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OVERVIEW OF A NEW NASA ACTIVITY FOCUSED ON PLANETARY DEFENSE

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Abstract

The National Aeronautics and Space Administration (NASA) has initiated a new Planetary Defense research activity, led by the NASA Ames Research Center. The objective of the effort is to provide tools for reliably assessing the impact damage that Potentially Hazardous Asteroids (PHAs) could inflict on the Earth. This research will support decisions regarding appropriate mitigation action in the event that an impact threat is discovered. The activity includes four interrelated tasks: PHA characterization, physics-based simulations of atmospheric entry/breakup, simulations of surface damage due to airbursts, land impacts, or tsunamis, and an integrated assessment of the overall risks posed by potential PHA strikes. This paper outlines the objectives, research approaches, products, and interrelations of the activity's four tasks, and presents an overview of their current progress and preliminary results. Companion papers in this conference provide additional details of the work in the four task areas.

Introduction

On February 13, 2013, a meteor approximately 20 m in diameter streaked through the early morning sky above Chelyabinsk, Russia at 19 km/s, underwent successive fragmentations and airbursts, and deposited meteorites over a wide area along its flight path. This highly publicized and well-documented [1-3] meteor strike and has stimulated renewed scientific interest in asteroids, their potential impact threats, and what should be done to protect the planet from those threats.

Many prior research efforts have studied meteor flight, including Baldwin and Sheaffer's [4] pioneering research related to re-entry spacecraft design [5], simplified descriptions of entry and fragmentation using adjustable parameters tuned to observations [6], and hydrocode simulations that reconstruct bolide events by introducing energy deposition along the trajectory [2]. Advancements in computational tools and infrastructure, however, are now enabling new techniques to be developed and applied to asteroid impact analyses and risk assessments.

On October 1, 2014, the National Aeronautics and Space Administration (NASA) initiated a new Planetary Defense research activity to develop tools for reliably assessing the impact damage that Potentially Hazardous Asteroids (PHAs) could inflict on the Earth. The goal is to consider realistic PHA test cases and simulate their entry, breakup, and surface damage with sufficient fidelity to produce reliable risk assessments with quantifiable uncertainties. Results will be validated against observations and ground testing, using methods similar to those employed by the re-entry spacecraft community. The research activity involves four main task elements: (1) PHA characterization and test case development, (2) physics-based simulations of entry and breakup, (3) simulations of impact scenarios to determine damage arising from land or water strikes, and (4) integrated risk assessment of the overall impact threat. The risk assessment results will ultimately be formulated into Predicted Impact Assessment Tools that will support decisions on how to implement mitigation action(s) in the event of an impending PHA strike. Figure 1 depicts the four tasks comprising the new activity, along with their research products and interrelationships.

This activity is sponsored by the NASA Near Earth Object (NEO) Program, and is led by a Planetary Defense Integrated Product Team (PD IPT) at NASA Ames Research Center. The NEO Office clearly defined objective questions and tasks for this effort, and granted authority to proceed on October 1, 2014.

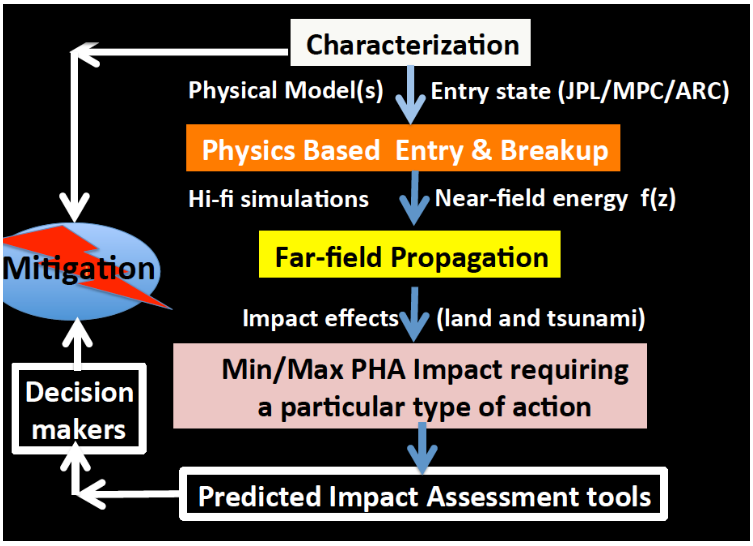

Figure 1. The four tasks, their products, and interrelations.

Task 1: Characterization

The objective of Task 1 is to determine the pre-entry physical characteristics of PHAs and, based on this data, provide relevant test cases to researchers conducting entry/breakup and surface damage simulations within Tasks 2 and 3. The test cases will evolve as more is learned from the simulation studies, and will eventually represent surface damage bounding scenarios for a range of PHA sizes, spectral classes, pre-entry properties, and initial entry variables. Initial entry variables will be based on data from the JPL NEO Program Office (neo.jpl.nasa.gov) and the Minor Planet Center (minorplanetcenter.net). For an actual PHA strike, the initial entry conditions must be known with the highest possible precision because the resulting impact location is a critical determinant in estimating casualties and surface damage.

The technical approach for Task 1 begins with collecting and analyzing results from existing literature on in-situ measurements, remote sensing data, or lab testing of meteorites. Task 1 will conduct new PHA characterization studies, including lab testing of meteorites and remote observations of asteroids. Because these PHA properties are of common interest to researchers conducting mitigation simulations (mass impacts and stand-off nuclear detonations), Task 1 is collaborating with the Lawrence Livermore National Laboratory (LLNL). Task 1 modelers will synthesize the asteroid property data gleaned from literature and new studies to create test cases for entry/breakup and surface damage simulations. The test cases will cover a variety of composition types, from simple, homogeneous “boulders” to heterogeneous “rubble piles” bonded together with cohesive forces ranging from gravity to fused melts and combinations thereof.

A companion paper in this conference presents the new characterization lab at NASA Ames and its associated research [7]. This research will provide light curves for observed meteor entry/breakup events, which will be compared to synthetic light curves produced via high-fidelity simulations from Task 2. Preliminary theoretical work to understand the energy required to disrupt a PHA’s self-gravity is discussed in [8]. In addition, an observational campaign has begun to determine the effects of the sun/object/telescope viewing phase angle on the determination of PHA diameters, albedos, and infrared beaming parameters. Task 1 will also create a website (scheduled to launch by October 1, 2015) focusing on the key PHA properties of importance to the NASA Ames Planetary Defense tasks and LLNL collaboration.

Task 2: Entry and Breakup Simulation

Task 2 conducts physics-based simulations of PHA entry and breakup in order to provide near-field energy deposition data and improved insight into the physics involved. The modeling approach leverages experience in aerothermodynamics and thermal protection system design for re-entry spacecraft [9]. Energy deposition is simulated using high-fidelity physical models of meteor entry and breakup. A “fast” engineering code then captures the high-fidelity simulation results to specify the near-field atmospheric disturbance as a function of altitude or time along the meteor’s trajectory. These data provide the energy deposition inputs for the surface damage simulations performed under Task 3.

Figure 2 shows the workflow of the simulation codes used for Task 2. The lower, red dotted rectangle contains the high-fidelity entry technology codes. The DPLR flow solver [10] has been modified so that it can treat shock layer temperatures and pressures up to those of interest for 20 km/s meteor entries

(~30,000 ^{O}K and 300 bar stagnation conditions). NEQUAIR [11] is used to predict the radiative properties of hot gases and the resulting radiative transport. Synthetic PHA light curves, as seen from ground or aircraft stations, will be predicted using methods pioneered by [12], which compares computed and observed spectral signatures of the Stardust sample return mission. TPS sizing codes, FIAT [13] (1D) and TITAN [14] (2D), will be employed to predict meteor ablation. The meteor's thermo-structural response to the severe entry conditions is simulated by the MARC code [15]. Once confidence is established for simulations of objects flying at 20 km/s, the additional physics needed to consider higher velocities will be added.

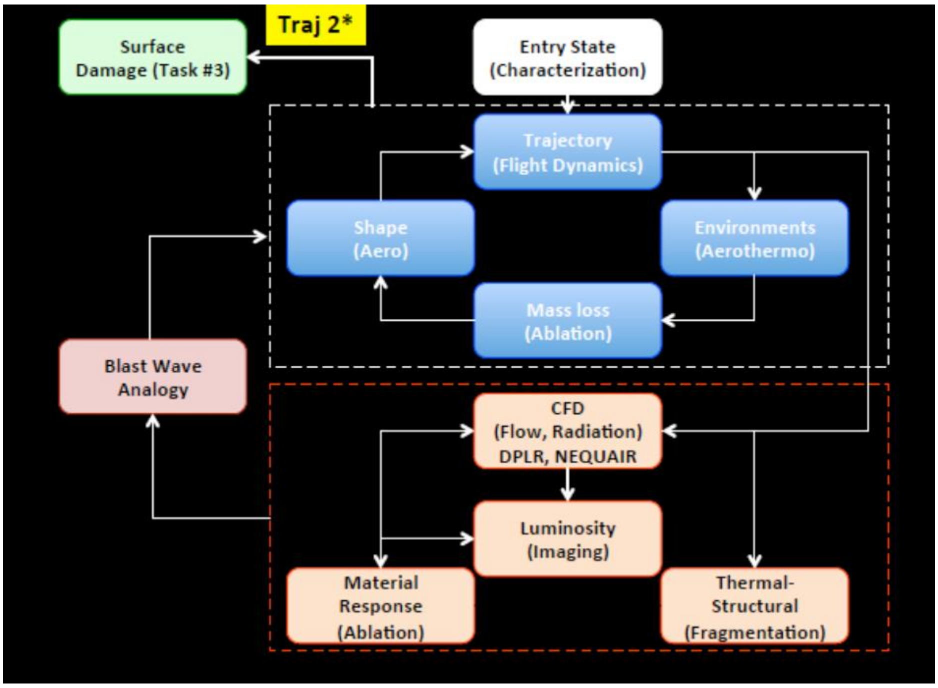

Figure 2. Workflow for Task 2 Codes [9].

The upper dotted rectangle in Figure 2 represents the workflow where the "Fast" engineering code rapidly captures results from the high-fidelity simulations just described. Following the approach used in [16], the high-fidelity simulation results are used to generate a database of energy deposition results for a broad range of possible meteor entry environments. Specific meteor trajectories are then "flown" through the database's matrix of results using the TRAJ 2 code. TRAJ 2 is a modified version of TRAJ [17]. This process ultimately generates energy deposition data that accounts for the aerothermal environment, mass loss due to ablation, airburst energy deposition, and aerodynamics due to shape change along the meteor's trajectory. The result is the near-field energy deposition that is handed off to Task 3.

As a preliminary example of ongoing Task 2 work [9], Figure 3 shows a high-fidelity DPLR solution for an ensemble of three objects of revolution flying in formation at 20 km/s. Ablation is not considered for this case. The figure shows a shock-shock structure in the flow between the objects, which will increase temperatures and pressures (body forces) in those areas and drive the spheres away from the central body. The Task 2 team is using this example as a guide to develop a better understanding of the flows that would occur shortly after meteor fragmentation. The temperatures and concentrations of gas species from such a flow field can be used as input to the NEQUAIR code to predict the complete spectral details of the light emitted from the moving formation, spanning from the vacuum ultra violet to the far infrared. By convolving this predicted spectrum with a panchromatic pass-band and accounting for the distance to an observation point, the Task 2 team can provide a synthetic light curve for comparison to observational data provided by Task 1.

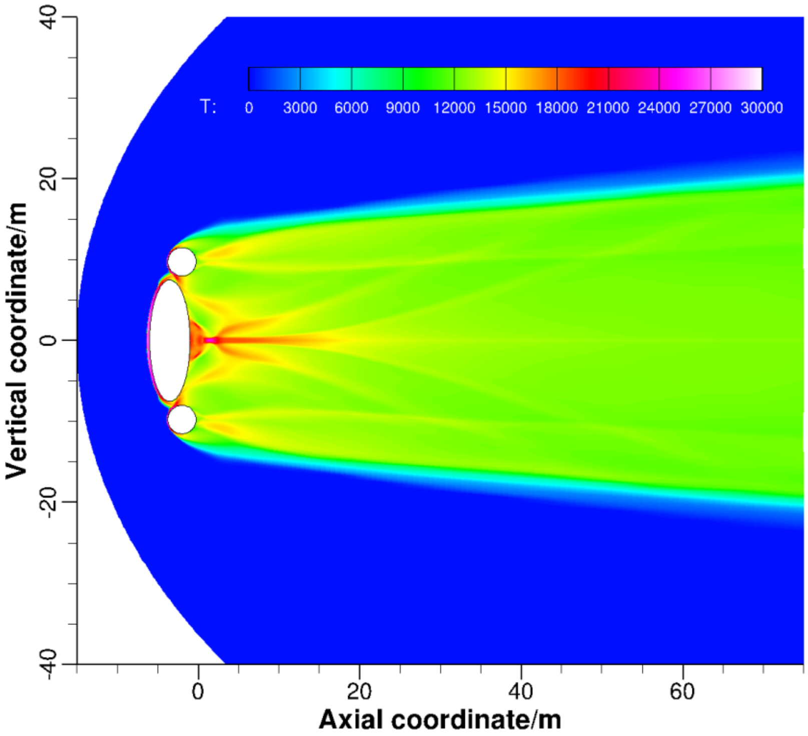

Figure 3. DPLR simulation [9] of multiple bodies (an ellipsoid and two 5 m spheres) flying in formation at 20 km/s (stagnation temperature ~27,000 ^{O}K, pressure 30 bar). Colors represent temperatures (see color bar).

Future simulations will consider entry, fragmentation, and airburst, including ablation and resulting shape change, for a variety of pre-atmospheric PHA test cases being established by Task 1. Modeling the fragmentation of the heterogeneous “rubble pile” cases will be the most challenging aspect of this work.

Task 3: Surface Damage Effects Modeling

Task 3 addresses the surface damage effects of PHA strikes, including propagation of airburst blast waves to the ground, crater-forming impacts, and tsunami generation from ocean airbursts and impacts. Characterization data from Task 1 and energy deposition profiles from Task 2 are used to set up the computational models. Results from the simulations serve as inputs to the Task 4 physics-based impact risk model.

Initial blast propagation simulations have been conducted using NASA’s Cart3D computational fluid dynamics code [18]. Energy deposition curves are used as a basis for adding time-dependent energy to the flow domain. The resulting shock front is then computationally propagated through an exponential atmosphere to produce time-dependent ground overpressure and velocity profiles. Figure 4 shows a sample of preliminary results [19], based on initial energy deposition published in [1]. The upper panel depicts the disturbance at altitude, while the lower one corresponds to the solution at the surface where reflections occur. The ordinate axes display attitude.

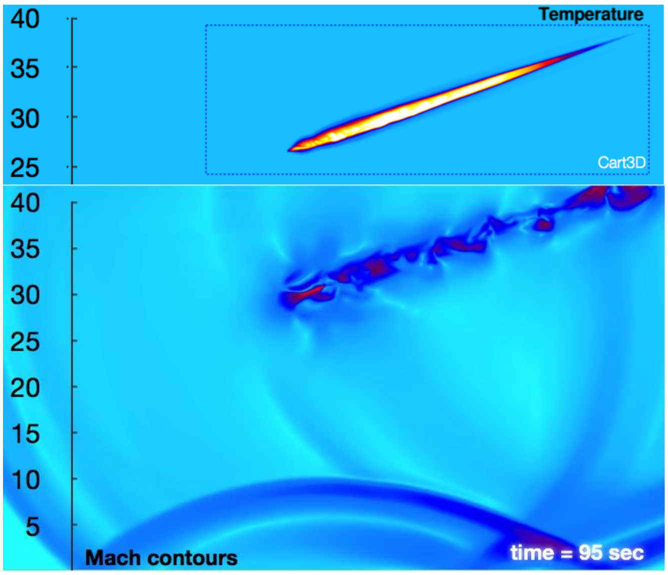

Figure 4. Preliminary Cart3D surface damage simulation, showing the near-field atmospheric disturbance predicted based on energy deposition as a function of altitude adopted from [1] (top) and Mach contours of the far-field disturbance reflecting from the surface (bottom) [19].

For airbursts over water, the unsteady surface disturbances are mapped to the tsunami assessment code, GeoClaw [20]. GeoClaw then propagates the ocean disturbance based on the local bathsymmetry. Currently, the Cart3D and GeoClaw codes have been linked and are being verified. The wave heights along coastlines will be combined with damage thresholds, and this will serve as an additional input to the Task 4 risk model.

Initial models of objects that persist to the surface of the earth have been prototyped using hydrocodes [21, 22]. To date, these models have been restricted to land impacts, but will be extended to model water impacts in the future. Water impact results will be propagated locally using the impact assessment codes, then an interface with GeoClaw will be created so that long-range tsunami propagation can be simulated at low computational cost. Future study of ground impacts will consider the effects of crater, blast, and ejecta levels to be used by the physics-based impact risk model.

Task 4. Physics-Based Impact Risk Modeling

Task 4 combines the results of physical models with impact frequency data to produce an integrated, physics-based impact risk assessment tool [23]. The tool uses a probabilistic Monte Carlo approach to sample from uncertainty distributions of PHA properties—such as density, strength, entry velocity, etc.—for a given size class and generate a fictitious set of potential impact cases. For each statistically sampled impact case, or “realization,” physical models are used to determine the extent of the potential ground damage. The damage zone is then used to calculate casualties, based either on an average world population density or a gridded population dataset combined with a specific selected or sampled impact location [24]. The individual impact realizations are also weighted by the strike frequency to generate estimated casualty rates. The tool is set up to accept a range of physical airburst/impact models, a variety of damage/fatality criteria, and user-supplied uncertainty distributions for key impactor properties.

The primary challenge of performing such a risk assessment is the high levels of uncertainty in the PHA characteristics, orbital mechanics (including impact location and entry angle), and physical models. The risk model can be run to assess the relative sensitivity of casualty estimates to uncertainties in the characterization data. Figure 5 provides an example of sensitivity study results, produced following an analytical casualty modeling approach used in [25]. Results are shown for two PHA sizes (50-m and 157-m diameters). Each data point represents one Monte Carlo realization (i.e., one statistically sampled impact case), with casualties per strike on the vertical axis, densities on the horizontal axis, and data points colored by strength. The results for the 50-m cases show a visible banding of color, which suggests that stronger objects cause more damage. This is intuitive, since the weaker objects tend to break up higher in the atmosphere with insufficient energy to cause significant ground overpressure. The 157-m results, on the other hand, do not show such color-banding, indicating that the strength correlation diminishes for larger PHA sizes.

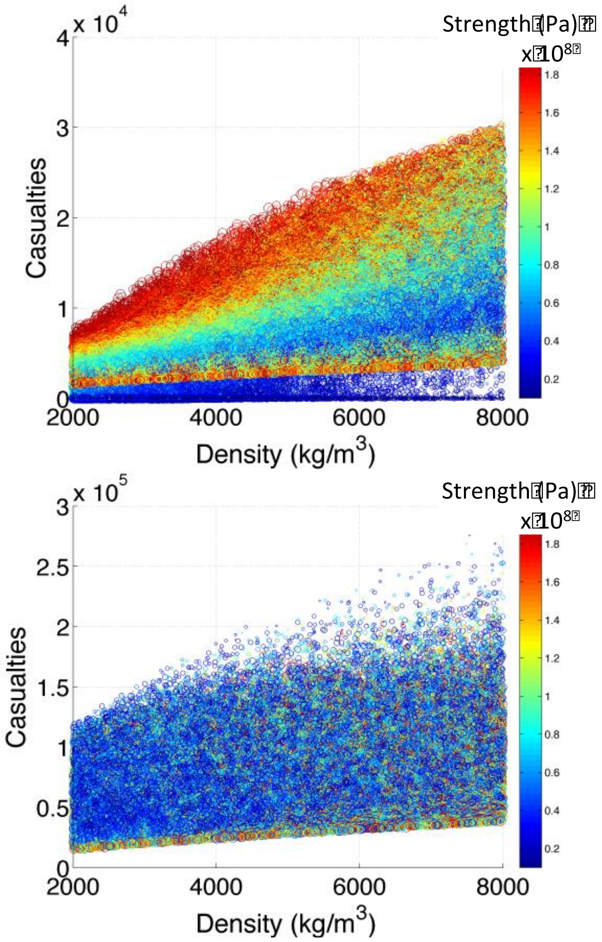

Figure 5. Sensitivity of casualty estimates to density and strength for a 50-m PHA (top) and 157-m PHA (bottom) [23]. Data points are colored by strength, ranging from 0.2 x 10^8 (blue) to 2 x 10^8 (red) Pascals.

Sensitivity plots provide valuable quantitative insight into the relative importance of the uncertainty parameters to casualty estimations. Results such as these will be provided to those working on Tasks 1-3, to help guide model refinement and prioritize characterization efforts. The risk model will be refined and expanded to incorporate higher-fidelity simulation results from Tasks 2 and 3, and PHA characteristics from Tasks 1. Future versions of the model will also consider secondary effects such as crater ejecta, thermal radiation, and tsunami effects. As the research progresses, risk studies will quantify uncertainties and provide bounds on the worst- and best-case scenarios. This information will be used to develop a tool support risk-informed mitigation decisions in the event of an impending PHA strike.

Partnerships

To date, the PD IPT has developed collaborations with two U.S. Department of Energy Laboratories—Sandia National Laboratory and Lawrence Livermore National Laboratory—with the intent of leveraging their unique capabilities in addressing the threat of PHAs. These collaborations are implemented via Non-Reimbursable Space Act Agreements (NRSAAs). The PD IPT will be seeking similar Non-Reimbursable collaborations with other labs in the future.

Multi-Lateral Workshop Near NASA Ames July 7–9, 2015

NASA's Near Earth Object Program is sponsoring a multi-lateral workshop near NASA Ames on July 7–9, 2015. The objective is to gather world experts in the four topical areas described above. Invited speakers will summarize their work in these areas, outline the future steps needed to advance the state-of-the-art in their respective fields, and suggest how international collaborations could help facilitate these advancements. The workshop will be open to those desiring to present posters Students are welcome. The co-leads developing the workshop are Ethiraj Venkatapathy (ethiraj.venkatapathy-1@nasa.gov) and David Morrison (david.morrison@nasa.gov). The website for the workshop is www.planetarydefenseworkshop2015.

Concluding Remarks

As of the drafting of this paper, the PD IPT has been in operation for a period of only five months. It is believed that good progress is being made as evidenced by preliminary results discussed above, and those in companion papers presented in this conference [7, 8, 9 and 19]. Forward work will continue in each of the four tasks described herein. This team effort will eventually meet the PD IPT's overarching objective of providing predictive damage assessment tools that will support mitigation decisions in the event of an impending PHA strike.

Acknowledgements

The PD IPT activity traces back to a suggestion by Jack Boyd and exceptional support by the recently retired Deputy Director of NASA Ames, Lewis Braxton III. Further, the success of our proposed work was made possible by the team that conducted the project planning effort in the summer of 2014, and the full support and advice of Ames management, including the Center Director, Dr. Simon. "Pete" Worden (retired March 2015). The work overviewed above is the result of an extensive team effort. Contributions by the PD IPT's chief scientist, David Morrison, chief technologist, Ethiraj Venkatapathy, and the research of each team member is greatly appreciated. Finally, the IPT would like to express its gratitude for the support and confidence granted to by us by the NASA NEO Program Executive, Lindley Johnson.

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