The Need for a Well-defined Modeling Pipeline for Planetary Defense

Angela M. Stickle
(240) 228-3822
Johns Hopkins University Applied Physics Laboratory
Angela.Stickle@jhuapl.edu

Co-authors and Co-signers:
Brent Barbee (NASA GSFC), Paul Chodas (JPL), R. Terik Daly (JHUAPL), Mallory E. DeCoster (JHUAPL), Jessie Dotson (NASA ARC), Rachel Klima (JHUAPL), Travis Gabriel (Arizona State University), Dawn Graninger (JHUAPL), Maria Gritsevich (MML), Devanshu Jha, Flora Paganelli (Greenbank Observatory), Cathy Plesko (LANL), Emma Rainey (JHUAPL), Megan Bruck Syal (LLNL), Lorien Wheeler (NASA ARC)

1. Executive Summary

A concerted national effort to establish a modeling pipeline, with standardized, well-defined interfaces at every step, would make the USA better equipped to assess and mitigate global Near-Earth Object (NEO) impact threats, and having coherent unified modeling among the US response will facilitate clearer international communication and collaboration (e.g., *Yang et al.*, 2020). The creation of a database to organize and retain modeling and simulation results relevant to a variety of potential threats would enable timely analysis of future hazards, and a deeper understanding of the events that could occur if an impactor hit Earth. Such a pipeline and database framework would provide an invaluable resource to planetary defense and scientific researchers, directly aligns with Goal 2 of the National Near-Earth Object Preparedness Strategy and Action Plan (*NSTC*, 2018), and supports connections between Goal 2 and Goals 1 and 3 of the plan. To achieve this framework, we suggest that resources be allocated within the planetary defense budget for collaboration between modeling teams and developers, including participation in workshops and hackathons. Integrated assessment (across all aspects of the problem) can guide prioritization of research and model development in areas that most affect overall risk mitigation capabilities. Many of the codes and models currently used for planetary defense were initially designed for other applications, and resources are also needed to validate and optimize them for the unique challenges of planetary defense.

2. Motivation

Planetary defense efforts address the global threat posed by NEOs that may have Earth-crossing trajectories. An incoming asteroid threat does not care about national borders and could pose significant global dilemmas. NASA's Planetary Defense Officer, Lindley Johnson, has recognized this, referring to planetary defense as a "team sport". Both national and international collaborations will be imperative to mitigate potential impact scenarios and minimize the resulting damage. The US scientific community must share in the responsibility and establish the needed coordination among research teams to better prepare for a potential impact.

Great strides have been made to better understand the threats facing the Earth from NEO impacts (*Mainzer et al.*, 2020). This includes surveying and cataloging potentially hazardous NEOs, and tracking NEO orbits to assess the level of hazard. Significant scientific research has advanced our understanding of the potential consequences of an impact, the risk posed by the asteroid population (*Stokes et al.*, 2017), and the potential mitigation capabilities necessary to prevent an impact. The Double Asteroid Redirection Test (DART), which will launch in 2021, is the first direct test of asteroid deflection capabilities and represents significant technological and scientific advances for planetary defense. Subsequent planetary defense test missions will build upon the heritage provided by DART.

Given the difficulty of direct testing and paucity of empirical data, computational modeling is critical to better understanding impact threats and developing effective planetary defense capabilities. A variety of computational models and simulations are used to assess potential asteroid impact and mitigation scenarios. They range from fast-running analytic, semi-analytic, and statistical models used to efficiently evaluate a broad range of cases to high-fidelity, multi-physics numerical codes that can take weeks to run on supercomputers. High-fidelity simulations are used to evaluate and predict the expected impact effects for a given impact case, to investigate the complex physical processes in the absence of empirical or experimental data, and to develop and validate faster-running, lower-fidelity analytical models or databases. The lower-fidelity analytical models can subsequently be used to rapidly evaluate a greater number of cases, damage trends, or sensitivities over a larger range of potential asteroid properties or impact characteristics. **Because rapid-response assessments of an impact threat may be needed while the specific properties of the NEO remain largely unknown, continued development of efficient, broadly applicable analytic models and databases is of particular importance in planetary defense.**

The models used for planetary defense research typically include NEO orbit determination, mitigation mission orbital design, statistical characterization of the probable NEO properties, impact and airburst effects, and probabilistic risk assessment. <u>To accurately predict a potential threat, it is vital that information be carried coherently from discovery through each modeling area.</u>

In general, operational planetary defense requires information flow from one model to the next and, ultimately, to decision makers. That process, and the structure of the necessary data products, are currently under development. Though effort has been made to ensure that statistical property models can be used as inputs to hazard models, and orbital models can be used as inputs to mission design models, <u>there is no integrated pipeline that includes all relevant modeling steps</u>. Each model is usually developed in isolation to solve a specific problem with few standardized inputs and outputs, and the specific information that flows between different models is not always well-defined. Further, many of these simulations are computationally expensive, which slows the knowledge transfer process and limits the number of specific cases that can be evaluated when response time is limited or uncertainties are large. This has important implications both for scientific research as well as for the planning and implementation of future planetary defense missions and activities.

2. Modeling Efforts

2.1 The Importance of a Modeling-based Approach for Planetary Defense

Modeling is critical to understanding the level of threat posed by an object in order to determine an appropriate response. A robust modeling chain forms the basis for enabling effective risk-informed response and mitigation decisions. Decision and policy-makers need to understand the potential consequences of an asteroid impact or airburst. Computational modeling is necessary to evaluate the range of potential damage, which remains highly uncertain due the paucity of direct empirical data on large damage-causing impact events, the difficulty of testing complex interacting physics at the extreme entry conditions and size scales relevant to asteroids, the wide potential range in asteroid properties, and the difficulty in obtaining direct measurements of those properties. Despite limited data, the planetary defense modeling community is working to provide information in an actionable format on a rapid timeline for decision makers. **However, in order for that information to be generated, information must be able to flow from one model to the next. This is still a challenge across the wide range of models currently in use**.

Unlike most natural hazards, a NEO impact has the potential to be predicted many years in advance with sufficiently capable NEO survey systems (*Mainzer et al.*, 2020). Furthermore, if detected sufficiently far in advance, Earth impact by a NEO is perhaps the only directly preventable natural disaster. A NEO could be deflected (or disrupted) using a spacecraft designed to alter the NEO's orbit such that it misses the Earth. Potential deflection techniques include "slow-push" techniques such as the gravity tractor, and "fast-push" techniques such as kinetic impactor or nuclear device detonation. Testing deflection methods is costly (flying a spacecraft to an asteroid) or challenging for non-technical reasons (e.g., detonating a nuclear device in space). If the NEO's collision with Earth cannot be prevented, advance warning combined with models of potential risks and impact outcomes can enable civil and emergency response to mitigate the effects.

Robust models address many aspects of NEO characterization, deflection/disruption, and potential Earth impact effects, which allow us to better understand the potential outcomes of either a NEO mitigation attempt or an Earth impact. Fast-running, lower-fidelity models can allow statistical representations of asteroid properties. This is vital due to the large uncertainties in asteroid properties, both for a specific threat scenario and in general knowledge about asteroid population (c.f. *Abell et al.*, 2020). Very few direct measurements of asteroid properties have been made to date. Even the basic size and mass estimates that drive the level of risk and mitigation requirements remain highly uncertain. Spacecraft have visited only a handful of asteroids, and of those, only a couple have observations of boulders of size < 1 m (of similar size to usual spacecraft), porosity of the near-surface, boulder strength, and mass. The lack of specific measurements and data points on asteroid properties increases the importance of modeling for understanding potential hazards posed by asteroid/comet impacts as well as the efficiency of potential mitigation techniques.

It is important that a clear pipeline exists from discovery and characterization models through mitigation, hazard, and risk models (see section 2.2), which provide vital information for decision makers in the case of a real asteroid threat. Ultimately, the goal of these combined modeling efforts is to enable effective mitigation and response decisions to be made throughout an evolving threat assessment process.

2.2. State-of-the-Art Modeling for Planetary Defense

A variety of computational models and simulations are currently used to assess potential asteroid impact scenarios, risks, and mitigation options.

Discovery and orbit risk analysis - When a NEO is discovered, its size is estimated from its brightness, and orbital modeling provides information about its trajectory. If the NEO is found to have an Earth-crossing trajectory, further modeling determines a potential "risk-corridor" on the Earth, namely the path along the Earth's surface where and when the NEO is likely to hit. The accuracy of this modeling is strongly dependent upon the available observations, and the precision of the potential risk corridor can range from a highly uncertain globe-spanning swath to a specific location as the scenario evolves. NASA-developed tools, maintained by the Jet Propulsion Laboratory Center for NEO Studies (CNEOS), are often used to provide the orbit details, impact probability, and risk corridors.

Mission architecture design and trade studies - Information from the NEO orbit models and size estimates feeds directly into tools to calculate requirements for potential deflection mission options. The JPL CNEOS group maintains a deflection tool designed to provide insight into kinetic impactor deflection options and provide a quick reference for mission design and mission size requirements. More rigorous mission design tools (e.g., NASA's MALTO and EMTG) return a feasible mission design that results in deflection of the NEO by some specified distance. With current tools, preliminary mission design results can be generated within a matter of days. Current approaches, however, generally base mission specifications on a single assumed set of properties and deterministic estimated deflection response. Future development should extend this approach to account for key property and mitigation uncertainties by tying mission design tools in with the other elements of the pipeline (particularly property inference, mitigation effects, and risk models) (see also section 3).

NEO physical property estimates - To fully simulate the results of either a deflection mission or an Earth impact, knowledge of the NEOs properties (e.g., size, density, porosity, material strength, etc.) is needed. The NASA Ames Asteroid Threat Assessment Project (ATAP) has developed a data-driven hybrid inference network to generate physical properties of virtual impactors for use in other planetary defense models. Considering the brightness estimates provided by the JPL CNEOS team, as well as other available observations, the network can be used to generate populations of plausible impactors whose distribution of physical sizes and properties are plausible, given the current state of knowledge about the NEO population and the object being considered. Property distributions can be refined based on additional observations, if available. These virtual impactors are fed into probabilistic risk models to evaluate the threat posed, given the full range of uncertainty in NEO properties. Specific, realistic combinations of impactor properties can also then be identified from these distributions and used in mitigation and impact effects models to evaluate specific cases of interest.

Physics-based impact simulations – Several codes, developed and maintained by institutions within academia, NASA, the Department of Energy (DOE), and by international partners, are currently used to simulate asteroid atmospheric entry and Earth impacts effects, such as airburst blast waves, thermal radiation, impact cratering, global circulation modeling, or water wave propagation. Such codes include the efficient computational fluid dynamics (CFD) solver Cart3D (NASA) and shock physics hydrocodes such as ALE3D (DOE, LLNL), CTH (DOE, SNL), GeoClaw, RAGE (DOE, LANL) and SPHERAL++ (DOE, LLNL), iSALE, and SOVA. These codes take different inputs types and formats and use a range of assumptions about material behavior and response to atmospheric entry or Earth impact. The level of interaction of these codes with other elements of the planetary defense modeling pipeline is varied. For example, in atmospheric entry models, burst altitudes or energy deposition profile inputs can be determined by lower-fidelity entry/breakup models or by other high-fidelity hydrocode entry simulations; no standard exists. The same shock physics codes used to predict impact effects on Earth are also used to predict asteroid mitigation via kinetic impact or nuclear detonation, alongside additional codes such as: PAGOSA (DOE, LANL), FLAG (DOE, LANL), ARES (DOE, LLNL). The material response due to impact or nuclear detonation are implemented differently across codes, with differences in inputs, outputs, and assumptions.

Risk assessment models - Finally, probabilistic models are used to evaluate the level of risk posed by an impact scenario. Risk assessments characterize both the severity and likelihood of the potential range of impact consequences, given key uncertainties in the asteroid properties, orbital impact trajectory/location, mitigation outcomes, and impact entry and damage effects. NASA's ATAP has developed a state-of-the-art Probabilistic Asteroid Impact Risk (PAIR) model (*Mathias et al.*, 2017; *Stokes et al.* 2017) that evaluates millions of probabilistically sampled impact cases representing the current knowledge and uncertainties of an impact threat scenario. For each case, fast-running analytic/semi-analytic models are used to estimate extent of ground damage and affected population due impact and airburst effects. The model is also being extended to account for the uncertain effects of potential mitigation missions and evaluate potential remaining risk due to cases that may not be sufficiently deflected or disrupted. This capability is being developed to support risk-informed design and decision processes (section 3). As described, these risk models serve as the common evaluation framework that brings together inputs from all other modeling types described above. Impact scenarios are fed by the NEO property and orbital models, and the fast-running entry, damage, and mitigation models are developed, anchored, refined, and/or constrained based on results from higher-fidelity physics-based impact simulations. **Current fast-running risk models are based on the best analytical models and simulation data presently available, but we lack an effective means of iteratively incorporating new modeling advancements or data as it becomes available from the numerous different codes and modeling groups.**

Model Integration - Because of the importance of modeling in planetary defense, and the sheer number of steps and forms of models required, individual models need to not only be able to feed efficiently from one to the next to assess a particular case, but need to be able to feed into refinement and constraint of probabilistic models and results. **To do this effectively, results/inputs (and associated uncertainties) from each different modeling area must be able to feed into a common evaluation framework to produce a unified set of risk metrics that can be used to compare alternate options and evaluate sensitivities or tradeoffs, with all key uncertainties.** The beginnings of these interfaces and processes are currently being developed through a multi-agency impact modeling group, formed to address Goal 2 of the NEO Action Plan (*NSTC*, 2018).

3. Risk-Informed Mitigation & Response Decisions Require Integrated Modeling Outputs

A critical goal in developing a modeling pipeline is to enable effective risk-informed response decisions throughout an evolving impact threat scenario on operationally relevant time-scales. Risk-informed decision support shifts the assessment process from independently considering the results of specific representative cases, to producing actionable decision metrics that reflect the full scope of potential outcomes when all key factors are accounted for together. In a risk-informed threat response process, evolving observational data and modeling results feed iteratively into a probabilistic risk assessment framework to characterize both the range and likelihoods of potential outcomes and consequences, given the current state of knowledge and all key uncertainties. These risk results can be used to determine whether a potential impactor poses enough risk to warrant mitigation, compare the effectiveness of alternate mitigation options at reducing the risk, evaluate sensitivities of the risk to key uncertainties for the purpose of prioritizing additional high-fidelity modeling or remote observation/in situ reconnaissance efforts that would be most effective in reducing uncertainties and informing the necessary decisions. Currently, the structure to rapidly incorporate shifting knowledge across the wide range of planetary defense models is lacking.

Including and propagating the significant amount of uncertainty and unknowns is one of the fundamental challenges in impact threat assessment, response decisions, and mitigation mission design. Uncertainties exist in observational measurements, asteroid's physical properties, potential impact corridor, and in the modeling used to estimate the potential impact damage or mitigation effects. Some of these uncertainties, such as size range and impact location, can be reduced with further observation or reconnaissance missions, while others may remain largely unconstrained. Critical mitigation decisions may be needed early in the threat process when little is known about the NEO and uncertainties are greatest (i.e., given potentially short impact warning times, launch windows for intercepting transfer orbits, and long lead-times/timeframes and large costs needed to develop space missions).

Given these uncertainties, effective response decisions cannot be made based on limited sets of high-fidelity results for specific cases or assumed nominal properties, but instead must be able to consider the probabilities across the full range of factors and outcomes. Instead of relying on representative point cases, effective response decisions must balance the level of risk (severity and likelihood of consequences) posed by a NEO against the difficulty of the possible mitigation options and their likely effectiveness at reducing the probabilistic risk outcome of the overall scenario. Decisions based on point-cases simply cannot represent the range or likelihood of outcomes and can result in decisions that leave significant remaining risk.

For example probabilistic risk assessments of hypothetical asteroid impact scenarios, such as those conducted for the IAA Planetary Defense Conferences (https://cneos.jpl.nasa.gov/pd/cs/pdc19/), have demonstrated that kinetic impactor deflection mission designs based on assumed asteroid properties can leave a significant amount of potential impact risk due to the large uncertainties in asteroid mass that remain at the time when mission decisions are needed (*Rumpf et al.*, 2020). If the asteroid turns out to be larger than expected, then the mitigation attempt may not change the trajectory sufficiently to miss Earth and may only shift the impact to another location—potentially including higher-population regions or other countries that were not previously at risk. Alternately, the size and other uncertainties also are large enough that attempting to design missions based on worst-case assumptions or complete mitigation success criteria can be unreasonable. Rather than designing missions based on the amount of deflection needed for a single assumed point-case, a risk-informed mission design process is needed to enable mitigation mission criteria to be scoped, compared, and/or optimized based on the degree to which they reduce the impact risk, accounting for all key uncertainties about the NEO's potential size, properties, orbital trajectory, and deflection response.

3.1. Current Gaps in Model Integration Reduce Ability to Enable Risk-Informed Response

Historically, the various models currently used for planetary defense research have been developed in isolation from one another. As such, the ease of using the outputs from one model as inputs for the next one varies greatly. Further, different codes make different assumptions in how they set up and simplify a given problem and this can lead to differences in input parameters or results that currently are not fully understood or mapped out among different research groups. Even models designed to solve the same problem (e.g., different shock physics hydrocodes) often require inputs in different formats, and the output files and types of information obtained from these simulations can vary greatly. The mismatch and lack of standard format and result types can be especially difficult when model outputs are required to inform simulations along the planetary defense timeline. Results produced by a model for isolated studies are often not in a form that can easily be ingested by other types of models. Some work has been done within specific institutions to alleviate these mismatches, but no standard approaches exist across the planetary defense community.

To support the creation of information relevant to planetary defense decision makers, the modeling pipeline needs to include not only interfaces to pass specific results from model to model, but also must enable all modeling areas to refine and constrain the data/models in the probabilistic risk modeling framework. Risk sensitivity assessments should be used to guide model development to refine areas that make the most difference to risk metrics and mitigation decision criteria across the spectrum of models used for planetary defense.

4. Needed Development and Recommendations

There is a need to develop a robust pipeline through the various models used in understanding the risk posed by an incoming NEO, the possible effects on human populations should the NEO strike the Earth, and potential ways to deflect the NEO. Many of these models are computationally expensive and require large supercomputers in order to produce results. Thus, it makes sense to have a database of pre-computed results for a wide variety of representative cases at hand. Such a database enables rapid initial inferences that can be used quickly as interim results while awaiting the more computationally expensive actual results for the given situation. That database can also be used by the scientific community for study purposes and to improve the quality of more rapid analytical models.

4.1 Important developments to ensure effective knowledge transfer

Further developments towards effective knowledge transfer between a modeling pipeline and decision makers in a timely fashion is needed and includes:

- Developing an integrated database or data server to house modeling results for easy incorporation and integration with other models. Such a database has the added benefit of minimizing duplication of effort by multiple researchers. Note that simulation refinement and development of result databases need to be developed in the context of the entire process, and its potential influence on key figures of merit for threat assessment and response decisions.
- Increasing knowledge sharing and creating a clearinghouse for model capabilities and results. Developing model capabilities or results in isolation can expend effort and tie up resources studying factors that may not make a difference to the ultimate decision factors once all the other modeling components and uncertainties come together. Increasing fidelity of one model at one step of the process may have little benefit if it can't feed into the rest of the process. Refining planetary defense models simply for the sake of refinement should be avoided.
- Developing an iterative pipeline process that can extend and refine the capabilities, data, and response techniques that we have on-hand (and ready to work in conjunction with each other), focusing on the areas that make the most difference to decision-critical results, or that are found to be the most limiting or introduce the most uncertainty.
- Standardizing parameters and input/output formats from different model types. Including standard coordinate systems as recommended by the IAU Working Group on Cartographic Coordinates and Rotational Elements (e.g., *Paganelli et al.*, 2020).
- Developing models that allow knowledge refinements provided by higher fidelity simulations or observations to be efficiently ingested into the risk modeling framework to show how they affect the relevant risk/mitigation/success figures of merit. Any pipeline or model connection

needs to be able to ingest more specific, refined inputs or constraints as higher-fidelity results become available or as more specific questions arise for the scenario at hand.

- Determining the uncertainty associated with each step of the planetary defense modeling chain, and evaluating the total uncertainty for hazards.
- Developing a process to tie model inputs to observable NEO parameters that incorporates uncertainties in quantities and reliable estimates for parameters that are not easily observed using current capabilities.

4.2 Recommendations

As is the case in most situations, it is easiest to build such a modeling pipeline process up front and develop individual modeling components in accordance with what is needed to best support the process. In this case, we already have many of the modeling components in place, and now we must develop the pipeline around them; this represents a significantly more challenging problem. Therefore, we recommend that:

- A peer review be undertaken to best advise what models need development and where development will provide the most utility,
- Resources be made available from the planetary defense budget to perform validation studies, including experiments needed for model validation specific to planetary defense,
- Resources be made available from the planetary defense budget for collaboration between modeling teams and code developers from a variety of institutions. This could potentially include topical workshops or hackathons to determine the specifics on code-to-code knowledge transfer and creation of the planetary defense model database. It is important that gaps between codes and institutions have a bridge.
- Resources be made available to create a national database of modeling results relevant to planetary defense.

Ultimately, the goal of these combined/integrated modeling efforts is to enable effective mitigation and response decisions to be made. The result is well worth the investment.

References

Abell, P. *et al.* (2020) Near-Earth Object Characterization Priorities and Considerations for Planetary Defense. Decadal Survey White Paper.

Mainzer, A., *et al.* (2020) The future of planetary defense in the era of advanced surveys: a white paper commissioned by SBAG for the planetary science and astrobiology decadal. Decadal Survey White Paper.

Mathias, D.L., Wheeler, L.F., Dotson J.L. (2017) A probabilistic asteroid impact risk model: assessment of sub-300m impacts. *Icarus* 289, 106–119.

National Science and Technology Council (NSTC) (2018) *National Near-Earth Object Preparedness Strategy and Action Plan*.

Paganelli, F., *et al.* (2020) The need for recommendations in support of planetary bodies cartographic coordinates and rotational elements standards. Decadal Survey White Paper.

Rumpf, C. (2020). Asteroid Impact Risk: The Uncertain Outcome of Deflection Missions.

Stokes, G., *et al.* (2017) Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration.

Yang et al. (2020) Critical Data Identification, Information Communication, and Readily Available Knowledge Base for Effective Asteroid Impact Mitigation. Decadal Survey White Paper.