Planetary Defense Decisionmaker Guide

What Leaders Around the World Should Know—and What They Can Do—If an Asteroid or Comet Threatens to Hit Earth

Jan Osburg

This draft guide is designed to serve as a ready reference to support leaders around the world in decisionmaking for planetary defense emergencies, especially in case of short-notice scenarios. It summarizes and synthesizes critical information that is currently distributed across a wide range of scientific, technical, and policy documents in the rapidly evolving field of planetary defense. While it aims to be in alignment with national policies as much as possible, it is not endorsed by any government or governmental organization or agency.

This draft guide has been reviewed by leading subject-matter experts in advance of distribution for an exercise at the International Academy of Astronautics (IAA) Planetary Defense Conference 2023. It should be considered preliminary.

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Acknowledgements

This guide draws on a wide range of sources, but three documents provided the bulk of its content and helped inform its structure: the materials for the U.S. National Aeronautics and Space Agency (NASA) and Federal Emergency Management Agency (FEMA) Planetary Defense Tabletop Exercise #4,[1] the European Space Agency's "Hitchhiker's Guide to Asteroid Impact Threats",[2] and NASA's 2017 "Report of the Near-Earth Object Science Definition Team."[3] The author truly appreciates the contributions of these organizations and their cadre of dedicated experts.

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[1] National Aeronautics and Space Administration Center for Near Earth Object Studies, "2022 Interagency Tabletop Exercise (PD TTX4)," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/

[2] ESA: "The Hitchhiker's Guide to Asteroid Impact Threats," ESA-S2P-PD-TN-0014, Draft, 2022.

[3] G. H. Stokes, B. W. Barbee, J. William F. Bottke, M. W. Buie, S. R. Chesley, P. W. Chodas, et al., "Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs ", 2017. https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf

[4] RAND Corporation, "RAND Space Enterprise Initiative," webpage, undated. As of January 18, 2023: https://www.rand.org/capabilities/space-enterprise-initiative.html

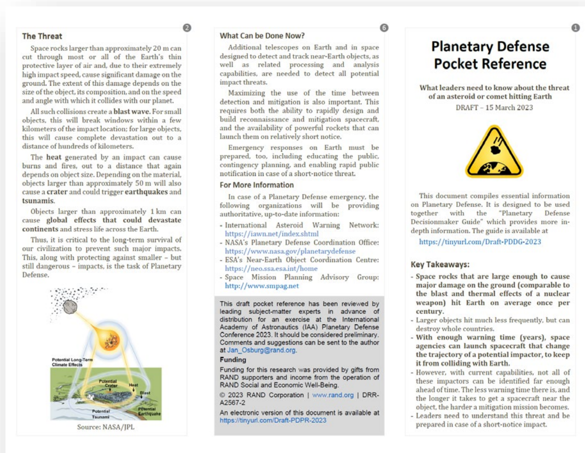
[5] International Academy of Astronautics, "IAA Planetary Defense Conference 2023" webpage, undated. As of January 18, 2023: https://iaaspace.org/pdc

[6] International Academy of Astronautics, "IAA Planetary Defense Conference 2023" webpage, undated. As of January 18, 2023: https://iaaspace.org/event/8th-iaa-planetary-defense-conference-2023/

Chapter Overview

An electronic version of this document is available at https://tinyurl.com/Draft-PDDG-2023

An electronic version of a companion document, the two-page "Planetary Defense Pocket Reference" (pictured below), is available at https://tinyurl.com/Draft-PDPR-2023



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The Threat

Space rocks larger than approximately 20 m can cut through most or all of the Earth's thin protective layer of air and, due to their extremely high impact speed, cause significant damage on the ground. The extent of this damage depends on the size of the object, its composition, and on the speed and angle with which it collides with our planet.

All such collisions create a **blast wave.** For small objects, this will break windows within a few kilometers of the impact location; for large objects, this will cause complete devastation out to a distance of hundreds of kilometers.

The **heat** generated by an impact can cause burns and fires, out to a distance that again depends on object size. Depending on the material, objects larger than approximately 50 m will also cause a **crater** and could trigger **earthquakes** and **tsunamis.**

Objects larger than approximately 1 km can cause **global effects that could devastate continents** and stress life across the Earth.

Thus, it is critical to the long-term survival of our civilization to prevent such major impacts. This, along with protecting against smaller – but still dangerous – impacts, is the task of Planetary Defense.

Source: NASA/JPL

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What Can be Done Now?

Additional telescopes on Earth and in space designed to detect and track near-Earth objects, as well as related processing and analysis capabilities, are needed to detect all potential impact threats.

Maximizing the use of the time between detection and mitigation is also important. This requires both the ability to rapidly design and build reconnaissance and mitigation spacecraft, and the availability of powerful rockets that can launch them on relatively short notice.

Emergency responses on Earth must be prepared, too, including educating the public, contingency planning, and enabling rapid public notification in case of a short-notice threat.

For More Information

In case of a Planetary Defense emergency, the following organizations will be providing authoritative, up-to-date information:

- International Asteroid Warning Network: https://iawn.net/index.shtml
- NASA's Planetary Defense Coordination Office: https://www.nasa.gov/planetarydefense
- ESA's Near-Earth Object Coordination Centre: https://neo.ssa.esa.int/home
- Space Mission Planning Advisory Group: http://www.smpag.net

This draft pocket reference has been reviewed by leading subject-matter experts in advance of distribution for an exercise at the International Academy of Astronautics (IAA) Planetary Defense Conference 2023. It should be considered preliminary. Comments and suggestions can be sent to the author at Jan_Osburg@rand.org.

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Planetary Defense Pocket Reference

What leaders need to know about the threat of an asteroid or comet hitting Earth

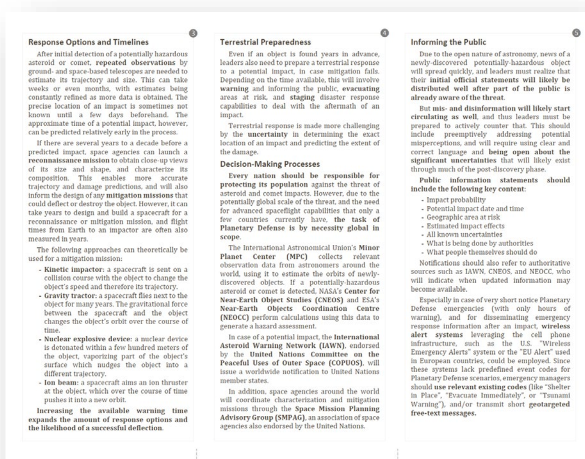
DRAFT – 15 March 2023

This document compiles essential information on Planetary Defense. It is designed to be used together with the "Planetary Defense Decisionmaker Guide" which provides more in-depth information. The guide is available at

https://tinyurl.com/Draft-PDDG-2023

Key Takeaways:

- **Space rocks that are large enough to cause major damage on the ground (comparable to the blast and thermal effects of a nuclear weapon) hit Earth on average once per century.**
- Larger objects hit much less frequently, but can destroy whole countries.
- **With enough warning time (years), space agencies can launch spacecraft that change the trajectory of a potential impactor, to keep it from colliding with Earth.**
- However, with current capabilities, not all of these impactors can be identified far enough ahead of time. The less warning time there is, and the longer it takes to get a spacecraft near the object, the harder a mitigation mission becomes.
- Leaders need to understand this threat and be prepared in case of a short-notice impact.



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Response Options and Timelines

After initial detection of a potentially hazardous asteroid or comet, **repeated observations** by ground- and space-based telescopes are needed to estimate its trajectory and size. This can take weeks or even months, with estimates being constantly refined as more data is obtained. The precise location of an impact is sometimes not known until a few days beforehand. The approximate time of a potential impact, however, can be predicted relatively early in the process.

If there are several years to a decade before a predicted impact, space agencies can launch a **reconnaissance mission** to obtain close-up views of its size and shape, and characterize its composition. This enables more accurate trajectory and damage predictions, and will also inform the design of any **mitigation missions** that could deflect or destroy the object. However, it can take years to design and build a spacecraft for a reconnaissance or mitigation mission, and flight times from Earth to an impactor are often also measured in years.

The following approaches can theoretically be used for a mitigation mission:

- **Kinetic impactor:** a spacecraft is sent on a collision course with the object to change the object's speed and therefore its trajectory.
- **Gravity tractor:** a spacecraft flies next to the object for many years. The gravitational force between the spacecraft and the object changes the object's orbit over the course of time.
- **Nuclear explosive device:** a nuclear device is detonated within a few hundred meters of the object, vaporizing part of the object's surface which nudges the object into a different trajectory.
- **Ion beam:** a spacecraft aims an ion thruster at the object, which over the course of time pushes it into a new orbit.

Increasing the available warning time expands the amount of response options and the likelihood of a successful deflection.

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Terrestrial Preparedness

Even if an object is found years in advance, leaders also need to prepare a terrestrial response to a potential impact, in case mitigation fails. Depending on the time available, this will involve **warning** and informing the public, **evacuating** areas at risk, and **staging** disaster response capabilities to deal with the aftermath of an impact.

Terrestrial response is made more challenging by the **uncertainty** in determining the exact location of an impact and predicting the extent of the damage.

Decision-Making Processes

Every nation should be responsible for protecting its population against the threat of asteroid and comet impacts. However, due to the potentially global scale of the threat, and the need for advanced spaceflight capabilities that only a few countries currently have, **the task of Planetary Defense is by necessity global in scope.**

The International Astronomical Union's **Minor Planet Center (MPC)** collects relevant observation data from astronomers around the world, using it to estimate the orbits of newly-discovered objects. If a potentially-hazardous asteroid or comet is detected, NASA's **Center for Near-Earth Object Studies (CNEOS)** and ESA's **Near-Earth Objects Coordination Centre (NEOCC)** perform calculations using this data to generate a hazard assessment.

In case of a potential impact, the **International Asteroid Warning Network (IAWN)**, endorsed by the **United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)**, will issue a worldwide notification to United Nations member states.

In addition, space agencies around the world will coordinate characterization and mitigation missions through the **Space Mission Planning Advisory Group (SMPAG)**, an association of space agencies also endorsed by the United Nations.

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Informing the Public

Due to the open nature of astronomy, news of a newly-discovered potentially-hazardous object will spread quickly, and leaders must realize that their **initial official statements will likely be distributed well after part of the public is already aware of the threat.**

But **mis- and disinformation will likely start circulating as well**, and thus leaders must be prepared to actively counter that. This should include preemptively addressing potential misperceptions, and will require using clear and correct language and **being open about the significant uncertainties** that will likely exist through much of the post-discovery phase.

Public information statements should include the following key content:

- Impact probability
- Potential impact date and time
- Geographic area at risk
- Estimated impact effects
- All known uncertainties
- What is being done by authorities
- What people themselves should do

Notifications should also refer to authoritative sources such as IAWN, CNEOS, and NEOCC, who will indicate when updated information may become available.

Especially in case of very short notice Planetary Defense emergencies (with only hours of warning), and for disseminating emergency response information after an impact, **wireless alert systems** leveraging the cell phone infrastructure, such as the U.S. "Wireless Emergency Alerts" system or the "EU Alert" used in European countries, could be employed. Since these systems lack predefined event codes for Planetary Defense scenarios, emergency managers should **use relevant existing codes** (like "Shelter in Place", "Evacuate Immediately", or "Tsunami Warning"), and/or transmit short **geotargeted free-text messages.**

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Executive Summary

Earth, like all planets, has been hit by other celestial objects since its formation billions of years ago, and even today small space rocks – from pebble-sized to about one meter in diameter – impact the atmosphere every single night.[7] Such meteoroids[8] usually disintegrate completely in the upper atmosphere, generating light that is visible as a "shooting star" from the ground for a short period of time.[9] However, rocks larger than 10 m – about the size of a single-family house – can cut through most of the Earth's thin protective layer of air and, due to their extremely high impact speed, cause significant damage.

The extent of this damage depends on the size of the object, its composition, and the speed and angle with which it collides with our planet. **Cosmic impactors the size of a large house can wipe out a small city, and asteroids or comets larger than approximately one kilometer in diameter – the size of a small mountain – could devastate a continent.**[10] One such large space rock hit what is now the Gulf of Mexico approximately 66 million years ago. The resulting blast and heat waves caused immediate destruction up to a distance of thousands of kilometers from the impact site. The impact also triggered earthquakes and tsunamis,[11] and led to changes in global climate. This wiped out the dinosaurs along with most other species on Earth in the months and years following the impact.[12]

Thus, **it is critical to the long-term survival of our civilization to prevent such major impacts. This, along with protecting against smaller – but still dangerous – impacts, is the task of Planetary Defense.**[13]

Luckily, our civilization has now reached the stage where we have the means to detect and deflect most of these threats. However, Planetary Defense emergencies can happen on relatively short timelines – **some objects are detected only weeks, days, or**

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[7] National Aeronautics and Space Administration, Solar System Exploration Our Galactic Neighborhood, "Meteors & Meteorites" webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/asteroids-comets-and-meteors/meteors-and-meteorites/in-depth

[8] A meteoroid is a small piece of rock moving through space. Meteors are streaks of light in the Earth's atmosphere that are created when a meteoroid enters the atmosphere. A bolide is a very bright meteor caused by large meteoroids. An asteroid is a larger rock, left over from the formation of the Solar System. A comet consists of a core of ice and dust, and – when getting closer to the sun – develops a "tail" sometimes visible from Earth. Appendix A.0 (page 35) contains additional definitions.

[9] National Aeronautics and Space Administration, "What's the Difference Between Asteroids, Comets and Meteors? We Asked a NASA Scientist: Episode 16" webpage, December 13, 2021. As of January 18, 2023: https://www.nasa.gov/feature/what-s-the-difference-between-asteroids-comets-and-meteors-we-asked-a-nasa-scientist-episode

[10] Stadler, Felix, "The Asteroid Impact Threat from Physical Parameters to Information," Technical University of Munich term paper, undated. As of January 18, 2023: https://iawn.astro.umd.edu/documents/supporting/ESA-SSA%20impact%20scale%20report%202016.pdf

[11] Range, M. M., Arbic, B. K., Johnson, B. C., Moore, T. C., Titov, V., Adcroft, A. J., et al. (2022). The Chicxulub impact produced a powerful global tsunami. *AGU Advances*, 3, e2021AV000627. As of January, 18 2023: https://doi.org/10.1029/2021AV000627

[12] Schulte P, Alegret L, Arenillas I, et al. "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary". *Science*. 2010;327(5970):1214-1218. https://doi.org/10.1126/science.1177265

[13] National Aeronautics and Space Administration, "Planetary Defense Frequently Asked Questions" webpage, undated. As of January 18, 2023: https://www.nasa.gov/planetarydefense/faq

even just hours before impact.[14] This guide therefore aims to provide essential information to leaders who are not Planetary Defense professionals themselves and may not have immediate access to trusted subject matter experts, but who may nevertheless be faced with having to make potentially high-stakes decisions on short notice in case an asteroid or comet threatens to hit Earth.

The main part of the guide consists of seven chapters containing answers to the following key questions:

1. **What are the odds of a catastrophic impact happening?**
2. **What kind of damage would it cause?**
3. **What are the timelines involved in Planetary Defense?**
4. **What can be done now to reduce the risk?**
5. **What are the options once such a threat materializes?**
6. **Who is involved in deciding what to do, and what are the related processes?**
7. **What are the best practices for informing and involving the general public?**

An appendix provides more in-depth coverage of theses issues, as well as information that may only be of relevance to some readers. The sources of the information used in this guide are cited in footnotes and documented in a references section at the end.

The following paragraphs provide a very brief summary of key Planetary Defense knowledge, following the same general outline as the chapters. The reader is urged to also peruse the more-detailed information in the main part of this guide.

How much of a risk is this? What are the odds? What would the damage be?

As described above, **the larger the object, the more damage it can cause**. At the same time, **larger objects hit Earth much less frequently than smaller ones**. Furthermore, **the larger the object, the more likely it is that it has already been discovered and is being tracked**, which makes it less likely for a larger object to hit Earth by surprise. Beyond the size of an object, its composition also plays a role in the type and extent of damage: stony asteroids are more likely to break up in the atmosphere, resulting in blast wave (similar to that caused by a very large explosion) and thermal (heat) damage, while a metallic asteroid is more likely to reach the ground and create a crater. Figure 1 below provides a general overview of these risk factors. Figure 2 shows approximately how often an impactor of a certain size can be expected to hit Earth.

[14] National Aeronautics and Space Administration Center for Near Earth Object Studies, "Asteroid 2008 TC3 Strikes Earth: Predictions and Observations Agree," webpage, Nov 4, 2008. As of January 18, 2023: https://cneos.jpl.nasa.gov/news/2008tc3.html

None of the near-Earth objects currently being tracked are predicted to hit Earth within the next century.[15] However, there are still **many smaller asteroids that are nevertheless large enough to destroy a city or small country that have not yet been discovered** – based on estimations of how many objects of a certain size can be expected to exist, NASA and others have so far identified less than half of those objects.[16] As the example of Asteroid 2023 DW illustrates,[17] new and potentially-threatening objects are being detected every year. And even an impact with geographically-limited physical damage could have higher-order effects, for example, on the global economy. Furthermore, comets are more difficult to discover and track, and thus the risk of a comet impact is harder to predict.[18]

Two recent examples serve to illustrate the damage that can be caused even by relatively small rocks of a size that can be expected to hit Earth about once per century:

- A meteoroid estimated to be about 20 m in diameter broke apart in the atmosphere about 27 km over the Russian city of Chelyabinsk in February 2013, releasing energy equivalent to that of a large nuclear bomb (in the 500 kiloton range)[19]. Over 1000 people were injured by the resulting blast wave, most from shattered glass, and several thousand buildings were damaged, again mostly due to broken glass.[20]
- A meteoroid estimated to be about 30 m in diameter entered the atmosphere near the Tunguska river in central Siberia in June 1908, breaking apart at an altitude of approximately 10 km. The energy released during that event was equivalent to a very large nuclear bomb (around 15 megatons), which started fires up to 15 km from the epicenter and pushed down trees at a distance up

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[15] National Aeronautics and Space Administration Center for Near Earth Object Studies, "NEO Earth Close Approaches," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/ca (However, there are known objects with the potential to impact Earth several hundred years from now; see National Aeronautics and Space Administration Center for Near Earth Object Studies, "Sentry: Earth Impact Monitoring," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/sentry

[16] . For example, in June 2022 astronomers discovered a small asteroid, subsequently named 2022 MM1, that is going to fly by Earth at about 10 times the distance to the Moon on 29 June 2023 (National Aeronautics and Space Administration Center for Near Earth Object Studies, "NEO Earth Close Approaches," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/ca). See also: National Science & Technology Council "National Near-Earth Object Preparedness Strategy and Action Plan," June 2018, As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf

[17] European Space Agency Near-Earth Objects Coordination Centre: "2023DW", webpage, 9 March 2023. As of 10 March 2023: https://neo.ssa.esa.int/search-for-asteroids?tab=possimp&des=2023DW

[18] Bottke, W.F., Morbidelli, A., Jedicke, R., et al. (2002). Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects. *Icarus*. 156(2):399-433. As of January 18, 2023: https://doi.org/10.1006/icar.2001.6788

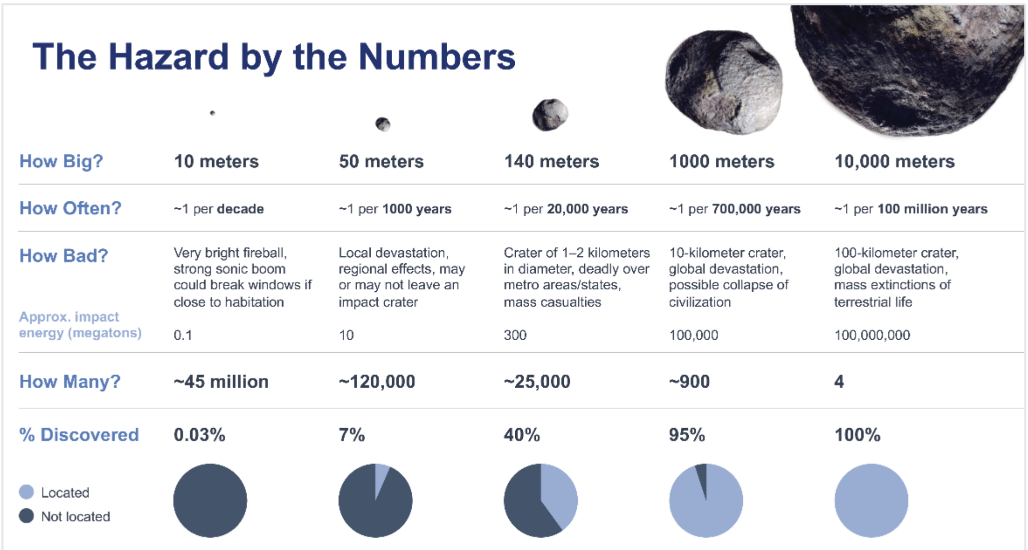
[19] Due to their high speed relative to Earth, impactors have a great amount of kinetic energy, some of which is converted into heat through atmospheric friction, which in turn can generate shockwaves and can also cause the object to break apart or even vaporize. However, while the energy set free by an impact can be compared to that of a nuclear weapon, and is often measured in the same units (kilotons or Megatons of TNT equivalent), an asteroid or comet impact has only some of the effects of a nuclear weapon, namely blast wave and thermal pulse. Most importantly, radioactivity, either instant or via fallout, is not a concern. Electromagnetic pulse (EMP) is not an issue, either.

[20] Popova, O.P., Jenniskens, P., Emel'yanenko, V., et al. (2013). Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization. *Science*.;342(6162):1069-1073. As of January 18, 2023: https://doi:10.1126/science.1242642

to 40 km. However, there were few casualties since the area was very sparsely populated. [21]

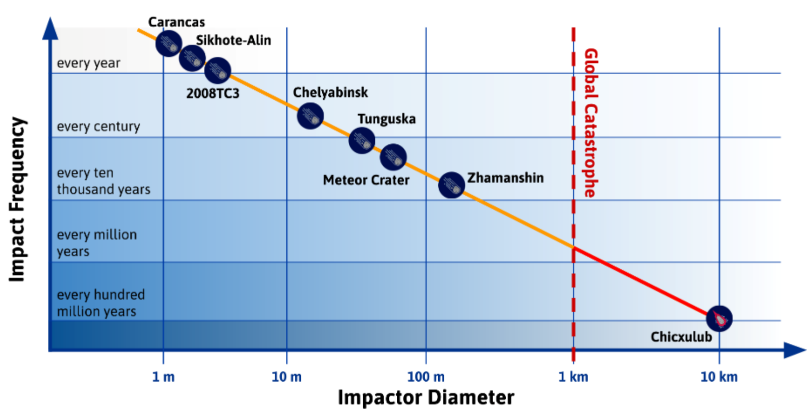
Chapters 1 and 2 provide important additional information on these topics.

Figure 1: Impact Risk From Asteroids



Source: NASA/FEMA Planetary Defense TTX4 Module 0 Presentation (https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf, February 2022)
Note: a larger version of this figure is provided in Appendix A.6 on page 111. "How many" reflects the estimated total population (i.e. approximately how many objects of a given size range there are), based on statistical analysis. "% Discovered" indicates the share of that total population that has been discovered by astronomers so far.

Figure 2: Impact Frequency by Object Size



Source: Near-Earth Objects Coordination Centre, "Public Outreach," webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/public-outreach. © European Space Agency – ESA. Used by permission.

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[21] Jenniskens, P., Popova, O.P., Glazachev, D.O., Podobnaya, E.D., and Kartashova, A.P. (2019). Tunguska eyewitness accounts, injuries, and casualties. *Icarus*. 327:4-18. As of January 18, 2023: https://doi.org/10.1016/j.icarus.2019.01.001

What are the timelines, and what are the options once a threat materializes?

After astronomers **detect** a new object in the Solar System, repeated observations – generally taken over the course of several days or weeks – allow an initial determination of its trajectory and rough estimation of its size. For objects whose orbit may intersect Earth's, and who thus present a potential threat, a global observation campaign involving both professional and amateur astronomers and both Earth-based and in-space telescopes is launched to further **refine the trajectory**, so that the likelihood of impact can be predicted more accurately. This, however, can take months to years, and the precise location of an impact is sometimes not known until a relatively short time – days or weeks – beforehand. Figure 24 on page 55 illustrates this uncertainty. The approximate time of a potential impact, however, can be predicted relatively early.

If there is sufficient time (several years to a decade) before a predicted impact, space agencies can launch a **reconnaissance ("characterization") mission** to the potentially hazardous object, to get close-up views of its size and shape, and characterize its composition. This will enable more accurate trajectory and damage predictions, and will also inform the design of any mitigation missions that aim to deflect or destroy the object so it no longer poses a threat. However, it currently takes years to design and build a spacecraft for a reconnaissance or mitigation mission, and flight times from Earth to its rendezvous with the threatening object likely also will be measured in years. Thus, this is only an option for Planetary Defense scenarios with a long lead time.

A **mitigation mission** is designed to change an object's trajectory so that it misses Earth ("**deflection**"), or to break the object into smaller, less dangerous parts ("**disruption**"). The following deflection approaches are generally considered the most technologically mature:

- **Kinetic impactor**: a spacecraft is sent on a collision course with the object to impart an impulse that will change the object's speed and thus its trajectory. The heavier the spacecraft, and the higher its speed on impact, the larger the deflection. This is the only mitigation approach that has actually been tested in space, by NASA's DART mission in 2022.[22]
- **Nuclear explosive device**: a nuclear device is detonated within a few hundred meters of the object. The energy released will vaporize part of the object's surface, resulting in a momentary thrust that will nudge the object into a different trajectory. This is the only relatively mature approach that can also be used for disruption.
- **Gravity tractor**: a spacecraft flies next to the object for many years. The gravitational forces between the spacecraft and the object, even though very small, will change the object's orbit over the course of time.
- **Ion Beam**: In this concept, a satellite keeps station near the object and directs a powerful ion beam generator (which could be based on an electric space propulsion engine) at it, thus imparting a small but permanent force. Another

[22] National Aeronautics and Space Administration Solar System Exploration Our Galactic Neighborhood, "Double Asteroid Redirection Test (DART)" webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/missions/dart/in-depth/

generator projects an ion beam in the opposite direction to balance the forces on the spacecraft. Over the course of years, this will change the trajectory of the object.

Again, distance and time play a critical role: if the object is still far away from Earth at the time of the mitigation (years before impact), then even a small change in its trajectory will cause an object to miss Earth. However, **the less warning time there is, and the longer it takes to get the mitigation spacecraft near the object, the more challenging the mitigation mission becomes**. Especially if time is short, a single spacecraft can be designed to provide both reconnaissance, and, if warranted, mitigation (e.g. by installing a nuclear explosive device on board). Deflection usually requires longer warning times than disruption.[23]

In addition to deflecting or disrupting a threatening object, even if an object is found years in advance, leaders also need to prepare a **terrestrial response** to a potential impact, in case mitigation fails. Depending on the time available, this will involve warning the public, evacuating areas at risk, and staging disaster response capabilities to deal with the aftermath of an impact. However, terrestrial response is made more challenging by the uncertainty in determining the exact location of an impact and predicting the extent of the damage.

Table 1 summarizes the options depending on the time available. Chapters 3 and 5 provide important additional information.

What can be done now to reduce the risk?

As mentioned above, increasing the available warning time expands the amount of response options and the likelihood of a successful deflection. Thus, Earth's first line of defense are **comprehensive detection capabilities** that constantly survey the whole sky for new threatening objects and that allow for a rapid determination of their trajectories. Over the course of the last two decades, the U.S. National Aeronautics and Space Agency (NASA), the European Space Agency (ESA), and other space agencies have started putting this infrastructure in place, but additional telescopes – both on the ground and in space – designed to detect and track near-Earth objects, and related processing and analysis capabilities, are still needed to find all potential impact threats.

Maximizing the use of the time between detection and mitigation is important as well. That means characterization and mitigation spacecraft have to be designed and assembled more rapidly once the need arises , which is something that can be fostered by additional related research and development. It also requires the availability of powerful rockets that can inject them into deep-space trajectories on relatively short notice. Large new launch vehicles like the SpaceX "Starship"[24] or Blue Origin's "New

[23] Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf
[24] SpaceX: "Starship", webpage, undated. As of 18 January 2023: https://www.spacex.com/vehicles/starship/

Glenn"[25] that are currently under development can make an important near-term contribution here.

Finally, for scenarios where mitigation fails, **emergency responses on Earth** must be prepared, with measures ranging from increasing awareness to contingency planning to public notification. For this, too, preparing well ahead of the need can save critical time especially in case of a short-notice emergency.

Chapter 4 provides important additional information on this topic.

[25] Blue Origin: "New Glenn", webpage, undated. As of 18 January 2023: https://www.blueorigin.com/new-glenn/

Table 1: Time Horizons for Planetary Defense Decision-Making

Warning Time Before Impact	Initial Discovery	Decisionmaking	Alerting the Population	Characterization	Mitigation	Terrestrial Response Options (for Government, Industry, Individuals)	Terrestrial Response Type	Example Scenarios**
No-Notice	Direct observation, bolide detection sensors	Reactive only	-	-	-	-	Comparable to earthquake response	**Chelyabinsk, 2013**
Minutes	Radar*	Comparable to nuclear attack response	EAS? WEA?	-	-	Isolate power grid? Shut down nuclear reactors? Stop trains and road traffic? Sheltering in place?	Comparable to earthquake response	
Hours	Radar*, telescopes?	Limited, high priority only	EAS, WEA, broadcast media, social media	Radar? Telescopes?	Disruption: ICBMs?	Above plus: self-evacuations, activating local emergency responders	Comparable to tornado response	**Sudan, 2008 (2008 TC_3)**
Days	Radar*, telescopes	Limited	EAS, WEA, broadcast media, social media, print media	Radar, telescopes	Disruption: ICBMs?	Above plus: staging regional responders and supplies, organized evacuations	Comparable to hurricane response	
Weeks	Radar*, telescopes	Deliberate but accelerated	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device?	Above plus: staging national and global responders and supplies, comprehensive evacuations, some permanent moves	Customized rapid response	NASA/FEMA TTX-1
Months	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device? Deflection: nuclear explosive device?	Above plus: more comprehensive permanent moves, relocation of certain industries / institutions / resources, building improvised shelters	Customized rapid response	PDC 2021, NASA/FEMA TTX-4
Years	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space mission	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor?	Above plus: potential permanent relocation of most populations / industries / institutions / resources (depending on deflection outcome), establishing long-term deep shelters	Customized long-lead response	NASA/FEMA TTX-2 & TTX-3, PDC 2015, PDC 2019
Decade+	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space missions	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor, gravity tractor, ion beam	Above plus: potential permanent relocation of all populations / industries / institutions / resources (depending on deflection outcome), establishing off-earth colonies	Customized long-lead response	**99942 Apophis, 2023 DW**; PDC 2013, PDC 2017, PDC 2023

Source: RAND Analysis

Notes: "*" only if radar happens to be looking in the right direction. "?"option might not apply. "**" **bold** = actual asteroid. All reconnaissance ("characterization"), mitigation, and terrestrial response options are discussed in detail, and references are provided, in Chapter 5. EAS: Emergency Alert System (in the U.S.) or similar government-run notification mechanism leveraging broadcast television/radio, electronic road signs, etc.; WEA: Wireless Emergency Alerts (in the U.S.) or similar government-run notification mechanism leveraging mobile phone infrastructure. See Appendix A.1 (page 101) for other abbreviations.

Who decides, and how?

As is the case for preparedness against other emergencies, **each nation should be responsible for protecting its population** against the threat of asteroid and comet impacts. However, due to the potentially global scale of the threat, and the need for advanced spaceflight capabilities that only very few countries currently have, Planetary Defense is by necessity global in scope.

In particular, detection and tracking is based on the contributions of astronomers – both professional and amateur – located around the world, operating sensors ranging from homebuilt backyard telescopes to large observatories designed specifically to discover threatening objects. They feed tens of millions of individual observations per year to the International Astronomical Union's **Minor Planet Center (MPC)**, the internationally recognized clearinghouse for such data.[26] The MPC, located in Cambridge, Massachusetts, then estimates a newly-discovered object's orbit based on those observations. If a potentially hazardous asteroid or comet is detected, the **Center for Near-Earth Object Studies (CNEOS)** at the Jet Propulsion Laboratory in California[27] and ESA's **Near-Earth Objects Coordination Centre (NEOCC)**[28] perform calculations using this data to generate a hazard assessment. In case of a potential impact, the **International Asteroid Warning Network (IAWN)**[29] will issue a worldwide notification, and also notify the **United Nations** which in turn will notify its member states.

If the threat warrants, these organizations will ask astronomers to conduct more detailed observations. Thanks to widespread automation, such requests can be completed in minutes.[30] In addition, space agencies around the world will likely start planning reconnaissance and/or mitigation missions. These efforts will be coordinated by the **Space Mission Planning Advisory Group (SMPAG)**,[31] an association of space agencies also endorsed by the United Nations. Both IAWN and SMPAG will become active when certain agreed-upon thresholds in terms of size and timing of impact will be met (see Chapter 6).

Many national governments will have their own notification and decision-making procedures for Near-Earth Object impact emergencies. In the United States, for example, the **Planetary Defense Officer** is responsible for informing senior U.S. federal government officials who will in turn issue warnings to the U.S. public (through the Department of Homeland Security) and other nations (through the Department of

[26] Center for Astrophysics, "The Minor Planet Center," webpage, undated. As of January 18, 2023: https://minorplanetcenter.net/
[27] National Aeronautics and Space Administration Center for Near Earth Object Studies, "Top News Stories," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/
[28] European Space Agency, Near-Earth Objects Coordination Centre, "NEOCC Database Statistics," webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/home
[29] International Asteroid Warning Network, "History," webpage, undated. As of January 18, 2023: https://iawn.net/about.shtml
[30] International Asteroid Warning Network, "Sixth Meteoroid Detected Prior to Impact," webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/-/sixth-meteoroid-detected-prior-to-impact
[31] International Asteroid Warning Network, "Space Mission Planning Advisory Group," webpage, undated. As of January 18, 2023: http://www.smpag.net

State).[32] Figure 35 on page 83 shows the U.S. process for deciding on launching reconnaissance and mitigation missions. Chapter 6 provides important additional information on this topic.

How should the general public be informed once a specific threat has been detected?

Due to the broad-based global participation in asteroid and comet detection, and observations as well as predictions routinely being widely and rapidly distributed among the astronomical community, **news of a newly discovered potentially hazardous object will spread quickly**. Leaders have to realize that parts of the public will likely already be aware of the threat by the time that initial official statements are distributed. However, **mis- and disinformation will likely start circulating as well**, and leaders must be prepared to actively counter that. This should include preemptively addressing potential misperceptions, and will require using clear and correct language as well as being open about the significant uncertainties that will likely exist through much of the post-discovery phase.

The general public will require overview information to put the threat in context, as well as detailed instructions regarding what to do to protect themselves, their loved ones, and their assets. The former includes describing the potential impact date, the impact area, the magnitude of the threat, any uncertainties involved, and what authorities are planning to do about it. Notifications should **refer to authoritative sources** such as CNEOS, and should indicate when updated information will become available.

If there is significant lead time (months or more), more comprehensive and sophisticated information strategies can be designed and implemented. However, short-notice emergencies benefit particularly from preparation, for example, from press releases that are drafted in advance and only require filling in the specifics.

Especially for Planetary Defense emergencies with very short notice (hours), and for broadcasting emergency response information after an impact, the main options for quickly alerting large parts of the population in the affected area are:

- **Wireless alert systems that leverage the cell phone infrastructure**, such as the U.S. "Wireless Emergency Alerts" system[33] or the "EU Alert" used in many European countries[34]
- Public warning systems tied to existing television and radio broadcast infrastructure, like the U.S. "Emergency Alert System"[35]

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[32] National Aeronautics and Space Administration, "Notification and Communications Regarding Potential Near-Earth Object Threats (Revalidated with Change 1)," webpage, February 15, 2022. As of January 18, 2023: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPD&c=8740&s=1

[33] Federal Communications Commission, "Wireless Emergency Alerts," webpage, January 11, 2023. As of January 18, 2023: https://www.fcc.gov/consumers/guides/wireless-emergency-alerts-wea

[34] European Telecommunications Standards Institute, "Technical Specification. Emergency Communications (EMTEL); European Public Warning System (EU-ALERT) using the Cell Broadcast Service," Sophia-Antipolis, France, 2019. As of January 18, 2023: https://www.etsi.org/deliver/etsi_ts/102900_102999/102900/01.03.01_60/ts_102900v010301p.pdf

[35] Federal Communications Commission, "The Emergency Alert System (EAS)" webpage, November 16, 2022. As of January 18, 2023: https://www.fcc.gov/emergency-alert-system

- Warning infrastructure such as sirens and voice-based alerting systems

Chapter 7 provides important additional information on this topic.

Further reading

Beyond this report, the following sources are recommended reading for those wishing to familiarize themselves more with this topic ahead of time:

- NASA's Planetary Defense Coordination Office website, particularly the "Frequently Asked Questions" page at https://www.nasa.gov/planetarydefense/faq
- ESA's Planetary Defence website at https://www.esa.int/Space_Safety/Planetary_Defence
- Papers presented at past Planetary Defense Conferences, available at https://iaaspace.org/event/8th-iaa-planetary-defense-conference-2023/ (halfway down the page)

In case of an actual Planetary Defense emergency, the following organizations will be providing authoritative, up-to-date information:

- Again, NASA's Planetary Defense Coordination Office (https://www.nasa.gov/planetarydefense)
- ESA's Planetary Defence Office (https://www.esa.int/Space_Safety/Planetary_Defence), also via its Near-Earth Objects Coordination Centre (https://neo.ssa.esa.int/home)
- The Center for Near-Earth Object Studies at JPL (https://cneos.jpl.nasa.gov/news)
- The International Asteroid Warning Network (https://iawn.net/index.shtml)
- The Space Mission Planning Advisory Group (http://www.smpag.net)

Again, see Chapter 6 and the "Contact Information" section in the Appendix for more detailed information.

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Chapter 1: What Are the Odds?

Small space rocks – from pebble-sized to about one meter in diameter – impact the atmosphere every single night.[36] This results in short-lived streaks of light ("shooting stars") that can be visible from the ground but don't cause any damage.[37] Slightly larger rocks called bolides – several meters in diameter – disintegrate in the atmosphere up to several times per year, causing a larger fireball. Figure 3 shows the location and magnitude of major[38] bolide events detected by NASA and DoD satellites since 1988, and Figure 8 shows known impact craters around the world. The virtually random patterns illustrates that **all countries are at risk**.

At the same time, the geological record shows that 66 million years ago a larger rock of approximately 15 km diameter hit in the Gulf of Mexico near what is now the Yucatan Peninsula, creating instant destruction across thousands of kilometers and triggering global changes that wiped out the dinosaurs along with most other higher life forms on Earth.[39] And in the early years of the Solar System, an even larger chunk of rock hit Earth with such force that a significant part of our planet was ejected into space and then formed our Moon.[40]

It is therefore important for humanity to detect and track asteroids and comets[41] that have the potential to collide with Earth – called "Potentially Hazardous Objects" (PHOs)[42] – so that these impactors can be diverted if possible, or at least an emergency response on Earth can be prepared (see Chapter 5). Systematically searching for such PHOs is part of the Planetary Defense mission, and several organizations worldwide are engaged in this (see Chapter 6 and Appendix A.5). Planetary Defense-related research has resulted in multiple insights that allow for an assessment of the likelihood of asteroid impacts:

- Most importantly, at this time, **no currently known near-Earth object of a size that could cause damage is predicted to hit Earth within the next**

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[36] National Aeronautics and Space Administration Solar System Exploration Our Galactic Neighborhood,"10 Things You Should Know About Planetary Defense," webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/news/900/10-things-you-should-know-about-planetary-defense/

[37] National Aeronautics and Space Administration, Solar System Exploration Our Galactic Neighborhood, "Meteors & Meteorites" webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/asteroids-comets-and-meteors/meteors-and-meteorites/in-depth

[38] The figure only shows bolide events with an estimated energy release of at least one kiloton of equivalent TNT explosive, comparable to that of a small nuclear bomb.

[39] Schulte P, Alegret L, Arenillas I, et al. "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary". *Science*. 2010;327(5970):1214-1218. https://doi.org/10.1126/science.1177265

[40] National Aeronautics and Space Administration Solar System Exploration Research Virtual Institute, "Early Formation of the Moon," webpage, undated. As of January 18, 2023: https://sservi.nasa.gov/articles/early-formation-of-the-moon/

[41] An asteroid is a larger space rock, left over from the formation of the Solar System. A comet consists of a core of ice and dust, and – when getting closer to the sun – develops a "tail" sometimes visible from Earth. Appendix A.0 (page 35) contains additional definitions.

[42] NASA defines PHOs as "the subset of [near-Earth objects] whose orbits predict they will come within 5 million miles of Earth's orbit; and of a size large enough (30 to 50 meters) to damage Earth's surface" (NASA: "Planetary Defense at NASA," webpage, undated. As of 10 March 2023: https://www.nasa.gov/specials/pdco/index.html)

century.[43] Table 2 shows all such objects, sorted by distance of closest approach. However, as the example of Asteroid 2023 DW illustrates,[44] new and potentially-threatening objects are being detected every year. Appendix A.2 (page 103) provides an additional table showing the most threatening potential impact events for the next several hundred years caused by currently known objects.

- **Larger objects hit Earth much less frequently than smaller ones**. At the same time, larger objects can also cause much more damage (see Chapter 2). Figure 4 shows the relationship between impact frequency and size/damage:
    - A small object that can cause light damage (broken windows across a city-sized area) can be expected to hit Earth once every decade. However, since most of the Earth's surface consists of oceans, actual damage over inhabited areas is expected to occur less frequently (see also Figure 3). The most recent of these impacts happened in 2013 over the Russian city of Chelyabinsk; [45] see the "Historical Examples" section in Chapter 2 (page 43).
    - Objects around 50 m in diameter hit Earth about once every thousand years, and can cause more substantial damage on the ground.
    - An object that can completely wipe out a major metropolitan area might hit Earth once every 20,000 years or so.
    - A kilometer-sized object that will cause global devastation and would likely bring about the end of human civilization is expected to hit every 700,000 years on average.
    - Finally, a very large object that will end most life on Earth, comparable to the Chicxulub impact [46] about 66 million years ago (see the "Historical Examples" section in Chapter 2), can be expected to hit every 100 million years or so.
- The larger an asteroid, the more likely it is that it has already been discovered and is being tracked, which makes it **less likely for a larger asteroid to hit Earth by surprise**. Figure 5 shows that most of the currently-known very large PHOs, which have the potential to destroy our civilization, were detected between 1998 and 2010. It also shows that several of these objects are still being detected every year.
- However, there are still **many smaller asteroids that are nevertheless large enough to destroy a city or small country which have not yet been**

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[43] National Aeronautics and Space Administration Center for Near Earth Object Studies, "NEO Earth Close Approaches," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/ca (However, there are known objects with the potential to impact Earth several hundred years from now; see National Aeronautics and Space Administration Center for Near Earth Object Studies, "Sentry: Earth Impact Monitoring," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/sentry

[44] European Space Agency Near-Earth Objects Coordination Centre: "2023DW", webpage, 9 March 2023. As of 10 March 2023: https://neo.ssa.esa.int/search-for-asteroids?tab=possimp&des=2023DW

[45] Popova, O.P., Jenniskens, P., Emel'yanenko, V., et al. (2013). Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization. *Science*.;342(6162):1069-1073. As of January 18, 2023: https://doi:10.1126/science.1242642

[46] Schulte P, Alegret L, Arenillas I, et al. "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary". *Science*. 2010;327(5970):1214-1218. https://doi.org/10.1126/science.1177265

discovered. As Figure 6 shows, NASA and others have so far identified less than half of those objects. Figure 7 illustrates that, unlike the drop in new discoveries of very large objects that is evident in Figure 5, detection of smaller – but still dangerous – objects has not peaked. The asteroid which caused damage around the Russian city of Chelyabinsk in 2013 (see the "Historical Examples" section in Chapter 2) was not discovered ahead of its impact.

Comets are more difficult to discover and track, since, due to their orbits, many are far away from the inner Solar System most of the time and are therefore more challenging to detect. Thus **the risk of a comet impact is harder to predict**.[47] However, in-depth analysis indicates that the risk from a comet impact is only **approximately 1% that of an asteroid impact**.[48]

Finally, since almost all potentially hazardous objects orbit around the Sun just like the Earth does, there is a chance of multiple encounters between Earth and an object over the course of time. Furthermore, Earth is large enough for its gravity to slightly change the orbit of an object that passes close by. This has to be taken into account for orbit predictions and collision risk assessment and mitigation. For some objects, passing through a specific, generally relatively small area of space (referred to as a "keyhole"), will deflect them just enough to impact Earth on a future occasion. This complicates long-term impact predictions.[49]

Bottom line: **asteroid and comet impacts have to be considered global catastrophic risks**.[50]

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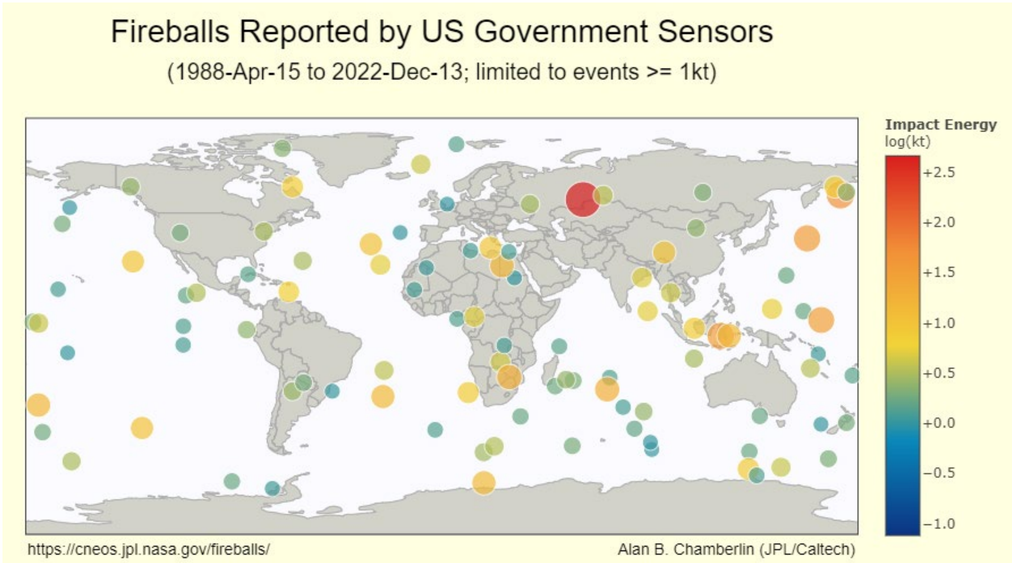
[47] Bottke, W.F., Morbidelli, A., Jedicke, R., et al. (2002). Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects. *Icarus*. 156(2):399-433. As of January 18, 2023: https://doi.org/10.1006/icar.2001.6788

[48] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf (Section 2.3)

[49] Chodas, P. (1999). Orbit Uncertainties, Keyholes, and Collision Probabilities. American Astronomical Society, DPS meeting #31, As of 18 January 2023: https://ui.adsabs.harvard.edu/abs/1999DPS....31.2804C/abstract

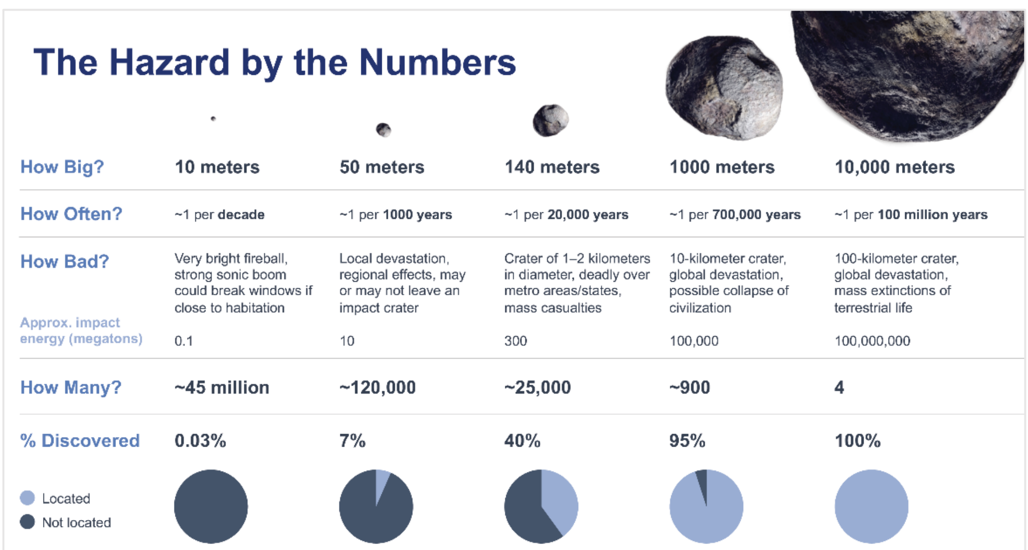
[50] Global Challenges Foundation, "Annual Report: GCF & Thought Leaders Sharing What You Need To Know About Global Catastrophic Risks In 2022," Electronic Report, undated. As of January 18, 2023: https://globalchallenges.org/wp-content/uploads/2022/12/GCF_Annual_Report_2022.pdf

Figure 3: Map of Large Bolide Events Detected by U.S. Government Sensors Since 1988



Source: National Aeronautics and Space Administration Center for Near Earth Object Studies, "Fireballs" webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/fireballs/

Figure 4: Impact Risk From Asteroids



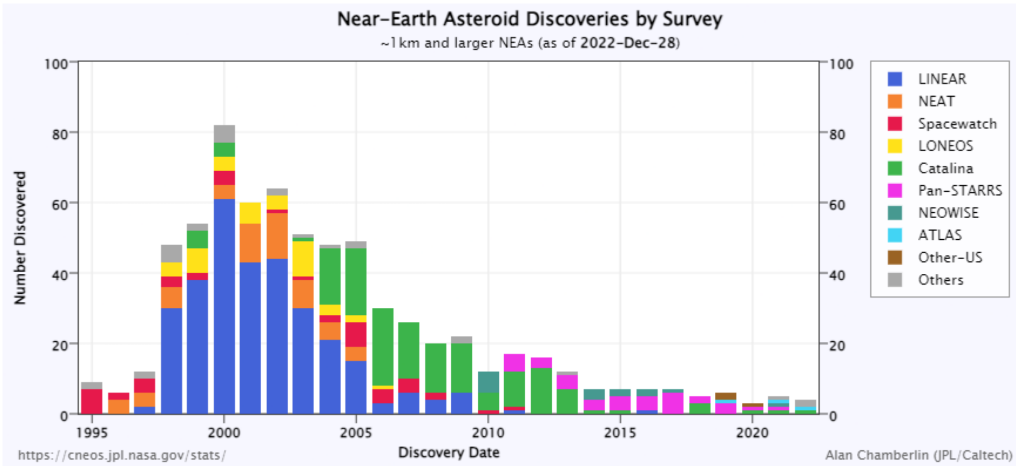
Source: NASA/FEMA Planetary Defense TTX4 Module 0 Presentation (https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf, February 2022)
Note: a larger version of this figure is provided in Appendix A.6 (page 111). "How many" reflects the estimated total population (i.e. approximately how many objects of a given size range there are), based on statistical analysis. "% Discovered" indicates the share of that total population that has been discovered by astronomers so far.

Table 2: All 35 Currently Known Potentially Hazardous Objects That Will Pass Inside the Orbit of the Moon Between Now and 2200

Object Name	Date of Closest Approach (UTC)	Closest Distance (Fraction of Lunar Distance)	Approx. Object Diameter (meters)
(2022 QX4)	2169-Sep-06	0.02	50
99942 **Apophis** (2004 MN4)	2029-Apr-13	0.08	340
(2018 NL)	2055-Jun-29	0.11	40
(2021 FT1)	2098-Mar-23	0.13	50
(2007 UW1)	2129-Oct-19	0.14	120
(2017 HZ4)	2162-Jun-01	0.15	30
(2015 XA378)	2053-Jun-01	0.21	30
(2012 UE34)	2041-Apr-08	0.27	90
(2008 DB)	2032-Aug-14	0.31	30
(2014 SM143)	2197-Oct-23	0.35	360
(2020 UL3)	2085-Nov-13	0.42	100
308635 (2005 YU55)	2075-Nov-08	0.47	400
(2015 XX128)	2095-Dec-09	0.47	30
101955 **Bennu** (1999 RQ36)	2135-Sep-25	0.49	480
(2007 YS56)	2071-Dec-25	0.49	30
(2011 JA)	2100-Apr-26	0.52	240
(2019 OV3)	2149-Dec-01	0.53	60
(2019 BE5)	2079-Jan-29	0.57	40
456938 (2007 YV56)	2101-Jan-02	0.60	270
153201 (2000 WO107)	2140-Dec-01	0.61	510
153814 (2001 WN5)	2028-Jun-26	0.63	930
(2019 YV1)	2061-Dec-19	0.65	40
(2012 XE133)	2157-Jan-01	0.68	90
(2009 DO111)	2146-Mar-23	0.73	120
85640 (1998 OX4)	2148-Jan-22	0.75	260
(2001 AV43)	2029-Nov-11	0.80	50
(2013 XY8)	2095-Dec-11	0.82	40
(2005 WY55)	2065-May-28	0.84	310
(2022 MK1)	2034-Jul-20	0.86	70
(2019 EM1)	2114-Mar-02	0.87	150
(2014 GY44)	2062-Mar-30	0.88	40
523809 (2007 TV18)	2058-Sep-22	0.90	70
(2015 XF261)	2090-Apr-11	0.91	40
530520 (2011 LT17)	2156-Dec-16	0.94	180
(2019 BE5)	2060-Jan-30	0.97	40

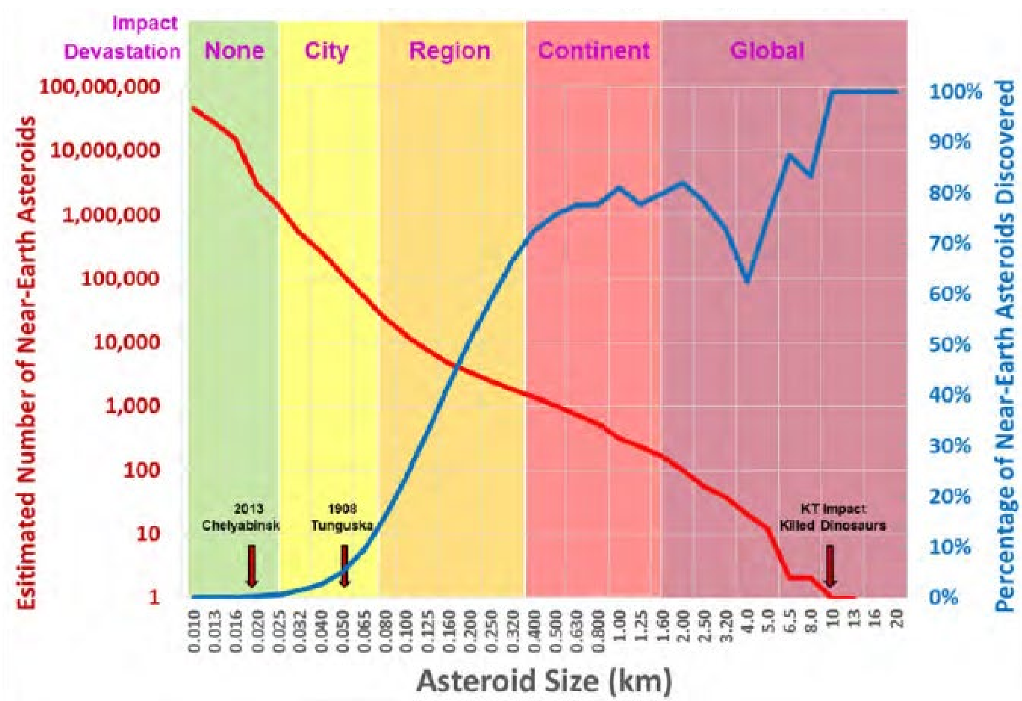
Data source: National Aeronautics and Space Administration Center for Near Earth Object Studies, "NEO Earth Close Approaches," webpage, undated https://cneos.jpl.nasa.gov/ca (as of 28 December 2022)
Sorted by closest distance. Orange highlights indicate a closest approach within the next decade.
Closest distance is the minimum possible distance (based on the uncertainties involved) between the upper edge of the Earth's effective atmosphere (van Karman line, 100 km above the Earth's surface) and the object's center. Lunar distance is 384400 km. Note that the closest two objects could get closer to Earth (approximately 9,000 km for QX4 and 32,000 km for Apophis) than geostationary satellites.
An extended table is provided in Appendix A2 (page 103).

Figure 5: Number of Discovered Near-Earth Asteroids Larger Than 1 km in Each Year Since 1995



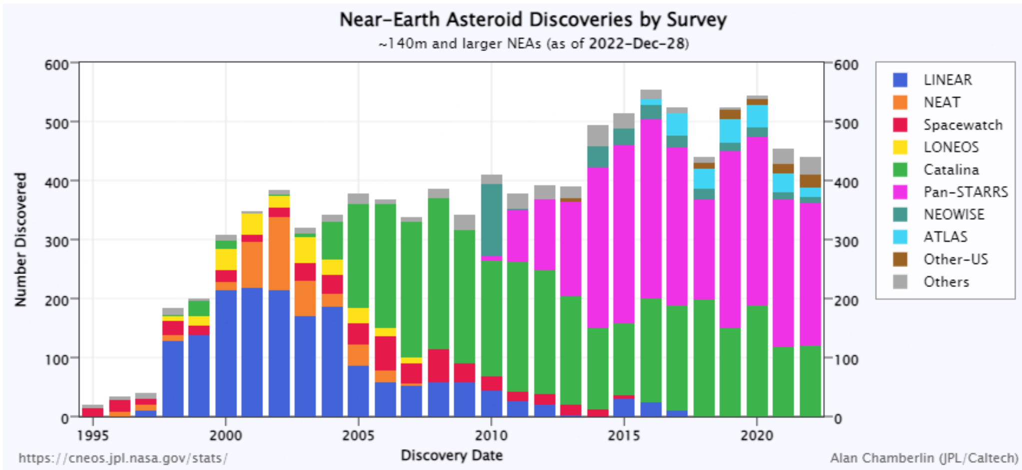
Source: NASA Center for Near Earth Object Studies, "Discovery Statistics by Survey (km)" webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/stats/site_km.html
Note: color indicates discovering telescope or survey campaign

Figure 6: Estimated Share of Near-Earth Asteroids Discovered (as of 2017)



Source: National Science & Technology Council "National Near-Earth Object Preparedness Strategy and Action Plan," June 2018, As of January 18, 2023:
https://www.nasa.gov/sites/default/files/atoms/files/ostp-neo-strategy-action-plan-jun18.pdf

Figure 7: Number of Discovered Near-Earth Asteroids Larger Than 140 m in Each Year Since 1995



Source: NASA Center for Near Earth Object Studies, "Discovery Statistics by Survey (140m)" webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/stats/site_140.html
Note: color indicates discovering telescope or survey campaign

Figure 8: Map of Known Asteroid Impact Craters Around the World (as of 2018)

(Figure omitted in this draft.)

http://www.passc.net/EarthImpactDatabase/Images/world%20map/worldmap%20(2).jpg

Source: Planetary and Space Science Centre, University of New Brunswick, "Earth Impact Database" webpage, undated. As of January 18, 2023: http://www.passc.net/EarthImpactDatabase/New%20website_05-2018/World.html

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Chapter 2: What Would Happen?

Chapter Contents

Earth, like all planets, has been hit by other celestial objects since its formation billions of years ago, and even today small space rocks – from pebble-sized to about one meter in diameter – impact the atmosphere every single night.[51] Such meteoroids[52] usually disintegrate completely in the upper atmosphere, generating light that is visible as a "shooting star" from the ground for a short period of time.[53] However, larger rocks – the size of a house and up – as well as comets can cut through most or all of the Earth's thin protective layer of air and, due to their extremely high speed, cause significant damage.

The extent of this damage depends mainly on the **size of the object** and the speed and angle at which it collides with our planet. **Cosmic impactors the size of a large house can wipe out a small city, and asteroids or comets larger than approximately one kilometer – the size of a small mountain – could devastate a continent.**[54] One such large space rock hit in the Gulf of Mexico, near what is now the Yucatan peninsula, approximately 66 million years ago. The resulting blast and heat waves caused immediate destruction up to a distance of thousands of kilometers from the impact

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[51] National Aeronautics and Space Administration, Solar System Exploration Our Galactic Neighborhood, "Meteors & Meteorites" webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/asteroids-comets-and-meteors/meteors-and-meteorites/in-depth

[52] A meteoroid is a small piece of rock moving through space. Meteors are streaks of light in the Earth's atmosphere that are created when a meteoroid enters the atmosphere. A bolide is a very bright meteor caused by large meteoroids. An asteroid is a larger rock, left over from the formation of the Solar System. A comet consists of a core of ice and dust, and – when getting closer to the sun – usually develops a "tail" that can be visible from Earth. Appendix A.0 (page 35) contains additional definitions.

[53] National Aeronautics and Space Administration, "What's the Difference Between Asteroids, Comets and Meteors? We Asked a NASA Scientist: Episode 16" webpage, December 13, 2021. As of January 18, 2023: https://www.nasa.gov/feature/what-s-the-difference-between-asteroids-comets-and-meteors-we-asked-a-nasa-scientist-episode

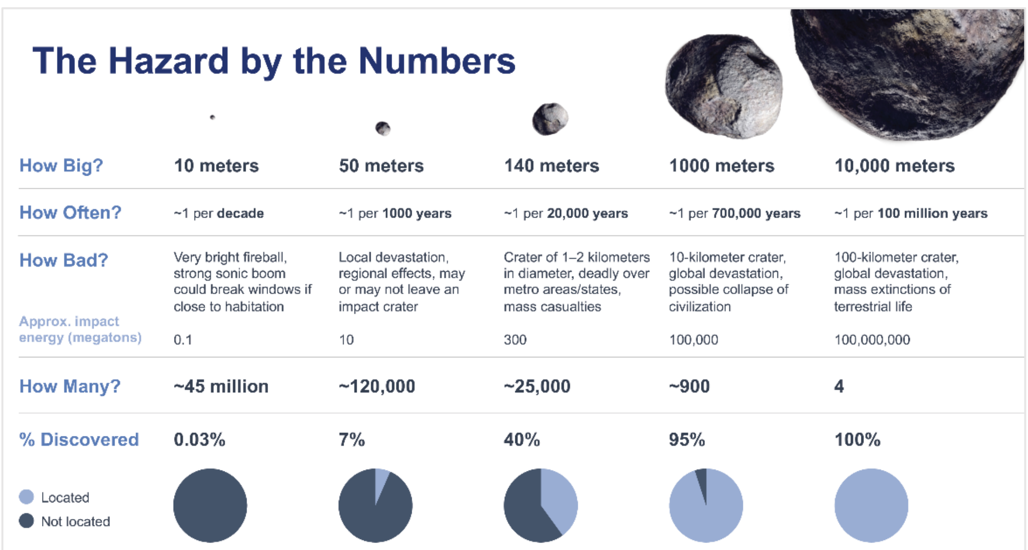
[54] Stadler, Felix, "The Asteroid Impact Threat from Physical Parameters to Information," Technical University of Munich term paper, undated. As of January 18, 2023: https://iawn.astro.umd.edu/documents/supporting/ESA-SSA%20impact%20scale%20report%202016.pdf

site. The impact also triggered earthquakes and tsunamis,[55] and led to changes in global climate. This wiped out the dinosaurs along with most other species on Earth in the months and years following the impact.[56] Figure 9 provides a general overview of size-related factors. Figure 10, which is based on close-up images taken by spacecraft, illustrates the range of different sizes and shapes of asteroids and comets.

An object's **composition also plays a role** in the type and extent of damage: stony asteroids are more likely to break up in the atmosphere, resulting in a blast wave (similar to that created by a large explosion) and thermal (heat) damage, while a metallic asteroid is more likely to reach the ground and also create a crater (and potentially trigger earthquakes and/or tsunamis).

Note that while the energy set free by an impact can be compared to that of a nuclear weapon, and is often measured in the same units (kilotons or Megatons of trinitrotoluol [TNT] explosive equivalent), an asteroid or comet impact has only some of the effects of a nuclear weapon, namely blast wave and thermal pulse. Most importantly, **radioactivity, either instant or via fallout[57], is not a concern**. Electromagnetic pulse (EMP) is not an issue, either.

Figure 9: Impact Risk From Asteroids



Source: NASA/FEMA Planetary Defense TTX4 Module 0 Presentation (https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf, February 2022)
Note: a larger version of this figure is provided in Appendix A.6 (page 111).

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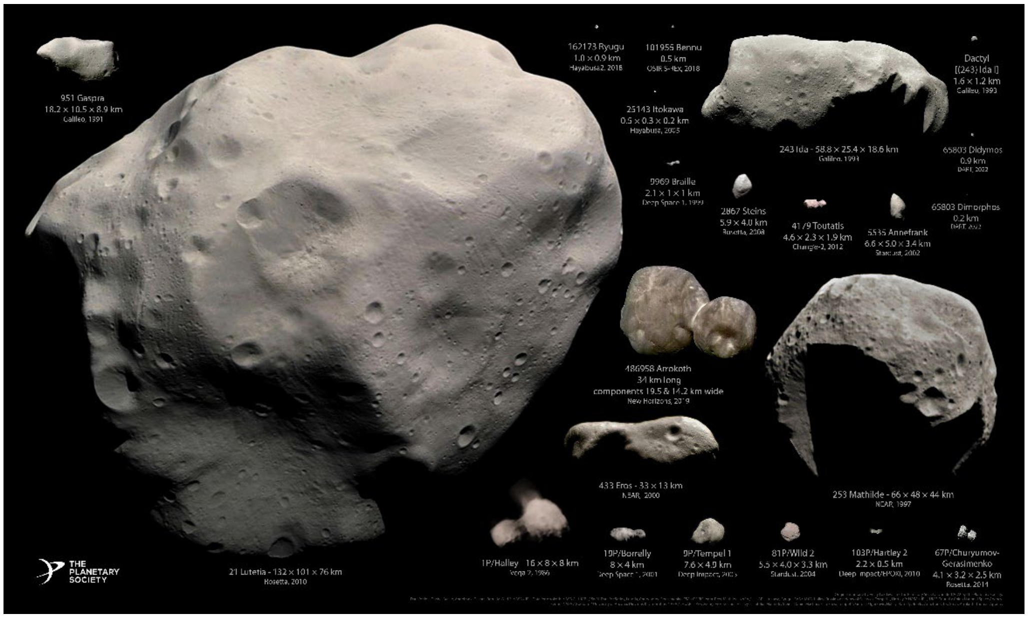
[55] Range, M. M., Arbic, B. K., Johnson, B. C., Moore, T. C., Titov, V., Adcroft, A. J., et al. (2022). The Chicxulub impact produced a powerful global tsunami. *AGU Advances*, 3, e2021AV000627. As of January, 18 2023: https://doi.org/10.1029/2021AV000627

[56] Schulte P, Alegret L, Arenillas I, et al. "The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary". *Science*. 2010;327(5970):1214-1218. https://doi.org/10.1126/science.1177265

[57] However, if an impact damages nuclear power plants, nuclear weapons factories, or similar nuclear infrastructure, then radioactive materials from those facilities can be set free.

Figure 10: Close-Up Images of Some Asteroids and Comets (To Scale)



Source: Planetary Society, Bruce Murray Space Image Library, “Small Asteroids and Comets Visited by Spacecraft as of September 2022,” webpage, undated. As of January 18, 2023:
https://www.planetary.org/space-images/asteroids-and-comets-visited-by-spacecraft
Used by permission.
Note: a larger version of this figure is provided in Appendix A.6 (page 112).

The following sections describe the direct and indirect hazards of an asteroid or comet impact in more detail. Again, **all of these effects are generally worse for larger objects**. The smallest impactors (below approximately 50 m in size for stony objects) generally only cause a blast wave (similar to that resulting from a large conventional or nuclear explosion) and a thermal (heat) pulse. At the other end of the spectrum, only the larger impactors (above approximately 500 m in size) will have a significant impact on global climate. Figure 11 provides an overview of key effects.

However, like with the detonation of a nuclear weapon, the extent of damage depends not just on the amount of energy involved, which in case of an impactor is determined by the impactor’s mass and speed, but also on the altitude at which it is released, which in turn depends on the impactor’s speed, angle of approach, composition (e.g. ice, rock, metal), and shape. Furthermore, weather and terrain effects (cloudiness, humidity, terrain shielding, etc.) can affect the exact shape of the damage footprint (see Figure 12). Furthermore, **an impact over land is likely to cause much more damage than an impact over water**, all else being the same. This is not just due to the much higher population density, but also due to different damage mechanisms.[58]

Many of these factors are not precisely known until shortly before impact, and some may not even be known then, which causes a large amount of uncertainty

[58] Rumpf CM, Lewis HG, Atkinson PM. “Asteroid Impact Effects and their Immediate Hazards for Human Populations,” Geophysical Research Letters. 2017;44(8):3433-3440. doi: https://doi.org/10.1002/2017GL073191

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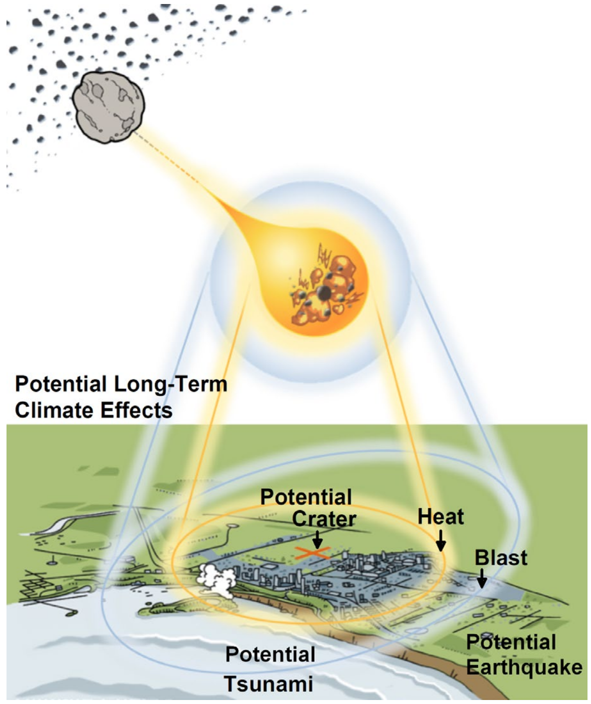
regarding predicting the impact effects and preparing a terrestrial response. However, even rough estimates will be helpful to decisionmakers, and can usually be refined as the time of impact nears (see Chapter 3, starting on page 47, and Appendix A.10, starting on page 123).

Finally, even though they are listed individually below, **effects interact, resulting in more severe damage and less-effective response efforts**. For example, debris from large-scale structural collapses will provide fuel for fires started by the thermal pulse and hot ejecta, which in turn will be made worse by fuel tanks and pipelines ruptured by the blast wave and/or earthquake.[59] Response efforts will be hindered by destroyed and blocked roads, and by damage to critical infrastructure such as hospitals (see Figure 13). Survivors with blast injuries may also suffer from severe burns, and those trapped by collapsed structures won't be able to escape fires. Furthermore, the destruction even from a relatively small impact will extend over many square kilometers, instantly **overwhelming any response capabilities**. Figure 14 shows the aftermath of the 15 kiloton nuclear airburst over Hiroshima, Japan, illustrating the large area that even a small impactor would completely destroy.[60] Figure 15 shows the actual damage footprint from the 1908 Tunguska impact (see "Historical Examples" section at the end of this chapter) overlaid over the New York City metropolitan area.

[59] United States Department of Defense and the Energy Research and Development Administration. "The Effects of Nuclear Weapons." Washington, DC. 1977: https://www.fourmilab.ch/etexts/www/effects

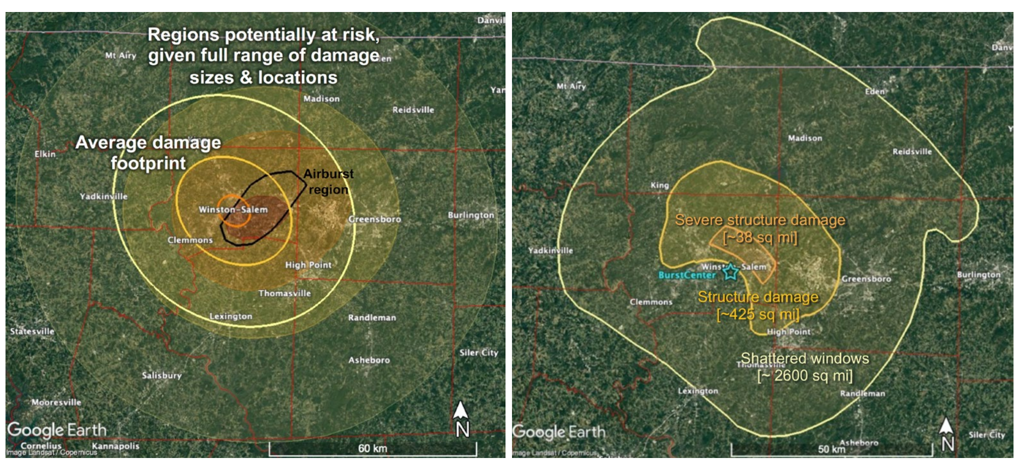
[60] However, typical detonation heights for nuclear airbursts are measured in hundreds of meters (Samuel Glasstone and Philip J. Dolan: "The Effects of Nuclear Weapons," third edition, 1977. As of 10 March 2023: https://doi.org/10.2172/6852629), while disintegrating impactors usually do so at altitudes above 20 km. Their energy is thus distributed over a much larger area, causing less damage compared to an energy release closer to the ground.

Figure 11: Impact Risk From Asteroids



Source: based on Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf
Note: not to scale.

Figure 12: Difference Between Simplified Pre-Impact Prediction (Left) and High-Fidelity Post-Impact Damage Contours (Right) Illustrate Impact of Uncertainty and Importance of Real-World Factors



Sources: Planetary Defense Interagency Tabletop Exercise 4, Module 3, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod3.pdf,
Planetary Defense Interagency Tabletop Exercise 4, Module 4, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod4.pdf
Note: fictitious impact scenario.

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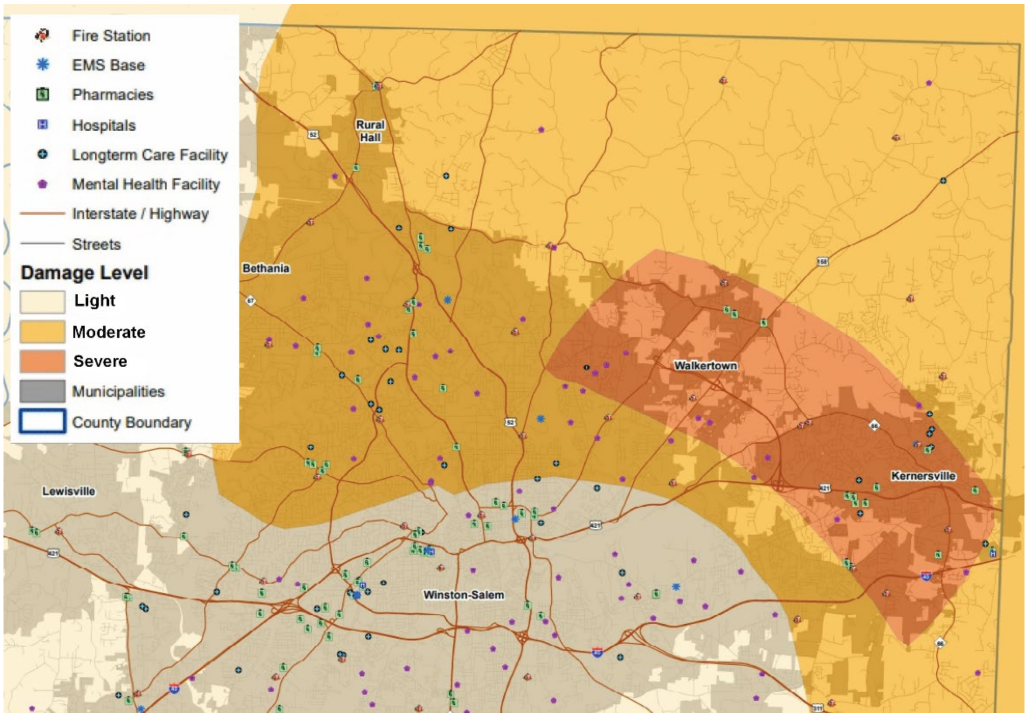
Figure 13: Damage to Critical Infrastructure of a Metropolitan Area Caused by a Hypothetical Small Impactor

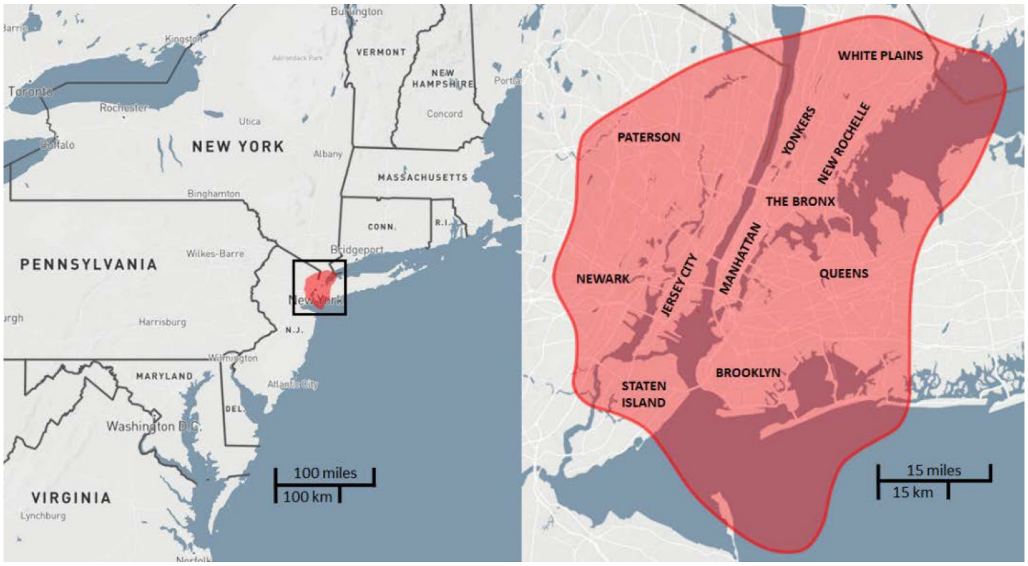


Source: based on Planetary Defense Interagency Tabletop Exercise 4, Module 4, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod4.pdf
Note: fictitious impact scenario

Figure 14: View of Hiroshima, Japan, After 15 kt Low-Altitude Airburst

Source: National Archives, “Photograph of Hiroshima After Atomic Bombing,” NAID: 148728174, March 1946. As of 21 January 2023: https://catalog.archives.gov/id/148728174

Figure 15: Tunguska Impact Damage Footprint Overlaid on New York City



Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

Blast Wave

A blast wave – a zone of very high pressure and winds moving through the atmosphere at high speed from the impact site outwards – causes the majority of the immediate destruction associated with an impact.[61] Like with the blast from a nuclear weapon or from conventional explosives, the degree of destruction depends on the magnitude of the high pressure carried by the blast wave, which generally increases with proximity to the impact site (or to the "ground zero" location under an airburst).

However, blast propagation is complex, with many factors besides distance influencing overpressure levels, including interactions among the shock waves and the ground.[62] Figure 16 shows a high-fidelity numerical simulation of the airburst caused by an impactor of 70 m diameter. The complex blast wave contours are clearly visible. Thus, as the right side of Figure 12 shows, actual blast damage areas are generally bounded by irregular shapes. Detailed computational simulation is required to accurately predict these areas; see Appendix A.7 (page 115) for more information. For initial planning purposes, though, distance can be used as the driving factor. Blast overpressure is commonly measured in Pascals (Pa), bar, or pounds per square inch (psi).

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[61] Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

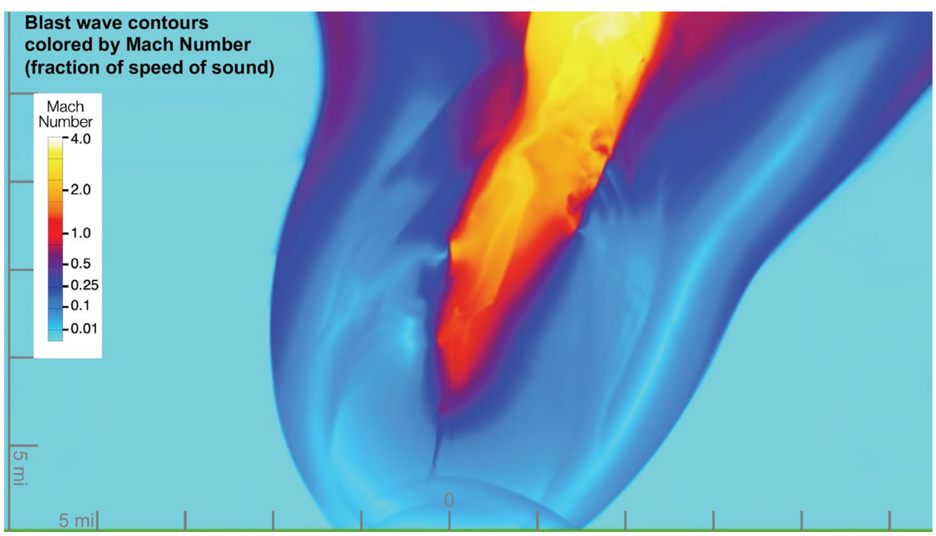
[62] United States Department of Defense and the Energy Research and Development Administration. "The Effects of Nuclear Weapons." Washington, DC. 1977. As of January 18, 2023: https://www.fourmilab.ch/etexts/www/effects

For planning and emergency response purposes, the following damage levels are generally used:[63]

- **Unsurvivable damage**: complete devastation. All but the very strongest buildings collapse, and everyone dies. This damage zone has overpressure levels above 10 psi (0.69 bar).
- **Critical damage**: most residential structures collapse. Universal serious injuries; most people die, including due to direct overpressure effects e.g. on the lungs. Corresponding overpressure levels are between 4 and 10 psi (0.28 and 0.69 bar).
- **Severe damage**: widespread structural damage, doors/windows blown out. Some residential structures collapse. Flying debris causes near-universal serious injuries and widespread fatalities. Overpressure levels are between 2 and 4 psi (0.14 and 0.28 bar).
- **Serious damage**: shattered windows, some additional structural damage. Destruction of some wood-frame houses. Widespread injuries from flying glass, broken bones from buckled walls and roofs. Overpressure levels between 1 and 2 psi (0.07 and 0.14 bar).
- **Light to moderate damage**: overpressure levels between 0.5 and 1 psi (0.03 and 0.07 bar) may lead to some shattered windows and associated injuries.

Note that earthquakes and/or tsunamis triggered by the impact, as well as falling ejecta (see below), can exacerbate structural damage caused by the blast wave.

Figure 16: High-Fidelity Computer Simulation of a ~11 Mt Airburst



Source: Planetary Defense Interagency Tabletop Exercise 4, Module 3, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod3.pdf
Stony asteroid of 70 m diameter, energy equivalent to 11.3 Megatons of TNT, entry velocity 15.5 km/s (~35,000 mph), entry angle 65 degrees, effective airburst altitude approximately 12.5 km (~8 miles).

[63] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf

Figure 17: Examples of Blast Damage

Serious **Severe** **Critical**

Sources: (left) Courtesy photo, U.S. Army Corps of Engineers; (center) Liz Roll, Federal Emergency Management Agency; (right) Sgt. Bradley Church, Defense Imagery Management Operations Center.

Thermal Pulse

The heat generated by the friction between the impactor and the Earth's atmosphere causes its temperature to rise to thousands of degrees (Celsius or Fahrenheit), and it therefore briefly (seconds) emits a great amount of heat. This thermal pulse can set vegetation and structures on fire and cause burn injuries. As with blast, the following damage levels are generally used:[64]

- **Unsurvivable damage**: structures ignite
- **Critical damage**: clothing ignites
- **Severe damage**: third-degree burns to exposed skin
- **Serious damage**: second-degree burns to exposed skin

In addition to fires started by the thermal pulse, hot ejecta (see below) and structural damage due to blast (see above) and earthquakes (see below) can start fires and cause burn injuries as well. Firefighting will be made more difficult by blast damage, which will block roads, degrade firefighting capabilities near the impact site, and may also damage the water supply system. The likely large number of patients with burn injuries and the degradation of the local healthcare system (cf. Figure 13) will increase mortality even further (Figure 18).

[64] Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

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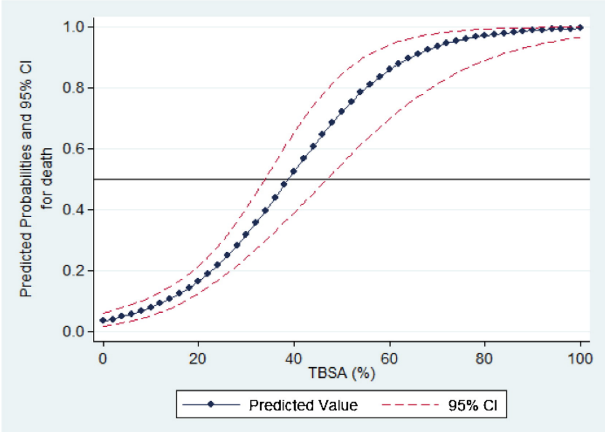
Figure 18: Mortality Rate for Burn Injuries Under Limited-Care Conditions



*TBSA= total body surface area (%)
†Based on a logistic regression model, adjusted for age and mechanism of burn

Source: reprinted from Anna F. Tyson, Laura P. Boschini, Michelle M. Kiser, Jonathan C. Samuel, Steven N. Mjuweni, Bruce A. Cairns, and Anthony G. Charles, "Survival After Burn in a Sub-Saharan Burn Unit: Challenges and Opportunities," Burns, Vol. 39, No. 8, 2013, with permission from Elsevier. As of January 18, 2023: https://doi.org/10.1016/j.burns.2013.04.013
Note: based on patients admitted to a hospital in Malawi, Africa, in 2011 and 2012.

Cratering

Impactors larger than approximately 50 m in diameter (less if they are composed of metal rather than rock) will reach the ground and, in addition to blast and thermal effects, also cause a crater. This of course causes the complete destruction of everything in the cratered area, including buried structures, but can also trigger an earthquake (if the impact is on land, or in sufficiently shallow water) and a tsunami (if the impact is in the ocean). Furthermore, material from the cratered area will be ejected into the atmosphere and may cause additional damage wherever it lands. Figure 19 shows one of the most well-known such craters, Meteor Crater near Winslow, Arizona.

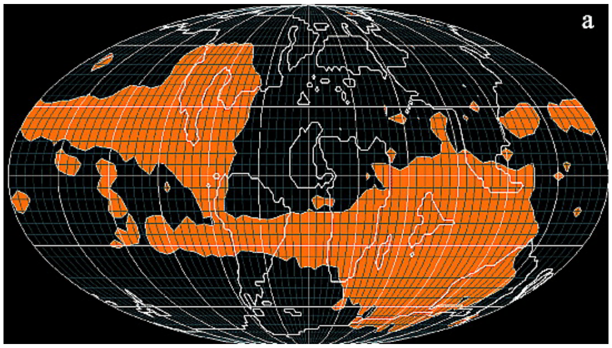
Figure 19: 1.3 km Diameter Crater Caused by a 50 m Sized Nickel-Iron Meteoroid

Source: James St. John, Flickr, CC BY 2.0. As of 10 March 2023: https://www.flickr.com/photos/jsjgeology/25214656020
Note: impact energy approximately 20 Mt. Crater depth approximately 175 m.

Hot Ejecta

Molten rock ejected from the impact site can cause fires where it lands, in addition to those started by the thermal pulse. Ejecta impact can also cause additional destruction due to the relatively high speed with which they hit the ground. Based on the energy of the impact, ejecta can land – and start fires – thousands of kilometers away (Figure 20) within an hour or less after an impact, and sufficiently-large impacts can even accelerate significant amounts of ejecta into space, potentially causing damage to satellites in Earth orbit.[65]

Figure 20: Worldwide Wildfires Started by Chicxulub Asteroid Impact



Source: Kring, D.A., Durda, D.D. (2002). Trajectories and Distribution of Material Ejected from the Chicxulub Impact Crater: Implications for Postimpact Wildfires. *Journal of Geophysical Research: Planets*,107(E8):6-1-6-22. As of January 18, 2023: https://doi.org/10.1029/2001JE001532

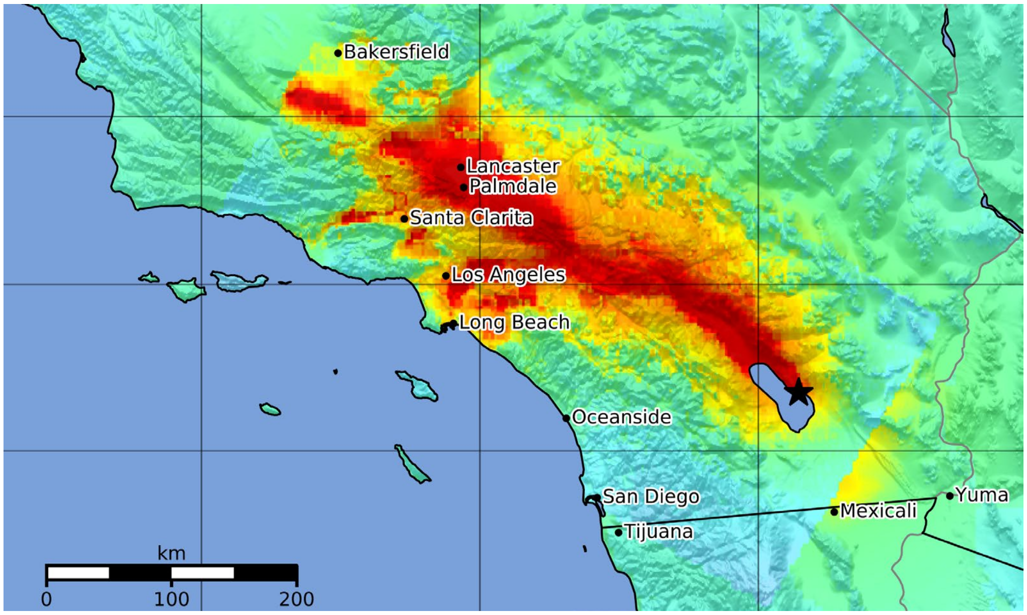
Earthquake

Even a small impactor has the potential to trigger an existing fault line, leading to an earthquake. Larger impactors will cause substantial seismic shocks due to their sheer mass.[66] This will further damage structures already weakened by the blast wave, and can cause damage far away from the impact site (Figure 21).

[65] Kring, D.A., Durda, D.D. (2002). Trajectories and Distribution of Material Ejected from the Chicxulub Impact Crater: Implications for Postimpact Wildfires. *Journal of Geophysical Research: Planets*,107(E8):6-1-6-22. As of January 18, 2023: https://doi.org/10.1029/2001JE001532

[66] Bermúdez, H.D., Vega, F.J., Martini, M., Ross, C., DePalma, R., Bolivar, L., et al. (2022). The Chicxulub Mega-Earthquake Evidence from Colombia, Mexico, and the United States. Geological Society of America Connects 2022 Programs. 54(5). As of January 18, 2023: https://doi.org/10.1130/abs/2022AM-377578

Figure 21: Extent of Damage for Hypothetical Magnitude 7.8 Earthquake in the San Andreas Fault Region of California



Source: U.S. Geological Survey Earthquake Hazards Program, "M 7.8 Scenario Earthquake - Ardent Sentry 2015 Scenario" webpage, undated. As of January 18, 2023: https://earthquake.usgs.gov/scenarios/eventpage/sclegacyardentsentry2015_se

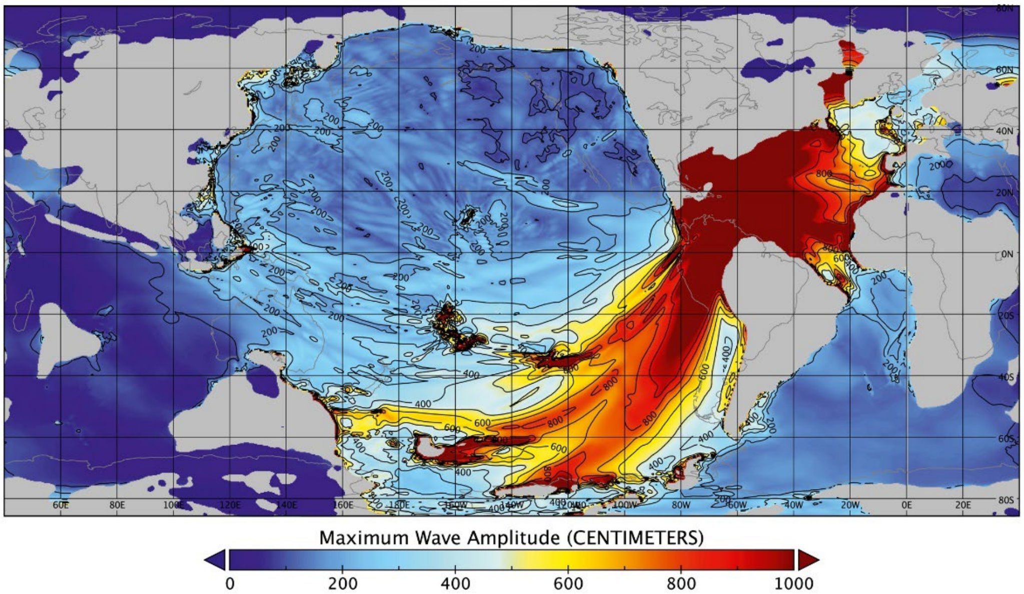
Note: an expanded version of this figure is provided in Appendix A.6 (page 113)

Tsunami

An impact over water, or an earthquake triggered in a coastal area, will cause a tsunami that can damage shorelines thousands of kilometers away from the impact site. Figure 22 shows a simulation-based map of global wave heights caused by the tsunami that was triggered by the large Chicxulub impact 66 million years ago (see also the "Historical Examples" section later in this chapter). Wave heights even 100s of kilometers from the impact area exceeded 100 m, and near most North American shores reached 10 m.[67]

[67] Range, M. M., Arbic, B. K., Johnson, B. C., Moore, T. C., Titov, V., Adcroft, A. J., et al. (2022). The Chicxulub impact produced a powerful global tsunami. *AGU Advances*, 3, e2021AV000627. As of January 18, 2023: https://doi.org/10.1029/2021AV000627 (a video animation of the simulation results is available at https://youtu.be/aJJOjWX3S1Q)

Figure 22: Wave Heights Map of Tsunami Triggered by Chicxulub impact



Source: Range, M. M., Arbic, B. K., Johnson, B. C., Moore, T. C., Titov, V., Adcroft, A. J., et al. (2022). The Chicxulub impact produced a powerful global tsunami. *AGU Advances*, 3, e2021AV000627. As of January, 18 2023: https://doi.org/10.1029/2021AV000627

Injection of Debris into the Atmosphere

Ejecta and dust generated by the impact, and soot from fires started by the thermal pulse or hot ejecta, can also contaminate the atmosphere up to significant distances. This poses an inhalation risk for survivors and animals in the affected area, and can also lead to a drop in average temperatures by several degrees Celsius.[68] Based on observations made after large volcanic eruptions and high-fidelity simulations of asteroid impacts, it can take a long time (months to years) after a large impact for this debris to settle (Figure 23), and many years for temperatures to return to normal.[69]

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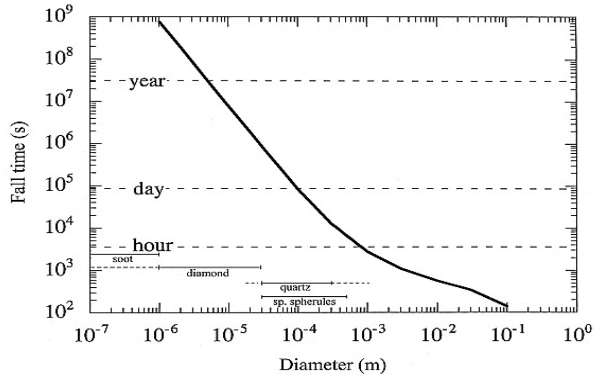
[68] Vellekoop, J., Sluijs, A., Smit, J., Schouten, S., Weijers, J. W., Sinninghe Damsté, J. S., & Brinkhuis, H. (2014). Rapid short-term cooling following the Chicxulub impact at the Cretaceous-Paleogene boundary. *Proceedings of the National Academy of Sciences of the United States of America*, 111(21), 7537–7541. As of January 18, 2023: https://pubmed.ncbi.nlm.nih.gov/24821785/

[69] 69 Vellekoop, J., Sluijs, A., Smit, J., Schouten, S., Weijers, J. W., Sinninghe Damsté, J. S., & Brinkhuis, H. (2014). Rapid short-term cooling following the Chicxulub impact at the Cretaceous-Paleogene boundary. *Proceedings of the National Academy of Sciences of the United States of America*, 111(21), 7537–7541. As of January 18, 2023: https://pubmed.ncbi.nlm.nih.gov/24821785/

Figure 23: Fall Time of Impact Ejecta Based on Diameter



Source: Kring, D.A., Durda, D.D. (2002). Trajectories and Distribution of Material Ejected from the Chicxulub Impact Crater: Implications for Postimpact Wildfires. *Journal of Geophysical Research: Planets*,107(E8):6-1-6-22. As of January 18, 2023: https://doi.org/10.1029/2001JE001532

Higher-Order Effects

The physical damage and the immediate loss of life caused by an impact can also trigger additional threats, for example:

- Secondary damage to dams and levees by the blast wave, earthquakes, or tsunamis, and resulting additional destruction due to dam/levee failures,
- Cascading failures of critical infrastructures,
- A global economic downturn,
- Mass migration,
- Opportunistic wars and revolutions,
- Collapse of governments in the affected area,
- Nations mistaking an impact for a nuclear attack,
- Famines due to persistent changes in climate and subsequently reduced agricultural production.

A detailed discussion would be beyond the scope of this guide, but decision-makers need to be aware of these potential higher-order consequences. Note that even an impact causing only geographically-limited physical damage will have higher-order effects, for example on the global economy. Furthermore, some of these consequences, for example economic downturns, mass migration, wars and revolutions, or even collapse of governments, could even happen before an impact.

Special Considerations Regarding Comets

While comets[70] are likely to have a higher impact velocity than asteroids (about double, on average) due to their different orbits, they are also significantly less dense

[70] A comet consists of a core of ice and dust, and – when getting closer to the sun – develops a "tail" sometimes visible from Earth. In contrast, an asteroid consists of rock or metal. Appendix A.0 (page 35) contains additional definitions.

than asteroids due to their composition (ice rather than rock or metal) and thus their average impact energy will only be about 30% higher.[71]

However, again due to their different orbits, many comets are only detected less than a year before they cross the Earth's orbit, which would leave little time for comprehensive terrestrial preparedness.[72] This is particularly concerning since comets tend to be larger.[73]

Historical Examples

Two relatively recent examples serve to illustrate the damage that can be caused even by relatively small rocks of a size that can be expected to hit Earth about once per century:

- A meteoroid estimated to be about 20 m in diameter broke apart in the atmosphere about 27 km over the Russian city of **Chelyabinsk** in February 2013, releasing energy equivalent to that of a large nuclear bomb (in the 500 kiloton range). Over 1000 people were injured by the resulting blast wave, most from shattered glass, and several thousand buildings were damaged, again mostly due to broken glass.[74] Dust from the bolide explosion produced a stratospheric dust belt.[75]
- A meteoroid estimated to be about 30 m in diameter entered the atmosphere near the **Tunguska** river in central Siberia in June 1908, breaking apart at an altitude of approximately 10 km. The asteroid was estimated to be 220 million pounds and entered Earth's atmosphere at 33,500 miles per hour. Heat and pressure caused the asteroid to explode. The resulting explosion consumed most of the asteroid, preventing the formation of an impact crater[76]. The energy released during that explosion was equivalent to a very large nuclear bomb (around 15 megatons), which started fires up to 15 km from the epicenter and pushed down trees at a distance up to 40 km. A seismic shockwave reached barometers in England. Dense clouds formed,

[71] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf (Section 2.3)
[72] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf (Section 2.3)
[73] Boe, B., Jedicke, R., Meech K.J., et al. (2019). The orbit and size-frequency distribution of long period comets observed by Pan-STARRS1. *Icarus*. 333:252-272. As of January 18, 2023: https://doi.org/10.1016/j.icarus.2019.05.034
[74] Popova, O.P., Jenniskens, P., Emel'yanenko, V., et al. (2013). Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization. *Science*.;342(6162):1069-1073. As of January 18, 2023: https://doi:10.1126/science.1242642
[75] Hansen, Kathryn. "Around the Word in Four Days: NASA Tracks Chelyabinsk Meteor Plume." NASA. As of: January 22, 2023: https://www.nasa.gov/content/goddard/around-the-world-in-4-days-nasa-tracks-chelyabinsk-meteor-plume
[76] Phillips, Tony. "The Tunguska Impact -- 100 Years Later." NASA. As of: January 22, 2023: https://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska

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night skies glowed, and local animals died[77]. However, there were few casualties since the area was very sparsely populated.[78]

Additional examples show the effects of larger asteroids impacting Earth:

- **Barringer Meteor Crater**: A 30 to 50 m in diameter iron meteor impacted northern Arizona 49 thousand years ago. The impact excavated 175 million tons of rock to form what is now called Meteor Crater or Barringer Meteorite Crater. The energy released is estimated to be 20 to 40 megatons, similar to a very large nuclear bomb blast. A shockwave from the blast, heat, and flying debris would have destroyed vegetation, injured and killed animals up to 24 km from the impact site, with hurricane-force winds out to 40 km.[79]
- **Chicxulub impact**: about 66 million years ago. The energy released was equivalent to 100 million megatons of TNT and resulted in a 180 km diameter crater[80]. The resulting blast and heat waves caused immediate destruction up to a distance of thousands of kilometers from the impact site. The impact also triggered earthquakes and tsunamis,[81] and led to changes in global climate. This wiped out the dinosaurs along with most other species on Earth in the months and years following the impact.[82] Global effects from the impact likely included acid rain (for 5-10 years) resulting from impact debris interacting with a shock-heated atmosphere. The impact debris also heated the atmosphere and surface causing wildfires. Eventually, dust and aerosols from the impact combined with soot from the wildfires and filled the atmosphere. This prevented sunlight from reaching the surface of the Earth, so surface temperatures initially decreased. The ozone was destroyed by chlorine and bromine chemicals released into the atmosphere as a result of the vaporization of materials from both the asteroid and the impact and vegetation wildfires. Carbon dioxide released from vaporized rocks likely led to subsequent greenhouse warming lasting an estimated decades to thousands of years.[83]

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[77] Phillips, Tony. “The Tunguska Impact -- 100 Years Later.” NASA. As of: January 22, 2023: https://science.nasa.gov/science-news/science-at-nasa/2008/30jun_tunguska

[78] Jenniskens, P., Popova, O.P., Glazachev, D.O., Podobnaya, E.D., and Kartashova, A.P. (2019). Tunguska eyewitness accounts, injuries, and casualties. *Icarus*. 327:4-18. As of January 18, 2023: https://doi.org/10.1016/j.icarus.2019.01.001

[79] Kring, David, A. and Bailey, Jake. “Barringer Meteor Crater and Its Environmental Effects”. Lunar and Planetary Institute. As of: January 11, 2023: https://www.lpi.usra.edu/science/kring/epo_web/impact_cratering/enviropages/Barringer/barringerstartpage.html
Hansen, Kathryn. “Arizona's Meteor Crater”. NASA. As of January 11, 2023: https://earthobservatory.nasa.gov/images/148384/arizonas-meteor-crater

[80] Kring, David A. “Chicxulub Impact Event Discovering the Impact Site.” Lunar and Planetary Institute. As of: January 11, 2023: https://www.lpi.usra.edu/science/kring/Chicxulub/discovery/

[81] Range, M. M., Arbic, B. K., Johnson, B. C., Moore, T. C., Titov, V., Adcroft, A. J., et al. (2022). The Chicxulub impact produced a powerful global tsunami. *AGU Advances*, 3, e2021AV000627. As of January, 18 2023: https://doi.org/10.1029/2021AV000627

[82] Schulte P, Alegret L, Arenillas I, et al. “The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary”. *Science*. 2010;327(5970):1214-1218. https://doi.org/10.1126/science.1177265

[83] Kring, David A. “Chicxulub Impact Event Global Effects.” Lunar and Planetary Institute. As of: January 11, 2023: https://www.lpi.usra.edu/science/kring/Chicxulub/global-effects/

- The ***Nördlinger Ries* Crater** in Germany formed 15 million years ago from an estimated 1 km diameter object. The impact event was believed to have occurred at the same time as the Steinheim Crater, 40 km southwest of the *Nördlinger Ries* Crater[84]. However, recent theories suggest a double-impact did not occur, but instead that the Steinheim impact occurred a few hundred thousand years later[85]. The Ries impact is believed to have triggered an earthquake, potentially of magnitude 8.5. The impact-quake resulted in a fireball that destroyed and burned forests. The extended effects included sand and dust in the atmosphere, heavy rain, and flooding.[86]
- The **Tenoumer Crater** in the Sahara Desert was formed from a meteorite impact an estimated 10,000 to 30,000 years ago. The impact created a 1.9 km wide crater. The Tenoumer Crater is near two other craters, but a 2003 study confirmed that these craters were not part of a multiple impact event.[87]
- **Wolfe Creek Crater** in Australia was formed from a meteorite impact event as well, estimated to have occurred 300,000 years ago. The crater is 880 m in diameter. The meteorite is believed to have weighed 50,000 t or more with an impact speed around 15 kilometers per second.[88]

[84] Koeberl, Christian and Sharpton, Virgil. "Ries, Germany." Lunar and Planetary Institute. As of: January 22, 2023: https://www.lpi.usra.edu/publications/slidesets/craters/slide_40.html
[85] Buchner, E., Sach, V. J. & Schmieder, M. (2020) New discovery of two seismite horizons challenges the Ries–Steinheim double-impact theory. Scientific Reports 10:22143, 14 p., doi: 10.1038/s41598-020-79032-4.
[86] Buchner, E., Sach, V. J. & Schmieder, M. (2020) New discovery of two seismite horizons challenges the Ries–Steinheim double-impact theory. Scientific Reports 10:22143, 14 p., doi: 10.1038/s41598-020-79032-4.
[87] National Aeronautics and Space Administration. "Tenoumer Crater, Mauritania." As of: January 22, 2023: https://earthobservatory.nasa.gov/images/8536/tenoumer-crater-mauritania
[88] National Aeronautics and Space Administration. "Wolfe Creek Crater." As of: January 22, 2023: https://earthobservatory.nasa.gov/images/8488/wolfe-creek-crater

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Chapter 3: What Are the Timelines Involved?

Chapter Contents

Planetary Defense emergencies can happen on relatively short timelines – **some objects are detected only weeks, days, or even just hours before impact.**[89] Even if an object is discovered years in advance, there may still be barely enough time to launch a mitigation mission. That means leaders who are not Planetary Defense professionals themselves, and may not have immediate access to trusted subject matter experts, may nevertheless be faced with having to **make potentially high-stakes decisions on short notice** in case an asteroid or comet threatens to hit Earth, and it is therefore important to understand the timelines involved in Planetary Defense scenarios.

However, as mentioned previously, none of the currently-known asteroids or comets that are large enough to cause damage on the ground will hit Earth within the next century.[90] Thus, **any threat will be from a yet-undiscovered object, making detection capabilities the most important contributor** to improving Planetary Defense timelines. Current detection capabilities are therefore discussed first in this chapter.

Once a threatening object is detected, it takes many **additional observations**, sometimes spread out over weeks, months, or even years, to refine the estimates of its trajectory and size, and determine whether or not it will hit Earth, and if so where. Even if the impact location and size of the object are relatively-well known, the **detailed prediction of impact effects**, using sophisticated modeling and simulation software,

[89] International Asteroid Warning Network, “Sixth Meteoroid Detected Prior to Impact,” webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/-/sixth-meteoroid-detected-prior-to-impact

[90] National Aeronautics and Space Administration Center for Near Earth Object Studies, “NEO Earth Close Approaches,” webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/ca (However, there are known objects with the potential to impact Earth several hundred years from now; see National Aeronautics and Space Administration Center for Near Earth Object Studies, “Sentry: Earth Impact Monitoring,” webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/sentry

may take days to weeks.[91] This complicates decisionmaking and terrestrial preparedness.

If a decision is made to divert or destroy a threatening object (which in itself takes time), **it can take years to design, build, and launch** the necessary reconnaissance ("characterization") and mitigation missions, and their flight time to the target can consume several more years (see Chapter 5).

Finally, terrestrial preparedness takes time as well. **Evacuating large populations** from an impact area poses a significant logistical challenge, and ideally critical industries as well as culturally significant items would be moved as well. However, this is made more complex by the aforementioned uncertainty regarding the exact impact location and size of the affected area.

The rest of this chapter discusses these issues in more detail.

Detection Capabilities and Associated Timelines

Both ESA and NASA have mostly-automated processes in place to detect potential impactors, based on position measurements sent to the Minor Planet Center. NASA's "Center for Near-Earth Object Studies" (CNEOS) automatically reviews data from the Minor Planet Center's "Near Earth Object Confirmation Page" (NEOCP)[92] for potential impact hazards. NASA's Scout system[93] then provides warnings of potential impactors hours or a few days ahead. ESA's Near-Earth Object Coordination Centre operates a similar system, called Meerkat.[94] These warnings are generated typically in a few minutes. Longer-term warnings, up to 100 years in the future, are computed based on officially designated NEOs, again both by NASA and ESA. These computations are performed on a daily basis.

NASA's "Sentry" software is an impact monitoring system that calculates the impact probability of confirmed NEO's on a close approach trajectory with Earth.[95] The Sentry system is considered a long-term impact system because the probability of impact is calculated for potential close approaches out to at least 100 years into the future.

Earth impact probabilities are based on an orbit determination process used to identify an orbit that best fits the observations collected for an object. Observations are collected via optical or radar measurements. Optical measurements occur when the object is bright enough to be observed. Viewing an object in the daytime is difficult

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[91] National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

[92] Center for Astrophysics, The Minor Planet Center, "The NEO Confirmation Page," webpage, undated. As of January 18, 2023: https://minorplanetcenter.net/iau/NEO/toconfirm_tabular.html

[93] NASA Center for Near Earth Object Studies: "Scout: NEOCP Hazard Assessment," webpage, undated. As of 10 March 2023: https://cneos.jpl.nasa.gov/scout/#/

[94] Gianotto, F., et al.: "Meerkat Asteroid Guard – ESA'S Imminent Impactor Warning Service." Proceedings of the 2nd NEO and Debris Detection Conference, 2023. As of 10 March 2023: https://conference.sdo.esoc.esa.int/proceedings/neosst2/paper/67/NEOSST2-paper67.pdf

[95] National Aeronautics and Space Administration: "Sentry: Earth Impact Monitoring ", webpage, undated. As of 21 January 2023: https://cneos.jpl.nasa.gov/sentry/intro.html

to accomplish and prevents observations. Similarly, there are times when an object's orbit can result in the object being too faint to detect from Earth. Radar measurements are possible when the object is adequately near the Earth to reflect the radar signal.

As more observations of the object are collected, the knowledge of the object's orbit may improve. A better understanding of the object's orbit results in improved predictions for the object's future trajectory. Sentry uses the best estimate trajectory of an object's orbit to propagate the object's path 100 years forward in time to estimate a potential a close approach with Earth.[96] Impact risk estimates become more accurate as an object’s orbit is better understood.

In Europe, ESA operates its “Aegis” software[97] for similar purposes, and the Italian company SpaceDyS runs an independent system called NEODyS.[98]

Both NASA and ESA publish the resulting impact risk assessments in online tables that are updated whenever a new threatening object is detected:

- NASA Sentry Object Table: https://cneos.jpl.nasa.gov/sentry/
- ESA NEOCC Risk List: https://neo.ssa.esa.int/risk-list

Based on the outputs of these systems, astronomers around the world can then conduct additional observations.[99]

To provide more context for the detection process, the most important dedicated telescopes used for this purpose are discussed below.

ATLAS

The “Asteroid Terrestrial-impact Last Alert System” (ATLAS) is an asteroid impact early warning system developed by the University of Hawaii and funded by NASA. It consists of four telescopes (two in Hawaii, and one each in Chile and South Africa), which automatically scan the whole sky several times every night looking for objects that move against the fixed background of the stars. ATLAS warning times depend on the size of the asteroid, since larger asteroids can be detected further from Earth. ATLAS can detect a small (~10 m) asteroid approximately two days before a close approach or impact, and a 100 m one approximately three weeks out.”[100]

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[96] National Aeronautics and Space Administration: “Sentry: Earth Impact Monitoring “, webpage, undated. As of 21 January 2023: https://cneos.jpl.nasa.gov/sentry/intro.html
[97] European Space Agency: “NEOCC orbit determination and impact monitoring software update ,” website, 20 December 2022. As of 10 March 2023: https://neo.ssa.esa.int/-/neocc-orbit-determination-and-impact-monitoring-software-update
[98] SpaceDyS: “NEODyS-2,” webpage, undated. As of 10 March 2023: https://newton.spacedys.com/neodys/
[99] National Aeronautics and Space Administration Center for Near Earth Object Studies, “Scout: NEOCP Hazard Assessment,” webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/scout/intro.html
[100] The ATLAS Project. “Asteroid Terrestrial-impact Last Alert System.” As of: January 11, 2023: https://fallingstar.com/home.php

Goldstone Solar System Radar

NASA's Goldstone Solar System Radar (GSSR) is a fully steerable, high resolution ranging and imaging radar located in California.[101] The GSSR was complemented by the National Astronomy and Ionosphere Center's Arecibo Observatory in Puerto Rico, which is no longer operational.[102] Compared to Arecibo, the GSSR has twice the sky coverage and longer tracking times as a result of its steerability, whereas Arecibo had twice the range and could observe three times the spatial volume of GSSR[103].

Goldstone's detectable range of an object is about half that of Arecibo's. Arecibo was able to detect 12 percent more 700 m diameter objects and 5 percent fewer 70 m diameter objects than Goldstone[104].

NEO observations using Goldstone depend upon the availability of the system whose primary mission is to support spacecraft communications. The fulfillment of radar observation requests varies from two days after a request to two weeks in advance. In contrast, the Arecibo system had greater flexibility with the scheduling of their observations[105].

The complementary set of radar observations inform the trajectory, size, shape, composition, and rotation period of the objects measured[106]. The advantages of radar vs optical measurements include reduced uncertainties in orbit estimates and meter-level characterization of NEO's. The disadvantages are the small field of view of the radar antennas and the general dependence on initial detection of NEO's by an optical system[107].

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[101] Rodriguez-Alvarez, Nereida (2019). Goldstone Solar System Radar (GSSR) Learning Manual. NASA. As of: January 11, 2023: https://deepspace.jpl.nasa.gov/files/GSSR_learning_manual.pdf; Jet Propulsion Laboratory. "Solar System Radar Group." NASA. As of: January 11, 2023: https://gssr.jpl.nasa.gov/index.html; Deep Space Network. "Antennas." NASA. As of: January 11, 2023: https://www.gdscc.nasa.gov/index.php/antennas/

[102] National Science Foundation: "The Arecibo Observatory Survey Salvage Committee Report", April 2022. As of 21 January 2023: https://www.naic.edu/ao/blog/arecibo-observatory-survey-salvage-committee-report

[103] Ostro, Steven J. "Asteroid Radar Research." NASA. As of: January 11, 2023: https://echo.jpl.nasa.gov/introduction.html; Rodriguez-Alvarez, Nereida (2019). Goldstone Solar System Radar (GSSR) Learning Manual. NASA. As of: January 11, 2023: https://deepspace.jpl.nasa.gov/files/GSSR_learning_manual.pdf

[104] National Research Council. 2010. *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12842

[105] National Research Council. 2010. *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12842

[106] Colorado School of Mines. "WHAT CAN WE LEARN ABOUT ASTEROIDS FROM PLANETARY RADAR OBSERVATIONS?." As of: January 11, 2023: https://cwp.mines.edu/project/what-can-we-learn-about-asteroids-from-planetary-radar-observations/; Rodriguez-Alvarez, Nereida (2019). Goldstone Solar System Radar (GSSR) Learning Manual. NASA. As of: January 11, 2023: https://deepspace.jpl.nasa.gov/files/GSSR_learning_manual.pdf

[107] Geldzahler, Barry, et al. 2010. "NEO Tracking and Characterization Facility." As of: January 11, 2023: https://www.lpi.usra.edu/sbag/meetings/aug2010/presentations/Geldzahler_NEO_Tracking_and_Characterization_Facility_v5.pdf

NEOWISE

The NEOWISE project uses the Wide-field Infrared Survey Explorer (WISE) spacecraft launched by NASA in 2009.[108] NEOWISE tracks asteroids and NEOs from sun-synchronous low Earth orbit.[109] Every six months, the infrared telescope completes a scan of the sky.[110]

Pan-STARRS

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) is a 1.8 m telescope located in Maui, Hawaii. The telescope images the sky at night and immediately reports any objects with motions expected of NEOs to the Minor Planet Center.[111]

IRTF

NASA's Infrared Telescope Facility (IRTF) is a 3.2 m telescope operated by the University of Hawaii.[112] This facility characterizes NEOs and provides rapid response observations of newly discovered NEOs.[113]

Catalina Sky Survey

The Catalina Sky Survey (CSS) telescopes located in Tucson, Arizona include 1.5 m, 1 m, and 0.7 m telescopes and detectors that support NEO survey efforts. Upgrades to the detector of their largest telescope have increased the area coverage by five times and significantly increased discoveries.[114] The 1 m telescope observes 40-80 targeted

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108 The NEOWISE Project. "What is NEOWISE?" Jet Propulsion Laboratory. As of: January 11, 2023: https://neowise.ipac.caltech.edu/

109 The NEOWISE Project. "NASA Telescope Takes 12-Year Time-Lapse Movie of Entire Sky." Jet Propulsion Laboratory. As of: January 11, 2023: https://neowise.ipac.caltech.edu/news/neowise20221018/; Mainzer, A., "Preliminary Results from NEOWISE: An Enhancement to the Wide-field Infrared Survey Explorer for Solar System Science", The Astrophysical Journal, vol. 731, no. 1, 2011. doi:10.1088/0004-637X/731/1/53, http://adsabs.harvard.edu/abs/2011ApJ...731...53M

110 The NEOWISE Project. "NASA Telescope Takes 12-Year Time-Lapse Movie of Entire Sky." Jet Propulsion Laboratory. As of: January 11, 2023: https://neowise.ipac.caltech.edu/news/neowise20221018/

111 Institute for Astronomy. "Pan-STARRS." University of Hawaii. As of: January 11, 2023: http://legacy.ifa.hawaii.edu/research/Pan-STARRS.shtml; Mulgrew, Paul. "Pan-STARRS1 data archive home page." Space Telescope Science Institute. As of: January 11, 2023: https://outerspace.stsci.edu/display/PANSTARRS/

112 Institute for Astronomy. "NASA Infrared Telescope Facility (IRTF)." University of Hawaii. As of: January 11, 2023: http://irtfweb.ifa.hawaii.edu/information/about.php

113 Planetary Defense Coordination Office. "Near-Earth Object Observations Program." NASA. As of: January 11, 2023: https://www.nasa.gov/planetarydefense/neoo

114 International Asteroid Warning Network. "Assets." As of: January 11, 2023: https://iawn.net/about/assets.shtml

NEOs per night.[115] The 0.7 m telescope can observe the entire viewable sky within three nights.[116]

General-Purpose Telescopes

In addition to these dedicated systems, general-purpose telescopes operated by professional and amateur astronomers around the globe also play an important role in discovering potential impactors.[117] Amateur astronomers can report newly discovered objects to the International Astronomical Union's Minor Planet Center (MPC)[118], where their observations are correlated with those of others in order to determine a new object's orbital parameters and predict its trajectory. Astronomers with a particular interest in near-Earth objects or Planetary Defense can become members of relevant organizations such as the International Asteroid Warning Network (IAWN).[119]

Timelines for In-Space Reconnaissance and Mitigation Missions

Traditional deep-space missions take many years, if not decades, between when the initial mission concept is proposed, and when the spacecraft actually arrives at its destination. A typical design-build-fly effort has the following stages, many of which can last years:[120]

1. Mission analysis, requirements definition, and conceptual design
2. Detailed design
3. Manufacturing or procuring spacecraft components and subsystems
4. Building the spacecraft
5. Testing the spacecraft
6. Integrating the spacecraft with the launch vehicle
7. Launch and flight to the destination
8. Potential sample return to Earth

The design and build process can be abbreviated if existing components – or even existing spacecraft that are being prepared for another mission – are repurposed. Flight times depend on where the destination (i.e. the potentially hazardous object that the spacecraft is supposed to investigate or deflect) is in relation to Earth, how heavy the spacecraft is, and how powerful the rocket it launches on is. Table 3 provides development and flight times for select NASA missions.

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[115] Lunar and Planetary Laboratory. "Catalina Sky Survey Facilities." University of Arizona. As of: January 11, 2023: https://catalina.lpl.arizona.edu/about/facilities

[116] International Asteroid Warning Network. "Assets." As of: January 11, 2023: https://iawn.net/about/assets.shtml

[117] Mainzer, A. (2017), The future of planetary defense, J. Geophys. Res. Planets, 122, 789– 793, doi:10.1002/2017JE005318. As of 21 January 2023: https://doi.org/10.1002/2017JE005318

[118] International Astronomical Union: "Guide to Minor Body Astrometry", webpage, November 2017. As of 9 February 2023: https://minorplanetcenter.net/iau/info/Astrometry.html

[119] International Asteroid Warning Network: "Frequently Asked Questions," January 2023. As of 9 February 2023: https://iawn.net/misc/faqs.shtml

[120] Wertz JR, Everett DF, Puschell JJ. Space mission engineering: the new SMAD. Space Tech. Library Volume 23 Springer Microcosm Press. 2011.

The less warning time there is, and the longer it takes to get a reconnaissance and/or mitigation spacecraft near the object, the more challenging the mitigation mission becomes. Especially if time is short, a single spacecraft can be designed to provide both reconnaissance, and, if warranted, mitigation (e.g. by installing a nuclear explosive device on board). For mitigation, deflection (changing the object's course so that it no longer impacts Earth) usually requires longer warning times than disruption (breaking the object apart into smaller, less-threatening parts).[121]

Table 3: Time and Cost Estimates for Typical Reconnaissance Missions

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

Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf
Note: dry mass is mass of structures only. Wet mass includes mass of propellant (rocket fuel) and other consumables.

Timelines for Terrestrial Response

Planetary Defense emergencies can occur with little to no warning time, as demonstrated by the impact over Chelyabinsk in 2013, limiting terrestrial efforts to a post-impact response. On the other hand, some close approaches can be tracked decades, if not centuries, in advance, providing more time for terrestrial preparedness. But even if there is enough time to send a mitigation mission, leaders on Earth need to prepare for the possibility that mitigation fails.

Terrestrial preparation and response is discussed in detail in Chapters 4 and 5. The main pre-impact activities are evacuations and staging of rescue capabilities, which become possible for warning timelines comparable to that of a hurricane (days) or more; for an example of national-level considerations, see the U.S. "Federal Evacuation Support Annex to the Response and Recovery Federal Interagency Operational Plans".[122] However, large-area and more comprehensive evacuation efforts can take

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[121] Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf
[122] Department of Homeland Security: "Federal Evacuation Support Annex to the Response and Recovery Federal Interagency Operational Plans," January 2021. As of 10 March 2023: https://www.fema.gov/sites/default/files/documents/fema_incident-annex_evacuation.pdf

significantly longer.[123] For shorter warning times (hours to minutes), damage to infrastructure can be mitigated if certain systems can be shut down in a controlled manner, comparable to what the U.S. "Federal Operating Concept for Space Weather Events"[124] outlines, and casualties can be limited by instructing populations to shelter in place.

The "Response Options" column in Table 4 summarizes what responses are possible based on the warning time before an impact.

Development of Uncertainty Over Time

Figure 24, which his based on a fictitious case developed for a Planetary Defense exercise, illustrates how the uncertainty of the predicted impact location develops over time, starting with an initial wide swath that spans much of the globe, down to kilometer-scale precision a few days or weeks before impact. Appendix A10, starting on page 123, provides a more in-depth explanation and illustration of how the risk area is refined as the time of impact draws closer. This highlights the need for frequent and timely updating of decisionmakers, stakeholders, and the general population.

Table 4 summarizes the key considerations for discovery, decisionmaking, warning, characterization, mitigation, and terrestrial response, depending on how long before impact an object is discovered and a track established. Discovery options are discussed in more detail in Chapter 4, decisionmaking in Chapter 6, public warning in Chapter 7, characterization, deflection, and terrestrial response in Chapter 5.

Note that, due to their different orbits, **many comets are only detected less than a year before their closest approach to Earth**, which would leave little to no time for mitigation missions or even comprehensive terrestrial preparedness.[125]

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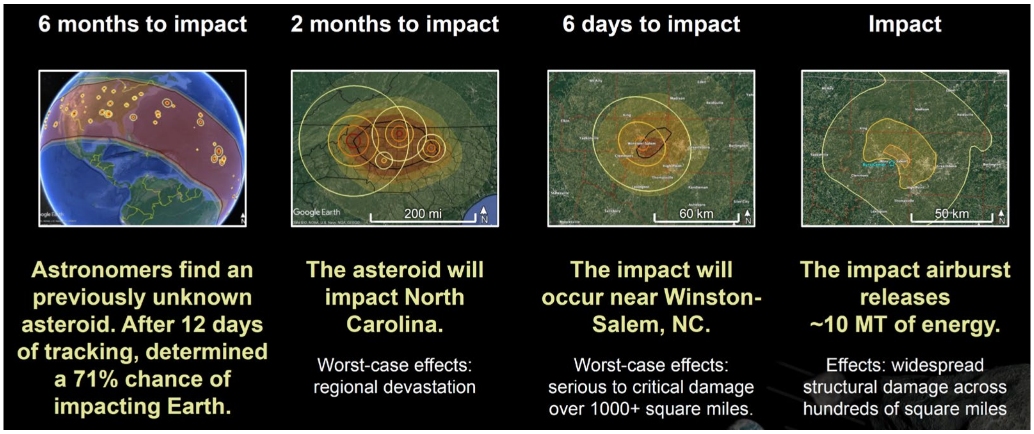
[123] Casey, J. (2019). Moving a town to save a mine: the story of Kiruna. *Mine*. As of January 18, 2023: https://www.mining-technology.com/features/moving-a-town-to-save-a-mine-the-story-of-kiruna

[124] Department of Homeland Security: "Federal Operating Concept for Space Weather Events," May 2019. As of 10 March 2023: https://www.fema.gov/sites/default/files/2020-07/fema_incident-annex_space-weather.pdf

[125] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf (Section 2.3)

Figure 24: Decreasing Uncertainty of Impact Location and Magnitude Over Time



Source: NASA/FEMA Planetary Defense TTX4 After Action Report Briefing, 27 April 2022. As of 19 January 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf
Note: red areas are where the object could impact based on prediction uncertainties at a given time. Ellipsoids illustrate the extent of damage for a random sample of potential impact points and of potential object sizes and compositions (red: total devastation, orange: serious damage, yellow: moderate damage). See Appendix A10, starting on page 123, for a more in-depth discussion.

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Table 4: Time Horizons for Planetary Defense Decision-Making

Warning Time Before Impact	Initial Discovery	Decisionmaking	Alerting the Population	Characterization	Mitigation	Terrestrial Response Options (for Government, Industry, Individuals)	Terrestrial Response Type	Example Scenarios**
No-Notice	Direct observation, bolide detection sensors	Reactive only	-	-	-	-	Comparable to earthquake response	**Chelyabinsk, 2013**
Minutes	Radar*	Comparable to nuclear attack response	EAS? WEA?	-	-	Isolate power grid? Shut down nuclear reactors? Stop trains and road traffic? Sheltering in place?	Comparable to earthquake response	
Hours	Radar*, telescopes?	Limited, high priority only	EAS, WEA, broadcast media, social media	Radar? Telescopes?	Disruption: ICBMs?	Above plus: self-evacuations, activating local emergency responders	Comparable to tornado response	**Sudan, 2008 (2008 TC_3)**
Days	Radar*, telescopes	Limited	EAS, WEA, broadcast media, social media, print media	Radar, telescopes	Disruption: ICBMs?	Above plus: staging regional responders and supplies, organized evacuations	Comparable to hurricane response	
Weeks	Radar*, telescopes	Deliberate but accelerated	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device?	Above plus: staging national and global responders and supplies, comprehensive evacuations, some permanent moves	Customized rapid response	NASA/FEMA TTX-1
Months	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device? Deflection: nuclear explosive device?	Above plus: more comprehensive permanent moves, relocation of certain industries / institutions / resources, building improvised shelters	Customized rapid response	PDC 2021, NASA/FEMA TTX-4
Years	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space mission	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor?	Above plus: potential permanent relocation of most populations / industries / institutions / resources (depending on deflection outcome), establishing long-term deep shelters	Customized long-lead response	NASA/FEMA TTX-2 & TTX-3, PDC 2015, PDC 2019
Decade+	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space missions	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor, gravity tractor, ion beam	Above plus: potential permanent relocation of all populations / industries / institutions / resources (depending on deflection outcome), establishing off-earth colonies	Customized long-lead response	**99942 Apophis, 2023 DW**; PDC 2013, PDC 2017, PDC 2023

Source: RAND Analysis

Notes: "*" only if radar happens to be looking in the right direction. “?”option might not apply. “**” **bold** = actual asteroid. All reconnaissance (“characterization”), mitigation, and terrestrial response options are discussed in detail, and references are provided, in Chapter 5. EAS: Emergency Alert System (in the U.S.) or similar government-run notification mechanism leveraging broadcast television/radio, electronic road signs, etc.; WEA: Wireless Emergency Alerts (in the U.S.) or similar government-run notification mechanism leveraging mobile phone infrastructure. See Appendix A.1 (page 101) for other abbreviations.

Chapter 4: What Can be Done Now to Reduce the Risk?

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As mentioned above, increasing the available warning time expands the amount of response options and the likelihood of a successful deflection. Thus, Earth's first line of defense are **comprehensive detection capabilities** that constantly survey the whole sky for new threatening objects and that allow for a rapid determination of their trajectories. Over the course of the last two decades, NASA, ESA, and other space agencies have started putting this infrastructure in place, but additional telescopes – both on the ground and in space – and related processing and analysis capabilities are still needed to find all potential threats. Threat characterization also benefits from a better understanding of asteroids and comets.

Accelerating the timeline between detection and mitigation is important as well (see Chapter 3). This requires the ability to rapidly design and manufacture spacecraft, and the availability of powerful rockets that can inject spacecraft into deep-space trajectories on relatively short notice.

Finally, for scenarios where mitigation fails, **emergency responses on Earth** have to be prepared, with measures ranging from increasing awareness to contingency planning to public notification.

A recent NASA/FEMA Planetary Defense tabletop exercise identified the following key gaps that likely also exist in many other nations:[126]

- "A short-warning asteroid scenario poses challenges to mounting an effective national response."
- "The nation has a limited ability to image small, rapidly moving asteroids."
- "The nation has a limited ability to rapidly launch a reconnaissance mission."
- "Large parts of the [U.S. Government] and the public are unfamiliar with an asteroid impact threat."
- "Only nascent strategies currently exist to address misinformation related to the asteroid threat scenario."
- "Currently there is minimal redundancy and robustness for […] modeling capabilities/expertise."
- "Understanding of the international legal and policy implications of using nuclear explosive devices (NEDs) for planetary defense and terminal phase mitigations remains limited."

These issues are discussed in more detail below.

[126] Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf

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Creating Additional Detection and Characterization Capabilities

Existing detection systems were discussed in Chapter 3. These provide much-improved capabilities compared to even a decade ago; however, "at the current rate, it will take more than 30 years to" detect all NEOs 140 m and larger.[127] Therefore, new capabilities are needed.[128]

One major system already in the development pipeline is the "NEO Surveyor," an infrared space telescope designed to find potentially hazardous asteroids and comets. The launch of this telescope is currently scheduled for no earlier than June 2028.[129] The telescope will be located at the Earth-Moon Lagrange Point 1, 1.5 million kilometers from Earth, where the gravity fields of the Earth and the Sun cancel each other out and thus create a more stable location. NEO Surveyor will contribute to NASA's ongoing efforts to characterize 90 percent or more of NEOs greater than 140 m diameter[130].

A replacement for the destroyed Arecibo radar telescope is also being discussed. Scientists have proposed leveraging the existing infrastructure to create an improved Next Generation Arecibo Telescope (NGAT). The proposed structural and instrument improvements will provide increased sensitivity, field of view, and frequency coverage. Combined with increased transmitting capabilities, the upgraded system will benefit Planetary Defense, Solar System science, and Space Situational Awareness.[131] Early costs estimates for the proposed NGAT are around $454M.[132]

The UN-affiliated Space Mission Planning and Analysis Group (SMPAG) has created a roadmap for additional future capabilities.[133]

Even though creating additional detection capabilities comes with significant cost (a new space-based telescope could have a life-cycle cost between $1B and $2B, while that of large new terrestrial telescopes is estimated to be between $100M and $300M),[134] a risk-benefit analysis recently conducted by NASA shows that, due to the

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127 Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

128 International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

129 National Aeronautics and Space Administration. "NEO Surveyor." As of: January 22, 2023: https://solarsystem.nasa.gov/missions/neo-surveyor/in-depth/

130 National Aeronautics and Space Administration. "Construction Begins on NASA's Next-Generation Asteroid Hunter." As of: January 22, 2023: https://www.nasa.gov/feature/jpl/construction-begins-on-nasa-s-next-generation-asteroid-hunter

131 Roshi, D. Anish, et al. "The Future of the Arecibo Observatory: The Next Generation Arecibo Telescope, Executive Summary." Arecibo Observatory. As of: January 26, 2023: http://www.naic.edu/ngat/NGAT_WhitePaper_ExecSummary_rv9_05192021.pdf

132 Roshi, D. Anish, et al. "The Future of the Arecibo Observatory: The Next Generation Arecibo Telescope, Full Version 2.0." Arecibo Observatory. As of: January 26, 2023: http://www.naic.edu/ngat/NGAT_WhitePaper_rv9_05102021.pdf

133 Space Mission Planning Advisory Group, "Roadmap of Relevant Research for Planetary Defence," electronic report, April, 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-001_3_0_Roadmap_2020-04-15+%282%29.pdf

134 Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic

very high damage that even a small impactor could cause (potentially trillions of dollars), and not even considering the existential risk to human civilization and all life on Earth that very large impactors represent, investments in Planetary Defense are prudent.[135]

However, there also are much lower-cost approaches to improving Planetary Defense detection capabilities, for example, by encouraging amateur astronomy and related citizen science. In particular, novel, easy-to-use and networked telescopes such as the eVscope[136] can help create distributed and responsive observer networks.

Conducting Foundational Research on Asteroids and Comets

Beyond more comprehensive and timely discovery of PHOs, foundational research into asteroids and comets in general will benefit Planetary Defense capabilities, since better understanding e.g. of asteroid composition and physical properties will help design better deflection and disruption technologies, and better understanding e.g. of how a comet's tail is formed will help improve comet trajectory prediction. This includes the following:[137]

- Scientific missions to, and increased ground- and space-based observations of, asteroids and comets (including those not categorized as potentially hazardous)
- Laboratory research into the mechanical and thermodynamic properties of asteroid and comet material
- Creating more sophisticated computer models of asteroids and comets, for use in mitigation and effects simulations
- Conducting additional deflection test missions

Regarding the first item, the flyby of Apophis in 2029 represents a "once-per-thousand-year" opportunity[138] to bring a massive amount of observation capabilities to bear on an object from relatively close range,[139] and may even allow for a lander or

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report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf

[135] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf

[136] SETI Institute, "Unistellar and SETI Institute Expand Worldwide Citizen-Science Astronomy Network," webpage, May 25, 2022. As of January 18, 2023: https://www.seti.org/press-release/unistellar-and-seti-institute-expand-worldwide-citizen-science-astronomy-network

[137] Space Mission Planning Advisory Group, "Roadmap of Relevant Research for Planetary Defence," electronic report, April, 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-001_3_0_Roadmap_2020-04-15+%282%29.pdf

[138] International Academy of Astronautics, "2019 Planetary Defense Conference Summary and Recommendations," electronic report, April 2019. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conferencereportpdc2019.pdf

[139] European Space Agency, "Apophis Reconnaissance Mission," electronic report, undated. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/Apophis_-_Moissl_2022-10-20.pdf

sample return mission.[140] The new "Decadal Survey for Planetary Science" issued by the U.S. National Academy of Sciences also advocates for leveraging this opportunity.[141]

Enabling Responsive Reconnaissance and Mitigation Missions

As will be discussed in Chapter 5, designing and building a reconnaissance or mitigation mission can be expected to take years, in addition to potentially years of flight time. The pre-launch process can be accelerated by designing, building, and storing key components of reconnaissance and mitigation spacecraft, especially those requiring long-lead items, well ahead of need, and by updating them every decade or so as technology advances.[142]

Flight times can be reduced by developing large-capacity, responsive-launch systems like the SpaceX "Starship" or the Blue Origin "New Glenn", and by developing advanced in-space propulsion systems such as nuclear thermal propulsion.

Developing these capabilities will also require testing everything well ahead of need; the recent DART mission was good example for mission concept and technology validation. Design, modeling, and simulation tools (including for mitigation effectiveness assessment) also need to be refined constantly so that they better reflect reality and consequently allow for faster and better designs.[143]

In particular, for nuclear mitigation options, the legal situation should be improved well ahead of a need,[144,145] including to allow for testing,[146] since once a specific threat is known, some nations may object to the use of nuclear explosive devices for mitigation as long as they are not directly at risk from a specific impact, for example

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140 International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

141 National Academies of Sciences, Engineering, and Medicine, Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032, Washington, DC: The National Academies Press, 2022. As of January 18, 2023: https://nap.nationalacademies.org/catalog/26522/origins-worlds-and-life-a-decadal-strategy-for-planetary-science

142 Space Mission Planning Advisory Group, "Work Plan," electronic report, September 2019. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-PL-002_2_0_Workplan_2019_09-01+%283%29.pdf

143 Space Mission Planning Advisory Group, "Roadmap of Relevant Research for Planetary Defence," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-001_3_0_Roadmap_2020-04-15+%282%29.pdf

144 Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

145 Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf

146 Osburg, J. (2019). Using "Wireless Emergency Alerts" for Planetary Defense Notifications, IAA-PDC-19-08-P03, presented at the 7th Planetary Defense Conference, Washington, DC, USA, April 2019. As of 23 December 2022: https://drive.google.com/file/d/1rXWhaVLl-a1x6Pwsu_c7cu6APJhUnvVA/view

because they are concerned about a nuclear arms race in space, or about nuclear proliferation on Earth (see also the "Dual Use" discussion in Chapter 6, page 86).

Preparing Emergency Responses on Earth

Finally, enough is known about the general effects of an asteroid or comet impact (see Chapter 2) that emergency managers on Earth can prepare contingency plans, to be ready in case an actual impactor is detected. Planning should address the following:

- Educating decisionmakers, responders, and the general public about the threat; the flyby of Apophis in April 2029 will be an excellent awareness-builder, and the Planetary Defense community is working on having 2029 declared the "Year of Planetary Defense."[147] However, currently, large parts of the population – including decisionmakers – are unfamiliar with the threat of asteroid and comet impacts.[148]
- Improving impact effects modeling and simulation tools
- Identifying related hazards
- Designing associated mitigation measures
- Conducting regular exercises
- Preparing for rapid public notification in case of short-notice threats

Finally, preventative measures in response to the global threat posed by very large impactors, such as making global food and energy supply systems more resilient to significant disruption, or geographic diversification of key industries, can also help mitigate against other threats to civilization such as major wars or pandemics.However, such measures would take vast quantities of capital and many years to implement.

[147] International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

[148] International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

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Chapter 5: What Are the Options Once a Catastrophic Impact Is Likely?

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After astronomers **detect** a new object in the Solar System, repeated observations – generally taken over the course of several days or weeks – allow an initial determination of its trajectory and rough estimation of its size. For objects whose orbit may intersect Earth's, and who thus present a potential threat, a global observation campaign involving both professional and amateur astronomers and both Earth-based and in-space telescopes is launched to further **refine the trajectory**, so that the likelihood of impact can be predicted more accurately. This, however, can take months to years, and the precise location of an impact is sometimes not known until a relatively short time – days or weeks – beforehand. Figure 24 on page 55 illustrates this uncertainty. The approximate time of a potential impact, however, can be predicted relatively early.

If there is sufficient time (several years to a decade, based on current capabilities) before a predicted impact, space agencies can also launch a **reconnaissance ("characterization") mission** to the potentially hazardous object, to get close-up views of its size and shape, characterize its composition, and better determine its mass and orbit. This will enable more accurate trajectory and damage predictions, and will also inform the design of any mitigation missions that aim to deflect or destroy the object so that it no longer poses a threat. However, it currently takes years to design and build a spacecraft for a reconnaissance or mitigation mission, and flight times from Earth to its rendezvous with the threatening object likely also will be measured in years. Thus, this is only an option for Planetary Defense scenarios with a relatively long lead time. Table 5 summarizes key considerations for characterization activities.

A **mitigation mission** is designed to change an object's trajectory so that it misses Earth ("**deflection**"), or to break the object into smaller, less dangerous parts ("**disruption**")[149]. The following deflection approaches are generally considered the most technologically mature:

- **Kinetic impactor**: a spacecraft is sent on a collision course with the object to impart an impulse that will change the object's trajectory. The heavier the spacecraft, and the higher its speed on impact, the larger the deflection. This is the only mitigation approach that has actually been tested in space, by NASA's DART mission in 2022.[150]
- **Nuclear explosive device**: a nuclear device is detonated within a few hundred meters of the object. The energy released will vaporize part of the object's surface, resulting in a momentary thrust that will nudge the object into a different trajectory. This is the only relatively mature approach that can also be used for disruption.
- **Gravity tractor**: a spacecraft flies next to the object for many years. The gravitational forces between the spacecraft and the object, even though very small, will change the object's orbit over the course of time.
- **Ion beam**: In this concept, a satellite keeps station near the object and directs a powerful ion beam generator (which could be based on an electric space propulsion engine) at it, thus imparting a small but permanent force. Another generator projects an ion beam in the opposite direction to balance the forces on the spacecraft. Over the course of years, this will change the trajectory of the object.

Again, distance and thus time plays a critical role: if the object is still far away from Earth at the time of the mitigation (years before impact), then even a small change in its trajectory will cause an object to miss Earth. However, **the less warning time there is, and the longer it takes to get the mitigation spacecraft near the object, the more challenging the mitigation mission becomes**. Especially if time is short, a single spacecraft can be designed to provide both reconnaissance, and, if warranted, mitigation (e.g. by installing a nuclear explosive device on board). Deflection usually requires longer warning times than disruption.[151] Table 6 summarizes key considerations for mitigation missions.

In addition to deflecting or disrupting a threatening object, leaders also need to prepare a **terrestrial response** to a potential impact, in case mitigation fails. Depending on the time available, this will involve warning the public, evacuating areas at risk, protecting critical infrastructure and economic as well as cultural assets, and staging disaster response capabilities to deal with the aftermath of an impact. The response to very large impactors may involve extreme measures such as creating self-sustaining

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[149] After a successful disruption, the resulting swarm of smaller objects would still follow the general trajectory of the original impactor, and thus at least some of those objects would still collide with Earth, but due to their smaller size they might disintegrate harmlessly in the upper atmosphere, or at least cause less damage on the ground than a single larger object would.

[150] National Aeronautics and Space Administration Solar System Exploration Our Galactic Neighborhood, "Double Asteroid Redirection Test (DART)" webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/missions/dart/in-depth

[151] Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

refuges underground or in space.[152] However, terrestrial response can be made more challenging by the uncertainty in determining the exact location of an impact and predicting the extent of the damage. Table 7 summarizes key considerations for terrestrial response options.

The rest of this chapter will discuss each of these topics in more detail. Table 9 at the end of this chapter summarizes which of these options are possible depending on the time available.

Table 5: Qualitative Assessment of Key Considerations for Characterization Options

Mission Type	Cost	Complexity	Prep Time Required[153]	Time to Get Results[154]
Existing Earth-based	Very Low ($k)	Low	Minutes to Days	Minutes to Days
Existing Satellite-based	Low ($kk)	Medium	Hours to Weeks	Minutes to Days
Flyby	High ($MMM)	High	Several Years	Hours to Weeks
Rendezvous	Very High ($B)	Very High	Many Years	Hours to Months
Sample Return	Extremely High ($BB)	Extremely High	Decade+	Years

Source: RAND Analysis

Table 6: Qualitative Assessment of Key Considerations for Mitigation Options

Mission Type	Cost	Complexity	Prep Time Required[155]	Time to Get Results[156]
Kinetic Impactor	High ($MMM)	Moderate	Years	Seconds*
Nuclear Explosive Device	High ($MMM)	Moderate	Years	Seconds
Gravity Tractor	High ($MMM)	High	Years	Years to Decades
Ion Beam	High ($MMM)	Moderate	Years	Years to Decades

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[152] Baum, S.D., Denkenberger, D.C., Haqq-Misra, J. (2015). Isolated refuges for surviving global catastrophes. *Futures*. 72:45-56. As of January 18, 2023: https://doi.org/10.1016/j.futures.2015.03.009
[153] Time to task existing asset, or time until flyby/rendezvous mission arrives near object
[154] Time between tasking/arrival and return of significant new insights
[155] Time until spacecraft arrives near object
[156] Time between when spacecraft arrives near object and desired mitigation effect (disruption or trajectory change) is achieved; however, it can take much longer (up to years) for the effect to be measurable.

Mission Type	Cost	Complexity	Prep Time Required[155]	Time to Get Results[156]
Near-Earth Disruption	Moderate ($MM)	Low	Months	Seconds
Less Mature Options	Likely Extremely High ($BB)	Very High	Decade+	Years

Source: RAND Analysis

Note: * significantly longer if multiple kinetic impacts are needed

Table 7: Qualitative Assessment of Key Considerations for Terrestrial Response Options

Response Type	Cost	Complexity	Prep Time Required[157]	Time to Get Results[158]
Public Notification	Very Low ($k?)	Very Low	Minutes to Hours	Minutes to Hours
Evacuating Populations	Moderate ($MM?) to High ($MMM?)	Low	Hours to Days	Days to Weeks
Protecting Assets	Moderate ($MM?) to High ($MMM?)	Moderate	Seconds to Months	Seconds to Years
Staging Capabilities	Low ($kk?) to Moderate ($MM?)	Low	Minutes to Days	Hours to Months

Source: RAND Analysis

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Improved Trajectory Determination Using Existing Capabilities

JPL's CNEOS automatically reviews data from the Minor Planet Center for potential impact hazards. Objects that warrant further attention are published on its "Scout" webpage, and professional as well as amateur astronomers around the world can then conduct additional observations.[159] This generally only takes minutes. Historic images of the sky can also be analyzed to see if they show the newly-discovered object[160], which would provide additional data for trajectory determination.[161]

In case of a severe new threat, telescopes on Earth and in space that are usually working on other efforts would be retasked to contribute additional data.

[157] Time until response can be initiated (e.g., notification sent, evacuation started)

[158] Time between when response is initiated and desired effect is achieved (e.g., evacuation completed)

[159] National Aeronautics and Space Administration Center for Near Earth Object Studies, "Scout: NEOCP Hazard Assessment," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/scout/intro.html

[160] This is called "pre-discovery" or "precovery" analysis.

[161] Kiker, K. (2022). Asteroid Institute Precovery API Announced. B612 Foundation, webpage, September 8, 2022. As of January 18, 2023: https://b612foundation.org/asteroid-institute-precovery-api-announced

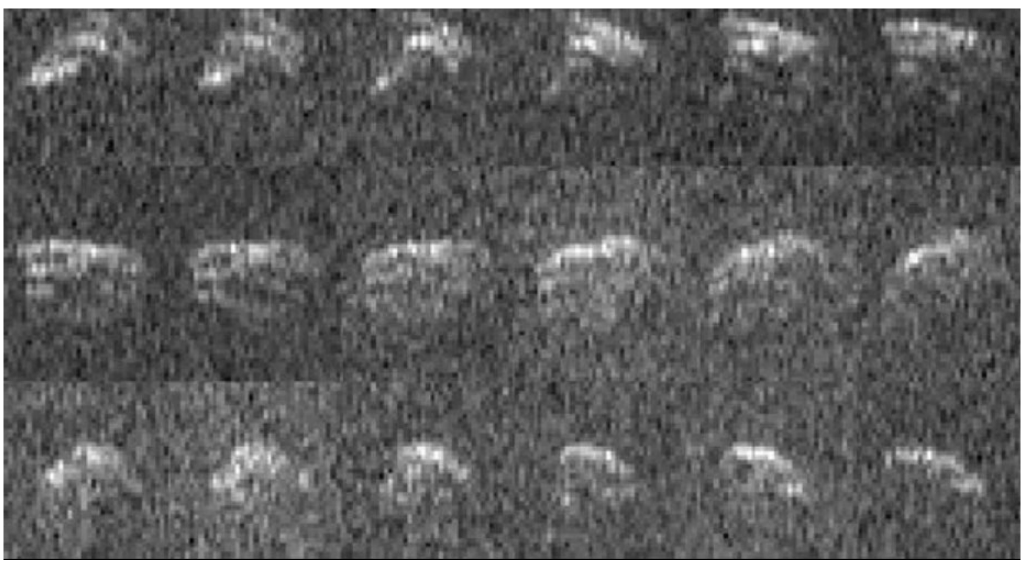
Characterization Using Existing Capabilities

Persistent observation by large Earth-based telescopes, as well as by in-space systems such as the James Webb Space Telescope, can provide additional insights into the size, shape, and potential composition of an object, even at larger distances and longer times to impact (weeks/months/years). This will reduce the related uncertainties and will allow for a more accurate prediction of the impact location and the extent of the damage.

Once an object gets closer to Earth (hours to days before impact, or during a previous “flyby”), it comes within range of radar telescopes whose measurements that can yield three-dimensional shape, relatively accurate size, rotation period[162], and precise trajectory. Radar observations can also detect the presence of smaller rocks) orbiting the NEOs. These natural satellites are found with 15% of NEOs larger than 200 m in diameter[163].

However, the most powerful radar telescope was the one at Arecibo on Puerto Rico, which is no longer operational (see Chapter 3). Figure 25 provides example images from the Goldstone astronomical radar, clearly showing the shape of an asteroid.

Figure 25: Radar Images of Asteroid 2013 ET



Source: Planetary Defense Interagency Tabletop Exercise 4, Module 3, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod3.pdf

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[162] National Research Council. 2010. *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*. Washington, DC: The National Academies Press. https://doi.org/10.17226/12842; Rodriguez-Alvarez, Nereida (2019). Goldstone Solar System Radar (GSSR) Learning Manual. NASA. As of: January 11, 2023: https://deepspace.jpl.nasa.gov/files/GSSR_learning_manual.pdf

[163] National Research Council. 2010. *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*. Washington, DC: The National Academies Press. As of 19 January 2023: https://doi.org/10.17226/12842

Customized Reconnaissance Missions

Sending one or more spacecraft to a potentially hazardous object in order to get close-up views of its size and shape, characterize its composition, and better determine its mass and orbit can be done in two ways: a spacecraft can fly past the object, which provides several minutes to hours of close-up observation time, or it can enter into an orbit around the object, which provides months or even years of observation time. However, such a “rendezvous mission” requires a larger spacecraft, a larger launch vehicle, and likely a longer flight time compared to the flyby mission, since the spacecraft will have to accelerate or decelerate near its destination in order to enter into an orbit around the object. Table 8 shows what each mission type can be expected to accomplish. Table 10 in Chapter 6 (page 84) shows related costs and timelines.

Table 8: Capabilities of Flyby and Rendezvous Reconnaissance Missions

Y+ = Yes, Excellent Y = Yes, Good P = Partial N = No

Capability	Flyby Reconnaissance	Rendezvous Reconnaissance
Improve Asteroid Orbit Estimate	Y	Y+
Reduce Uncertainties in Asteroid Earth Impact Location	Y	Y+
Reduce Uncertainties in Asteroid Earth Impact Probability	Y	Y+
Estimate Asteroid Mass	N	Y
Observe Asteroid Shape	P	Y+
Estimate Asteroid Size	P	Y+
Estimate Asteroid Rotation State	P	Y+
Observe Asteroid Composition and Other Details	P	Y+
Carry Along Asteroid Deflection Mechanism	Y	Y
Continue Monitoring Asteroid After Deflection Attempt	N	Y

Source: Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

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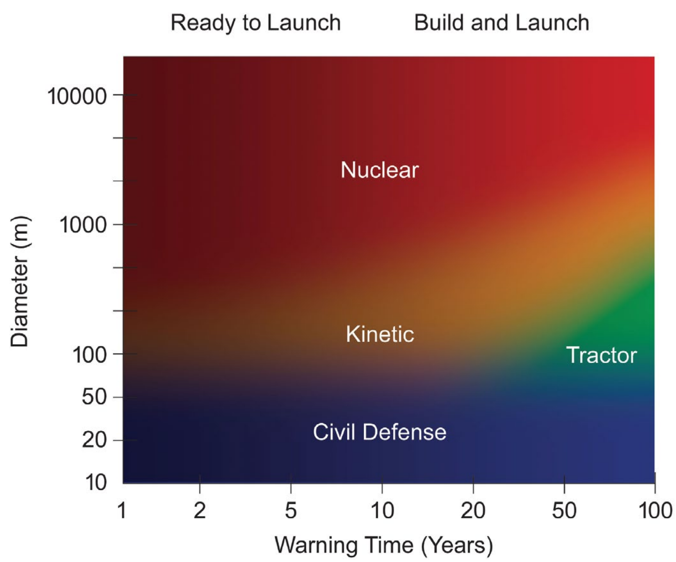
Mitigation Missions

Available options for mitigation depend on the size of the threatening object, available warning time, and the technological maturity of the different mitigation approaches. Figure 26 shows which of the four mitigation approaches generally considered most mature (nuclear explosive devices for deflection or disruption, as well as kinetic impactor and gravity tractor for deflection) are the most promising for different combinations of object size and warning time, based on analysis conducted by the U.S. National Research Council.[164] These approaches, and several less-mature ones, are discussed below.

[164] National Research Council. 2010. Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies. Washington, DC: The National Academies Press. As of 9 January 2023: https://doi.org/10.17226/12842

Figure 26: Preferred Primary Mitigation Options Based on Object Size and Time Available



Source: Used with permission of National Academies Press, from Space Studies Board, National Research Council, Division on Engineering and Physical Sciences, Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies, and National Research Council, *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*, National Academies Press, 2010. As of 9 January 2023: https://doi.org/10.17226/12842

Note: mitigation becomes impossible with current technologies for object sizes significantly above 10 km. “Nuclear” – nuclear explosive device, “Kinetic” = kinetic impactor, “Tractor” = gravity tractor, “Civil Defense” = terrestrial preparedness.

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Kinetic Impactor

For this mitigation approach, a spacecraft is sent on a collision course with the potentially hazardous object to impart an impulse that will change the object’s speed and therefore its trajectory. The heavier the spacecraft, and the higher its speed on impact, the larger the deflection. This is the only mitigation approach that has actually been tested in space, by NASA’s DART mission in 2022.[165]

However, kinetic deflection imparts less energy, and thus leads to a smaller change in the object’s trajectory, than a comparably-sized mission based on Nuclear Explosive Devices. It therefore requires more lead time and/or can only be used for comparatively smaller objects (see Figure 26). For larger objects and/or shorter warning times, multiple launches and multiple impactors may be needed.[166] Kinetic impact also requires the spacecraft to have a very sophisticated Guidance, Navigation, and Control system.

[165] National Aeronautics and Space Administration Solar System Exploration Our Galactic Neighborhood, “Double Asteroid Redirection Test (DART)” webpage, undated. As of January 18, 2023: https://solarsystem.nasa.gov/missions/dart/in-depth

[166] Wang, Y., Li, M., Gong, Z., Wang, J., Wang, C., and Zhou, B. (2021). Assembled Kinetic Impactor for Deflecting Asteroids by Combining the Spacecraft with the Launch Vehicle Upper Stage. Icarus. 368:114596. As of January 18, 2023: https://doi.org/10.1016/j.icarus.2021.114596

While kinetic impactors are generally considered for deflection missions only, smaller objects (tens of meters) could potentially also be disrupted relatively close to Earth – minutes before impact – by using interceptor missiles equipped with multiple kinetic kill vehicles.[167,168]

Nuclear Explosive Device (NED)

This mitigation approach is based on setting off a nuclear device within a few hundred meters of the threatening object, while the object is still in deep space – months to years before a predicted impact. The energy released by the nuclear detonation will vaporize part of the object's surface, resulting in a momentary thrust that will nudge the object into a slightly different trajectory, hopefully one that will not intersect with Earth. This approach imparts the most energy for a given spacecraft mass, and thus is the preferred approach for larger objects and/or shorter notices (see Figure 26). However, in contrast to the Kinetic Impactor approach, it has never been tested. Just like with kinetic impactors, multiple NEDs can be detonated in series in order to increase the impulse imparted on the object and thus increase the deflection.

Furthermore, given current technologies, mitigation by **disruption** in deep space can only be accomplished by a nuclear explosive device. Disruption requires less warning time than deflection, and deep-space disruption is possible even with relatively short warning times (months) if a mission can be launched quickly. For a disruption mission, the nuclear explosive device would be detonated closer to the PHO's surface, or even below the surface. However, the latter would increase the complexity of the mission, since interaction with the PHO would be required to excavate or blast a tunnel. Figure 27 shows the size and density ranges of asteroids that can be disrupted with large-yield nuclear explosive devices.

Disruption of small objects may also be possible very close to Earth, minutes before impact, using intercontinental ballistic missiles (ICBMs) with nuclear warheads.[169] Figure 28 illustrates this concept. However, depending on the detonation altitude, this creates a risk of High-Altitude Electromagnetic Pulse which can damage electronics on Earth and also affect satellites in Earth orbit.[170]

However, the use of nuclear explosive devices in outer space, even for beneficial purposes such as Planetary Defense, is currently prohibited by international treaties.[171] Even a mere collaboration among countries for the purpose of planning a nuclear

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167 Melamed, Nahum, Brochier, Andre, Craun, Mitch, Hemmi, Naoki, Goldstein, Selma, Thangavelu, Chelsea, and Gaal, Alex: "Asteroid Interception and Disruption at Atmospheric Entry". IAA-PDC-19-04-P09. Proceedings of the 6th IAA Planetary Defense Conference, 29 April to 3 May 2019, Washington, DC, USA.

168 Lubin, P., Cohen, A.N. (2022). Asteroid interception and disruption for terminal planetary defense. *Advances in Space Research*. 71(3):1827-1839. As of January 18, 2023: https://doi.org/10.1016/j.asr.2022.10.018

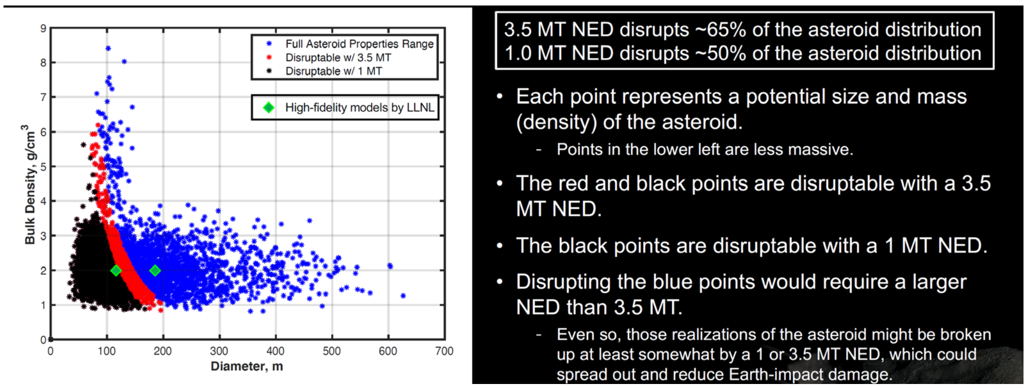
169 Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf

170 International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023: https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

171 Osburg, J., Blanc, A., Barbee, B., Dunk, F.G. (2020). Nuclear Devices for Planetary Defense. As of January 18, 2023: https://ntrs.nasa.gov/citations/20205008370

mitigation mission may violate the Nuclear Non-Proliferation Treaty.[172] While it could be argued that these restrictions would be set aside in case of an imminent threat to human civilization, and the United Nations Security Council – which has the authority to override international treaties[173] – could decide accordingly, this is less likely to be disregarded for the in-space testing and general experimentation that is needed to develop and validate NED-based concepts for deflection and disruption, and to have them ready if and when an impactor is identified. The use of nuclear explosive devices in space is also politically challenging due to the emotions attached to the topic of nuclear weapons. Chapter 6, starting on page 81, provides additional background on this issue.

Figure 27: Disruption Performance of 1 Mt and 3.5 Mt Nuclear Explosive Devices

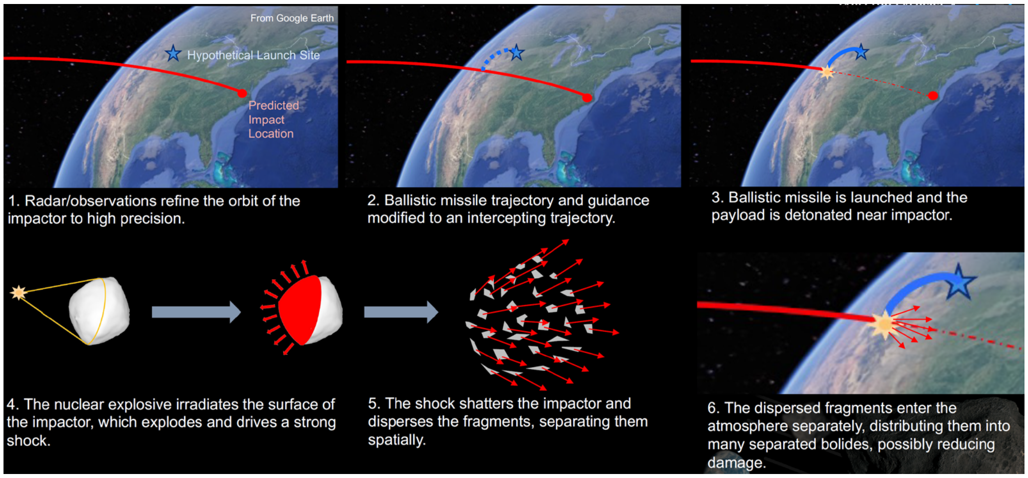


Source: Planetary Defense Interagency Tabletop Exercise 4, Module 1b, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod1b.pdf

[172] Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

[173] Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

Figure 28: Ballistic Missile Nuclear Intercept Concept for Short-Notice Scenarios



Source: Planetary Defense Interagency Tabletop Exercise 4, Module 1b, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod1b.pdf

Gravity Tractor

Under the Gravity Tractor approach, a very heavy spacecraft flies next to the threatening object for many years. The gravitational forces between the spacecraft and the object, even though very small, will change the object's orbit over the course of time. This approach, too, has never been tested, and it requires very long warning times to be an option, since the momentum transfer to the object is much lower than in case of a nuclear explosive device and even a kinetic impactor. It also requires a very powerful launch vehicle due to the need for a high-mass spacecraft.

Ion Beam Deflection

In this concept, a satellite keeps station near the threatening object and directs a powerful ion beam generator (which could be based on an electric space propulsion engine) at it, thus imparting a small but permanent force. Another generator projects an ion beam in the opposite direction to balance the forces on the spacecraft. Over the course of years, this will change the trajectory of the object.

Less Mature Mitigation Options

Beyond the three approaches described above, others have also been conceptualized:

- **Focused solar ablation**: spacecraft equipped with large mirrors are used to increase the temperature of part of the threatening object, leading to vaporization which in turn generates thrust that changes the object's trajectory.

- **Directed Energy ablation**: spacecraft equipped with powerful lasers fly near the asteroid, vaporizing a small part of its surface with every laser pulse, which creates thrust that, over time, changes the object's trajectory.[174]
- **Mass driver**: a spacecraft lands on the threatening object, digs into its surface, and ejects the collected material into space, again creating thrust that changes the object's trajectory.
- **Surface coating**: select parts of the surface of the threatening object are coated with reflective or anti-reflective materials to change the amount of infrared radiation it emits, thus changing the impact of the Yarkovsky Effect and, subsequently, slightly changing the object's orbit. However, this approach has the lowest momentum transfer of all discussed approaches, and thus would require the longest warning time.
- **"Cosmic billiards**:" a smaller asteroid is diverted by one of the above methods so that it collides with the larger object and nudges it into a new orbit. However, this requires finding a smaller object on a suitable trajectory.

However, these approaches are considered less mature and would therefore require significant additional research before they can be considered viable, let alone be relied on in a Planetary Defense emergency.

Terrestrial Pre-Impact Actions

Independently of in-space mitigation, leaders on Earth need to prepare a terrestrial response in case the mitigation mission fails or there is not enough time for one. Terrestrial preparedness efforts depend on the predicted location and severity of the impact, and also on the timeline available; see Table 9 at the end of this chapter. For short-notice events (minutes to hours), pre-impact actions can be informed by plans for other short-notice scenarios, such as tornadoes and space weather events.[175]

In particular, the population density in the predicted impact area will determine the potential loss of life. It also influences the resources that can be expected to be made available to respond to an impact. As Figure 29 shows, population density varies significantly worldwide, but also within individual countries. Sophisticated damage prediction tools take population density into account when estimating the expected number of casualties based on what is known about impact likelihood, location, and severity at any given time before impact (Figure 30).

Hazards to protect against can include (see Chapter 2, starting on page 29, for details):

- A massive blast wave that can destroy structures and injure people and animals
- A thermal pulse that can start fires and cause burn injuries

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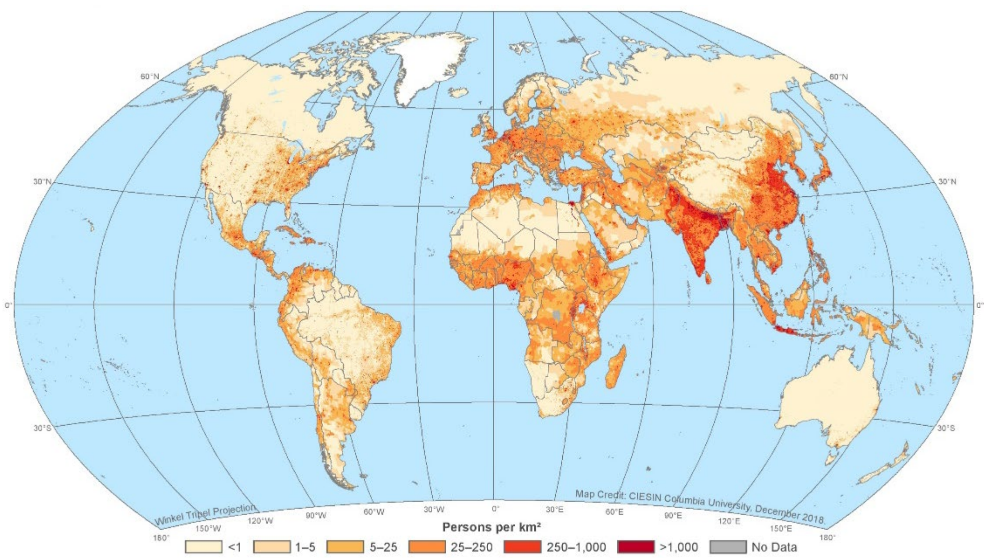
[174] Zhang Q, Walsh KJ, Melis C, Hughes GB, Lubin P. Orbital Simulations for Directed Energy Deflection of Near-Earth Asteroids. *Procedia Engineering*. ISSN 1877-7058, Vol. 103, pp. 671-678. As of 20 January 2023: https://doi.org/10.1016/j.proeng.2015.04.087

[175] As an example for the latter, see: Department of Homeland Security: "Federal Operating Concept for Space Weather Events," May 2019. As of 10 March 2023: https://www.fema.gov/sites/default/files/2020-07/fema_incident-annex_space-weather.pdf

- An impact crater within which even hardened structures are completely destroyed
- Large quantities of hot rocks being ejected from the crater, causing additional damage (potentially even to satellites in Earth orbit) and starting fires further away from the impact site
- A seismic shock wave similar to an earthquake
- A tsunami, if the impact is over an ocean
- Dust and soot from the impact and resulting fires being injected into the atmosphere, potentially leading to a decrease in temperatures worldwide
- Higher-order effects such as cascading failures of critical infrastructures like the power grid, a global economic downturn, mass migration, opportunistic wars, nations mistaking an impact for a nuclear attack, famine due to persistent changes in climate and subsequently reduced agricultural production, and other crises

Figure 29: Map of Global Population Density in 2020



Source: NASA Socioeconomic Data and Applications Center, "Population Density, v4.11 (2000, 2005, 2010, 2015, 2020) » Maps" webpage, undated. As of January 18, 2023: https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/maps
Note: a larger version of this figure is provided in Appendix A.6 (page 114).

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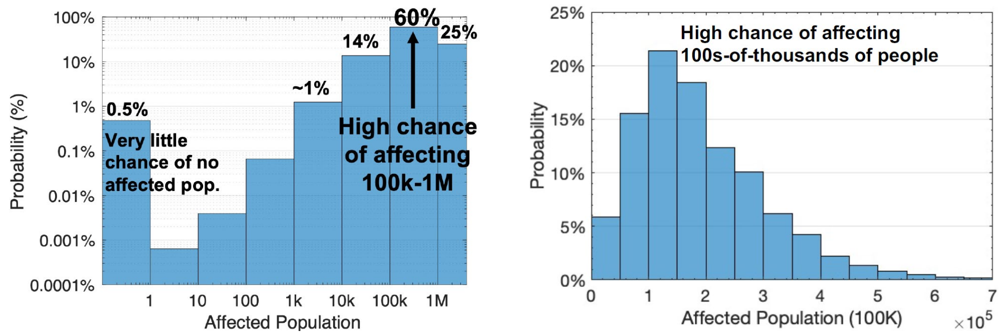
Figure 30: Example for Casualty Prediction Based on Population Density for Fictitious Impact Scenario



Early Estimate (left) and Refined Estimate (right)

Source: (left) Planetary Defense Interagency Tabletop Exercise 4, Module 2, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod2.pdf; (right) Planetary Defense Interagency Tabletop Exercise 4, Module 3, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod3.pdf

In the most likely case of a **small object** comparable in size to the Chelyabinsk one, which will most likely disintegrate in the atmosphere and have a limited damage footprint, preparatory measures include temporary evacuations and protecting windows (comparable to hurricane preparations), informing the population about how to protect themselves from injuries caused by flying glass, and staging emergency response capabilities.

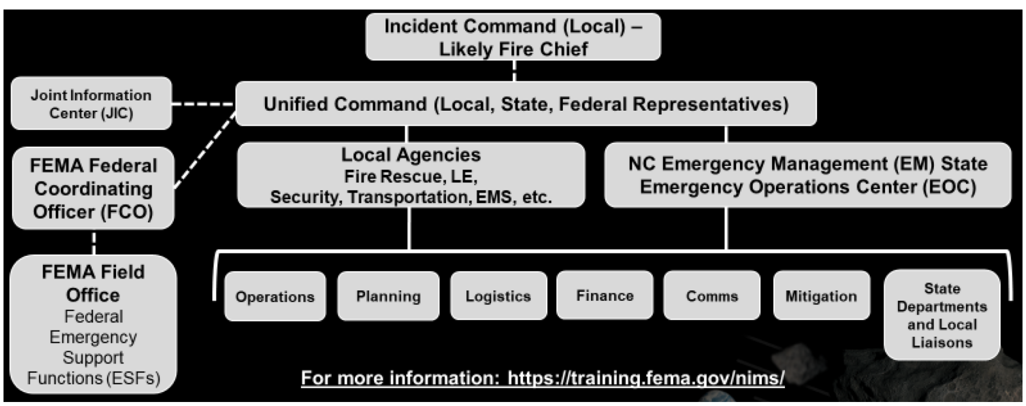
However, for all but the smallest impactors, due to the extent of the damage, professional emergency responders will likely be overtaxed, and thus preparations must include informing the population about the threat and about the likely need for self-aid immediately after the impact. This also means **educating the public – and professional responders** – about the hazards to expect, and providing regular pre-impact updates as ongoing characterization efforts reduce uncertainty about impact location and effects.

Key to reducing loss of life is to prepare for a **comprehensive evacuation** of the affected area, comparable to that taking place e.g. before a major hurricane. However, similar to the uncertainty involved in forecasting where exactly a hurricane will make landfall, and how strong winds will be, more than a day or two ahead of time, the impact location and severity may not be known until days or hours beforehand. Furthermore, a large impactor will affect a larger area than a typical hurricane, will likely affect an area that is not as prepared for major evacuations as a hurricane-prone location is, and damage from most impactors will be significantly worse than that caused by even a major hurricane. The latter also means that, if there is time, economic and cultural assets will have to be removed from the impact area, and evacuations may have to be permanent rather than – as in case of a hurricane – temporary for most of the evacuees. The U.S. "Federal Evacuation Support Annex to the Response and Recovery Federal Interagency Operational Plans" provides an example for evacuation considerations at the national level.[176] Long-term permanent evacuation of large areas is going to be a costly, disruptive, and time-consuming effort; the ongoing slow evacuation of the Swedish city of Kiruna can serve as a small-scale example for this,[177] as can the rapid evacuation of the Finnish city of Viipuri after the Russian attack on Finland in 1939.[178]

Staging post-impact response capabilities and supplies is important as well to enable a rapid and effective post-impact response. However, the uncertainties involved make this a challenge as well: with exact impact location and extent of expected damage likely remaining unknown until relatively soon before impact (days if not hours), staging has to take place well outside the possible impact area, which means it will take longer to get resources and capabilities to the affected area after an impact. Response preparations should also include setting up an organizational and command structure for the responding forces. Figure 31 shows a notional post-impact incident command structure under the "Incident Command System" (ICS) used in the U.S.[179]

Last but not least, there is the possibility of governments in an affected area no longer being functional after a major impact, at least temporarily, or governmental functions breaking down in advance of one. Response planning should take this possibility into account.

Figure 31: Notional Post-Impact Incident Command System



Source: Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf

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[176] Department of Homeland Security: "Federal Evacuation Support Annex to the Response and Recovery Federal Interagency Operational Plans," January 2021. As of 10 March 2023: https://www.fema.gov/sites/default/files/documents/fema_incident-annex_evacuation.pdf
[177] Casey, J. (2019). Moving a town to save a mine: the story of Kiruna. *Mine*. As of January 18, 2023: https://www.mining-technology.com/features/moving-a-town-to-save-a-mine-the-story-of-kiruna
[178] Kohout, T., Turunen, S., (2021). Rapid Evacuation of the Viipuri (Vyborg) City – Experience from the Finnish Winter War 1939-1940. 7th IAA Planetary Defense Conference, April 2021. As of January 18, 2023: https://ui.adsabs.harvard.edu/abs/2021plde.confE..75K/abstract
[179] Federal Emergency Management Agency Emergency Management Institute, "National Incident Management System," webpage, undated. As of January 18, 2023: https://training.fema.gov/nims/

Terrestrial Post-Impact Response

Immediately after an impact, emergency managers should leverage all available information sources to obtain an overview of the actual extent of the damage, since size, shape, and severity of effects are likely to be different from pre-impact predictions due to the uncertainties involved (see Figure 24 on page 55).

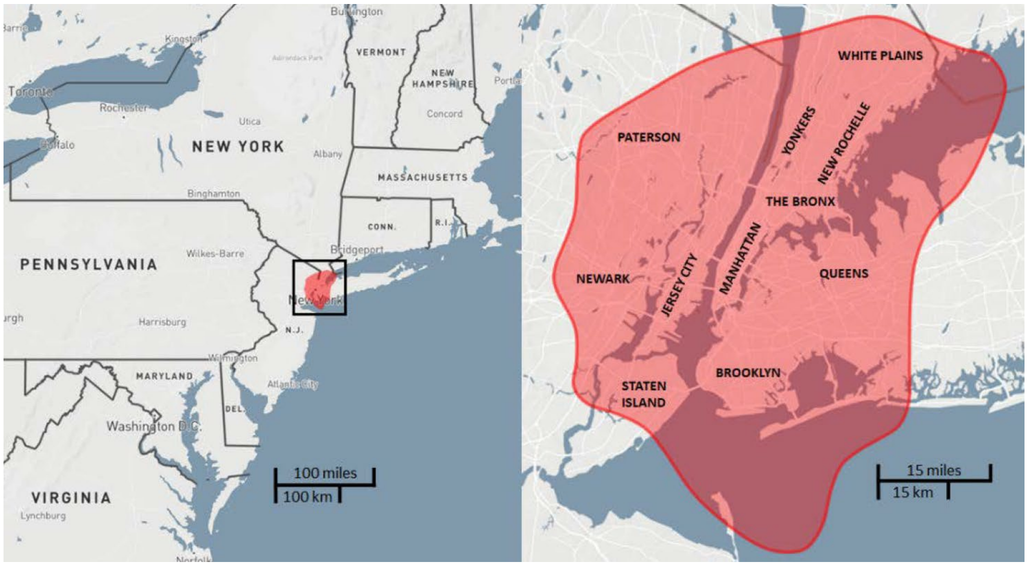
For all but the smallest objects, if the impact is in a populated area, the extent of damage on the ground will likely exceed the capacity of any emergency response (cf. Figure 32). Thus, emergency managers and responders will have to focus their efforts.

However, no matter the actual size of the impactor, a large part of whatever the affected area ends up being will only experience moderate damage (cf. the light area in Figure 33). There, people should be instructed to take care of themselves and of those around them to the degree possible, so that professional rescuers can focus on the more severely affected areas where, however, people may still have survived (the "severe" area in Figure 33). Response to the most heavily damaged areas ("critical" and "unsurvivable" in Figure 33) will likely have to be delayed, since rescue services will almost certainly be overtaxed given the large area affected by structural collapse and fires, and so there will be little that they can do.

In addition to the immediate response to the areas directly affected by the impact, higher-order effects will also need to be addressed and mitigated: economic disruptions, cascading damage to critical infrastructure such as national or regional electrical grids, potential changes in global weather and climate, potential opportunistic aggression by state and nonstate actors, mass migration, and other complex threats.

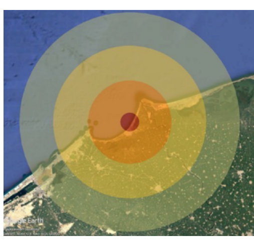
Due to the similarity of some impact effects with those of a nuclear detonation (sudden bright light, massive blast wave, thermal pulse), a special consideration for impacts that happen with no or very short (minutes to hours) warning is the possibility of the affected country's government initially mistaking it for a surprise nuclear strike, and responding accordingly. This is a particular concern in case of countries who have both a nuclear arsenal and nuclear-armed adversaries, but who at the same time are lacking the full suite of strategic warning and detection sensors that e.g. the United States has at its disposal, which could immediately confirm that a destructive blast was due to a non-nuclear event.

Figure 32: Tunguska Impact Damage Footprint Overlaid on New York City



Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

Figure 33: Mapping of Affected Area



Damage Level	Potential Blast Damage Effects	Potential Thermal Damage Effects
Serious	Shattered windows, some structural damage	Second-degree burns
Severe	Widespread structural damage, doors and windows blown out	Third-degree burns
Critical	Most residential structures collapse	Clothing ignition
Unsurvivable	Complete devastation	Structure ignition, incineration

Source: Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

Considerations for Very Large Impactors

If an object of more than approximately 1 km in size impacts, the resulting effects have the potential to destroy human civilization or, in case of much larger objects, even wipe out most life on Earth. Thus, the focus of terrestrial preparations would have to shift from localized response to ensuring the survival of our species, in case mitigation fails. However, costs for such measures would be extremely high, and timelines would be measured in decades or even centuries.

Regarding in-space mitigation, according to an authoritative study by the U.S. National Academy of Sciences, **"[o]ther than a large flotilla (100 or more) of massive**

spacecraft being sent as impactors, nuclear explosions are the only current, practical means for changing the orbit of large NEOs (diameter greater than about 1 kilometer)."[180]

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[180] https://nap.nationalacademies.org/catalog/12842/defending-planet-earth-near-earth-object-surveys-and-hazard-mitigation

Table 9: Time Horizons for Planetary Defense Decision-Making

Warning Time Before Impact	Initial Discovery	Decisionmaking	Alerting the Population	Characterization	Mitigation	Terrestrial Response Options (for Government, Industry, Individuals)	Terrestrial Response Type	Example Scenarios**
No-Notice	Direct observation, bolide detection sensors	Reactive only	-	-	-	-	Comparable to earthquake response	**Chelyabinsk, 2013**
Minutes	Radar*	Comparable to nuclear attack response	EAS? WEA?	-	-	Isolate power grid? Shut down nuclear reactors? Stop trains and road traffic? Sheltering in place?	Comparable to earthquake response	
Hours	Radar*, telescopes?	Limited, high priority only	EAS, WEA, broadcast media, social media	Radar? Telescopes?	Disruption: ICBMs?	Above plus: self-evacuations, activating local emergency responders	Comparable to tornado response	**Sudan, 2008 (2008 TC_3)**
Days	Radar*, telescopes	Limited	EAS, WEA, broadcast media, social media, print media	Radar, telescopes	Disruption: ICBMs?	Above plus: staging regional responders and supplies, organized evacuations	Comparable to hurricane response	
Weeks	Radar*, telescopes	Deliberate but accelerated	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device?	Above plus: staging national and global responders and supplies, comprehensive evacuations, some permanent moves	Customized rapid response	NASA/FEMA TTX-1
Months	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes	Disruption: ICBMs, nuclear explosive device? Deflection: nuclear explosive device?	Above plus: more comprehensive permanent moves, relocation of certain industries / institutions / resources, building improvised shelters	Customized rapid response	PDC 2021, NASA/FEMA TTX-4
Years	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space mission	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor?	Above plus: potential permanent relocation of most populations / industries / institutions / resources (depending on deflection outcome), establishing long-term deep shelters	Customized long-lead response	NASA/FEMA TTX-2 & TTX-3, PDC 2015, PDC 2019
Decade+	Telescopes	Deliberate	Broadcast media, print media, social media	Radar, telescopes, space missions	Disruption: nuclear explosive device; deflection: nuclear explosive device, kinetic impactor, gravity tractor, ion beam	Above plus: potential permanent relocation of all populations / industries / institutions / resources (depending on deflection outcome), establishing off-earth colonies	Customized long-lead response	**99942 Apophis, 2023 DW**; PDC 2013, PDC 2017, PDC 2023

Source: RAND Analysis

Notes: "*" only if radar happens to be looking in the right direction. “?”option might not apply. “**” **bold** = actual asteroid. All reconnaissance (“characterization”), mitigation, and terrestrial response options are discussed in detail, and references are provided, in Chapter 5. EAS: Emergency Alert System (in the U.S.) or similar government-run notification mechanism leveraging broadcast television/radio, electronic road signs, etc.; WEA: Wireless Emergency Alerts (in the U.S.) or similar government-run notification mechanism leveraging mobile phone infrastructure. See Appendix A.1 (page 101) for other abbreviations.

Chapter 6: Who Decides, and How?

Chapter Contents

As is the case for preparedness against other emergencies, **each nation should be responsible for protecting its population** against the threat of asteroid and comet impacts. However, due to the potentially global scale of the threat, and the need for advanced spaceflight capabilities that only very few countries currently have, **Planetary Defense is by necessity global in scope**. Global involvement even in a smaller-scale impact may also be required since the governments in an affected area may no longer be functional after an impact, or may even break down in advance of one.

In particular, detection and tracking is based on the contributions of astronomers – both professional and amateur – located around the world, operating sensors ranging from homebuilt backyard telescopes to large observatories designed specifically to discover threatening objects. They feed tens of millions of individual observations per year to the International Astronomical Union's **Minor Planet Center (MPC)**, the internationally-recognized clearinghouse for such data.[181] The MPC, located in Cambridge, Massachusetts, then estimates a newly-discovered object's orbit based on those observations. If a potentially hazardous asteroid or comet is detected, the **Center for Near-Earth Object Studies (CNEOS)** at the Jet Propulsion Laboratory in California[182] and ESA's **Near-Earth Objects Coordination Centre (NEOCC)**[183] perform calculations using this data to generate a hazard assessment. Figure 34 shows the survey and alert process used by the U.S. Government.

In case of a potential impact, the **International Asteroid Warning Network (IAWN)**,[184] a virtual network of space agencies, observatories, and individual astronomers endorsed by the **United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)**, will issue a worldwide notification, and also notify the **United Nations** which in turn will notify its member states (see also Appendix A.9, page 121).[185]

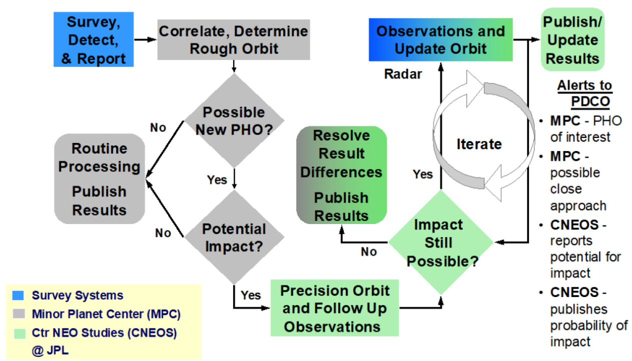
WHO/HOW

[181] Center for Astrophysics, The Minor Planet Center, homepage, undated. As of January 18, 2023: https://minorplanetcenter.net/
[182] National Aeronautics and Space Administration Center for Near Earth Object Studies, "Top News Stories," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov
[183] European Space Agency, Near-Earth Objects Coordination Centre, "NEOCC Database Statistics," webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/home
[184] International Asteroid Warning Network, "History," webpage, undated. As of January 18, 2023: https://iawn.net/about.shtml (see Appendix A.11 on page 101 for a list of IAWN members)
[185] United Nations Office for Outer Space Affairs, "Near-Earth Objects and Planetary Defence," electronic report, June 2018. As of January 18, 2023: https://www.unoosa.org/documents/pdf/smpag/st_space_073E.pdf

If the threat warrants, these organizations will ask astronomers to conduct more detailed observations. Thanks to widespread automation, the turnaround time for these types of requests can be measured in minutes.[186] In addition, space agencies around the world will likely start planning reconnaissance and/or mitigation missions (see Chapter 5). These efforts will be coordinated by the **Space Mission Planning Advisory Group (SMPAG)**,[187] an association of space agencies also endorsed by the United Nations. The SMPAG is already conducting studies on topics such as threat scenarios and response thresholds, Planetary Defense missions and technologies, and communication guidelines.[188] It is also addressing related legal questions,[189] which are an important aspect of any international collaborative effort and have to be taken into account by decisionmakers.[190]

Many national governments will have their own notification and decision-making procedures for Planetary Defense emergencies. In the United States, for example, the **Planetary Defense Officer** is responsible for informing both the rest of the U.S. federal government and the U.S. public.[191] Figure 35 shows the U.S. process for assessing the need for reconnaissance and mitigation missions, based on certain thresholds. ESA's thresholds are compatible with those of IAWN and SMPAG (see next section).[192]

Figure 34: NASA NEO Survey and Alert Process



Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

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186 International Asteroid Warning Network, "Sixth Meteoroid Detected Prior to Impact," webpage, undated. As of January 18, 2023: https://neo.ssa.esa.int/-/sixth-meteoroid-detected-prior-to-impact

187 Space Mission Planning Advisory Group, homepage, undated. As of January 18, 2023: http://www.smpag.net

188 Space Mission Planning Advisory Group, "Work Plan," electronic report, September 2019. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-PL-002_2_0_Workplan_2019_09-01+%283%29.pdf

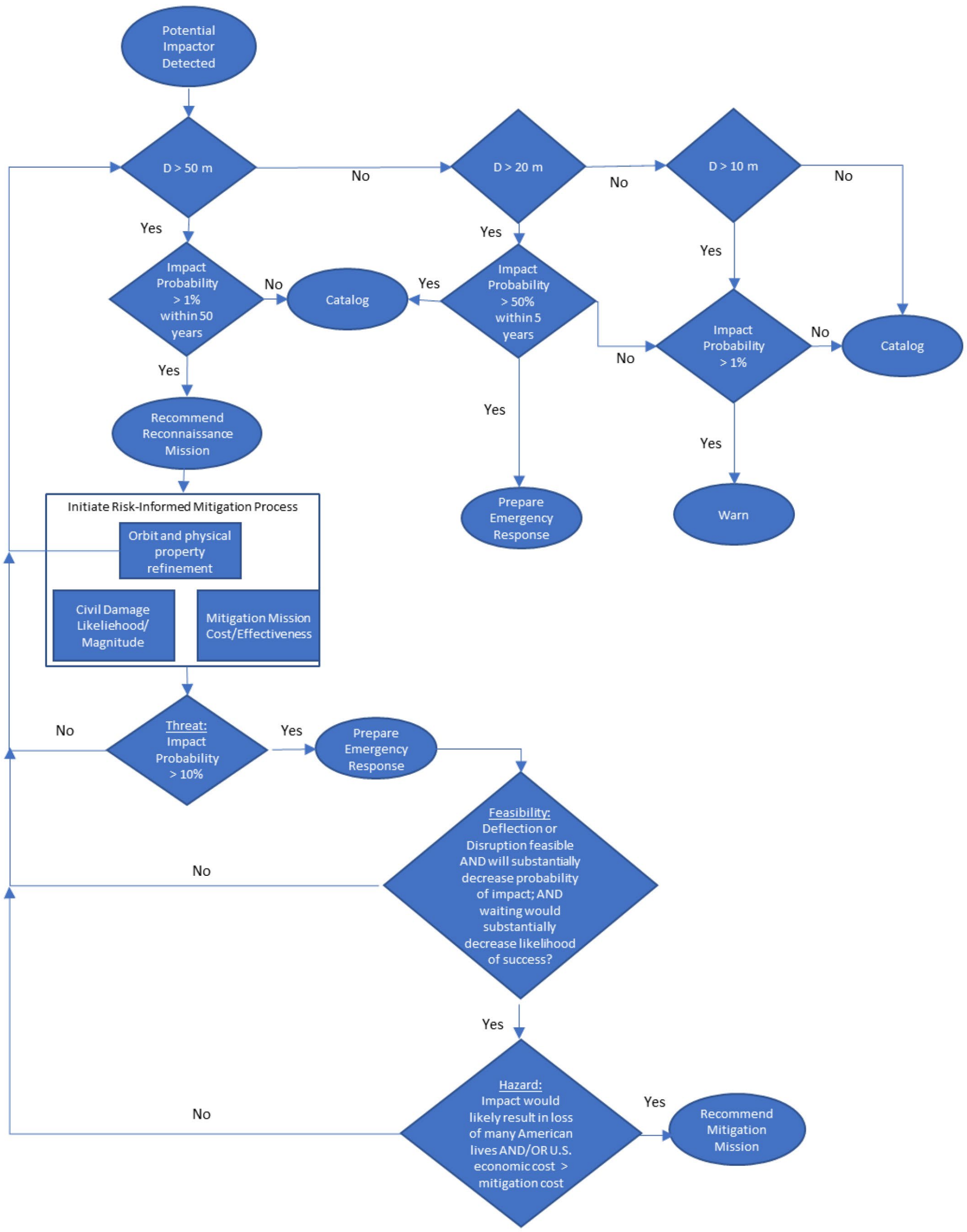
189 Space Mission Planning Advisory Group, "Work Plan," electronic report, September 2019. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-PL-002_2_0_Workplan_2019_09-01+%283%29.pdf

190 Marboe I. Legal Aspects of Planetary Defence. Brill; 2021.

191 National Aeronautics and Space Administration, "Notification and Communications Regarding Potential Near-Earth Object Threats (Revalidated with Change 1)," webpage, February 15, 2022. As of January 18, 2023: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPD&c=8740&s=1

192 E-mail communication from former ESA official, 28 February 2023.

Figure 35: U.S. Mission Recommendation Flowchart for Planetary Defense Emergencies



Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

WHO/HOW

Thresholds for Action

Timely warning of a potential impact, and the timely start of response activities, is critical to minimize the hazard. However, many objects pass close by Earth without impacting, and many impactors cause no damage due to their small size (see the discussion in Chapter 1, starting on page 21). Too many premature warnings and false alerts can therefore lead to actual threats no longer being taken seriously anymore, and will also cause limited funds to be spent unnecessarily. On the other hand, failing to warn of a threat that turns out to be real of course must be avoided as well. Thus, well-defined criteria are needed to guide Planetary Defense decisionmaking.

IAWN and SMPAG use the following thresholds, which represent a best practice:[193]

- IAWN will **warn** the global community if
  - a) The impact probability is greater than 1%, and
  - b) The object is greater than 10 m in size (or, if only brightness data is available, the object has an absolute magnitude of 28 or brighter)
- IAWN will recommend beginning **terrestrial preparedness** planning when a possible impact is:
  - a) Predicted to be within 20 years,
  - b) With an impact probability greater than 10%, and
  - c) The object is greater than 20 m in size (or, if only brightness data is available, the object has an absolute magnitude of 27 or brighter)
- SMPAG will start reconnaissance and mitigation mission planning when a possible impact is:
  - a) Predicted to be within 50 years,
  - b) With an impact probability greater than 1%, and
  - c) The object is greater than 50 m in size (or, if only brightness data is available, the object has an absolute magnitude of 26 or brighter)

However, individual countries, municipalities, or organizations may want to develop their own thresholds for action.

Cost Considerations

Planetary Defense capabilities as well as emergency preparations on Earth come with a cost, both in direct funding needed but also in opportunity cost and potential

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193 Space Mission Planning Advisory Group, "Status Report of Activity Recommended Criteria & Thresholds for Action for Potential NEO Impact Threat," electronic report. February 17, 2016. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/1879207/SMPAG-RP-003_01_0_Thresholds%26Criterion_2018-10-18.pdf

higher-order consequences. Thus, decision-makers have to take cost into account. While a detailed treatment of cost would be beyond the scope of this guide, key considerations in this context are:[194]

- Cost of Planetary Defense measures such as detection and tracking programs, preparation and execution of reconnaissance and mitigation missions (see Table 10), and related coordination efforts
- Cost of terrestrial emergency preparedness measures specific to Planetary Defense scenarios
- Benefits (financial and otherwise) of avoiding asteroid and comet impacts, based on likelihood and resulting damage (see Chapter 2)

A recent NASA study concluded that even substantial investments in Planetary Defense capabilities are worth it based on the likelihood of damage that can be prevented, with break-even points typically reached after only a few years.[195] However, in this context it is also important to note that there is no specific international legal obligation, beyond general humanitarian and ethical reasons and a state's duty to protect its own territory and population, for any nation to participate in international Planetary Defense activities.[196]

Table 10: Cost and Time Estimates for Typical Reconnaissance Missions

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

Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf
Note: dry mass is mass of structures only. Wet mass includes mass of propellant (rocket fuel) and other consumables.

WHO/HOW

[194] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
[195] Stokes, G.H., Barbee, Jr., B.W., Bottke, W.F., Buie, M.W., Chesley, S.R., Chodas, P.W., et. al., (2017) Update to Determine the Feasibility of Enhancing the Search and Characterization of NEOs. electronic report, September 2017. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
[196] Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

Dual-Use Concerns

Carl Sagan and Steven Ostro were the first to publicly raise concerns about the dual-use potential, i.e. military in addition to civilian applications, of Planetary Defense capabilities,[197] based on the insight that a system that can nudge an asteroid's trajectory away from Earth can, theoretically, also be used to nudge one towards Earth, or to change its course so that instead of hitting one country it hits another.

Thus, Planetary Defense capabilities could turn an asteroid into a weapon with a potential for destruction much greater than that caused by a nuclear bomb. International cooperation and trust, as well as effective safeguards, are therefore required for Planetary Defense activities. On the other hand, a country may try to prevent the deflection of an asteroid away from Earth if it is predicted to hit one of that country's adversaries. Again, this complication needs to be taken into account when designing decisionmaking processes for Planetary Defense, and technical safeguards should be implemented to protect Planetary Defense capabilities – especially mitigation missions – against unauthorized access and sabotage.

There also is a concern that using nuclear explosive devices in space for any purpose, even for a beneficial one such as Planetary Defense, would set a precedent for other, less benign uses, and may also hinder nuclear nonproliferation efforts on Earth.[198] A recent report by SMPAG provides further illumination of this challenging issue.[199]

Risk of Competing Efforts

Another concern: if different spacefaring nations pursue different mitigation approaches to a specific threat, there is a chance that these competing efforts could counteract each other or otherwise result the likelihood of a successful deflection. Thus, the work of SMPAG is of critical importance, providing coordination for deconfliction and – ideally – fostering collaboration.[200]

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Unintended Consequences

Deflection of a threatening object is affected by an unavoidable degree of uncertainty, as is long-term orbit prediction, and thus preventing what could be a near-miss could increase the likelihood of impact for future encounters. This may cause conflict among nations about the best mitigation approach, and could also lead to

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[197] Sagan, C., & Ostro, S. J. (1994). Long-range consequences of interplanetary collisions. Issues in Science and Technology, 10(4), 67–72. As of 9 January 2023: https://issues.org/wp-content/uploads/2022/07/Sagan-and-Ostro.pdf

[198] Osburg, J., Blanc, A., Barbee, B., Dunk, F.G. (2020). Nuclear Devices for Planetary Defense. As of January 18, 2023: https://ntrs.nasa.gov/citations/20205008370

[199] Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

[200] Space Mission Planning Advisory Group, homepage, undated. As of January 18, 2023: http://www.smpag.net

subsequent litigation and potential liability.[201] Again, having an internationally-accepted body of technical subject matter experts, like SMPAG, is critical to enabling a coordinated global response that leverages synergies and minimizes the chance of disagreements.

Planetary Defense measures taken in response to an impact threat could also affect the general risk of violent conflict on Earth,[202] for example if nuclear devices are used or unannounced short-notice launches are taking place. The risk of this can be minimized by increased transparency that is fostered by established forums for international cooperation and collaboration.

WHO/HOW

[201] Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020. As of January 18, 2023: https://www.cosmos.esa.int/documents/336356/336472/SMPAG-RP-004_1_0_SMPAG_legal_report_2020-04-08+%281%29.pdf

[202] Baum, S.D., (2021). Accounting for violent conflict risk in planetary defense decisions. *Acta Astronautica*. 178:15-23. As of January 18, 2023: https://doi.org/10.1016/j.actaastro.2020.08.028

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Chapter 7: How to Inform the Public?

Chapter Contents

Due to the broad global participation in astronomy in general and asteroid and comet detection in particular, and since observations as well as predictions are routinely widely and rapidly distributed among the astronomical community, **news of a newly discovered potentially hazardous object will spread quickly**. Leaders have to realize that parts of the public will likely already be aware of the threat by the time that initial official statements are distributed. However, **mis- and disinformation will likely start circulating as well**, and thus leaders must be prepared to actively counter that. This should include preemptively addressing potential misperceptions, and will require using clear and correct language as well as **being transparent about the likely significant uncertainties** that will exist through much of the post-discovery phase. Note that states that are signatories to the Outer Space Treaty are **required to inform "the United Nations** as well as the public and the international scientific community, to the greatest extent feasible and practicable, of the […] results of" in-space activities including those that lead to the discovery of potentially hazardous objects.[203] [204]

Citizens will require **both overview information**, to put the threat in context, **and detailed instructions** regarding what everyone can do to protect themselves, their loved ones, and their assets. Notifications should **refer to authoritative sources** such as IAWN, CNEOS, and NEOCC, who will indicate when updated information may become available.

If there is significant lead time (months or more), more comprehensive and sophisticated information strategies can be designed and implemented. However, short-notice emergencies benefit particularly from preparation, for example, from having press releases that are drafted in advance and only require filling in the specifics.

Finally, interactive tools such as NASA's "Eyes on Asteroid" webpage[205] can help communicate otherwise complex details on orbits and approach distances in an intuitive, accessible manner (Figure 36).

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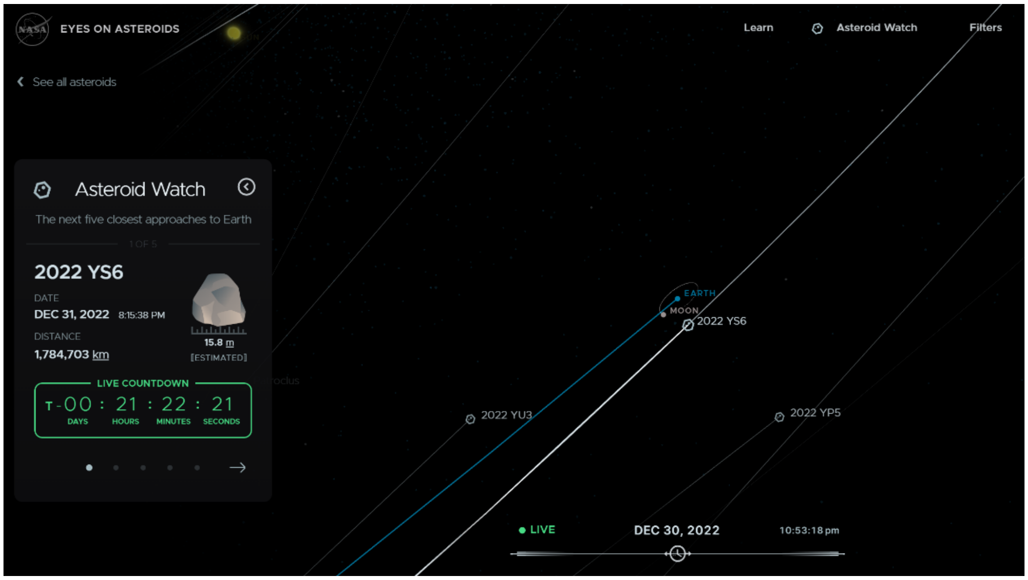
[203] United Nations Office for Outer Space Affairs, Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, webpage. December 19, 1966, As of January 18, 2023: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

[204] The SMPAG Working Group on Legal Issues provides more detailed information on related duties and liabilities. (Space Mission Planning Advisory Group, "Planetary Defence Legal Overview and Assessment," electronic report, April 2020.)

[205] National Aeronautics and Space Administration, "Eyes on Asteroids," webpage, undated. As of January 18 2023: https://eyes.nasa.gov/apps/asteroids/#/asteroids

Figure 36: Intuitive Interactive Orbit Visualization



Source: National Aeronautics and Space Administration, “Eyes on Asteroids” webpage, undated. As of January 18, 2023: https://eyes.nasa.gov/apps/asteroids/#/asteroids/watch/2022_ys6

Public Alerting Mechanisms

Especially for Planetary Defense emergencies with very short notice (hours), and for broadcasting emergency response information after an impact, the main options for quickly alerting large parts of the population in the affected area are:

- Existing **Wireless alert systems** that leverage the cell phone infrastructure, such as the U.S. “Wireless Emergency Alerts” system[206] or the “EU Alert” used in many European countries.[207] However, these systems usually do not have a predefined alert code for “Planetary Defense emergency”, “asteroid impact”, or the like, and thus alerting organizations will have to improvise with freetext messages or existing alert codes, such as “shelter in place” or “tsunami warning”, which takes more time and introduces potential error sources.[208]
- Public warning systems tied to already-existing **television, radio broadcast**, and World Wide Web infrastructure, like the U.S. “Emergency Alert System”[209]
- Existing **Sirens** and other sound-based alerting systems

[206] Federal Communications Commission, “Wireless Emergency Alerts,” webpage, January 11, 2023. As of January 18, 2023: https://www.fcc.gov/consumers/guides/wireless-emergency-alerts-wea

[207] European Telecommunications Standards Institute, “Technical Specification. Emergency Communications (EMTEL); European Public Warning System (EU-ALERT) using the Cell Broadcast Service,” Sophia-Antipolis, France, 2019. As of January 18, 2023: https://www.etsi.org/deliver/etsi_ts/102900_102999/102900/01.03.01_60/ts_102900v010301p.pdf

[208] Osburg, Jan: *Using “Wireless Emergency Alerts” for Planetary Defense Notifications*, IAA-PDC-19-08-P03, presented at the 7th Planetary Defense Conference, Washington, DC, USA, April 2019. As of 23 December 2022: https://drive.google.com/file/d/1rXWhaVLl-a1x6Pwsu_c7cu6APJhUnvVA/view

[209] Federal Communications Commission, “The Emergency Alert System (EAS),” webpage, November 16, 2022. As of January 18, 2023: https://www.fcc.gov/emergency-alert-system

- Established government **websites**, which can also provide key additional information

In case of an actual Planetary Defense emergency, the following organizations will be **providing authoritative, up-to-date information**:

- NASA's Planetary Defense Coordination Office (https://www.nasa.gov/planetarydefense)
- ESA's Planetary Defence Office (https://www.esa.int/Space_Safety/Planetary_Defence), also via its Near-Earth Objects Coordination Centre (https://neo.ssa.esa.int/home)
- The Center for Near-Earth Object Studies at JPL (https://cneos.jpl.nasa.gov/news)
- The International Asteroid Warning Network (https://iawn.net/index.shtml)
- The Space Mission Planning Advisory Group (http://www.smpag.net)

Notification Coordination Process

All national-level stakeholders should **coordinate their notification activities** and content among their government agencies, ideally also with sub- and supranational stakeholders. This will avoid conflicting messaging and reduce confusion and doubt among the population. Figure 37 provides an example of a national-level notification process, Figure 38 shows how this would connect to state and local notification in the U.S. Figure 39 shows the European Space Agency's notification policies. Appendix A.9 on page 121 documents the United Nations process.

Content of Press Releases and Other Official Communications

Initial communications should cover the following information elements:[210, 211]

- the current likelihood of impact, in colloquial terms ("unlikely", "possible", "likely", "certain")
- the potential impact date and time (including time zone)
- the predicted impact area
- the expected extent and severity of damage[212]
- the uncertainties involved
- what is being done to reduce those uncertainties, and by whom
- what is being done to mitigate the threat, and by whom
- what people should do
- The asteroid name or designation
- authoritative sources for more detailed information

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[210] Planetary Defense Interagency Tabletop Exercise 4, Presentation Module 1a Early Mitigation Options, February 23, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod1a.pdf
[211] International Asteroid Warning Network, "Workshop on Communicating About Asteroid Impact Warnings and Mitigation Plans," electronic report, September 2014, As of January 18, 2023: https://iawn.net/documents/201409_Communications/iawn_communication_workshop_report.pdf
[212] If the energy released by an impactor is provided in kilotons or Megatons (of TNT equivalent), or the concept of an "airburst" is mentioned, or other terminology related to nuclear weapons is used, it should be made clear that an asteroid or comet impact does not pose any kind of nuclear radiation hazard.

- when to expect updates, and from whom

However, some notification channels, such as the U.S. "Wireless Emergency Alerts" system, only allow for a very limited amount of information to be transmitted – sometimes as few as 90 characters.[213] Thus, even if multiple messages are sent, only part of the information above can be transmitted – for example, impact time and location, plus a short URL pointing to a website with more information. Appendix A.12 on page 133 shows notional examples of short-form notifications.

Updates should reiterate basic information for context and so that they can stand on their own. Figure 40 provides an example of an initial press release informing the public of an impending impact threat. Figure 41 illustrates an update press release. Appendix A.4 (page 107) offers a template for similar notifications. Appendix A.3 (page 105) and Appendix A.13 (page 135) show two of ESA's templates for disseminating key information about a near-Earth object.

Visual aids are important to clearly communicate on this complex topic, but they need to be designed right to avoid confusion and misinterpretation, and they will ideally be accompanied by explanations from subject-matter experts.[214] This guide contains multiple figures illustrating good practices of information visualization for Planetary Defense (e.g. Figure 4, Figure 11, Figure 12, Figure 15, Figure 22, Figure 24, Figure 26, Figure 36, Figure 40, and Figure 41).

Due to the similarity of some impact effects with those of a nuclear detonation (sudden bright light, massive blast wave, thermal pulse), a special consideration for impacts that happen with no or very short (minutes to hours) warning is the possibility of the affected country's government initially **mistaking it for a surprise nuclear strike**, and responding accordingly. This is a particular concern in case of countries who have both a nuclear arsenal and nuclear-armed adversaries, but who at the same time are lacking the full suite of strategic warning and detection sensors that e.g. the United States has at its disposal, which could immediately confirm that a destructive blast was due to a non-nuclear event. Thus, countries that do operate such global sensor networks[215] should be prepared to rapidly inform nations – especially nuclear powers – that are affected by a no- or short-notice impact that it was not a nuclear blast. Making this notification publicly would also help reassure both the affected population and the global community.[216]

Finally, different audiences (general population, local leaders and emergency managers, national and international decisionmakers, the scientific community, industry, mass media) require different content and different communication styles.[217]

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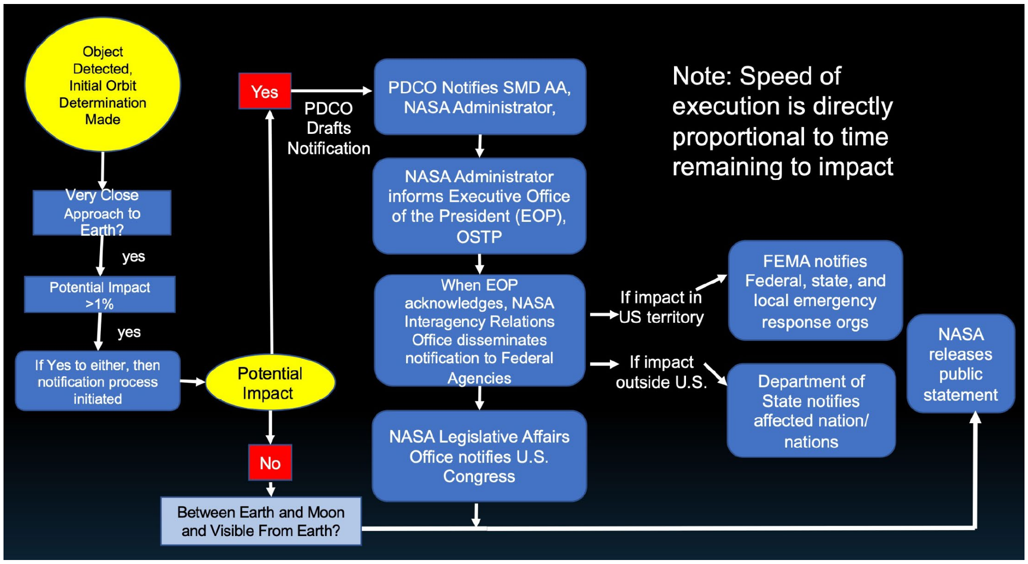
[213] The original version of the U.S. "Wireless Emergency Alerts" (WEA) system limited freetext messages to 90 characters. The current version allows for 360 characters, but older phones cannot receive this format. See https://www.weather.gov/wrn/wea360 for more information and examples.
[214] Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf
[215] National Aeronautics and Space Administration Center for Near Earth Object Studies, "Fireballs" webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/fireballs/
[216] Planetary Defense Interagency Tabletop Exercise 4, After Action Report, August 5, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/PD-TTX4-AAR-master-05August2022_final.pdf
[217] International Asteroid Warning Network, "Workshop on Communicating About Asteroid Impact Warnings and Mitigation Plans," electronic report, September 2014. As of January 18, 2023: https://iawn.net/documents/201409_Communications/iawn_communication_workshop_report.pdf

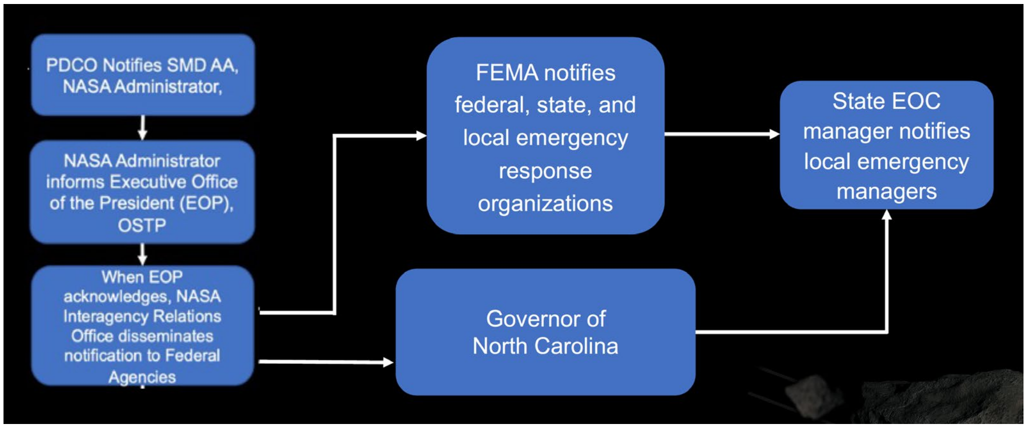
However, ideally, **content for all audiences will be part of a single document**, with a section for each type of audience, thus allowing each recipient to select the most appropriate section for themselves while also having access to the content for other audiences. This increases transparency and thus helps counter conspiracy theories and misinformation.

Figure 37: U.S. National Notification Process for Planetary Defense Emergencies



Source: Planetary Defense Interagency Tabletop Exercise 4, Presentation Module 1a Early Mitigation Options, February 23, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod1a.pdf

Figure 38: U.S. State and Local Notification for Planetary Defense Emergencies



Source: Planetary Defense Interagency Tabletop Exercise 4, Presentation Module 1a Early Mitigation Options, February 23, 2022. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod1a.pdf

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Figure 39: ESA Notification Process for Planetary Defense Emergencies

2.3 Procedure in the event of a credible impact threat

In the event of a credible NEO impact threat as defined in Section 2.1.1, the following procedure will be applied:

1) When a credible impact threat is identified, the data are validated by an independent source (e.g. NASA's Jet Propulsion Laboratory (JPL) or another independent European source) before publication.
2) The SSA-NEO segment publishes orbital information for the NEO and information on a potential impact (at least the impact probability and time) on its website http://neo.ssa.esa.int. This will be essentially the same information provided for all known NEOs with non-zero impact probability.
3) The SSA-NEO segment calculates the potential impact zone on ground and the expected energy release, including uncertainties. If possible, the results will be validated by an independent source before publication.
4) The SSA-NEO segment calculates impact effects on ground including uncertainties (as far as its capabilities allow). Best and worst cases will be given.
5) The SSA-NEO segment prepares information for each of the following target groups:
   a) The relevant political entity(ies)
   b) Emergency response agencies
   c) The media/public.
6) The following information (including uncertainties) can be expected from ESA. In some cases, only part of this information will be available:
   a) Orbit prediction
   b) Astrometric (position) measurements
   c) Impact probability
   d) Impact time
   e) Size/mass estimation
   f) Impact velocity
   g) Impact energy estimation
   h) Spectroscopic observations / estimate of material
   i) Predicted impact zone on ground
   j) Potential impact effects on ground.
7) This information will be distributed as an 'impact warning'.
   a) For the dissemination of NEO threat information for target groups I and II, ESA will follow a previously-established internal process as described in RD02. These target groups will be provided with priority with all available information (a) to (j).
   b) For any communication to media/public (target group III), information items (a) to (f) may be provided in accordance with the Crisis Media Communications Plan.
8) ESA will subsequently provide updated information regularly on the impact threat in coordination with other cooperating NEO and related organisations3. The update intervals will depend on the time until impact:
9) If the impact is more than 3 months away, information will be generated whenever new information is available.
10) For times closer than 3 months, the following rules are defined in the System Requirements Document: (RD01):
   a) At least every 24 hours if the impact threat is less than 3 months and more than 1 month away.
   b) At least every 12 hours if the impact threat is less than 1 month and more than 2 weeks away.
   c) At least every 3 hours if the impact threat is less than 2 weeks away.

It will not always be possible to provide new information on a regular basis. In that case, an estimate of when new information will be available will be given.

Source: European Space Agency, "Near-Earth Object Information Plan - Distribution of information for a credible asteroid impact threat," electronic report, September 5, 2016. As of January 18, 2023: https://iawn.net/documents/supporting/ESA-SSA-NEO-PL-0017_1_1_NEO_Information_plan_2016-05-09.pdf

Figure 40: Example of Initial Public Notification of a Notional Potential Impactor

EXERCISE ***EXERCISE*** ***EXERCISE***

NOT A REAL-WORLD EVENT *This is part of a hypothetical asteroid threat exercise conducted at the 2019 IAA Planetary Defense Conference*

DAY 1

PRESS RELEASE

NEWLY DISCOVERED ASTEROID POSES SMALL RISK OF EARTH IMPACT

College Park, Maryland, USA – April 29, 2019 – The International Asteroid Warning Network has announced that a recently discovered near-Earth asteroid could pass very close to the Earth 8 years from now, on April 29, 2027, and there is a small chance – 1 in 100 -- that it could impact our planet.

The asteroid, designated 2019 PDC, was discovered on March 26, 2019, by the Pan-STARRS near-Earth object survey project operated by the University of Hawaii for the NASA Planetary Defense Program, and it has been tracked nightly since then by astronomers around the world. Impact monitoring systems at NASA's Center for Near-Earth Object Studies at the Jet Propulsion Laboratory and ESA's NEO Coordination Centre determined from the observations that the chance of impact in 2027 is 1 in 100. That is, chances are 99 out of 100 that the asteroid will safely pass by our planet in 2027.

Astronomers will be able to track 2019 PDC through January 2020 and contribute additional observations to refine the orbit and possibly eliminate the risk of impact in 2027.

Based on the apparent brightness of 2019 PDC, astronomers now estimate that the asteroid is roughly 100 to 300 meters (330 to 1000 feet) in size. The asteroid will approach within 19 million kilometers (12 million miles) of Earth on May 13, but by the end of the year it will no longer be observable by Earth-based telescopes. It will not make another close approach to Earth until 2027.

The International Asteroid Warning Network is disseminating the present information pursuant to United Nations General Assembly resolution 71/90, paragraph 9. The International Asteroid Warning Network (IAWN) is an international network of organizations that detect, track and characterize potentially hazardous asteroids. IAWN will publish weekly updates of impact probability as this asteroid is tracked throughout 2019.

For more information, see https://cneos.jpl.nasa.gov/pd/cs/pdc19/day1.html and www.iawn.net.

Contact: http://iawn.net/misc/contacts.shtml

Source: https://cneos.jpl.nasa.gov/pd/cs/pdc19/day1.html
Note: this press release was generated as part of a **hypothetical asteroid threat exercise** at the Planetary Defense Conference 2019. A template for such a press release is provided in Appendix A.4 (page 107).

Figure 41: Example of Public Notification Update for a Notional Potential Impactor

EXERCISE *EXERCISE* *EXERCISE*
NOT A REAL-WORLD EVENT *This is part of a hypothetical asteroid threat exercise conducted at the 2019 IAA Planetary Defense Conference*

DAY 2

PRESS RELEASE

ASTEROID NOW HAS 1 IN 10 CHANCE TO IMPACT EARTH

July 29, 2019 - Based on observations conducted over the last four months, the International Asteroid Warning Network (IAWN) reports that the chance the asteroid designated 2019 PDC could impact Earth on April 29, 2027, is now 1 in 10. This possible impact prediction supersedes the previous prediction of chance of impact that IAWN reported back in April.

Hundreds of observations made by multiple observatories around the world have enabled IAWN experts to improve the understanding of the asteroid's orbital path and update the possible impact predictions made last April. The updated information means that in 9 chances out of 10 the asteroid will pass safely by Earth in 2027. 2019 PDC will remain observable over the next 6 months, and observers around the world will continue to track the asteroid until it moves out of range early next year. These additional observations will enable the experts to further refine their predictions of the asteroids future position and potential for impact in 2027.

The size of asteroid 2019 PDC also still remains uncertain, since the asteroid did not approach close enough to Earth to be directly observed by planetary radar. The best indication of size came from a few space-based infrared observations made by NASA's NEOWISE spacecraft in late April. This allowed astronomers to narrow the estimate of size of 2019 PDC to roughly 140 to 260 meters (460 to 850 feet).

Based on this size estimate, NASA experts supporting IAWN calculate that if this asteroid were to impact Earth it could release in the range of 100 to 800 megatons of equivalent energy, possible producing serious devastation over a large region. IAWN emphasizes, however, that this asteroid is too small to cause globally damaging effects if an impact were to occur.

The international forum for space agencies called the Space Mission Planning Advisory Group (SMPAG) is meeting to consider a coordinated international response to the impact risk posed by 2019 PDC. SMPAG recommends that space-capable nations begin development of a suite of space missions to characterize the asteroid and be prepared to deflect it should it be confirmed it is likely to be on a collision course with Earth

For more information, see: https://cneos.jpl.nasa.gov/pd/cs/pdc19/day2.html. IAWN will publish weekly updates of impact probability as this asteroid is tracked throughout 2019.

Contact: http://iawn.net/misc/contacts.shtml

Source: National Aeronautics and Space Administration Center for Near Earth Object Studies, "Planetary Defense Conference Exercise - 2019," webpage, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/pdc19/day2.html
Note: this press release was generated as part of a **hypothetical asteroid threat exercise** at the Planetary Defense Conference 2019.

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Appendix

The appendix provides more detailed coverage of key topics, and reference information that may only be of relevance to some readers.

Appendix Contents

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A.0 Definitions

NASA policy defines related terms as follows:[218]

- "**Near-Earth Object** (**NEO**): an asteroid or comet that has an orbit that brings it within 1.3 astronomical units (au), approximately 120 million miles [about 195 million kilometers], of the Sun. They may also be referred to as either a **Near-Earth Asteroid** (**NEA**) or an **Earth Approaching Comet** (**EAC**) as appropriate."
- "**Potentially Hazardous Object** (**PHO**): includes NEAs and EACs [i.e. NEOs] coming within 0.05 au, about 5 million miles [about 8 million kilometers], of Earth. All comets are considered PHOs when coming this close to Earth because the size cannot be readily determined."
- "**Potentially Hazardous Asteroids** (**PHAs**) are further discriminated as those of a size that could survive entry through Earth's atmosphere and could be expected to cause damage at Earth's surface (e.g., >50 meters in size)."

The International Astronomical Union defines additional relevant terms:[219]

- "**Meteor** is the light and associated physical phenomena (heat, shock, ionization), which result from the high speed entry of a solid object from space into a gaseous atmosphere."
- "**Meteoroid** is a solid natural object of a size roughly between 30 micrometers and 1 meter moving in, or coming from, interplanetary space."
- "**Meteorite** is any natural solid object that survived the meteor phase in a gaseous atmosphere without being completely vaporized."

The U.S. "Report on Near-Earth Object Impact Threat Emergency Protocols" offers additional definitions:[220]

- "**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."
- "**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

[218] National Aeronautics and Space Administration, "Notification and Communications Regarding Potential Near-Earth Object Threats (Revalidated with Change 1)," webpage, February 15, 2022. As of January 18, 2023: https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPD&c=8740&s=1

[219] International Astronomical Union: "Definition of Terms in Meteor Astronomy," undated. As of 10 March 2023: https://www.iau.org/static/science/scientific_bodies/commissions/f1/meteordefinitions_approved.pdf

[220] National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

get close to the sun and dust and gas are blown off the comet by the solar wind."

Finally, the following terms also need to be defined and distinguished for effective communication:

- "**Hazard**" is a general source of danger[221]
- "**Threat**" is any circumstance or event with the potential to have an adverse impact[222]
- "**Risk**" is the measure of the extent to which a threat exists[223]

[221] Merriam-Webster. (n.d.). Hazard. In Merriam-Webster.com dictionary. Retrieved January 20, 2023, from https://www.merriam-webster.com/dictionary/hazard
[222] National Institute of Standards and Technology, Computer Security Resource Center Glossary, "threat," webpage, undated. As of January 18, 2023: https://csrc.nist.gov/glossary/term/threat
[223] National Institute of Standards and Technology, Computer Security Resource Center Glossary, "risk," webpage, undated. As of January 18, 2023: https://csrc.nist.gov/glossary/term/risk

A.1 Abbreviations

ATLAS	Asteroid Terrestrial-impact Last Alert System
au	Astronomical Unit
CNEOS	Center for Near-Earth Object Studies
COPUOS	Committee on the Peaceful Uses of Outer Space
CSS	Catalina Sky Survey
EAC	Earth-Approaching Comet
EMP	Electromagnetic Pulse
ESA	European Space Agency
FEMA	Federal Emergency Management Agency
GSSR	Goldstone Solar System Radar
IAA	International Academy of Astronautics
IAWN	International Asteroid Warning Network
IRTF	Infrared Telescope Facility
JPL	Jet Propulsion Laboratory
MPC	Minor Planet Center
NASA	National Aeronautics and Space Administration
NEA	Near-Earth Asteroid
NED	Nuclear Explosive Device
NEO	Near-Earth Object
NEOCP	Near Earth Object Confirmation Page
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PDC	Planetary Defense Conference
PDCO	Planetary Defense Coordination Office
PHA	Potentially Hazardous Asteroid
PHO	Potentially Hazardous Object
SMPAG	Space Mission Planning Advisory Group
TNT	Trinitrotoluol
TTX	Tabletop Exercise
UNOOSA	United Nations Office of Outer Space Affairs

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APPENDIX

A.2 Table of the Most Threatening Potential Impact Events for the Next Several Hundred Years Caused by Currently-Known Objects (March 2023)

Source: National Aeronautics and Space Administration Center for Near Earth Object Studies, “Sentry: Earth Impact Monitoring,” webpage, undated. As of 11 March 2023: https://cneos.jpl.nasa.gov/sentry/vi.html

Object Designation	Date (UTC)	Impact Probability	Impact Energy (Mt of TNT)
(2023 DW)	2046-Feb-14	0.002400	4.0
(2000 SG344)	2071-Sep-16	0.001000	1.0
101955 Bennu (1999 RQ36)	2182-Sep-24	0.000370	1421.0
(2000 SG344)	2070-Sep-17	0.000230	1.0
(2000 SG344)	2071-Sep-10	0.000140	1.0
(2022 UE3)	2093-Oct-13	0.000120	2.3
(2000 SG344)	2099-Aug-25	0.000110	1.0
(2000 UK11)	2122-Nov-01	0.000097	1.0
(2021 GX9)	2032-Apr-16	0.000082	1.6
101955 Bennu (1999 RQ36)	2187-Sep-25	0.000071	1422.0
(2000 SG344)	2099-Aug-30	0.000069	1.0
(2023 DW)	2049-Feb-14	0.000064	3.9
(2020 MJ)	2102-Jun-12	0.000063	1.8
(2000 SG344)	2098-Aug-22	0.000062	1.0
(2019 VB37)	2049-Apr-26	0.000056	4.2
(2000 SG344)	2097-Aug-19	0.000052	1.0
(2000 SB45)	2080-Oct-08	0.000048	2.8
(2000 SG344)	2096-Aug-16	0.000045	1.0
(2000 SG344)	2110-Sep-10	0.000045	1.0
(2000 SG344)	2101-Sep-14	0.000044	1.0
(2021 EU)	2056-Aug-29	0.000043	2.0
(2000 SG344)	2074-Feb-10	0.000041	1.0
(2000 SG344)	2095-Aug-14	0.000041	1.0
(2000 SG344)	2074-Feb-08	0.000040	1.0
101955 Bennu (1999 RQ36)	2192-Sep-24	0.000039	1422.0
(2005 QK76)	2030-Feb-26	0.000038	2.5
(2000 SG344)	2094-Aug-11	0.000036	1.0
(2000 SG344)	2109-Sep-09	0.000033	1.0
(2015 XA378)	2107-Dec-20	0.000032	1.3
(2000 SG344)	2101-Sep-16	0.000031	1.0
(2007 DX40)	2056-Aug-18	0.000030	3.8
29075 (1950 DA)	2880-Mar-16	0.000029	75190.0
(2021 EU)	2024-Feb-27	0.000029	2.1
(2000 SG344)	2093-Aug-08	0.000029	1.0
(2000 SG344)	2108-Sep-09	0.000029	1.0
(2020 MJ)	2102-Jun-12	0.000028	1.8
(2000 SG344)	2102-Aug-23	0.000028	1.0
(2000 SG344)	2100-Sep-15	0.000028	1.0
(2008 EX5)	2072-Oct-09	0.000027	7.2
(2000 SG344)	2098-Aug-30	0.000027	1.0
(2000 SG344)	2091-Aug-03	0.000026	1.0
(2007 DX40)	2056-Aug-18	0.000023	3.8

APPENDIX

Object Designation	Date (UTC)	Impact Probability	Impact Energy (Mt of TNT)
(2000 SB45)	2084-Oct-08	0.000023	2.8
(2000 SG344)	2102-Aug-22	0.000023	1.0
(2000 SG344)	2107-Sep-10	0.000023	1.0
(2000 UK11)	2122-Nov-02	0.000022	1.0
(2015 JJ)	2111-Nov-07	0.000021	82.1
(2014 GN1)	2061-Sep-16	0.000021	6.3
(2022 UY14)	2043-Apr-28	0.000021	2.8
(2010 GM23)	2105-Apr-15	0.000021	3.0
(2000 SG344)	2092-Aug-05	0.000021	1.0
(2008 EX5)	2083-Oct-09	0.000020	7.2
(2017 YM1)	2091-Dec-16	0.000020	1.3
(2012 EK5)	2095-Mar-24	0.000020	1.0
(2020 DJ1)	2114-Jul-30	0.000019	2.5
(2011 UM169)	2102-Oct-24	0.000019	1.9
(2000 SG344)	2106-Sep-10	0.000019	1.0
(2000 SG344)	2110-Sep-12	0.000017	1.0
101955 Bennu (1999 RQ36)	2193-Sep-24	0.000016	1421.0
(2005 QK76)	2038-Feb-26	0.000016	2.4
(2022 VE1)	2053-Oct-26	0.000016	5.4
(1994 GK)	2061-Apr-03	0.000016	6.1
(2000 SG344)	2100-Sep-11	0.000016	1.0
(2007 KE4)	2029-May-26	0.000015	1.0
(2022 UE2)	2119-Apr-18	0.000015	3.3
101955 Bennu (1999 RQ36)	2187-Sep-24	0.000014	1422.0
(2000 SG344)	2105-Sep-10	0.000014	1.0
(2016 YM4)	2121-Jul-20	0.000013	114.7
(2005 QK76)	2048-Feb-26	0.000013	2.4
(2008 CC71)	2066-Feb-27	0.000013	1.4
(2010 GM23)	2105-Apr-15	0.000013	3.0
(2000 SG344)	2073-Feb-01	0.000013	1.0
101955 Bennu (1999 RQ36)	2194-Sep-24	0.000012	1420.0
(2010 GM23)	2111-Apr-15	0.000012	3.0
(2000 SG344)	2097-Aug-30	0.000012	1.0
(2021 JA1)	2119-May-08	0.000011	1.6
(2000 SG344)	2099-Sep-11	0.000011	1.0
(2008 CC71)	2034-Feb-27	0.000010	1.4
(2016 AB166)	2102-Jan-12	0.000010	7.8
(2008 ST7)	2094-Sep-10	0.000010	4.9
(2000 SB45)	2088-Oct-08	0.000010	2.8
(2000 SG344)	2073-Feb-12	0.000010	1.0

Notes: sorted by impact probability. Impact probabilities at least 10^{-5}. Impact energies at least 1 Mt. Several objects (e.g. 1999 RQ36 Bennu) pass close by Earth multiple times over the centuries, and thus are listed multiple times in this table.

A.3 ESA "Close Approach Fact Sheet" Example

Source: https://neo.ssa.esa.int/documents/20126/740124/Close+approach+fact+sheet+for+asteroid+2023+BU+%28version+1.0%29.pdf (as of 10 March 2023)

Additional ESA "Close Approach Fact Sheets" are available at https://neo.ssa.esa.int/cafs

→ CAFS FOR 2023 BU

ESA's NEO Coordination Centre

Close approach fact sheet for asteroid 2023 BU

The small near-Earth asteroid 2023 BU will have a close encounter with Earth on 27 January 2023.

Fly-by date	2023-01-27
Closest approach time	00:27:10 UTC (± 25 s)
Fly-by distance from Earth surface	3 606 km, 0.009 Lunar Distances (± 4 km)
Fly-by speed	9.26 km/s
Size	3—8 m
Discovery date	2023-01-21
Discovery site	MARGO, Nauchnij

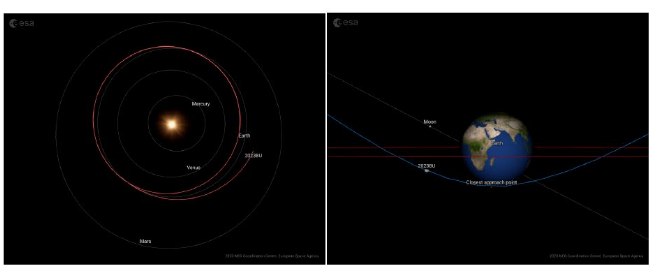
All error bars quoted in this table correspond to one standard deviation.

Orbit information

As the approach distance of the nominal trajectory to the Earth is very small, changes in its orbital elements due to the Earth gravity are very noticeable.

Date before and after fly-by	Orbital period (year/day)	Aphelion distance (au)	Perihelion distance (au)	Eccentricity	Inclination (deg)
2022-12-28	0.982/359	1.051	0.925	0.064	2.357
2023-02-26	1.165/425	1.230	0.984	0.111	3.749

All orbital elements in this table are referred to the ecliptic at the epoch of J2000.0



In the left image, the orbit of 2023BU is displayed (red line) – showing how it is affected by the close encounter with Earth. In the image to the right, the flyby trajectory (blue line) and the geostationary ring (red line) are visualised. N.B.: the size of the object has been magnified.

APPENDIX

Physical and mitigation information

Days to closest approach	Cumulative impact probability	Composition	Rotation period (hours)
~ 1	Not applicable	Unknown	Unknown

Observational information

Peak brightness	Visual observability	Geometric observability
~ 10	Visually observable with medium sized telescope from the optimal location (South America), larger apertures required elsewhere.	The object's incoming and outgoing trajectories are both in the Northern sky, favoring observability from Northern latitudes both before and after the closest approach. However, the closest approach will happen over the Southern Pacific Ocean, and will only be observable (poorly) from Southern locations.

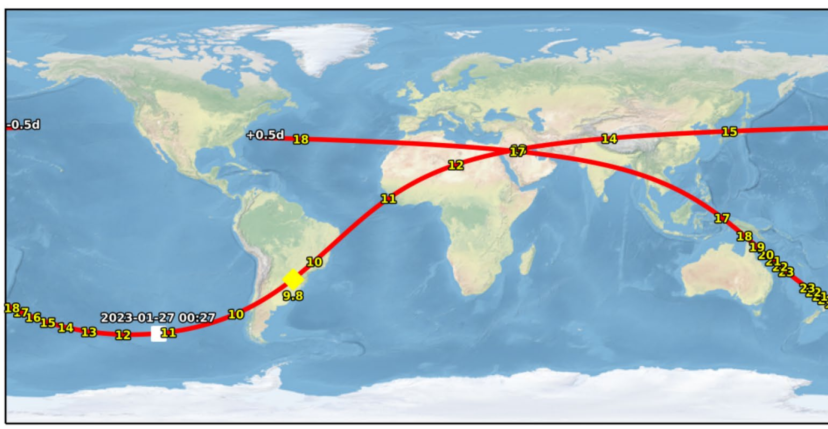
Other information

Encounter peculiarities	Previous encounter	Next encounter
None	2020-08-21	2066-01-28

Only encounters within 0.05 au are considered.

Asteroid ground track

The asteroid comes from mid-Northern latitudes, and heads South near close approach, reaching a peak brightness of about 10 over South America. Closest approach happens over the Southern Pacific Ocean, but by then the solar elongation is already lower, resulting in poorer observability conditions during and right after the closest distance. The object then recedes from Earth heading North again, and becomes observable again favoring Northern latitudes.



Links

NEO information:
https://neo.ssa.esa.int/search-for-asteroids?sum=1&des=2023BU
Orbit visualiser:
https://neotools.ssa.esa.int/ovt?object=2023BU
Close approaches page:
https://neo.ssa.esa.int/close-approaches

neo.ssa.esa.int
To subscribe to this newsletter fill the form at **https://neo.ssa.esa.int/subscribe-to-services**
To unsubscribe or for any further information please send an email to **neocc@esa.int**

A.4 NASA Planetary Defense Coordination Office Public Notification Template

Source: National Science & Technology Council, "Report on Near-Earth Object Impact Threat Emergency Protocols," Washington, DC, 2022. As of January 18, 2023: https://www.nasa.gov/sites/default/files/atoms/files/neo-impact-threat-emergency-protocols-jan2021.pdf

NASA PLANETARY DEFENSE COORDINATION OFFICE

IMPACT NOTIFICATION

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 Planetary Defense Officer
- Executive Office of the President Point of Contact
- FEMA Point of Contact
- Others as appropriate

Graphics:

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

A.5. Contact Information for Organizations Involved in Planetary Defense

As of January 2023

- NASA's Planetary Defense Coordination Office (https://www.nasa.gov/planetarydefense)
- ESA's Planetary Defence Office (https://www.esa.int/Space_Safety/Planetary_Defence)
- ESA's Near-Earth Objects Coordination Centre (https://neo.ssa.esa.int/home)
- The International Asteroid Warning Network (https://iawn.net/index.shtml)
- The Space Mission Planning Advisory Group (http://www.smpag.net)

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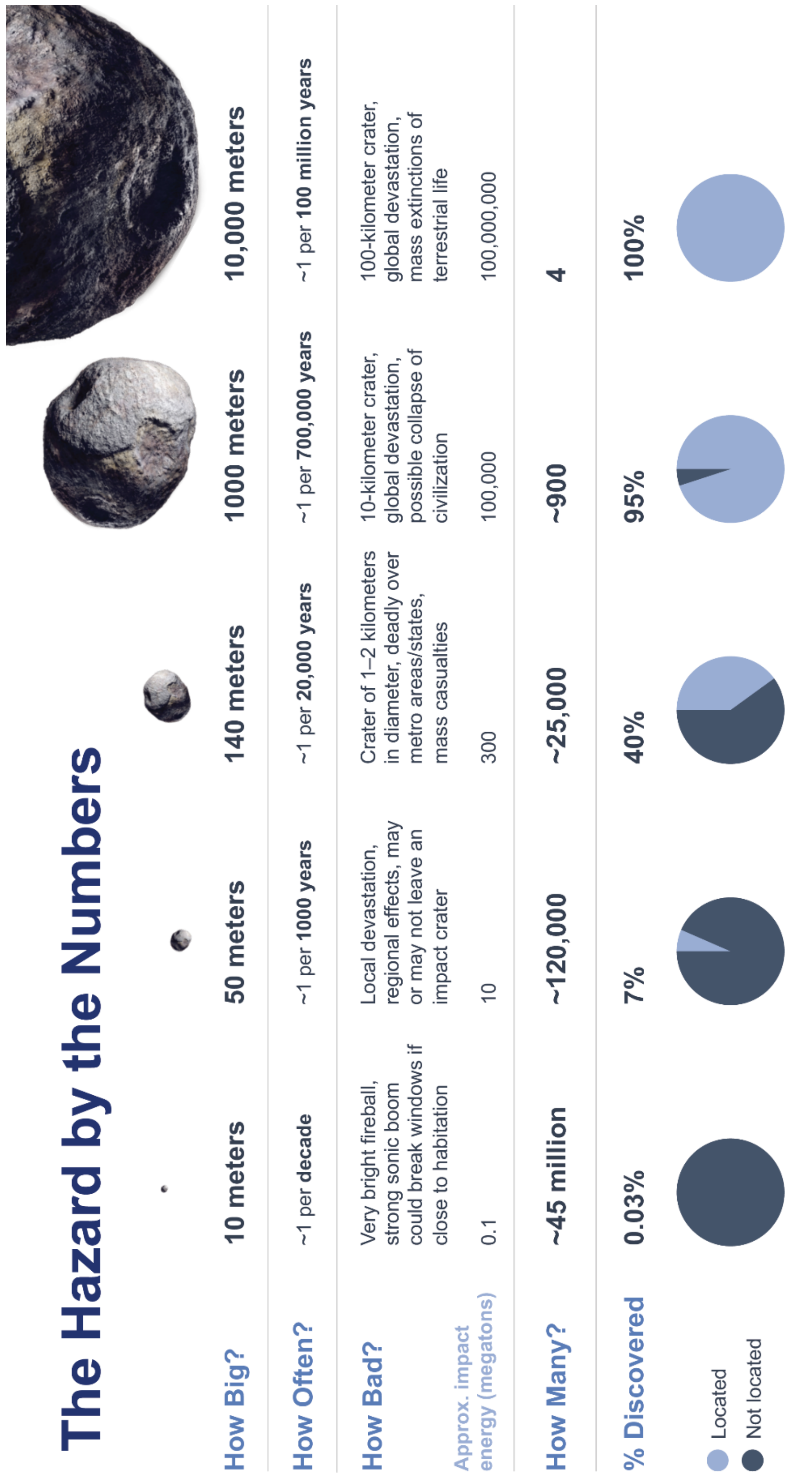
A.6 Larger-Sized Versions of Key Figures

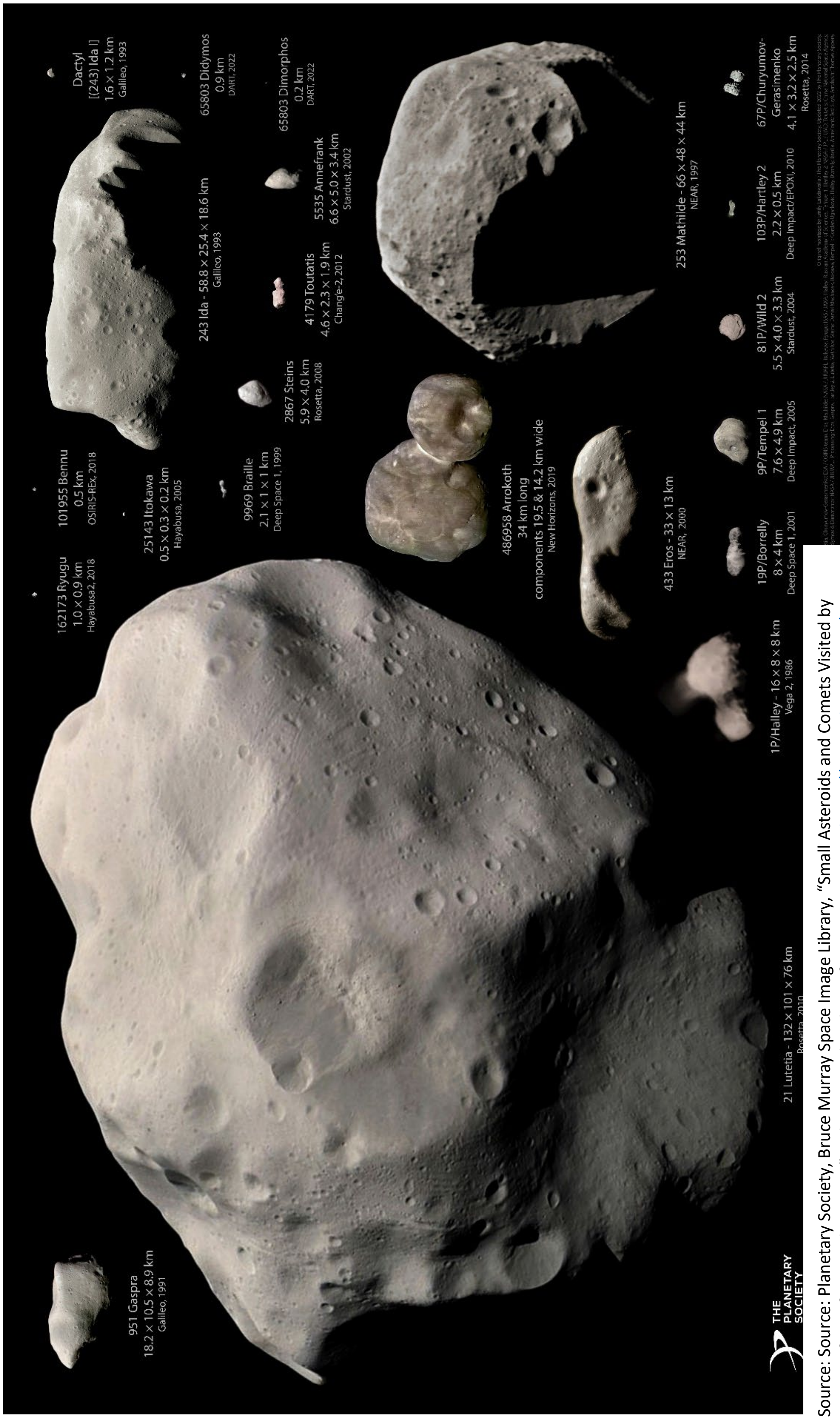
Impact Risk From Asteroids



Source: Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

APPENDIX

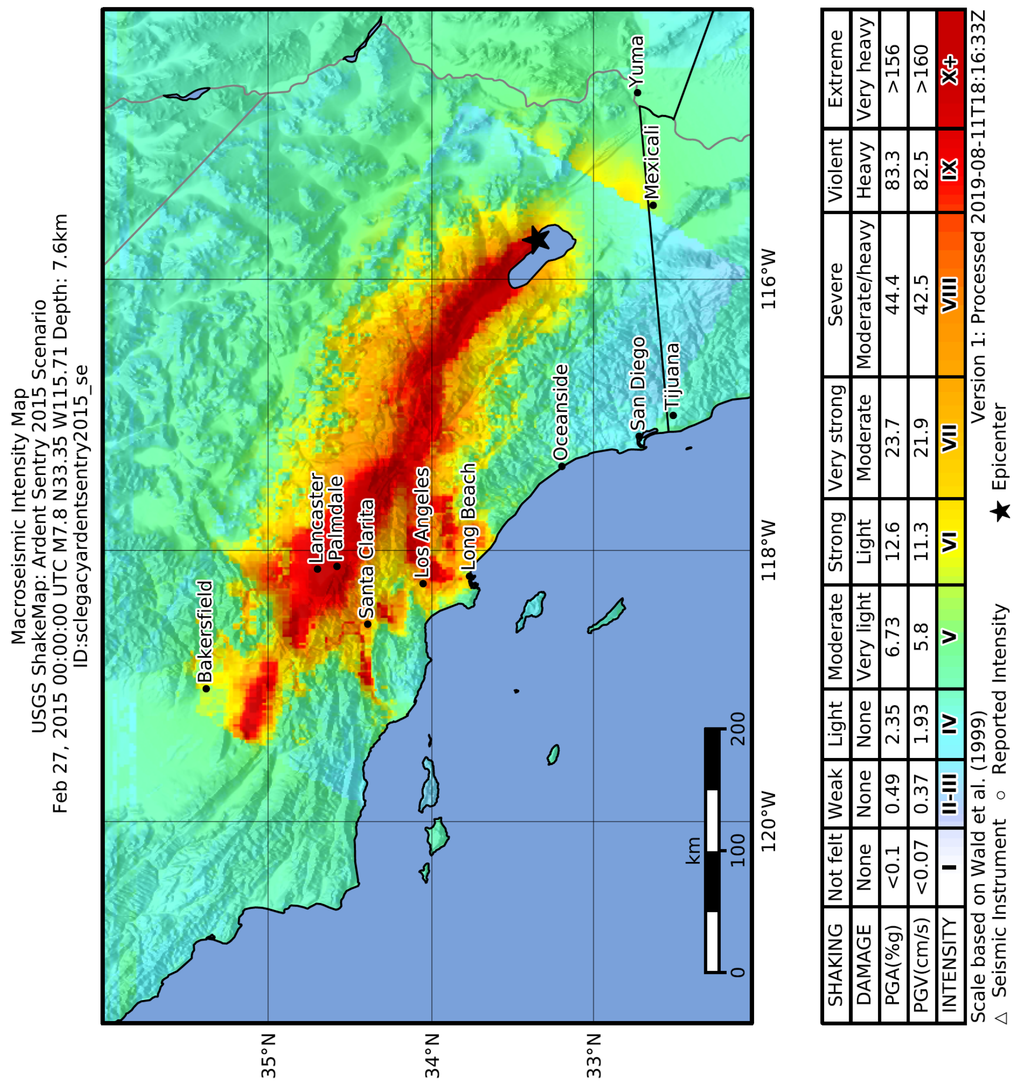
Close-Up Images of Some Asteroids and Comets (To Scale)



Source: Source: Planetary Society, Bruce Murray Space Image Library, "Small Asteroids and Comets Visited by Spacecraft as of September 2022," webpage, undated. As of January 18, 2023: https://www.planetary.org/space-images/asteroids-and-comets-visited-by-spacecraft. Used by permission.

APPENDIX

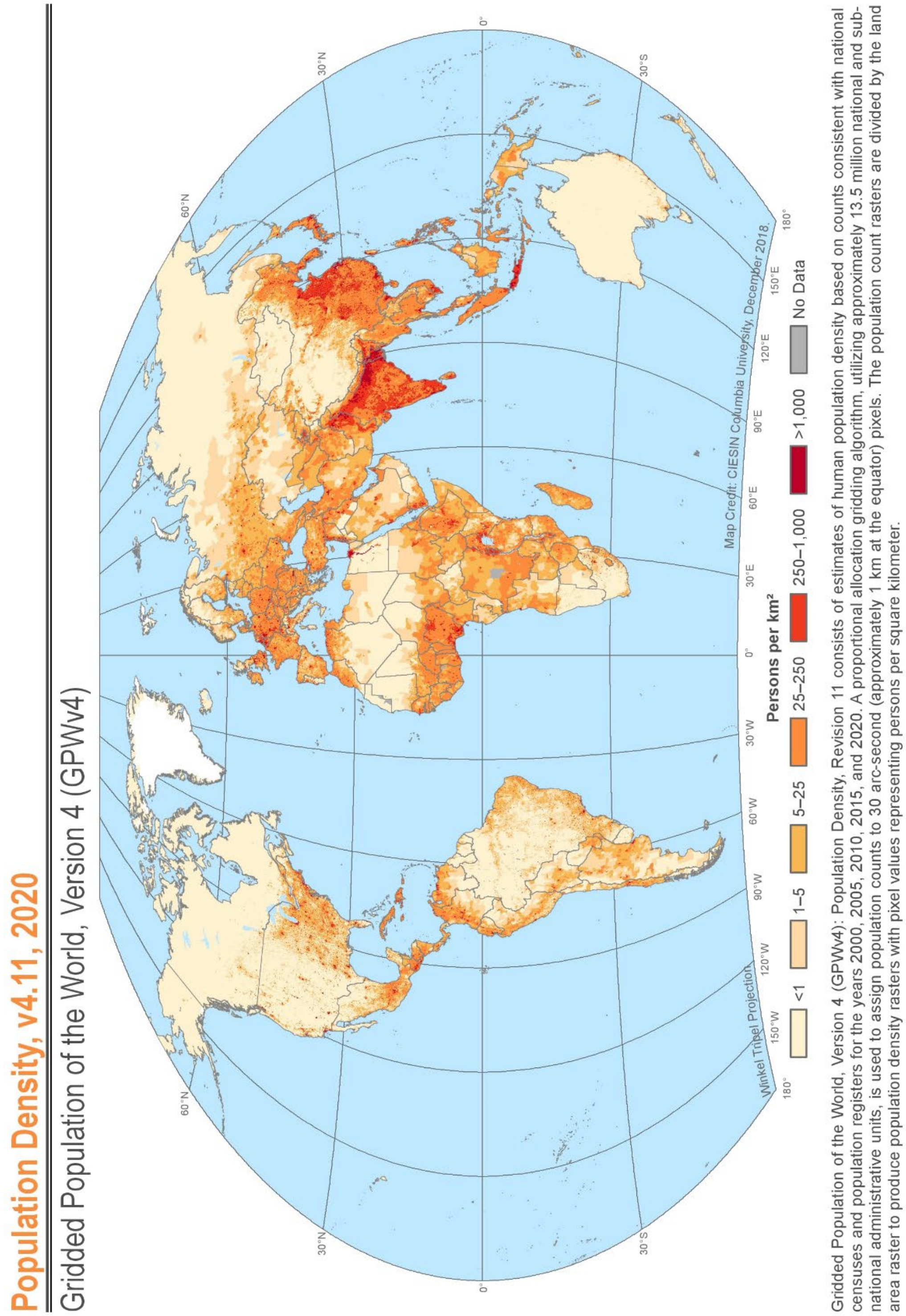
Extent of Damage for Hypothetical Magnitude 7.8 Earthquake in the San Andreas Fault Region of California



Source: U.S. Geological Survey Earthquake Hazards Program, "Macroseismic Intensity Map USGS ShakeMap: Ardent Sentry 2015 Scenario" webpage, undated. As of January 18, 2023: https://earthquake.usgs.gov/product/shakemap-scenario/sclegacyardentsentry2015_se/us/1565551856337/download/intensity.pdf

APPENDIX

Map of Global Population Density in 2020



Source: NASA Socioeconomic Data and Applications Center, "Population Density, v4.11 (2000, 2005, 2010, 2015, 2020) » Maps" webpage, undated. As of January 18, 2023: https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-density-rev11/maps

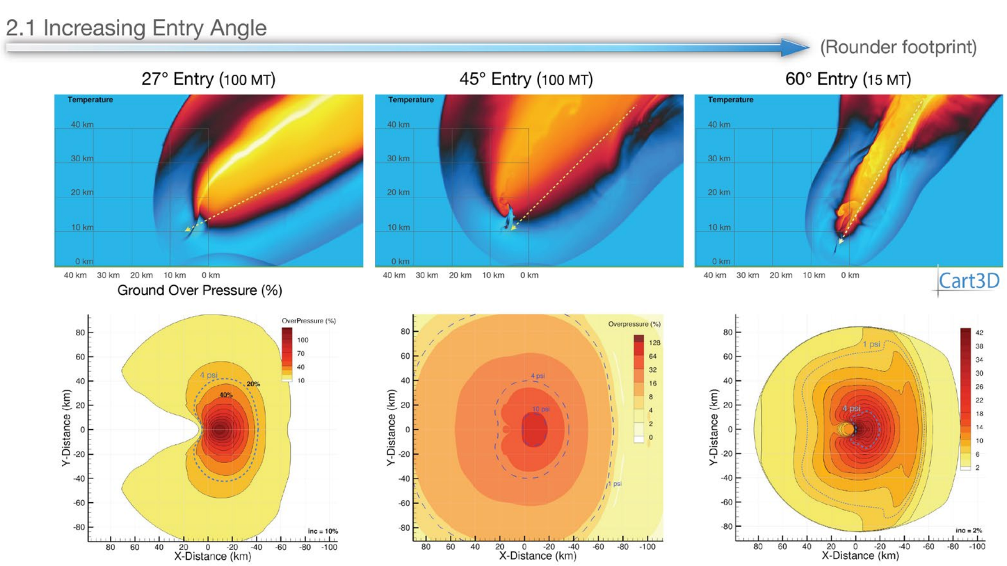
A.7 Insights from High-Fidelity Computational Simulation of Impact Effects

The figures below illustrate the complex shapes of the pressure waves caused by the airburst of a meteoroid and of the resulting overpressures on the ground. In addition, they also show how those overpressure footprints depend on specific factors:

- Figure 42 shows how the entry angle (i.e. the angle at which an impactor hits the Earth's atmosphere, with 0° being tangential to the Earth's surface) influences the shape and extent of the ground overpressure footprint. The left and center images are for an impact energy of 100 megatons, corresponding to a medium-sized object. The right image is for an impact energy of 15 megatons, corresponding to a smaller object.
- Figure 43 illustrates how impact energy, which is related to object size, affects the size and shape of the overpressure footprint.
- Figure 44 captures the influence of object strength, which depends on object composition. For example, a metal-core asteroid is stronger and will break apart later during entry into the atmosphere than a stony object, which in turn is stronger than the ice core of a comet.

This kind of high-fidelity numerical simulation requires large supercomputers and specialized software, as well as experienced experts who can properly leverage these capabilities.

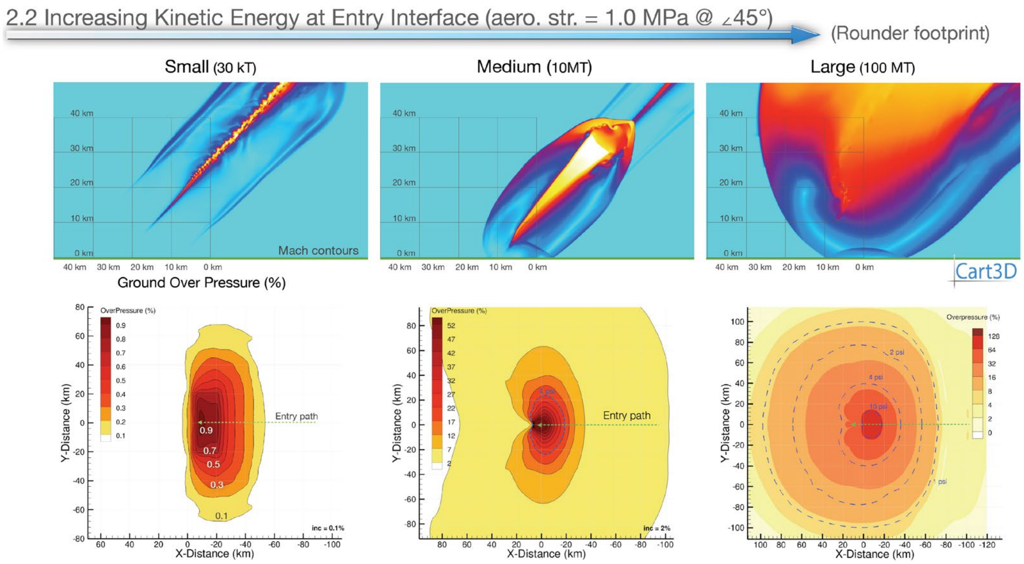
Figure 42: Influence of Object Entry Angle



Source: NASA Technical Reports Server, "A Ground Footprint Eccentricity Model For Asteroid Airbursts,"poster from webpage, undated. . As of January 18, 2023: https://ntrs.nasa.gov/citations/20190027570

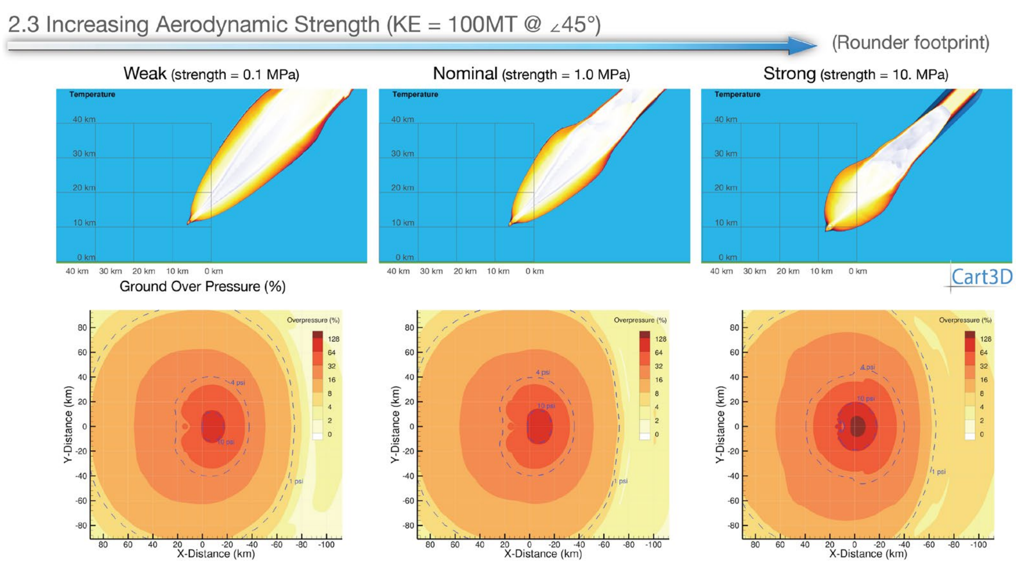
APPENDIX

Figure 43: Influence of Object Size



Source: NASA Technical Reports Server, “A Ground Footprint Eccentricity Model For Asteroid Airbursts,”poster from webpage, undated. . As of January 18, 2023: https://ntrs.nasa.gov/citations/20190027570
Note different scales for the right images.

Figure 44: Influence of Object Composition



Source: NASA Technical Reports Server, “A Ground Footprint Eccentricity Model For Asteroid Airbursts,”poster from webpage, undated. . As of January 18, 2023: https://ntrs.nasa.gov/citations/20190027570

A.8 Conversion Tables for Metric and Imperial Units of Measurement

Source: National Institute of Standards and Technology, Office Of Weights And Measures, "NIST Handbook 44 - Current Edition," webpage, undated. As of January 18, 2023: https://www.nist.gov/pml/owm/publications/nist-handbooks/handbook-44-current-edition

Units of Pressure
(All underlined figures are exact.)

Starting Unit ↓	Ending Unit →	Pascal (Pa)	Kilopascal (kPa)	Megapascal (MPa)	Pound-force per square inch (psi) (lbf/in^2)	Millimeter of mercury (mm Hg [0 °C])	Inch of water (in H_2O [4 °C])
		Multiply by the Conversion Factor Below the Ending Unit:					
1 Pa =		1	0.001	0.000 001	0.000 145 037 74	0.007 5006 15	0.004 014 742 13
1 kPa =		1000.0	1	0.001	0.145 037 744	7.500 615 05	4.014 742 133
1 MPa =		1 000 000	1 000	1	145.037 744	7 500.615 05	4 014.742 13
1 psi (lbf/in^2) =		6 894.757	6.894 757	0.006 894 757	1	51.714 918 1	27.680 671 4
1 mmHg (0 °C) =		133.322 4	0.133 322 4	0.000 133 322 4	0.019 336 78	1	0.535 255 057
1 inH_2O (4 °C) =		249.082	0.249 082	0.000 249 082	0.036 126 291	1.868 268 198	1

Units of Length[11]
(All underlined figures are exact.)

Starting Unit ↓	Ending Unit →	Inches	Feet	Yards	Miles	Centimeters	Meters
		Multiply by the Conversion Factor Below the Ending Unit:					
1 inch (in) =		1	0.083 333 33	0.027 777 78	0.000 015 782 83	2.54	0.025 4
1 foot (ft) =		12	1	0.333 333 3	0.000 189 393 9	30.48	0.304 8
1 yard (yd) =		36	3	1	0.000 568 181 8	91.44	0.914 4
1 mile (mi) =		63 360	5 280	1 760	1	160 934.4	1609.344
1 centimeter (cm) =		0.393 700 8	0.032 808 40	0.010 936 13	0.000 006 213 712	1	0.01
1 meter (m) =		39.370 08	3.280 840	1.093 613	0.000 621 371 2	100	1

NOTE: Per *Federal Register*, July 1, 1959, Vol. 24, No. 128, p. 5348, the following are exact mathematical relationships:

1 U.S. survey foot = $^{1200}/_{3937}$ meter (exactly)
1 international foot = 12 × 0.0254 meter = 0.304 8 (exactly)
1 international foot = 0.999 998 survey foot (exactly)
1 international foot = 0.0254 × 39.37 U.S. survey foot (exactly)
1 international mile = 0.999 998 survey mile (exactly)

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Units of Area[14]
(All underlined figures are exact.)

Starting Unit ↓	Ending Unit →	Square Inches	Square Feet	Square Yards
1 square inch (in^2) =		1	0.006 944 444	0.000 771 604 9
1 square foot (ft^2) =		144	1	0.111 111 1
1 square yard (yd^2) =		1 296	9	1
1 square mile (mi^2) =		4 014 489 600	27 878 400	3 097 600
1 square centimeter (cm^2) =		0.155 000 3	0.001 076 391	0.000 119 599 0
1 square meter (m^2) =		1550.003	10.763 91	1.195 990

Multiply by the Conversion Factor Below the Ending Unit:

Starting Unit ↓	Ending Unit →	Square Miles	Square Centimeters	Square Meters
1 square inch (in^2) =		0.000 000 000 249 097 7	6.451 6	0.000 645 16
1 square foot (ft^2) =		0.000 000 035 870 06	929.030 4	0.092 903 04
1 square yard (yd^2) =		0.000 000 322 830 6	8361.273 6	0.836 127 36
1 square mile (mi^2) =		1	25 899 881 103.36	2 589 988.110 336
1 square centimeter (cm^2) =		0.000 000 000 038 610 22	1	0.0001
1 square meter (m^2) =		0.000 000 386 102 2	10 000	1

Multiply by the Conversion Factor Below the Ending Unit:

Units of Volume[16]
(All underlined figures are exact.)

Starting Unit ↓	Ending Unit →	Cubic Inches	Cubic Feet	Cubic Yards
1 cubic inch (in^3) =		1	0.000 578 703 7	0.000 021 433 47
1 cubic foot (ft^3) =		1 728	1	0.037 037 04
1 cubic yard (yd^3) =		46 656	27	1
1 cubic centimeter (cm^3) =		0.061 023 74	0.000 035 314 67	0.000 001 307 951
1 cubic decimeter (dm^3) =		61.023 74	0.035 314 67	0.001 307 951
1 cubic meter (m^3) =		61 023.74	35.314 67	1.307 951

Multiply by the Conversion Factor Below the Ending Unit:

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Units of Mass Not Less Than Avoirdupois Ounces
(All underlined figures are exact.)

Starting Unit ↓	Ending Unit →	Avoirdupois Ounces	Avoirdupois Pounds	Short Hundredweights	Short Tons
1 avoirdupois ounce (oz) =		1	0.0625	0.000 625	0.000 031 25
1 avoirdupois pound (lb) =		16	1	0.01	0.000 5
1 short hundredweight (ctw) =		1 600	100	1	0.05
1 short ton (tn) =		32 000	2 000	20	1
1 long ton =		35 840	2 240	22.4	1.12
1 kilogram (kg) =		35.273 96	2.204 623	0.022 046 23	0.001 102 311
1 metric ton (t) =		35 273.96	2204.623	22.046 23	1.102 311

Starting Unit ↓	Ending Unit →	Long Tons	Kilograms	Metric Tons
1 avoirdupois ounce (oz) =		0.000 027 901 79	0.028 349 523 125	0.000 028 349 523 125
1 avoirdupois pound (lb) =		0.000 446 428 6	0.453 592 37	0.000 453 592 37
1 short hundredweight (ctw) =		0.044 642 86	45.359 237	0.045 359 237
1 short ton (tn) =		0.892 857 1	907.184 74	0.907 184 74
1 long ton =		1	1016.046 908 8	1.016 046 908 8
1 kilogram (kg) =		0.000 984 206 5	1	0.001
1 metric ton (t) =		0.984 206 5	1 000	1

Conversion Equations for Units of Temperature
(exact)

Units	To Degree Fahrenheit ($°F$)	To Degree Celsius ($°C$)	To Kelvin (K)
Degree Fahrenheit ($°F$)	$°F$	$\frac{(°F - 32)}{1.8}$	$\frac{(°F - 32)}{1.8} + 273.15$
Degree Celsius ($°C$)	$(°C \times 1.8) + 32$	$°C$	$(°C) + 273.15$
Kelvin (K)	$(K - 273.15) * 1.8 + 32$	$K - 273.15$	K

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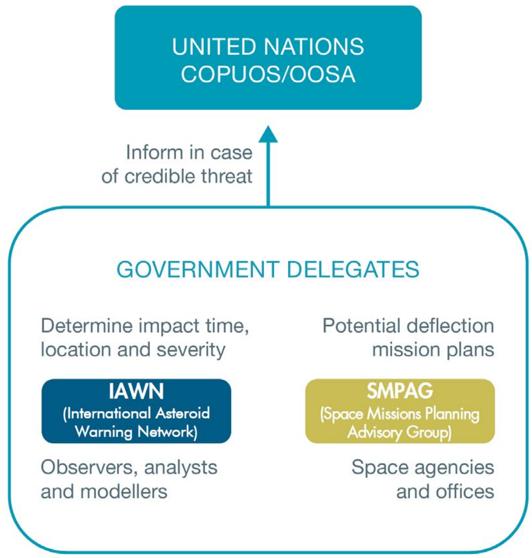
A.9 Flowchart for United Nations Planetary Defense Notification Process



This figure shows the relationship of IAWN and SMPAG to the United Nations. IAWN and SMPAG provide annual progress reports to the Scientific and Technical Subcommittee (STSC) of COPUOS on their work. They have non-permanent observer status at the meetings of the STSC. Information flow is facilitated via their parent government delegations.

Source: United Nations Office for Outer Space Affairs, "Near-Earth Objects and Planetary Defence," electronic report, June 2018. As of January 18, 2023:
https://www.unoosa.org/documents/pdf/smpag/st_space_073E.pdf
Note: for short-notice threats, reports might also have to go directly to the United Nations Security Council.[224]

[224] International Academy of Astronautics, "Summary Report 2021 IAA Planetary Defense Conference," electronic report, April 2021. As of January 18, 2023:
https://iaaspace.org/wp-content/uploads/iaa/Scientific%20Activity/conf/pdc2021/pdc2021report.pdf

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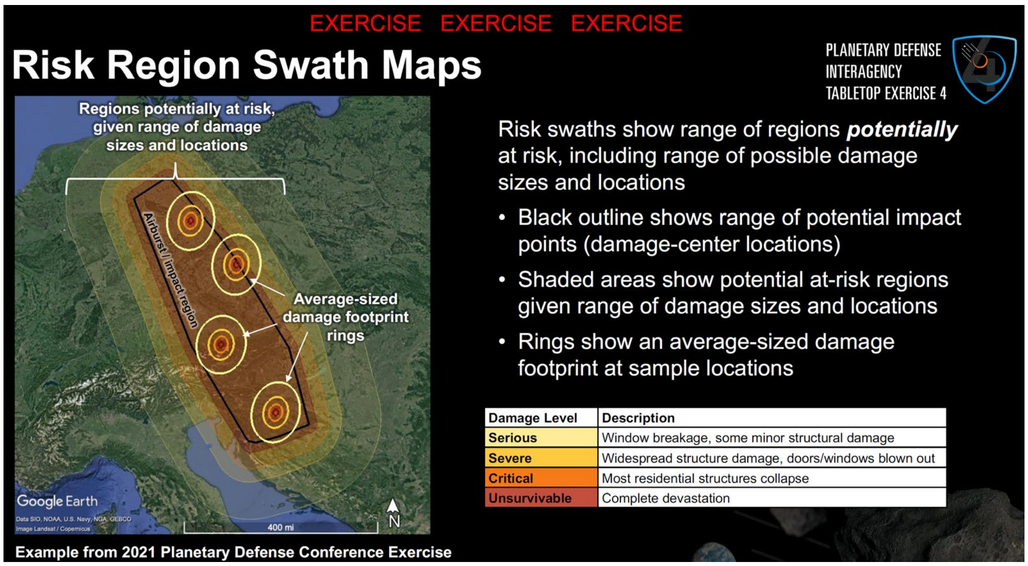
A.10 Refinement of Impact Location and Damage Predictions Over Time

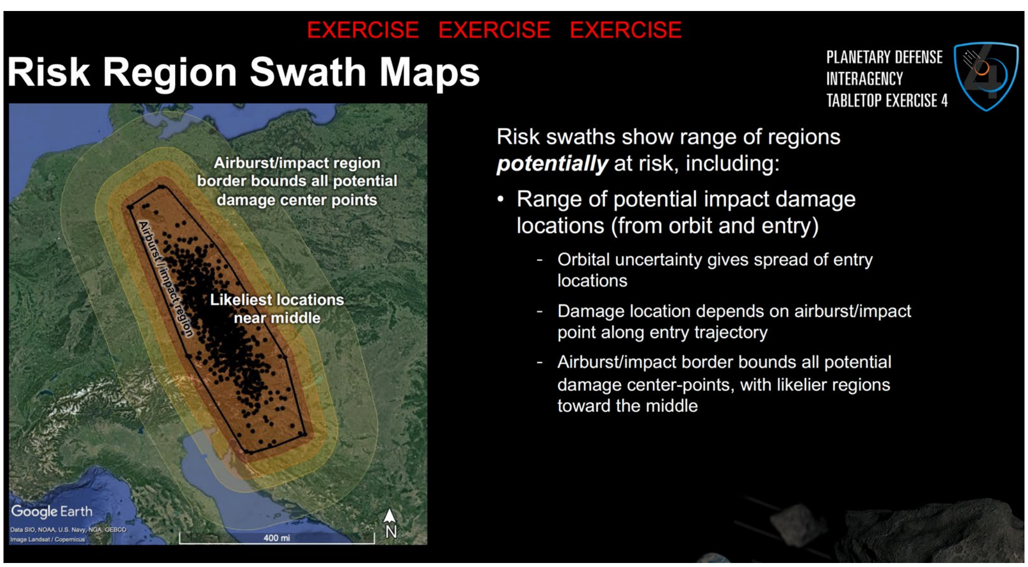
Source: Planetary Defense Interagency Tabletop Exercise 4, presentation, undated. As of January 18, 2023: https://cneos.jpl.nasa.gov/pd/cs/ttx22/ttx22_mod0.pdf

This series of figures explains in detail how to interpret a "Risk Region Swath Map" and also illustrates how the risk region shrinks as the impact location can be predicted more accurately over time.

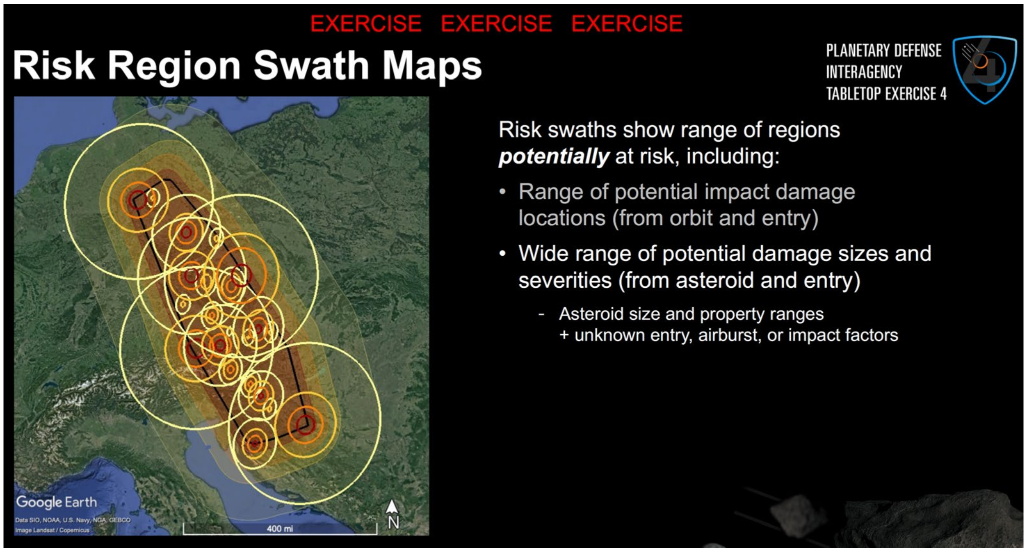
Explanation of Map Elements



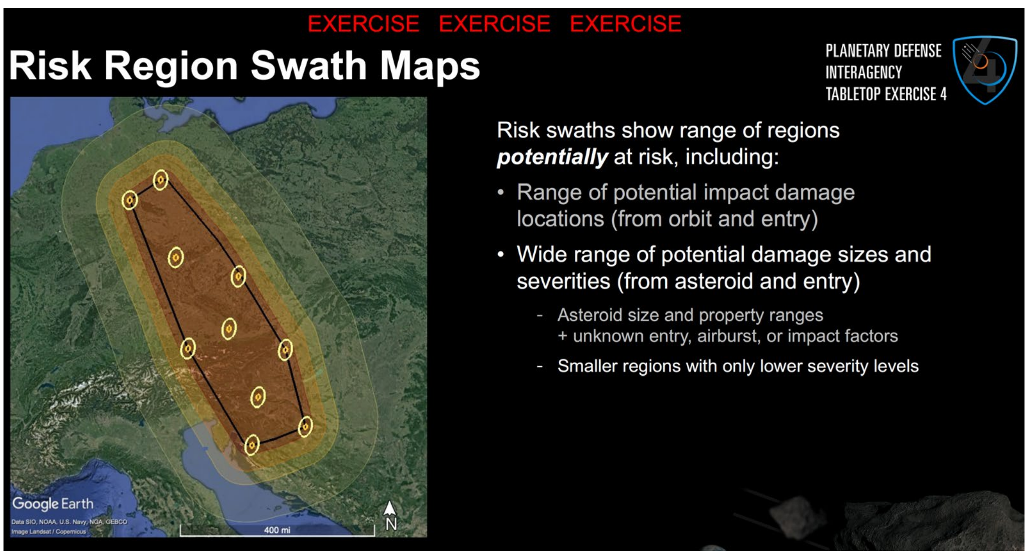
Uncertainty About Impact Location



Uncertainty About Impactor Size



Example Damage Areas if Impactor is on Small End of the Uncertainty Range



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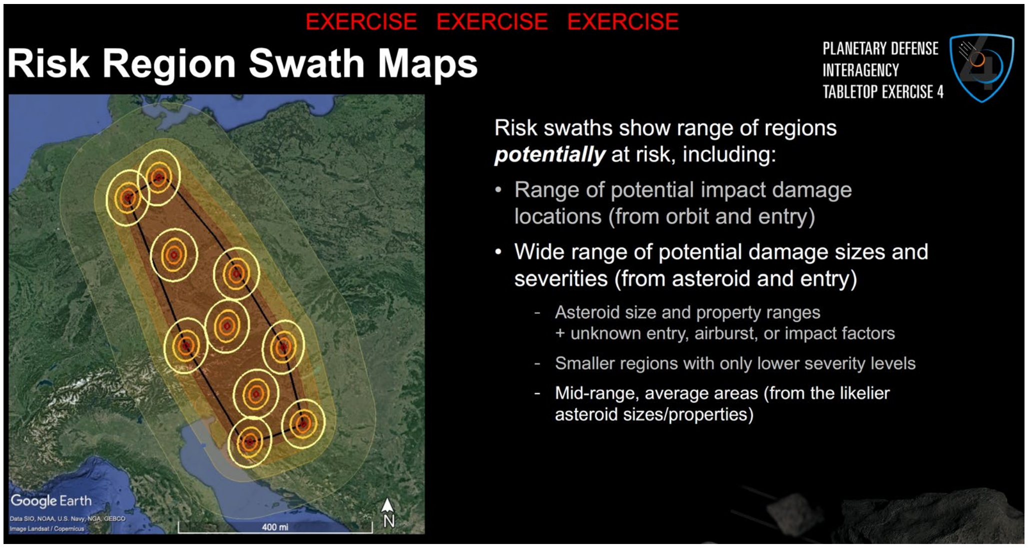
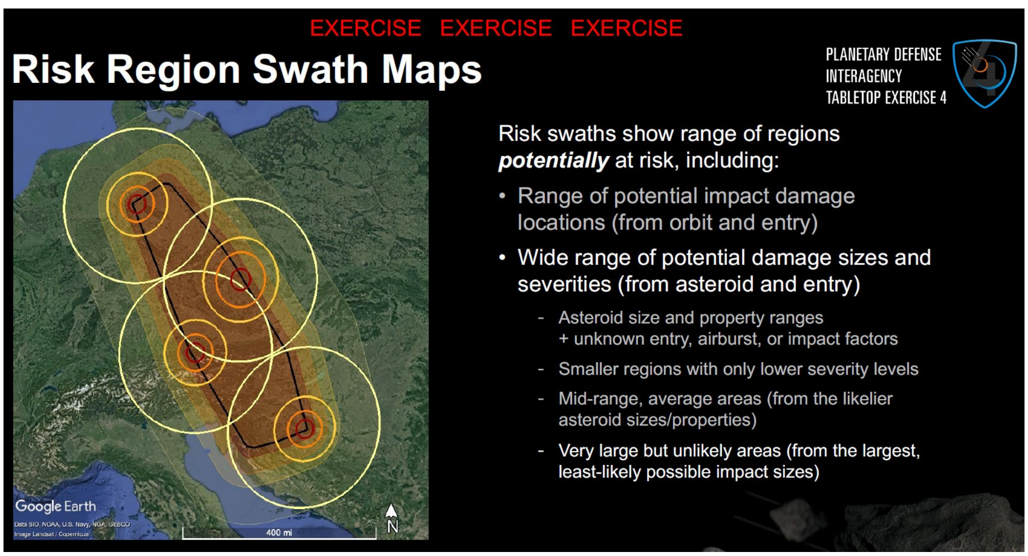
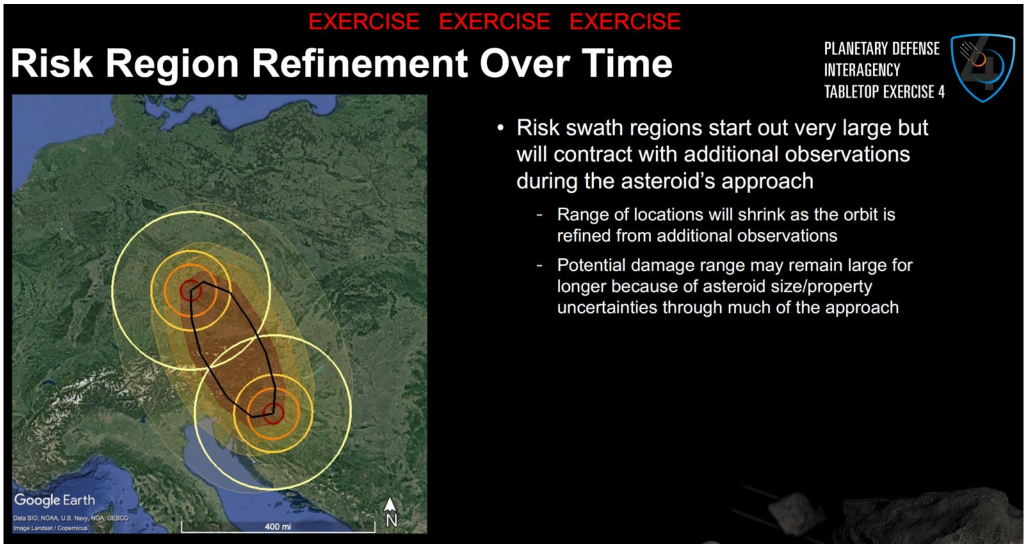
Example Damage Areas if Impactor is in the Middle of the Uncertainty Range



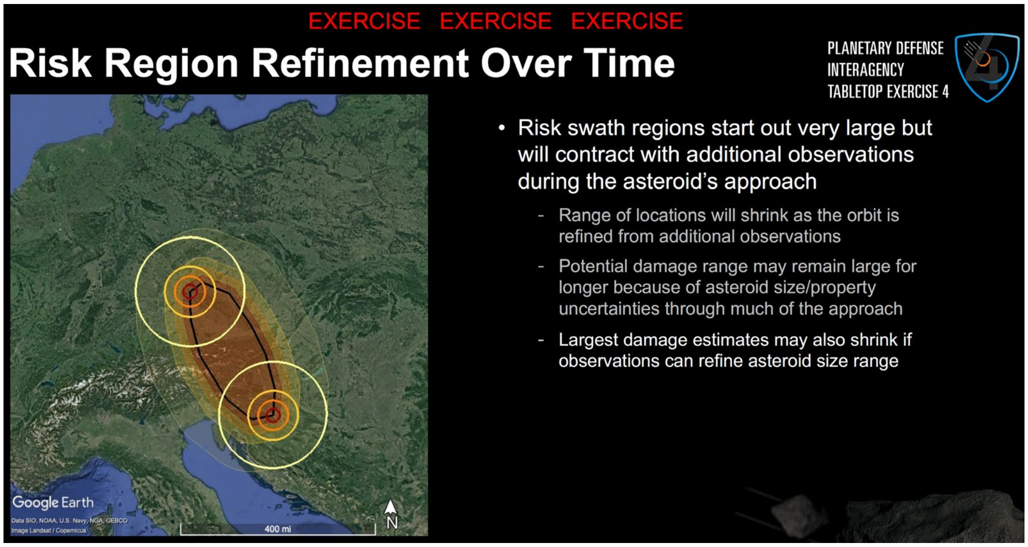
Example Damage Areas if Impactor is on Large End of the Uncertainty Range



Risk Region Shrinks Over Time



Size Range of Impactor Also Likely to Shrink Over Time



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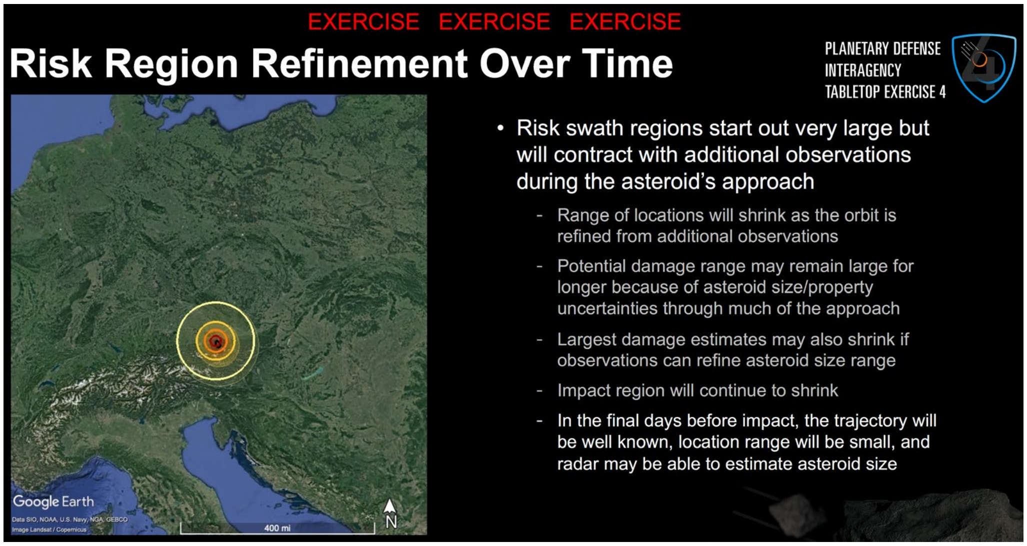
Threatened Area Region Will Continue to Shrink As Impactor Trajectory is Refined



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A.11 Members of IAWN and SMPAG (as of January 2023)

IAWN[225]

> *"IAWN's functions are:*
> *a) To discover, monitor, and physically characterize the potentially hazardous NEO population using optical and radar facilities and other assets based in both the northern and southern hemispheres and in space;*
> *b) To provide and maintain an internationally recognized clearing house function for the receipt, acknowledgement and processing of all NEO observations;*
> *c) To act as a global portal, serving as the international focal point for accurate and validated information on the NEO population;*
> *d) To coordinate campaigns for the observation of potentially hazardous objects;*
> *e) To recommend policies regarding criteria and thresholds for notification of an emerging impact threat;*
> *f) To develop a database of potential impact consequences, depending on geography, geology, population distribution and other related factors;*
> *g) To assess hazard analysis results and communicate them to entities that should be identified by Member States as being responsible for the receipt of notification of an impact threat in accordance with established policies*
> *h) To assist Governments in the analysis of impact consequences and in the planning of mitigation responses."*[226]

<u>Steering Committee</u>

- Sergio Camacho (former Chair of UNCOPUOS Action Team on NEOs)
- Lindley Johnson (NASA Hq)
- Boris Shustov (INASAN)
- Giovanni Valsecchi (INAF-IAPS/NEODyS)
- Patrick Michel (Observatoire de la Côte d'Azur)
- Alan Harris (DLR)
- Detlef Koschny (ESA/ESTEC)
- Paul Chodas (JPL)
- Gonzalo Tancredi (Universidad de la República, Uruguay)

<u>Signatories of the IAWN Statement of Intent</u>

- Peter Birtwhistle, West Berkshire, England:
- CNSA (Chinese National Space Administration)
- CrAO (Crimean Astrophysical Observatory, Russian Academy of Sciences)
- ESA (European Space Agency)

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[225] International Asteroid Warning Network, "Membership," webpage, undated. As of January 18, 2023: https://iawn.net/about/members.shtml
[226] International Asteroid Warning Network, "History," webpage, undated. As of January 18, 2023: https://iawn.net/about.shtml

- ESO (European Southern Observatory)
- INAOE (the National Institute of Astrophysics, Optics, and Electronics in Cholua, Mexico)
- INASAN (the Institute of Astronomy, Russian Academy of Sciences)
- ISTP (Institute of Solar-Terrestrial Physics, Russian Academy of Sciences) statement
- KAO UrFU (Kourovka Astronomical Observatory of the Ural Federal University)
- KASI (Korea Astronomy Space Science Institute, Daejeon, South Korea)
- SAO RAS (Special Astrophysical Observatory of the Russian Academy of Sciences)
- NASA (National Aeronautics and Space Administration, United States)
- University of Narino, Pasto, Colombia
- Višnjan Observatory, Croatia: Višnjan Observatory
- Zwicky Transient Facility (ZTF)
- NBO (Northolt Branch Observatories)
- Sormano Astronomical Observatory
- David Balam, Spaceguard Consulting, Canada
- Patrick Wiggins, United States
- SONEAR Observatory, Brazil
- Instituto de Astrofisica de Canarias (IAC)
- Fondazione GAL Hassin
- Jordi Camarasa, Paus Observatory (B49)
- Israel Space Agency (ISA)
- Gennady Borisov, Mobil Astronomical Robotics Genon Observatory (MARGO)
- Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM RAS)
- Agenzia Spaziale Italiana (ASI)
- Baldone Astrophysical Observatory, Latvia
- Osservatorio Astronomico “G.V. SCHIAPARELLI”, Italy
- Observatoire de la Côte d'Azur
- Xingming Observatory
- 6ROADS Company
- Squirrel Valley Observatory (Columbus, North Carolina, USA)
- Golden Ears Observatory (Maple Ridge, British Columbia, Canada)
- Astronomical Institute of the Romanian Academy
- MAP, Alain Maury, San Pedro De Atacama, Chile
- Hampshire Astronomical Group, David Briggs, United Kingdom
- NOAK Observatory, Nick Sioulas, Ioannina, Greece
- La Cañada Observatory (J87)
- Gr.A.M. (Gruppo Astrofili Montelupo, K83)

SMPAG[227]

> *"The purpose of the SMPAG is to prepare for an international response to a NEO impact threat through the exchange of information, development of options for collaborative research and mission opportunities, and NEO threat mitigation planning activities."*[228]

Members:

- AEM (Mexico)
- ASE (Association of Space Explorers, observer)
- ASI (Italy)
- BELSPO (Belgium)
- Czech Republic
- CNSA (China)
- CNES (France)
- COSPAR (observer)
- DLR (Germany)
- ESA (European Space Agency)
- ESO (observer)
- FFG (Austrian Research Promotion Agency, Austria)
- IAA (observer)
- IAU (observer)
- IAWN (ex officio)
- ISA (Israel)
- JAXA (Japan)
- KASI (Korea)
- NASA (USA)
- ROSA (Romania)
- ROSCOSMOS (Russian Federation)
- SSAU (Ukraine)
- SWF (Secure World Foundation; observer)
- SUPARCO (Pakistan)
- UK Space Agency (UK)
- UN Office of Outer Space Affairs (observer)

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[227] International Asteroid Warning Network, "Space Mission Planning Advisory Group, Members" webpage, February 2022. As of January 18, 2023: https://www.cosmos.esa.int/web/smpag/smpag_members
[228] European Space Agency, "Terms of Reference for the Near-Earth Object Threat Mitigation Space Mission Planning Advisory Group v2.0," webpage, September 13, 2019. As of January 18, 2023: https://www.cosmos.esa.int/web/smpag/terms_of_reference_v2

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A.12 Short-Form Notification Templates for Wireless Alert Systems

Source: Osburg, Jan: *Using "Wireless Emergency Alerts" for Planetary Defense Notifications*, IAA-PDC-19-08-P03, presented at the 7th Planetary Defense Conference, Washington, DC, USA, April 2019. As of 23 December 2022: https://drive.google.com/file/d/1rXWhaVLl-a1x6Pwsu_c7cu6APJhUnvVA/view

Taking into account best practices for emergency notification, freetext alert messages to be used in case of **short-notice Planetary Defense scenarios** should address what is going to happen (or has happened) and when, where, and what immediate action to take. Ideally, the sending agency should also be mentioned in each alert, in order to increase the credibility of the message and thus the likelihood of recipients taking appropriate action. In addition to the initial warning, a message containing a web link (URL) pointing to an authoritative webpage with more information should be sent.

Four general types of messages should be considered:

1. **Actionable pre-impact instructions, geotargeted at the directly-affected area** while taking in to account its potentially complex shape and covering the following:
   - Type of threat (e.g. "Asteroid impact")
   - Impact time (in local time)
   - Instructions to stay away from windows and seek cover (ideally including examples of what constitutes suitable cover)
   - Instructions to seek high ground if there also is a threat of tsunamis generated by an ocean impact
   - An identifier for the sending organization

   The following example message, based on the risk corridor of the Planetary Defense Conference 2019 exercise scenario,[229] has 89 characters: "**Asteroid impact imminent in this area at 12:02am. Stay clear of windows, seek cover -FEMA**" It contains the bare minimum of information and the 90-character restriction[230] leaves no room for e.g. the time zone of the impact time (which would require sending separately-geotargeted messages in case the affected area crosses multiple time zones).

2. **Actionable pre-impact instructions, geotargeted at the indirectly-affected areas**, covering the following:
   - Type of threat
   - Impact time and time zone
   - Regional landmark city nearest to the center of the area affected by blast
   - Instructions to prepare for secondary threats such as infrastructure disruptions, earthquakes or tsunamis
   - An identifier for the sending organization

   The following example message has 89 characters: "**Asteroid impact expected at 12:02am EDT near Grove City PA. Prepare for power outage -FEMA**" Again, the 90-character limit only allows for the bare minimum of information to be included

3. **Nationwide pre-impact notification** (or post-impact, in case of zero-notice impacts), covering the following:
   - Type of threat

[229] "Planetary Defense Conference Exercise – 2019" website. NASA Jet Propulsion Laboratory, 2019. As of 3 March 2019: https://cneos.jpl.nasa.gov/pd/cs/pdc19/

[230] The original version of the U.S. "Wireless Emergency Alerts" (WEA) system limited freetext messages to 90 characters. The current version allows for 360 characters, but older phones cannot receive this format. See https://www.weather.gov/wrn/wea360 for more information and examples.

- Impact time and time zone
- Major city nearest to the center of the area affected by blast
- Expected extent of damage
- An identifier for the sending organization

The following example message has 89 characters: "**Asteroid impact expected 12:02amEDT N of Pittsburgh PA. Damage likely up to 150miles-FEMA**" (note that the damage radius was calculated using the "Impact Earth" tool,[231] based on the NEO from the PDC 2019 scenario: 300m diameter, dense rock, impact speed 19km/s and impact angle 73 degrees).

4. A series of **post-impact information and instructions** geotargeted at the directly affected area, covering the extent of damage, instructions to evacuate or continue sheltering in place, locations of public shelters, where to obtain more information (for example, a FEMA web page with detailed post-impact instructions, prepared ahead of time and updated with specifics for the event), etc.

[231] Purdue University: "Impact Earth" website. As of 9 January 2023: https://www.purdue.edu/impactearth/

A.13 Example for Message from ESA's Semi-Automated Notification System

This message was generated for the hypothetical impactor to be used for the exercise at the 2023 Planetary Defense Conference. It does not reflect a real impact threat, but illustrates the structure and content of the message ESA would issue in case of one.

Source: e-mail communication from ESA official, 24 February 2023.

```
This is a special interest event for the 2023 PDC hypothetical exercise.
The very large asteroid 2023 PDC has a chance of impacting the Earth on 22
October 2036.
The minimum distance will be inside the geostationary ring.
The estimated impact probability is: 0.01

Possible impact date: 2036-10-22
Possible impact time: 15:01 UTC (+/- 1200 s)
Fly-by-distance from Earth surface: 29920 km (+/- 36000 km)
Velocity at entry interface point: 12.8 km/s
Size range: 350 - 899 m
Discovery date: 2023-01-10
Discovery site: DECam, Cerro Tololo Inter-American Observatory in Chile

Orbit information:
The fly-by causes a change in the orbit elements.
Orbit date before and after fly-by: Before = 2023-02-03 After = 2036-10-23
Orbital periods in year/day: Before = 1.008 / 359 After = 1.022 / 364
Aphelion distances in au: Before = 1.06 After = 1.05
Perihelion distances in au: Before = 0.90 After = 0.95
Eccentricities: Before = 0.087 After = 0.01
Inclinations in deg: Before = 10.17 After = 10.0

Mitigation information:
Torino Scale: 4
Follow-up observations required. Global impact effects estimated for very
large sized (above 140 m) objects. Deflection assessments are advised.
Expected energy: 0.54 to 160 Gt TNT equiv.
Impact angle: 0 to 90 deg of elevation
Days until closest approach: 5034
Composition (Taxonomic type): Unknown
Rotation period in hours: Unknown

Other information:
Peak brightness magnitude: 5
Date of previous encounter: 1980-01-01
Date of next encounter: 2036-10-22T
Encounter peculiarities: This is an exercise for the PDC 2023
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*Key references are highlighted in **bold font**.*

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European Space Agency, “Close Approach Fact Sheets,” webpage, 26 January 2023. As of 10 March 2023: https://neo.ssa.esa.int/cafs

European Space Agency: “Hitchhiker’s Guide to Asteroid Impact Threats”, Draft, ESA-S2P-PD-TN-0014, 2022.

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