Multiple Mass Drivers as an Option for Asteroid Deflection Missions

Presentation to 2007 Planetary Defense Conference | March 5-8, 2007, Washington, D.C.

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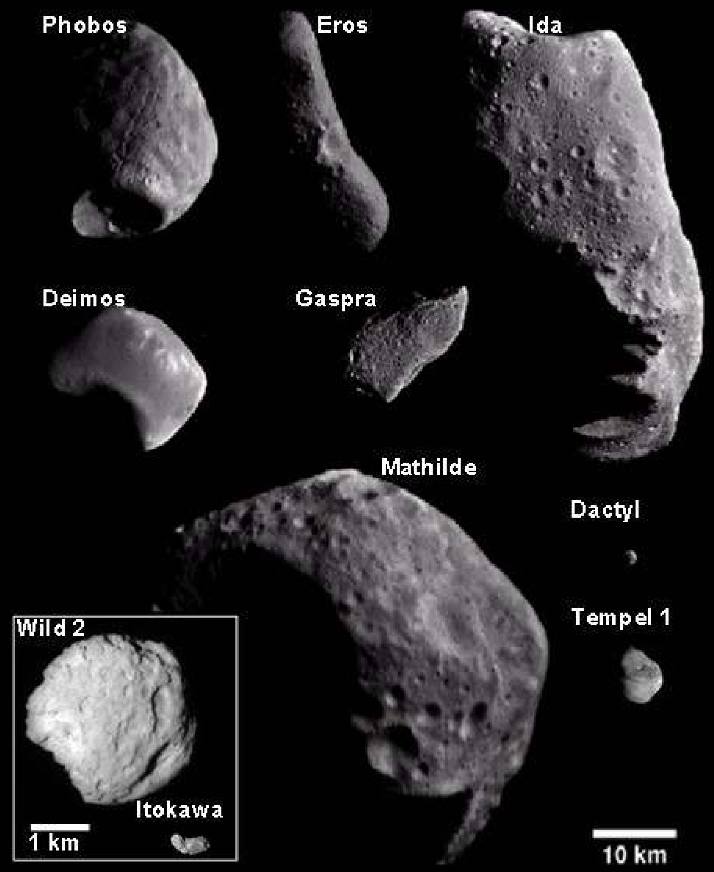
C O N T E N T S

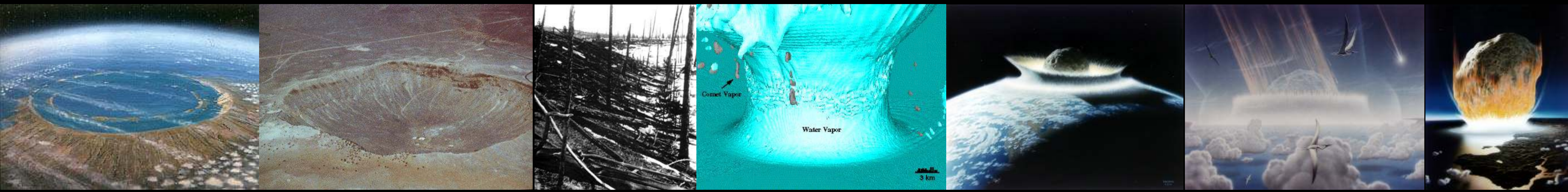
I INTRODUCTION

SEI CORPORATE STRATEGY INCLUDES INVESTIGATION OF NEO **MITIGATION** OPTIONS

ANTI-NEO TACTICS

- DETECTION
- CHARACTERIZATON
- MITIGATION





T H R E A T

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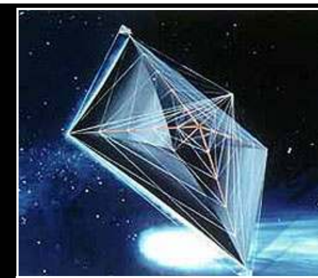
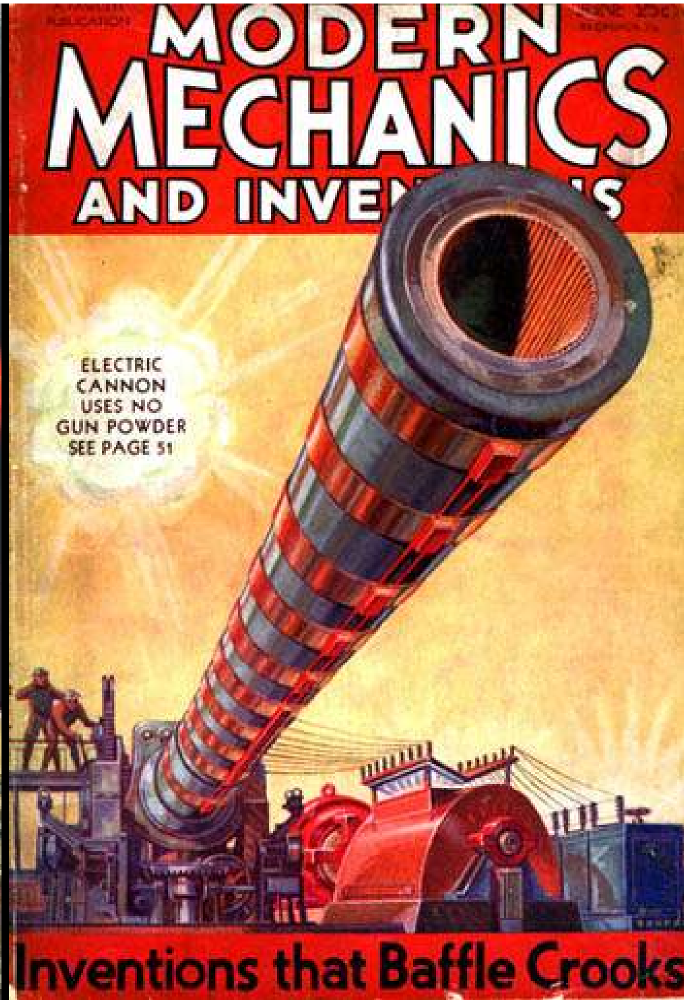
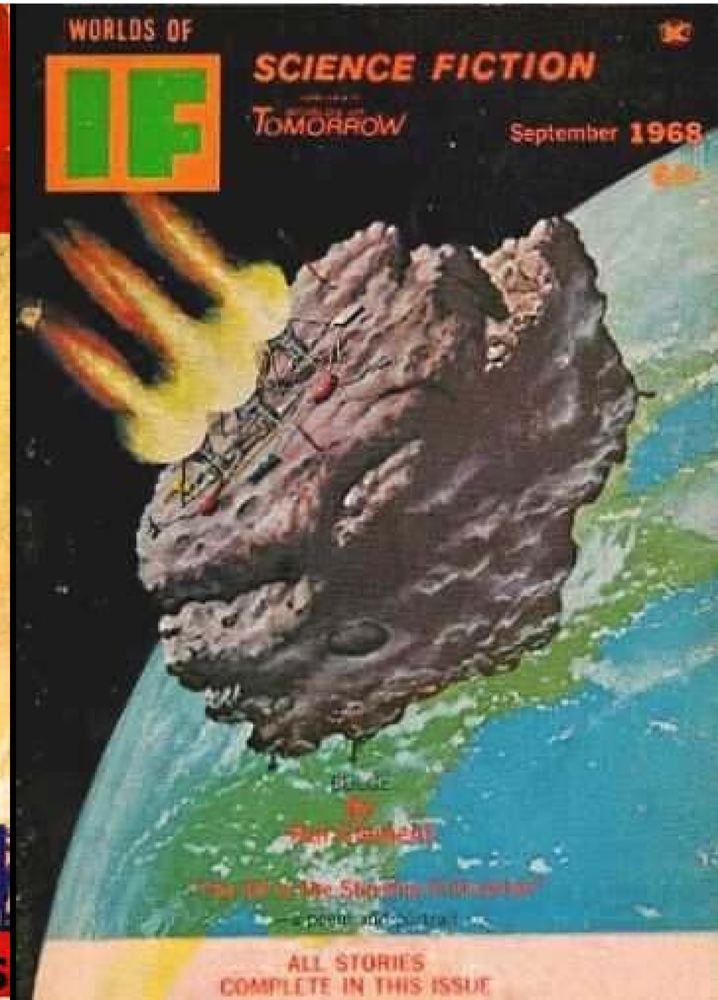
MITIGATION APPROACH	DESCRIPTION
EXPLOSIVE	
Nuclear Explosives - Standoff	Standoff nuclear explosion / vaporization
Nuclear Explosives - Surface	Surface nuclear explosion
Nuclear Explosives – Subsurface	Subsurface nuclear explosion
Magnetic Flux Compression	EMP generates mag force
HIGH THRUST	
Chemical Propulsion	Attach chemical rocket
SpaceTug (VASIMR)	Nuclear powered electric propulsion (VASMIR)
SIMPLE IMPACTOR	
Kinetic Impactor (without Explosive)	Impact with spacecraft
Kinetic Impactor (with Explosive)	Impact with spacecraft and on-board explosive
NEO-to-NEO Collision	Collide with another NEO
LOW THRUST	
Gravity Tractor	Deflect with spacecraft's gravity
NEO Painting	Paint to increase Yarkovsky effect
NEONet	Momentum net
Mass Driver	Ejects materials from the surface
Laser Ablation	Deflect with Earth/space-based laser
Solar Sail	Reflect solar photons
Solar Mirror / Concentrator	Reflects and concentrate sunlight to deflect
Space Pebbles	Metallic swarm kinetic impact
NEPTug (Ion or Hall)	Nuclear powered electric propulsion (Ion or Hall)

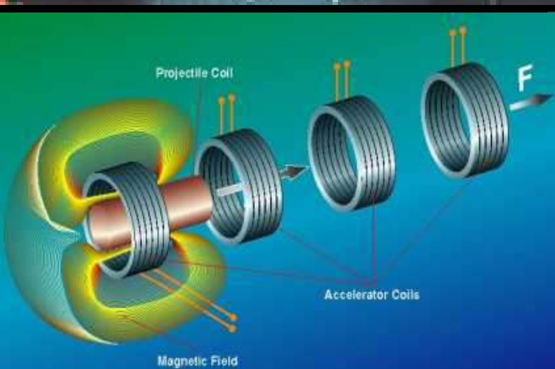


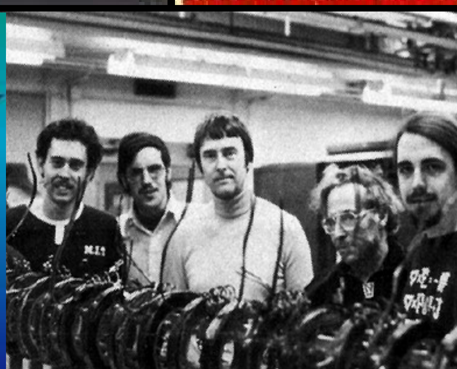


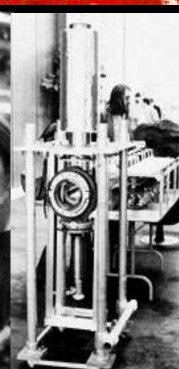

O P T I O N S











M A S S D R I V E R S

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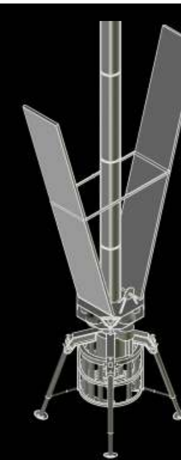
II M A D M E N

MADMEN

MODULAR ASTEROID DEFLECTION MISSION EJECTOR NODE



- <u>NASA Institute for Advanced Concepts (NIAC) Phase I Study</u> (November 2003 – April 2004)

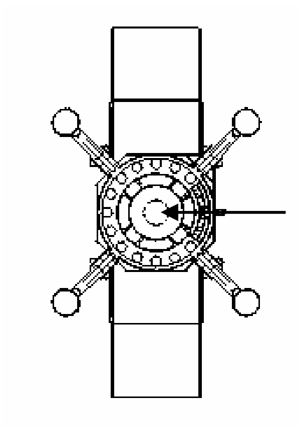
- <u>Original Concept Features</u>
  - Coring drill and ejecta conveyor
  - Deployable Mass Driver and strongback (approximately 10 m tall)
  - Small space-based nuclear reactor for efficient power (<45 kWe)
  - Self-anchoring landing legs
  - In-space Delta-V of 5.6 km/s in separate in-space stage (assumes pre-deploy in L4/L5, Delta IV-H launcher)
  - Ejecta velocities ~180 m/s, mass ~2 kg/shot, rate ~1 shot/minute, surface action time ~60 days

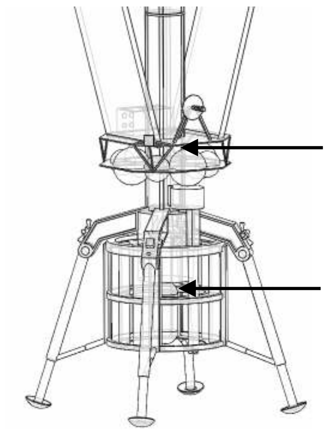
Reference: Charania, A., Graham, M., Olds, J. R., "Rapid and Scalable Architecture Design for Planetary Defense," AIAA-2004-1453, 1st Planetary Defense Conference: Protecting Earth from Asteroids, Orange County, California, February 24-27, 2004 [Available at www.sei.aero].

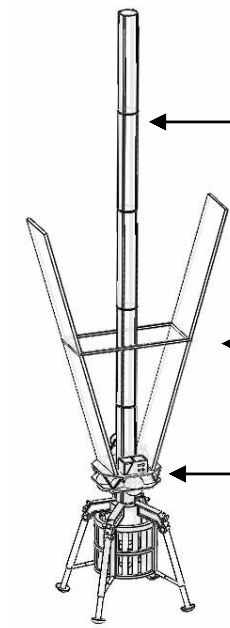
M A D M E N O R I G I N

- Allows Precise and Controllable Application of Delta-V
  - Delta-V is applied slowly over time, avoiding uncertainties of direct impactors
- Uses In-situ Propellants
  - Brings power supply to the asteroid, not Earth-derived propellants
  - Yields long duration surface operations for low initial mass
- Avoids Political and Societal Concerns of Nuclear Weapons in Space
  - Nuclear detonation options may prove to be internationally unacceptable
- Scalable to Small or Large Asteroids
  - Individual landers can be scaled up or down
  - Overall quantity of landers can be scaled to meet the need
- Offers Natural Redundancy and System-Level Robustness
  - Multiple MADMEN landers sent to one target ensures mission success
  - Use of modular construction, reduces overall cost of production
  - Swarm-based autonomous control of spacecraft reduces ground control burden

A D V A N T A G E







Note: Landing legs, mass ejection tube, and radiators collapse for launch vehicle packaging

M A D M E N I M A G I N E

SEVERAL MODIFICATIONS TO 2003-2004 MADMEN CONCEPT DESIGN

Mission Approach

- Allow rendezvous many years ahead of Impact, longer lead time (lowers Delta-V)
- Reduce required miss distance by ~5x (to 5 Earth radii from 0.5 Earth-moon distances)
- Adopt direct launch approach (no pre-staging in L4/L5)
- Allow long periods of surface operations (up to one year)
- Replace in-space cryogenic upper stage with simple cruise/braking stage approach
- Use of alternate launch vehicles

Modeling Improvements

- N-body trajectory propagator with low thrust perturbation (vs. previous two-body, final approach analyses)
- Improved spacecraft and mass driver sizing estimates and power balances
- Improved parametric scaling of lander and cruise stage for quick trade studies

U P D A T E S

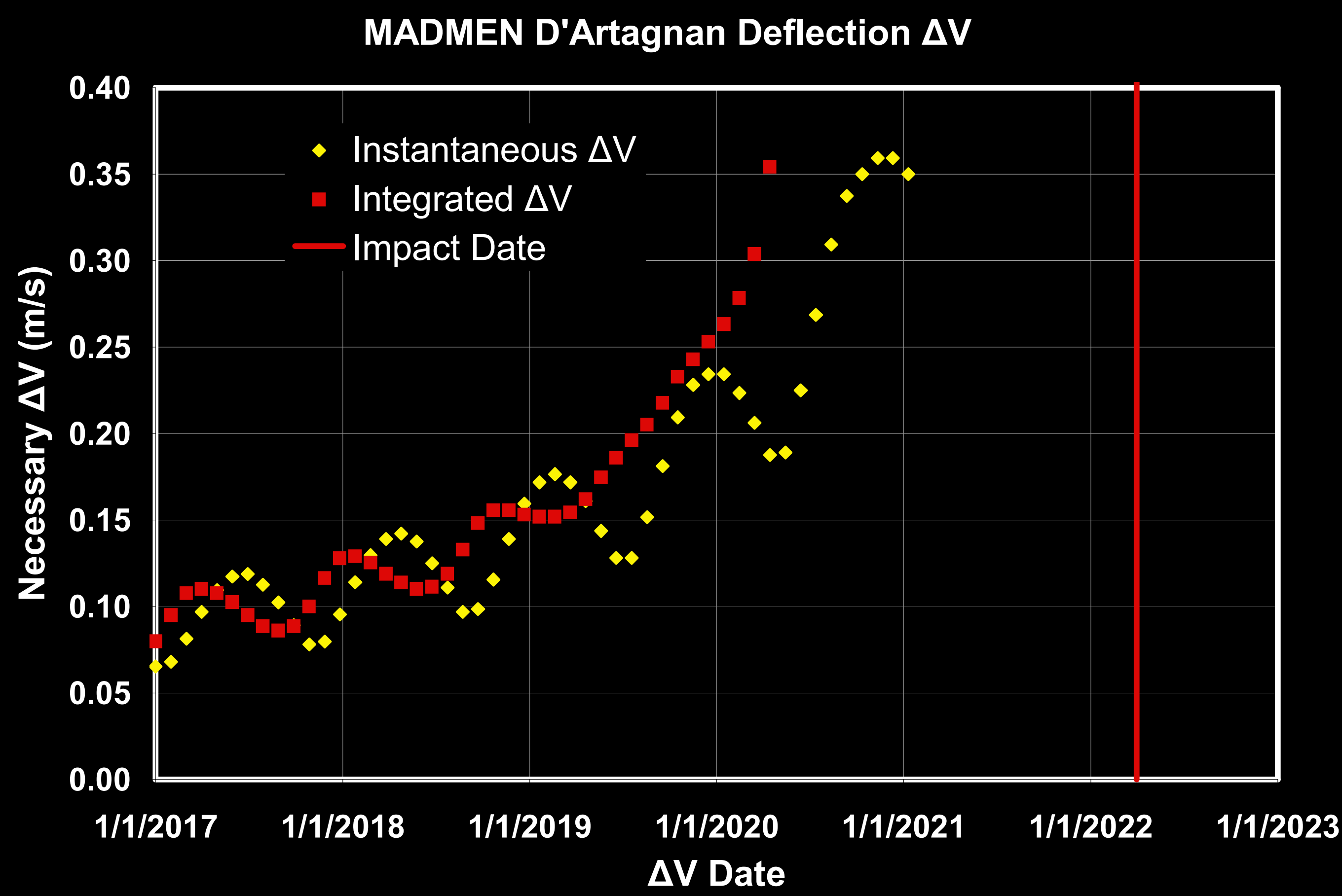
III CASE STUDIES

- MADMEN multiple mass driver concept applied to two case studies that reflect a potential range of mitigation threats

- Case Study 1: Target = D'Artagnon
  - As modified from 2004 Planetary Defense Conference
  - Adjusted some parameters of orbital elements to reflect discovery date of January 1, 2017 and an impact date of April 1, 2022
    - Semi-major axis, eccentricity, and inclination preserved from original dataset, but position angles adjusted to reflect new dates of discovery and impact
  - Assumed use of NASA Ares V Launch Vehicle in this timeframe

- Case Study 2: Target = (99942) Apophis
  - Current high interest object
  - Smaller Delta-V imparted to target than case study 1
  - Use of Space Exploration Technologies (SpaceX) Falcon 9 launch vehicle

C A S E   S T U D I E S

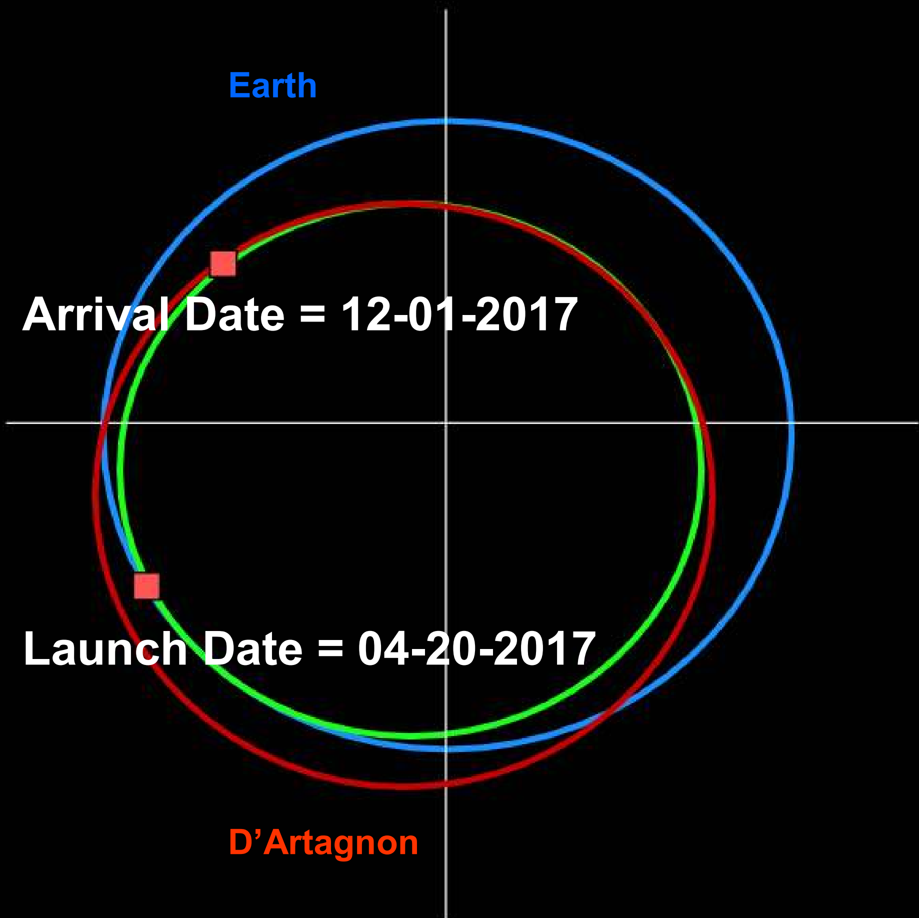


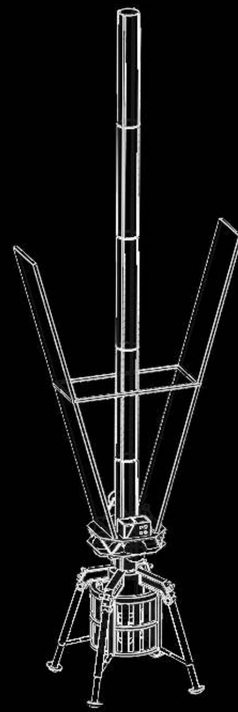
Expected Date of Impact	April 1, 2022
Approximate orbital elements at time of detection	Semi-major axis (a): 0.90220435 AU, Eccentricity (e): 0.30245951 Inclination (i): 4.78620700°, Longitude of Ascending Node: 191.15627122° Argument of Periapsis: 227.57988257°, Mean Anomaly Angle: 27.28864277° Epoch: January 1, 2017 0.0 UT
Class | Type Size | Mass | Density | Spin Period	Aten | Type S Asteroid 130 m (irregular) | 2.7x10^9 kg | 3.0 g / cm^3 | 19 minutes

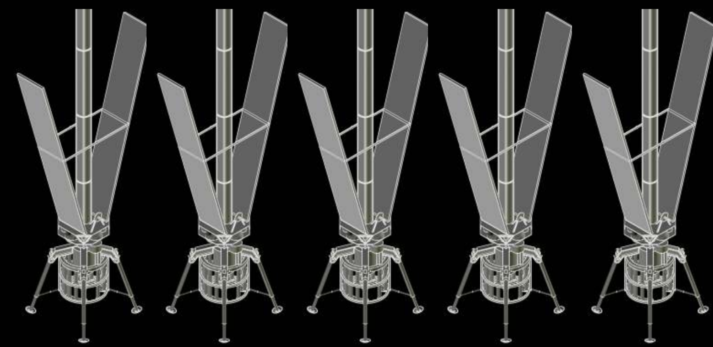
C. S. 1 : D' A R T A G O N

C. S. 1 : CONOPS

- Time of Flight = 225 days
- Departure C3= 20 km^2/s^2
- Arrival C3 = 8.737 km^2/s^2
- Cruise stage Delta-V = 3,024 m/s
- Includes 2.5% Delta-V margin







- Individual MADMEN lander wet mass = **1,650 kg**
- Mass of 5 cruise stages and landers = 30,600 kg
- Delta-V applied to D'Artagnon = 0.125 m/s
- Shift in miss distance = 5 Earth radii
- Ejection velocity = 570 m/s
- Shot frequency = 3 per minute (when firing)
- Hole diameter = 5.64 cm per hole
- Nominal mission surface action time = 365 days
- Estimated Life Cycle Cost = $2,256 M (FY2007)

SPACECRAFT SUMMARY

- Five landers, one launch (using Ares V)
  - Predicted payload capability of 43,000 kg to that c_3 for the Ares V, based on publicly-released Ares V information
  - MADMEN landers use monoprop hydrazine for propulsion, cruise stage uses biprop NTO/MMH
  - 15% duty cycle for each lander once on the surface due to asteroid rotation (continuous drilling throughout)
- MADMEN lander wet mass = 1,650 kg each
  - Combined mass of all five cruise stages and lander = 30,600 kg (with a payload adapters, the overall launch mass margin = 42.81%)
  - Base diameter = 3.5 m (base of spacecraft bus)
  - Available Delta-V directly on the lander (orbital maneuvering, landing) = 220 m/s
- Cost and Reliability
  - Estimated ROM Life Cycle Cost = $2,256 M (FY2007), includes technology development, DDT&E, acquisition, launch, and operations
    - Lander Only DDT&E Cost: $723.2 M (FY2007)
    - Lander Only TFU Cost: $118.5 M (FY2007)
  - Over 99% chance of success (if at least 3 out of 5 landers required), from 99.38% to 99.95% (probability of individual failure from 10% to 20%)

EJECTION SUMMARY

- Delta-V applied to D'Artagnon = 0.125 m/s (for a shift in miss distance of 5 Earth radii arriving around mid-2018 or earlier)
- Ejecta mass per shot = 0.50 kg (tennis ball-sized)
- Ejection velocity = 570 m/s
- Mass driver length (total of acceleration segment and deceleration segment) = 15 m
- Shot frequency = 3 per minute (when firing)
- Total shots required to be fired = ~1,180,000
- Hole diameter = 5.65 cm per hole
- Hole depth = 4.70 m (constrained to be <=less 5.75 m)
- Nominal surface action time = 365 days (five landers, 15% duty cycle each) longer with fewer landers
- SAFE-400-class nuclear reactor power = 16.5 kWe (92 kW thermal), reactor activated once the MADMEN rendezvous with D¹Artagnon

C. S. 1 : S O L U T I O N

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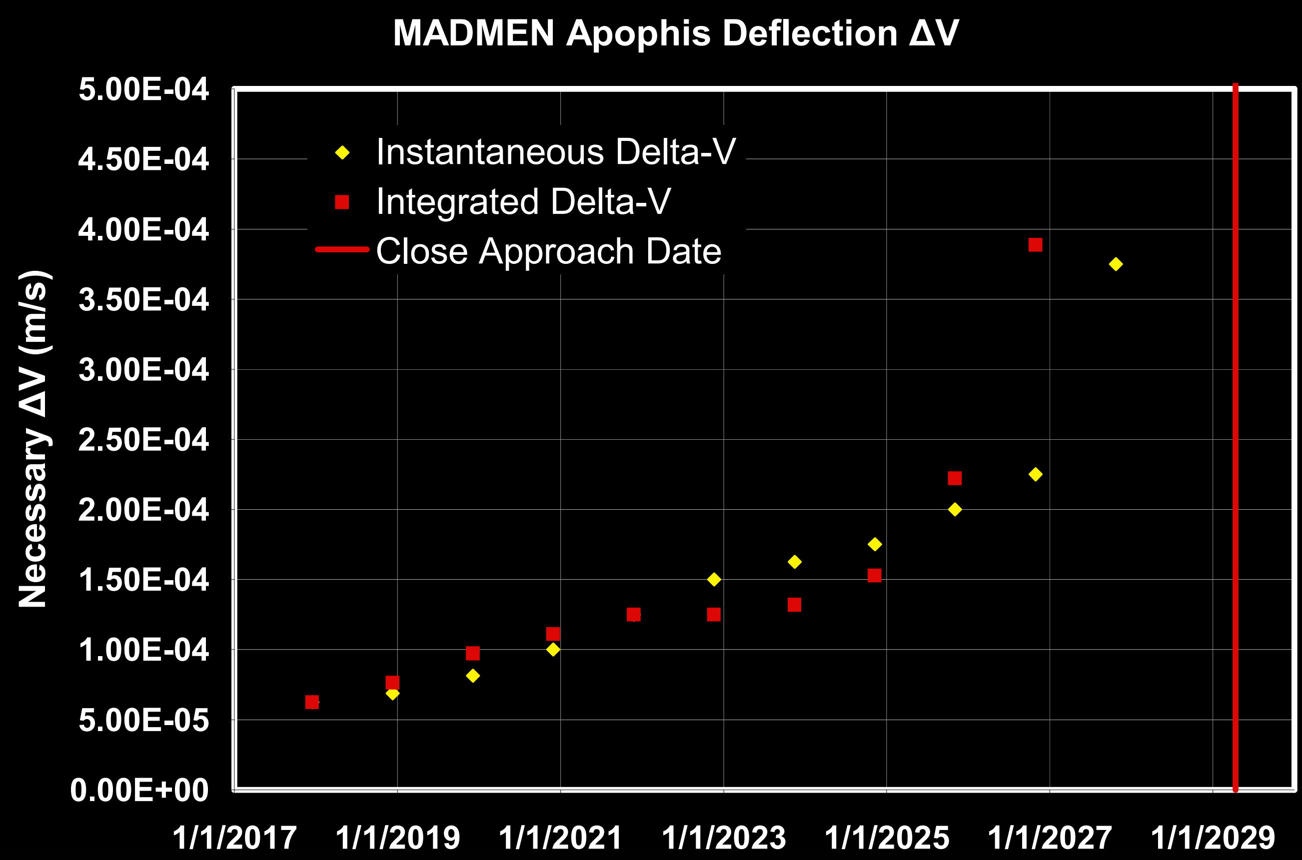
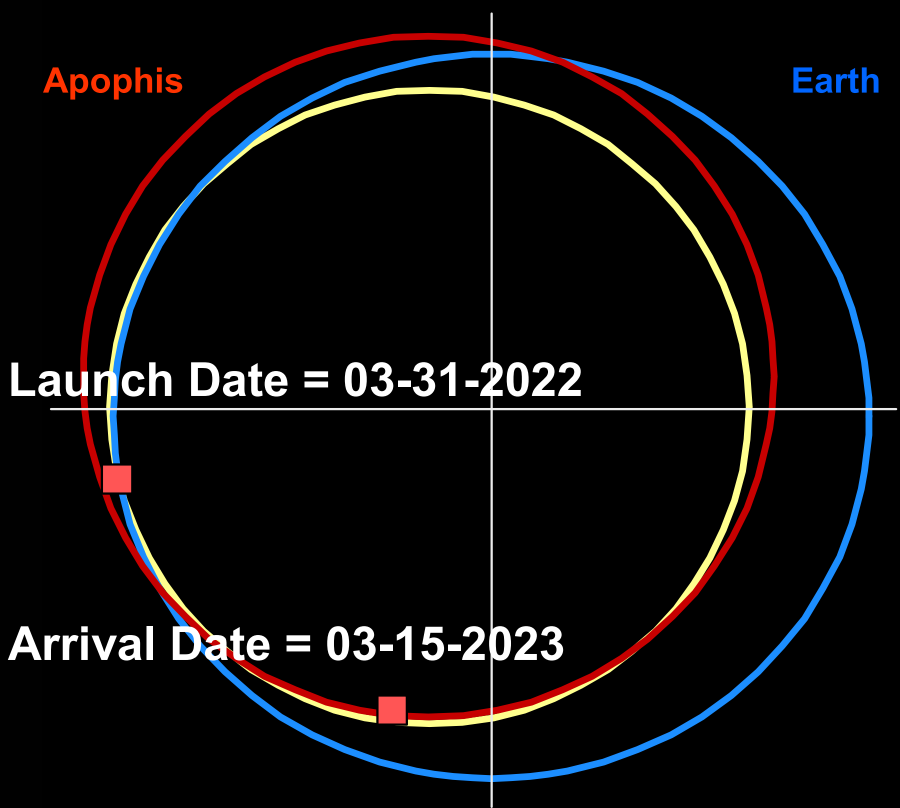
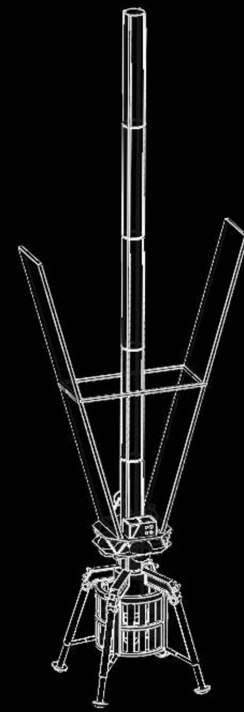


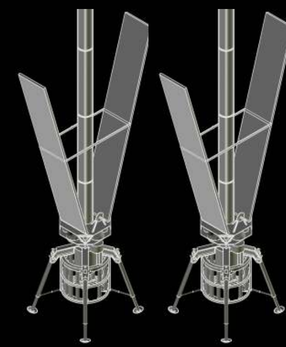
Item	Value
Expected Date of Impact	Unknown
Approximate orbital elements at time of detection	Semi-major axis (a): 0.92226142 AU, Eccentricity (e): 0.19105942 Inclination (i): 3.33131464°, Longitude of Ascending Node: 204.45915230° Argument of Periapsis: 126.38557131°, Mean Anomaly Angle: 307.36307853° Epoch: April 10, 2007 0.0 UT
Class | Type Size | Mass | Density | Spin Period	Aten | Type S Asteroid 250 m (irregular) | 2.1×10^{10} kg | 2.6 g / cm^3 | 30.54 hours

C. S. 2 : A P O P H I S

- Time of Flight = 346 days
- Departure C3= 15 km2/s2
- Arrival C3 = 1.6 km2/s2
- Cruise stage Delta-V = 1,296 m/s
- Includes 2.5% Delta-V margin
- One additional solar orbit before arriving at Apophis in 2023







- Individual MADMEN lander wet mass = **455 kg**
- Mass of cruise stage plus 2 landers = 940 kg
- Delta-V applied to Apophis = 1.3E-4 m/s
- Shift in miss distance = 60 km in 2029 keyhole pass
- Ejection velocity = 150 m/s
- Shot frequency = 2 per minute (when firing)
- Hole diameter = 2.52 cm per hole
- Nominal mission surface action time = 140 days
- Estimated Life Cycle Cost = $815.2 M (FY2007)

C. S. 2 : C O N O P S

SPACECRAFT SUMMARY

- Two landers, two launches (using SpaceX Falcon 9)
  - Calculated payload capability of 1,350 kg to c_3 of 15 km/s^2 for the Falcon 9
  - MADMEN landers use monoprop hydrazine for propulsion, cruise stage uses biprop NTO/MMH
  - Base diameter = 1.25 m (base of spacecraft bus)
  - 15% duty cycle for each lander once on the surface due to asteroid rotation (continuous drilling throughout)
- MADMEN lander wet mass = 455 kg each
  - Combined mass of cruise stage and lander = 940 kg each (with a payload adapters of 47 kg, the overall launch mass margin = 37.5% per launch)
  - Available Delta-V directly on the lander (orbital maneuvering, landing) = 220 m/s
- Cost and Reliability
  - Estimated ROM Life Cycle Cost = $815.2 M (FY2007), includes technology development, DDT&E, acquisition, launch, and operations
    - Lander Only DDT&E Cost: $317.7 M (FY2007)
    - Lander Only TFU Cost: $48.8 M (FY2007)
  - Over 96% chance of success (if at least 1 out of 2 landers required), from 96% to 99% (probability of individual failure from 10% to 20%)

EJECTION SUMMARY

- Delta-V Applied to Apophis = 1.3E-4 m/s (for a shift of 60 km in miss distance in 2029 keyhole pass)
- Ejecta mass per shot = 0.15 kg (golf ball sized)
- Ejection velocity = 150 m/s
- Mass driver length (total of acceleration segment and deceleration segment) = 3 m
- Shot frequency = 2 per minute (when firing)
- Total shots required to be fired = 79,333
- Hole diameter = 2.52 cm per hole
- Hole depth = 1.86 m
- Nominal surface action time = 140.4 days (two landers, 15% duty cycle each), about 280.8 days for one lander working alone (two landers for redundancy)
- HOMER-class nuclear reactor power = 1.6 kWe (8.6 kW thermal), reactor activated once the MADMEN rendezvous with Apophis

C. S. 2 : S O L U T I O N

IV OBSERVATIONS

– What target asteroid characteristics must we know well for this concept to work?

– **Required**

- – Orbital elements (to estimate velocity perturbation required)
- – Gross mass properties (mass, center of mass, density)
- – Spin state (spin axis orientation and rate)
- – Surface composition and hardness (for landing and anchoring)
- – Subsurface composition (to about 2-3 meters, for drilling)

– **Nice to Have**

- – Surface topography (for selection of preliminary landing sites)

C H A R A C T E R I Z A T I O N

There are certainly technology challenges with this concept, but we believe that with proper funding, all issues can be resolved in 5-10 years yielding an initial operating capability (IOC) in 2015-2020

- Drilling
  - Uncertainty of drilling/mining in near zero g/no atmosphere
  - Drilling/core rate for an asteroid must be estimated
- Landing/anchoring
  - Safe landing and secure attachment of lander to the surface
- Power Source
  - LANL work in space reactors is a good start
- On-site dust
  - Effect on mining/coring/drilling/mass ejecting operations
  - Specific effects include thermal systems degradation, seal failure, vision obscuration, competing processes, etc.
- General Technology Needs
  - Long life surface hardware requirements
  - AI technology for autonomous swarm operation in space

C H A L L E N G E S

- Candidate precursor mission
  - Evaluate and test technologies in-situ
  - Evaluate intentional change in asteroid trajectory using mitigation technique
  - Test on small, non-binary, non-earth-crossing asteroid (mass < 1E9 kg)
  - Would prefer radar observations of candidate target
  - Potential target: 2002 XY38 (Aten, diameter = 70-160 m)

- Minimum of two landers
  - Redundancy
  - Potential swarm communication
  - Different attachment, drilling techniques

- Small launch vehicle
  - Nominal launch on SpaceX Falcon 1 or 9

- Schedule and cost
  - Launch date between 2011-2015
  - Estimated budget cap is 1-2 times price of Discovery/Scout class mission

P R E C U R S O R

- General Modeling Improvements to MADMEN concept
  - Refinement of trajectory, Life Cycle Cost (LCC), and reliability analysis
  - Discrete Event Simulation (DES) of MADMEN swarm

- Resolution of Open Issues at the System Level
  - Resolve question of suitability of approach to rock pile or metallic type NEA target versus more common stony-type targets
  - Resolve effect of asteroid spin/movement on shot direction and duty cycle
  - End-state and potential danger of ejecta from mass driver operations

- SpaceWorks Engineering, Inc. (SEI) is pursuing partnerships with relevant organizations to address various technology challenges

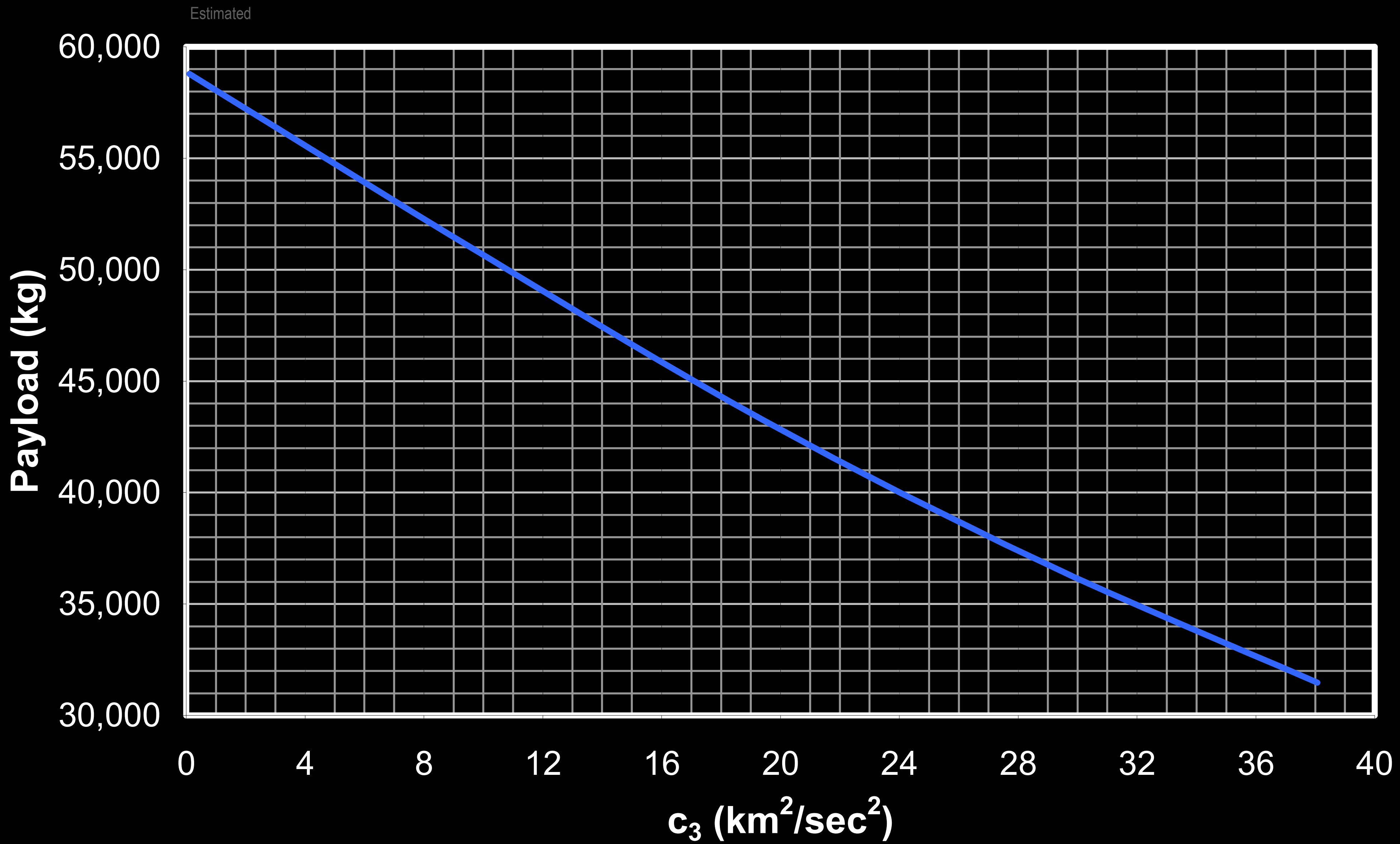
- SEI is leading a team to respond to 2007 Apophis Mission Design Competition sponsored by The Planetary Society

- Continued Public Outreach and Awareness Activities
  - SEI theme web page: www.sei.aero/planetarydefense
  - planetarydefense.blogspot.com

O N G O I N G W O R K

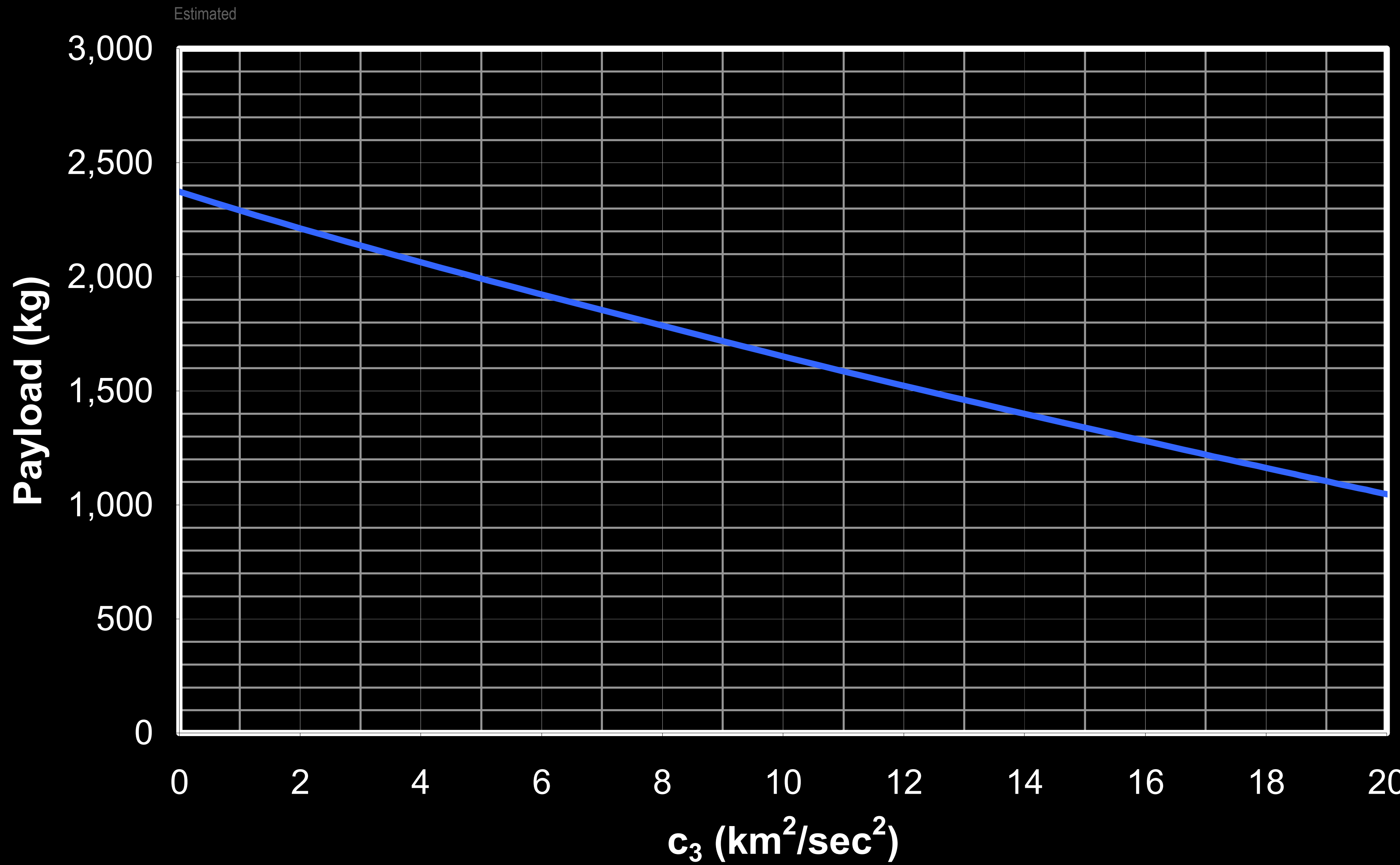
V APPENDIX

Ares V Payload vs c_3



L A U N C H   V E H I C L E S (1)

Falcon 9 Payload vs c_3



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R E F E R E N C E S