# GPU Accelerated 3-D Modeling and Simulation of a Blended Kinetic Impact and Nuclear Subsurface Explosion

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# Introduction

- Last minute scenarios with short warning time require a large amount of energy to be transferred to the NEO.
- Highest technological readiness for deflection options include kinetic impactors and explosives – highest energy density of available payloads.
- David Dearborn and others have shown that complete disruption of a body is not always an undesirable effect.
- Dispersion along the NEO orbit can substantially reduce the amount of mass remaining on impacting trajectories.

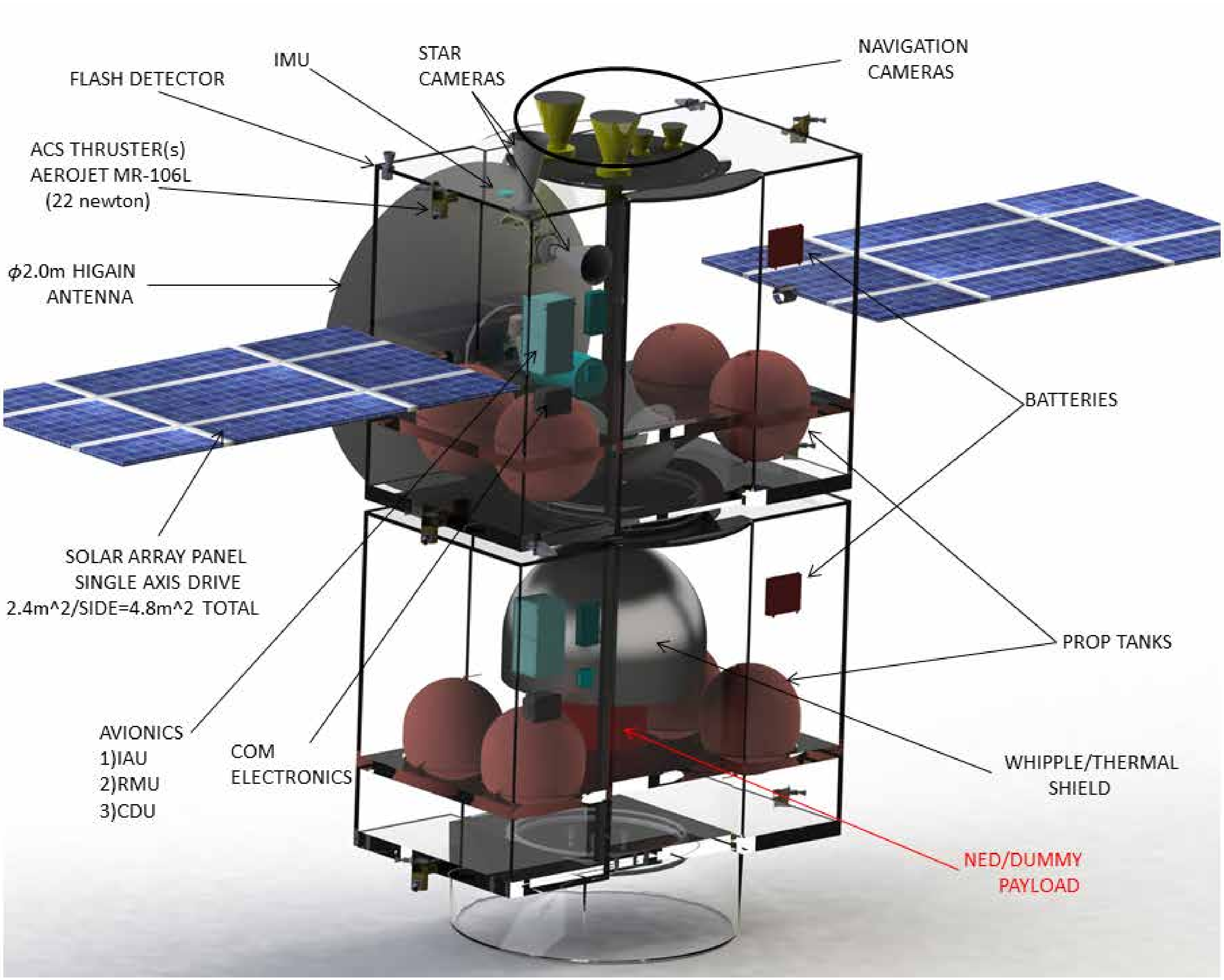
# Introduction

- Energy coupling through subsurface explosions is substantially higher than other options, but this requires a rendezvous-type mission.
- Changing the arrival velocity can directly affect mission feasibility, particularly at the last minute.
- Hypervelocity Asteroid Intercept Vehicle (HAIV) attempts to work around this velocity limitation by blending the concepts of a kinetic impactor and  a subsurface explosion.

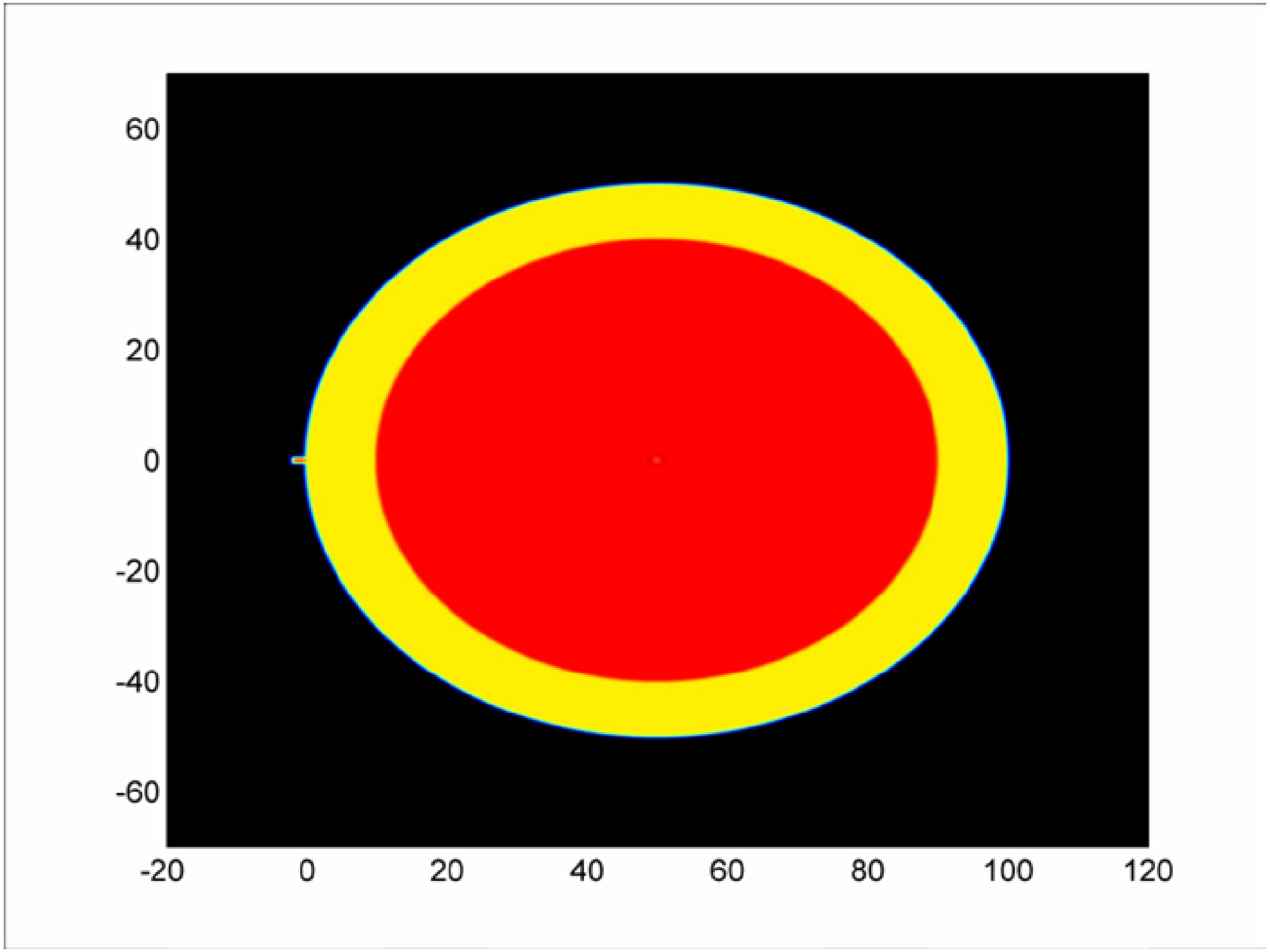
# Introduction

- HAIV consists of two bodies. One impacts the target and forms a crater. The second detonates inside the crater, simulating a subsurface blast without the required velocity change.
- The present computational model simulates NEO fragmentation using subsurface, impacting, and standoff explosions.
- Focus on high-performance computing of these simulations allows us to integrate efficacy simulation into the mission design cycle.

# Hypervelocity Asteroid Intercept Vehicle (HAIV) Concept



# Introduction



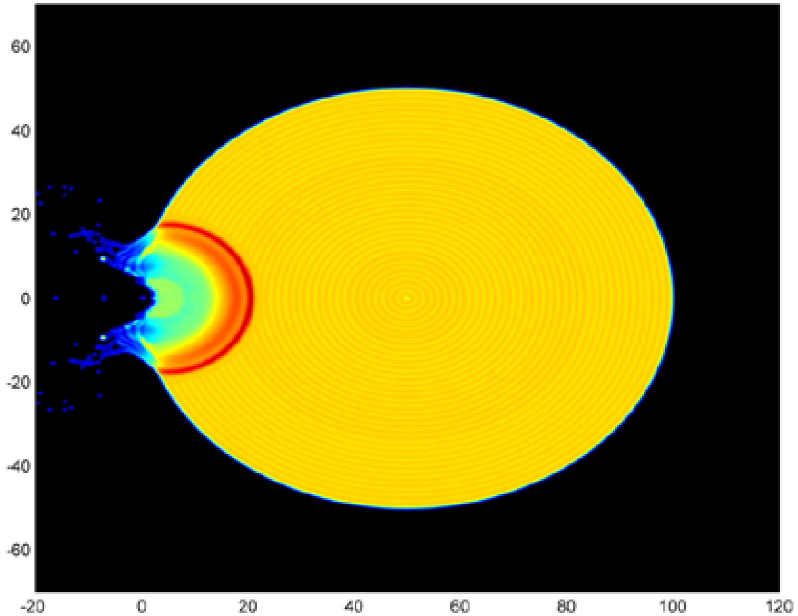
# Spherical Target Model Description

- 100 meter diameter reference targets.
- Source energy equivalent to 100 kT.
- “Rubble-Pile” target with density of 1.91 g/cm^3 (no material strength model)
- Solid granite target with density of 2.6 g/cm^3 (linear elastic-plastic strength model)
- “Mixed” target with granite core and shell of rubble.
- Desired Resolution for largest cells: 0.1 m

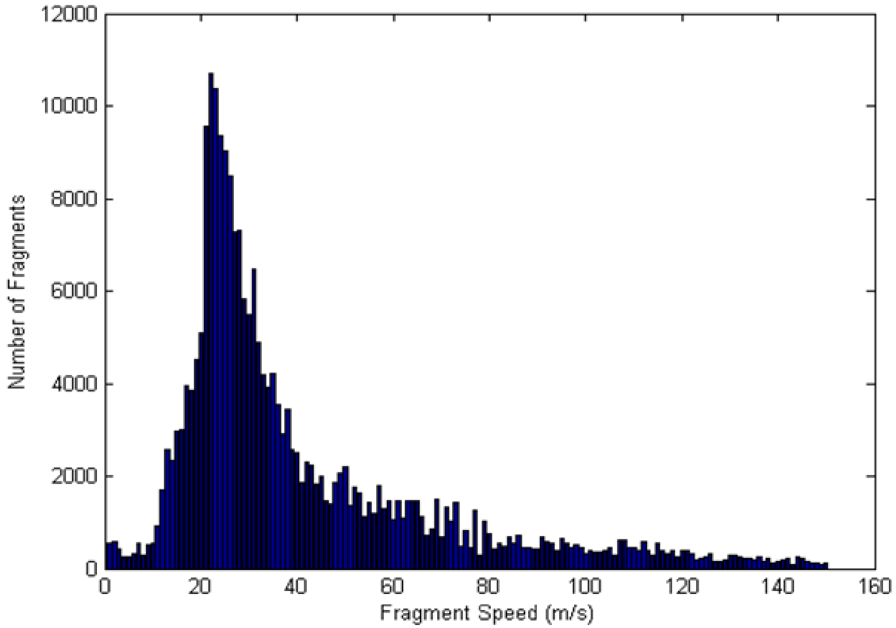
# Energy Source Description

- 5 different disruption methods were tested on the two reference targets.
- A static, “buried” explosive at 5 meter depth.
- Static, surface blast with no relative velocity, explosion surrounded by aluminum projectile casing.
- Dynamic blast at surface with 6.1 km/s velocity.
- Two impactor case, penetrator followed by explosive.
- “Standoff” blast at 10 m height to ablate surface material.

# Fragmentation Model Description

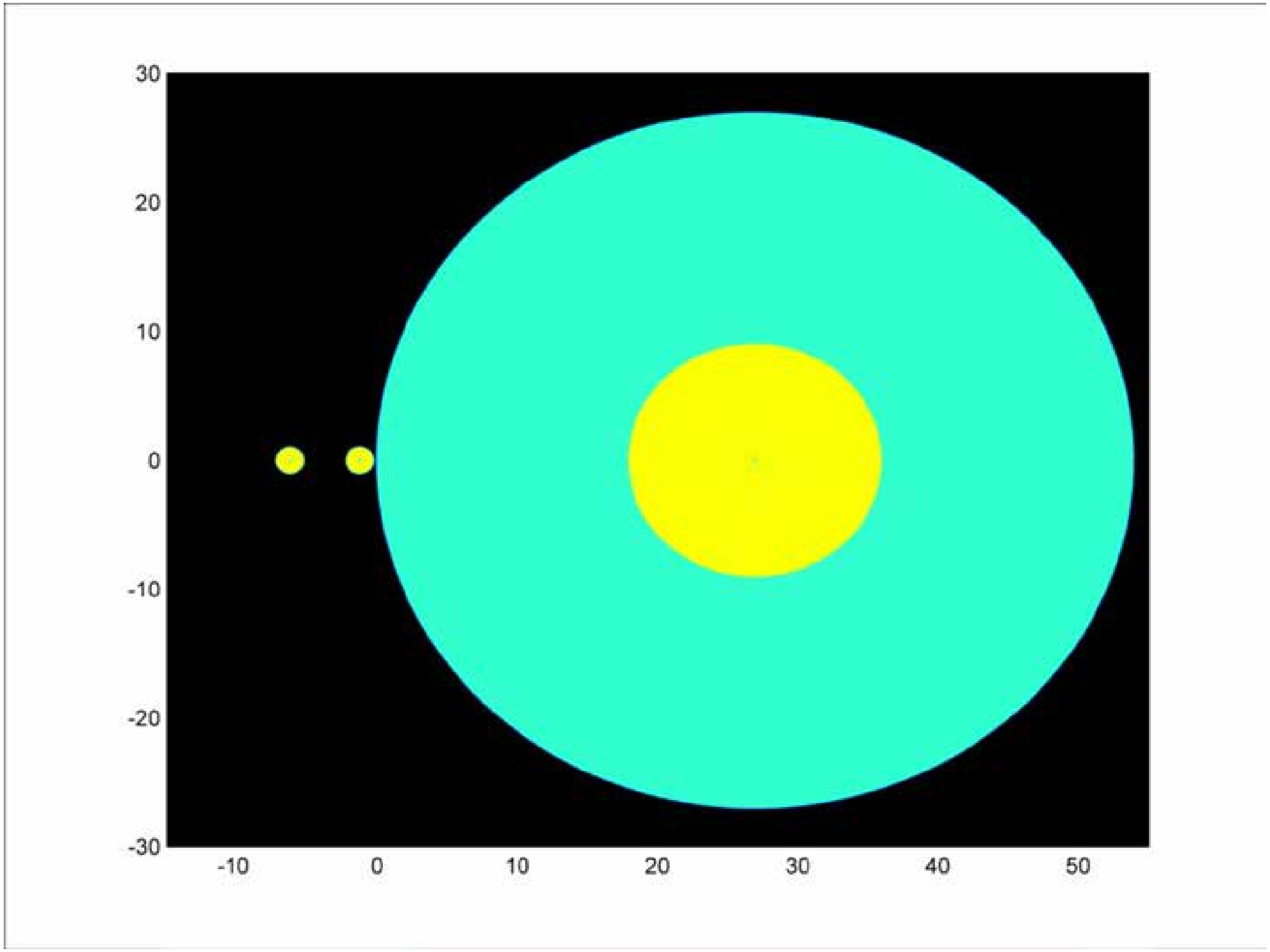



***Subsurface Explosion in Solid Target***




***Resulting Fragment Velocities***

# Fragmentation Model Description



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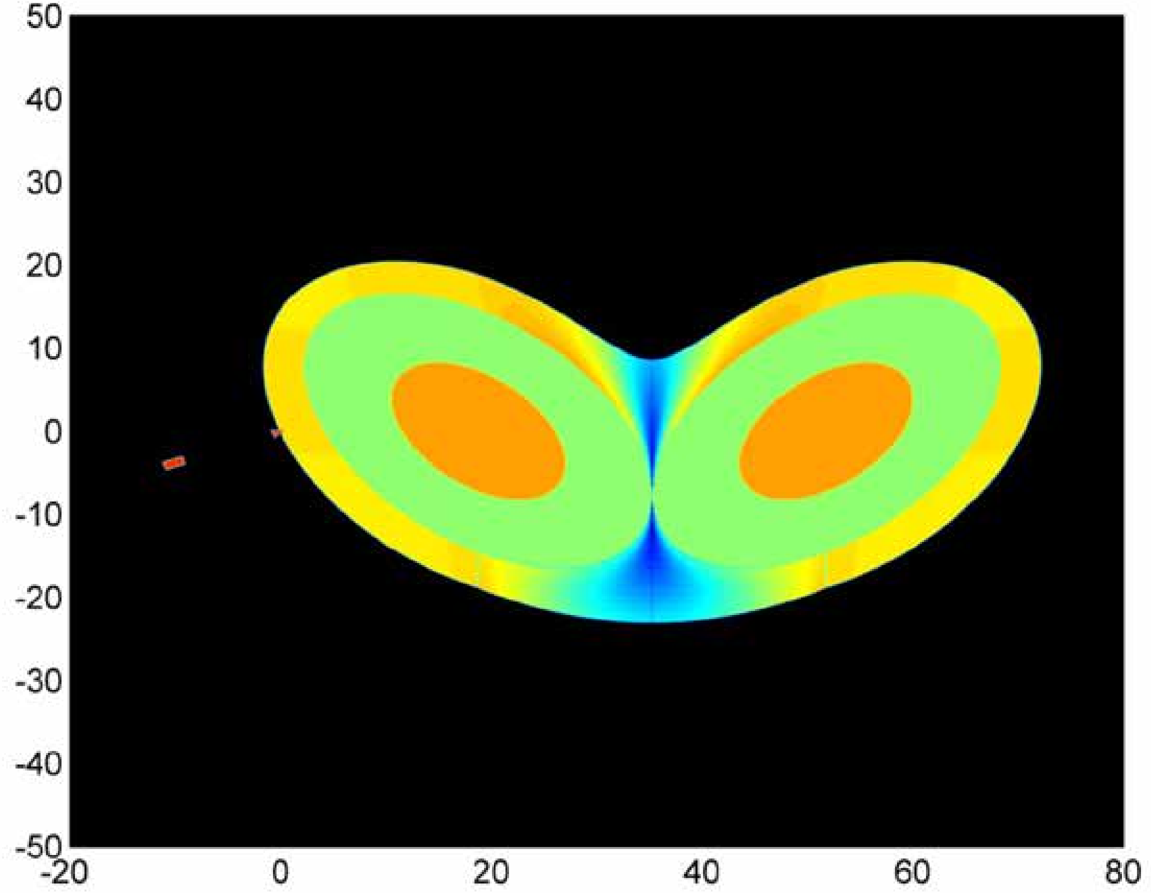

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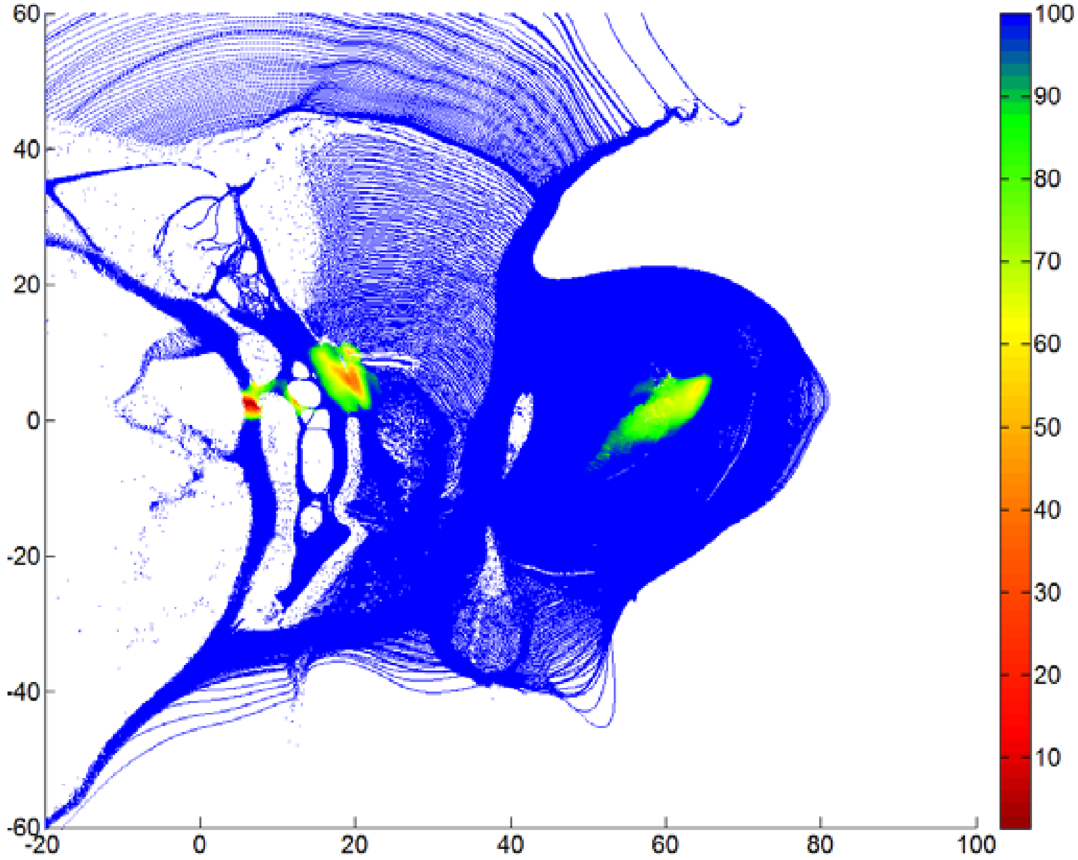
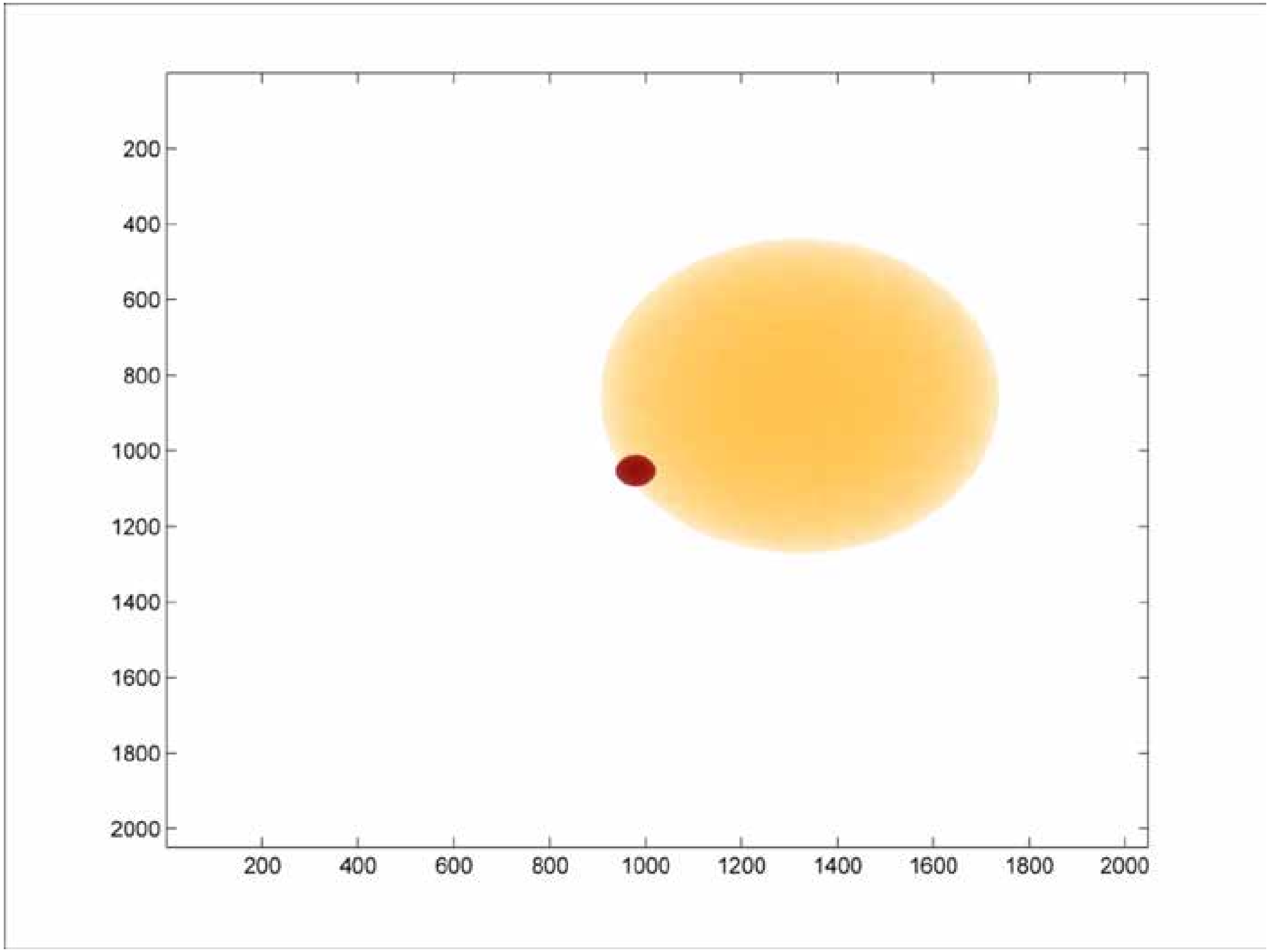
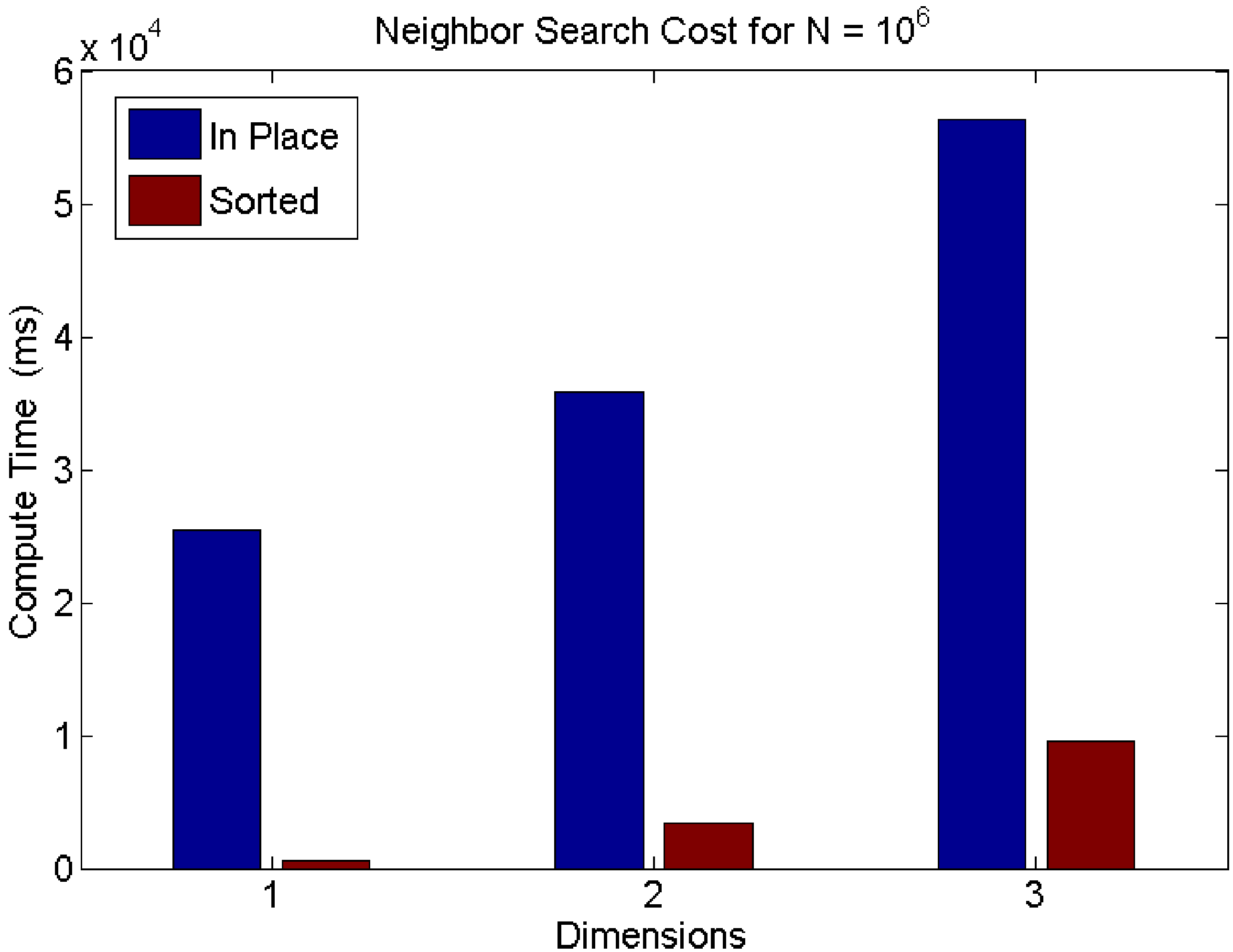



***Slowest Moving Debris***

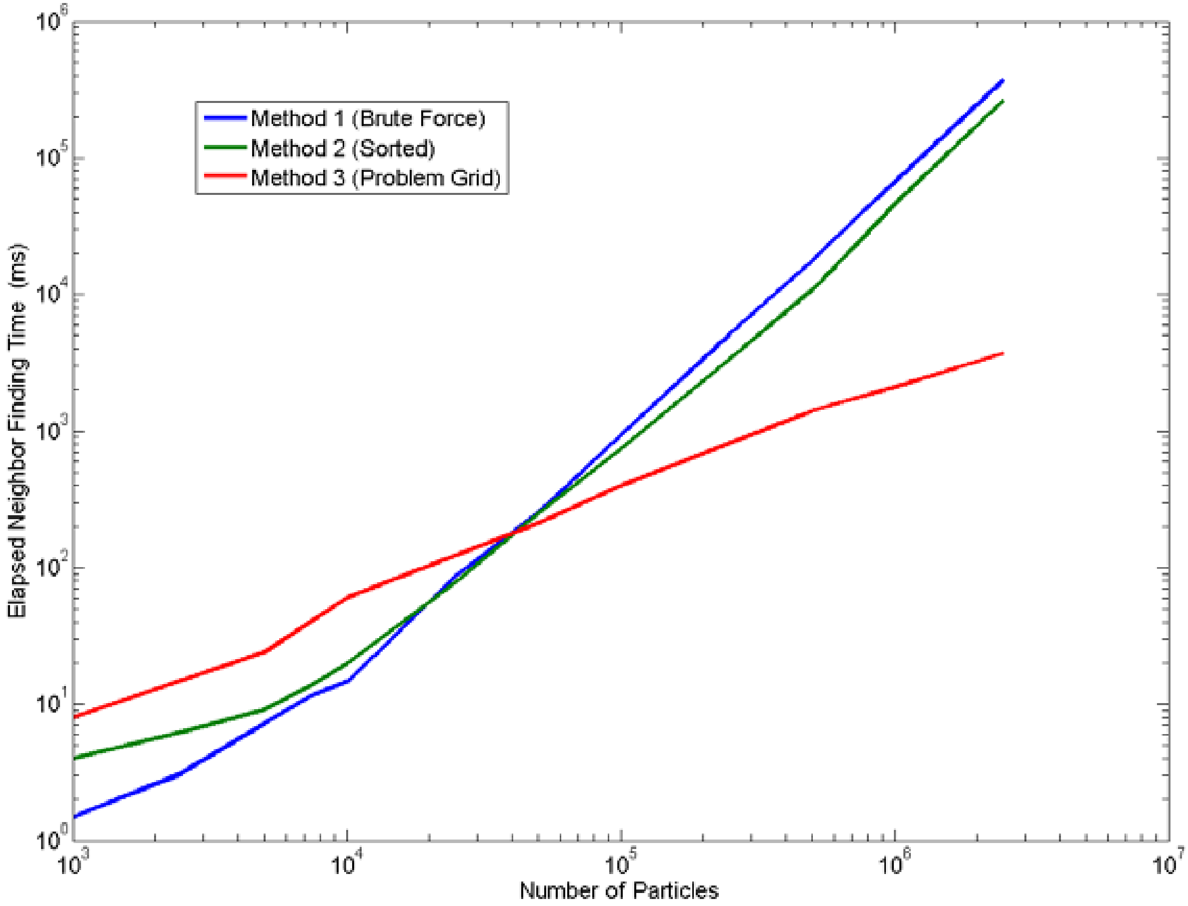
# Fragmentation Model Description



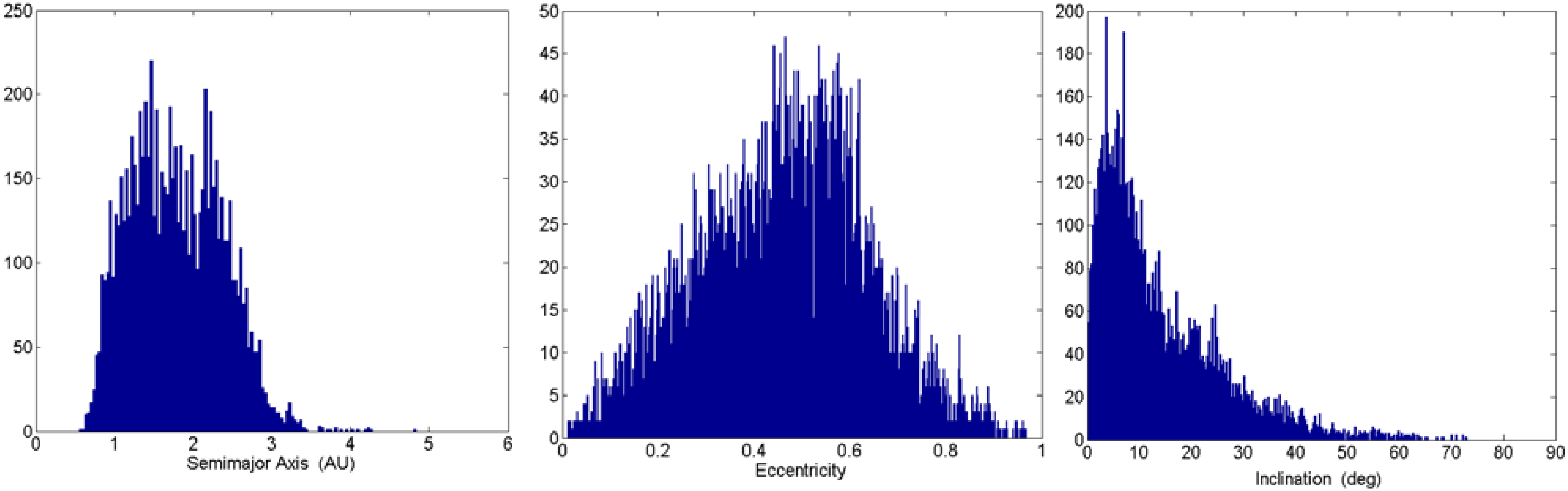
# Neighbor Search



# Neighbor Search (Cont)

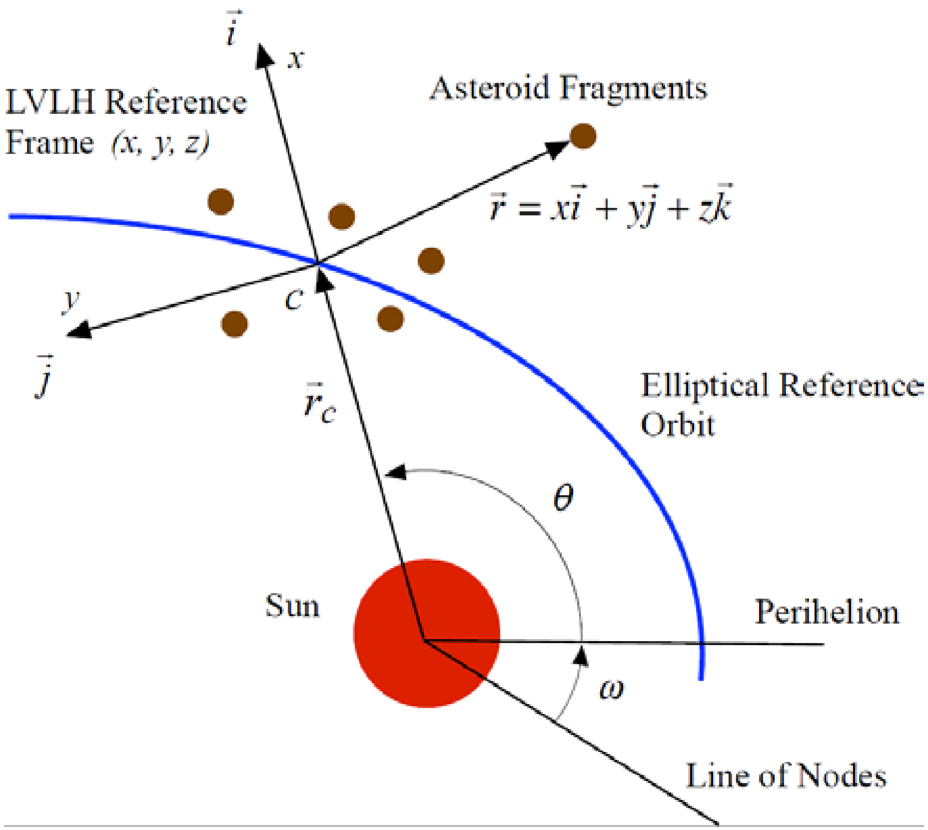


# Virtual Impactor Orbits




***Orbital Parameter Histograms of Observed Earth-Crossing Asteroids***

# Orbital Equations of Motion

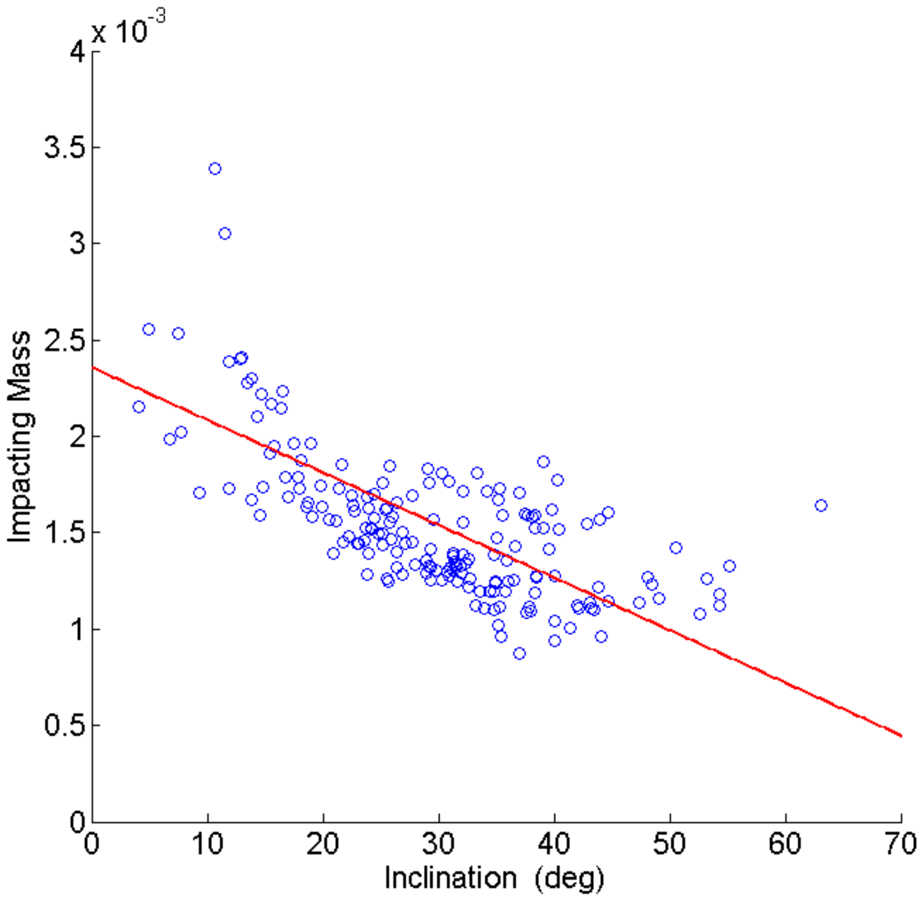



***LVLH Coordinate System for Fragment Dispersion Model***

- **Relative motion form of equations useful for mutual gravitational terms and collision modeling.**
- **Integrator uses LVLH coordinate system (shown).**
- **Simulated deflections occur along radial, transverse, and normal axes. In general, radial is found to be near optimal for 15 day lead time.**

# Orbital Analysis Results

- No strong correlation was found between semimajor axis or eccentricity and impact probability for 15 day lead time.
- Deflection on higher inclination orbits were more effective.



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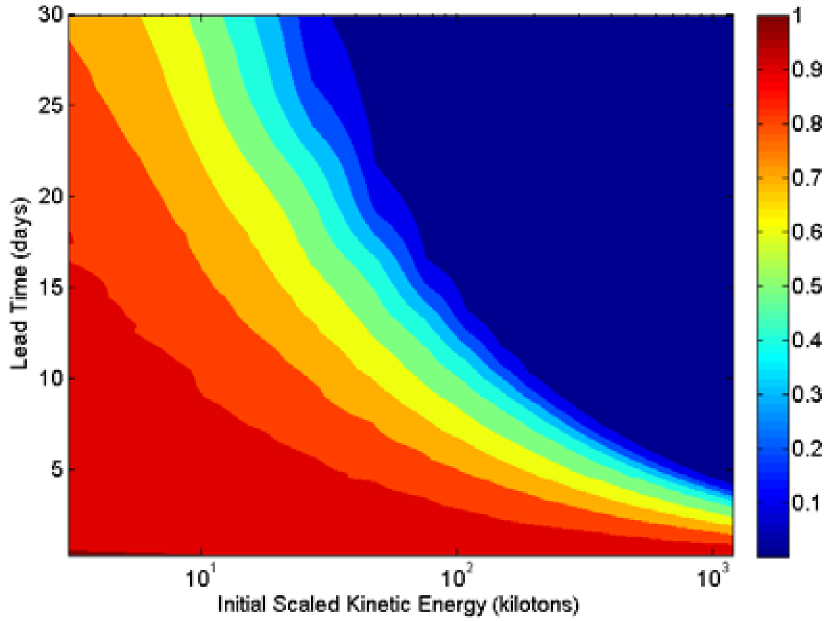


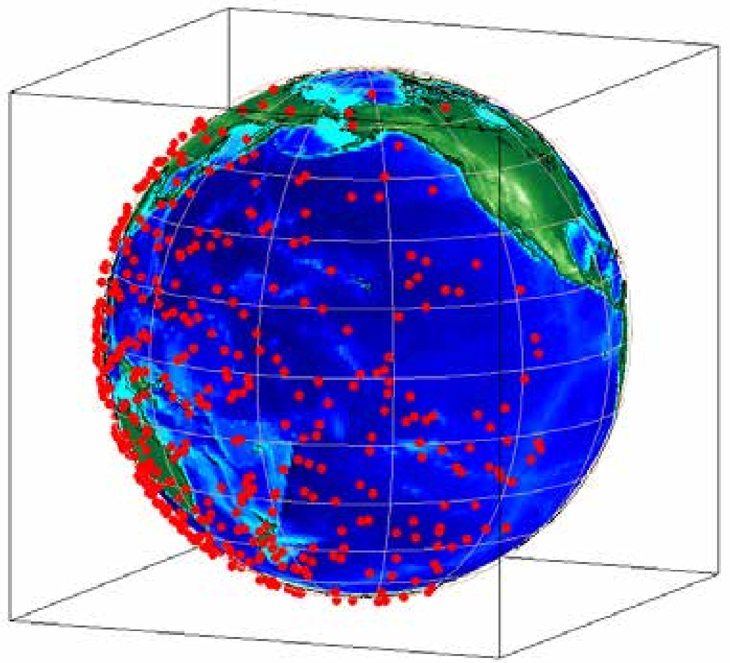

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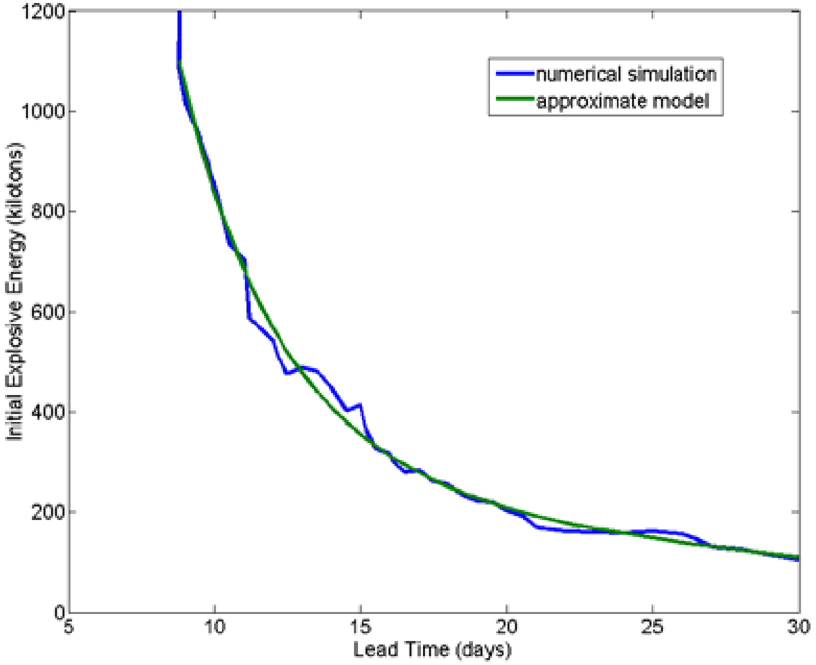
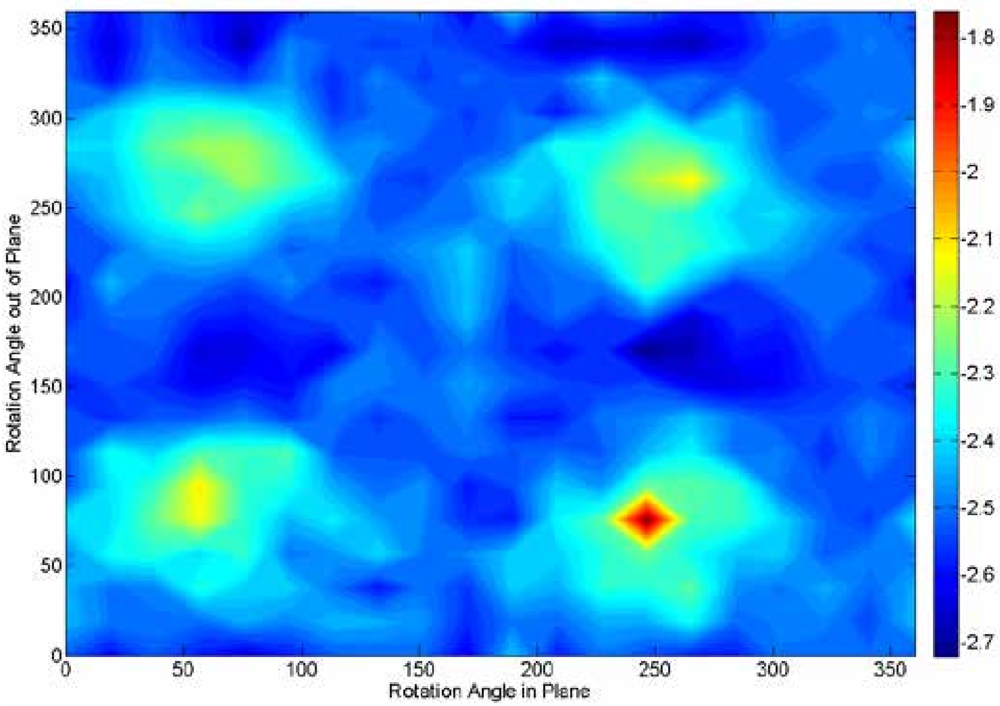
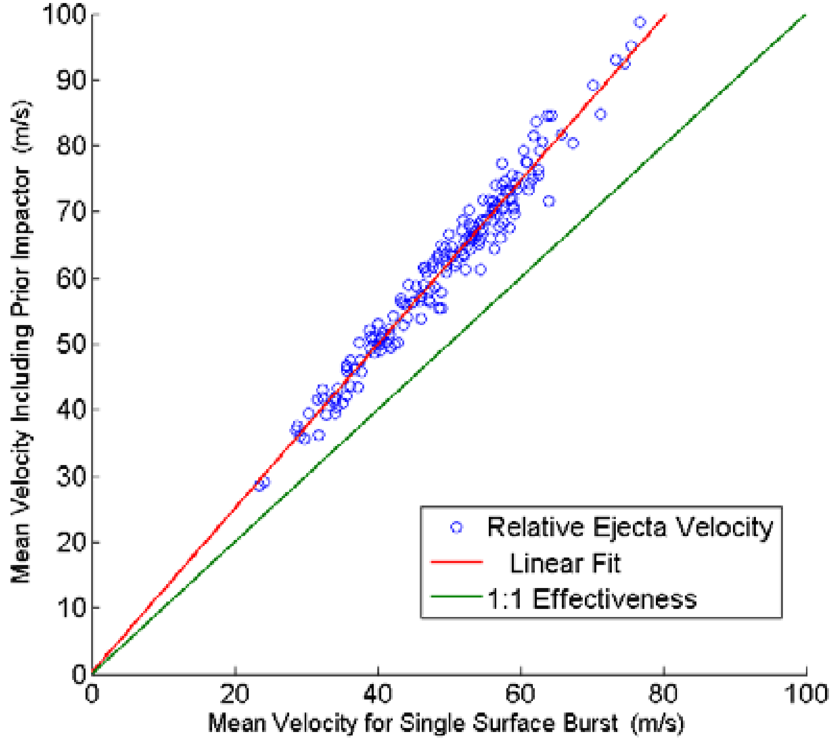


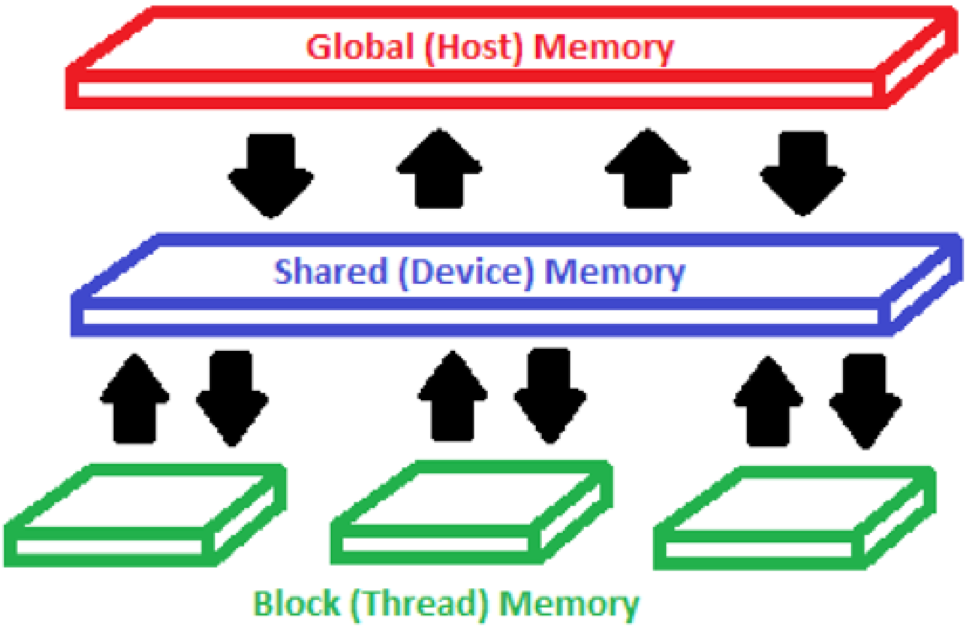



# Orbital Analysis Results

- Two impactor approach is viable from an effectiveness standpoint.
- 25% better dispersion velocities on average than single surface blast.
- Major problems with GNC for this arrangement, particularly with uncertainty.



# Computational Approach

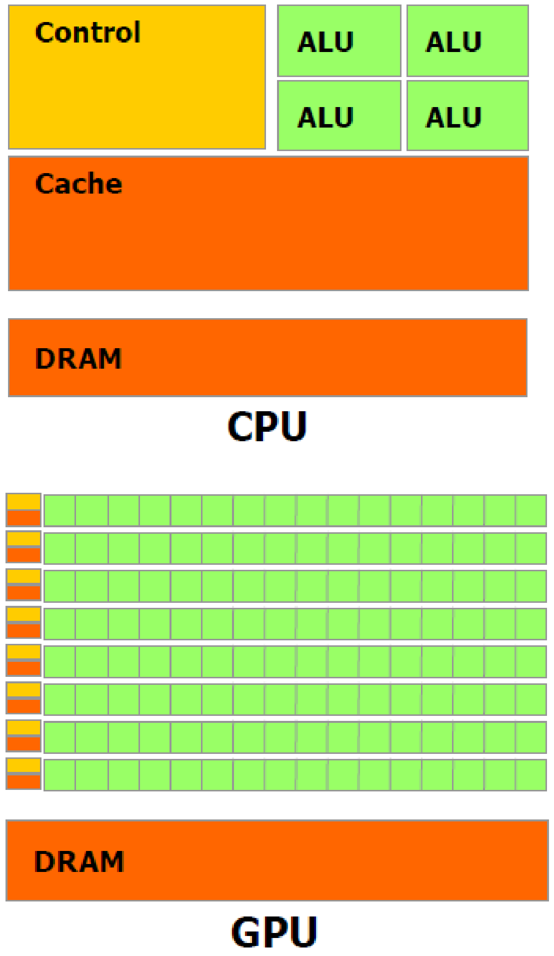



*Qualitative GPU Memory Model*

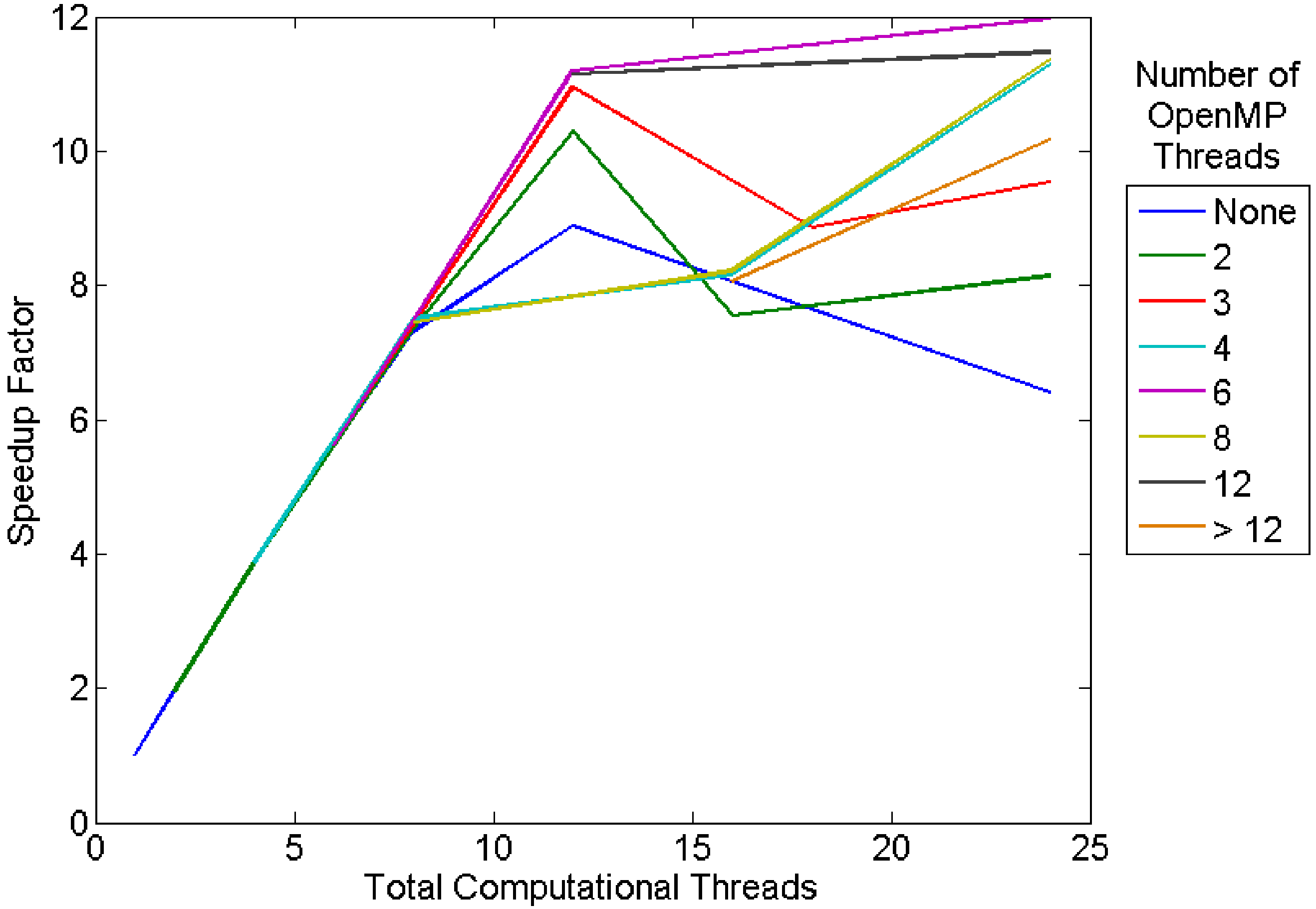
- Evaluating performance on single node of planned GPU computing cluster.
- 3 approaches: MPI, Hybrid with OpenMP, CUDA.
- Identify threading relationship yielding best speedup, and limitations of MPI/GPU implementation.
- Make use of memory footprint optimization to increase available resolution. Current limits ~6M part/node or ~18M part/node at 30% performance.

# Computational Approach (Cont.)

- Huge difference, particularly in memory design.
- Core-level cache, common in CPU design, not present on the GPU.
- More than one thread per core in general, due to different floating point operators.
- Example: 4x improvement fusing access for cores rather than independent memory.

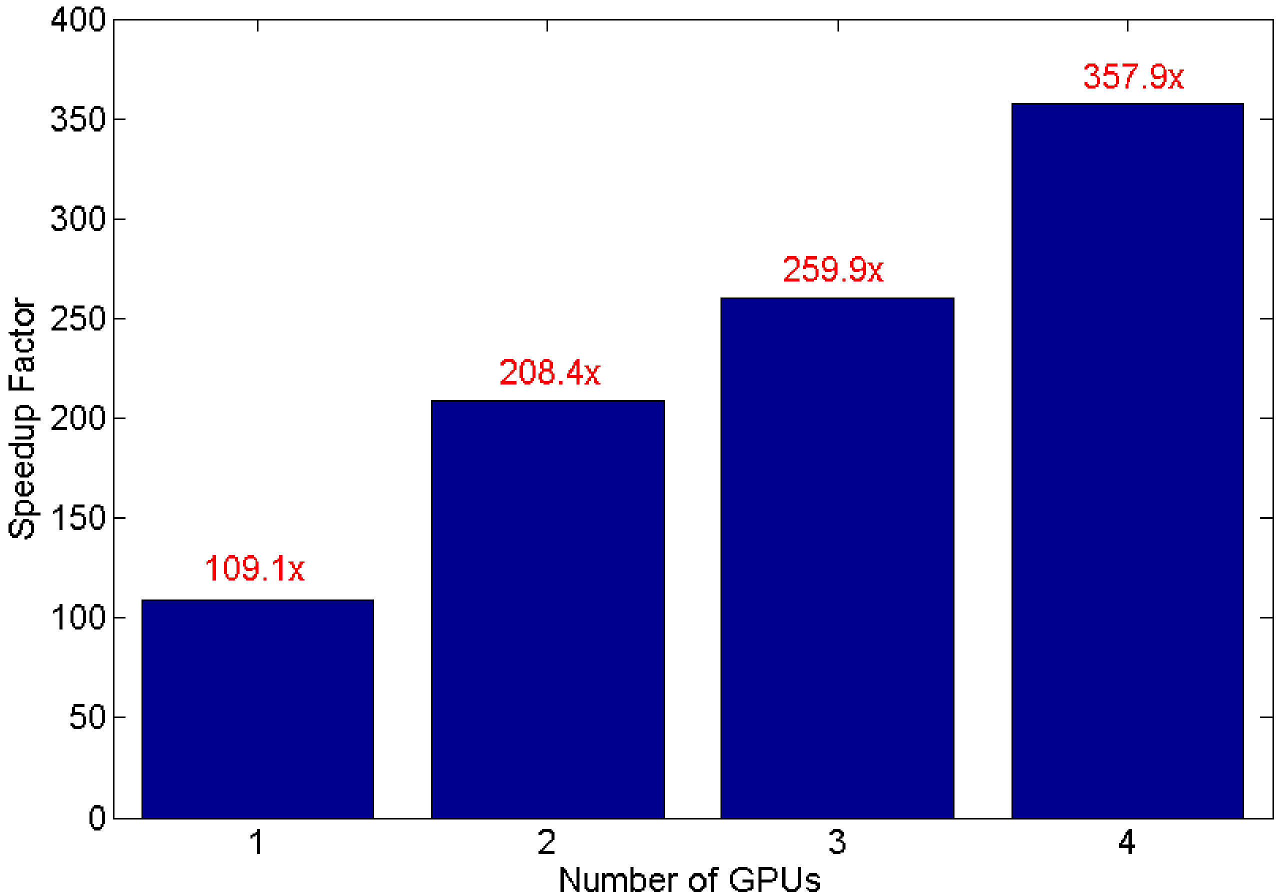


# Results – CPU Performance




***Speedup Factors for Several MPI and Hybrid Schemes***

# Results – Performance (Cont.)




***CUDA Algorithm Speedup Factors (N=3.1M)***

# Conclusions

- An improved model has been developed and tested to simulate hypervelocity impact and explosive disruption.
- SPH presents a viable option for the simulations needed by ADRC.  The present model agrees strongly with work done at LLNL.
- Statistical representation of observed NEO orbits indicates that a 100 m target could be safely disrupted on all orbits with 15 days of lead time.
- Cost effectiveness in relation to comparable top-of-the-line cluster architecture is 15x.
- Additional uses for GPU computing for simulations of interception and characterization have been identified.

# Acknowledgements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- This research work is also supported by NASA Innovative Advanced Concepts Phase I and Phase II grants.
- The author would additionally like to thank the research teams at LLNL, particularly Dr. David Dearborn, Dr. Mike Owen, for collaborating on this work as part of the NASA EPSCoR Fellowship.

# Questions?

- Kaplinger, B.D., Wie, B., and D. Dearborn, "Earth-Impact Modeling and Analysis of a Near-Earth Object Fragmented and Dispersed by Nuclear Subsurface Explosions," published in *The Journal of the Astronautical Sciences.*
- Kaplinger, B.D., Wie, B., and D. Dearborn, "Nuclear Fragmentation/Dispersion Modeling and Simulation of Hazardous Near-Earth Objects," published in *Acta Astronautica.*
- Pitz, A., Kaplinger, B., Vardaxis, G., Winkler, T., and B. Wie, "Conceptual Design of a Hypervelocity Asteroid Intercept Vehicle and Its Flight Validation Mission," to appear in *Acta Astronautica.*
- 19 Related Conference Papers.

# Hardware Table

| System | Machine 1 | Machine 2 | Machine 3 | Machine 4 | Machine 5 |
|---|---|---|---|---|---|
| CPU | 1x Core2 Q6600 | 1x Core2 Q6600 | 1x Xeon X5550 | 2x Xeon E5520 | 2x Xeon X5650 |
| CPU Cores | 4 | 4 | 4 | 8 | 12 |
| CPU TPEAK | 9.6 GFLOPs | 9.6 GFLOPs | 12.8 GFLOPs | 21.36 GFLOPs | 32.04 GFLOPs |
| GPU | 1x 8800GTS | 1x GTX470 | 1x GTX480 | 4x Tesla c1060 | 4x Tesla c2050 |
| GPU Cores | 112 | 448 | 480 | 960 | 1792 |
| GPU TPEAK | 84 GFLOPs | 324 GFLOPs | 385 GFLOPs | 336 GFLOPs | 2060 GFLOPs |
| CUDA CC | CC 1.0 | CC 2.0 | CC 2.0 | CC 1.3 | CC 2.0 |