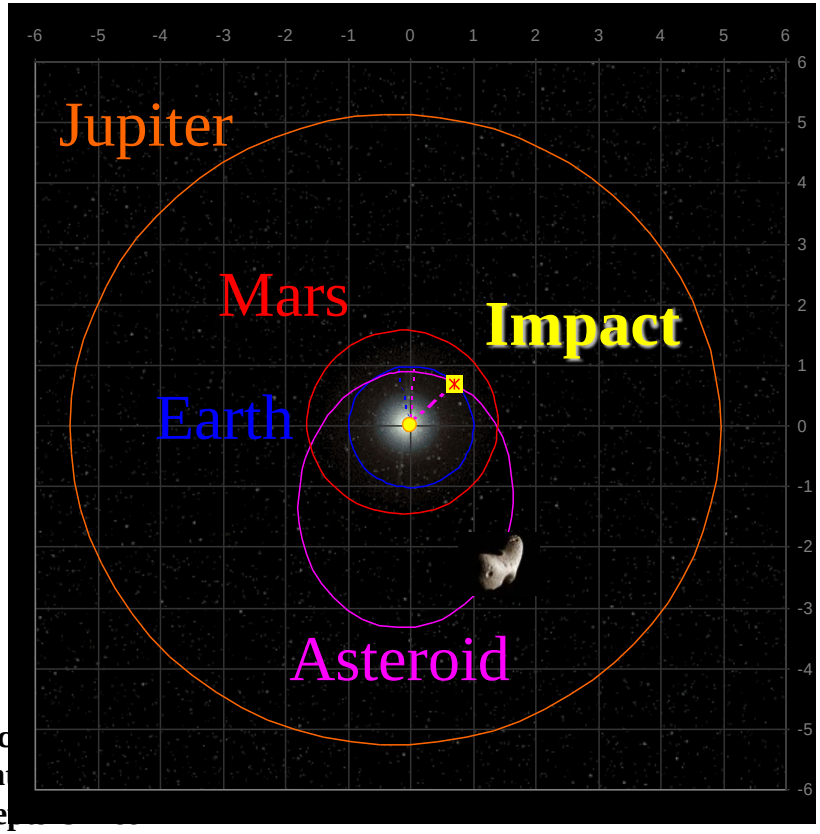
Inbound Trajectory



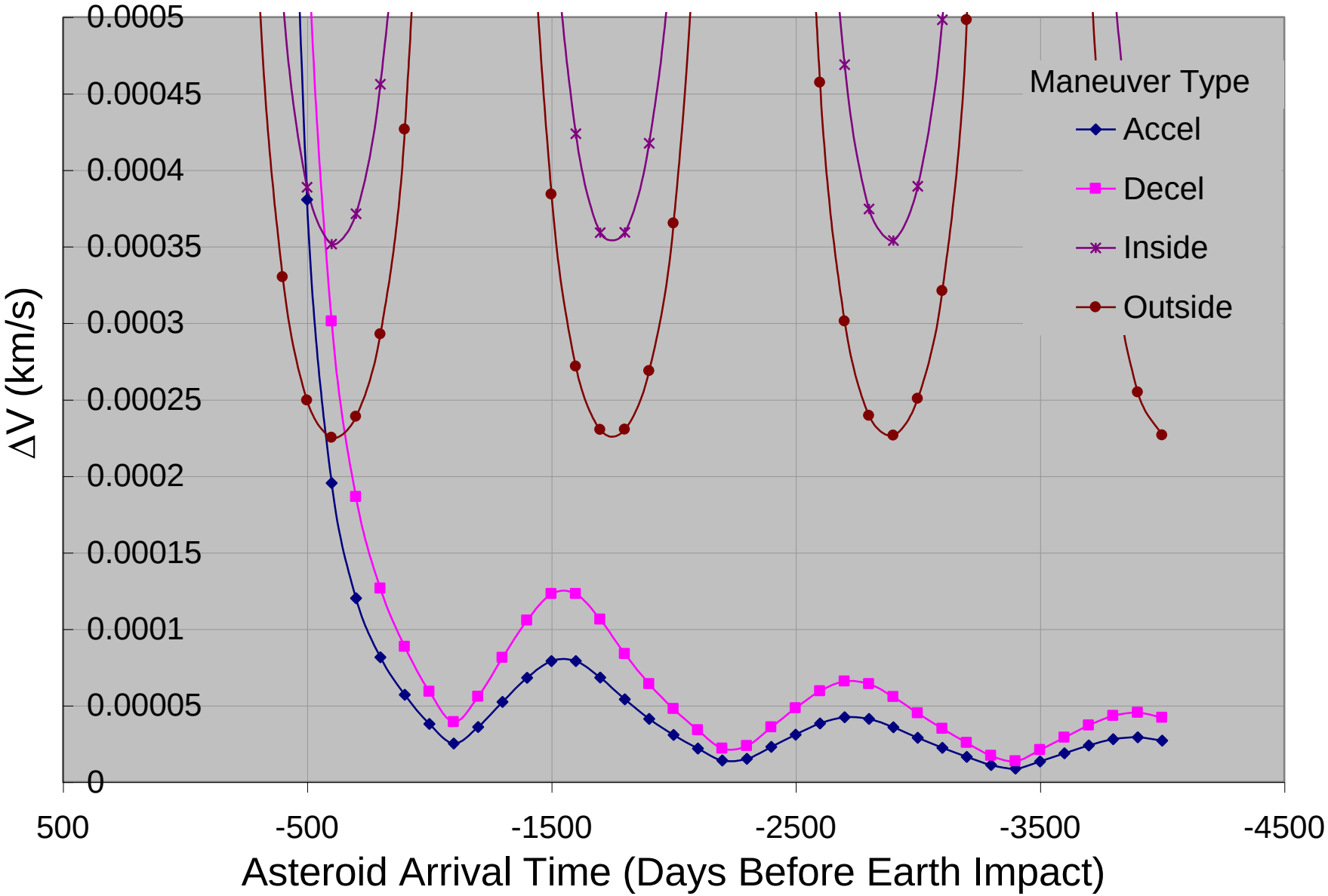
Inbound Trajectory

- 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.

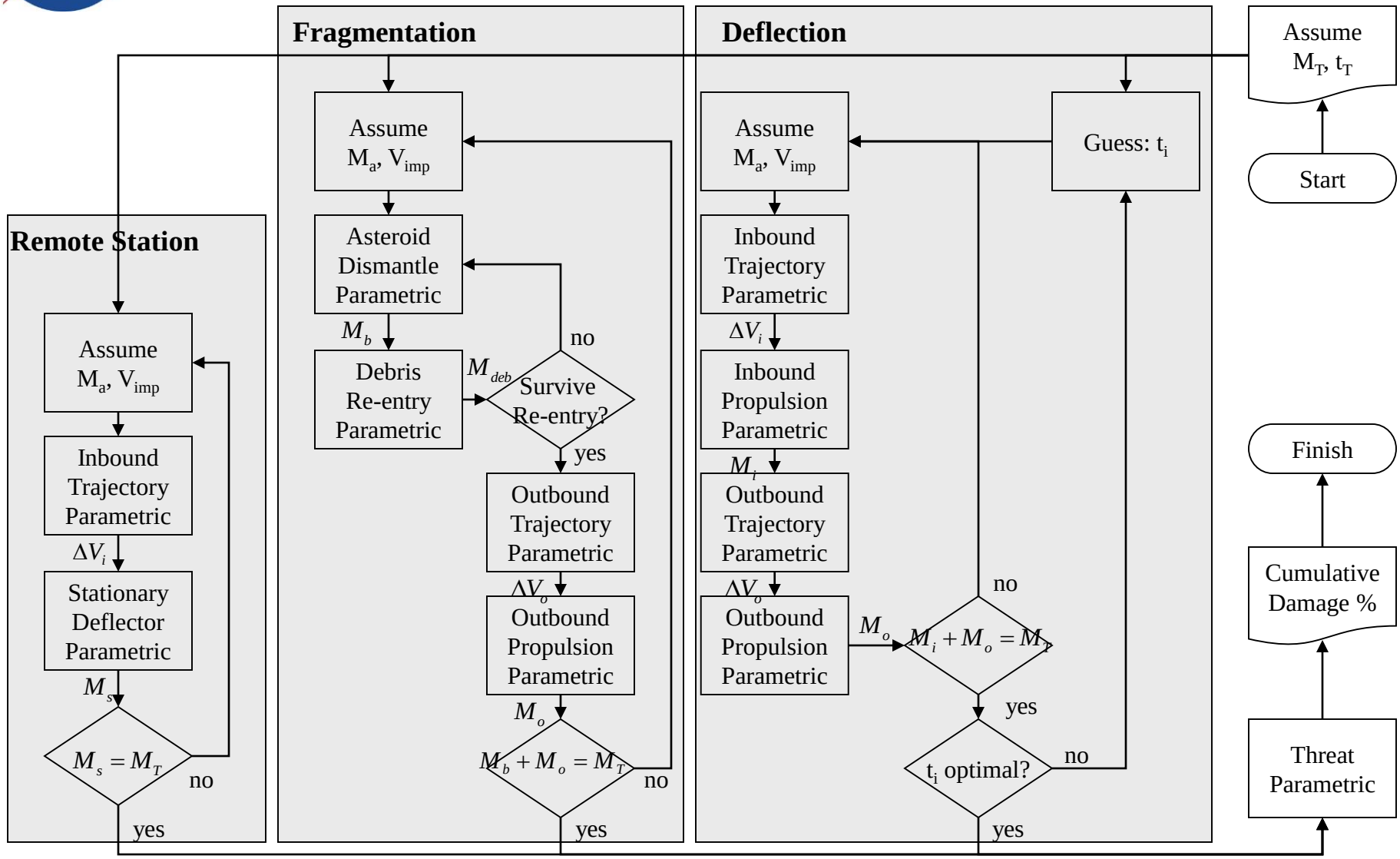
Semimajor Axis (AU)	2.13
Eccentricity	0.578
Inclination	11.46
Ascending Node (deg)	45.02
Argument of Periapsis (deg)	41.83



Inbound Trajectory



Integrated Analysis



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

•Chapman, C. R, and Morrison, D., "Impacts on the Earth by Asteroids and Comets: Assessing the Hazard," *Nature*, 6 January 1994.

•Gold, R. E., "SHIELD – A Comprehensive Earth Protection System: A Phase I Report to the NASA Institute for Advanced Concepts," 28 May 1999.

•Lewis, John S., *Comet and Asteroid Impact Hazards on a Populated Earth*, Academic Press, 1999.

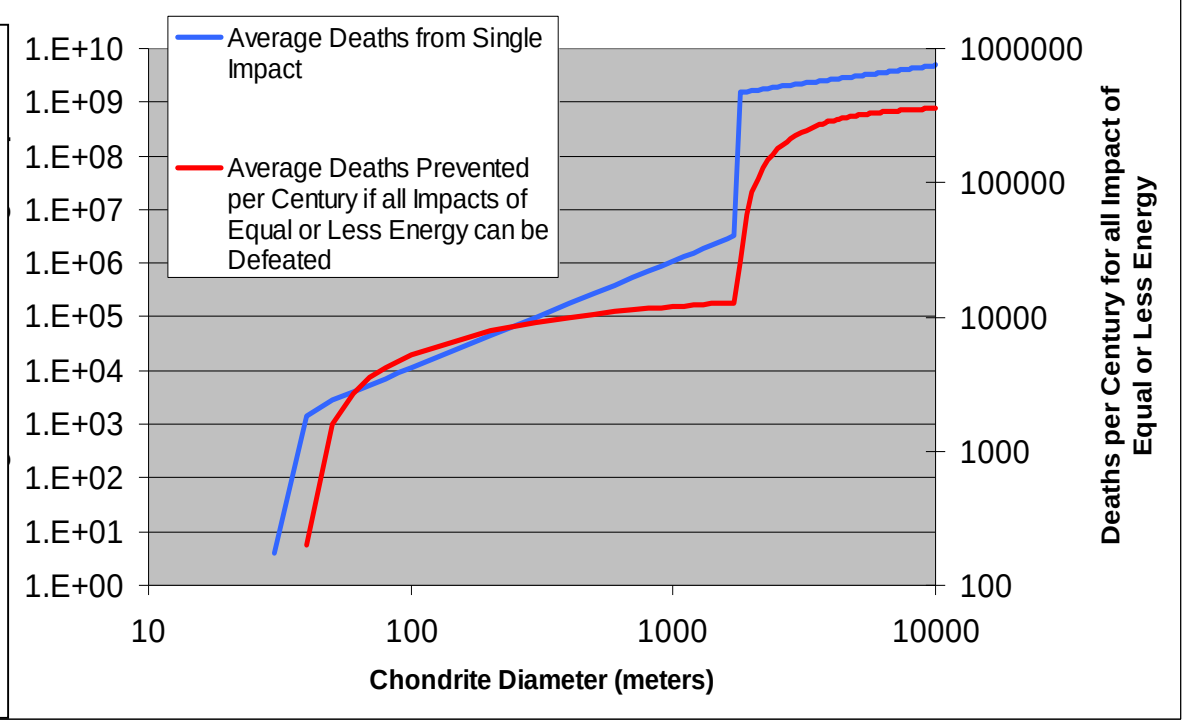
•Jeffers, S. V., Manley, S. P., Bailey, M. E., and Asher, D. J., "Near-Earth Object Velocity Distributions and Consequences for the Chicxulub Impactor," *Mon. Not. R. Astron. Soc.*, 327 (2001).

•Chesley, S, Chodas, P, Milani,, A., Valsecchi, G., Yeomans. D., "Quantifying the risk posed by Potential Earth impacts," *Icarus Asteroids*, 2001.

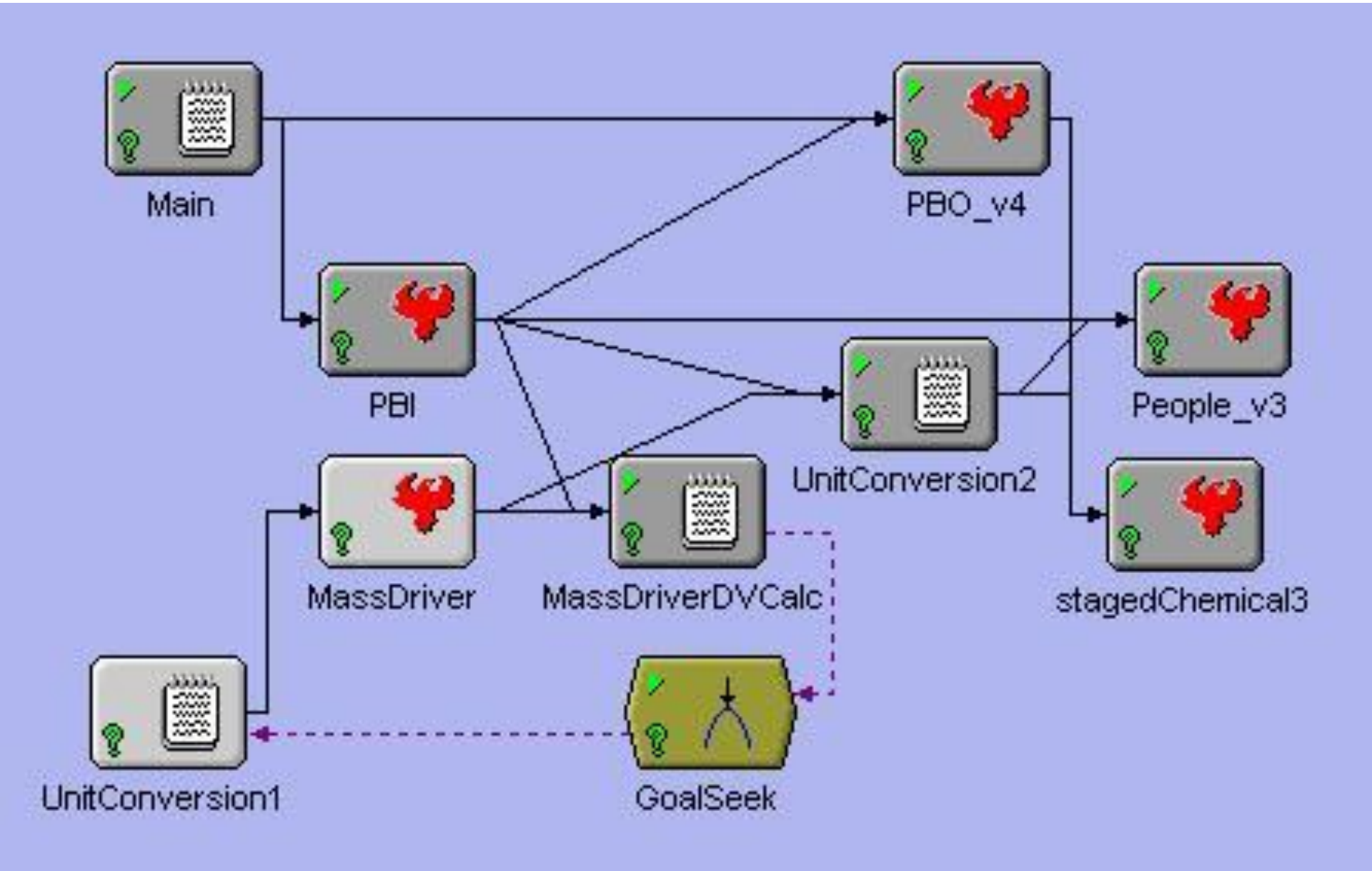
•Ivezic, Zeljko, *et al*, "Solar System Objects Observed in the Sloan Digital Sky Survey Commissioning Data," *The Astronomical Journal*, November 2001.

•Shoemaker, E. M., "Asteroid and Comet Bombardment of the Earth," *Annual Review of Earth and Planetary Sciences*, 11: 461-494.

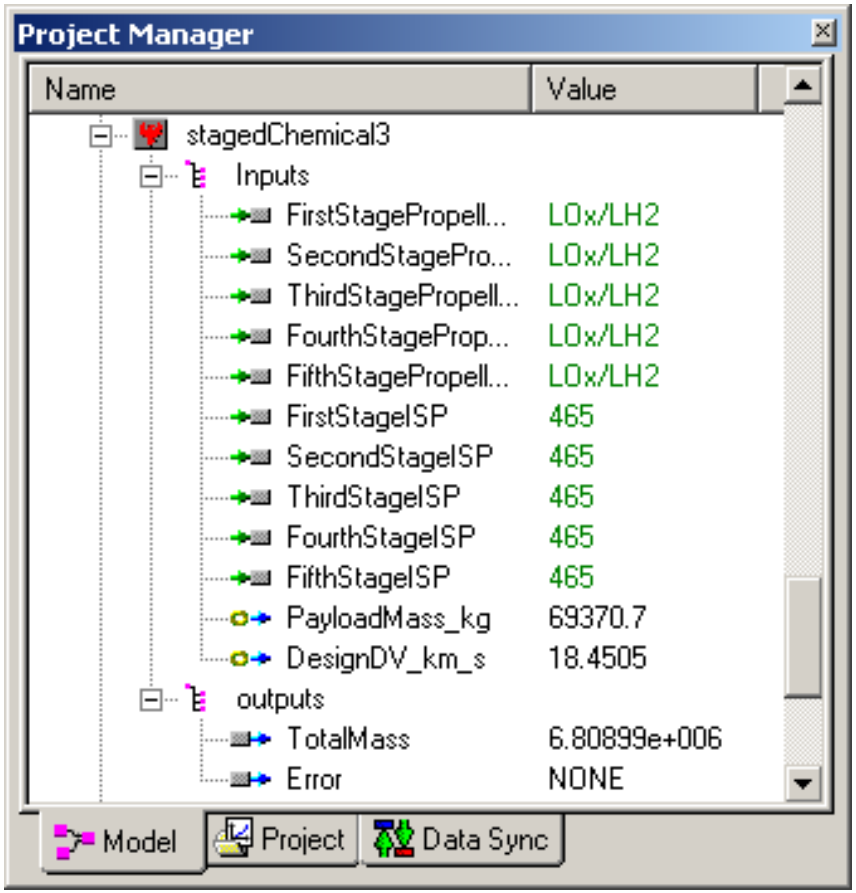
•Chapman, C.R. & Morrison, D., 1994, Nature 367, 33-40



Integrated Analysis



The Staged Chemical Vehicle



5 stage vehicle

Isp = 465 sec (LOx-LH_2)

Stage structural fraction based on historical data

ΔV split between stages is optimized

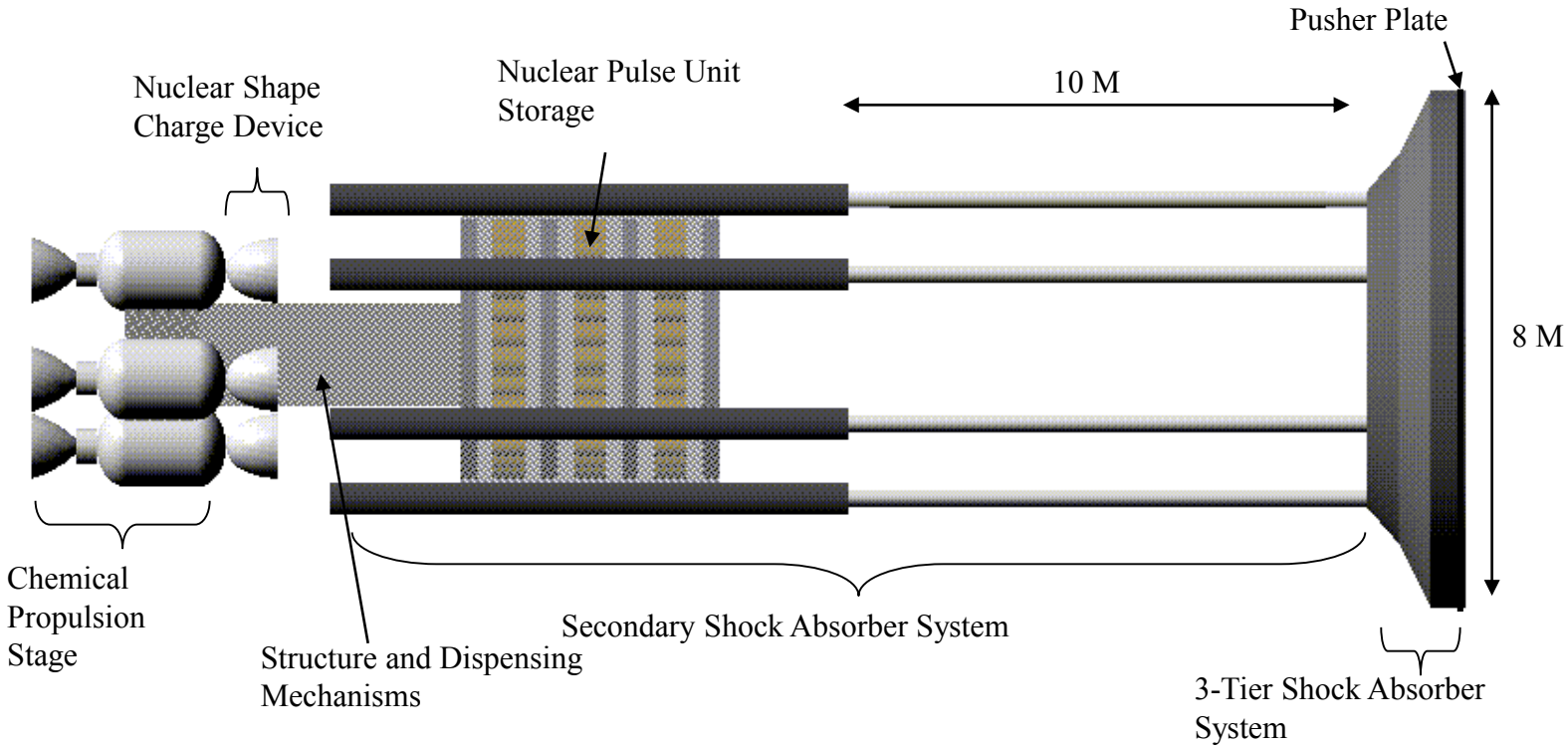
Conclusions (2003-4 study)

System	Maneuver	Time Before Impact (days)#/ Outbound Travel Time (days)	Total System Mass at SOI (mT) for Different Asteroid Diameters (meters)			Maximum Diameter of Asteroid (meters)/Total System Mass at Earth SOI (mT)
			100	1000	10000	
Staged Chemical + Mass Driver	Rendezvous	2900/2400	n/a	n/a	n/a	50/6,849 80/6,918
Staged Chemical + Nuclear Deflection	Intercept	1509/599	0.847	8.27	1300	9000/1000
	Rendezvous	1075/943	5.62	568	87,800	1000/1000
Staged Chemical + Kinetic Deflection	Intercept	1025/800	73.8	n/a	n/a	260/1,000
Nuclear Pulse	Rendezvous	2170/970	29.7	41.8	1240	9000/1000
Solar Collector	Rendezvous (~3 yr)	1076/1011**	0.637	1.07	167	§
	Rendezvous (~10 yr)	3635/3520**	0.550	0.636	34.6	§

*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)

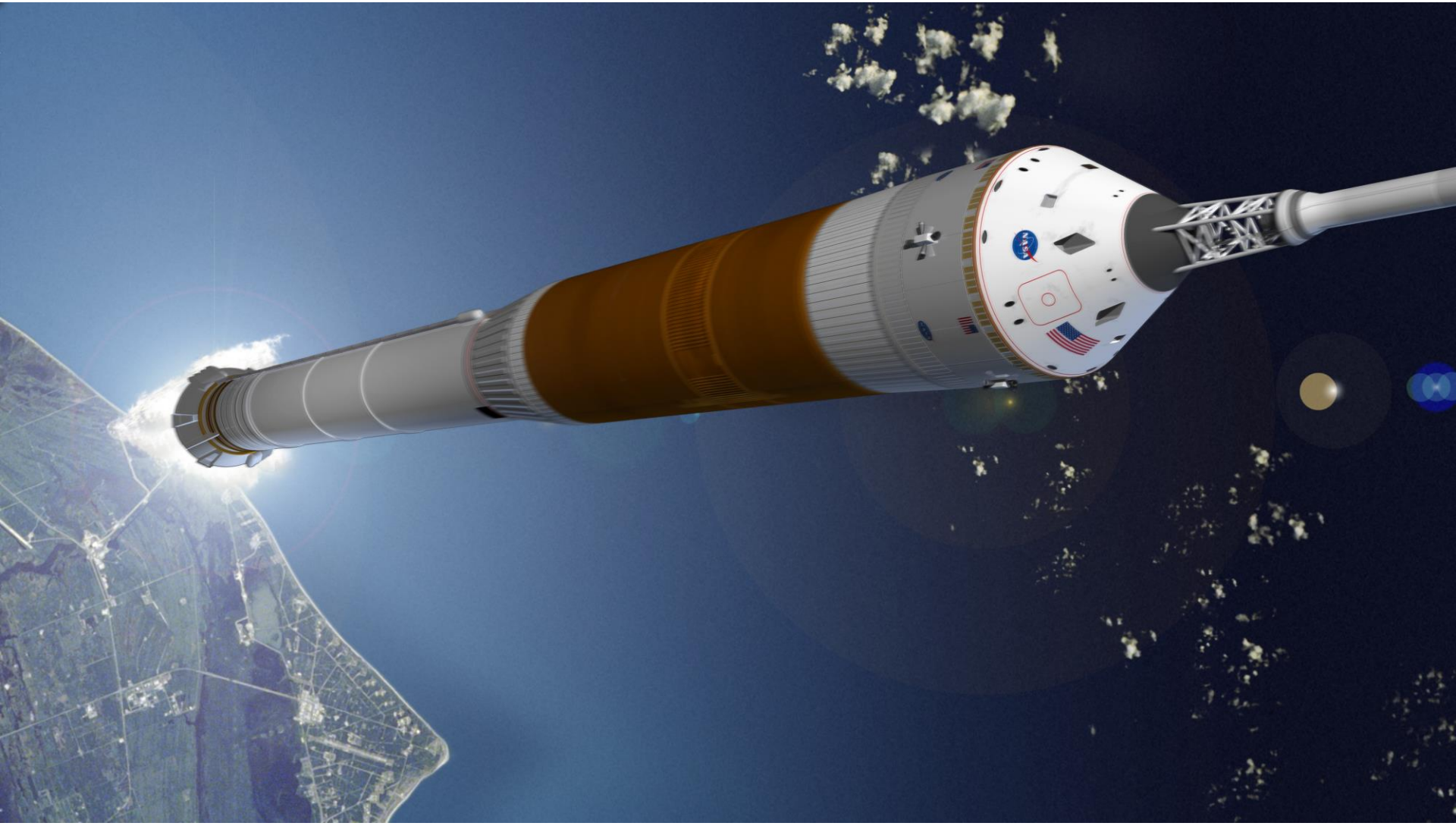
- Baseline case is Nuclear Pulse outbound with Nuclear Deflection inbound



Introduction to the 2007 Study

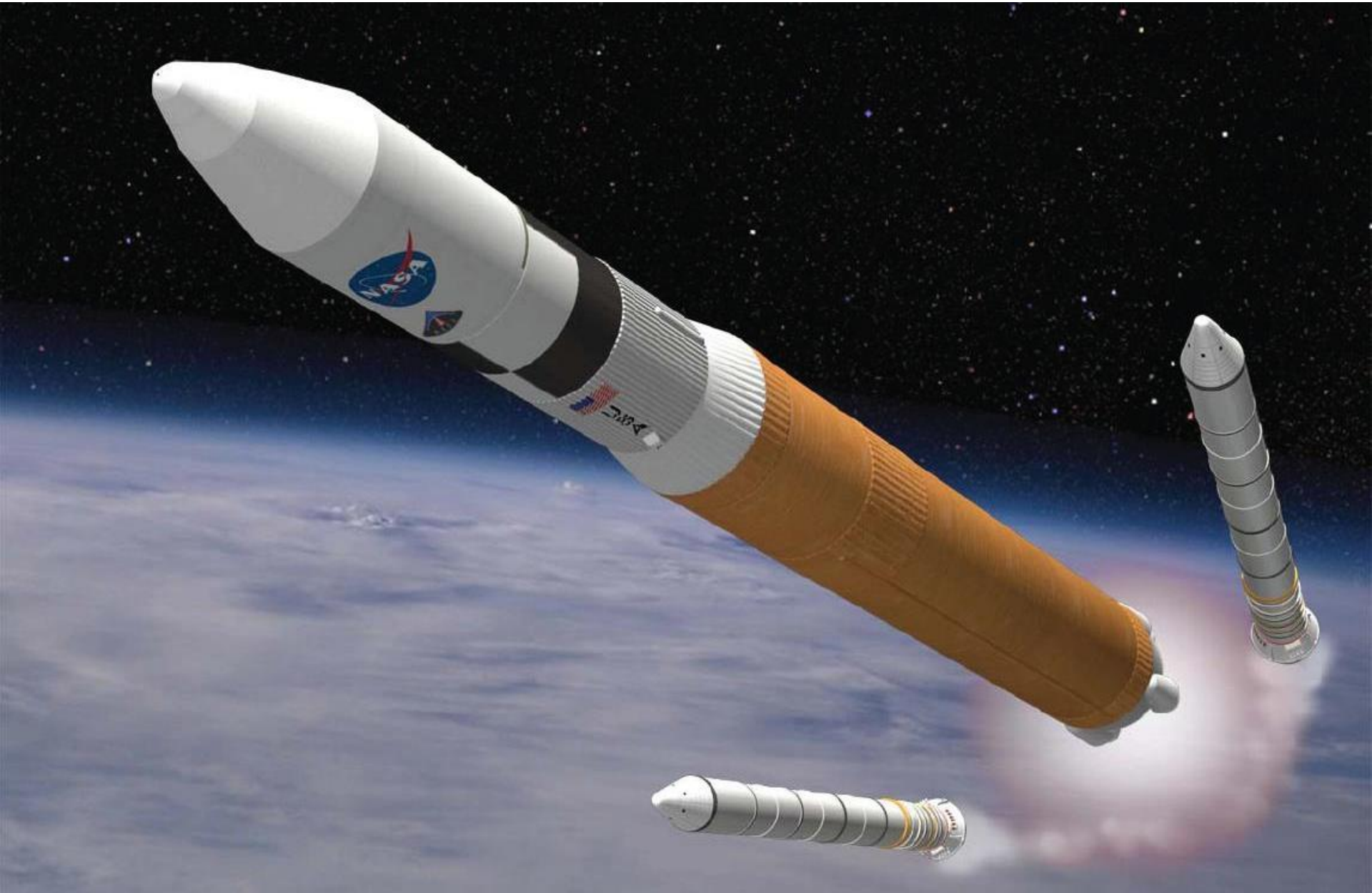
- Premise was to evaluate the potential of the Constellation architecture (specifically the Ares I and V vehicles) to support NEO deflection
- Emphasis here was to consider operational difficulties in a near term deflection scenario
  - Address the premise that mitigation should be considered after a “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



National Aeronautics and Space Administration
Marshall Space Flight Center
ED04/Advanced Concepts Office

Exploration Vehicles

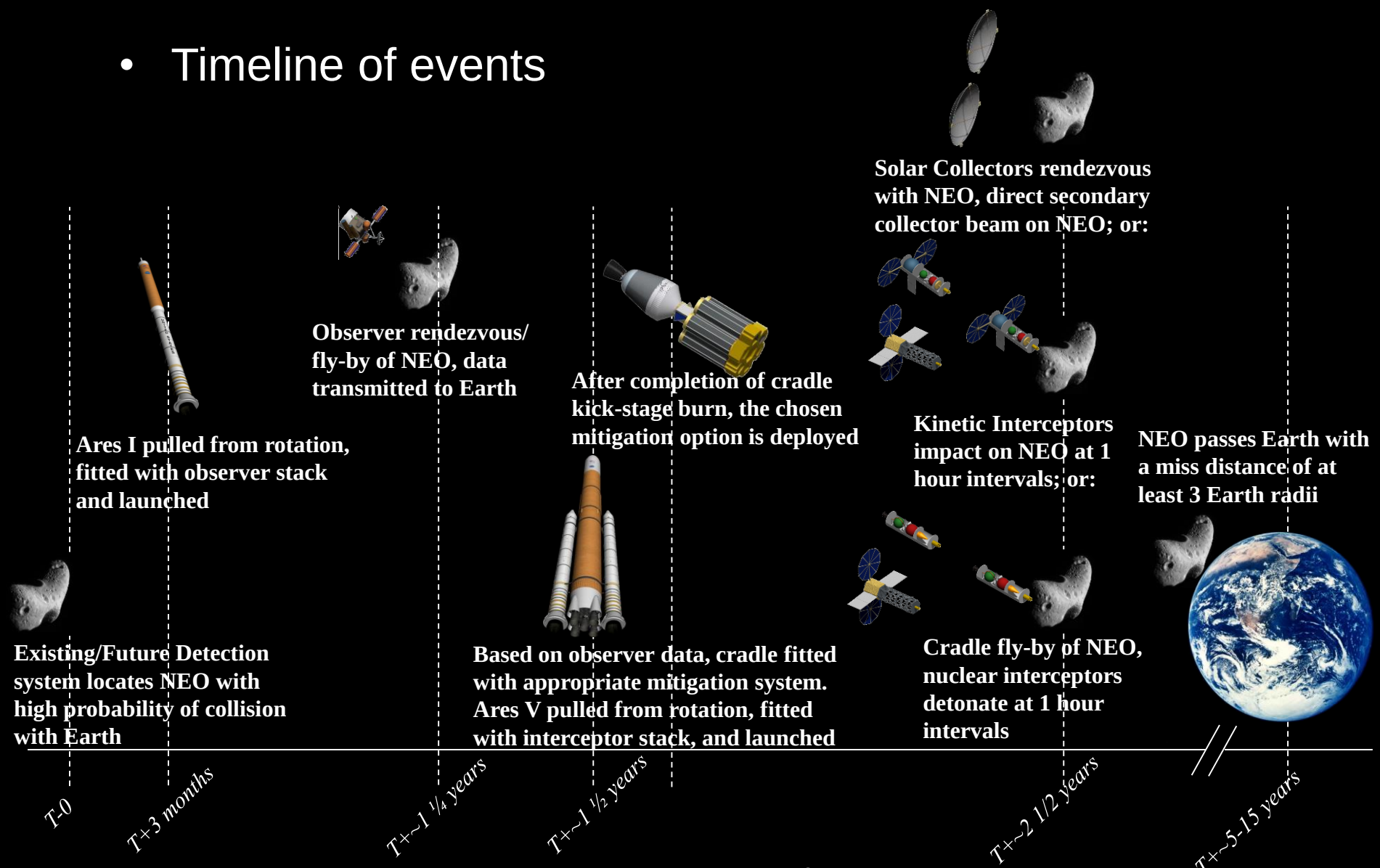


Groundrules and Assumptions

- 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.

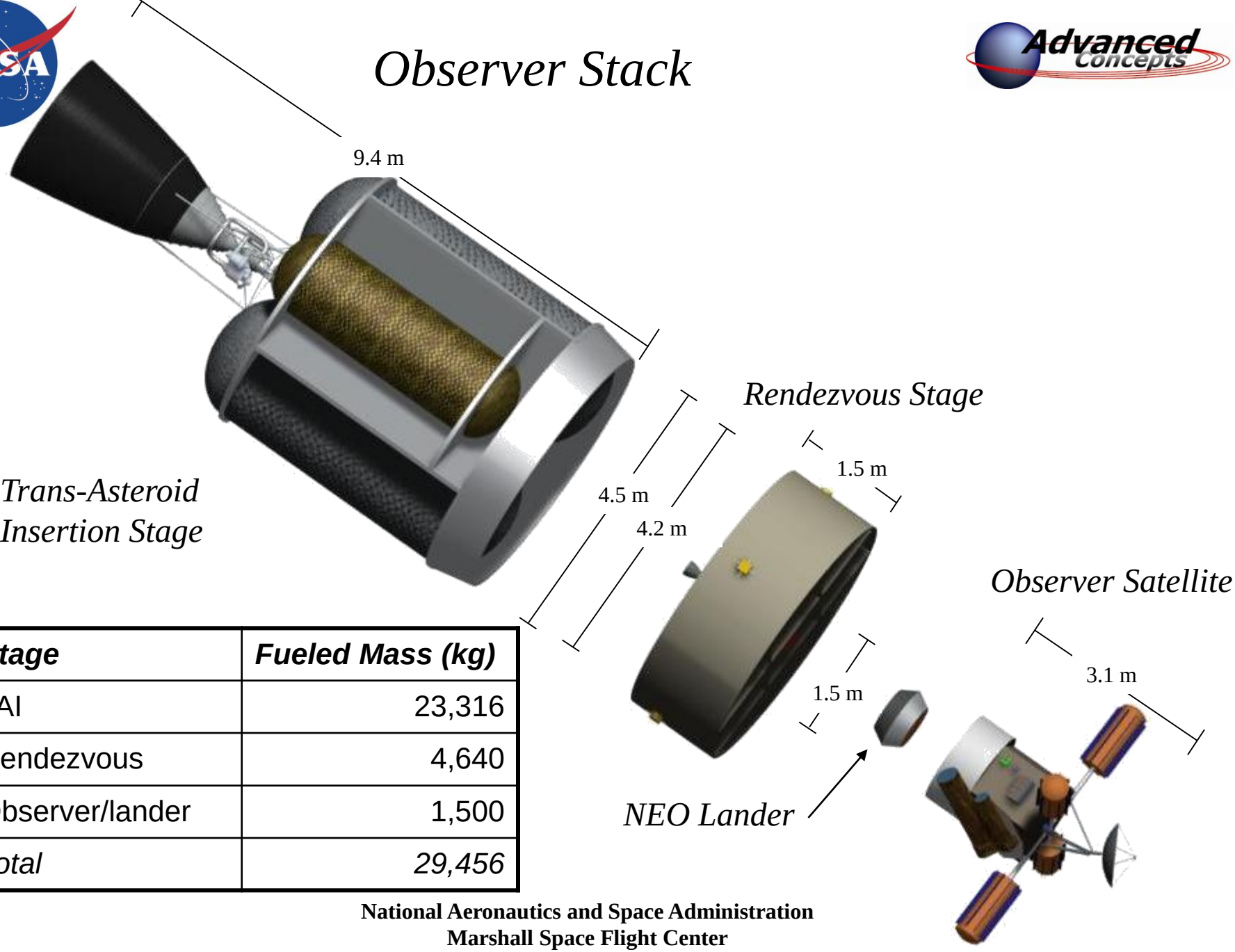
Operational Concept

- Timeline of events



(Actual times will be based on particulars of threatening NEO)

Observer Stack



Stage	Fueled Mass (kg)
TAI	23,316
Rendezvous	4,640
Observer/lander	1,500
Total	*29,456*

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

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

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

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

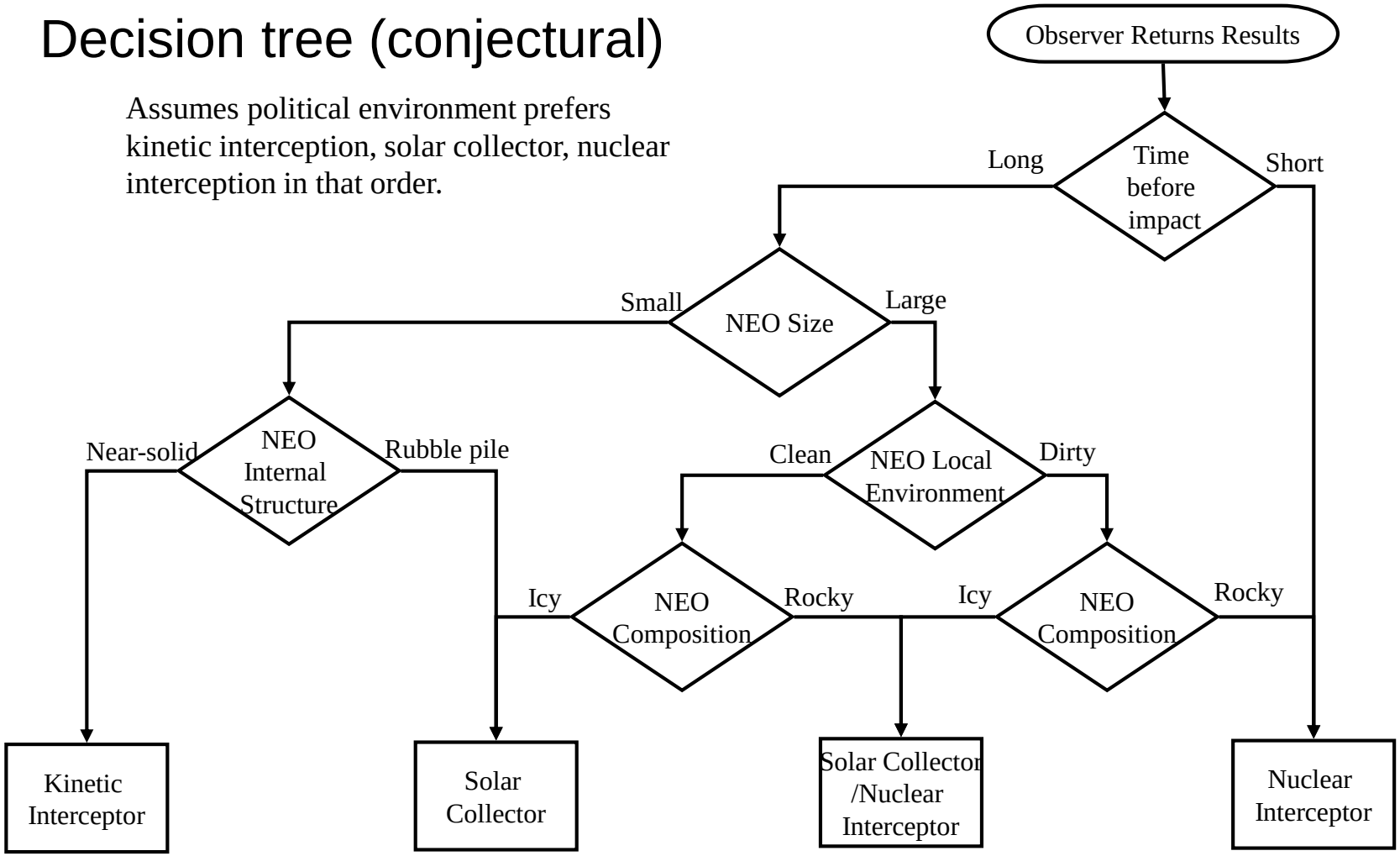
  - Instruments and measurements on lander

Instruments	***Planned measurements***
Chemical analysis package	Composition
Seismic sensor	Internal structure
Fly-by balls	Mass, Gravitational field

Observer Stack

- Decision tree (conjectural)

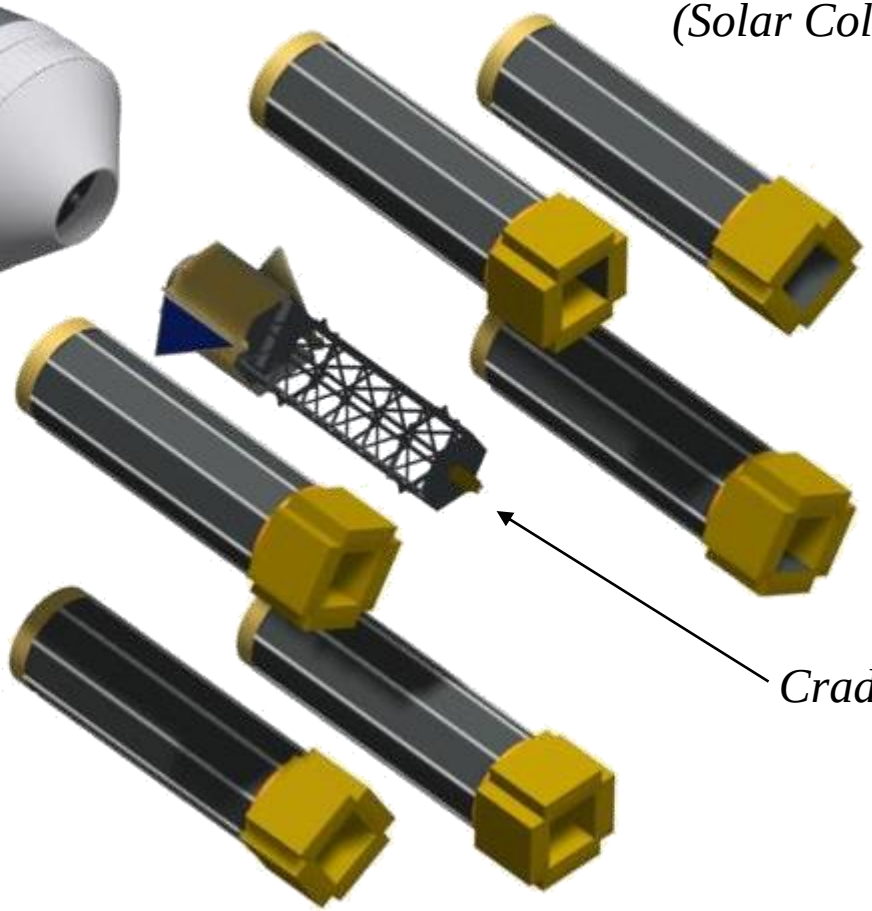
Assumes political environment prefers kinetic interception, solar collector, nuclear interception in that order.



Interceptor Stack

Kick Stage

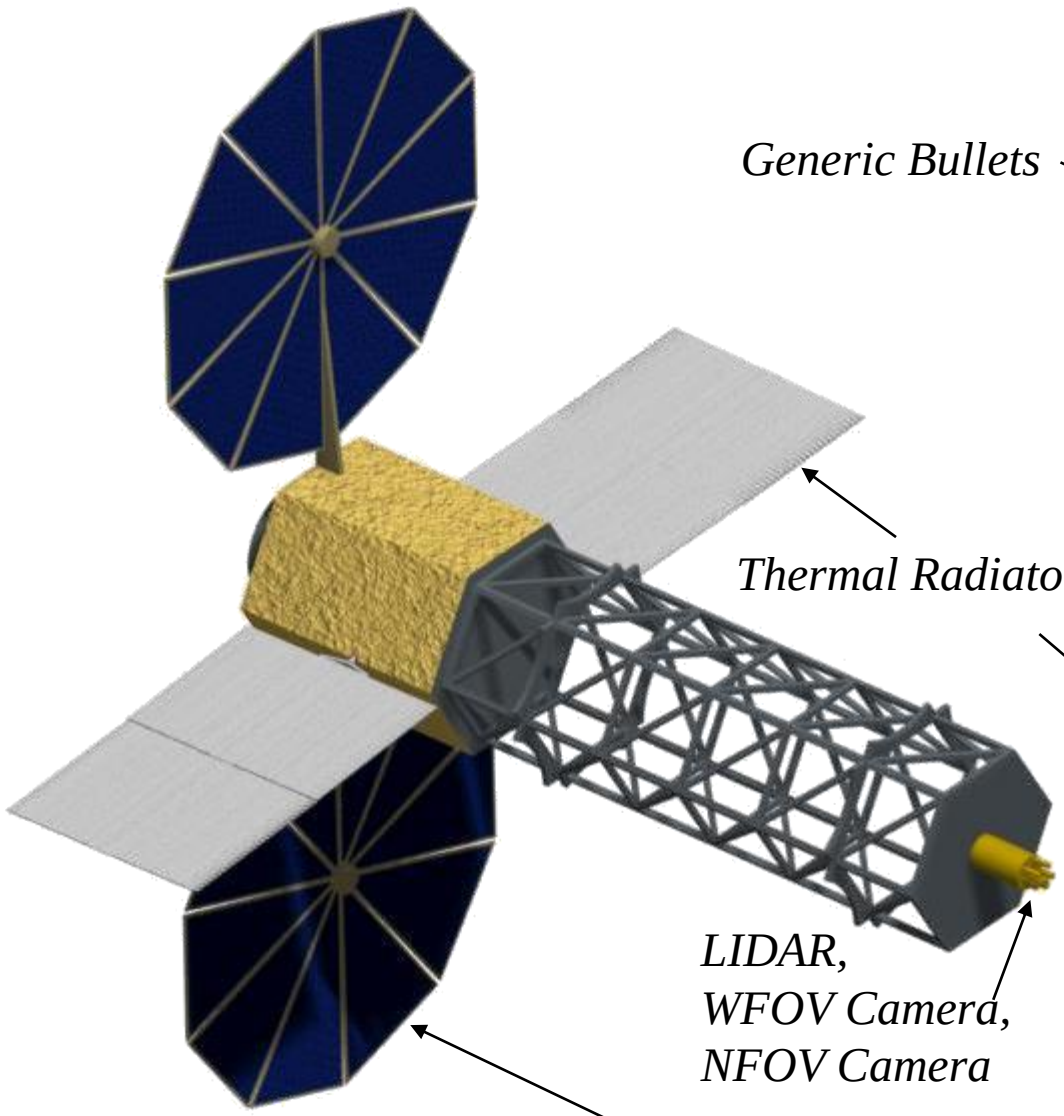
Interceptor Bullets
(Solar Collector shown)

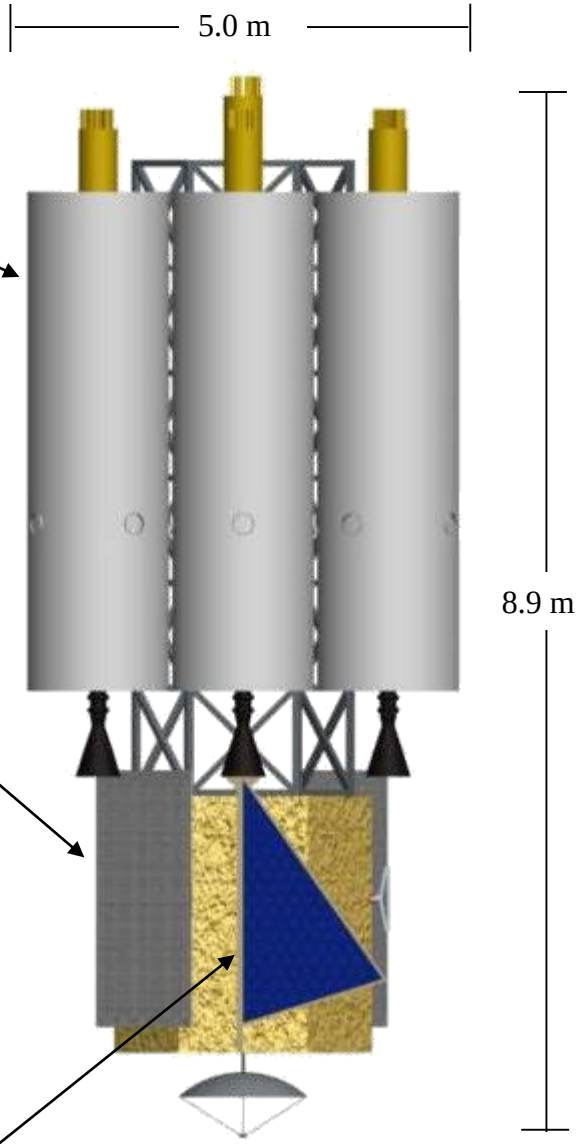


Cradle

Stage	***Fueled Mass (kg)***
Kick	45,359
Cradle	2,005
Bullets (6)	9,000
Total	*56,364*

Interceptor Stack

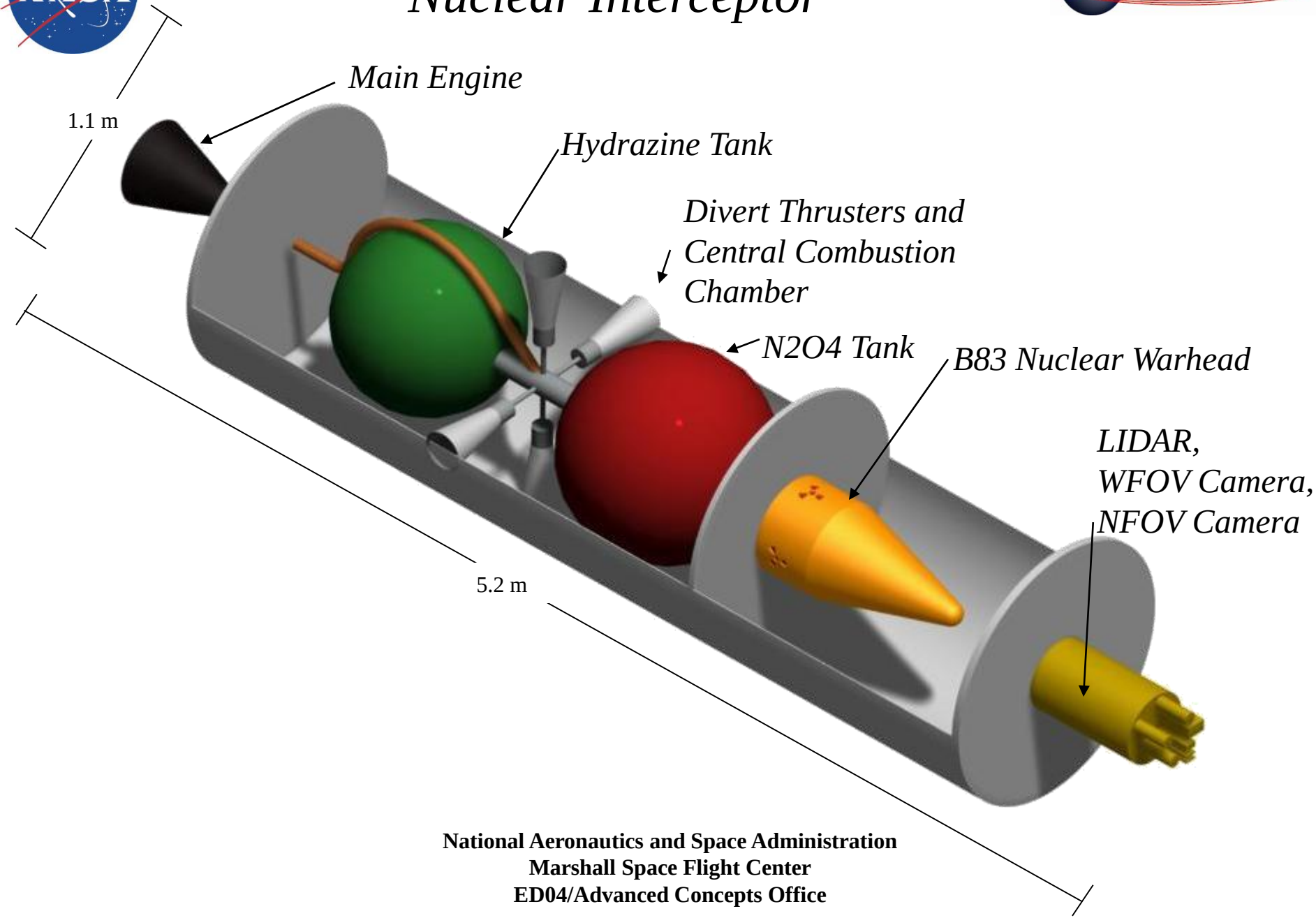




Interceptor Stack

- Design and Performance
  - Ares V Earth Departure Stage (EDS)
    - Half full (approx.) of propellant at Low Earth Orbit. ΔV – 3940 m/s
  - Interceptor Kick-Stage
    - Lox/LH2 upper stage ignites immediately after EDS burnout and separation. ΔV – 4650 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

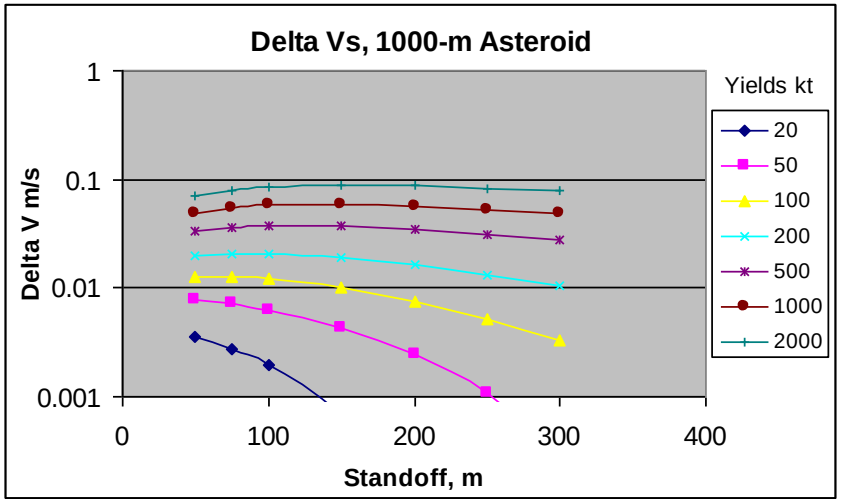
Nuclear Interceptor

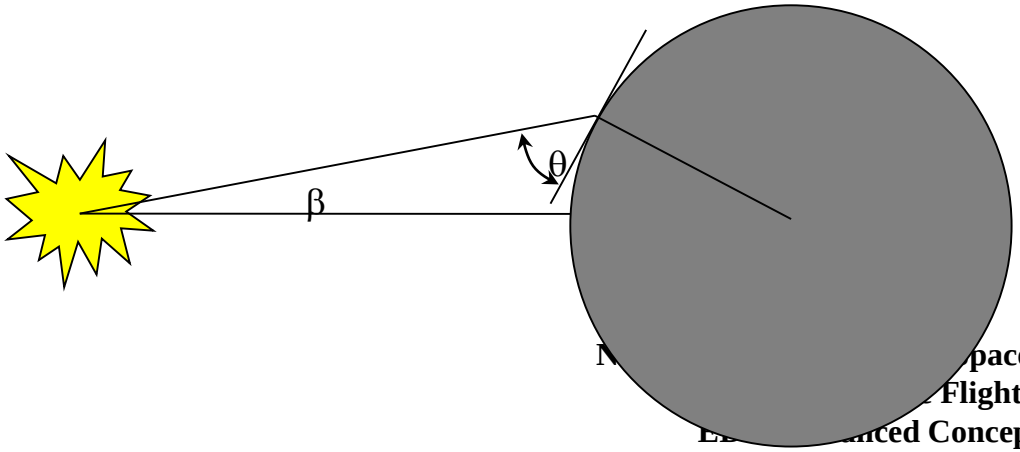


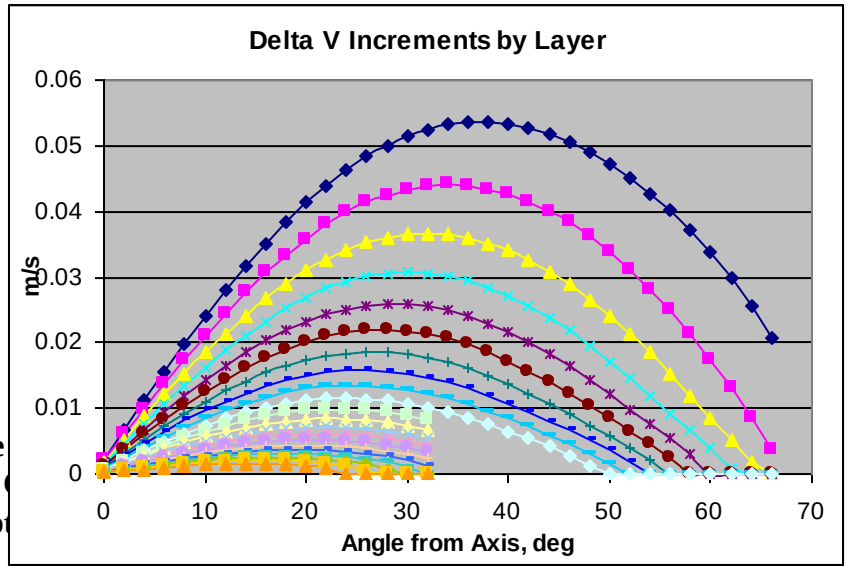
National Aeronautics and Space Administration
Marshall Space Flight Center
ED04/Advanced Concepts Office

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

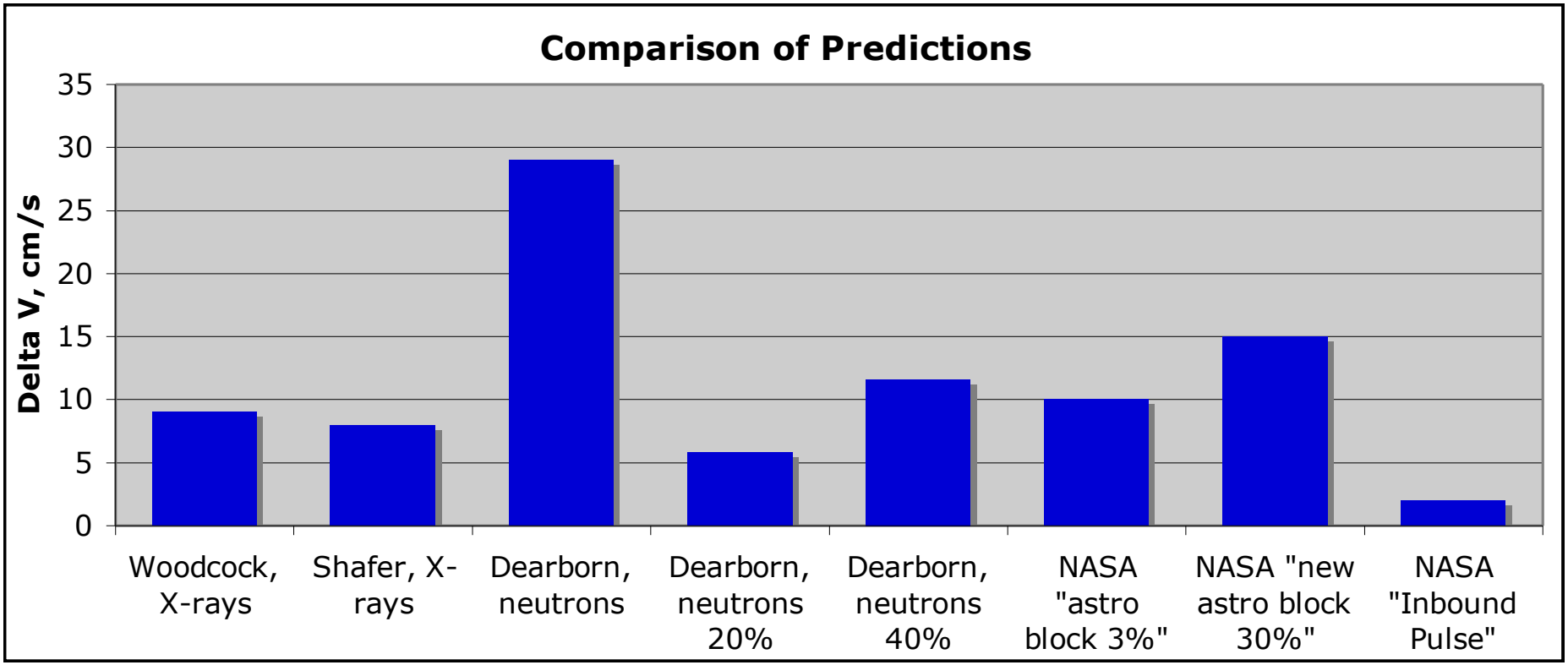






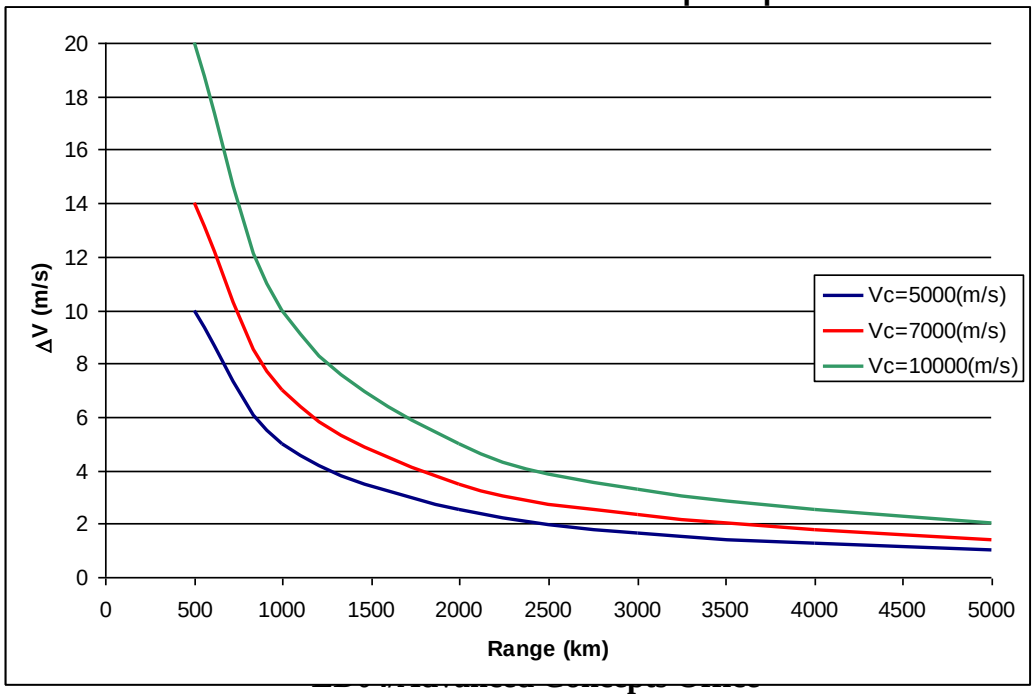
Nuclear Interceptor

- Prediction comparison against other models in literature



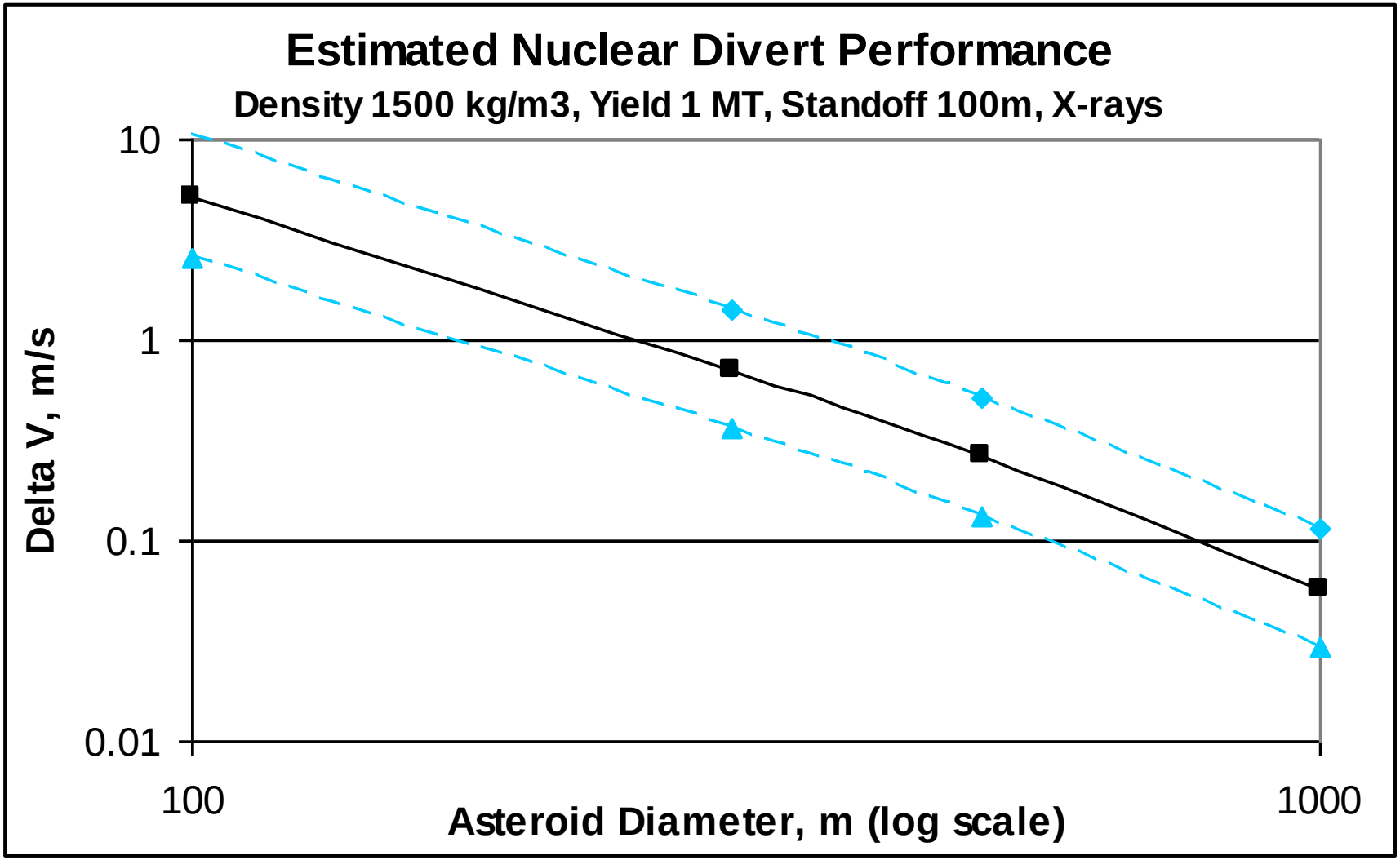
Nuclear Interceptor

- 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
  - ΔV requirements for terminal intercept shown below. Design assumes 200 m/s for terminal intercept operations

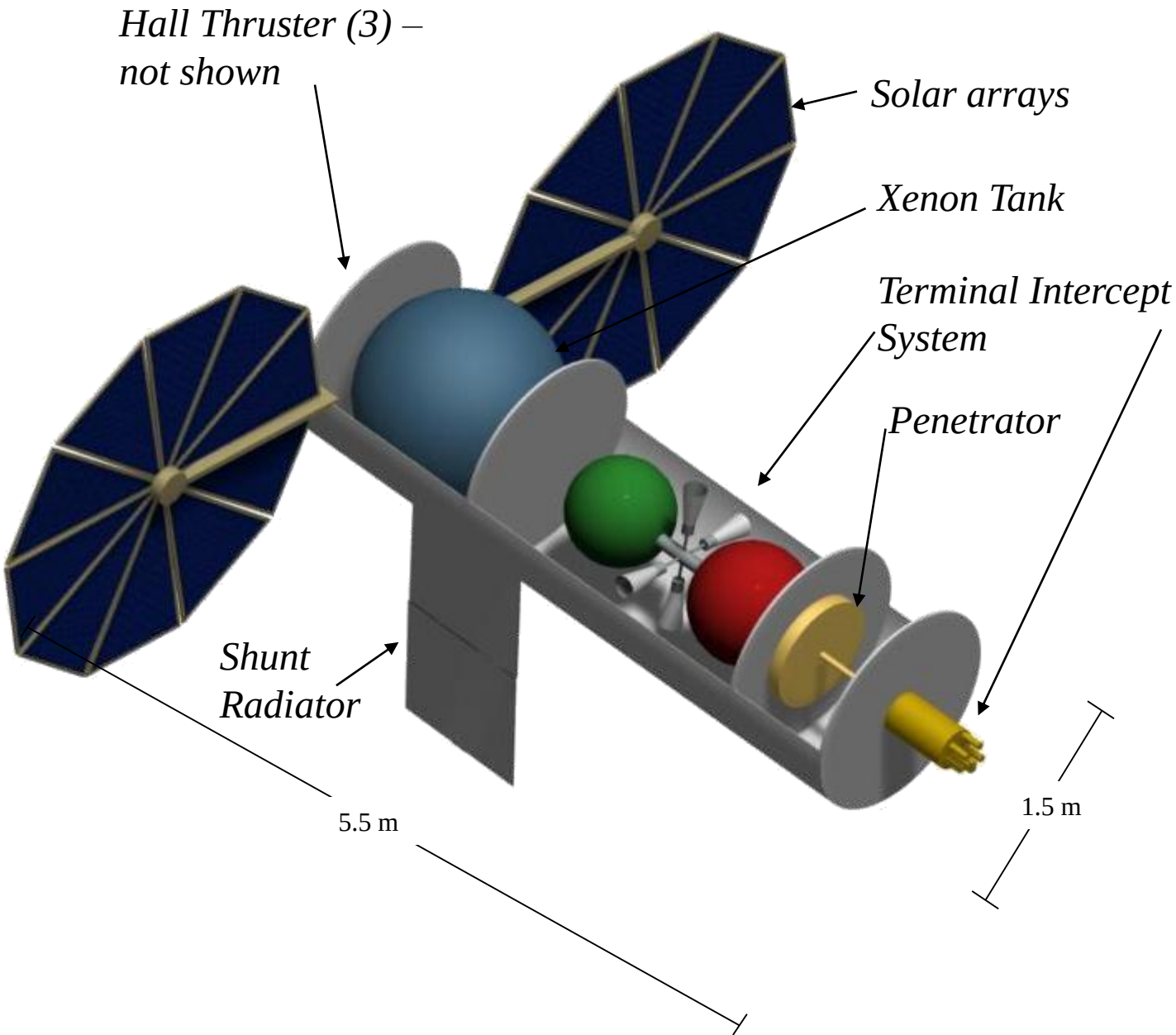


Nuclear Interceptor

- Nuclear Interceptor Effectiveness (single interceptor)

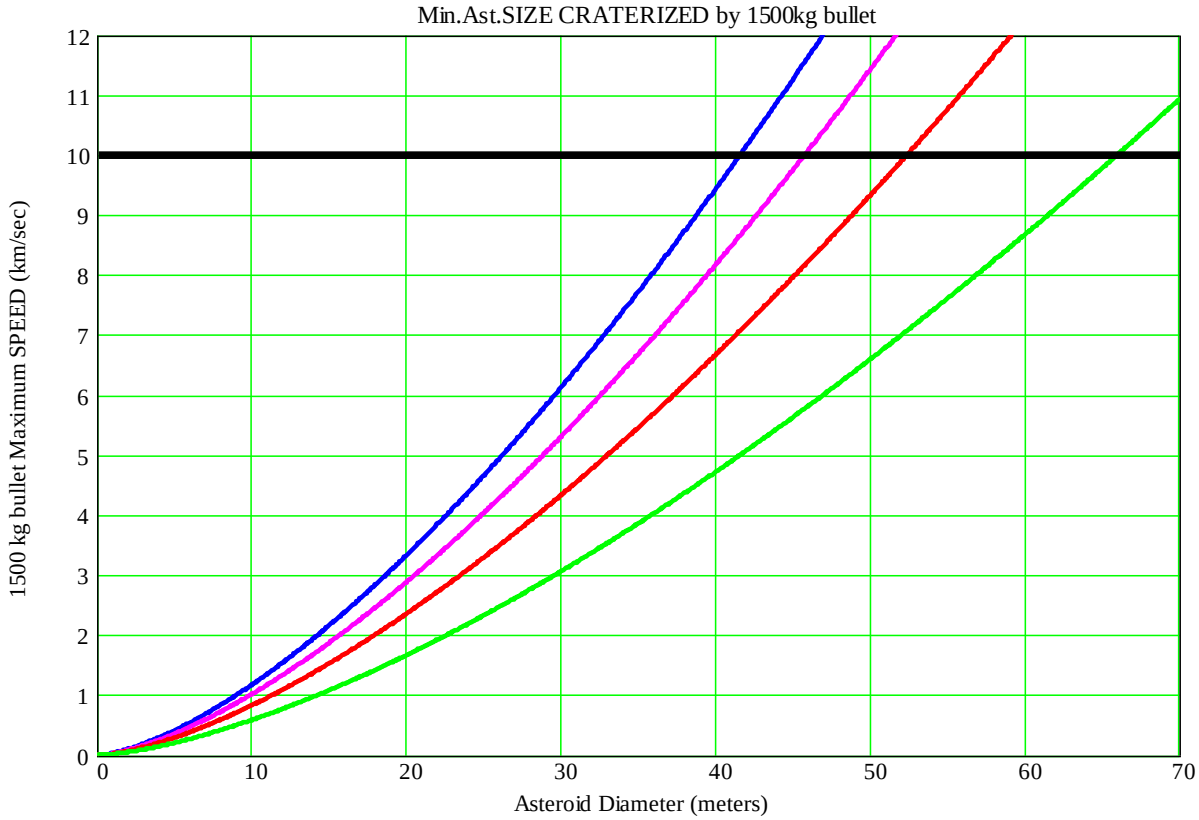


Kinetic Interceptor



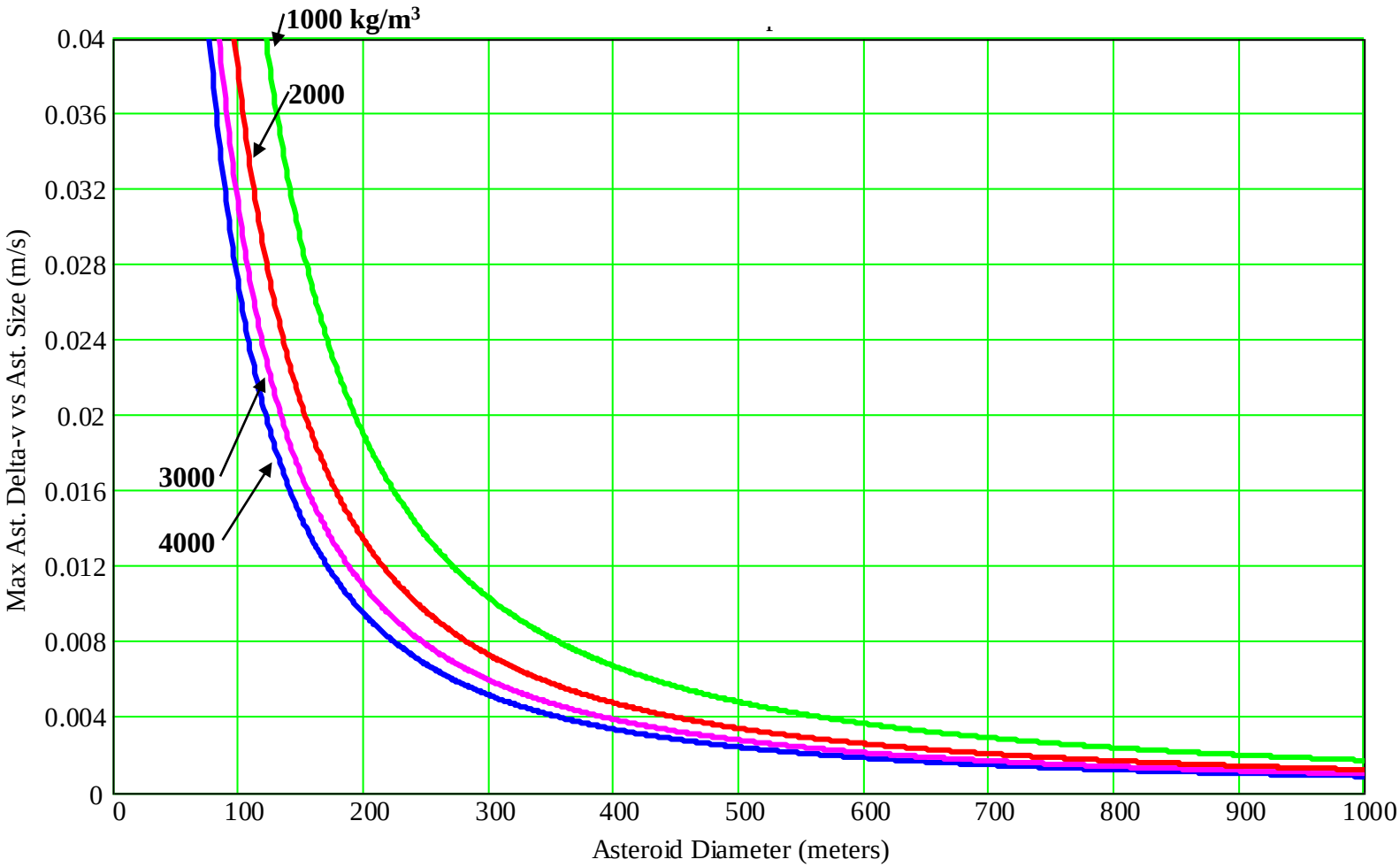
Kinetic Interceptor

- 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



Kinetic Interceptor

- Kinetic Interceptor Effectiveness (single interceptor)



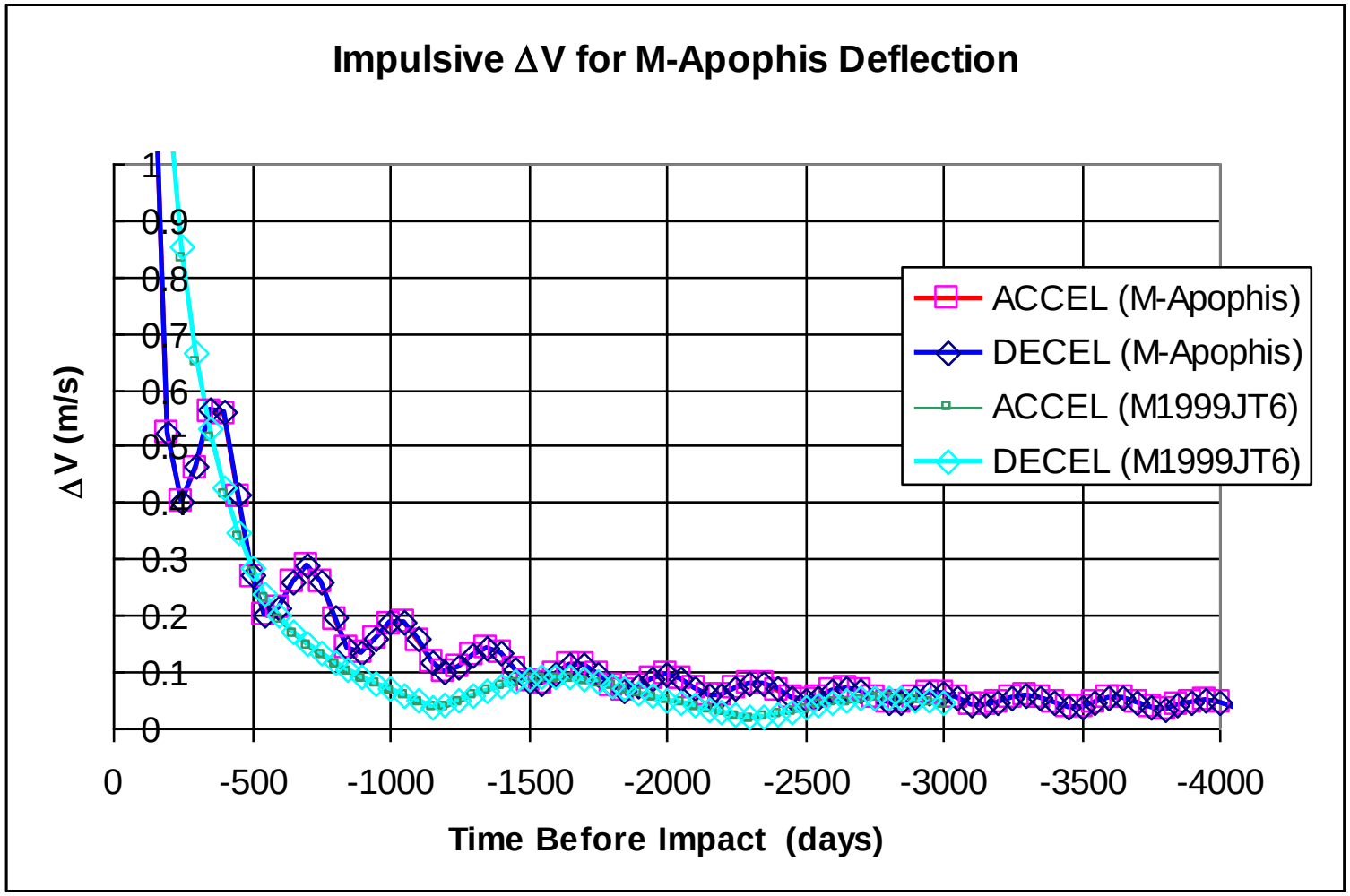
Comparative Analysis

- 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

Orbital Element	***Original***	***Modified***
Semi-major axis (m)	137986931.808626	137978976.28259
Eccentricity	0.19114698829234	0.19091399221024
Inclination (deg)	3.34145210222811	3.333348213097
Right ascension of the ascending node (deg)	203.874080430574	212.35750466471
Argument of perigee (deg)	126.695719648246	127.46966492194
Mean anomaly (deg)	137.86541454524	127.25811549492

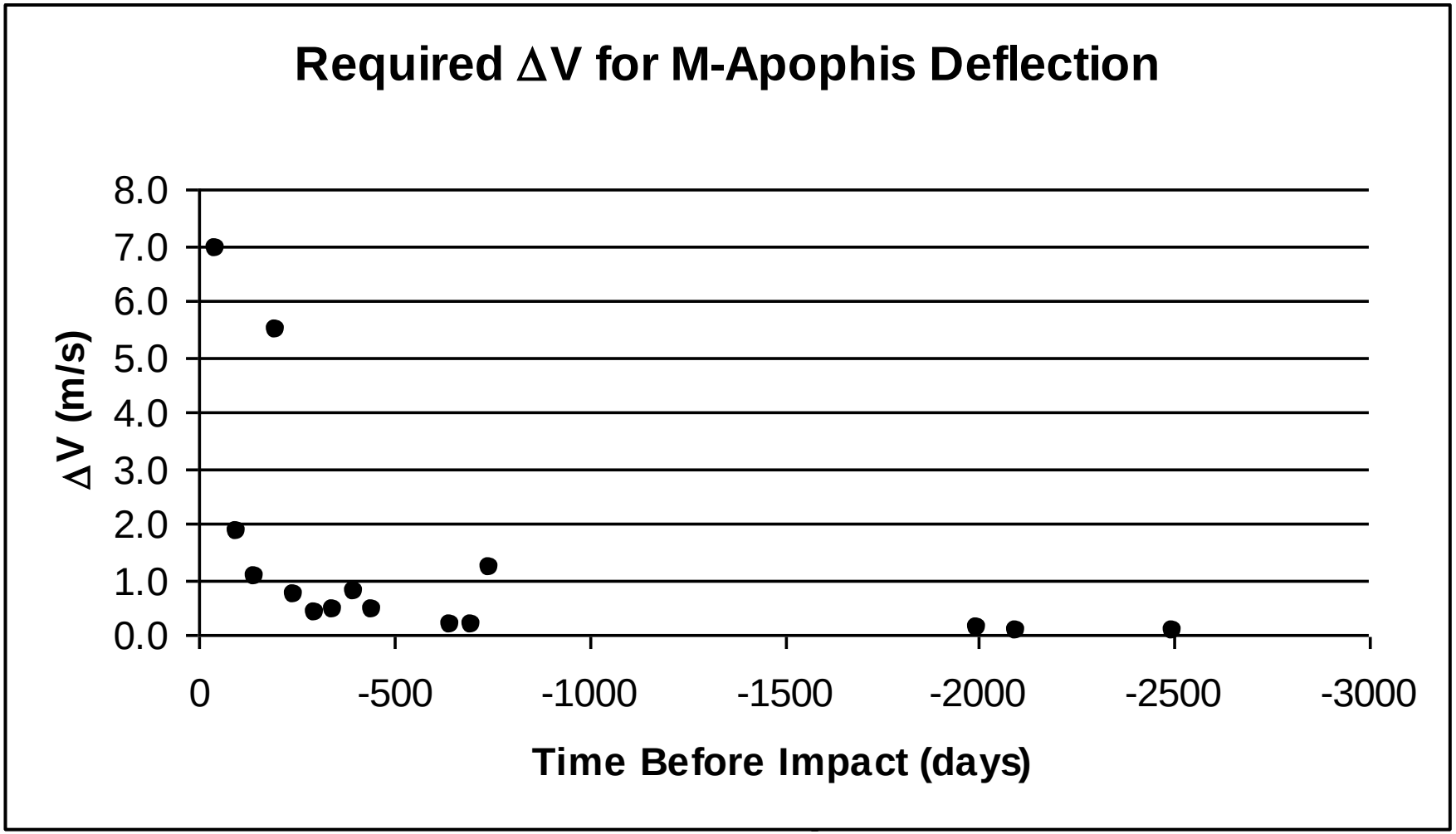
Comparative Analysis

- Required ΔV for impulsive deflection using nuclear interceptors



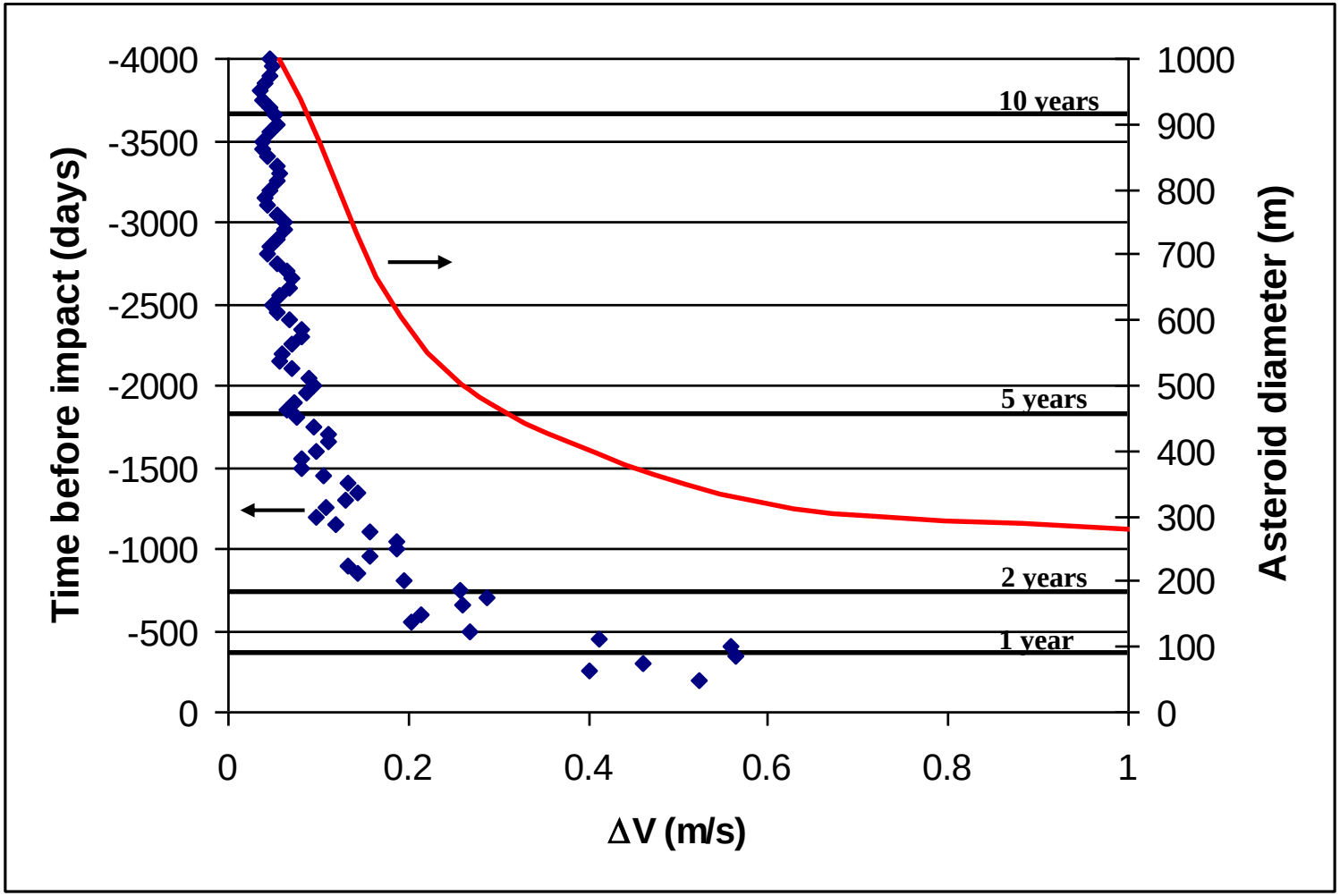
Comparative Analysis

- Required ΔV for impulsive deflection using kinetic interceptor



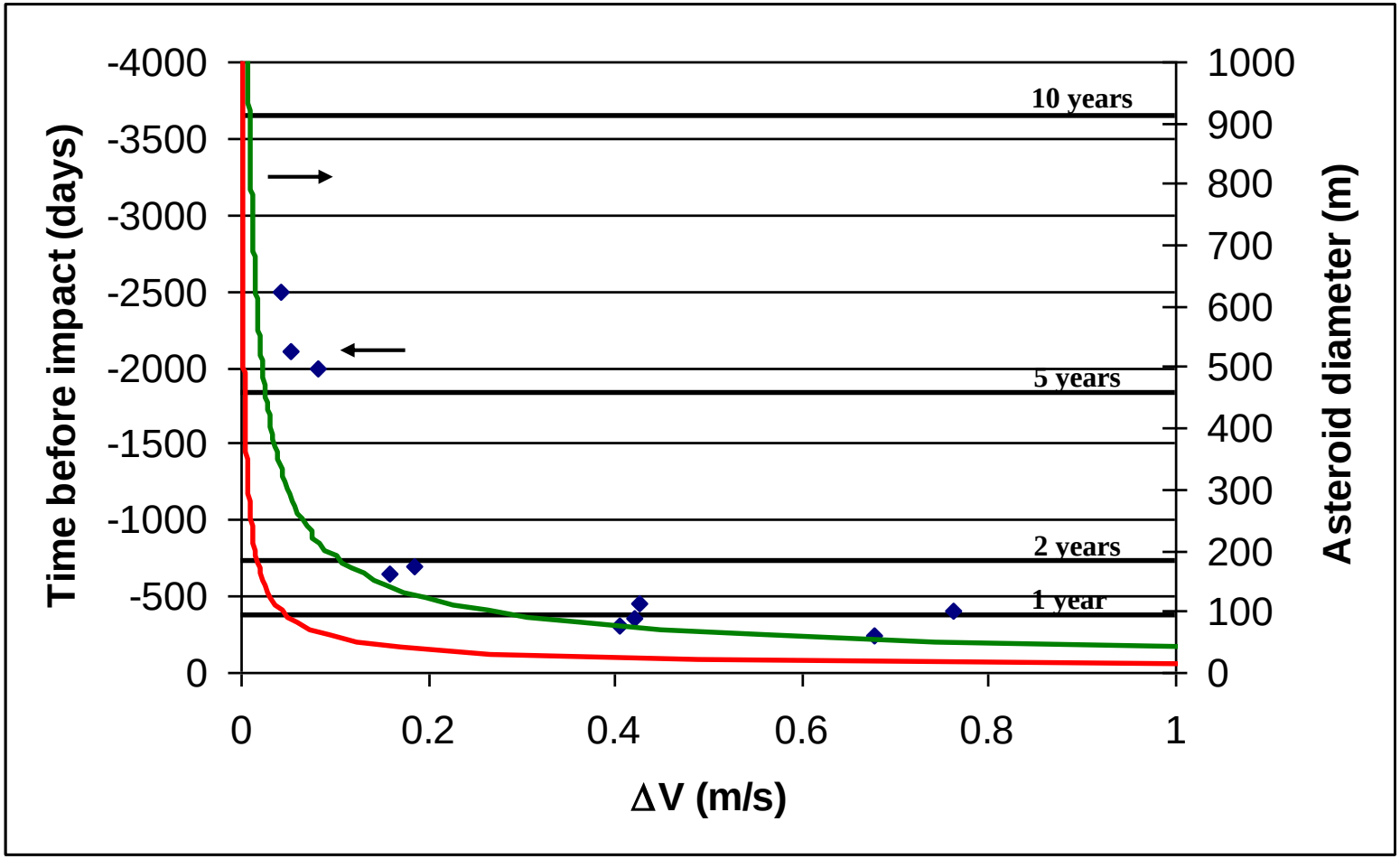
Comparative Analysis

- 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

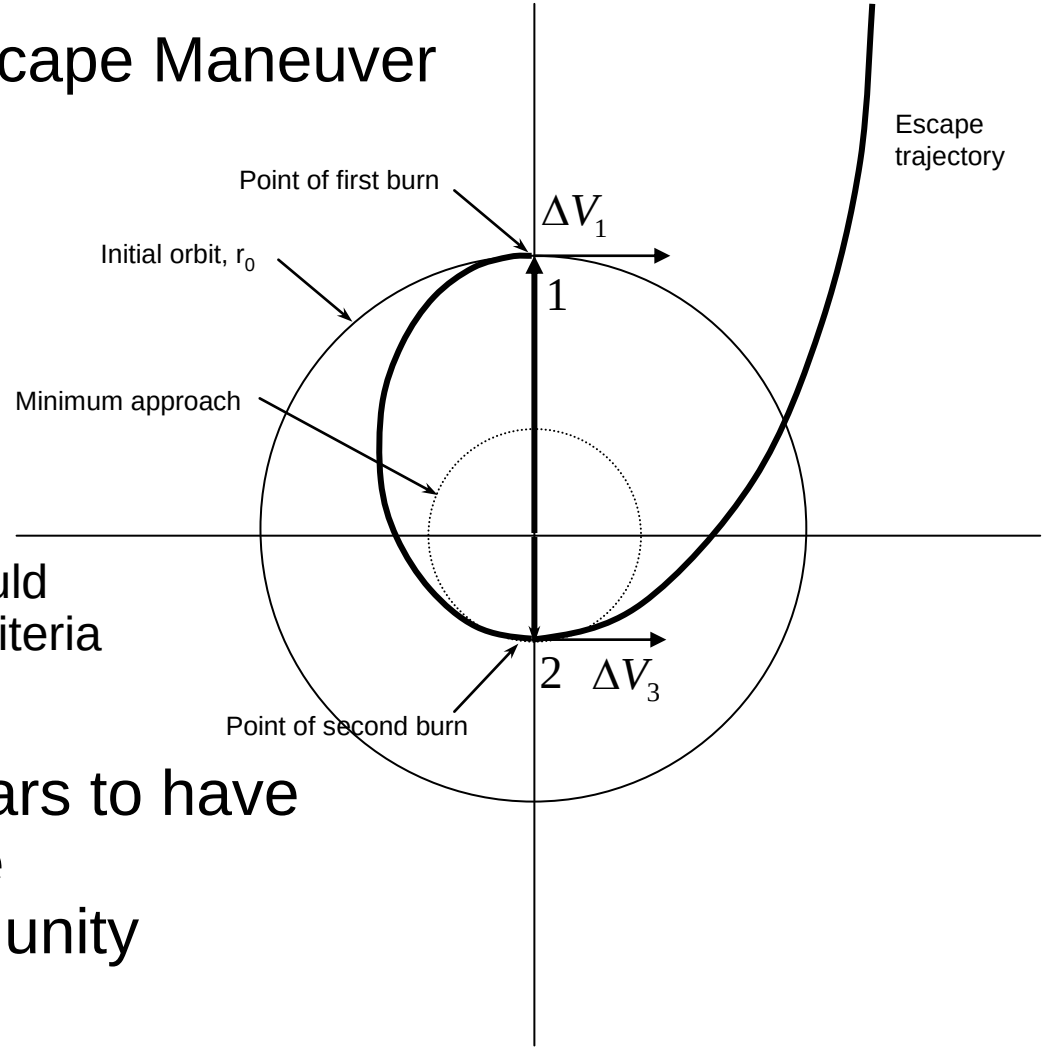
New Maneuver for Kinetic Deflection

- 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

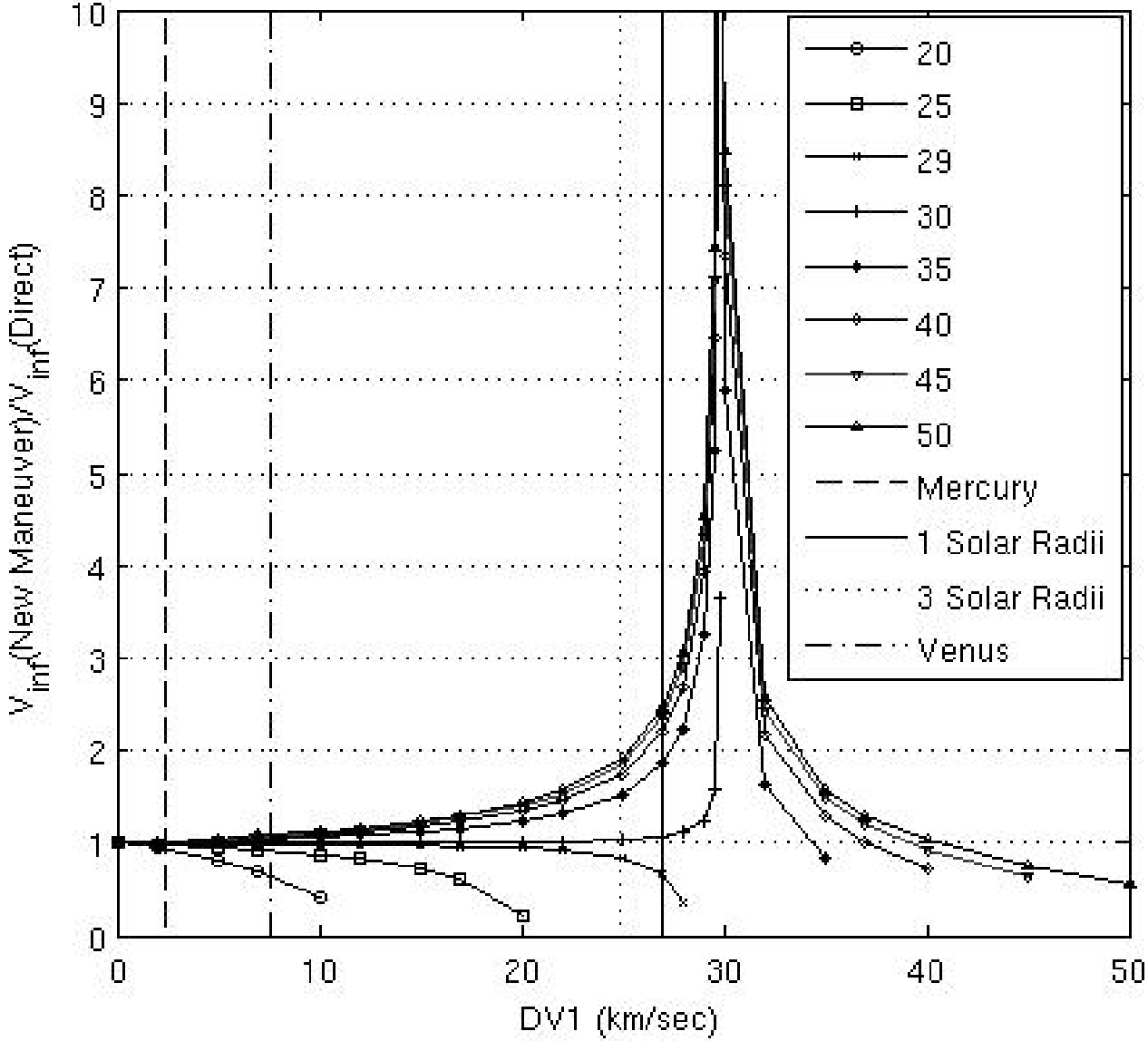
- Underlying physics
  - Vis-visa equation

$$\zeta = \frac{V^2}{2} - \frac{\mu}{r}$$

  - 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

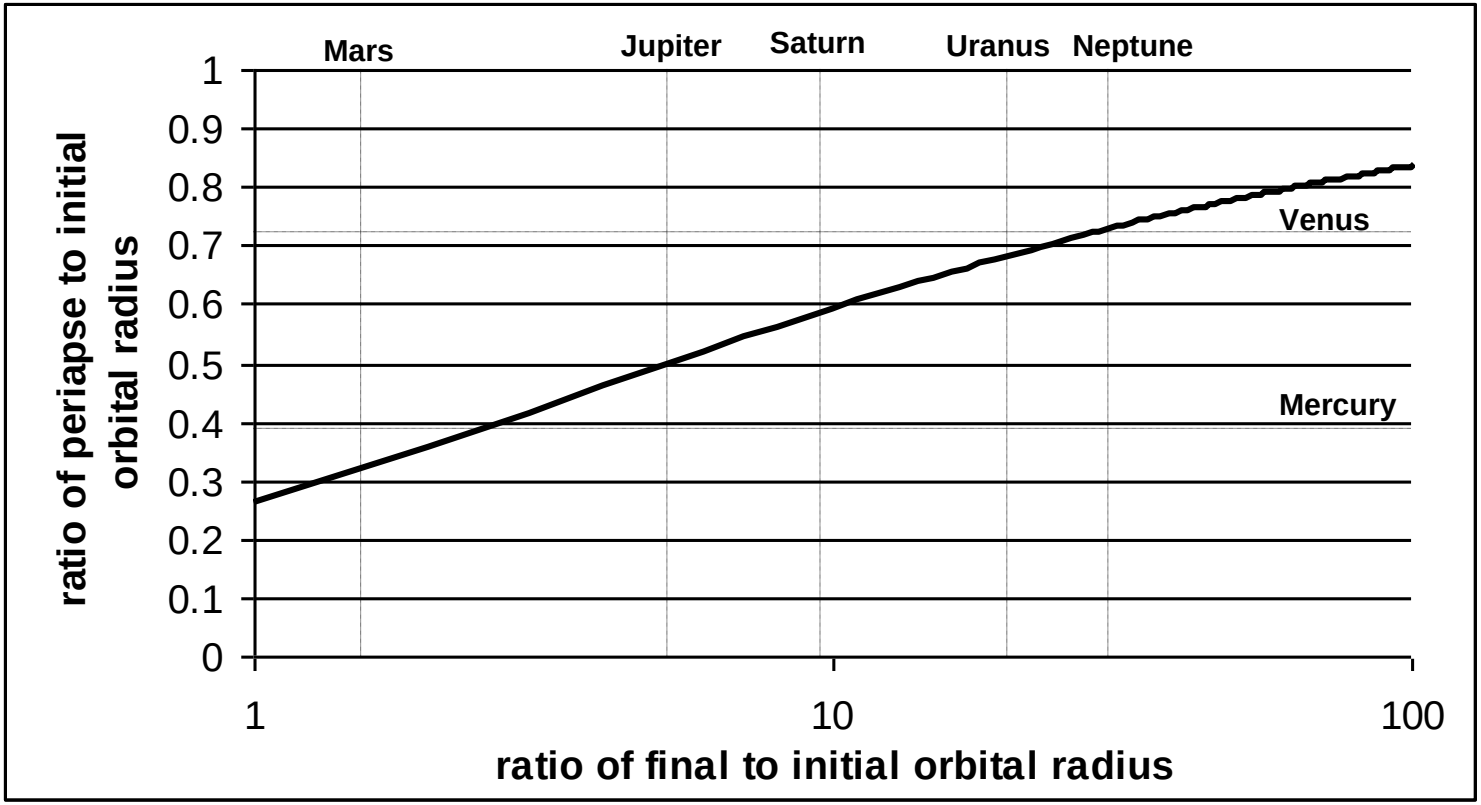
Potential

- This maneuver can dramatically increase achievable escape velocity



Potential

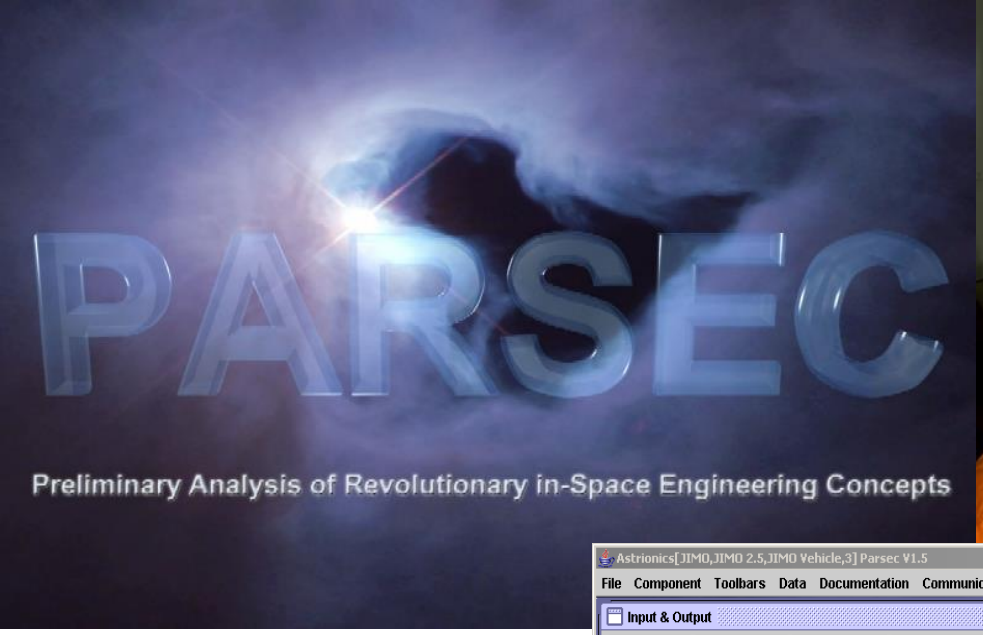
- Using the two burn maneuver can raise orbit much faster than Hohmann transfers



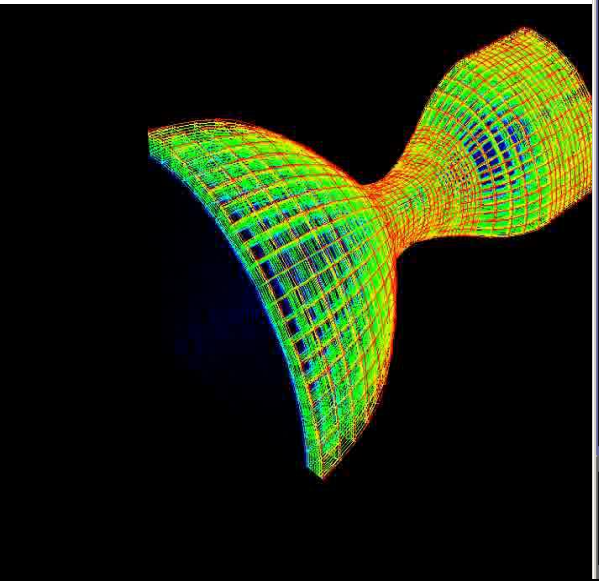
Note that the dotted lines show ratios relative to Earth

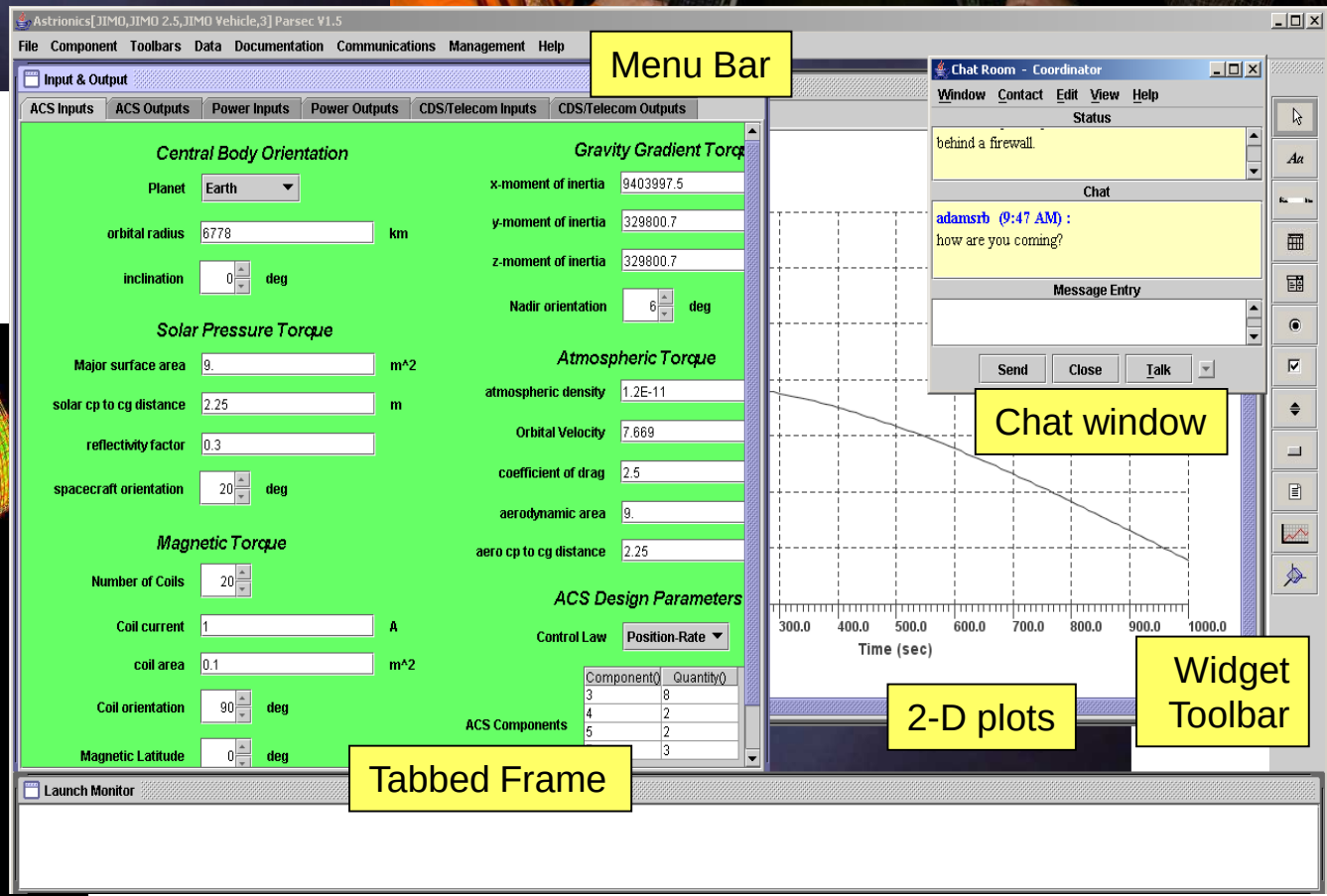
Current MSFC Efforts

- 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

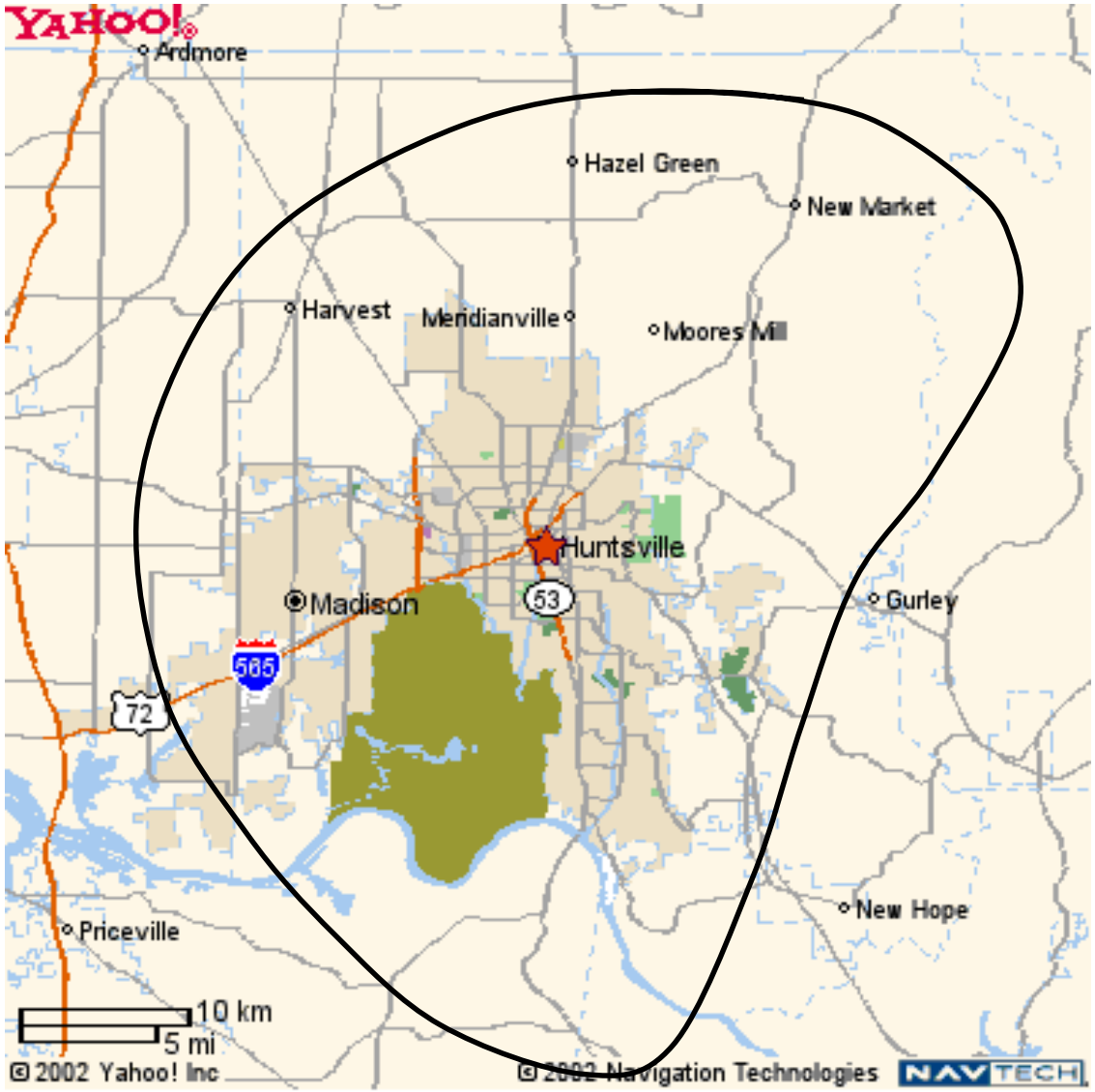
- My Co-Participants of the 2007 study
  - Jonathan W. Campbell, Randall C. Hopkins and W. Scott Smith*, National Aeronautics and Space Administration, Marshall Space Flight Center*
  - William Arnold*; Jacob Sverdrup*
  - Mike Baysinger and Tracie Crane*; Qualis Corporation*
  - Pete Capizzo and Steven 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

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

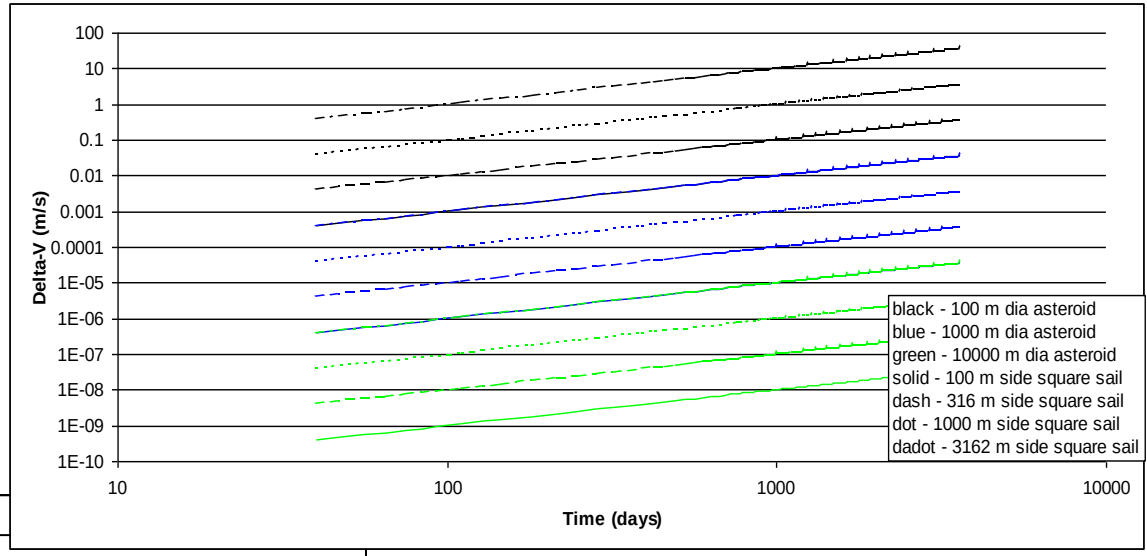
Total population within damage area ~ 350,000

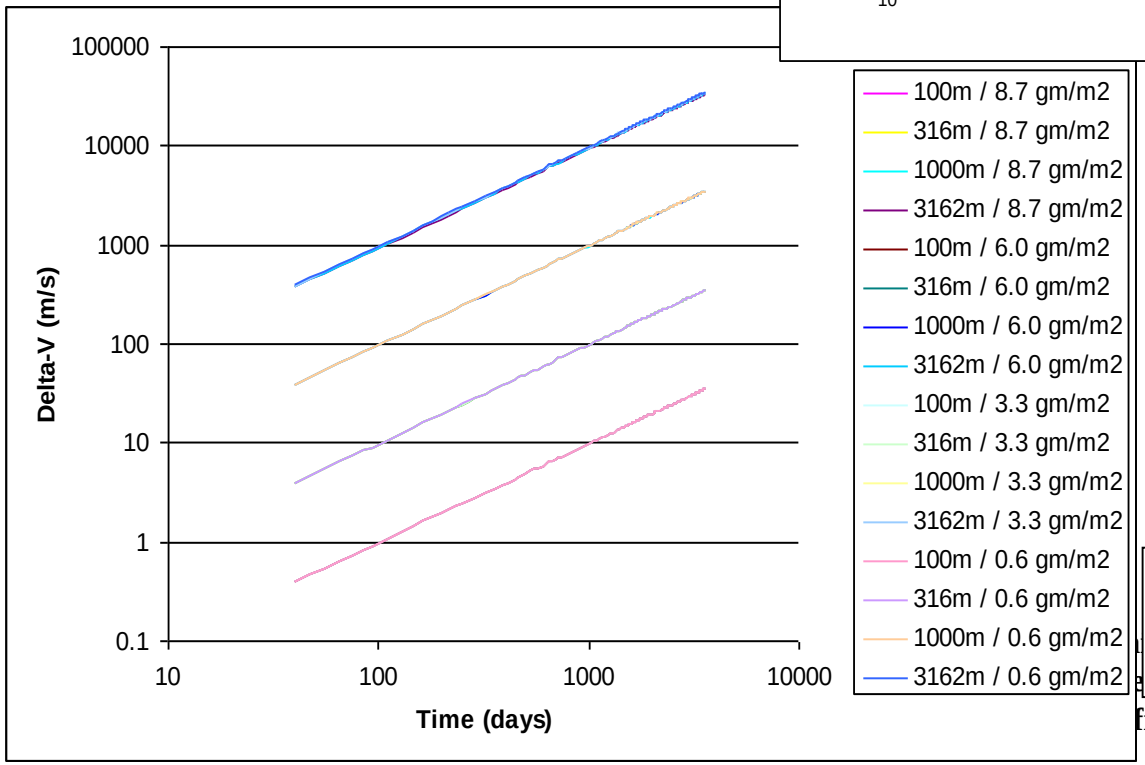
Pertinent Websites

- 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





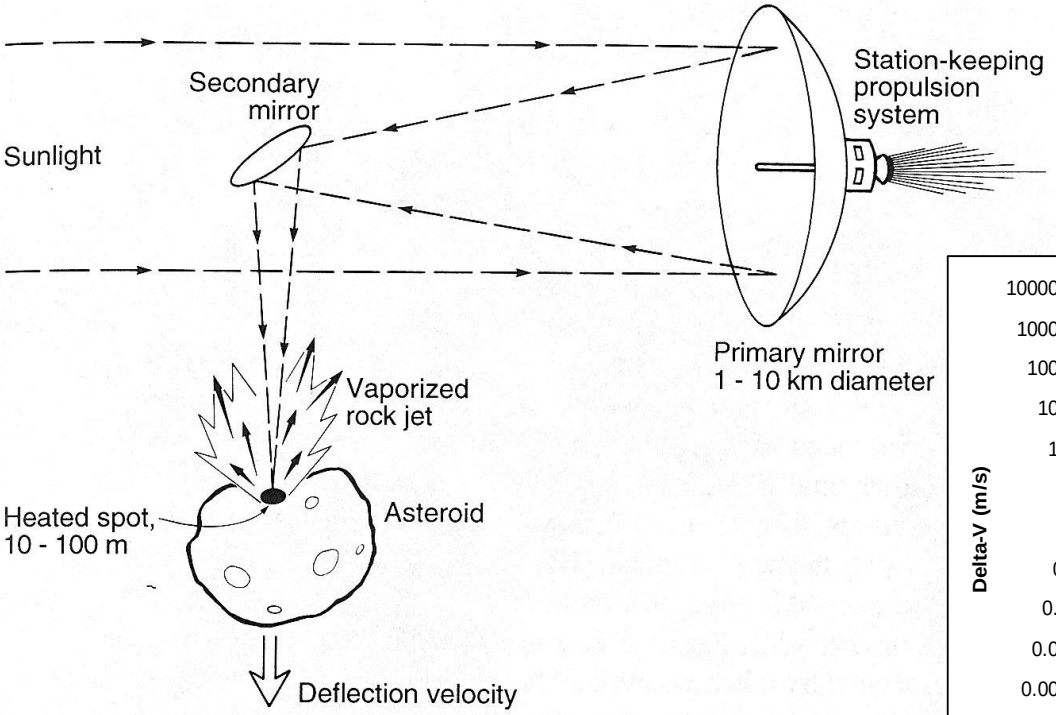
–Thrust simply not sufficient for any but the smallest objects

Melosh, H. J., Nemchinov, I. V., Zetzer, Yu. I., "Non-Nuclear Strategies for Deflecting Comets and Asteroids", *Hazards Due to Comets and Asteroids*, p1111-1132, The University of Arizona Press, Tucson, 1994

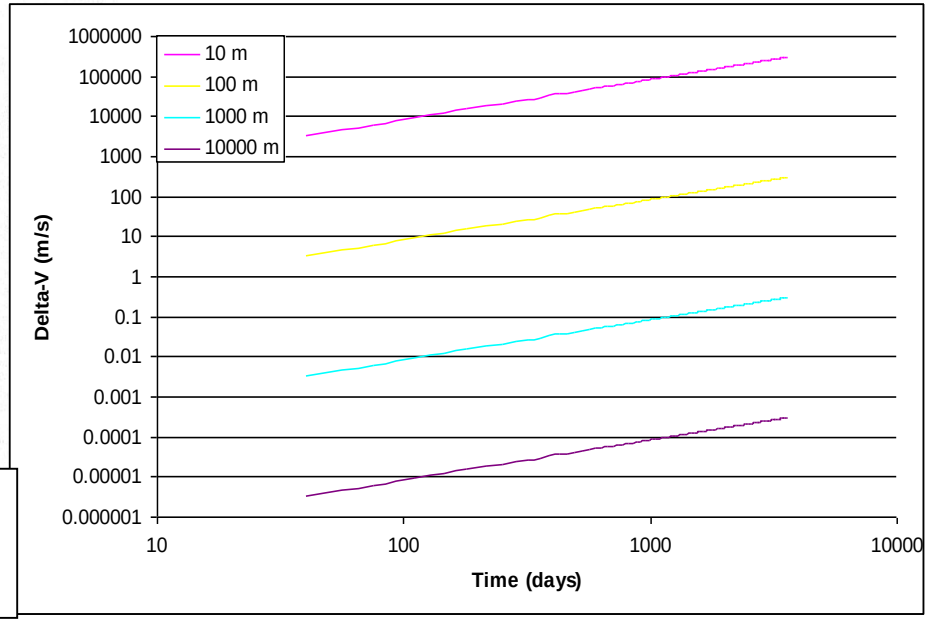
fice

Threat Mitigation

- 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



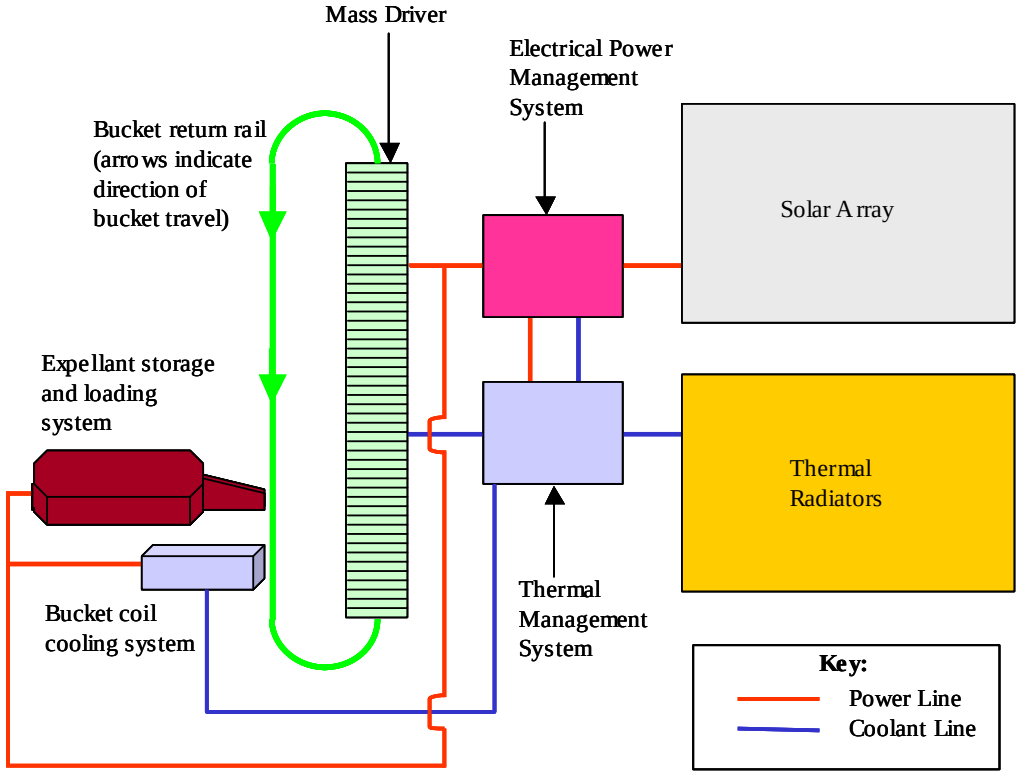
-100 m collector could concentrate enough energy to move up to 1 km objects



Melosh, H. J., Nemchinov, I. V., Zetzer, Yu. I., "Non-Nuclear Strategies for Deflecting Comets and Asteroids", *Hazards Due to Comets and Asteroids*, p1111-1132, The University of Arizona Press, Tucson, 1994

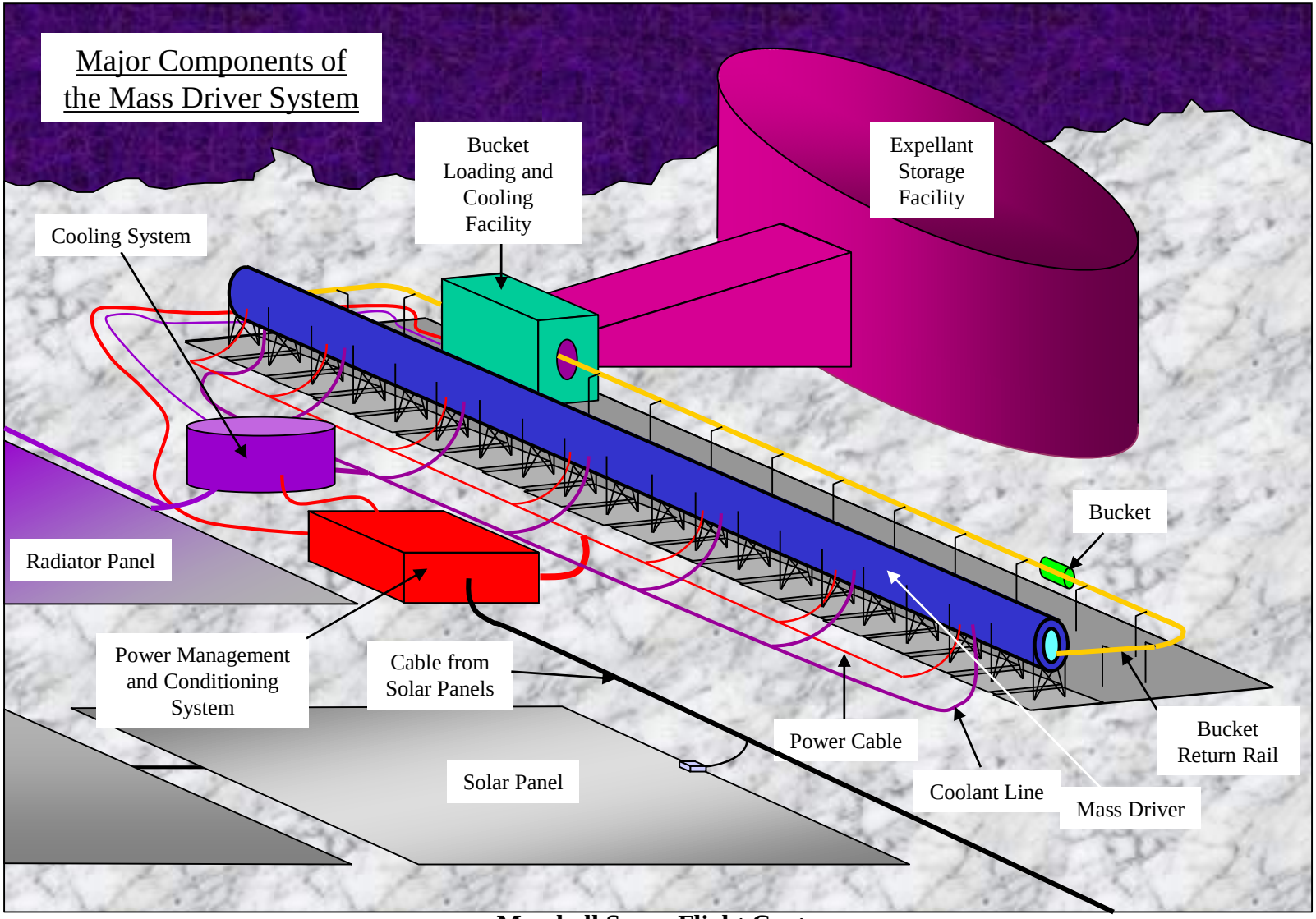
Threat Mitigation

- 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

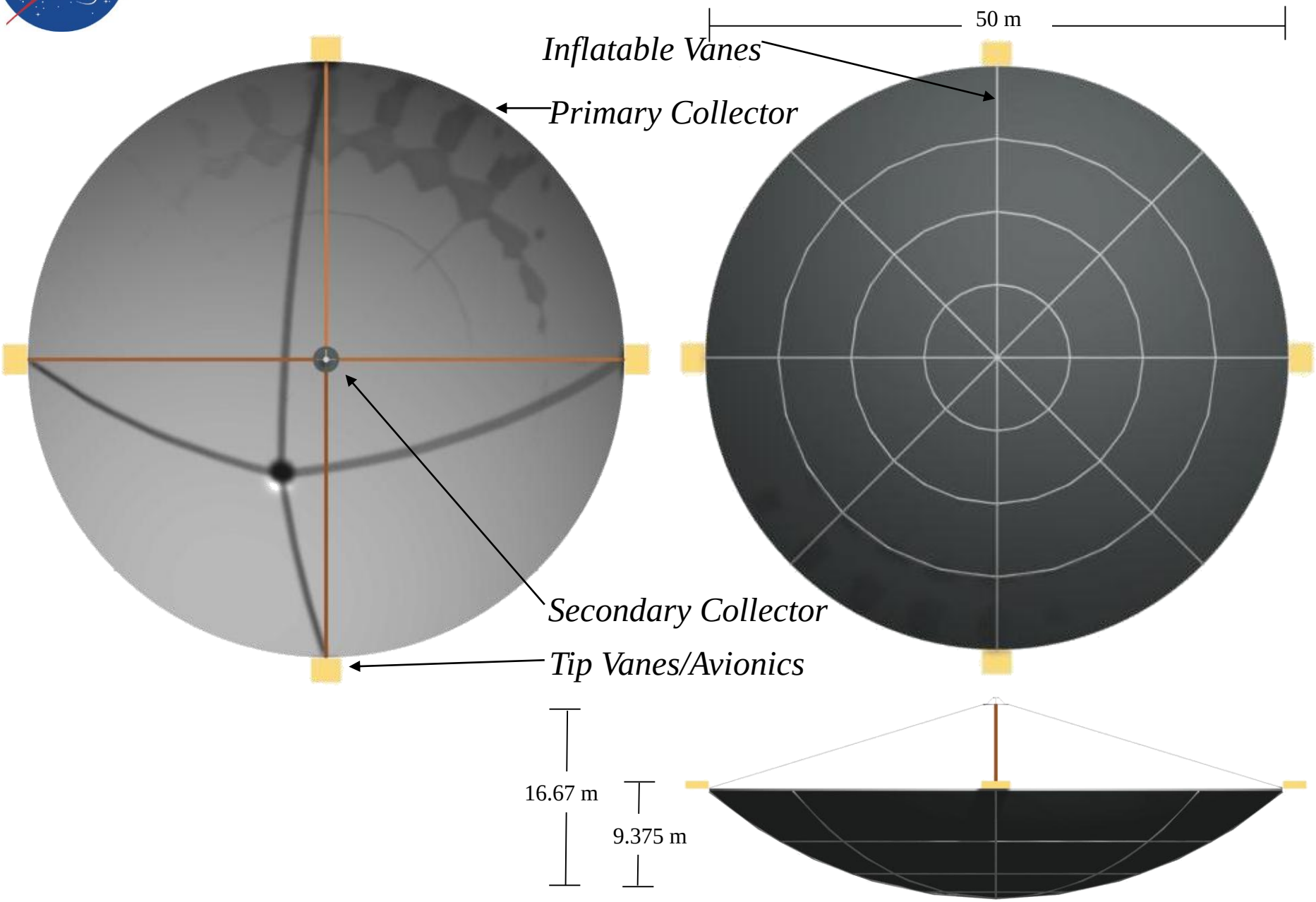


•O'Neill, G.K. and O'Leary, B, "Space-Based Manufacturing from Nonterrestrial Materials", Progress in Astronautics and Aeronautics, Volume 57, published by the American Institute of Aeronautics and Astronautics, 1977.

Mass Driver Design – Main Components



Solar Collector

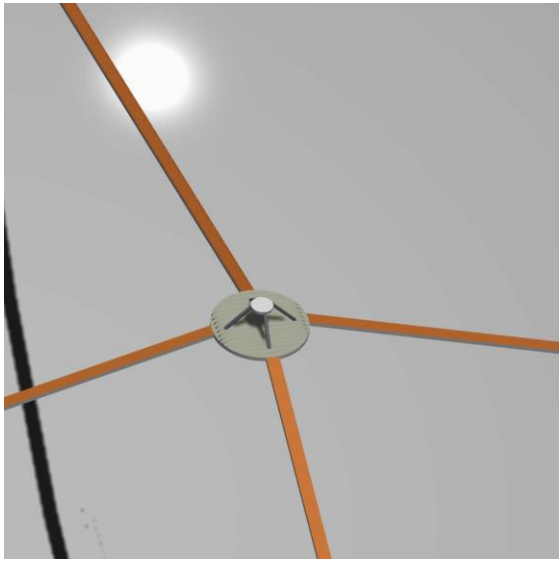


Solar Collector

- 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

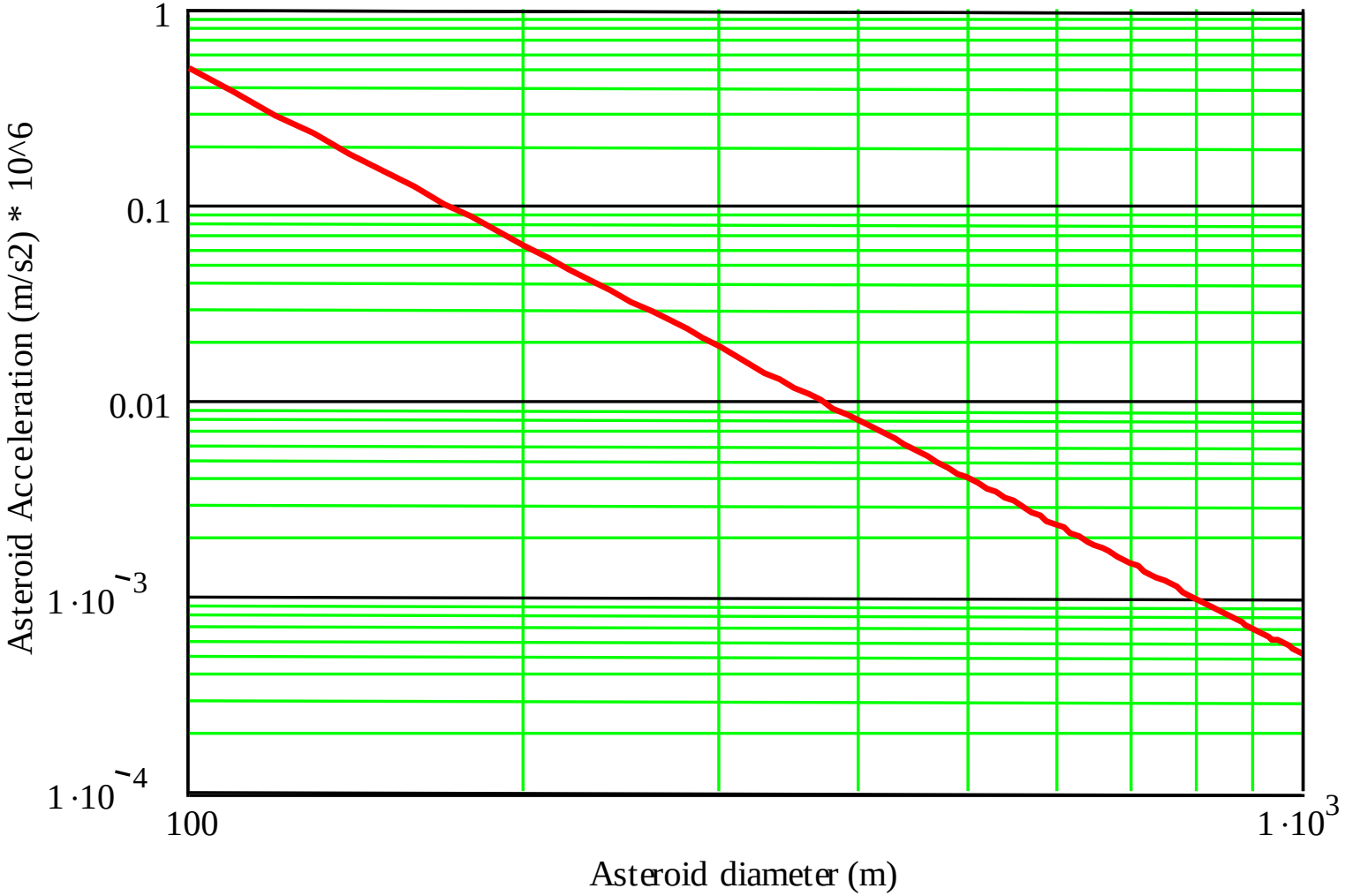
Solar Collector

- 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



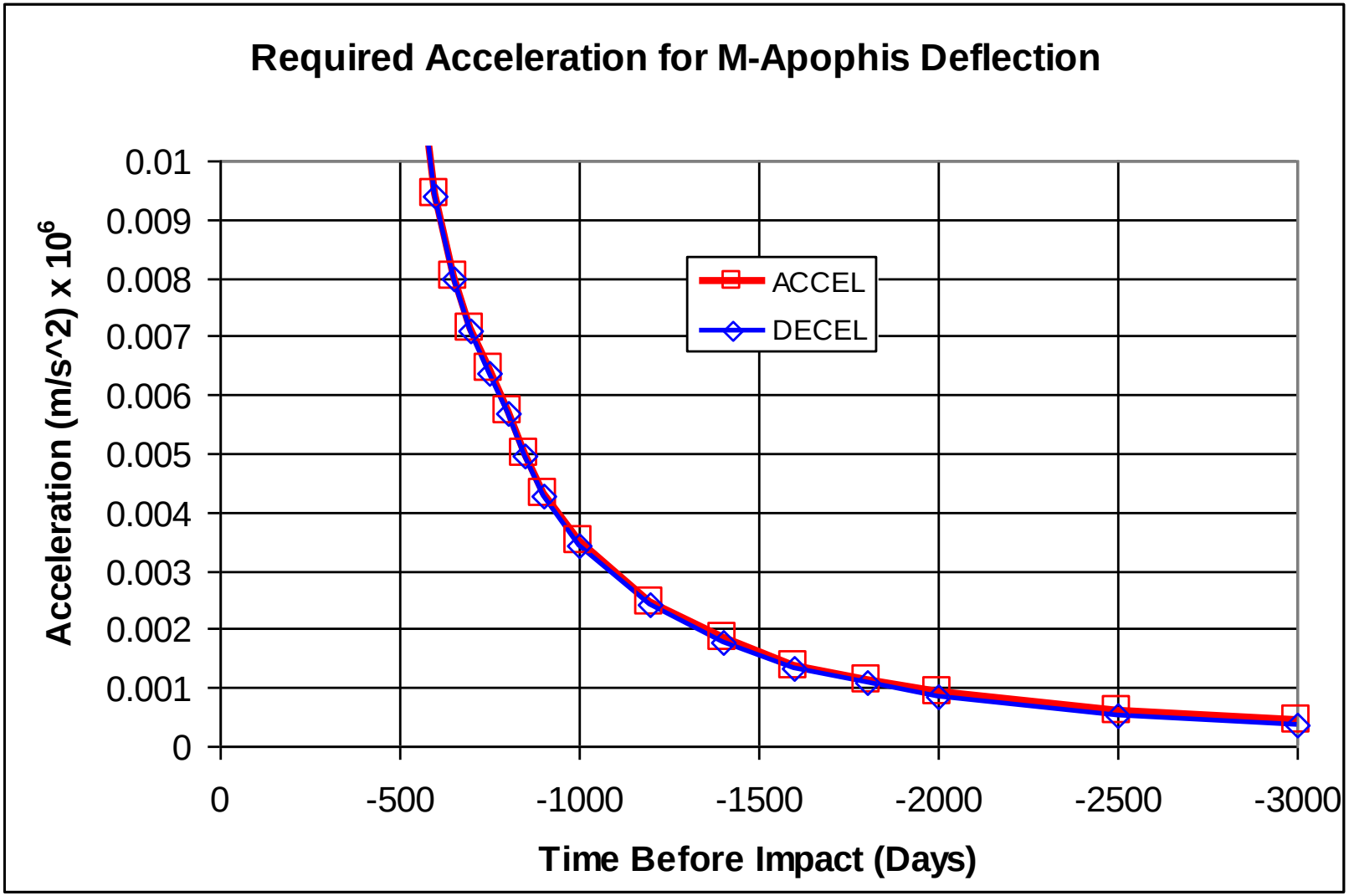
Solar Collector

- Solar Collector Effectiveness (single collector)



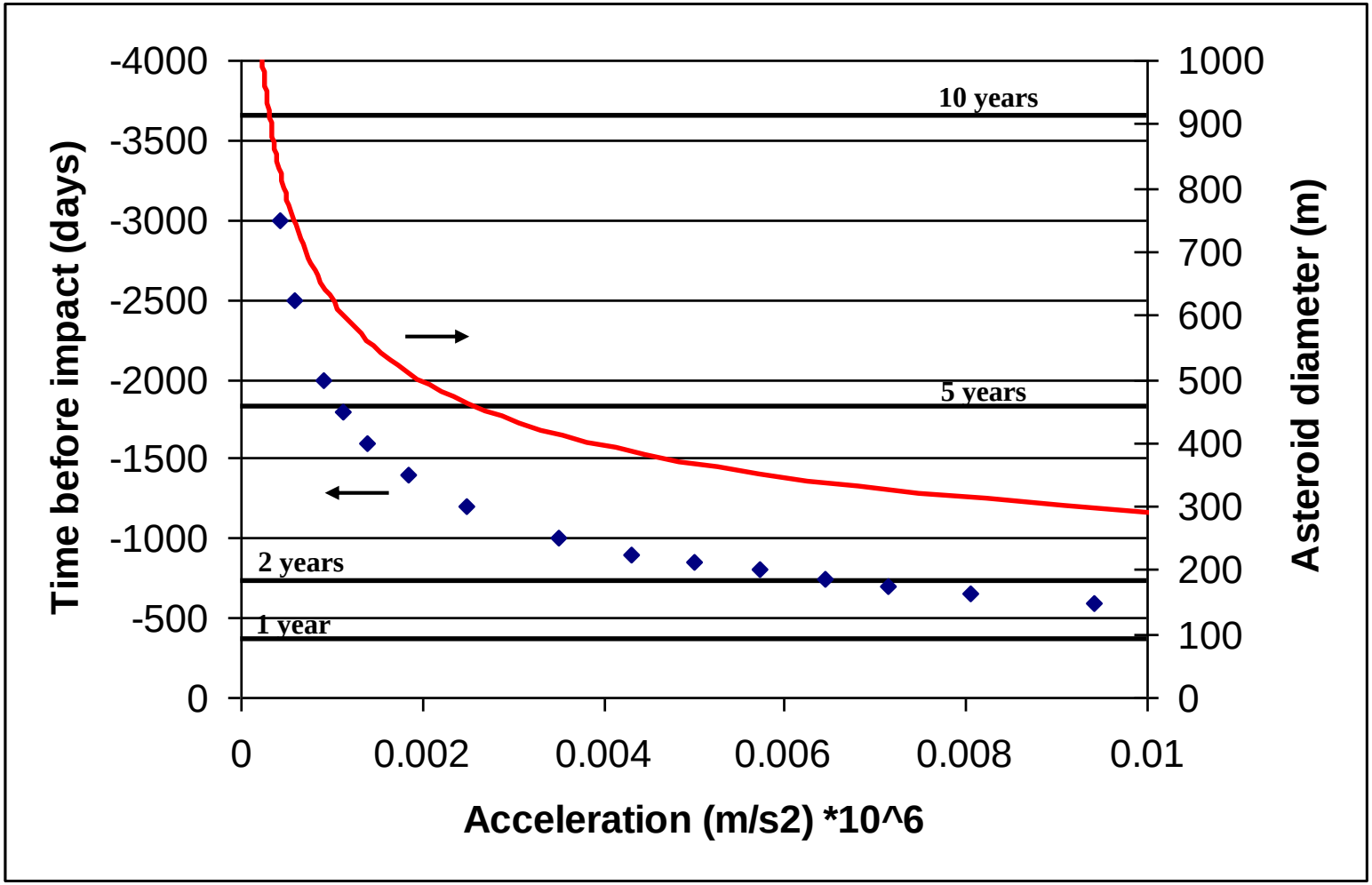
Comparative Analysis

- Required acceleration for continuous deflection



Comparative Analysis

- Combined solar collector performance against asteroid diameter



Itokawa