

NEA Mitigation Studies for Short Warning Time Scenarios

Presentation to:

15th Meeting of the NASA Small Bodies Assessment Group (SBAG) Meeting

By:

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Description and Objectives:

- Conduct end-to-end systems analysis of NEO intercept mitigation scenarios for the class of potentially hazardous asteroids (PHA) ranging in size from 100 and 500 meters in diameter
- Study the short warning scenario, where warning times below 10 years are indicated and emergency response solutions are a last resort
- Investigate the range of impulsive solutions for hypervelocity impactor architectures, model the deflection/disruption scenarios using physics based models and advanced mission design concepts
- Conduct detailed timeline analysis for each mitigation scenario



HAMMER – Hypervelocity Asteroid Mitigation Mission for Emergency Response

Strategic Partnership:

- Joint research project with LANL, LLNL, SNL DOE/NNSA National Laboratories – IAA
- Parse this multi-dimensional, combinatorially complex problem and solve by parts; recompile using a scenario-based approach
- Set up an off-Lab repository for DRA/DRMs in the short term and design/develop a Framework prototype for the longer run

Accomplishments and Next Milestones:

- ✓ Interagency Agreement signed January, 2015
- ✓ Teams awarded funding from DOE and NASA last quarter, 2014
- ✓ Code-to-code comparison completed April, 2016
- DRA 2 – Didymos Binary – collaborating with APL and ESA on AIDA/DART
- Publication of Case Study 1 complete by Fall 2016

Key Challenges/Innovation:

- High speed approach trajectory
- Uncertainties in asteroid physical properties and overall effectiveness of deflection missions
- Autonomous navigation
- Big Data

Key Collaborators:

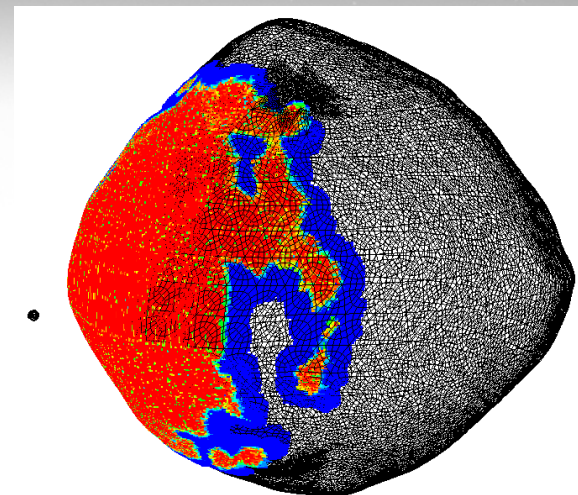
- NNSA HQs
- LLNL
- LANL
- SNL

3 Year Study Period:

- January 2015– December 2017

Our collaboration is employing a scenario-based approach to the planetary-defense problem

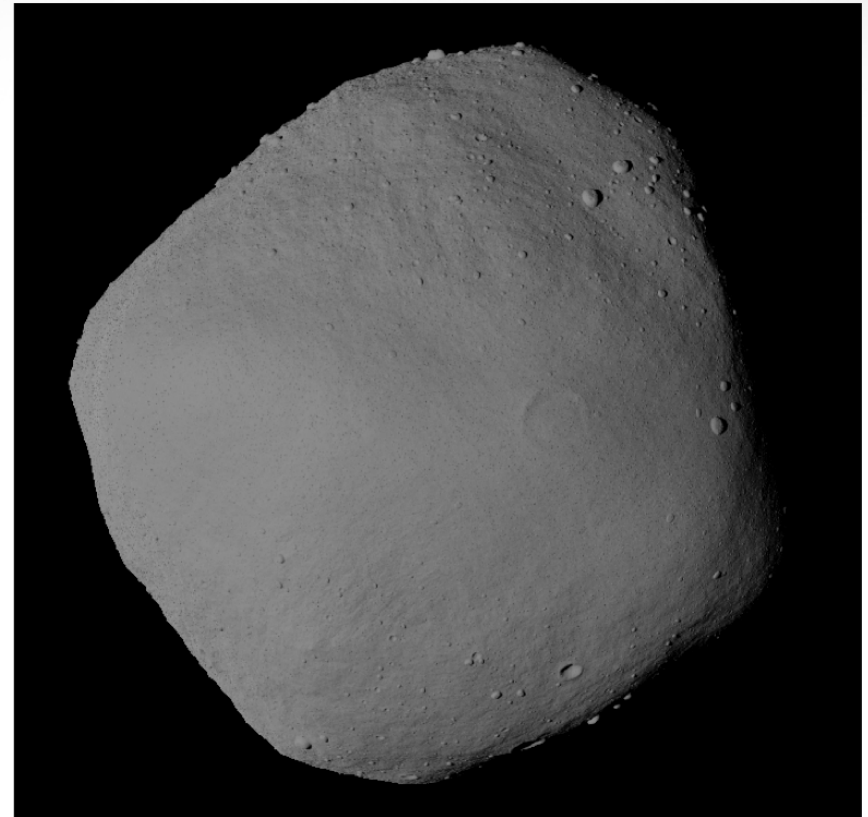
- Case Study 1: Bennu scenario
- The NNSA contributions have included:
 - Contributions to the definition of the scenario
 - Participation in the MDL (2-6 November 2015, at GSFC)
 - Comparisons of simulation methods (code-to-code study)
 - Numerical modeling of deflection events
 - kinetic impactor
 - nuclear deflection
 - Studies of sensitivity of results to parameter variations
 - Debris-field estimates and evolution
 - Estimation of deflection velocities in the context of launch windows and spacecraft trajectories (for comparison with NASA results)
- The GSFC contributions have included:
 - Contributions to the definition of the scenario
 - Leadership of the MDL study
 - Detailed physical and orbital data for Bennu
 - Mission design for Bennu intercept
 - Trajectory optimization for Bennu deflection



Credit: J. Michael Owen

Case 1 Study Target: Bennu

- Carbonaceous asteroid
 - B-type
 - Low albedo (~4%)
- Approximately 500 m in diameter
- Bulk density is approximately 1.26 g/cm^3
- Rotation period is ~4.3 hours
- OSIRIS-REx Design Reference Asteroid (DRA) document provides full details and is available online
 - <http://arxiv.org/abs/1409.4704>
 - <http://arxiv.org/ftp/arxiv/papers/1409/1409.4704.pdf>
- One of the best (remotely) characterized and most hazardous known NEOs
- NASA's OSIRIS-REx mission, scheduled to launch September 2016, will map Bennu in great detail and return samples to Earth



Simulated Image of Bennu

LLNL and LANL have documented a code-to-code comparison of simulation methodologies

- The 36-page report was completed in February (LLNL-MI-680901, LA-UR-16-20205)
- Test problems were defined and run
- Kinetic impactors
 - problem defined
 - cases run and compared
- Nuclear deflection
 - problems defined — both neutron and x-ray deposition
 - cases run and compared

Los Alamos and Lawrence Livermore National Laboratories
Code-to-Code Comparison of Inter Lab Test Problem 1
for Asteroid Impact Hazard Mitigation

LANL Project Lead: Robert Weaver¹, LLNL Project Lead: Paul Miller²,
Report Editor: Kirsten Howley²

ABSTRACT (*P. Miller*)

The NNSA Laboratories have entered into an interagency collaboration with the National Aeronautics and Space Administration (NASA) to explore strategies for prevention of Earth impacts by asteroids. Assessment of such strategies relies upon use of sophisticated multi-physics simulation codes. This document describes the task of verifying and cross-validating, between Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL), modeling capabilities and methods to be employed as part of the NNSA-NASA collaboration. The approach has been to develop a set of test problems and then to compare and contrast results obtained by use of a suite of codes, including MCNP, RAGE, Mercury, Ares, and Spheral. This document provides a short description of the codes, an overview of the idealized test problems, and discussion of the results for deflection by kinetic impactors and stand-off nuclear explosions.

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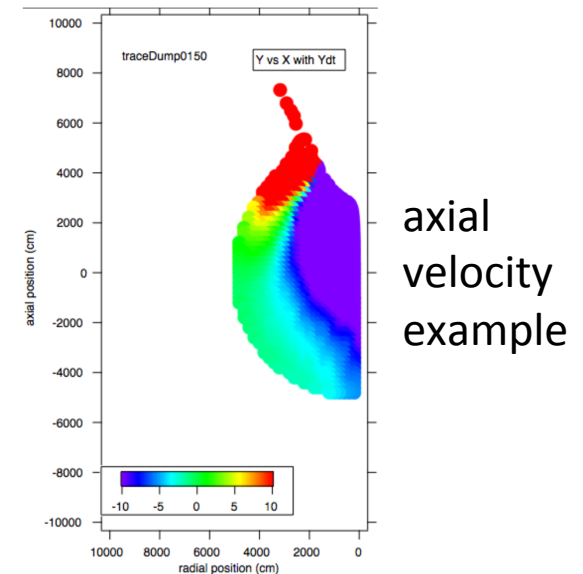
Differences were reconciled and there are currently no significant concerns regarding the comparison

Results by LLNL and LANL for the kinetic-impactor test problem agree well

- There was an initial discrepancy for the porous case, but that was resolved to be a consequence of a particular model
- Once models were run consistently, the results were quite similar

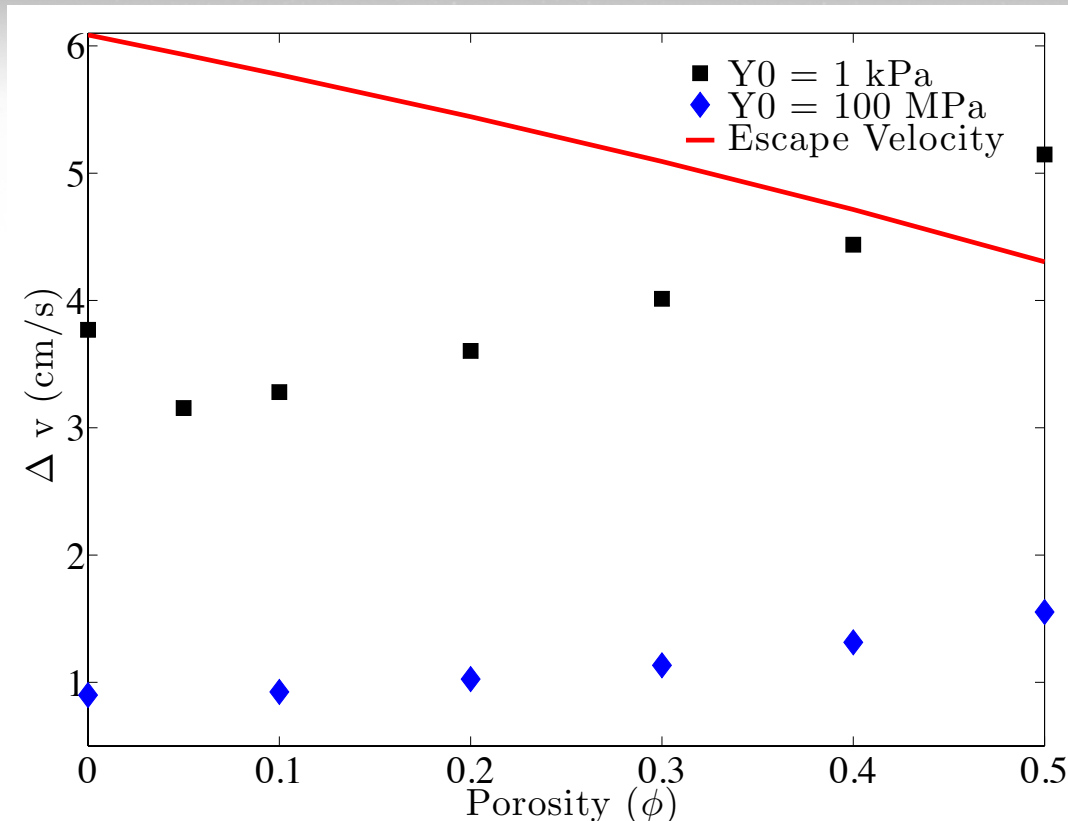
Source Type	Kinetic Impactor (ILTP1i)
Impactor Shape	Sphere
Impact speed	10 km/s
Mass	1 metric ton
Composition	Al (^{27}Al)
Density	2.7 g/cm ³
Porosity	None
Strength	None
Impactor EOS	Mie-Gruneisen $C_0 = 5.24 \times 10^5$ [cm/s] $S_1 = 1.4$ [unitless] $S_2 = 0$ [unitless] $S_3 = 0$ [unitless] $\gamma_0 = 1.97$ [unitless] $b = 0.48$ [unitless]

β	LANL result	LLNL result
Full density	31	31.5
40% porosity	3.73	3.69



Credits: Megan Bruck Syal, Galen Gisler

Increased asteroid porosity *enhances* deflection (primarily due to lower target mass) while lowering disruption risk



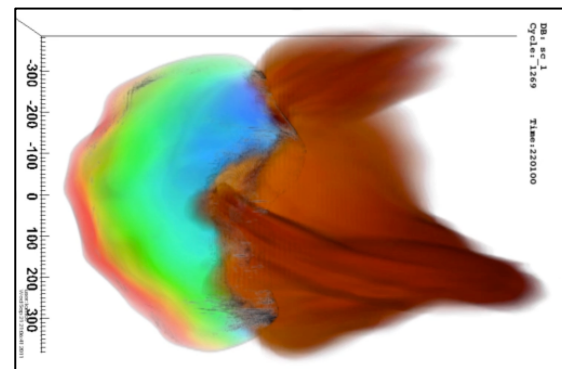
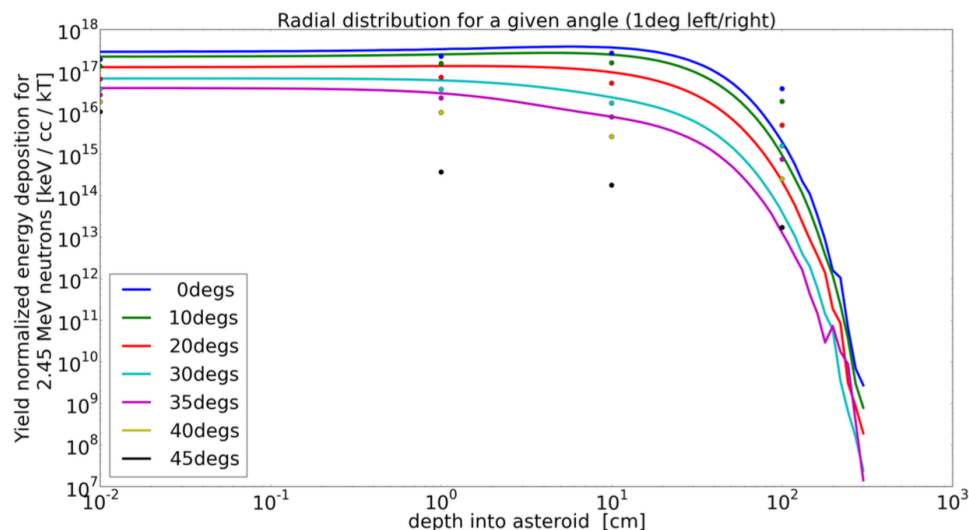
- 10-ton steel impactor at 5 km/s
- Larger Δv at greater porosities, shown for 100-m asteroids
- Even a little porosity protects against unintentional disruption

Credit: Megan Bruck Syal

Neutron and X-Ray Depositions Were Compared

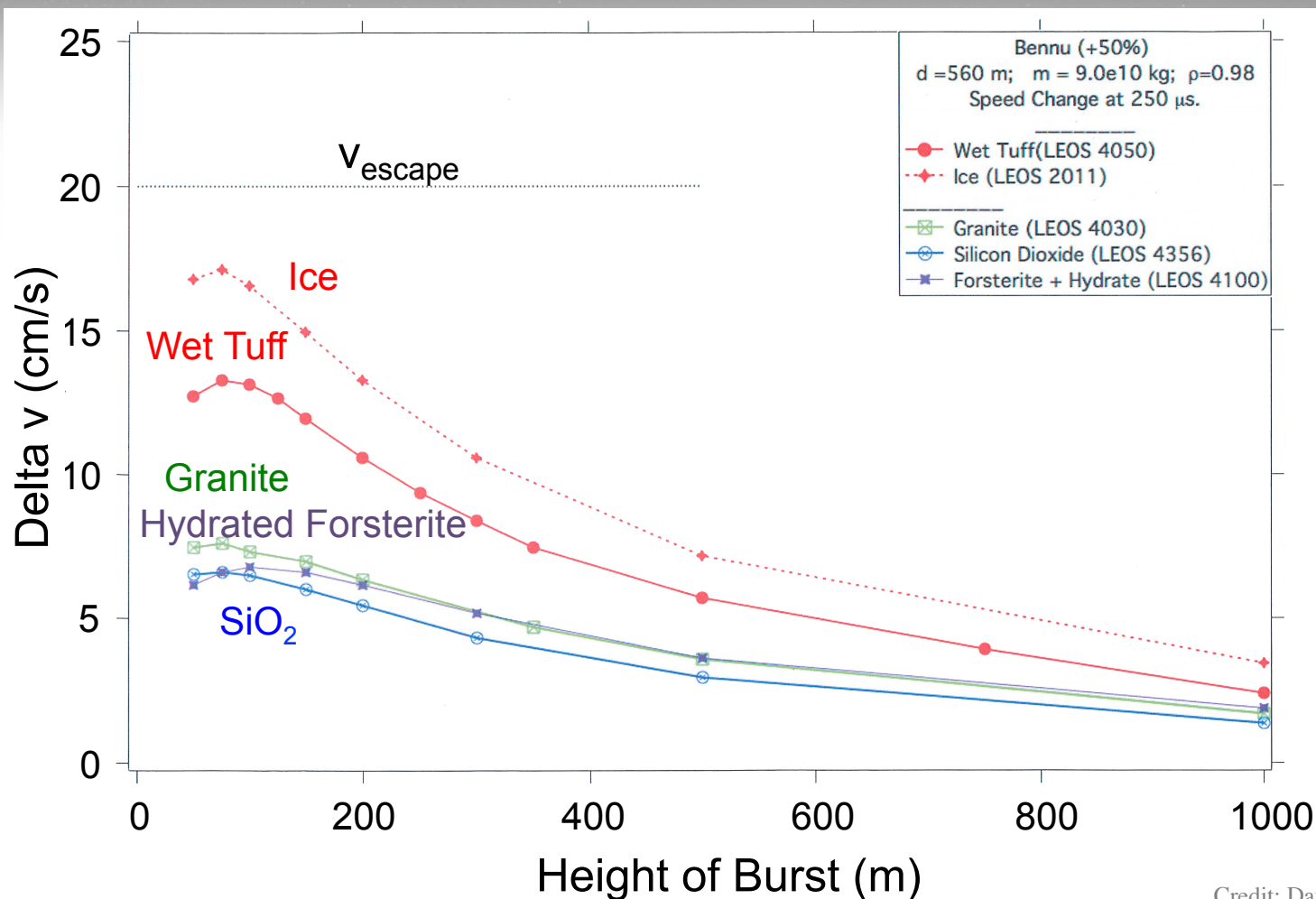
- Two problems were examined
 - neutron deposition (ILTP1n)
 - x-ray deposition (ILTP1x)
- The neutron deposition results were in relatively close agreement

Source Type	Stand-off Nuclear Explosion
Stand-off Dist	100 m
Source Geometry	Point
Pulse Length	0 μ s (instantaneous)
Source Yield	(20, 240, 1000) kT
Energy Type	(1) Mono-energetic neutrons (ILTP1n) (a) 14.1 MeV (b) 2.45 MeV (2) Planckian x-ray spectra (ILTP1x) (a) 1 keV (b) 2 keV



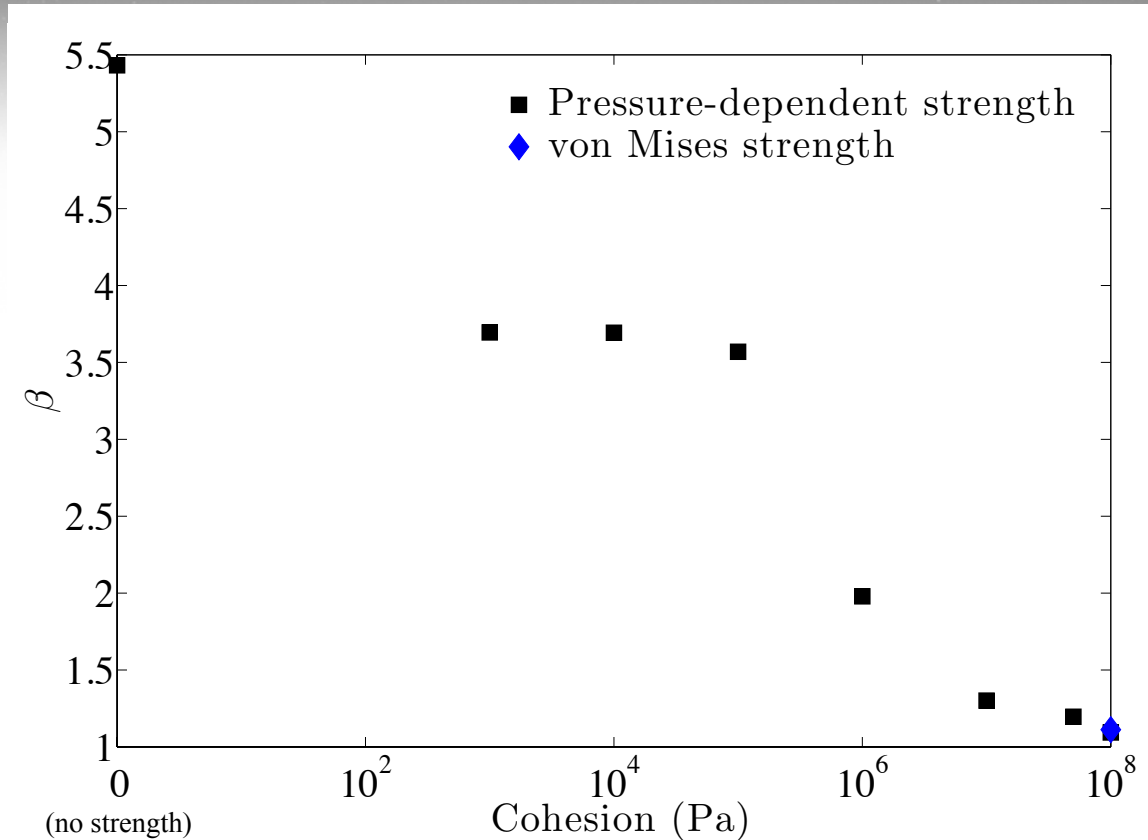
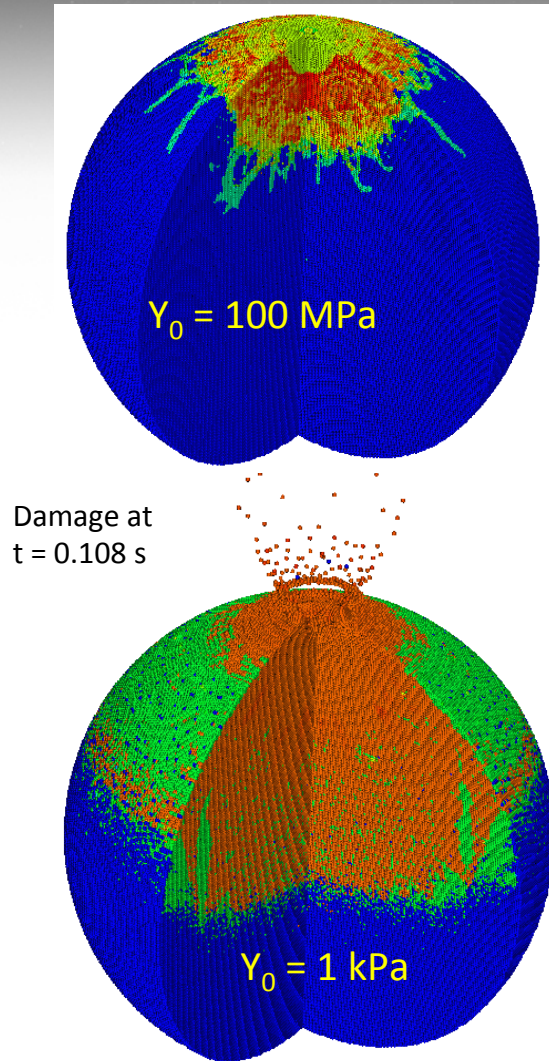
Credits: Kirsten Howley, Jim Ferguson, Rob Managan, Joe Wasem, Ilya Lomov

Composition of an asteroid affects deflection results



Credit: David Dearborn

Cohesion of asteroid material affects deflection: significant decrease for cohesion greater than 100 kPa



$$Y_i = Y_0 + \frac{\mu_i P}{1 + \mu_i P / (Y_M - Y_0)}$$

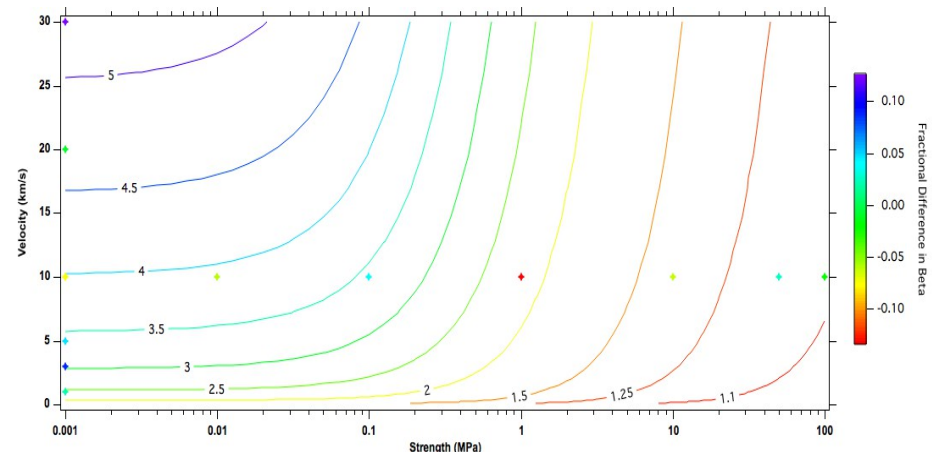
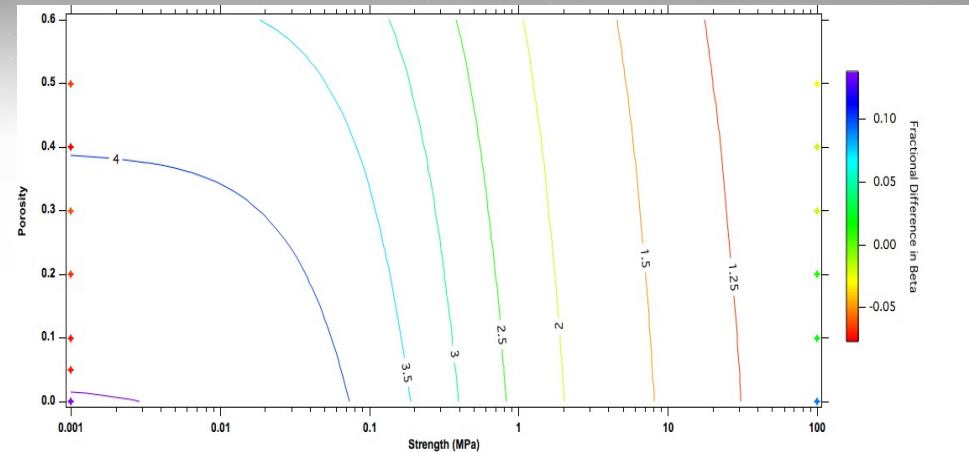
Credit: Megan Bruck Syal

Kinetic impact results can be combined into scaling relations across velocity, strength, and porosity

These relations feed into deflection mission design:

- Selection of launch window
- Kinetic or nuclear choice

Note that modeling resolution matters: Under-resolved simulations over-estimate damage accumulation and momentum transfer for impactors

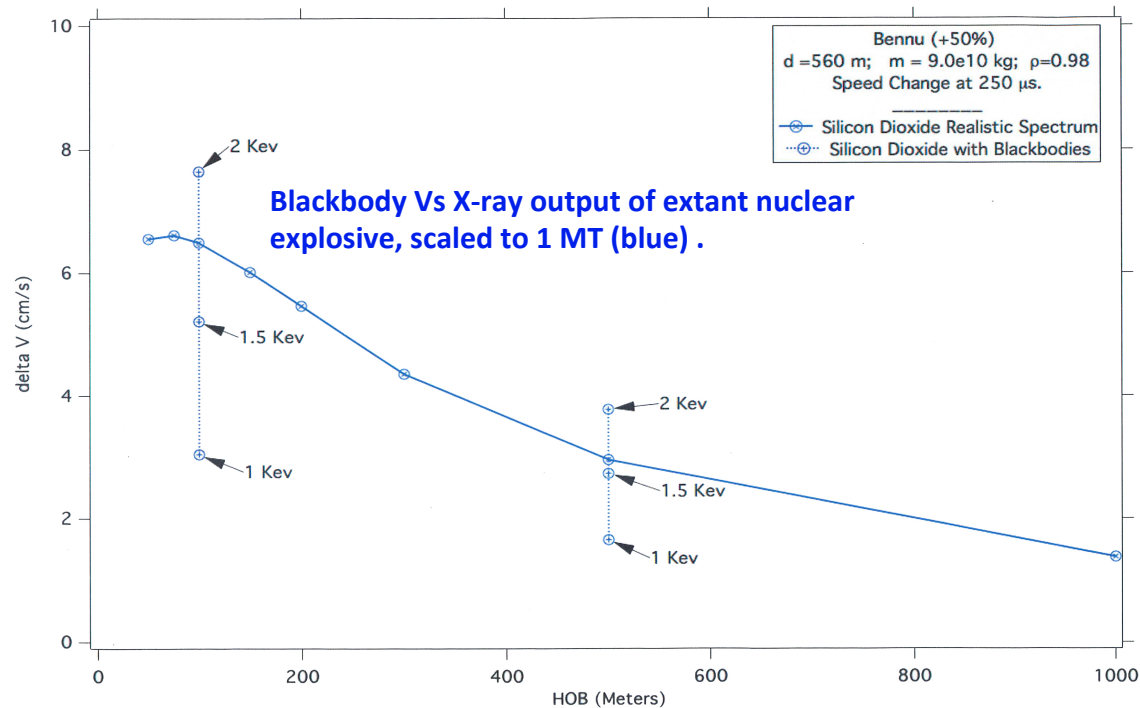


Credit: David Dearborn & Megan Bruck Syal

Deflection velocities from standoff nuclear burst, applied to Case 1 target Bennu, are consistent across codes

LLNL 2D Rad-Hydro Code:	7 cm/s
LLNL 3D Spheral: Extrapolate to	6 cm/s
LANL Parametric study:	6.8 cm/s
LANL 2 or 3D EAP project Code:	TBD est ~ 6.8 cm/s

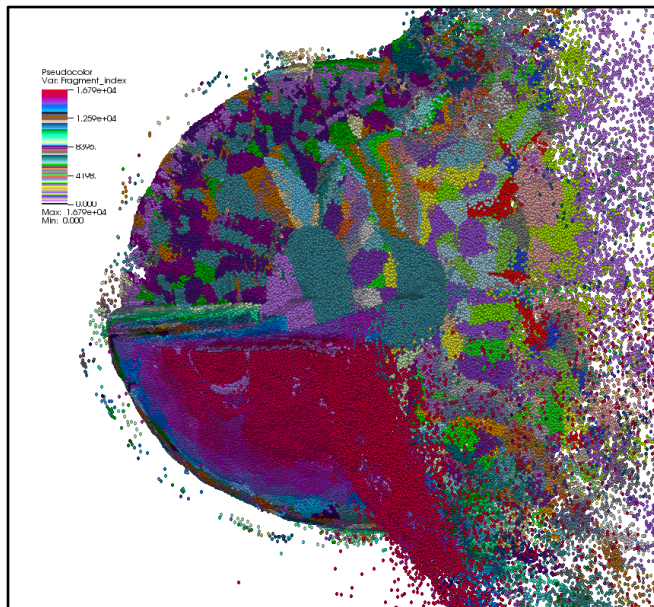
Again, modeling resolution matters: resolving X-ray deposition is important for correct effect.



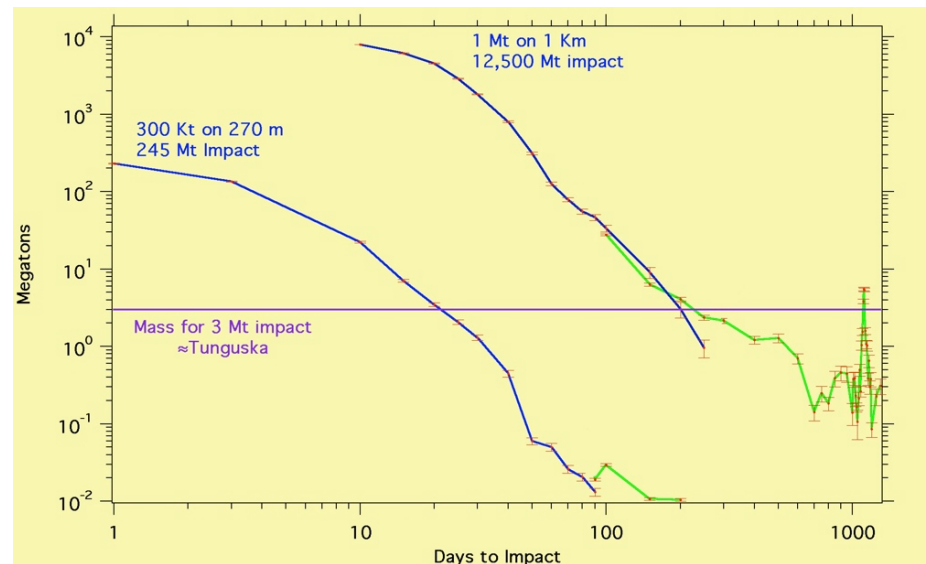
Credit: David Dearborn

Deliberate, robust disruption is an option for smaller objects and/or short warning times

- Example calculation: 270-m body disrupted by 300 Kt Surface burst, 100 days pre-impact
- Satellite damage probability $\approx 6 \times 10^{-6}$ (1 mm dust grain impact on 10 m² body)
- For Case 1 (Bennu), disruption not a likely option and is not explored in-depth
 - 500-m diameter is large
 - High porosity makes disruption more difficult

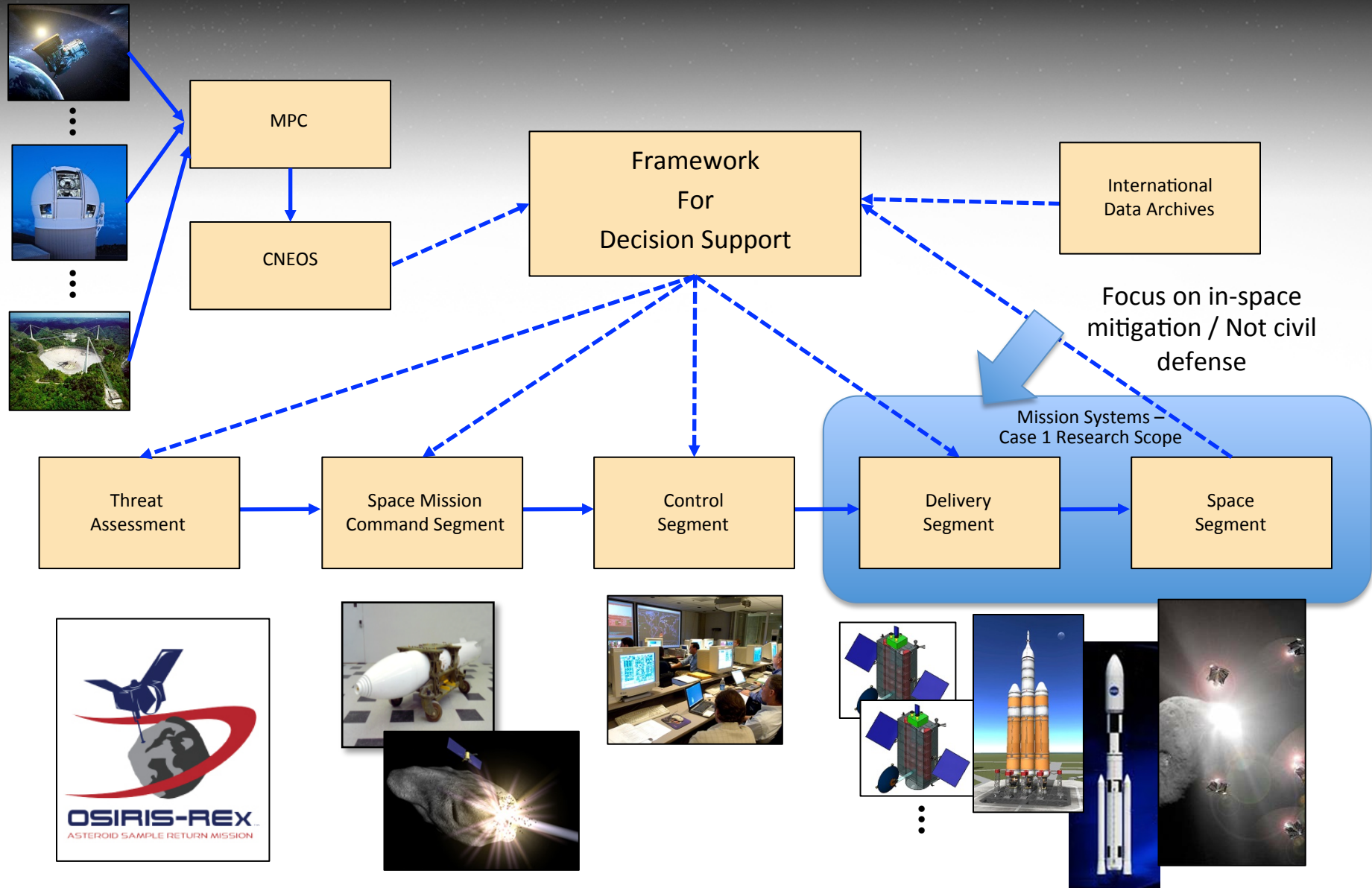


Example: 1 Mt surface burst on 50 m metallic asteroid (similar to Meteor Crater (AZ) impactor); colors represent individual fragments (credit: J. Michael Owen)



Credit: David Dearborn

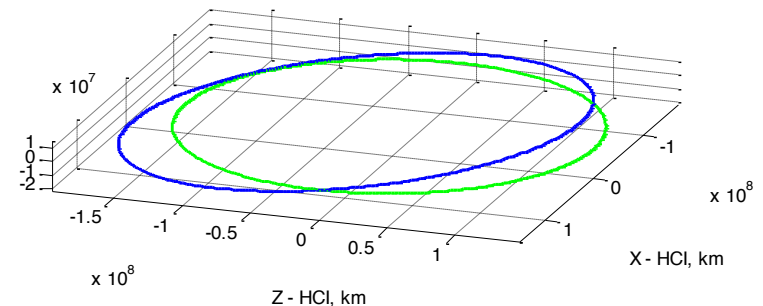
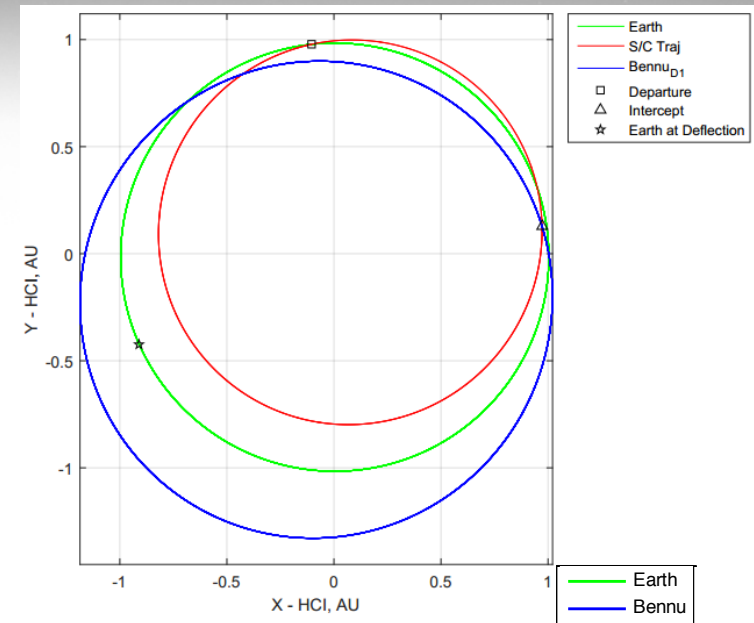
NEA Mitigation Architecture



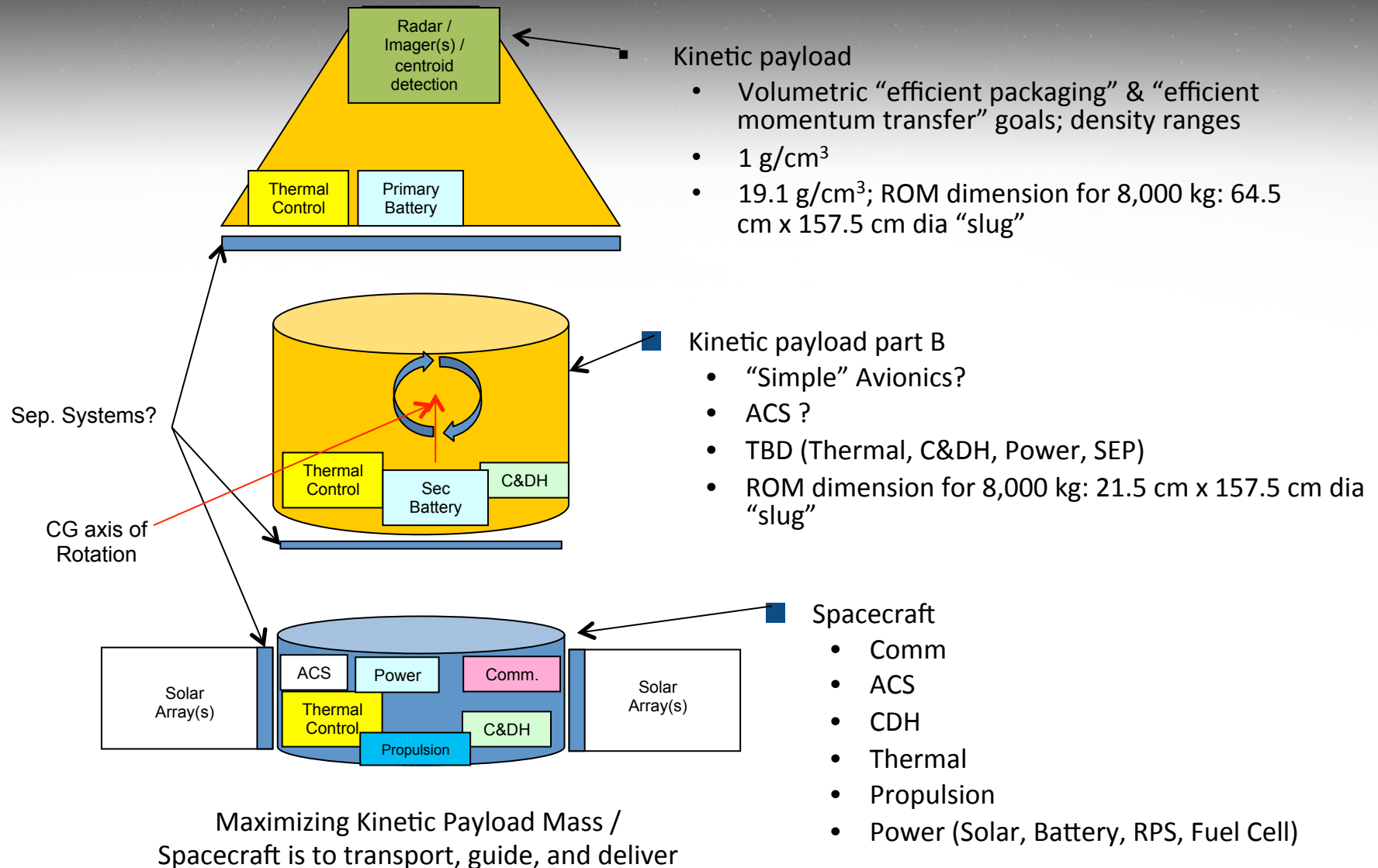
Bennu Deflection Trajectory Design

Formulation Concept Design Metrics

- Hypervelocity intercept of the hazardous asteroid
- An asteroid intercept spacecraft capable of carrying out a deflection attempt
- Spacecraft can function as either nuclear explosive carrier or kinetic impactor
- Spacecraft trajectories optimized to maximize deflection of Bennu away from Earth
- Assumed Delta IV Heavy (currently largest launch vehicle in the U.S. inventory)
- Designed GNC subsystem to be capable of tracking and intercepting an NEA as small as 100 m at 10 km/sec



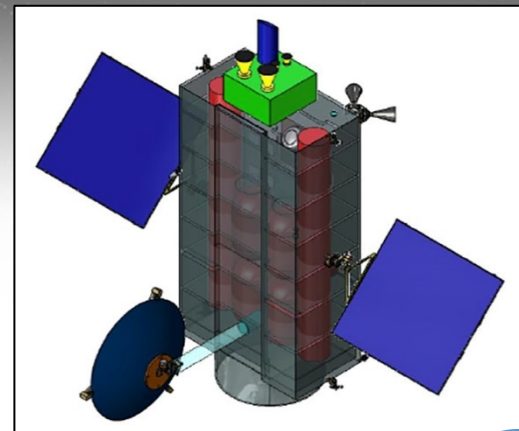
Notional Functional Allocation Concept



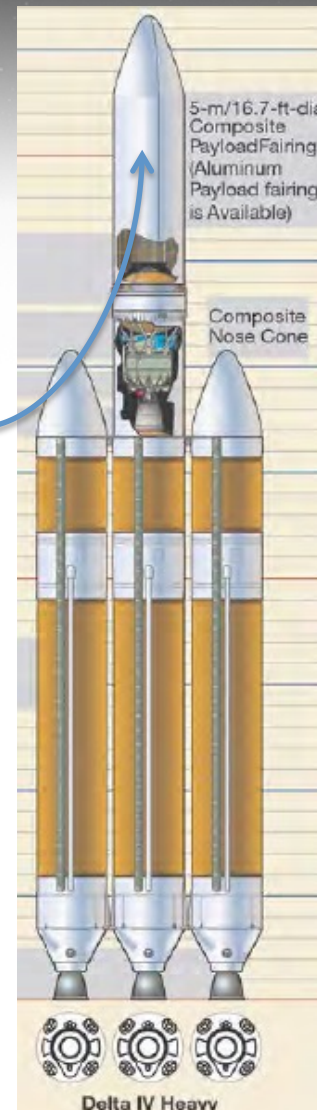
Hypervelocity Asteroid Mitigation Mission for Emergency Response

Mission POD Concept Formulation Features

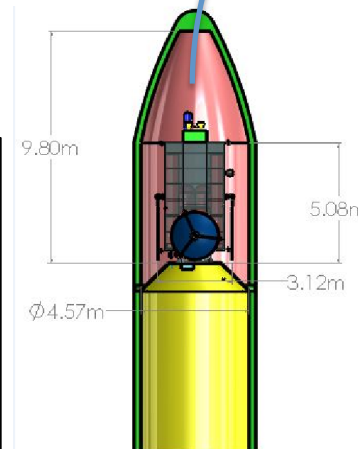
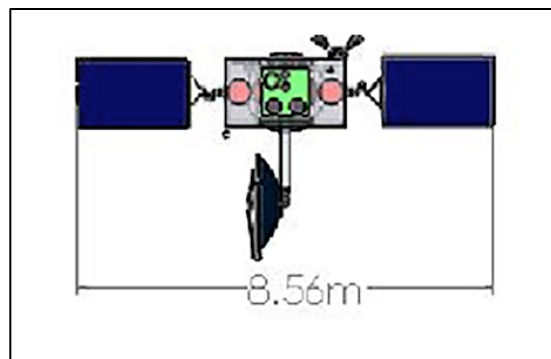
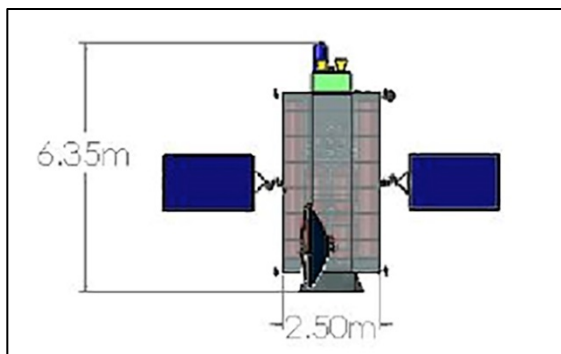
- Class A+ reliability for the deployed system
- Simple, dual string vehicle with triple voting scheme for mission-critical events
- Mass of 8800 kg chosen to max out Delta IV-H for Earth departure C_3 of $10 \text{ km}^2/\text{sec}^2$ (from baseline design reference trajectory)
- Fail operational during mission-critical phases
- Bearing and range (?) sensors on-board
- Uplink encryption included for device commanding (arm and execute)
- Autonomous navigation from I – 60 minutes



HAMMER



Delta IV Heavy



KI Deflection Analysis Summary (w/ $\beta=1$)

Available Launch Lead Time (yrs)	Launch Vehicle	Number of Launches	Used KI Mass (kg)	Specific Energy Imparted to NEO (J/kg)	Time from Deflection to Earth Encounter (yrs)	Δv Imparted to NEO (cm/s)	Defl. (R_E)	Defl. Perigee (R_E)	Defl. Bplane (R_E)
10	Delta IV Heavy	1	6508.07	0.434288	5.40	0.029388	-0.010	0.990	0.008
10	Delta IV Heavy (HAMMER)	1	7300.00	3.542383	4.77	0.088893	-0.010	0.990	0.012
10	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	1	7300.00	3.542383	4.77	0.088893	-0.010	0.990	0.012
10	SLS Block 1 w/iCPS	1	18223.49	3.330753	5.94	0.136191	-0.009	0.991	0.061
10	Delta IV Heavy	49	380708.89	253.88421	8.33	5.434662	1.526	2.526	3.779
10	Delta IV Heavy (HAMMER)	51	372300.00	248.27655	8.33	5.314624	1.448	2.448	3.695
10	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	50	362589.96	264.85812	8.33	5.417174	1.419	2.419	3.663
10	SLS Block 1 w/iCPS	19	377773.06	251.92638	8.33	5.392752	1.499	2.499	3.750
25	Delta IV Heavy	1	5355.51	1.288569	14.13	0.045921	-0.009	0.991	0.115
25	Delta IV Heavy (HAMMER)	1	7300.00	1.976445	19.00	0.066399	-0.010	0.990	0.016
25	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	1	7300.00	1.976445	19.00	0.066399	-0.010	0.990	0.016
25	SLS Block 1 w/iCPS	1	13031.30	12.733071	20.29	0.225175	-0.007	0.993	0.287
25	Delta IV Heavy	21	168708.60	105.5428	21.44	2.332612	1.417	2.417	3.662
25	Delta IV Heavy (HAMMER)	23	167900.00	115.05577	21.44	2.429624	1.472	2.472	3.721
25	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	23	167900.00	115.05577	21.44	2.429624	1.472	2.472	3.721
25	SLS Block 1 w/iCPS	9	186034.78	116.38192	21.44	2.572168	1.759	2.759	4.030

- A KI may not do the job for large asteroids or really short warning times
- Transportable mass may not be sufficient, given today's launch vehicle inventory
 - surface ablation is more mass efficient
- $\beta > 1$ scales these results approximately linearly
 - Higher β reduces required # of launch vehicles

KI Results For Smaller Deflections (w/ $\beta=1$)

Even just barely pushing the NEO from a dead-center Earth impact out to a minimalist Earth flyby perigee of ~ 1.25 Earth Radii requires a large number of launch vehicles

Available Launch Lead Time (yrs)	Launch Vehicle	Number of Launches	Used KI Mass (kg)	Specific Energy Imparted to NEO (J/kg)	Time from Deflection to Earth Encounter (yrs)	Δv Imparted to NEO (cm/s)	Defl. (R_E)	Defl. Perigee (R_E)	Defl. Bplane (R_E)
10	Delta IV Heavy	31	240856.65	160.62062	8.33	3.438263	0.285	1.285	2.389
10	Delta IV Heavy (HAMMER)	32	233600.00	155.78137	8.33	3.334673	0.225	1.225	2.317
10	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	32	232057.57	169.50919	8.33	3.466998	0.247	1.247	2.343
10	SLS Block 1 w/iCPS	12	238593.51	159.1114	8.33	3.405956	0.266	1.266	2.366
25	Delta IV Heavy	14	116411.75	55.565216	21.46	1.405917	0.230	1.230	2.323
25	Delta IV Heavy (HAMMER)	15	109500.00	72.254588	21.46	1.554890	0.253	1.253	2.350
25	Delta IV Heavy (HAMMER) Adjusted Mass (max	15	109500.00	72.254588	21.46	1.554890	0.253	1.253	2.350

So, What Can a HAMMER Do?

- The HAMMER in kinetic impactor mode is clearly not an adequate solution for deflecting Bennu (or similar/more challenging NEOs)
- For what size NEO can a single HAMMER in kinetic impactor mode produce an adequate deflection?
 - We want the system to be fully capable of robustly achieving the threshold mission with a single spacecraft.
 - We then deploy a campaign of several spacecraft, for redundancy/robustness.
- **It turns out that with a 10 year launch lead time, a single HAMMER in kinetic impactor mode can minimally deflect an NEO $\leq \sim 150$ m (with bulk density of 1 g/cm³, Bennu's orbit, and $\beta=1$)**
- The largest NEO a single HAMMER in kinetic impactor mode can handle will vary based upon NEO orbit, NEO bulk density, β , and launch lead time (and warning time, which is not the same as launch lead time)



For Bennu's Orbit, HAMMER could handle at most a ~240 m asteroid with 25-year warning (assumes density=1, $\beta=2.5$)



Single HAMMER vs. Bennu's orbit ($a=1.126$ AU, $e=0.2037$, $i=6.035^\circ$)

These tables show the largest diameter NEA that a single HAMMER in Kinetic Impactor mode can deflect under the associated conditions.

(For Larger (~1.50 ER perigee altitude) Deflections)

Available Launch Lead Time (yrs)	β	Asteroid Density (g/cm ³)	Diameter (m)	Deflection (R_E)
10	1	1	135	1.435
10	1	2.6	98	1.454
10	2.5	1	183	1.448
10	2.5	2.6	133	1.454
25	1	1	176	1.461
25	1	2.6	128	1.461
25	2.5	1	238	1.498
25	2.5	2.6	174	1.445

(For Smaller (~0.25 ER perigee altitude) Deflections)

Available Launch Lead Time (yrs)	β	Asteroid Density (g/cm ³)	Diameter (m)	Deflection (R_E)
10	1	1	157	0.243
10	1	2.6	114	0.252
10	2.5	1	213	0.246
10	2.5	2.6	155	0.242
25	1	1	203	0.245
25	1	2.6	147.5	0.251
25	2.5	1	275.5	0.246
25	2.5	2.6	200.5	0.241

$$D_2(\text{Lead Time}) = \left(\frac{\rho_1 \beta_2}{\beta_1 \rho_2} \right)^{\frac{1}{3}} D_1(\text{Lead Time})$$

Lead times must be equal



For 2015 PDC's Orbit, HAMMER could handle at most a ~400 m asteroid with 25-year warning (assumes density=1, $\beta=2.5$)

Single HAMMER vs. 2015 PDC's orbit (a=1.78 AU, e=0.49, i=5°)

These tables show the largest diameter NEA that a single HAMMER in Kinetic Impactor mode can deflect under the associated conditions.

(For Larger (~1.50 ER perigee altitude) Deflections)

Available Launch Lead Time (yrs)	β	Asteroid Density (g/cm ³)	Diameter (m)	Deflection (R_E)
10	1	1	210	1.413
10	1	2.6	152	1.441
10	2.5	1	285	1.413
10	2.5	2.6	207	1.419
25	1	1	300	1.420
25	1	2.6	218.5	1.408
25	2.5	1	407	1.423
25	2.5	2.6	296	1.422

(For Smaller (~0.25 ER perigee altitude) Deflections)

Available Launch Lead Time (yrs)	β	Asteroid Density (g/cm ³)	Diameter (m)	Deflection (R_E)
10	1	1	282.5	0.243
10	1	2.6	205	0.25
10	2.5	1	383	0.246
10	2.5	2.6	279	0.241
25	1	1	406.5	0.245
25	1	2.6	295.6	0.245
25	2.5	1	551.7	0.245
25	2.5	2.6	401	0.240

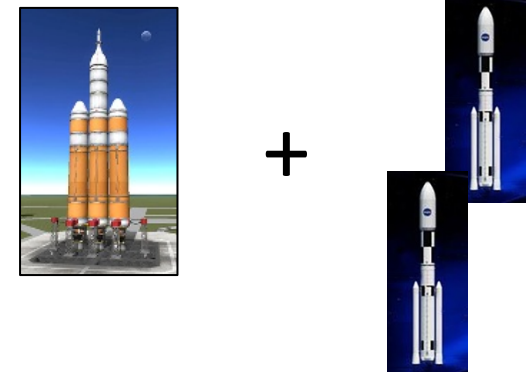
$$D_2(\text{Lead Time}) = \left(\frac{\rho_1 \beta_2}{\beta_1 \rho_2} \right)^{\frac{1}{3}} D_1(\text{Lead Time})$$

Lead times must be equal

Formulation Con-OPS Considerations

("Operational" Impact Trades)

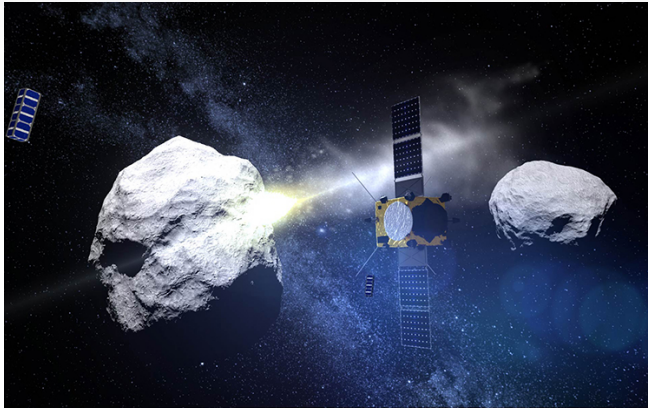
- Reliability-driven campaign mode would require unprecedented launch and operations cadence
- Each of the (notional) redundant "impactor / mitigation" spacecraft in such a campaign would likely be similar in operations to OSIRIS-REx
- All would probably need to be launched within a 20 day window
 - they would additionally need to intercept the target within a 20 day window for deflection operations
- Results from each (serial) deflection would be used to revise models and tune the simulations for higher fidelity and increased confidence in subsequent deflection attempts



- Our research thrust is a scenario-based approach, and it seems effective at addressing the end-to-end integrated problem, from launch readiness to post impact. Still need to complete the impact model runs, AF&F engineering for C.S. 1, and uncertainty analyses
- Successful kinetic and nuclear deflection LLNL/LANL code comparisons
- Deflection using both kinetic and nuclear device momentum delivery systems was examined in the short response regime
- Design reference mission (DRM) 1 involved the formulation and optimization of intercept trajectories, architecture and mission design, high fidelity modeling of both kinetic impact and nuclear detonation, and system uncertainty analyses (TBD)
- A HAMMER spacecraft in KI mode is not adequate for deflecting Bennu-class objects, because of required multiple large launchers and stress on launch site resources
- Nuclear surface ablation is more mass efficient and is the preferred option for this class of NEAs in the limit of short response times
- Our analyses to date have validated the notion that KI is most effective for small, competent asteroids, whereas ablative methods appear best for non-competent bodies, very short warning times, and large (e.g., >150m) NEAs
- Suggest further consideration of using SLS with co-manifesting multiple “HAMMERS” as another formulation architecture segment trade

Next 2 case studies

DRA 2 - Didymoon



- 150 meter diameter object
- Likely spherical or oblate spheroid
- Supports APL/Double Asteroid Redirection Test (DART) with KI model output
- Adds nuclear explosive-based deflection/disruption to our case study compendium

DRA 3 – Comet 67P



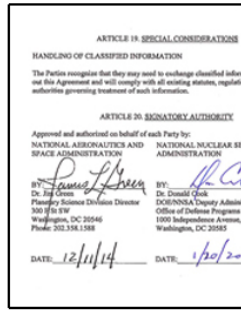
- Less frequent, but more dangerous target
- Size scaled down to 215x205 m, high speed, short warning
- Both intercept and deflection/disruption are challenging
- Early shape model based on remote sensing grossly misjudged the “as is” object

QUESTIONS?



Appendices

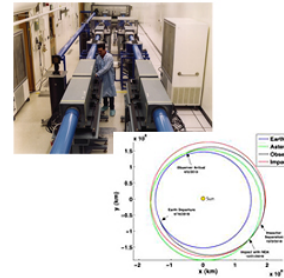
Strategic Partnerships



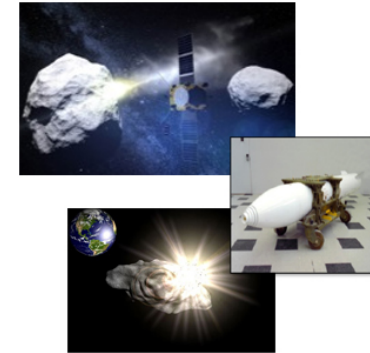
Small Body Characterization



Model Input



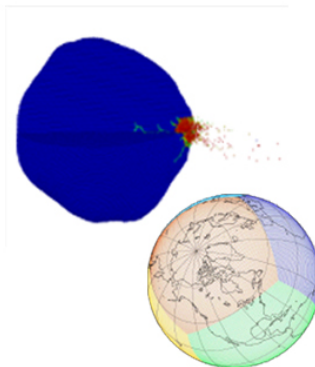
Engagement Approaches



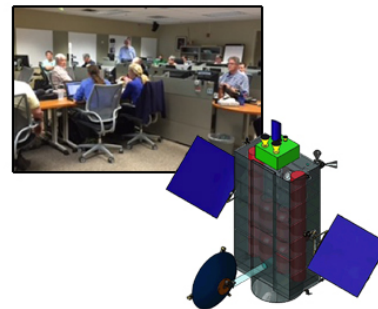
Peta-Scale Computing



2-D and 3-D Simulations



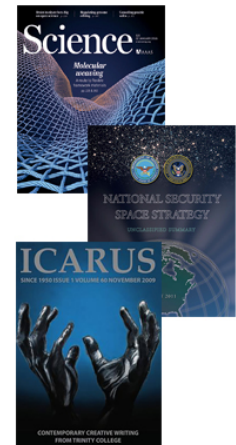
Design Reference Missions



Big Data Framework



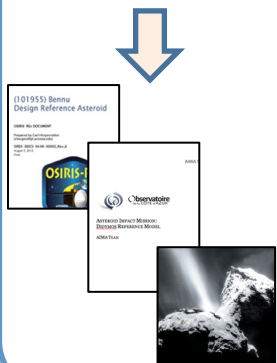
Publish



Framework for NEO Mitigation

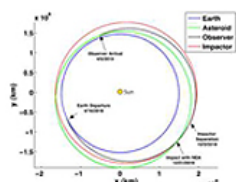
Design Reference Asteroids

Physical and Chemical Characterization Data



Optical/Radar Data

Astrodynamics

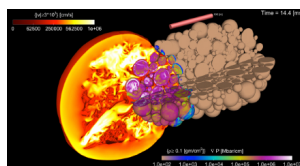


Impact Modeling & Simulation

Model run intercomparisons

Physics-based 2D/3D model output

Data quality

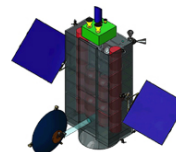


Design Reference Missions

NEO Impact Modeling

Space mission Design including:

Spacecraft launcher
Control Center
Payload I/F
Flight Ops



Decision Support

Deflection/Disruption Uncertainty analyses

Space Mission reliability estimates

Physics-based risk modeling

Deflection/Disruption effectiveness

Big Data Processing



Data Discovery, Access, Simulations & Analytics



Powered by Cloud & High Performance Computing



Hybrid Cloud Computing



LLNL



David Dearborn
• Energy Deposition
• Deflection/Disruption



Souheil Ezzedine
• Entry and Impact Modeling



Eric Herbold
• Physical/Chemical Properties
• Shock Propagation



Kirsten Howley
• Energy Deposition
• Shock Propagation



Rob Managan
• Shock Propagation



Mike Owen
• Shape Rotation Effects



Damian Swift
• Physical/Chemical Properties



Megan Bruck Syal
• Physical/Chemical Properties



Joe Wasem
• Energy Deposition
• Shape Rotation Effects

GSFC



Brent Barbee
• Astrodynamics



Bill Farrell
• Plasma Environment



Keith Noll
• Characterization

SNL



Mark Boslough
• Risk Analyses
• Air Bursts

LANL



Jim Ferguson
• Energy Deposition



Galen Gisler
• Physical/Chemical Properties



Cathy Plesko
• Energy Deposition



Bob Weaver
• Energy Deposition

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Randy Summer

Megan Syal

Joseph Wasem

Robert Weaver

Mission Design Lab (MDL) Team

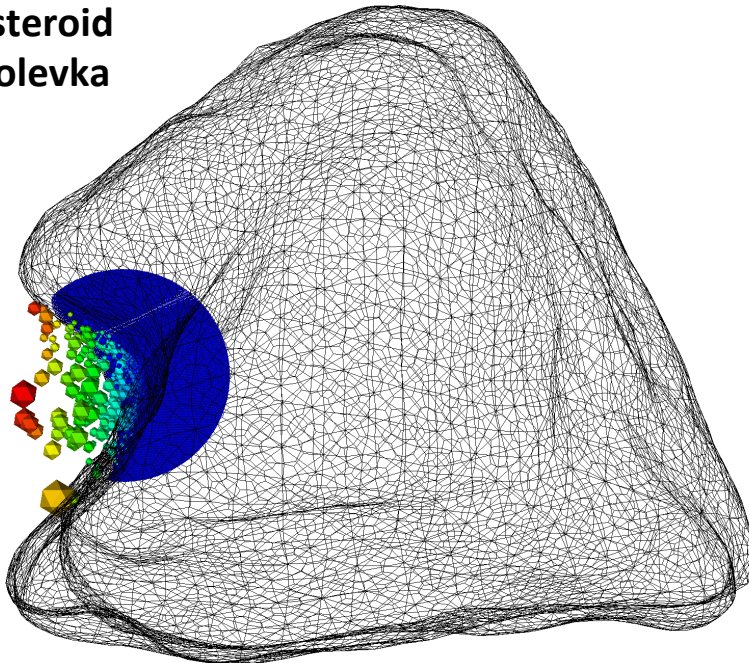
Note: Substantial post-MDL contributions in this talk from Joshua Lyzhoft, GSFC Pathways Intern

Discipline	Supporting Engineer	Discipline	Supporting Engineer
Attitude Control	Paul Mason	Mechanical Designer	Sara Riall-Waldsachs
Avionics	Porfy Beltran	Mechanical Systems	Acey Herrera
Communications	Blake Lorenz	Mission Ops	Dale Fink
Costing	Larry Phillips	Mission Systems / Launch Vehicle	Frank Kirchman / James Sturm
Debris Analysis/EOM	Ivonne Rodriguez	Propulsion	Dewey Willis
Elect. Power	Bob Beaman / David Kim	Radiation	Alvin Boutte / Shannon Alt
Flight Dynamics	Cinnamon Wright / Frank Vaughn	Reliability	Aron Brall
Flight Software	Kequan Luu	Thermal	Juan Rodriguez-Ruiz
I&T	Pat Kilroy / Lakesha Bates	MDL Team Lead	Mark Steiner
NED – LANL	Catherine Plesko	NED/Import – LLNL	David Dearborn
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GSFC – Study PI	Brent Barbee	NNSA Lead Executive	Kevin Greenough
NNSA Project Lead	Anthony Lewis	GSFC Asteroid Science	Joe Nuth
GSFC Asteroid Science	Keith Noll	LANL – Specialist	Galen Gisler

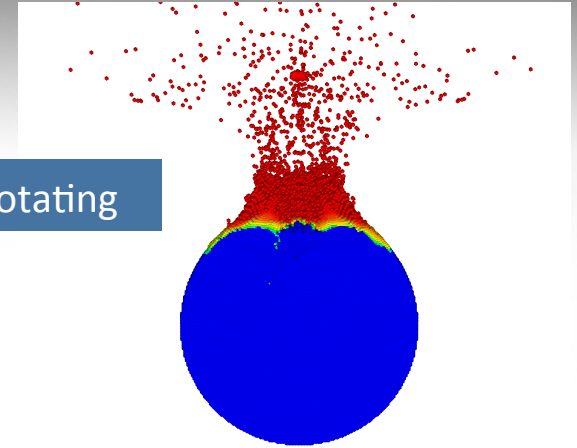
Rotation & Shape do not significantly affect deflection but do affect disruption risk

- Rotation enhances ejecta, but not beta
- Slope matters, and may be difficult to control
 - Submitted paper with J. Feldhacker & D. Scheeres, UC Boulder

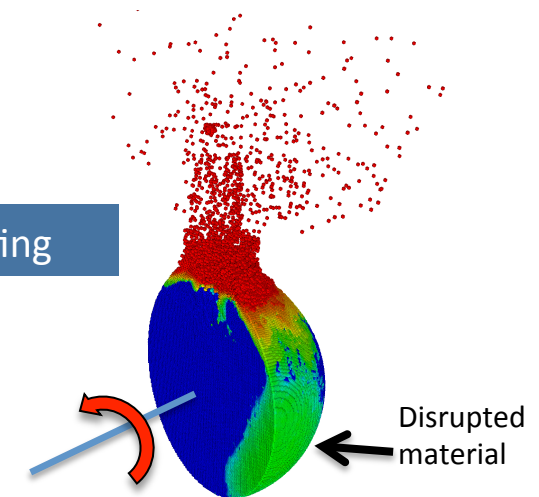
Asteroid Golevka



Non-rotating



Rotating



Credit: Megan Bruck Syal

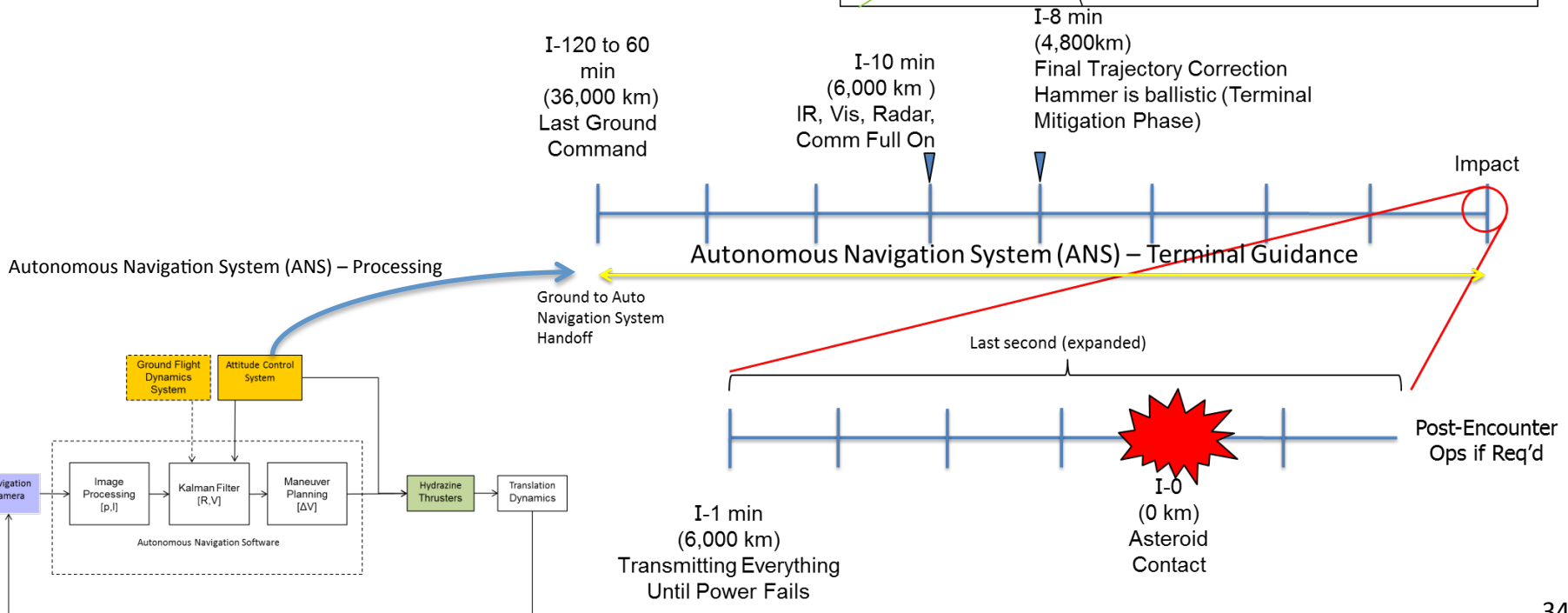
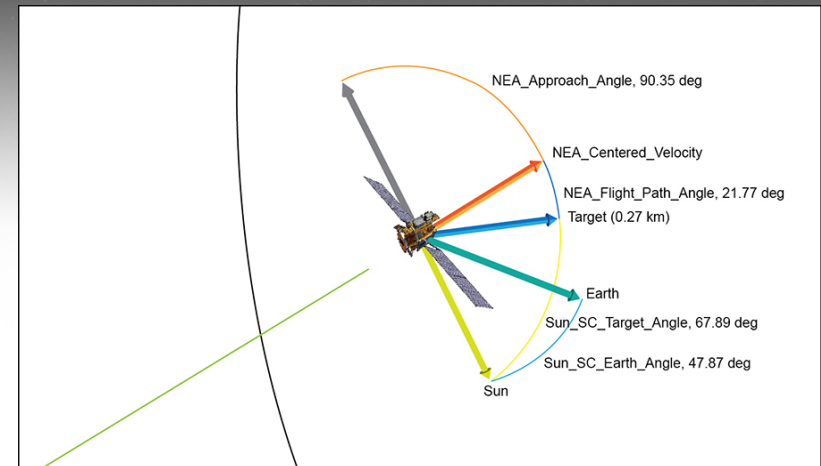
See also: Bruck Syal et al. 2016. Deflection by Kinetic Impact: Sensitivity to Asteroid Properties. *Icarus* **269**, 50-61.

Feldhacker et al., 2016 (submitted) Shape Dependence of the Kinetic Deflection of Asteroids, *Journal of Guidance, Control and Dynamics*

Navigation & Guidance Drivers

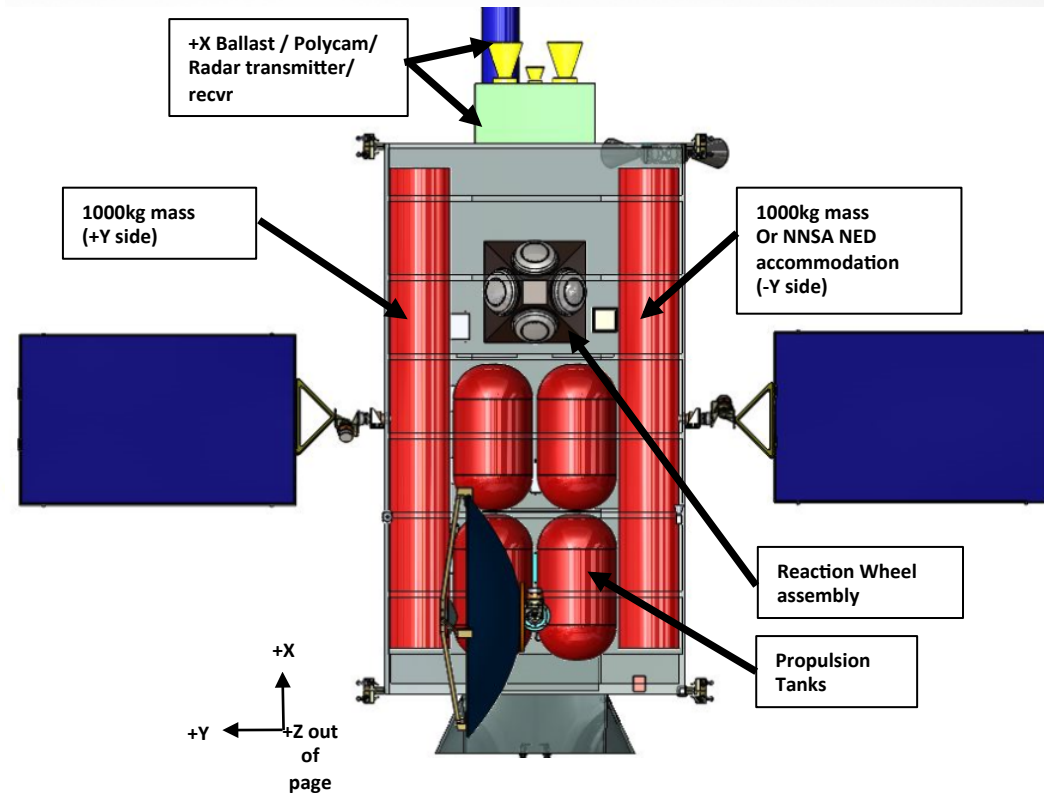
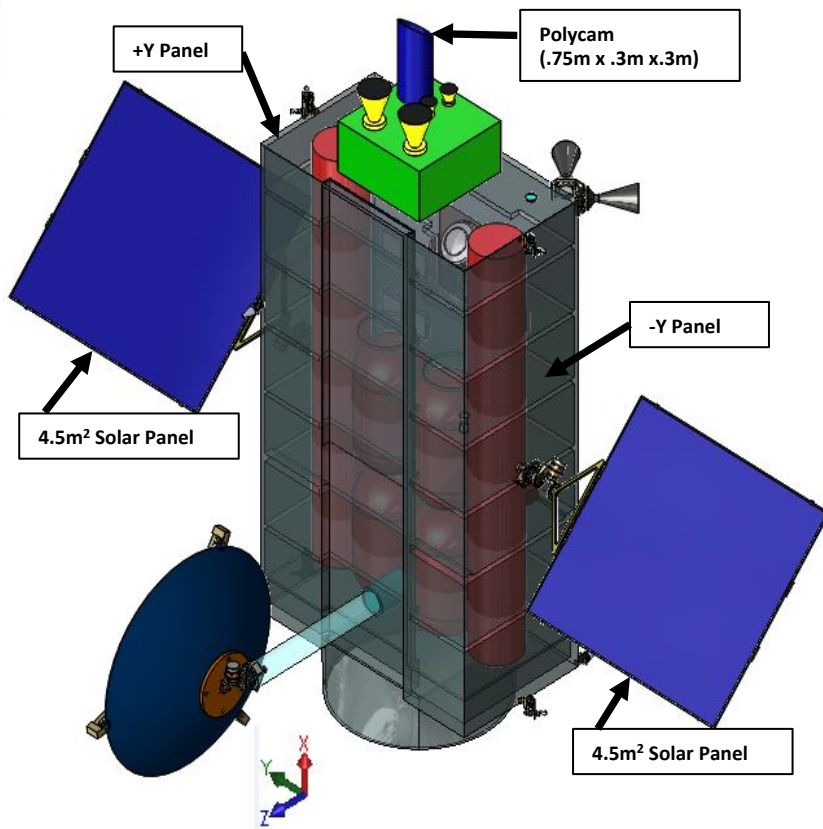
Terminal Mitigation Phase

- Case 1 assumptions (drivers):
 - Time of Flight: 740 days
 - Intercept Date: July 11, 2113
 - Target relative velocity at intercept: 4.48 km/s; concept goal ~10 km/s upper bound, target area goal 100 m dia
 - Approach phase angle at intercept: 90.35°
 - Maximum Distance from Earth: 1.6 AU
 - Maximum Distance from Sun: 1.06 AU
 - Total Mission ΔV : 99.2 m/s

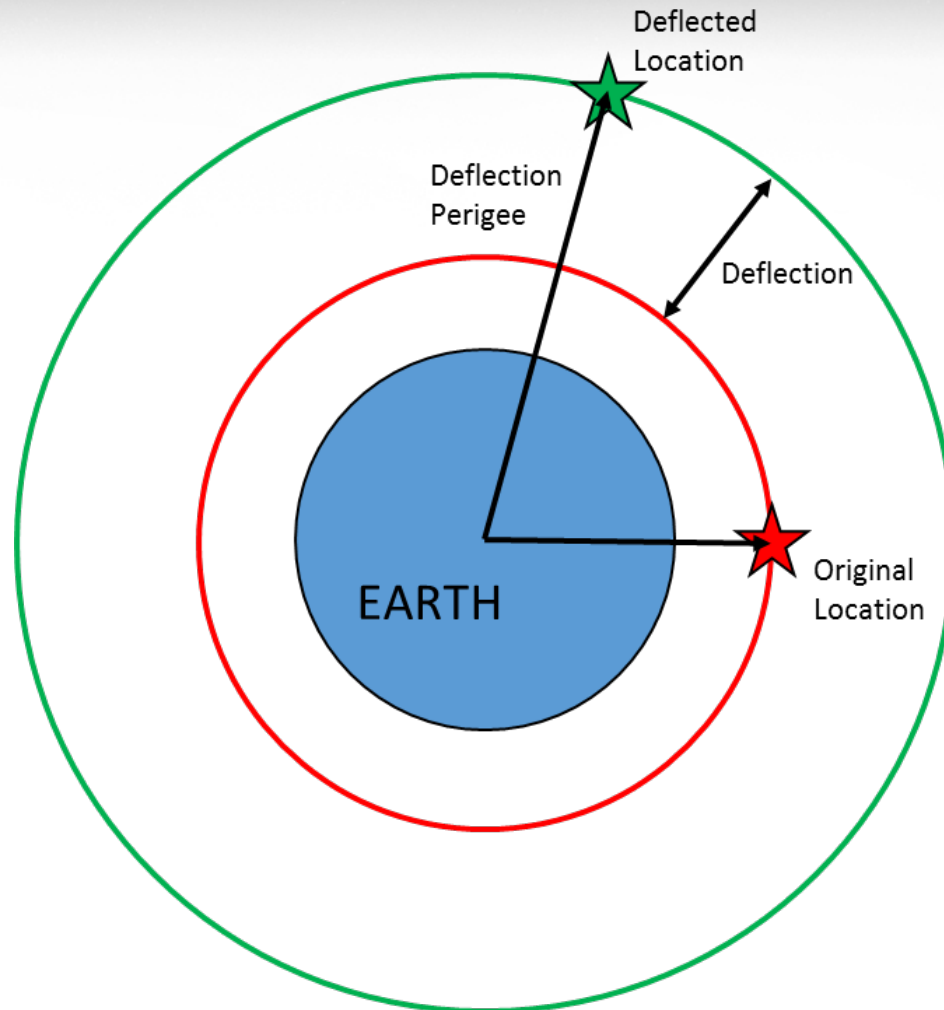


HAMMER Concept

- Coordinate system / System overview



Deflection Definition



Deflection Results w/ $\beta=2.5$

Available Launch Lead Time (yrs)	Launch Vehicle	Number of Launches	Used KI Mass (kg)	Specific Energy Imparted to NEO (J/kg)	Time from Deflection to Earth Encounter (yrs)	Δv Imparted to NEO (cm/s)	Defl. (R_E)	Defl. Perigee (R_E)	Defl. Bplane (R_E)
10	Delta IV Heavy	1	4961.20	3.922845	4.71	0.19279	-0.010	0.990	0.047
10	Delta IV Heavy (HAMMER)	1	7300.00	1.646286	2.41	0.15150	-0.010	0.990	0.048
10	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	1	7300.00	1.646286	2.41	0.15150	-0.010	0.990	0.048
10	SLS Block 1 w/iCPS	1	21722.50	3.444975	5.97	0.37805	-0.008	0.992	0.165
10	Delta IV Heavy	19	147621.82	98.444898	8.33	5.26831	1.423	2.423	3.667
10	Delta IV Heavy (HAMMER)	21	153300.00	102.23152	8.33	5.47096	1.549	2.549	3.804
10	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	20	145035.98	105.94325	8.33	5.41719	1.419	2.419	3.663
10	SLS Block 1 w/iCPS	8	159062.34	106.07427	8.33	5.67660	1.683	2.683	3.948
25	Delta IV Heavy	1	7075.84	0.377054	17.82	0.07138	-0.009	0.991	0.116
25	Delta IV Heavy (HAMMER)	1	7300.00	2.800896	21.46	0.19761	-0.007	0.993	0.267
25	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	1	7075.84	0.377054	17.82	0.07138	-0.009	0.991	0.116
25	SLS Block 1 w/iCPS	1	22311.59	3.401781	17.85	0.38073	-0.007	0.993	0.218
25	Delta IV Heavy	9	72303.69	45.232628	21.44	2.49923	1.654	2.654	3.918
25	Delta IV Heavy (HAMMER)	9	65700.00	42.797199	21.41	2.31735	1.244	2.244	3.473
25	Delta IV Heavy (HAMMER) Adjusted Mass (max mass 7300)	9	65700.00	42.797199	21.41	2.31735	1.244	2.244	3.473
25	SLS Block 1 w/iCPS	4	77013.41	52.774495	21.44	2.78609	1.969	2.969	4.254