REPORT ON NEAR-EARTH OBJECT IMPACT THREAT EMERGENCY PROTOCOLS

A Report by the

INTERAGENCY WORKING GROUP ON NEAR-EARTH OBJECT IMPACT THREAT EMERGENCY PROTOCOLS

SUBCOMMITTEE ON SPACE WEATHER, SECURITY, AND HAZARDS

COMMITTEE ON HOMELAND AND NATIONAL SECURITY

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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About the Interagency Working Group on Near-Earth Object Impact Threat Emergency Protocols

The Interagency Working Group (IWG) on Near-Earth Object Impact Threat Emergency Protocols (NITEP) is organized under the Subcommittee for Space Weather, Security, and Hazards, which is part of the NSTC Committee on Homeland and National Security. NITEP seeks to coordinate the activities of Executive departments and agencies to implement select actions within the National Near-Earth Object (NEO) Strategy and Action Plan associated with strengthening NEO impact emergency procedures and action protocols.

About this Document

This document was developed by the NITEP IWG to address coordinated implementation of assigned portions of the National Near-Earth Object Strategy and Action Plan related to strengthening NEO impact emergency procedures and protocols. This document was reviewed by the Subcommittee on Space Weather, Security, and Hazards and the Committee on Homeland and National Security, and was finalized and published by OSTP. This document will be reviewed and updated as appropriate.

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Table of Contents

Abbreviations and Acronyms iii

Introduction 1

Action 5.2: Establish a procedure and timeline for conducting and updating a threat assessment upon detection of a potential NEO impact 2

Action 5.3: Revisit and validate the current notification protocol chain-of-command for NEO threats 4

Action 5.4: Develop protocols for notifying the White House and Congress, State and local governments, the public, foreign governments, and other international organizations regarding NEO threats 6

Action 5.6: Establish a procedure and timeline for conducting a risk/benefit analysis for space-based mitigation mission options following a NEO threat assessment 9

Action 5.7: Develop benchmarks for determining when to recommend NEO reconnaissance, deflection, and disruption missions 11

Conclusion 16

Appendix A: Example impact notification template 17

Appendix B: Example asteroid impact FAQ 22

Appendix C: Risk-informed mitigation process flow 25

Appendix D: Comparing costs of deploying space missions with costs of natural disasters 28

Abbreviations and Acronyms

ATAP	Asteroid Threat Assessment Project
ATP	authority to proceed
CNEOS	Center for Near-Earth Object Studies
COPUOS	Committee on the Peaceful Uses of Outer Space
DART	Double Asteroid Redirection Test
DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
EOP	Executive Office of the President
FAQ	frequently asked questions
FEMA	Federal Emergency Management Agency
IAWN	International Asteroid Warning Network
IWG	interagency working group
JPL	Jet Propulsion Laboratory
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEO	near-Earth object
NITEP	Near-Earth Object Impact Threat Emergency Protocols
NSC	National Security Council
OSTP	Office of Science and Technology Policy
PAIR	Probabilistic Asteroid Impact Risk
PDCO	Planetary Defense Coordination Office
PHA	Potentially Hazardous Asteroid
PHO	Potentially Hazardous Object
SIMPLEx	Small Innovative Missions for Planetary Exploration
SMPAG	Space Missions Planning Advisory Group
State	Department of State
UN	United Nations

Introduction

The Near-Earth Object Impact Threat Emergency Protocols (NITEP) Interagency Working Group (IWG) was convened by the National Science and Technology Council's (NSTC) Subcommittee on Space Weather, Security and Hazards (SWSH) to initiate key policy development called for in the 2018 *National Near-Earth Object Preparedness Strategy and Action Plan*.[1] The Subcommittee requested tangible products that will meet the strategic objectives outlined in the Action Plan with the aim of strengthening the ability of the Nation to effectively respond when an asteroid or comet is discovered that may be on an impact trajectory with Earth.

The NITEP IWG coordinated implementation of five select actions within the *National Near-Earth Object (NEO) Strategy and Action Plan* associated with Goal 5: Strengthen and Routinely Exercise NEO Impact Emergency Procedures and Action Protocols:

- Action 5.2. Establish a procedure and timeline for conducting and updating a threat assessment upon detection of a potential NEO impact.
- Action 5.3. Revisit and validate the current notification protocol chain-of-command for NEO threats.
- Action 5.4. Develop protocols for notifying the White House and Congress, State and local governments, the public, foreign governments, and other international organizations regarding NEO threats.
- Action 5.6. Establish a procedure and timeline for conducting a risk/benefit analysis for space-based mitigation mission options following a NEO threat assessment.
- Action 5.7. Develop benchmarks for determining when to recommend NEO reconnaissance, deflection, and disruption missions.

The IWG included representation from relevant departments, agencies, and components across the Federal Government, and began its work in September 2019. This document summarizes the implementation of these objectives, and identifies recommendations for continued progress in strengthening NEO impact emergency procedures and action protocols.

[1] National Science and Technology Council Interagency Working Group for Detecting and Mitigating the Impact of Earth-bound and Near-Earth Objects, *National Near-Earth Object Preparedness Strategy and Action Plan*, June 2018. https://www.whitehouse.gov/wp-content/uploads/2018/06/National-Near-Earth-Object-Preparedness-Strategy-and-Action-Plan-23-pages-1MB.pdf

Action 5.2: Establish a procedure and timeline for conducting and updating a threat assessment upon detection of a potential NEO impact

Action description: Standardize the threat assessment content to provide suitable inputs for subsequent decisions regarding notification, mitigation, response, and recovery. It should include specified thresholds for time to impact (e.g., hours, days, months, years, decades); probability of impact (e.g., greater than 0.1%, 1%, 10%, 50%); expected level of damage (e.g., local, regional, global); and whether a deflection/disruption mission is feasible for mitigation. This action should culminate in a NEO Preparedness Threat Assessment format and protocol, including key points of contact from relevant agencies, delivered to the Office of Science and Technology Policy (OSTP), the National Aeronautics and Space Administration (NASA), the Department of Homeland Security (DHS)/Federal Emergency Management Agency (FEMA), and other agencies.

Status: Action 5.2 is completed. NASA has a process in place that effectively manages processes to rapidly assess NEO threats (see Figure 1).

Discussion: NASA has a well-exercised procedure in place for calculating orbits and generating hazard warnings for NEOs with a directive to notify the U.S. Government regarding objects that are projected to pass within 36,000 km of Earth. Projected orbits are updated as new data are submitted from observatories worldwide and autonomously calculated. However, at this time, data can only be collected at night and new data collection may be prevented by adverse weather conditions. The calculated orbit is refined over days/weeks/months following detection, and the orbits are continuously refined as long as the object remains in view. Likewise, remote characterization to refine knowledge of the asteroid size and composition are collected from available space- and ground-based assets and used to make the initial assessment of impact effects.

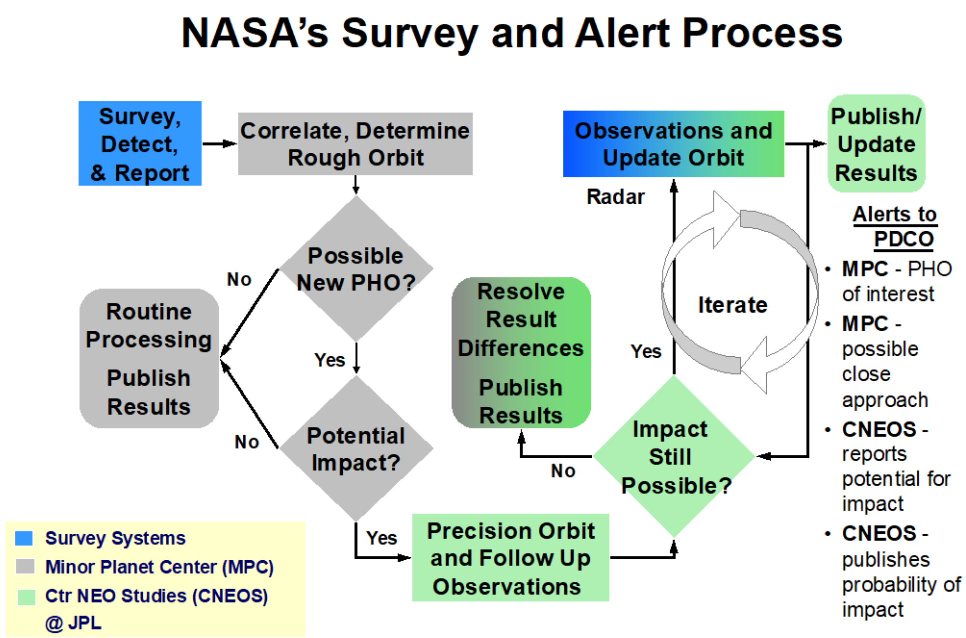

Figure 1. NASA NEO survey and alert process.

The NASA Jet Propulsion Lab's (JPL) Center for Near-Earth Object Studies (CNEOS) computes high-precision orbits for NEOs in support of the NASA Planetary Defense Coordination Office (PDCO). These orbit solutions are used to predict NEO close approaches to Earth, and produce comprehensive assessments of NEO impact probabilities over the next century. Continually updated calculations of orbital parameters, close approaches, impact risks, discovery statistics, and mission designs to possibly human-accessible asteroids are made available on the CNEOS website. CNEOS supports observers through the JPL Horizons high-precision ephemeris computation capability.

The CNEOS is the home of JPL's Sentry impact monitoring system, which performs long-term analyses of possible future orbits of hazardous asteroids, searching for impact possibilities over the next century. Similarly, the CNEOS Scout system monitors the Minor Planet Center (MPC) databases for new potential asteroid discoveries and computes the possible range of future motions even before these objects have been confirmed as discoveries.

The size and composition of the object determines impact effects. Smaller and less dense objects will not reach the Earth's surface but most frequently disintegrate in the atmosphere with an "airburst." Therefore, airburst overpressure assessments are calculated, as are tsunami potential from a water impact, in addition to ground damage impact assessments. The NASA PDCO leads the conduct of these analyses, incorporating expertise from other government departments and agencies expected to be critical for government decision-making. The process for assessing potential impact effects and the characterization requirements to determine these effects are detailed under Action 5.6.

Action 5.3: Revisit and validate the current notification protocol chain-of-command for NEO threats

Action description: Adjust accordingly the protocols for notifying and communicating within the Federal Government regarding NEO threats. This action should culminate in an action flowchart and updated or revalidated memo for NASA PDCO and FEMA.

Status:

- Action 5.3 is completed.
  - NASA's internal process, as defined in NASA Policy Directive 8740.1, is adequate.
  - NASA will review its internal process annually, and will update points of contact as appropriate, to ensure that notification can be made efficiently. This process ensures that essential offices/departments are included, and that notifications are issued via both email and telephone.
  - NASA completed its first annual notification review process in December 2020.
- NITEP recommends that member agencies continue to review, and update as necessary, notification protocols and mechanisms for short-warning scenarios.

Discussion: NASA Policy Directive 8740.1 is intended to provide "a timely and accurate reporting of a very close approach or predicted impact" of a NEO. The Directive covers NASA-internal decision processes intended to ensure prompt, factual notification of an Earth-threatening asteroid, as well as establishing responsibilities for notification external to NASA. When determination is made that a close-approaching asteroid meets the criteria to merit notification, based on collected observations, the current process is for the NASA Administrator to notify, in priority order, designated points of contact at the National Security Council, OSTP, the National Military Command Center, U.S. Strategic Command, U.S. Space Command, the U.S. Department of State (State), DHS (if the impact is determined to cause effects within the territory of the United States), U.S. Northern Command, and U.S. Indo-Pacific Command.

Working with the NITEP IWG, NASA developed a procedure for annually updating the contact list used for these notifications, and completed its first annual review in December, 2020.

These notifications include details about the object, associated uncertainties, and whether observations in the near term will be possible. While the probability of impact is one key variable that may take considerable time to refine, the exact date of the possible impact will be the first known fact. NASA's goal is to find Earth-bound asteroids years in advance of a possible impact to enable possible prevention of a catastrophic impact, and in most cases a notification would be released years in advance. NASA's policy is to release a formal notification only after the early probability assessments have been validated, while recognizing that it would be public knowledge that a potentially impacting asteroid had been detected. The urgency of notification is not reduced by the length of time before impact; decisions would need to be made well in advance to take advantage of a long warning time.

NITEP finds that additional notification protocols and mechanisms might be appropriate when warning time is short. In some short-warning scenarios, rapid coordination may be needed for the first threat messaging. This should include an initial call with Federal emergency management officials in appropriate departments/agencies to coordinate necessary actions within the emergency management community. Once the initial emergency management coordination is completed and a national emergency response has been directed, the Emergency Support Function (ESF)-15 National

Incident Communications Conference Line (NICCL) call is a suitable means to coordinate messaging amongst Federal Government agencies. The NICCL is a standing conference line designated, maintained, and supported by DHS Public Affairs as the primary means for interagency incident communications information sharing during an incident requiring Federal coordination.

Action 5.4: Develop protocols for notifying the White House and Congress, State and local governments, the public, foreign governments, and other international organizations regarding NEO threats

Action description: Adopt or modify existing NASA PDCO and the International Asteroid Warning Network (IAWN) plans for exchange of information among national emergency response stakeholders. Develop appropriate modifications from existing emergency alerts based on specific NEO impact factors. Use tabletop exercises to determine effectiveness with emergency managers at local, state, and national levels. This action should include developing an action flowchart for NASA PDCO. It should also include developing warnings and text for emergency alerts.

Status:

- Action 5.4 is completed.
    - NASA's Policy Directive 8740.1 contains procedures for notifying the Executive Office of the President (EOP), Congress, other Federal agencies, and State and local governments.
    - NITEP worked with NASA and EOP to clarify that EOP approval is not required before NASA can inform other Federal agencies of a NEO impact threat, particularly in scenarios involving short warning times (on the order of hours or less).
    - NITEP developed guidance for relevant agencies based on existing FEMA disaster notification checklists to help determine who/what offices within agencies should be notified following initial notification from NASA, based on the predicted severity of a NEO impact threat.
    - NITEP developed guidance for the content of notifications and communications to the public and Congress.
    - NITEP worked with NASA to develop a standardized threat assessment report format (see Appendix A) that includes: Time to impact; Key facts such as size and composition, if known; Uncertainties regarding size, impact probability, and time required to reduce uncertainties; Expected level of damage based on knowledge to date; Determination of whether deflection or disruption is feasible and desirable; and Key points of contact from relevant agencies.
    - NITEP developed an example asteroid impact Frequently Asked Questions (FAQ) document (see Appendix B) to help inform NEO hazard communications both within and outside the government.
    - NITEP worked with NASA and State to develop a set of NEO impact threat talking points for use in bilateral and multilateral international engagements.

- NITEP and member agencies will continue to improve and exercise notification protocols and policies related to Action 5.4.
    1. NITEP will coordinate development of additional content for notifications and communications to the public and Congress, additional guidance on conditions or thresholds for which particular Congressional committees should be informed, and what information is important to which subcommittees (i.e., what they oversee and how that will be affected by a particular NEO impact). This will be dependent on the situation, but there may be certain conditions or thresholds for which certain other committees may need to be informed.
    2. NITEP will work with NASA and the EOP to review and update, as appropriate, NASA Policy Directive 8740.1 to ensure that notification protocols include all relevant agencies and account for the full range of potential circumstances. In particular, it may be appropriate to add the Department of Energy (DOE) to the notification protocol, and to clarify that EOP

approval is not required before NASA can inform other Federal agencies, particularly in scenarios involving short warning times (on the order of hours or less).

3. NITEP recommends that a national-level exercise, or at a minimum a White House/National Security Council (NSC)-directed Senior Officials Exercise (SOE), focused on an asteroid impact event, be held by the end of calendar year 2025. NASA PDCO, the DHS Exercise and Evaluation Program, and FEMA will work together to schedule and coordinate such an event.

Discussion: NASA's Policy Directive 8740.1 contains procedures for notifying the EOP, Congress, other Federal agencies, and State and local governments. Working with the NITEP IWG, NASA is revising the protocol and contact list, as recommended by NITEP and discussed under Action 5.3. DHS/FEMA has notification procedures in place for spacecraft re-entry that may be a suitable format for asteroid notifications for use by FEMA. Space weather incident warnings may also apply.

Notification protocols should account for the roles and responsibilities of Executive Branch entities with respect to NEO impact threat response. NITEP recommends the following roles and responsibilities for NEO impact threat response:

- The National Security Advisor, through the NSC and in consultation with the Director of OSTP, should provide overall coordination of U.S. response in the event of an actual NEO threat.
- The Director of OSTP should coordinate national policy, planning, and supporting R&D related to NEO response.
- The Administrator of NASA should:
  - Lead capabilities and efforts associated with NEO detection, tracking, cataloguing, and characterization, in coordination with the Secretary of Defense as appropriate; and
  - Lead space-based response planning and execution, in coordination with the Secretary of Defense and the Secretary of Energy as appropriate.
- The Secretary of Defense should:
  - Support capabilities and efforts associated with NEO detection, tracking, and characterization; and
  - Support space-based response to NEO impact threats.
- The Secretary of Homeland Security, through the Administrator of FEMA as appropriate, should lead and coordinate ground-based NEO impact emergency response and recovery.
- The Secretary of State should lead coordination and communication with international partners.
- The Secretary of Energy should support technical assessment of space-based prevention of NEO impacts.

NITEP finds that existing notification protocols mostly account for the roles and responsibilities recommended above. However, NASA should review its Policy Directive 8740.1 and update as necessary to ensure that notification protocols include all relevant agencies and account for the full range of potential circumstances. In particular, it may be appropriate to add DOE to the notification protocol, and to clarify that approval from EOP is not required before NASA can inform other Federal agencies, particularly in scenarios involving short warning times (on the order of hours or less).

Following initial notification from NASA of a NEO impact threat, additional notifications within agencies will be necessary. To facilitate internal agency planning, NITEP developed guidance to help determine who/what offices within agencies should be notified, based on the predicted severity of a NEO impact threat.

NITEP also developed guidance for the content of notifications and communications to the public and Congress. NITEP will coordinate development of additional content for notifications and communications to the public and Congress, to include how Congress should be briefed, which committees or subcommittees should be briefed, and what information is important to which subcommittees (i.e., what they oversee and how that will be affected by a particular NEO impact). This will be highly dependent on the situation, but there may certain conditions or thresholds for which certain other committees may need to be informed.

The information contained in notifications and briefings, as well as which stakeholders would receive such briefings and when, is highly dependent on the specifics of an impact threat. Different variables affect the scope of a given impact threat, and notifications should be tailored to specific threats using flowcharts because different situations require different prioritization in information transmitted to different stakeholders. A draft template for impact notification is included as Appendix A.

To help inform NEO hazard communications both within and outside the government, NITEP developed an example asteroid impact Frequently Asked Questions (FAQ) document (see Appendix B). NITEP recommends this FAQ document for providing watch officers and other staff greater context and basis of understanding, as part of a threat notification. In the coming year, NITEP will coordinate development of additional content for notifications and communications to the public and Congress, and additional guidance on conditions or thresholds for which particular Congressional committees should be informed.

NASA works closely with the Department of State, other Federal agencies, and the private sector to strengthen U.S. leadership in space and raise awareness of specific matters relevant to the broader international space community through bilateral and multilateral discussions with other spacefaring nations, and through U.S. participation in various organizations, such as the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS). The Department of State and NASA have developed a priority list of other nations to engage, with a goal of improving global awareness of NEO hazards, and to encourage broader international participation in IAWN and the Space Missions Planning Advisory Group (SMPAG).

NASA provided to the Department of State a list of nations with whom improved communication or participation would be desirable. IWG members are developing strategies for reaching out to these nations using existing mechanisms. Exercises and workshops have been successful means to articulate communication requirements while building greater awareness of the NEO hazard. NASA and FEMA have conducted four exercises to date to familiarize FEMA officials with the hazard and to improve NASA's ability to communicate information. Continued impact scenario planning events to familiarize staff and improve communications should be conducted at regular intervals. In particular, NITEP recommends that a national-level exercise, or at a minimum a White House/NSC-directed Senior Officials Exercise (SOE), focused on an asteroid impact event, be held by the end of calendar year 2025. NASA PDCO, the DHS Exercise and Evaluation Program, and FEMA will work together to schedule and coordinate such an event.

Action 5.6: Establish a procedure and timeline for conducting a risk/benefit analysis for space-based mitigation mission options following a NEO threat assessment

Action description: When a threat assessment concludes that a NEO poses a real impact threat and that space-based mitigation is feasible, that assessment should initiate a process to develop recommendations for the President regarding space-based reconnaissance and mitigation missions. This process includes an analysis of mitigation alternatives to examine the risks, benefits, and uncertainties associated with various approaches, leading to recommendations on how to proceed. Flowcharts will incorporate decision thresholds based on time to impact, probability of impact, expected level of damage, and impact location.

Status:

- Action 5.6 is completed. The Risk-informed Mitigation Process Flow developed by the Modeling Working Group satisfies the requirement to establish a procedure and timeline for conducting a risk/benefit analysis for space-based mitigation mission options following a NEO threat assessment.
- NITEP and member agencies will continue to improve capabilities and processes related to Action 5.6.
  1. The Modeling Working Group will continue to refine the models and timelines needed for required data products and other inputs needed at each stage of the assessment and recommendation process.
  2. NITEP will work with DHS/FEMA, the United States Space Command Office of the Chief Scientist, the Cybersecurity and Infrastructure Security Agency's (CISA) National Risk Management Center, and the Defense Threat Reduction Agency (DTRA) to identify experts in infrastructure risk assessment, airburst modeling, high-energy explosive devices, and disaster effects mapping to directly participate in the asteroid-impact Modeling Working Group (MWG).

Discussion: The PDCO, in working to complete the actions under Goal 2 of the Action Plan, which focuses on coordinating disparate resources (human and technical) to enable rapid analysis and characterization of an asteroid impact hazard, chartered an asteroid-impact Modeling Working Group. The MWG held its first asteroid impact exercise meeting on November 18–19, 2019, at NASA Ames Research Center, and a follow-on meeting was held February 28–29, 2020, at Lawrence Livermore National Laboratory. These exercises serve to iteratively test the application of the current modeling and simulation tools that would be used to assess potential asteroid impact threats and to establish assessment processes and data pipelines among the multi-agency modeling groups, and to identify potential capability improvements.

Participants included risk assessment, hazard simulation, and asteroid characterization teams from the NASA Ames Asteroid Threat Assessment Project (ATAP); mitigation and impact modelers from the National Nuclear Security Administration (NNSA), Lawrence Livermore National Laboratory, and Los Alamos National Laboratory; orbital modelers from the JPL CNEOS; and mission designers from NASA Goddard Spaceflight center. Representatives from the Department of Defense (DoD) and the U.S. Geological Survey also attended these meetings.

NASA's ATAP has developed a state-of-the-art Probabilistic Asteroid Impact Risk (PAIR) model for evaluating the potential consequences of asteroids striking Earth. The PAIR model combines fastrunning physics-based models of asteroid entry and damage along with probabilistic distributions of asteroid properties in a Monte Carlo simulation framework to estimate the range and relative likelihoods of potential impact damage. The PAIR model starts by sampling uncertainty distributions of the potential asteroid properties and entry parameters to generate millions of specific impact cases. For each case, the atmospheric entry and breakup is modeled using the Fragment-Cloud Model (FCM) approach, and analytic hazard models are used to estimate the extent of ground damage and affected population due to blast overpressure, thermal radiation, tsunami inundation, and/or global climatic effects for each impact case. The PAIR model is envisioned as a critical resource for conducting risk/benefit analyses to inform decisions.

The PAIR model has also recently been extended to incorporate the uncertain deflection effects from mitigation missions and evaluate the remaining level of risk posed by the cases that may not be fully deflected off the Earth. This capability is being developed to support risk-informed design and decision processes, in which mitigation mission criteria can be scoped, compared, or optimized based on the degree to which they reduce the impact risk, when all key uncertainties about the object's potential size and properties, orbital trajectory, and deflection response are accounted for. ATAP has also developed a prototype module that searches FEMA's HAZUS database to determine the infrastructure potentially at-risk within PAIR damage regions, including counts of different structural types and identification of specific points of interest, such as nuclear or electric facilities.

To support effective mitigation response decisions, Modeling Working Group teams and mission design groups developed a risk-informed mission design process connecting Goals 2 and 3 of the NEO Preparedness Strategy and Action Plan. This process enables mitigation mission criteria to be scoped, compared, and optimized based on the degree to which they reduce the impact risk, accounting for key uncertainties about the object's size, properties, orbital trajectory, and deflection response.

Figure 2 shows the procedure developed by the Modeling Working Group to perform integrated risk assessment in support of NEO mitigation missions following the detection of a potentially Earth-impacting asteroid. Appendix C provides more details, including timelines and key descriptors.

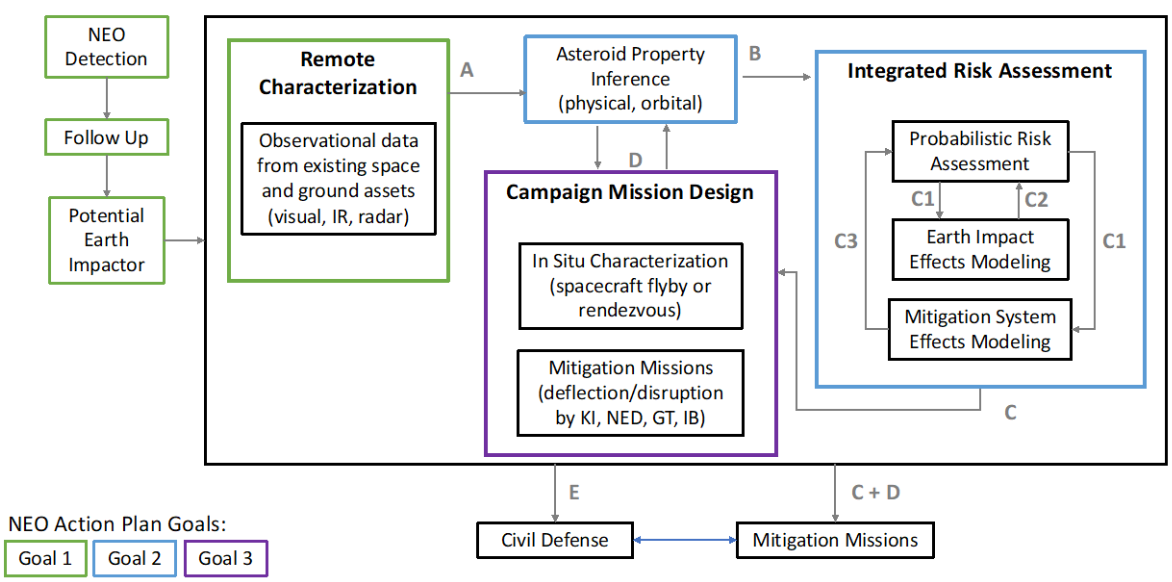

Figure 2. Process flow diagram for risk-informed NEO impact mitigation mission analysis.
Label codes A-E designate data product flow elements described in Table C2.

Action 5.7: Develop benchmarks for determining when to recommend NEO reconnaissance, deflection, and disruption missions

Status: Action 5.7 is completed. NITEP recommends the following benchmarks:

- The United States should follow SMPAG Criterion 3 for initial planning of NEO mitigation missions, including prevention missions.
- The United States should consider undertaking a reconnaissance mission in any scenario that meets the SMPAG criteria for initial planning of impact prevention missions, and where there is sufficient time to execute the mission prior to the predicted impact.
- The United States should consider undertaking a deflection and/or disruption mission in any scenario that meets the risk, feasibility, and hazard benchmarks established below. These benchmarks incorporate risk/benefit analyses focused on the assessed loss of life and economic cost of forgoing mitigation.

Discussion: The decision to launch a space-based response should account for key factors that include the costs of the response, time available before impact, the knowns and unknowns about the object (size, composition, etc.), the potential impact location, and the expected human and economic costs of forgoing impact prevention. In the event of a confirmed asteroid impact threat, these issues would be assessed by the procedures put in place under Action 5.6.

NITEP members recognize that benchmarks based on technical feasibility and simple economic cost/benefit analysis will not be the sole basis for decision making with regard to launching a NEO mitigation mission. However, the political, social, and legal considerations around deflection or disruption are outside of the scope of NITEP coordination activities.

As an element of determining benchmarks for recommending whether a potential asteroid impact could and should be prevented, assessments should be made of the potential loss of human life, and comparisons should be made between the cost of deploying space-based impact prevention missions and the assessed costs that the Nation would incur in responding to, and remediating damage resulting from, the impact. These human and economic costs should be informed by comparison with other natural disasters such as hurricanes, earthquakes, and wildfires. Appendix D provides a discussion of costs of space missions and natural disasters.

Existing Benchmark – Space Missions Planning and Advisory Group

The United States (through the Department of State and NASA) participates in the United Nations-endorsed Space Missions Planning Advisory Group,[2] an international organization of space agencies. SMPAG was established in 2013 by recommendation of the UN COPUOS Scientific and Technical Subcommittee, but is not under the auspices of the UN.

[2] Space Missions Planning Advisory Group (SMPAG) is a UN-endorsed voluntary organization of space agencies, working together with the goal to enable an international response to a threat by a NEO. The SMPAG's function is to exchange information, develop options for collaborative research and mission opportunities, and "to conduct NEO threat mitigation planning activities." Accessed December 4, 2019, at https://www.cosmos.esa.int/web/smpag.

In 2017 SMPAG adopted Recommended Criteria & Thresholds for Action for Potential NEO Impact Threat,[3] addressing terrestrial warning and preparedness, as well as thresholds for developing space-based mitigation missions. The SMPAG thresholds do not include decisions to deploy space-based reconnaissance missions or other mitigation missions. The SMPAG Recommended Threshold Criteria for Action are:

1. IAWN shall warn of predicted impacts exceeding a probability of 1% for all objects characterized to be greater than 10 meters in size, or roughly equivalent to absolute magnitude of 28 if only brightness data can be collected.

2. Terrestrial preparedness planning should begin when warned of a possible impact:

- Predicted to be within 20 years,
- Probability of impact is assessed to be greater than 10%, and
- Object is characterized to be greater than 20 meters in size, or roughly equivalent to absolute magnitude of 27 if only brightness data can be collected.

3. SMPAG should start mission option(s) planning when warned of a possible impact:

- Predicted to be within 50 years,
- Probability is assessed to be greater than 1%, and
- Object is characterized to be greater than 50 meters in size, or roughly equivalent to absolute magnitude of 26 if only brightness data can be collected.

NITEP recommends that the United States follow SMPAG Criterion 3 for initial planning of NEO mitigation missions, including prevention missions. The discovery of a NEO meeting these benchmarks for a potential impact will begin the Risk-Informed Mitigation Process. Following the discovery of a potential impactor, follow-up astrometric observations should, over time, drive the probability of impact either to zero or to 100% within an expected risk corridor, providing the needed decision criteria in the Mission Recommendations Flowchart.

NITEP Benchmark for Recommending Space-Based Reconnaissance

Reconnaissance missions would be highly valuable (given enough time to develop and deploy such missions) for gaining critical data to validate whether a deflection mission is warranted and to assess its requirements and likelihood for success. Current analysis indicates that even a well-defined spacecraft design would require at least three years to be built and readied for launch. It would then require additional time for the spacecraft to reach the object and collect the required data. Thresholds for deploying one or more reconnaissance missions should be lower than thresholds for undertaking deflection or disruption missions.

NITEP recommends that the Nation consider executing a reconnaissance mission in any scenario that meets **all** of the following conditions:

- Meets all of the SMPAG guidelines for initiating planning of in-space prevention missions:
  - Impact predicted to be within 50 years;
  - Impact probability is assessed to be greater than 1%; and

[3] https://www.cosmos.esa.int/documents/336356/1503750/SMPAG_5.1_Report_NASA.pdf/f399e4eb-5947-867c-2422-b9dcb7e3649c

  - o Object is characterized to be greater than 50 meters in size, or roughly equivalent to absolute magnitude of 26 if only brightness data can be collected;
- **AND** there is sufficient time to conduct the mission prior to the predicted impact. This will likely require more than three years advanced warning.

The rationale for this benchmark is that a reconnaissance mission would be comparable in scope to science and exploration missions that the United States and other nations choose to conduct even absent an impact threat. If a potential impact threat is sufficient to warrant initiation of U.S. planning for space-based impact prevention missions, then – if time before impact permits - the United States should quickly proceed with a reconnaissance mission, in cooperation with international partners if possible. Such a mission can provide information critical to determining whether prevention is necessary and, if so, to enabling its success. A reconnaissance mission will offer scientific and exploration value in any case, and funding that would otherwise be spent on similar missions could be redirected if necessary.

The Risk-Informed Mitigation Process Flow developed by the Modeling Working Group and described under Action 5.6 and in Appendix C includes the potential need for *in situ* asteroid characterization from reconnaissance spacecraft. In the event of an impact threat, this process would play an important role in informing reconnaissance mission planning.

NITEP Benchmark for Recommending Space-Based Impact Prevention

NITEP recommends that the Nation consider executing a space-based impact prevention mission in any scenario that meets the following conditions:

- Satisfies **both** of the following ***threat benchmarks***:
  - o Impact predicted to be within 50 years
  - o Impact probability is assessed to be greater than 10%
- **AND all** of the following ***feasibility benchmarks*:**
  - o Prevention is technically feasible
  - o Prevention mission is substantially more likely to decrease than to increase the probability of impact (i.e., if there is equal probability of making the problem better or worse, then should recommend not proceeding with the mission)
  - o Waiting longer to improve confidence in impact prediction will substantially decrease the likelihood of successful prevention
- **AND at least one** of the following ***hazard benchmarks*:**
  - o Impact would likely[4] result in loss of many lives within the United States (of order 100 or more)[5]
  - o Impact would likely result in U.S. economic cost exceeding the financial cost of prevention

This process and benchmarks for recommending NEO mitigation missions, encompassing the SMPAG criteria for process initiation, are shown in Figure 3 as a flow chart. For scenarios that do not meet the U.S. damage thresholds but do threaten that level of damage elsewhere, NITEP recommends that the

[4] In the hazard benchmarks, likelihood refers to a conditional probability of damage, given that the impact occurs, based on best technical assessment and accounting for uncertainties.

[5] In scenarios where there is sufficient time for impact prevention, there will be ample time for evacuation. Therefore, the loss of life benchmark refers to assessed loss of life that evacuation cannot prevent, either because some cannot evacuate or the risk corridor is too large to organize an effective evacuation.

United States consult with international partners prior to any decision to undertake space-based impact prevention. Therefore, NITEP does not recommend U.S. prevention benchmarks for such scenarios.

The Risk-Informed Mitigation Process Flow developed by the Modeling Working Group and described under Action 5.6 and in Appendix C will play an important role in determining whether an actual scenario meets the feasibility and hazard benchmarks, and is therefore critical to informing prevention mission planning.

Based on the information provided in Appendix D (estimated cost of prevention mission ~$400-$800 million; Economic cost of Chelyabinsk impact ~$33 million; economic cost of 2018 California wildfires ~$28 billion; U.S. economic cost of hurricanes ~$110 billion per year), a Chelyabinsk-like event (~20 meter object) would not meet the hazard benchmarks. The following scenarios likely would meet the hazard benchmarks:

- Impact of NEO at least 50 meters in size over a U.S. populated area
- Impact of NEO at least 140 meters in size over North America
- Impact of NEO at least 300 meters in size anywhere in the world

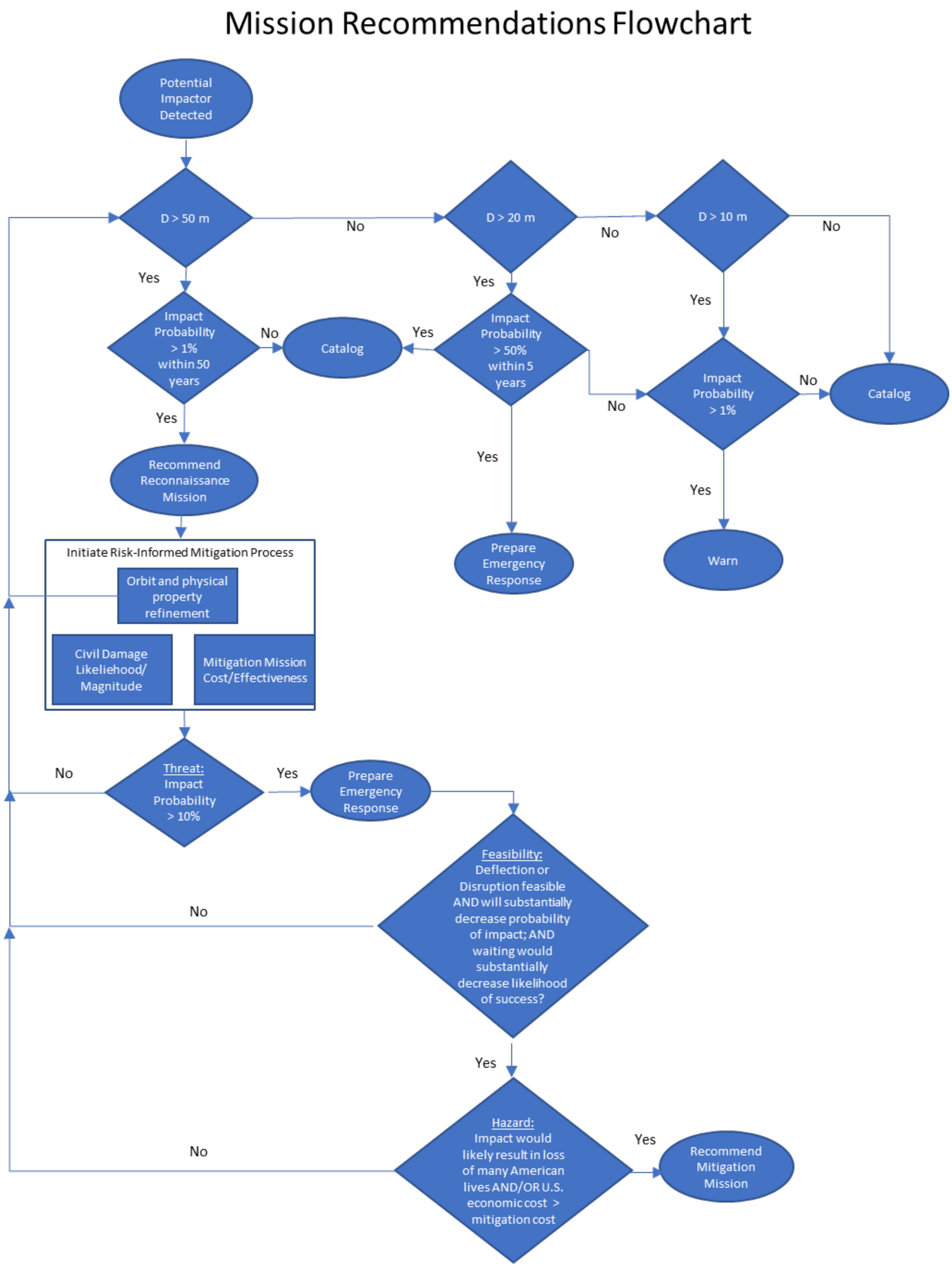

Figure 3. Mission recommendations flowchart.

Conclusion

The NITEP IWG has made significant progress towards the goal of strengthening and routinely exercising NEO impact emergency procedures and action protocols. Federal agencies now have in place procedures for conducting NEO impact threat assessments and risk/benefit analyses for space-based mitigation mission options, and for providing NEO threat notifications to government and non-government entities. NITEP also has provided benchmarks determining when to recommend NEO reconnaissance, deflection, and disruption missions. Sustained focus in this area will allow for further progress in strengthening these procedures and protocols, and greater national preparedness to address NEO impact hazards.

Appendix A: Example impact notification template

NASA PLANETARY DEFENSE COORDINATION OFFICE

IMPACT NOTIFICATION – TEMPLATE
TITLE:

DETAILS:
Impact Probability: cite percent probability as calculated by JPL CNEOS
Impact/Close Approach Date/Time: day/month/year, Time in UT/Zulu (EST in parentheses)
Impact Risk Corridor: Initially can reference portion of globe, e.g., "Current data shows impact in NE CONUS possible"
Approximate Size: in feet (meters in parentheses) in size, with min-max size range
Expected Level of Damage if Impact Occurs: None/Minimal/Local/Regional/Continent/Global
Impact Prevention Feasible: Yes/No

1. Impact probability:
    a. Summary statement with supporting text including the reliability of the information to date.
    b. Depending on length of time before impact, add few sentences on what uncertainties there are and an initial assessment on how these might be reduced.

2. Details known on day/year, include boilerplate on why the date and time are understood, for example "while uncertainties in impact probability persist, the asteroid's trajectory shows that it will come close to, or enter, Earth's atmosphere, at this date and time."

3. Summarize what is known about the impact risk corridor. Include boilerplate text on what an impact risk corridor is.

4. Summarize the estimated area of impact effects. Include damage estimates (i.e., local, regional, national, etc.). Include parameters such as minimal/maximal.

5. Summarize opportunity for next observations, including statement on when the object will no longer be observable and why, and including any potential opportunities for in-space reconnaissance mission(s). Example: "Object will be observable by a multitude of observatories over the next 2 months until it becomes too faint for any observatory to detect." Or "The object will be observable for the next three months, until it passes too close to the Sun to be observable with current technologies. The next opportunity to observe the object will be in XX months when it will once again come close enough to detect."

6. Summarize what is known about the feasibility of impact prevention space mission(s).

Background

- Include boilerplate sentences on how diameter predicts size of potential threat and that the size can only be estimated unless/until we get radar data or photographs.

- Include boilerplate sentences on NASA's PDCO and the authorization for this notification. Include text on agreed-to notification thresholds.

Points of Contact:
NASA PDO
EOP POC
FEMA POC
Others as appropriate

Graphics:

- Helio-centric orbit diagram relative to Earth orbit
- Impact risk corridor map
- Size/damage correlation

Example Graphics:

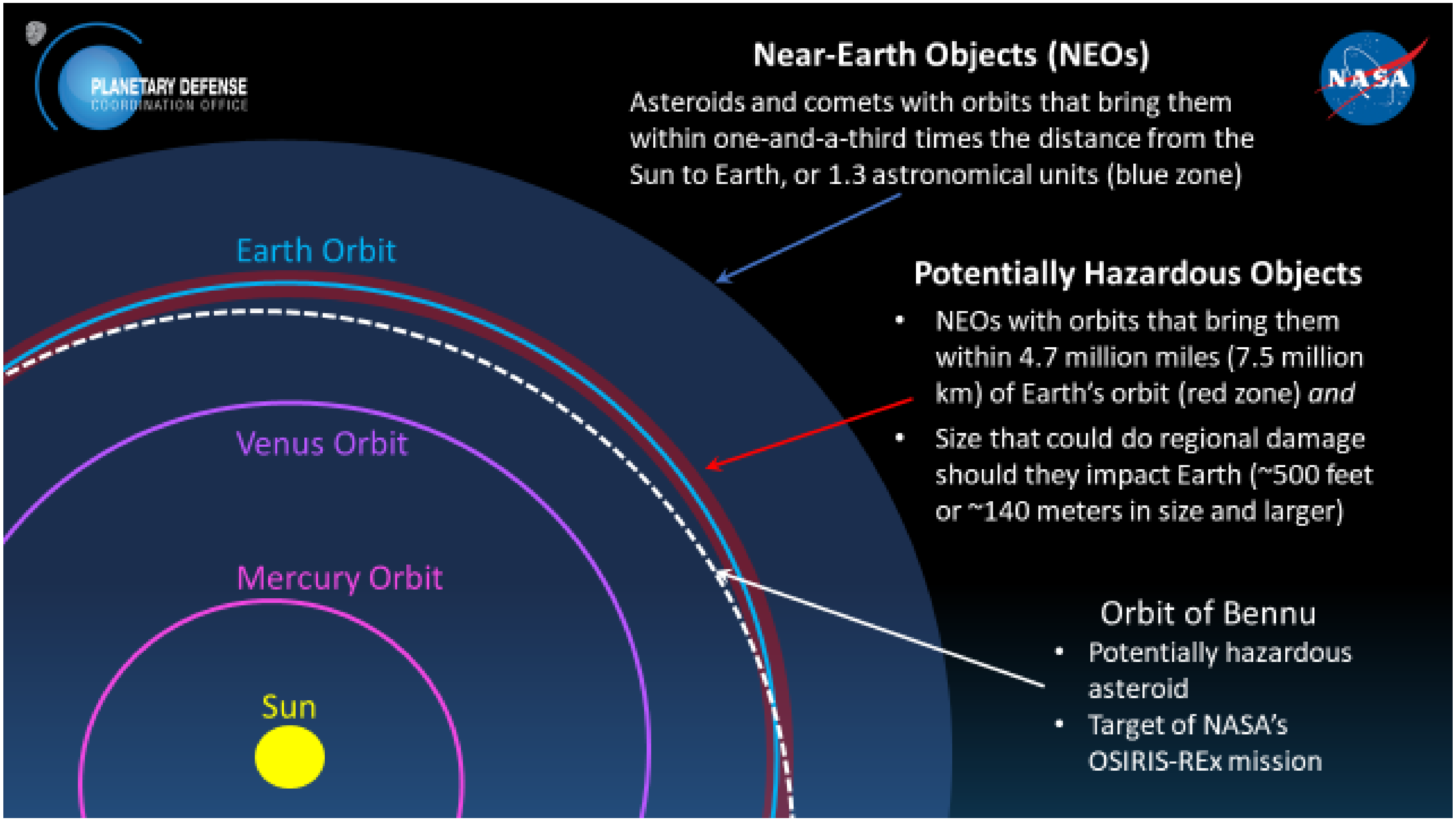

Figure A1. Heliocentric orbit description.

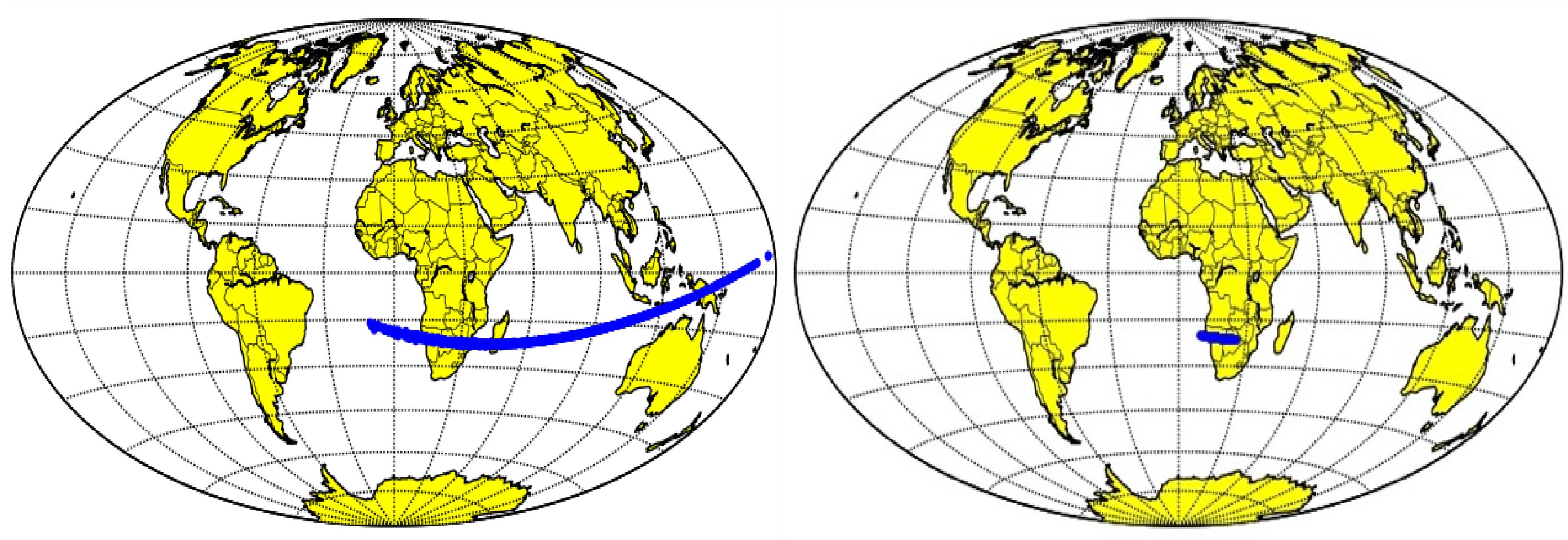

Figure A2. Example of evolving Impact Risk Corridor for 2018 LA.
Initial risk corridor on left, final refined risk corridor on right. Impact could occur at any point along the blue line.

Table A1: Size/Devastation Correlation

Local scale is the size of a metropolitan area. Regional scale is state, province, or smaller country sized.

Diameter of Impacting Asteroid	Type of Event	Approximate Impact Energy (MT)	Average Time Between Impacts (Years)
5 m (16 ft)	Bolide	0.01	1
10 m (33 ft)	Superbolide	0.1	10
25 m (80 ft)	Major Airburst	1	100
50 m (160 ft)	Local Scale Devastation	10	1000
140 m (460 ft)	Regional Scale Devastation	300	20,000
300 m (1000 ft)	Continent Scale Devastation	2,000	70,000
600 m (2000 ft)	Below Global Catastrophe Threshold	20,000	200,000
1 km (3300 ft)	Possible Global Catastrophe	100,000	700,000
5 km (3 mi)	Above Global Catastrophe Threshold	10,000,000	30 million
10 km (6 mi)	Mass Extinction	100,000,000	100 million

Appendix B: Example asteroid impact FAQ

FAQS TO BE ATTACHED TO IMPACT WARNING/NOTIFICATION

Note: These FAQs are specifically for use with an impact warning/notification that would be sent by NASA to EOP, FEMA, and other agencies. This is intended to inform watch officers, duty station staff, and others with a specific and immediate need to know more about the hazard so they can assess who to contact in their agency, and how fast to do it. This is not intended for general public use.

Q: What is an asteroid, meteor, meteorite, bolide, and comet?

A: Asteroids, sometimes called minor planets, are rocky remnants left over from the early formation of our solar system about 4.6 billion years ago. Asteroids may exist in a number of different orbit families within the solar system.

Meteoroids are small pieces that have broken off of asteroids or comets.

Meteors are the streaks of light seen in the sky when a meteoroid enters the Earth's atmosphere and is vaporized. Commonly called "shooting stars."

Meteorites are meteoroids that are not completely vaporized in the atmosphere but land on the surface of the Earth.

Bolides are extremely bright meteors, sometimes also called fireballs. These are caused by very large meteoroids or very small asteroids entering the atmosphere. Some bolides explode in the atmosphere.

Comets are bodies composed of ice and dust left over from the early formation of our solar system about 4.6 billion years ago. They originate from farther out in the solar system than asteroids and develop visible tails as they get close to the sun and dust and gas are blown off the comet by the solar wind.

Q: What is an impact risk corridor?

A: The impact risk corridor is a narrow path along a near-Earth asteroid's orbit that intersects with the Earth's orbit along which the asteroid impact could occur at any point. The beginning and the end of the corridor, and the length and width of the corridor, reflect the degree of uncertainty in our understanding of the asteroid's orbit.

Q: Why doesn't NASA know with certainty if, and where, it will impact?

A: The uncertainty in an impact, and the location prediction, depend on our knowledge of the asteroid's orbit. The accuracy of the orbit determination depends on the number of observations available, the accuracy of these individual observations, and the amount of time until the moment of impact. Immediately after discovery, when there are few observations, the impact probability and location will be most uncertain. As more observations are collected the probability of an impact will either be reduced (e.g., the asteroid will miss Earth) or be confirmed, in which case the asteroid is predicted to enter the atmosphere. As the time to impact gets closer, the impact location will be more refined and certain, similar to how hurricane landfall predictions are improved as more observations are collected and the time to landfall nears.

Q. How much does the size of the object contribute to the hazard?

A: The size of the object is the primary contributor to the hazard estimates. The uncertainties in estimates of the size and composition of the asteroid are expressed as a size range. At the larger end, it can be assumed that the asteroid will survive passage through the atmosphere to have an effect on the surface – either through an airburst or an actual impact.

Q: What are the most common threats/hazards (such as fire, airburst, tsunami) from an asteroid impact?

A: The threat of an asteroid impact is primarily dependent on the predicted impact location. For smaller impactors, up to 25 meters in diameter for common compositions, airbursts are likely as the object heats as it passes through the atmosphere. Airbursts can produce damage through blast overpressures as well as fires. Asteroids are very diverse in composition and structure, and an accurate determination of density and structure may not be possible before impact. If there are enough observations that allow composition assessment, hazard calculations can be refined. An asteroid impact in the shallow ocean coastal waters could cause a local tsunami. A ground impact could cause local destruction including loss of all surface infrastructure in proximity to the impact site.

Table B1: Asteroid Impact Effects vs. Object Size

Diameter of Impacting Asteroid	Type of Event	Approximate Impact Energy (MT)	Average Time Between Impacts (Years)
5 m (16 ft)	Bolide	0.01	1
10 m (33 ft)	Superbolide	0.1	10
25 m (80 ft)	Major Airburst	1	100
50 m (160 ft)	Local Scale Devastation	10	1000
140 m (460 ft)	Regional Scale Devastation	300	20,000
300 m (1000 ft)	Continent Scale Devastation	2,000	70,000
600 m (2000 ft)	Below Global Catastrophe Threshold	20,000	200,000
1 km (3300 ft)	Possible Global Catastrophe	100,000	700,000
5 km (3 mi)	Above Global Catastrophe Threshold	10,000,000	30 million
10 km (6 mi)	Mass Extinction	100,000,000	100 million

Q: What is being done to monitor the asteroid and predict the impact location?

A: Observatories world-wide routinely conduct follow-on observations for any newly detected near-Earth object, and the data is submitted to the Minor Planet Center. Data on all objects that come within 5 million miles of Earth are automatically sent to the JPL Center for NEO Studies (CNEOS) for further analysis.

Q. What is planetary defense?

A: Planetary defense is the term used to encompass capabilities and activities associated with detecting the possibility of potential asteroid or comet impacts with Earth, providing warning, and preventing such impacts or mitigating their consequences. Planetary defense involves:

- Finding and tracking near-Earth objects that pose a hazard of impacting Earth;
- Characterizing those objects to determine their orbit trajectory, size, shape, mass, composition, rotational dynamics, and other parameters, so that experts can determine the severity of the potential impact event, warn of its timing and potential effects, and determine means to mitigate the impact; and
- Planning and implementation of measures to deflect or disrupt an object on an impact course with Earth, or to mitigate the effects of an impact that cannot be prevented. Mitigation measures that can be taken on Earth to protect lives and property include evacuation of the impact area and movement of critical infrastructure.

To learn more about planetary defense, visit www.nasa.gov/planetarydefense. To see a complete catalogue of the known potentially hazardous objects and their calculated probabilities of impact, visit https://cneos.jpl.nasa.gov/sentry/.

Appendix C: Risk-informed mitigation process flow

The effectiveness of potential mitigation efforts depends upon many interrelated factors that could remain uncertain when threat response decisions must be made. These include:

- Asteroid size and properties (porosity, strength, shape, etc.)
- Orbital trajectory (position, speed, potential impact corridor)
- Mitigation deflection or disruption response factors (e.g., beta factor)
- Spacecraft functionality (reliability, targeting accuracy, etc.)
- Impact consequences (damage severities and likelihoods)

The Risk-Informed Mitigation Process Flow (see Figure C1) is an iterative process that determines the potential for damage based on the currently available information, while also informing the need for additional observational data and mission requirements to obtain these data with *in situ* characterization. Updated asteroid properties derived from *in situ* characterization inform updates to Earth Impact Effects Modeling and Mitigation System Effects Modeling and Mitigation Mission Design. These in turn are used to refine the risk assessment. Assessment timeframes and associated data products flow are shown in Tables C1 and C2, respectively.

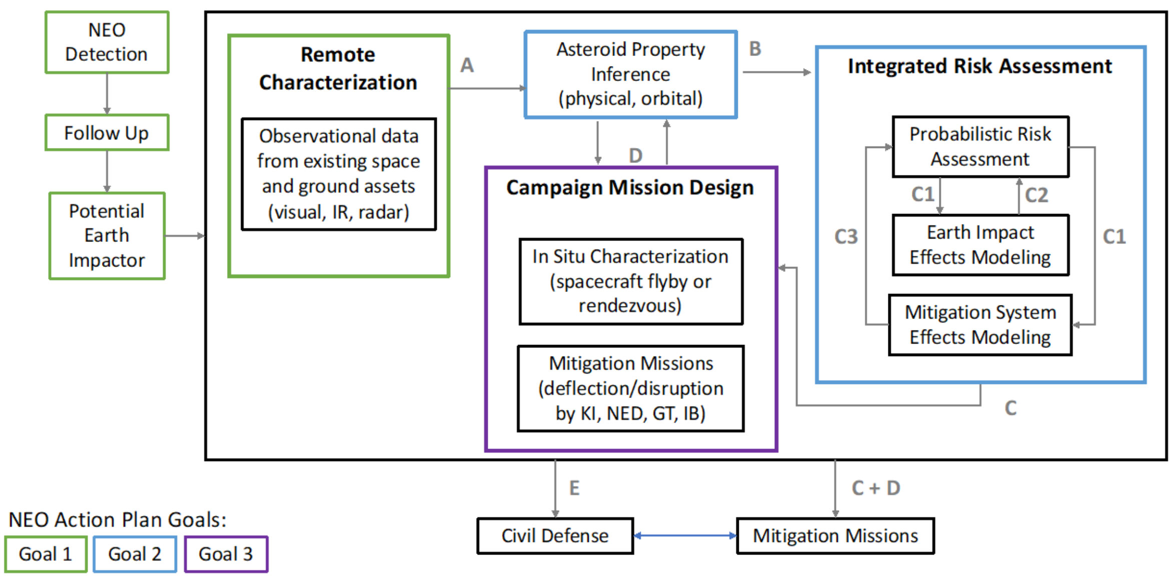

Figure C1. Process flow diagram for risk-informed NEO impact mitigation mission analysis.
Label codes A-E designate data product flow elements described in Table C2.

Table C1: Assessment Product Timelines

Assessment Element	Total time to generate	Compute Time (wall-clock)	Notes
Asteroid orbital determination			
Asteroid physical property inference			• Dependent on availability and types of observations
Probabilistic Risk Assessment	0.5-3 days	0.5-8 hours	• PAIR baseline impact scenario: 0.5-2 hours compute time (depending on impactor size regime and number of property/location samples needed), 1-2 hours setup, 2-4 hours post-processing for basic risk results • PAIR with mitigation mission deflection: 2-8 hours compute time, 1-2 days setup, 1 day post-processing • More detailed sensitivity studies or specific analyses could take several days
Earth Impact Effects Modeling	3 days – 8 weeks	12 hours – 4 weeks	• Large range depending on code, fidelity, domain size, etc.
Cart3D CFD airburst/blast simulations	3-5 days	12-24 hours	• Computer time: 12-24 hours computing time (8000 cores), up to 2 days job queue time for standard non-priority jobs. • Setup time 1-2 days, Post-processing time 1-2 days
ALE3D hydrocode airburst/blast simulations	1-6 weeks	4 days – 2 weeks	• 2D spherical cases: ~ 1 week (setup 1 day, run time 4 days, post-processing 2 days) • 3D non-spherical asteroid shapes: 3-6 weeks (setup 1-3 weeks, run time 1-2 weeks, post processing 1 week)
ALE3D hydrocode ground/water impact simulations	3-8 weeks	1-4 weeks	• 2D vertical impact: 3 weeks (setup 1 week, run time 1 week, post-processing 1 week) • 3D vertical impact: 8 weeks (setup 2 week, run time 1 month, post-processing 1 week)
Mitigation System Effects Modeling			
Campaign Mission Design		NA	

Table C2: Assessment Data Products Flow

Label Code	Source	Recipients	Data Products
A	Remote Characterization	Asteroid Property Inference	• Astrometry (RA, DEC, time) • Photometry (H, colors, light-curves) • Spectroscopy (taxonomy) • IR (size, albedo) • Radar astrometry (range, Doppler) and radar imaging
B	Asteroid Property Inference	Campaign Mission Design Integrated Risk Assessment	• Orbital solution (impact probability, impact risk corridor, B-plane coordinates, B-plane deflection partials, covariance matrix, SPK file) • Physical property distributions and states (diameter, density, mass, porosity, aerodynamic strength, albedo, taxonomic type, structure, shape, rotation state)
C	Integrated Risk Assessment	Campaign Mission Design Mitigation Mission Response Decisions	• Affected population and damage probabilities • Hazard types and severities • Damage corridor (at-risk regions) • Infrastructure at-risk • Economic effects • Risk sensitivities
C1	Probabilistic Risk Assessment	Earth Impact Effects Modeling Mitigation Effects Modeling	• Asteroid properties of high-priority impact cases (prioritized by likelihood, uncertainty, and/or consequence)
C2	Earth Impact Effects Modeling	Probabilistic Risk Assessment	• Specific damage regions for prioritized cases (from C1) • Reduced-order models for damage regions from each hazard as a function of impactor properties
C3	Mitigation System Effects Modeling	Probabilistic Risk Assessment	• Reduced-order models for ΔV and/or disruption as a function of (B) • Specific ΔV and/or disruption models for prioritized cases (C1)
D	Campaign Mission Design	Asteroid Property Inference (orbital) Integrated Risk Assessment Mitigation Mission Response Decisions	• Available or needed launch assets (vehicles, sites) • Spacecraft and mitigation system properties • Mission timelines (launch dates, flight times, intercept dates, recon timeframes) • Mitigation requirements (ΔV requirements, disruption requirements)
E	Integrated Risk Assessment	Civil Defense	• Damage region plots for risk percentiles

Appendix D: Comparing costs of deploying space missions with costs of natural disasters

As an element of determining benchmarks for recommending whether a potential asteroid impact could and should be prevented, NITEP recommends that assessments should be made of the potential loss of human life, and comparisons should be made between the cost of deploying space-based impact prevention missions and the assessed costs that the Nation would incur in responding to, and remediating damage resulting from, the impact. These human and economic costs should be informed by comparison with other natural disasters such as hurricanes, earthquakes, and wildfires. The following is a preliminary analysis by the NASA PDCO on mission cost to help inform implementation of the benchmarks.

Planetary Defense Missions and Concepts

NASA has flown missions and conducted mission design studies that provide useful bounding cases for considering the cost and schedule constraints involved in mounting a response to a NEO impact threat. The missions flown or studied include rendezvous and reconnaissance "SmallSat" missions, impactor missions, and a full science mission to characterize a near-Earth asteroid via a large suite of scientific instrumentation plus a return of sampled material to Earth. Each of these missions demonstrates capabilities that would be required for a successful planetary defense mitigation mission. The mission profiles of these missions are summarized in brief below.

Rendezvous and Reconnaissance

Regardless of the timescale for impact, a newly identified hazard or risk may warrant a near-term response such as sending a reconnaissance mission to characterize the object. Such reconnaissance would yield valuable information on object size, shape, composition, and density that would be essential inputs to deflection mission design. Such missions were included as options in the recent Planetary Defense Conference (PDC 2019) exercise scenario.[6] Examples include the following:

> **NEAR:** The Near Earth Asteroid Rendezvous (NEAR) was the first NASA Discovery mission, approved in December 1993. Its mission was to study the near-Earth asteroid Eros from a close orbit, providing data to determine the asteroid bulk properties, composition, mineralogy, morphology, internal mass distribution, and magnetic field. The spacecraft instrumentation included an x-ray/gamma ray spectrometer, a near-infrared imaging spectrograph, a multi-spectral camera fitted with a charge-coupled device (CCD) imaging detector, a laser rangefinder, and a magnetometer. The spacecraft had a dry mass of 487 kg, and a launch mass of 800 kg. The spacecraft launched on a Delta II vehicle in February 1996 and performed a flyby of the asteroid Mathilde on June 27, 1997. NEAR reached Eros for rendezvous in December 1998, but the initial rendezvous burns failed and a "go-around" contingency plan was implemented. The spacecraft then successfully entered orbit around Eros on February 14, 2000. The total mission cost for NEAR was $211 million in 1996 year dollars (equivalent to $346 million in 2019). The Delta II launch

[6] The 2019 Institute for Aeronautics and Astronautics Planetary Defense Conference featured an exercise with a hypothetical impact scenario focused on the impending impact of a fictitious asteroid titled "PDC 2019."

vehicle cost $43.5 million in 1996, but had a projected cost of $137 million in its final year of use, 2018.[7]

Reconnaissance of Apophis (RA): Reconnaissance of Apophis (RA) **-** A 2019 study by the NASA Goddard Mission Design Laboratory (MDL) scoped a possible reconnaissance mission to the Potentially Hazardous Asteroid (PHA) Apophis. Mission design was scoped to NASA Small Innovative Missions for Planetary Exploration (SIMPLEx) constraints, which require shared launch [Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Ring, class D SmallSat], $55 million mission total cost. The study worked to a schedule constraint of a three-year mission development, with authority to proceed (ATP) date of Jan. 1, 2024, and a nominal launch date of Jan. 1, 2027. This launch window is constrained by the need to rendezvous with Apophis in time for the Earth close approach of April 2029. The payload suite for characterization of the asteroid consisted of a thermal mapper, visible camera, and a neutron detector. The final three-year mission concept included a flyby in September 2028 for initial characterization and imaging, with a multi-month rendezvous and survey of the asteroid from February 2029 – April 2029. An "emergency scenario" allowed for a shortened mission with just a rendezvous in a case where a later launch date was needed. The contingency mission could launch as late as Jan. 13, 2028, and rendezvous by March 2029. The final spacecraft design assumed use of 5m (vs 4m) fairing and ESPA-Grande, which allowed the larger spacecraft volume needed to meet the mission specifications. The study report expressed doubt that the 2019 SIMPLEx $55 million cost cap could be met, but expected the mission could be accomplished within a 25% variance of this (~$69 million in 2019 dollars).

Kinetic Impactor

The most direct analogs for considering kinetic impactors for PHA mitigation are the Deep Impact mission, launched by NASA in 2005, and the Double Asteroid Redirection Test (DART) mission, planned for launch in July 2021. Both missions deliver(ed) kinetic impactors to near-Earth objects.

Deep Impact: The Deep Impact mission, designed to excavate comet material with an impactor and analyze the material via remote observation from a "flyby" spacecraft, encountered comet Tempel 1, delivering a 372 kg impactor and a 601 kg flyby observation spacecraft. The mission was selected by NASA in 1999, and launched in January 2005 on a Delta II vehicle. Deep Impact reached Tempel 1 for the impact on July 4, 2005. Following the data collection at Tempel 1, the Deep Impact spacecraft was re-tasked to rendezvous with several other comets to collect data before a fatal system failure in August 2013. The mission cost for Deep Impact was $330 million in 2005 dollars ($435 million in 2019 dollars). As noted above, Delta II launch costs were $137 million in 2018, its final year of availability.

DART: The Double Asteroid Redirection Test is a NASA planetary defense mission that was confirmed for development in August 2018, with a planned launch Date of July 2021 on a Falcon 9 launch vehicle. Its target, the binary asteroid Didymos A/B, will be reached in September 2022, with the spacecraft impacting Didymos B, the smaller "moon" in the system. The mission will measure the change in orbital parameters of the asteroidal moon and compare the results to

[7] Federal Aviation Administration Office of Commercial Space Transportation Delta II Fact Sheet, Annual Compendium of Commercial Space Transportation: 2018, January 2018.

theoretical models of the effects of kinetic impacts on asteroid trajectories. The spacecraft itself has a mass of 500 kg and impacts entirely into the asteroid. The budgeted mission cost is $313 million, with a launch cost of $69 million for the Falcon 9 vehicle.

Rendezvous/Land/Sample Return

OSIRIS-REx: The most complex near-Earth asteroid mission being flown by NASA is the OSIRIS REx mission, which includes a rendezvous with the asteroid Bennu. The New Frontiers mission has multiple science instruments and includes a sample collection and return component. The mission was selected by NASA in May 2011, launched in September 2016, and arrived at Bennu in December 2018. The spacecraft has a dry mass of 880 kg, and a wet mass at launch of 2110 kg. It launched on an Atlas V vehicle. The mission cost is ~$800 million, with an additional $183 million for the launch vehicle.

Relevance of Mission Data to NEO Mitigation Cost Estimates

Unique to planetary defense is the premise that asteroid impacts are *preventable* natural disasters. The term "in-space mitigation" refers to spacecraft missions or campaigns of missions whose goal is to deflect the object away from Earth, or to disrupt it (i.e., break into smaller pieces) to reduce the harm to Earth. Planetary defense mitigation scenarios may include one or more types of space missions, depending on the estimated damage threshold, impact uncertainty, and advance warning time. Options for response could include one or more of reconnaissance, kinetic impactor, nuclear deflection, or other mitigation technique missions.

Table D2: NASA NEO Missions and Concept Studies

Mission	Mission Type	ATP Date	Launch Date	Development (months)	Asteroid Arrival Date	Cruise Phase (months)	Spacecraft Cost ($2019)	Mass (kg)	Launch Cost ($2019)
NEAR	Recon	12/93	2/17/96	50	12/20/98^	34	$346M	487 dry 800 wet	$137M
RA**	Flyby + Recon	1/24	1/1/27	36	2/29	25	$69M	217 dry 381 wet	(Shared launch)
RA (fast)**	Recon (contin-gency)	1/25	1/13/28	36	3/29	14	$69M	217d 381w	(Shared launch)
Deep Impact	Impactor/ Recon	7/99	1/05	65	7/4/05	6	$435M	973	$137M
DART*	Impactor	8/18	7/21	35	10/22	15	$313M	500	$69M
OSIRIS REx	Sample Return	5/11	9/16	64	12/18	27	$800M	880 dry 2110wet	$183M

** Study by NASA Goddard Mission Design Laboratory
* Planned launch/arrival schedule
^ Eros arrival date, successful orbit achieved 2/14/2000

Based on the mission and study data above, the minimal response of a reconnaissance SmallSat mission could be built for ~$70 million, with launch costs ranging from nil for a ride share arrangement, to up to $90 million for a dedicated launch vehicle (2019 dollars). Timeframes for reaching the asteroid must include three to four years for spacecraft build (if there is a well-understood design in place and ready for development and implementation), plus the amount of time after launch required to reach the asteroid. While the cruise phase depends on the NEO orbit, time to rendezvous of 6 months to two years seem reasonable estimates based on data and experience.

For kinetic impactors, the most direct analogs in the existing data are the Deep Impact and DART kinetic impactors. Both of these missions would contain all of the required technology for guidance and controls needed to perform the asteroid deflection mission. Deflection of a large asteroid would likely require larger impactors than either of these missions carried, and therefore require larger launch vehicles [e.g., Delta IV Heavy, Space Launch System (SLS), or Falcon Heavy]. If the kinetic impactor mission cost is dominated by the spacecraft complexity for guidance and control, and not by inert mass of the impactor, we can use the Deep Impact and DART missions to estimate the kinetic impactor cost at $300 million to $400 million per spacecraft. Heavy launch vehicle cost estimates range from $150 million for a fully expendable Falcon Heavy[8] to $400 million (2018) for the Delta IV Heavy.[9]

The OSIRIS REx mission, which includes a sophisticated instrument suite and large science mission, as well as the capability for sample collection and return, is likely too complex to use as a good analog for a NEO mitigation mission. However, we might consider it as an upper bound for nuclear deflection missions, because the complexity of incorporating the nuclear explosive device (NED) with a spacecraft for deployment and detonation at the correct point in relation to the asteroid could approach the level of a sample collection mission. Lacking other knowledge at present of the cost of NED design for NEO mitigation, an estimate of $800 million for the cost of this option is reasonable.

Cost of Emergency Response and Operations

Other factors in a decision on whether to deploy reconnaissance and mitigation missions in the event of a predicted impact are the estimates of the potential damage to Earth if the impact were to occur. A report issued by the National Oceanic and Atmospheric Administration (NOAA) showed that in 2018 the United States experienced more than $91 billion in costs associated with natural disasters in that year alone (see Table D2).[10] For example, California's Camp Fire, the Mendocino Complex Fire, the Carr Fire, and the Woolsey Fire, cost a record $24 billion. During the years 2017-2019, hurricanes and other weather disasters cost the nation an estimated total of $442 billion, with Hurricane Harvey alone accounting for $125 billion of that total.[11] In 2018, the United States also managed less frequent disasters such as a volcano eruption in Hawaii and three back-to-back 1,000-year floods not associated with hurricanes.

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8 https://www.cnbc.com/2018/02/12/elon-musk-spacex-falcon-heavy-costs-150-million-at-most.html

9 Federal Aviation Administration Office of Commercial Space Transportation Delta IV Fact Sheet, Annual Compendium of Commercial Space Transportation: 2018, January 2018.

10 Smith, Adam. February 7, 2019. "2018's Billion Dollar Disasters in Context" taken from https://www.climate.gov/news-features/blogs/beyond-data/2018s-billion-dollar-disasters-context. Accessed on 12/2/2019.

11 https://coast.noaa.gov/states/fast-facts/hurricane-costs.html. Accessed on 12/11/2020.

Table D2: Natural Catastrophe Losses in the United States, 2018

(*Source: The Insurance Information Institute. https//:www.iii.org/graph-archive/96537. Accessed 12/2/2019.*)

As of March, 2019	Number of Events	Fatalities	Estimated Overall Losses (US $bn)	Estimated Insured Losses (US $bn)*
Severe Thunderstorm	56	66	18.8	14.1
Winter Storms & Cold Waves	9	26	4.2	3
Flood, Flash Flood	20	49	2.6	1.2
Earthquake & Geophysical	2		0.5	0.4
Tropical Cyclone	5	107	30.4	15.6
Wildfire, Heat Waves, & Drought (ongoing drought condition without loss estimation for the half year)	16	107	25.4	18
Totals	**108**	**355**	**$81.9**	**$52.3**

Asteroid strikes, while statistically rare, do happen on a somewhat sporadic frequency, with large asteroids impacting Earth more rarely and smaller asteroids more frequently, as is shown in the Earth's geologic record (see Table D3). This matches the known near-Earth asteroid population in that there are millions more 60 meter sized objects than 1 km objects. As of November 30, 2019, 8,839 NEOs have been discovered out of a predicted population >25,000.[12] The table below summarizes current understanding of size, impact intervals, overall population estimates, and potential damage.

Table D3: Comparisons of Estimated Size to Potential Estimated Damage

Characteristic Diameter (in meters) of Impacting Object	Approximate Average Impact Interval (years)	Estimated Object Population	Energy Released (Megatons TNT)	Estimated Damage or Comparable Event
25-30	100-200	>1.3 million	<2	Fireball, airburst, shockwave, minor damage
50	1,000	200,000	10	Local damage comparable to that of largest existing thermonuclear weapon
140	20,000	25,000	~500	Destruction on regional or national scale
300-500	~100,000	5,000	<10,000	Destruction on continental scale, many millions dead
1,000	700,000	930	100,000	Global effects, 100s of millions of casualties
10,000	100 million	4	100 million	Mass extinction of many species, including humans

[12] https://www.cneos.jpl.nasa.gov/stats/totals.html. Accessed on 12/4/2019.

A recent example is the 2013 Chelyabinsk event. On February 15, 2013, an approximately 20 meter sized object exploded 25 km from the Russian city of Chelyabinsk. Occurring during a winter morning (about 9 AM local time), many of the city's inhabitants were commuting to, or already at work. The bolide airburst, bright in the dawn sky, drew people to windows all over the city. The airburst overpressure wave, arriving about 3 minutes later, caused widespread glass breakage, resulting in injury to approximately 1,500 people. Damage estimates were roughly estimated at $33 million USD. The energy from this "superbolide" is estimated to have been greater than 400 kilotons.

Another example is the 1908 Tunguska event. The object that caused the devastation of 2,000 square km of forest in Siberia is estimated to have been approximately 50 meters in size. There are no documented fatalities from that event because the region was sparsely inhabited. The outline of the destruction zone is superimposed over major U.S. cities in Figure D1, showing that the potential destruction from an object as small as ~50 m could have significant consequences. A Tunguska-sized event over a major metropolitan area would inflict economic costs far exceeding the approximately $1 billion cost of the most expensive mission to a Near-Earth asteroid thus far undertaken (see Table D1).

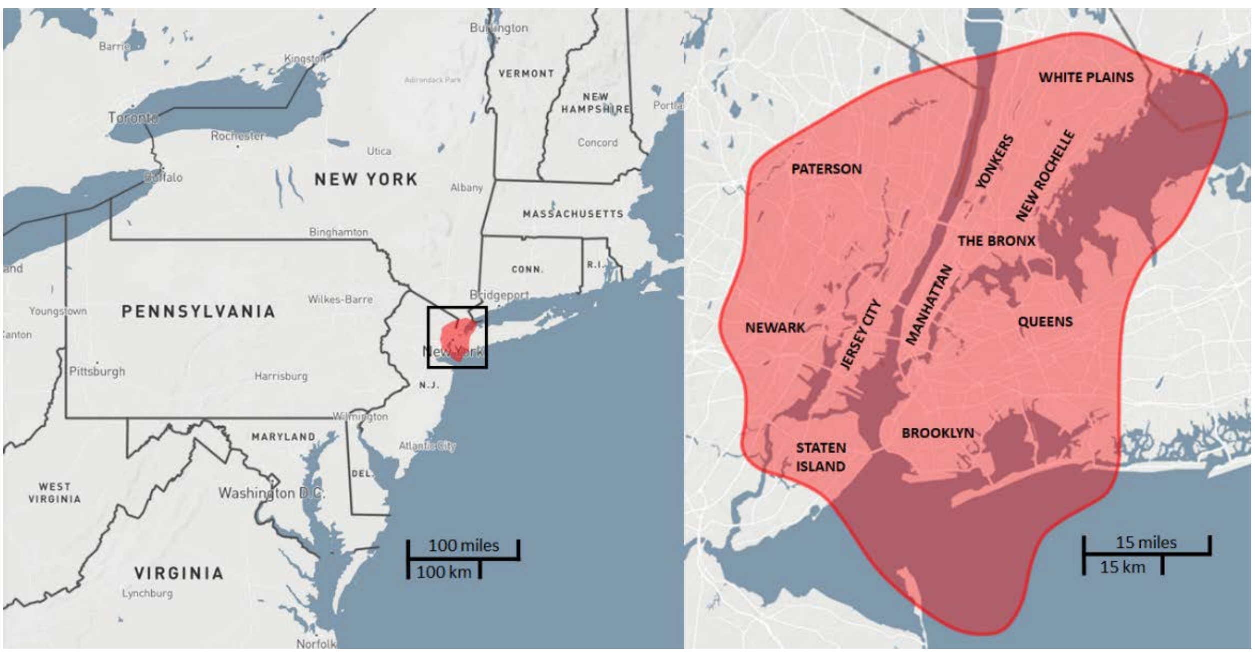

Figure D1. Equivalent area of destruction for a Tunguska-sized asteroid over New York City. Background map imagery from Mapbox; Damage pattern from Boyarkina, A. P., D. V. Demin, I. T. Zotkin, and W. G. Fast. 1964. Estimation of the blast wave of the Tunguska meteorite from the forest destruction. *Meteoritika* 24:112-128 (in Russian).

Associated Social and Economic Considerations

The primary goal for the NASA survey program is to identify PHAs with enough lead time to be able to mitigate the risk, or even to prevent the impact. This implies that when an object is discovered with a probability >1% of impacting Earth, there would optimally be several years in which uncertainties can be reduced and decisions can be made on how to best respond to the threat. These decisions will have to be made under conditions in which key questions may be unanswered, and will be made in full view of the public. While the impact risk corridor may be quickly identified, it may be years until the uncertainties can be reduced to either remove the risk altogether or shorten the impact risk corridor to a specific region or locale. It can be anticipated that states and regions in the risk corridor will see public concern rise and economic impacts such as loss of business and reductions in real estate values.