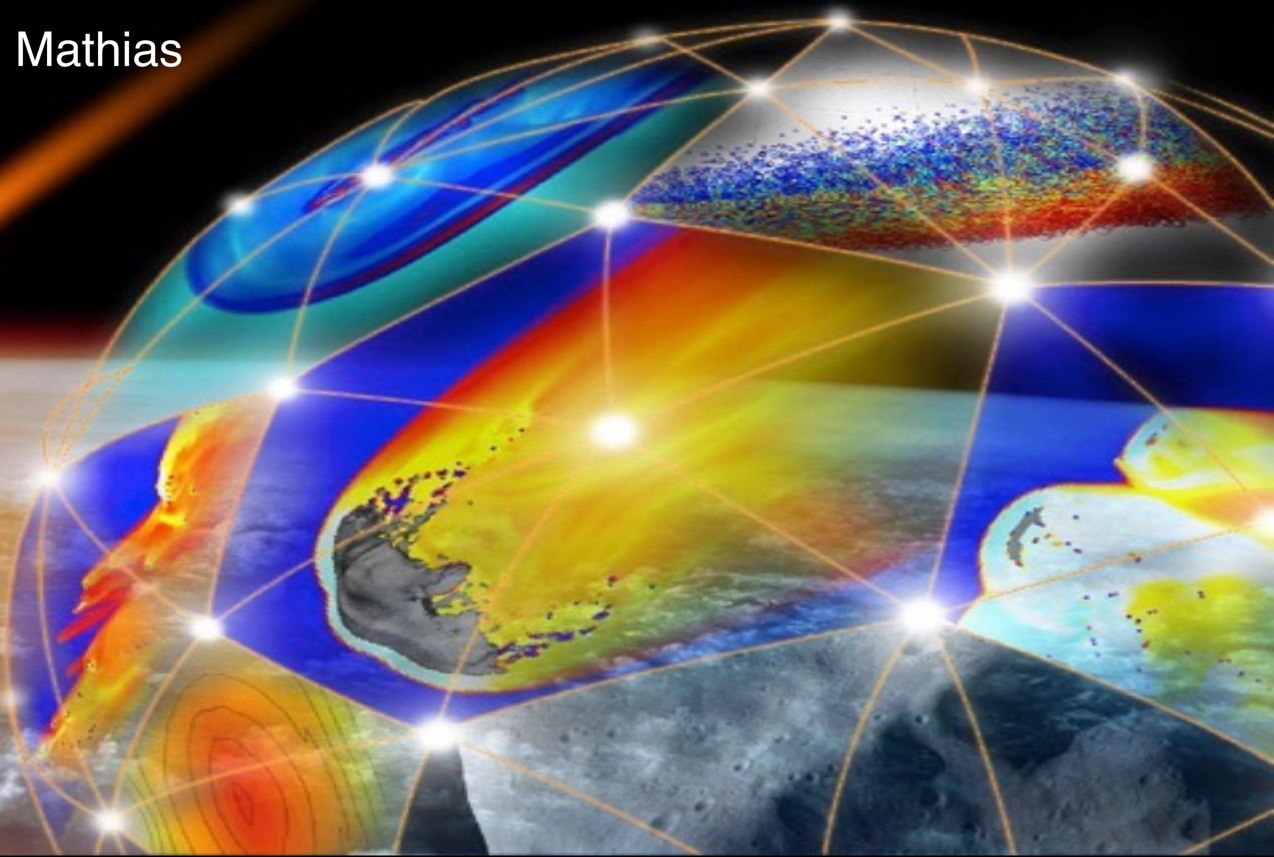
Introduction to Asteroid Impact Risk Assessment

Lorien Wheeler

Jessie Dotson, Michael Aftosmis, Eric Stern, Donovan Mathias

NASA Ames Research Center

Asteroid Threat Assessment Project (ATAP)



8th IAA Planetary Defense Conference

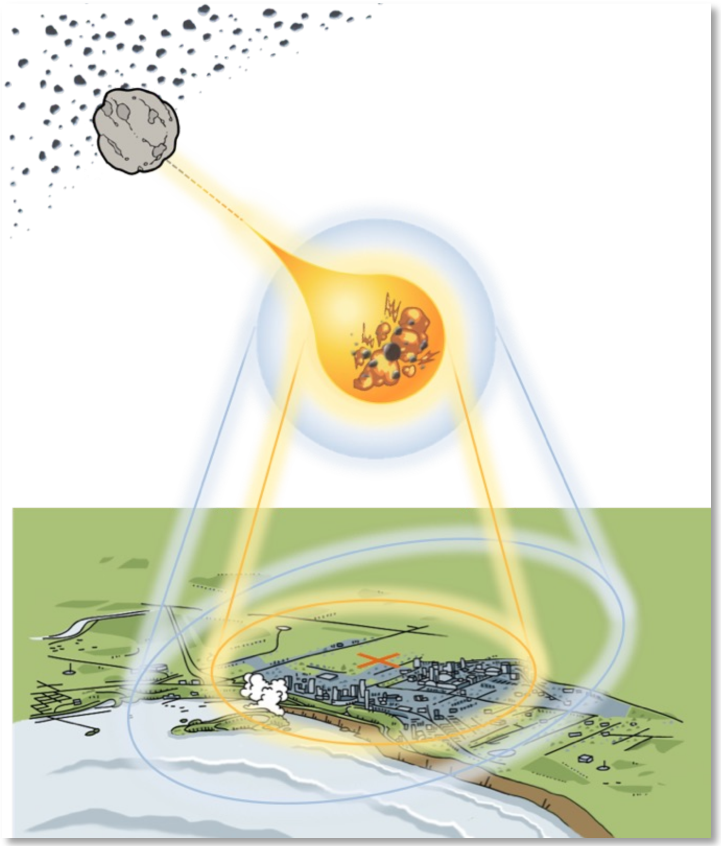
April 2023

Contents

This presentation provides an introductory overview of key factors involved in the asteroid impact threat assessment and risk modeling performed for the Planetary Defense Conference hypothetical impact exercises.

Contents:

- Asteroid threat assessment overview
  - What is asteroid impact risk assessment?
  - Asteroid size uncertainties
  - Cascade of asteroid property and damage uncertainties
  - Impact hazards and damage effects
- Asteroid threat assessment for impact scenarios
  - Impact risk assessment process
  - Affected population risks for impact hazards
  - Local ground damage risk regions and swath maps
  - Impact risk summary dashboard key
- References



ASTEROID THREAT ASSESSMENT OVERVIEW

What is asteroid impact risk assessment?

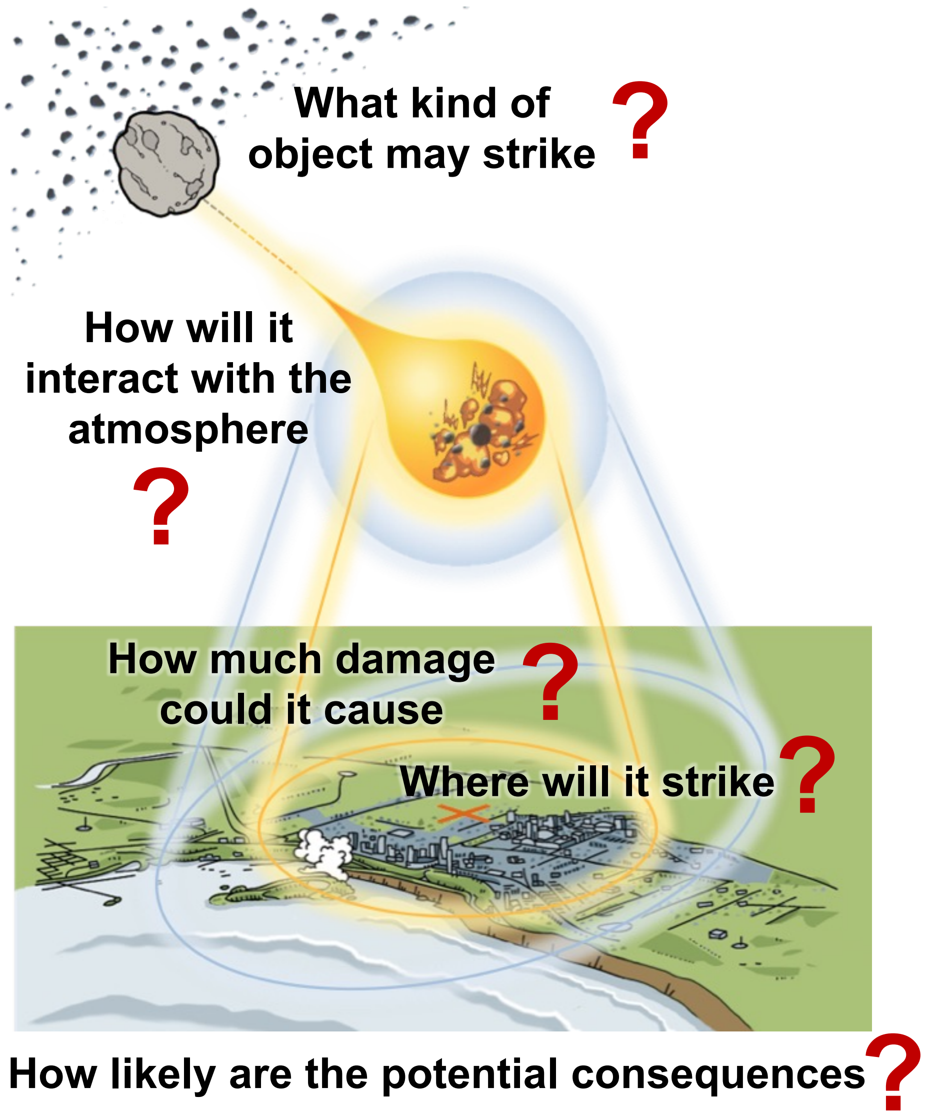
Asteroid size uncertainties

Cascade of asteroid property and damage uncertainties

Impact hazards and damage effects

HYPOTHETICAL EXERCISE

What is Asteroid Impact Risk Assessment?



- Risk assessment evaluates both the severity and likelihood of potential outcomes, given the level of uncertainty about all the contributing factors
- Evaluating asteroid impact risks involves large uncertainties across all aspects of the problem:
  - Impact probability, potential impact locations, entry trajectories (speed, entry angle)
  - Initial asteroid sizes and properties (density, strength, structure, composition, shape, etc.)
  - Atmospheric entry, breakup, airburst or impact behavior
  - Severity and range of resulting hazards
  - Population and infrastructure within damage regions
- Some uncertainties shrink as we gain knowledge over time (impact locations, asteroid size), while some remain unknown (specific asteroid properties, entry/breakup behavior, damage uncertainties)

HYPOTHETICAL EXERCISE

Asteroid Size & Property Uncertainty

What we would like to know about the object:
Direct mass, size, type, and composition data from reconnaissance space missions to the asteroid

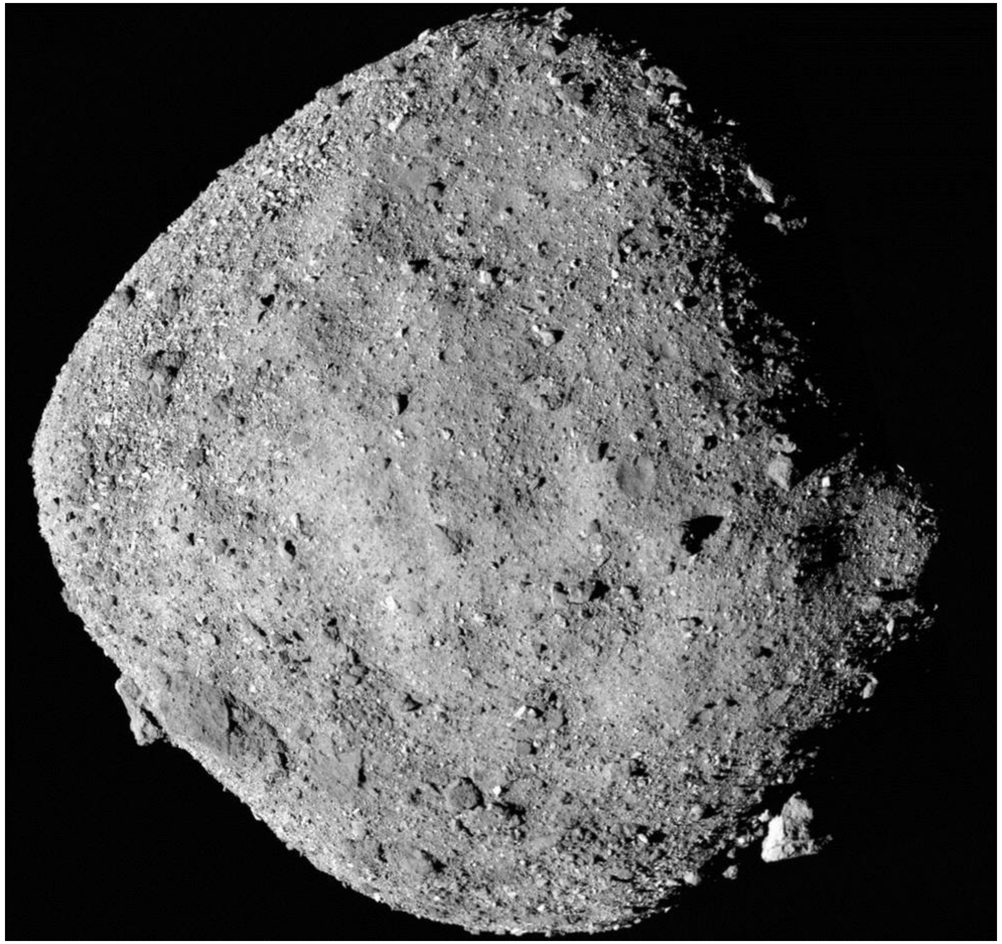
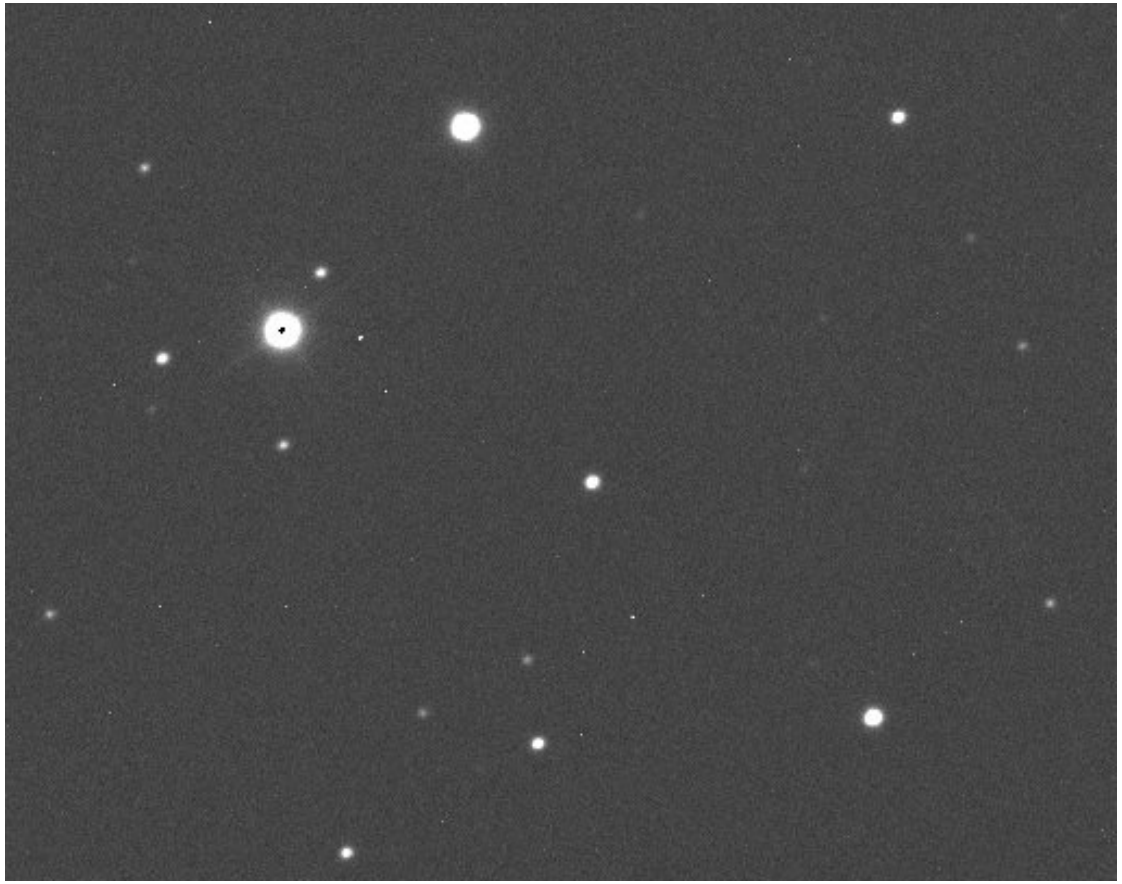


Image of asteroid Bennu from OSIRIS-Rex mission (Image credit: NASA)

What we actually know initially:
Just a tiny point of light with an estimated brightness and orbital motion from remote telescope observations



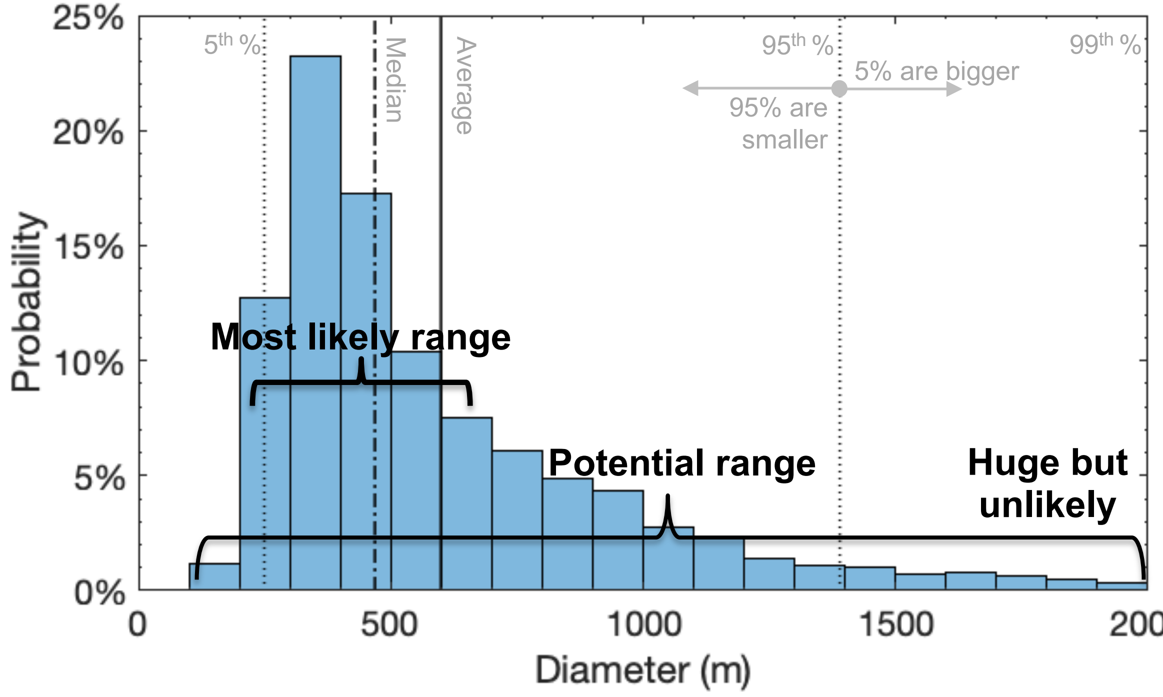
Telescope observation of asteroid Apophis.
(Credit: Nic Erasmus, SAAO's Lesedi Telescope, IAWN Apophis 2021 Observing Campaign, https://iawn.net/obscamp/Apophis/apophis_gallery.shtml)

Asteroid Size & Properties

Asteroid sizes and physical properties are highly uncertain

- Upper size range is large but relatively unlikely
- Smaller size ranges are more likely
- Asteroid properties (density, composition structure, strength) are usually unknown, ranging from more common stony types and rubble piles to rarer high-density iron types
- Size and density uncertainties together result in very large ranges of potential mass and impact energy

Asteroid Size Ranges & Probabilities



Asteroid diameter distribution for the initial discovery (Epoch 1) of the 2023 PDC hypothetical scenario, based on an H magnitude (brightness) estimate of 19.4 from initial remote observations, and unknown albedo (reflectiveness).

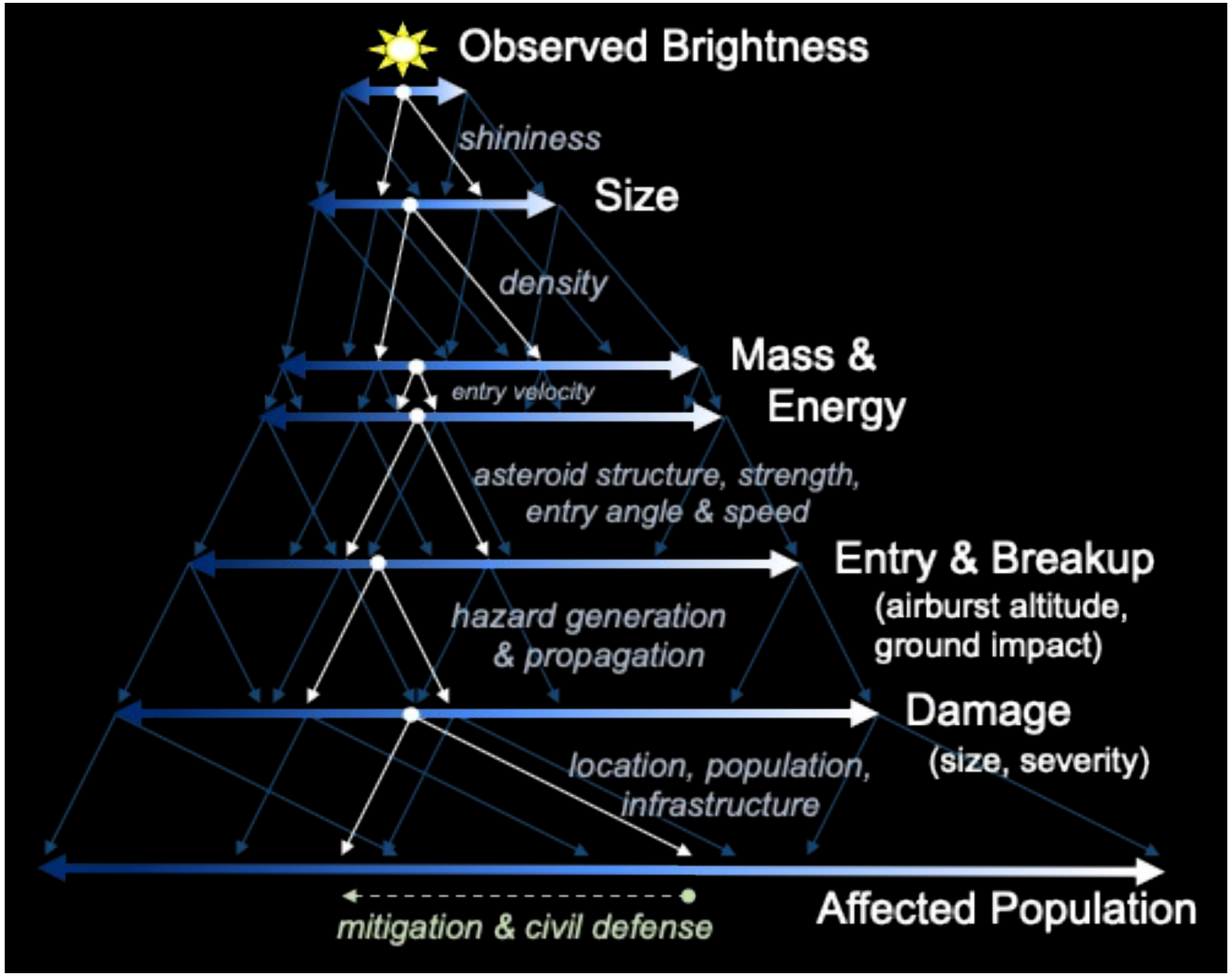
The "most likely" ranges shown in 2023 PDC exercise risk results encapsulate the highest-probability 68% of sizes, and the full "potential ranges" extend up to the 99th percentile of sizes.

[Property inference model: J. Dotson PDC 2021]

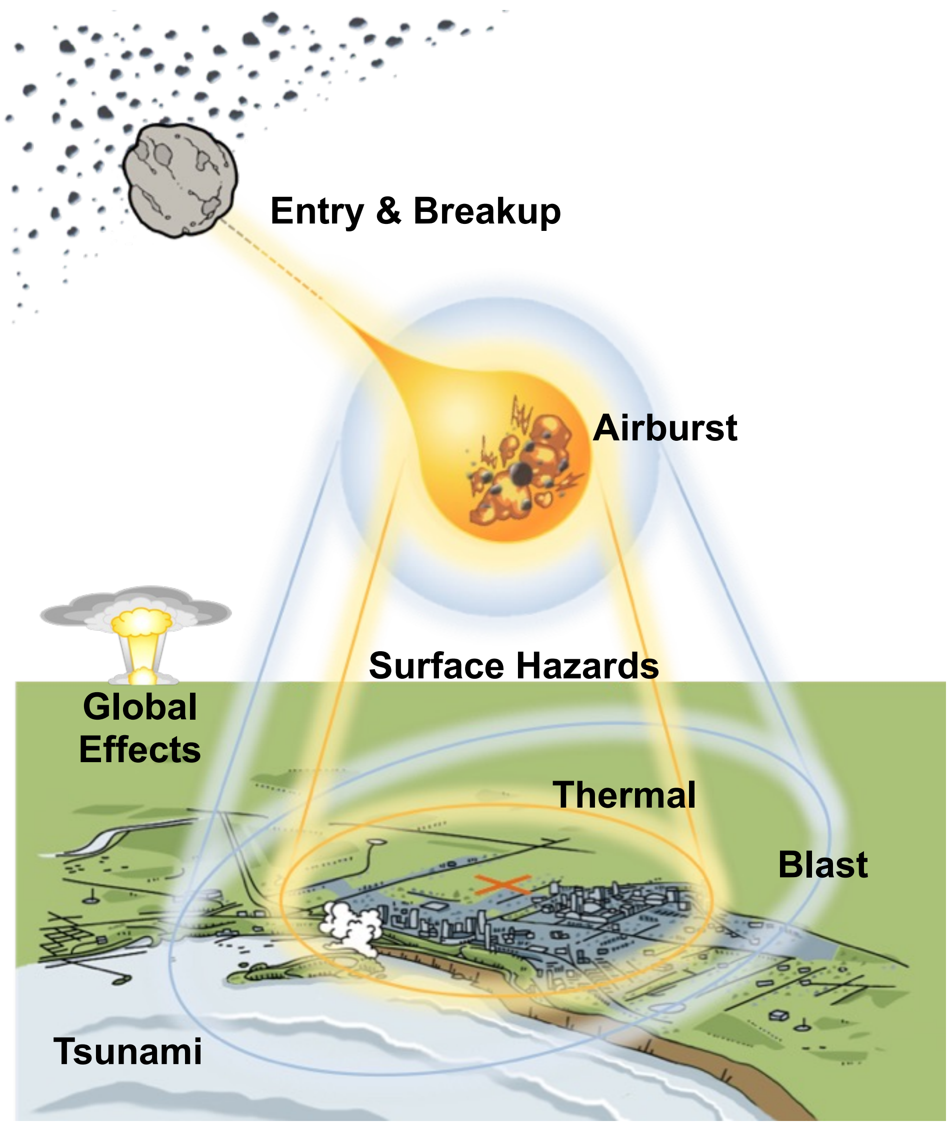
Asteroid Property & Damage Uncertainties

- Size and density uncertainties together result in very large ranges of potential mass and impact energy
- Unknown composition and structural properties affect range of mass, strength, and atmospheric entry/breakup
- These properties determine how much energy the asteroid can deliver to the various hazards and how much damage they could do
- Asteroid impact energy:
    - Initial kinetic energy of the asteroid at atmospheric entry (asteroid mass, entry velocity)
    - Usually given in units of megatons (Mt) of TNT equivalent

Cascade of uncertainty ranges from asteroid observation to damage potential



Asteroid Impact Hazards



[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

- Asteroids can cause damage either by breaking up and bursting in the atmosphere or impacting the surface
  - “Asteroid impact” generally refers to an asteroid hitting Earth, including airbursts (not just ground-cratering events)
- Local blast & thermal damage:
  - Airbursts and surface impacts can produce explosive blast waves, that can cause damage ranging from shatter windows to flatten structures.
  - Thermal heating from airburst/impact fireballs can cause damage ranging from mild to lethal skin burns, forest fires, or structure fires.
- Tsunami damage:
  - Ocean impacts could cause significant inundation if impact is very large and/or near to a populated coast.
- Global effects:
  - Large-scale impacts could produce enough atmospheric ejecta to cause global climatic effects.

HYPOTHETICAL EXERCISE

THREAT ASSESSMENT FOR IMPACT SCENARIOS

Risk modeling process

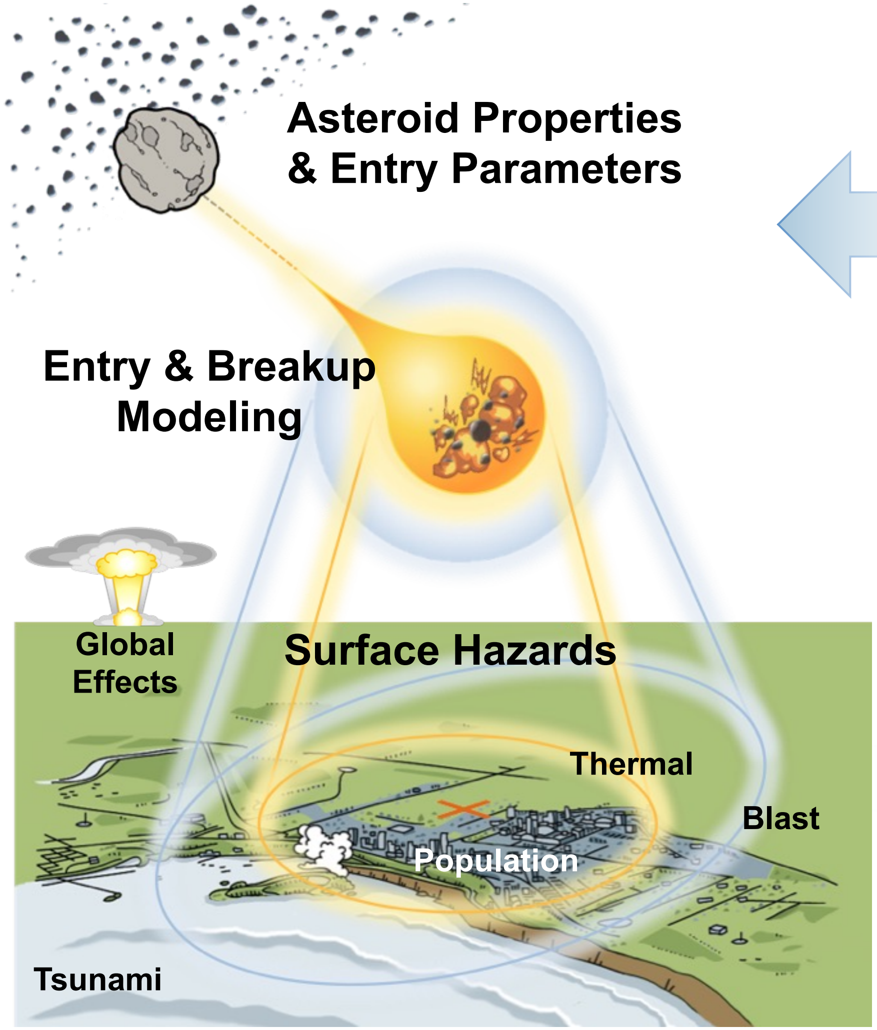
Affected population estimates

Risk Region Swath Maps

Impact Risk Summary Dashboard

Asteroid Impact Risk Assessment

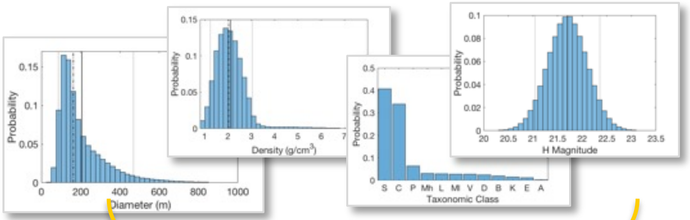
Probabilistic Asteroid Impact Risk (PAIR) Model

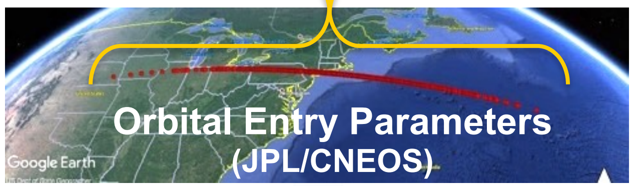


[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

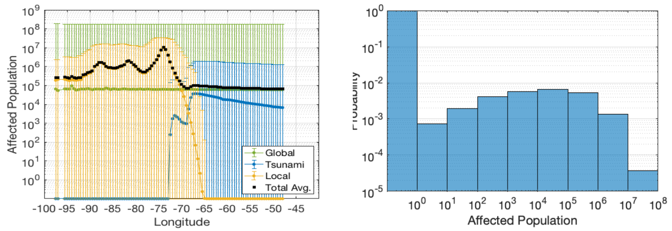
Impact Threat Scenario

Asteroid Property Distributions





Probabilistic Damage and Risk



- PAIR Risk model uses fast-running physics-based models to assess millions of impact cases representing the range of possible asteroid properties and impact locations.
- Atmospheric entry, breakup, and resulting hazards (blast, thermal, tsunami) are modeled for each case.
- Probabilities of the resulting damage sizes, severities, and affected populations are computed.
- Regions at-risk are mapped.

HYPOTHETICAL EXERCISE

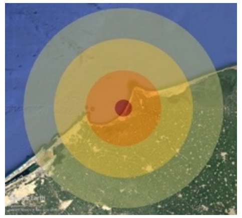
Ames Research Center

NASA

Affected Population Risks

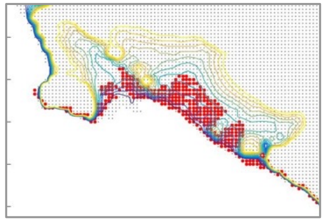
- For each impact case modeled, PAIR computes the estimated number of people affected by each hazard type, based on the modeled damage location, area, severity, and local population
  - **Local blast & thermal ground damage:** affects 10–100% of local population depending on severity (additional details in following slides)
  - **Tsunami:** affects up to 10% of the local population depending on flood depth in each coastal area (based on tsunami wave height and ground elevation)
  - **Global effects:** affects estimated fractions of total world population, based on total impact energy and a randomly sampled severity factor
  - **Total affected population** estimates for each impact case are taken as the number of people affected by the largest hazard produced (not sums of multiple hazards)
- **Affected population risks:** population results for each impact case are aggregated to compute total population ***risks,*** reflecting the likelihoods of the possible effects for the overall impact scenario (i.e., probabilities of the impact affecting given ranges or thresholds of people)
- **Population data source:** SEDAC Gridded Population of the World (GPW) v4.11 gridded population counts, year 2020 UN-adjusted values

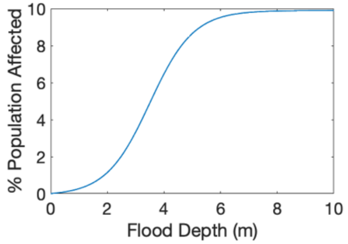
Local Blast & Thermal Affected Population



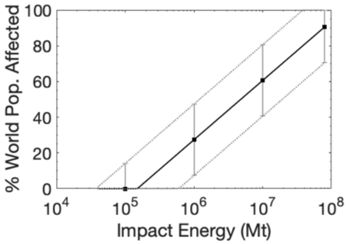
Severity	% Pop. Affected
Serious	10%
Severe	30%
Critical	60%
Unsurvivable	100%

Tsunami Affected Population



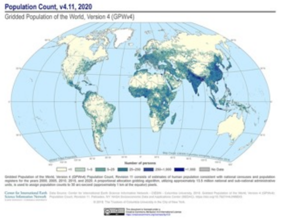


Global Effects Affected Populations

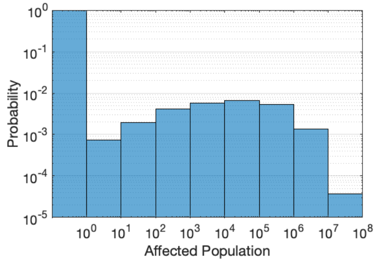


Impact Energy (MT)	% Population Affected		
	Min	Nominal	Max
4.E+04	0	0	0
8.E+04	0	0	10
2.E+05	0	0	20
3.E+05	0	10	30
6.E+05	0	20	40
1.E+06	10	30	50
2.E+06	20	40	60
5.E+06	30	50	70
1.E+07	40	60	80
2.E+07	50	70	90
4.E+07	60	80	100
8.E+07	70	90	100

SEDAC Gridded Population Data



Population Risks

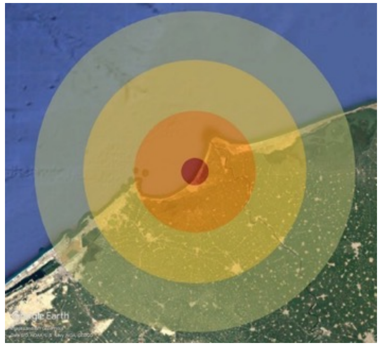


[PAIR model details: Mathias et al., 2017; Stokes et al., 2017]

HYPOTHETICAL EXERCISE

Local Blast & Thermal Ground Damage

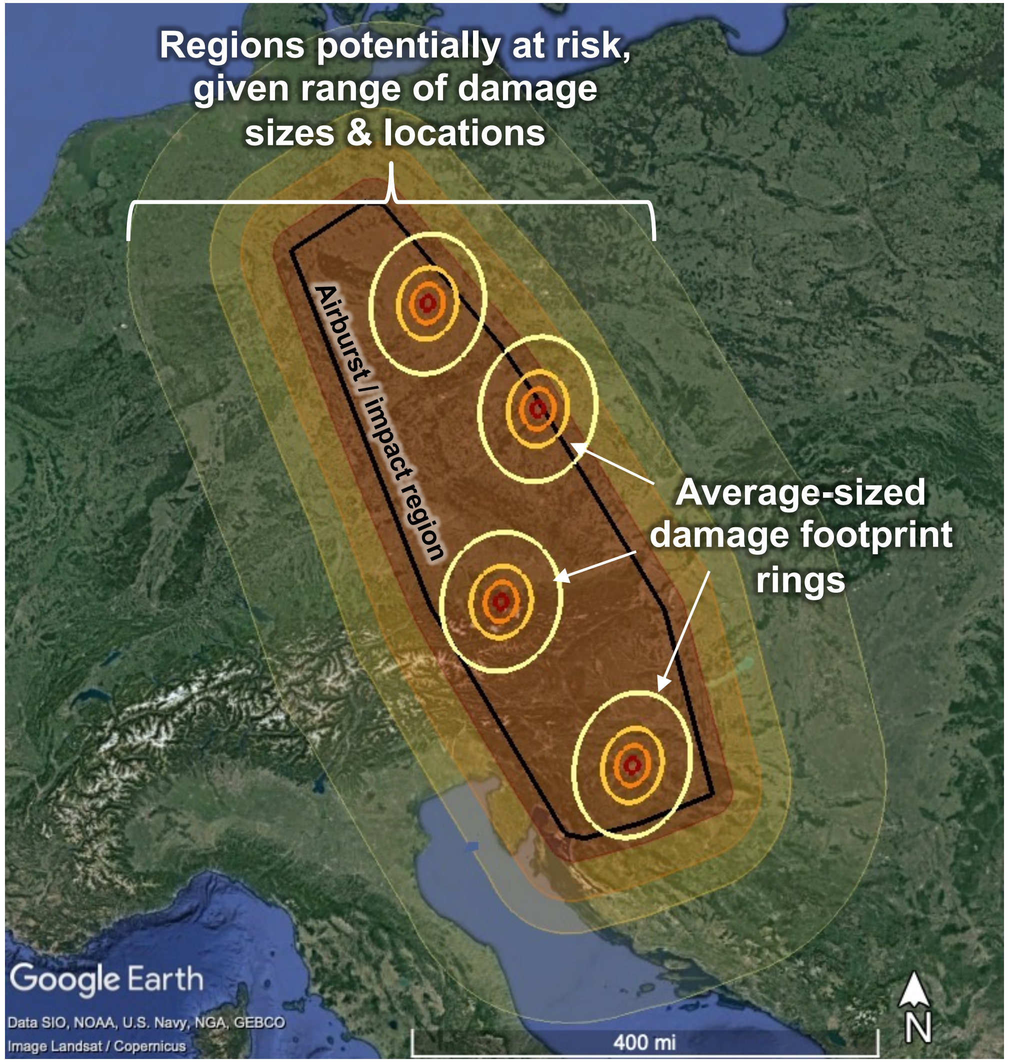
- Large impacts or airburst can generate destructive blast waves and thermal heat that can cause various levels of injury, fatalities, structural damage, and/or fires extending far around the impact location.
- Risk model assesses blast and thermal ground damage *independently* at four equivalent severity levels
  - The damage region for each severity level is determined from the *larger* of the equivalent blast *or* thermal damage area
  - Local ground damage regions indicate *either* blast or thermal effects could exceed the given severity threshold (*not* necessarily the occurrence of both effects within the entire region)
  - Local affected population estimates within each region are scaled by the relative severity of each damage level
- Blast is the predominant hazard for most sub-global-scale asteroid sizes
  - Blast tends to be larger and more severe than the potential thermal damage in most cases, and usually define the larger outer serious and severe risk regions for emergency response planning
  - Critical and unsurvivable thermal damage areas can be larger than equivalent blast levels for the larger impact sizes



Damage Level	Relative Severity	Blast Damage Effects	Thermal Damage Effects
Serious	10%	Shattered windows, some structural damage	2nd degree burns
Severe	30%	Widespread structural damage	3rd degree burns
Critical	60%	Most residential structures collapse	Clothing ignites
Unsurvivable	100%	Complete devastation	Structures ignites, incineration

HYPOTHETICAL EXERCISE

Risk Region Swath Maps



Example from 2021 Planetary Defense Conference Exercise

Risk swaths show range of regions ***potentially*** at risk to local ground damage, including range of possible damage sizes* and locations

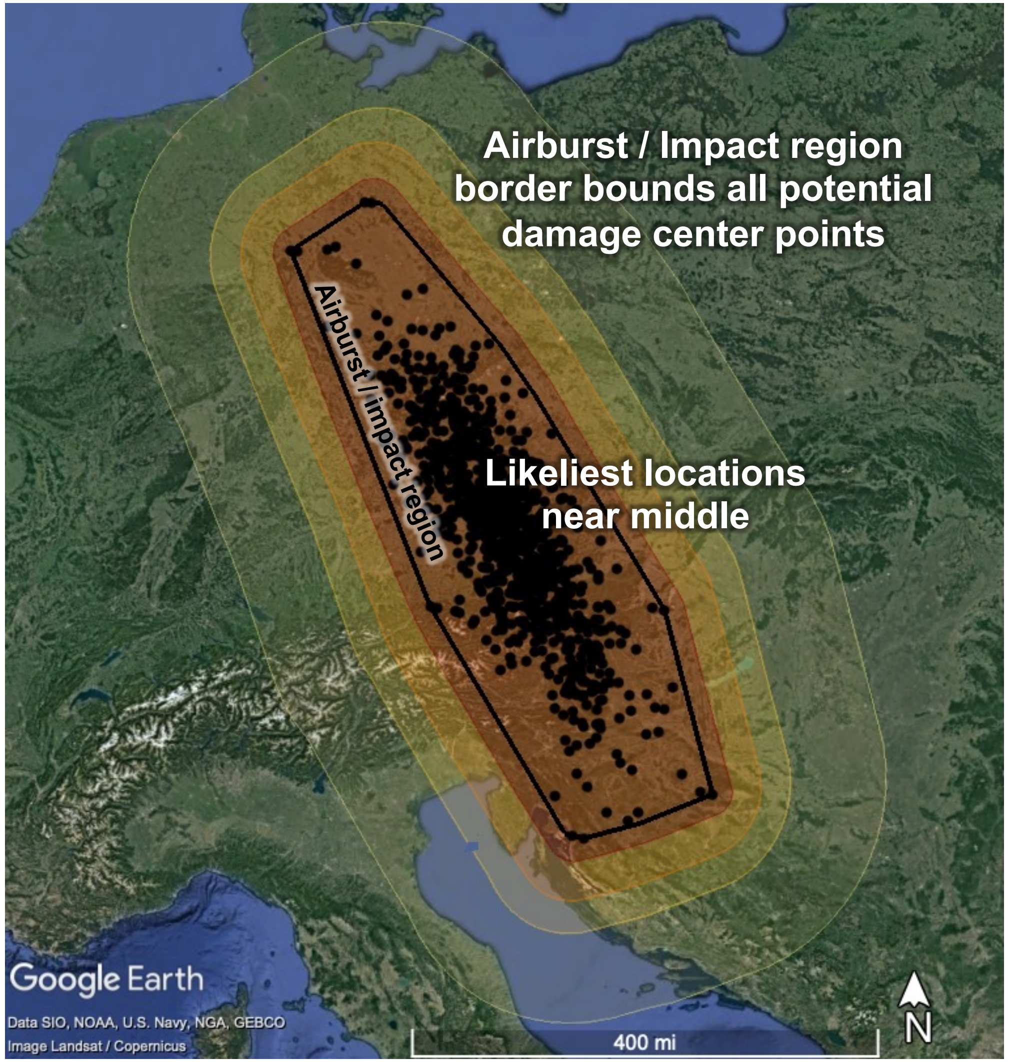
- Black outline shows range of potential impact points (damage-center locations)
- Shaded areas show potential at-risk regions given range of damage sizes and locations
- Rings show an average-sized damage footprint at sample locations

Damage Level	Description
Serious	Window breakage, some minor structure damage
Severe	Widespread structure damage, doors/windows blown out
Critical	Most residential structures collapse
Unsurvivable	Complete devastation

* Swath extents shown for the 2023 PDC results cover local ground damage sizes out to the 95th percentile. Local damage maps do not include regions potentially at at risk to tsunami or global effects.

HYPOTHETICAL EXERCISE

Risk Region Swath Maps

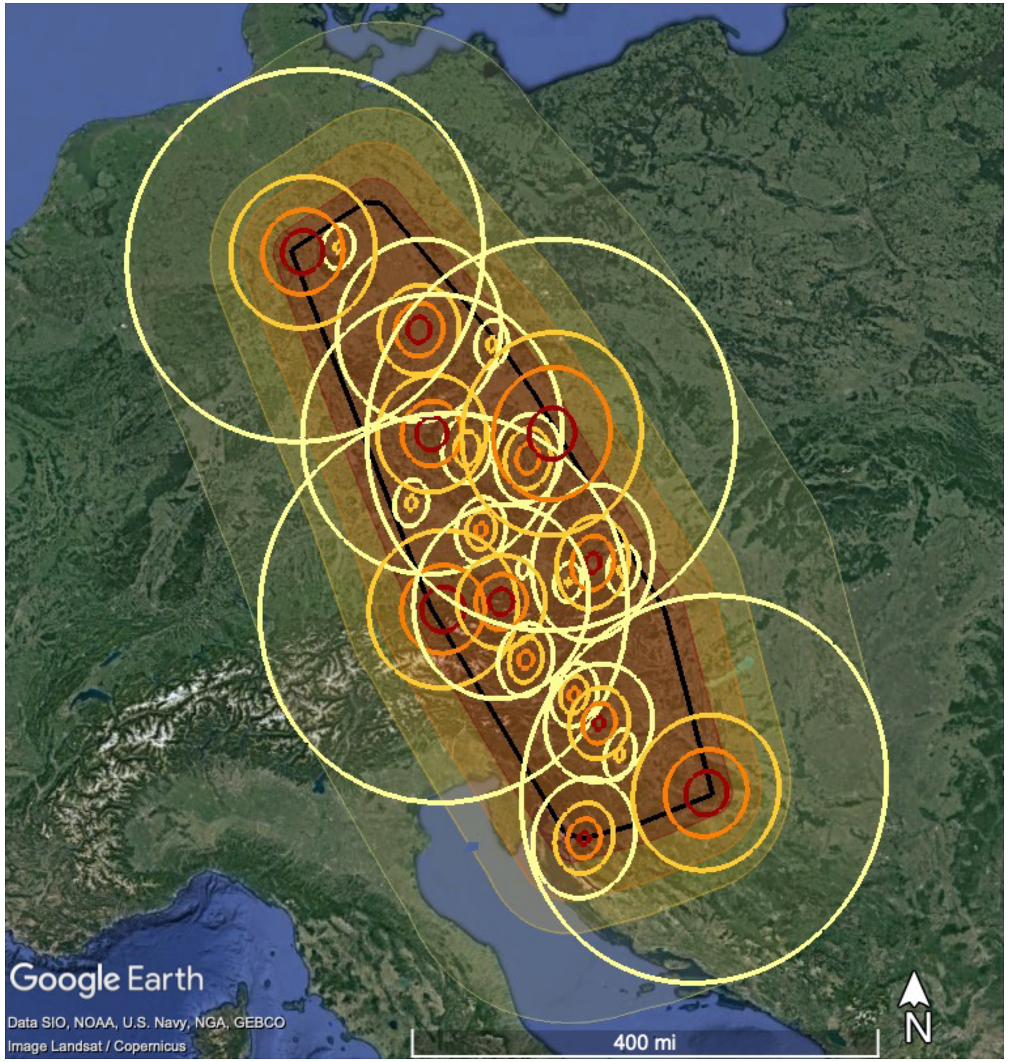


Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
  - Orbital uncertainty gives spread of entry locations
  - Damage location depends on airburst/impact point along entry trajectory
  - Airburst / Impact border bounds all potential damage center-points, with likelier regions toward the middle

Risk Region Swath Maps



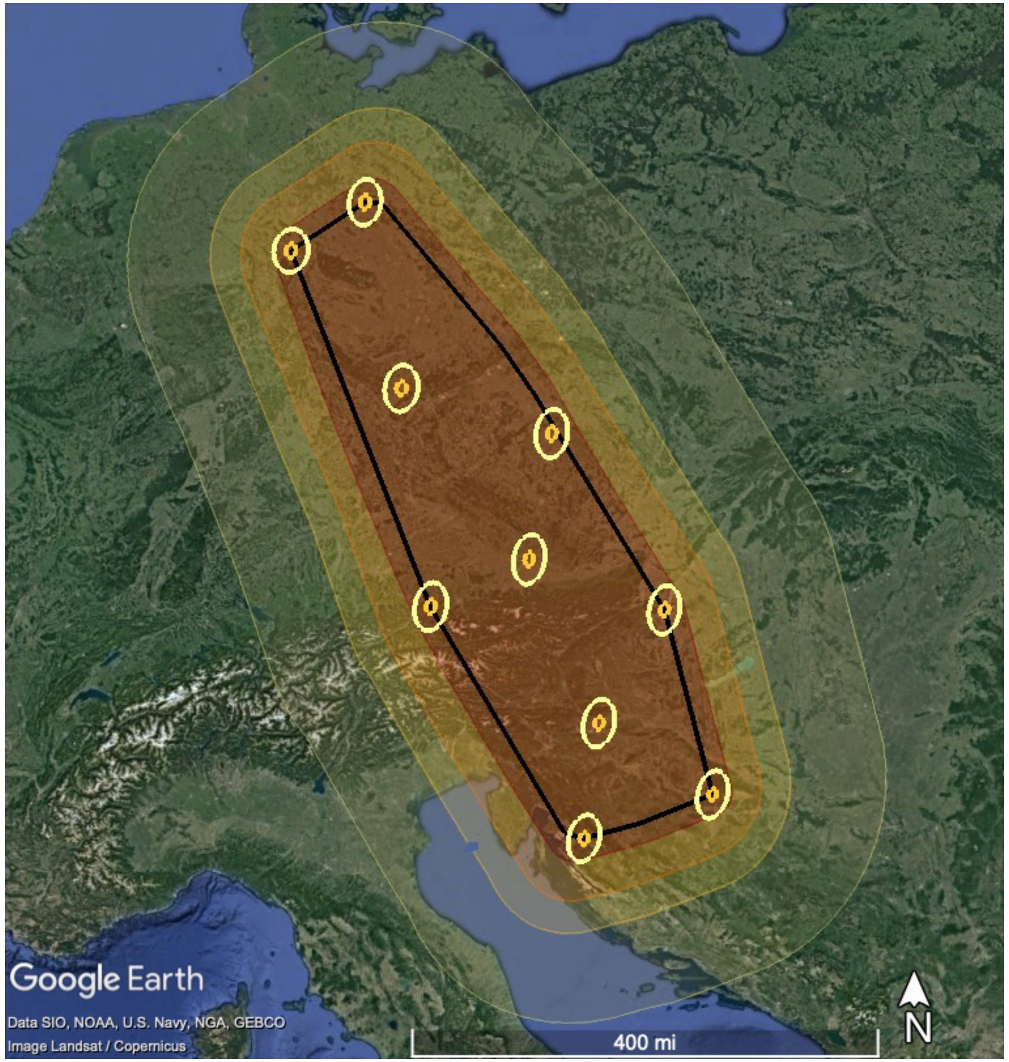
Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges
    + Unknown entry, airburst, or impact factors

HYPOTHETICAL EXERCISE

Risk Region Swath Maps

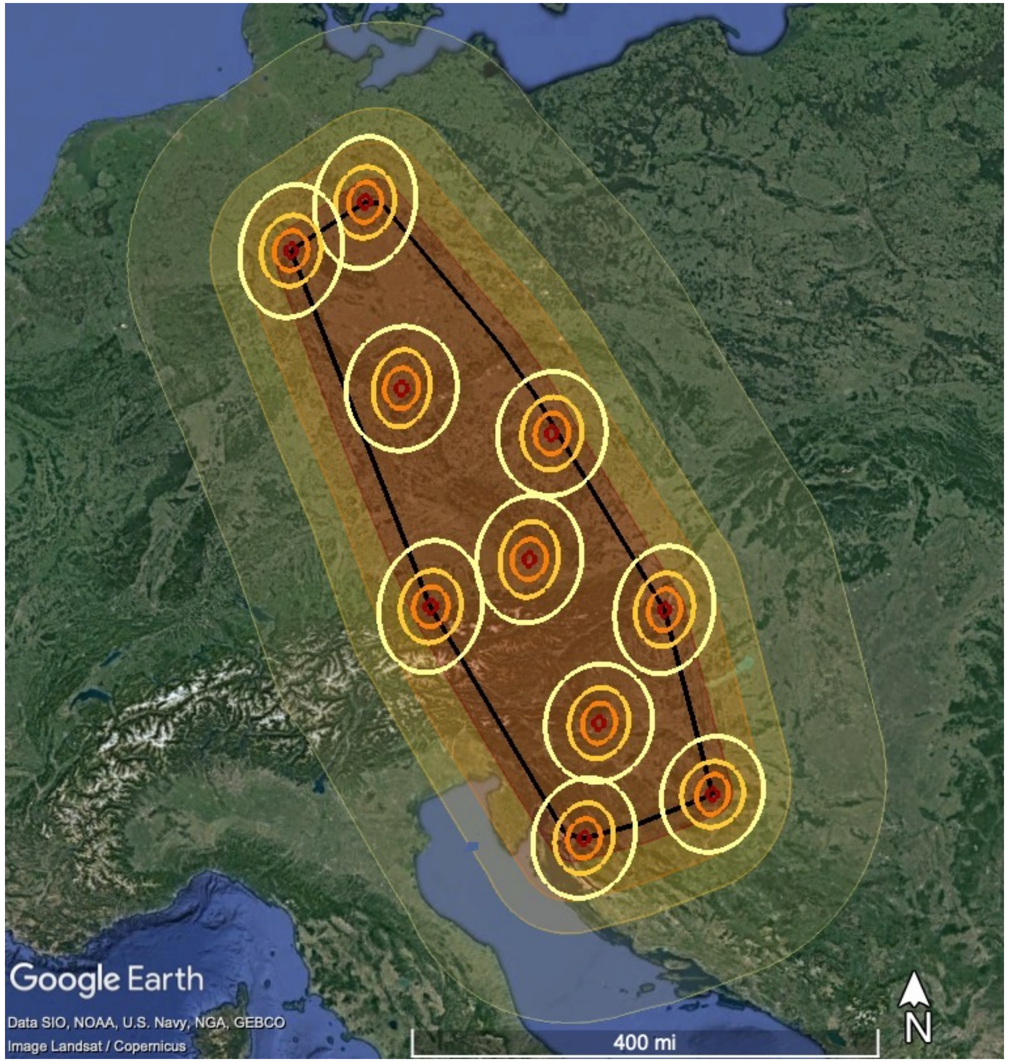


Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges
    + Unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels

Risk Region Swath Maps



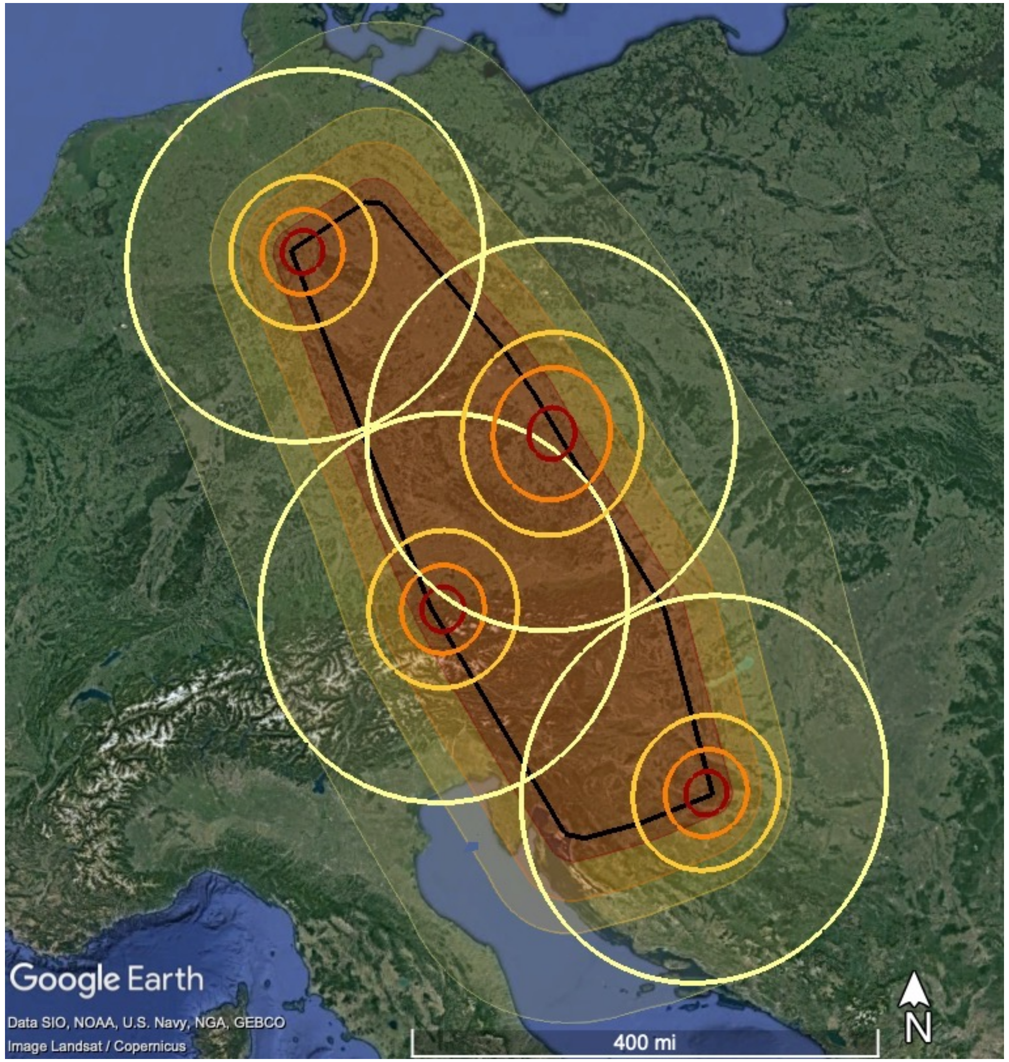
Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges
    + Unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)

HYPOTHETICAL EXERCISE

Risk Region Swath Maps

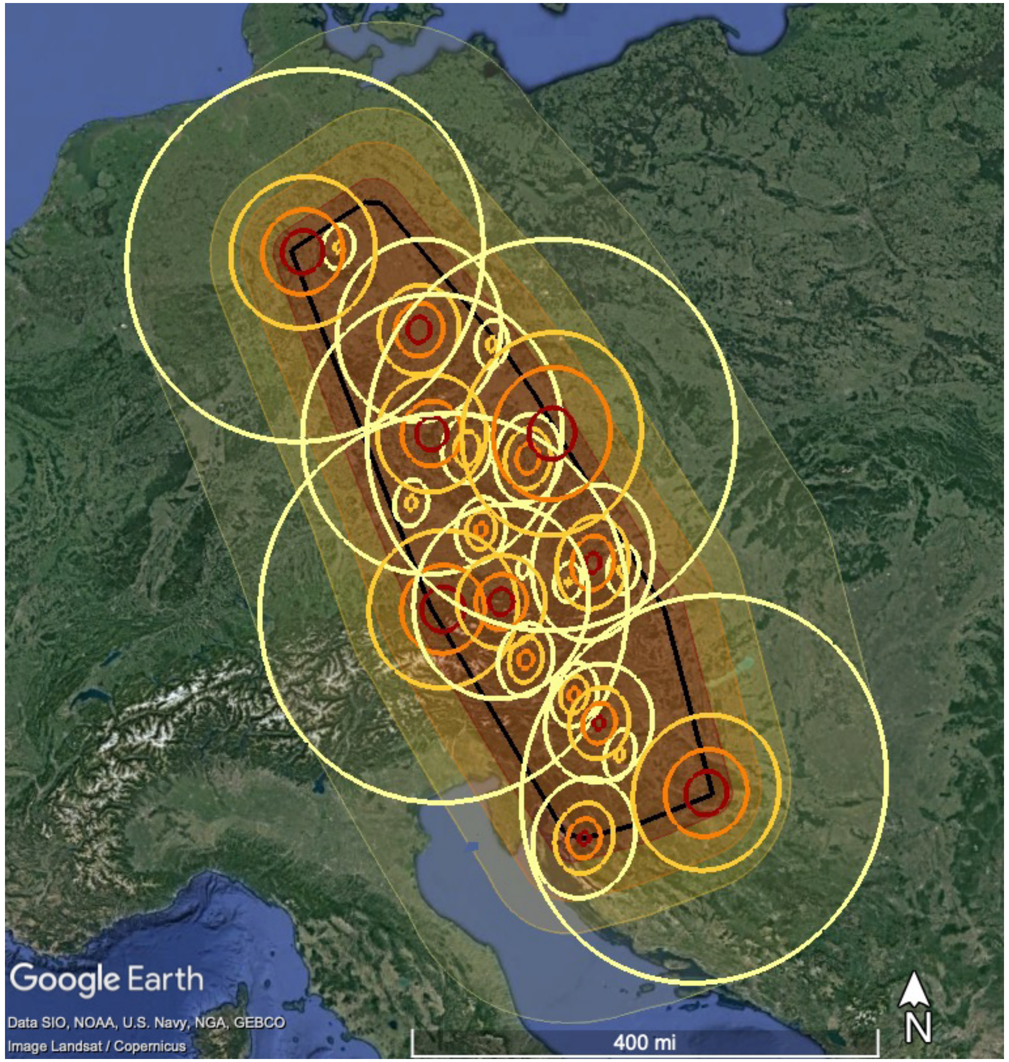


Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges
    + Unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)
  - Very large but unlikely areas (from the largest, least-likely possible impact sizes)

Risk Region Swath Maps

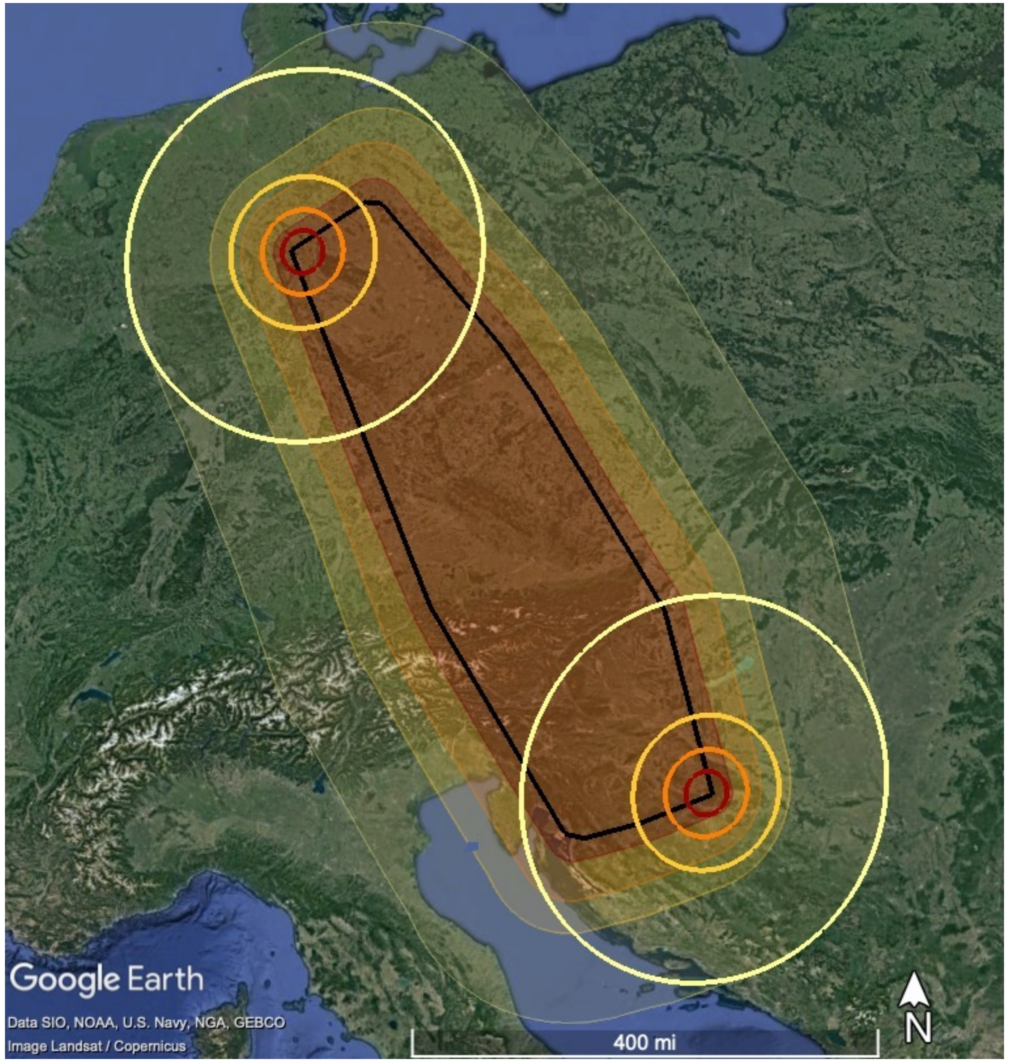


Example from 2021 Planetary Defense Conference Exercise

Range of regions ***potentially*** at risk includes:

- Range of potential impact damage locations (from orbit and entry)
- Wide range of potential damage sizes and severities (from asteroid and entry)
  - Asteroid size and property ranges
    + Unknown entry, airburst, or impact factors
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)
  - Very large but unlikely areas (from the largest, least-likely possible impact sizes)
  - And everything in between….

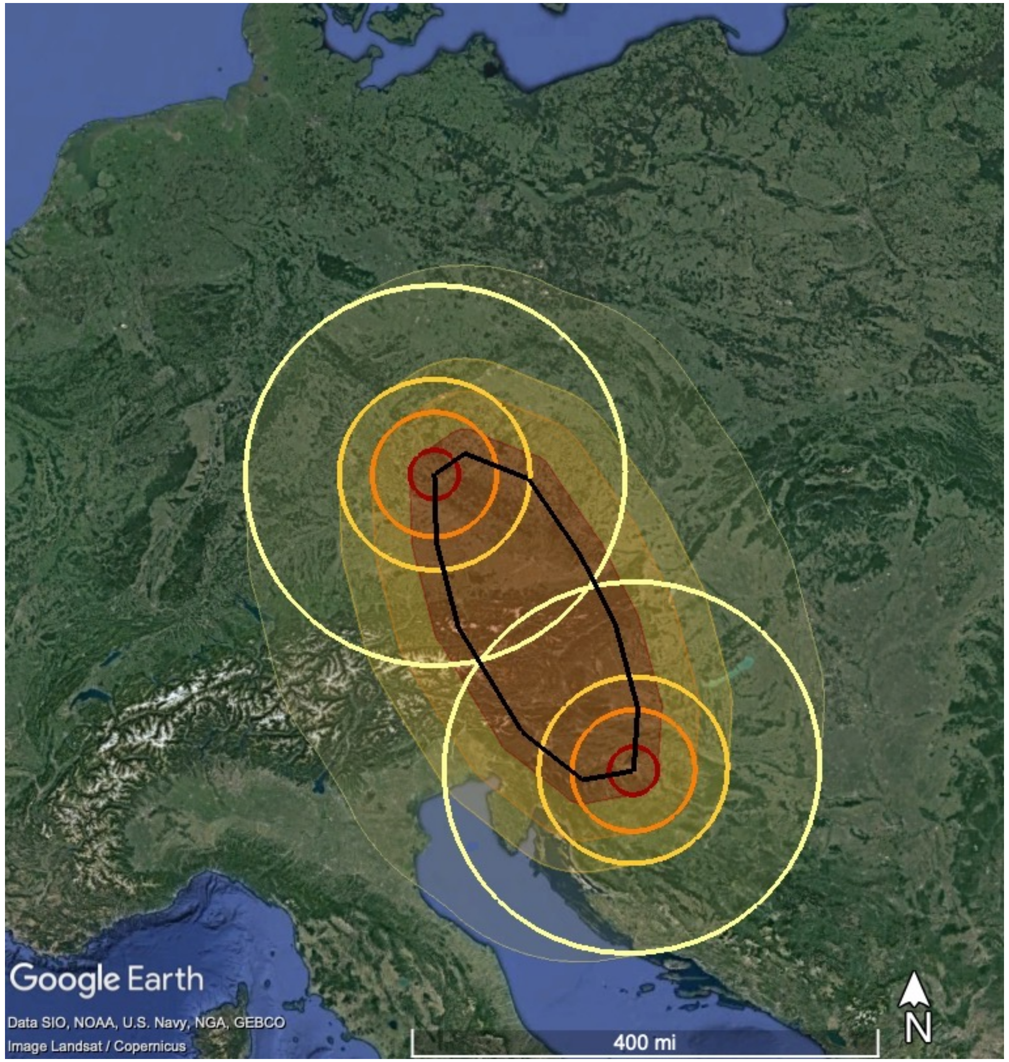
Risk Region Refinement Over Time



Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach

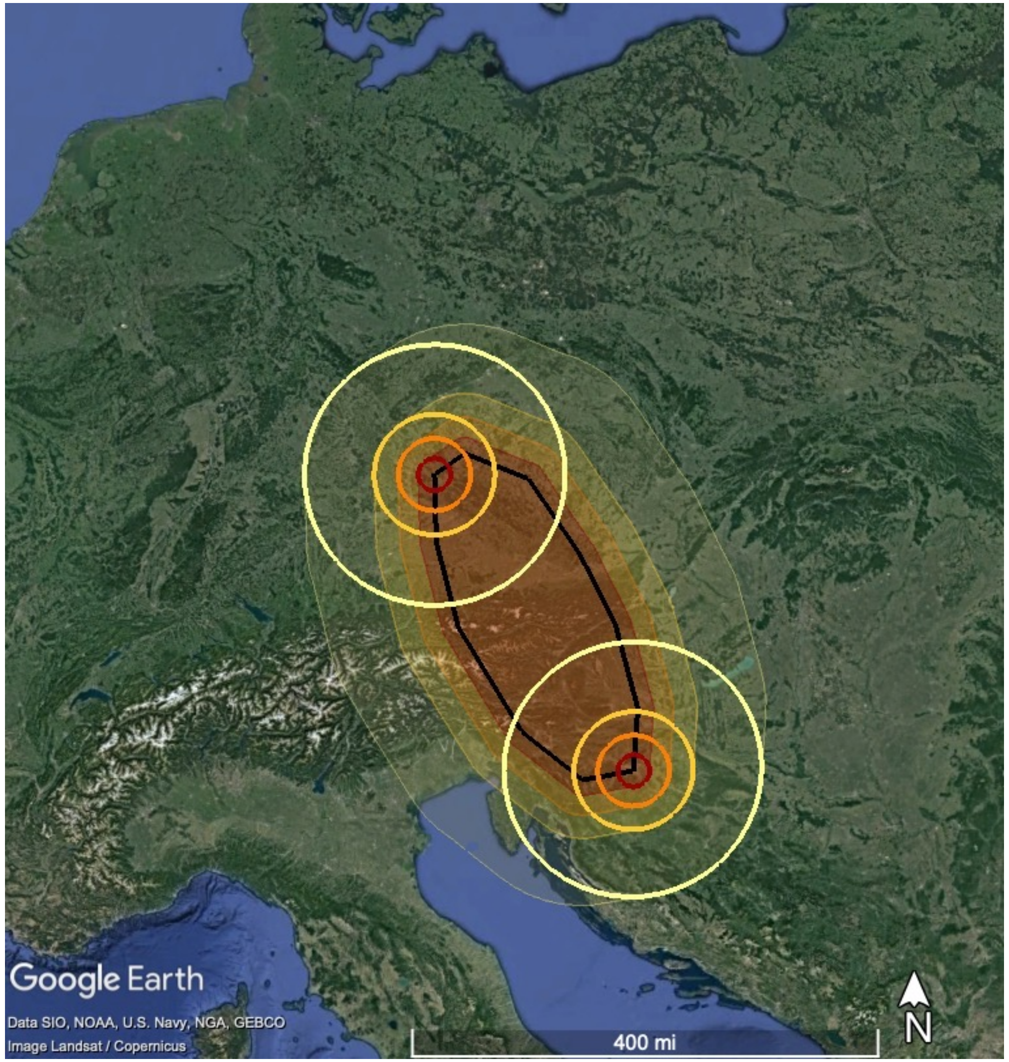
Risk Region Refinement Over Time



Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer due to asteroid size/property uncertainties through much of the approach

Risk Region Refinement Over Time



Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer due to asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range

Risk Region Refinement Over Time

Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer due to asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink

Risk Region Refinement Over Time

Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer due to asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink
  - In the final days before impact, the trajectory will be well-known, location range will be small, and radar may be able to better estimate asteroid size

Risk Region Refinement Over Time

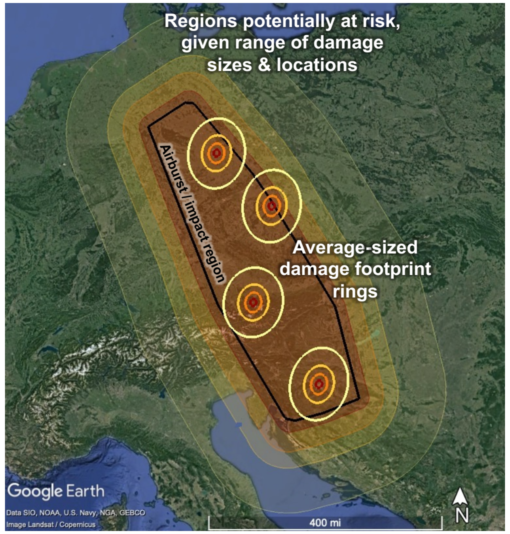
Example from 2021 Planetary Defense Conference Exercise

- Risk swath regions start out very large, but will contract with additional observations during the asteroid's approach
  - Range of locations will shrink as the orbit is refined from additional observations
  - Potential damage range may remain large for longer due to asteroid size/property uncertainties through much of the approach
  - Largest damage estimates may also shrink if observations can refine asteroid size range
  - Impact region will continue to shrink
  - In the final days before impact, the trajectory will be well-known, location range will be small, and radar may be able to better estimate asteroid size
  - Only after impact will we know how much damage actually occurs from the wide range of initial possibilities

Impact Risk Summary Dashboard

Asteroid Characterization Summary

- Earth-impact data to-date (impact probability, potential impact date)
- Updates on any new observational data on the asteroid
- Estimated asteroid sizes, energies, or other properties



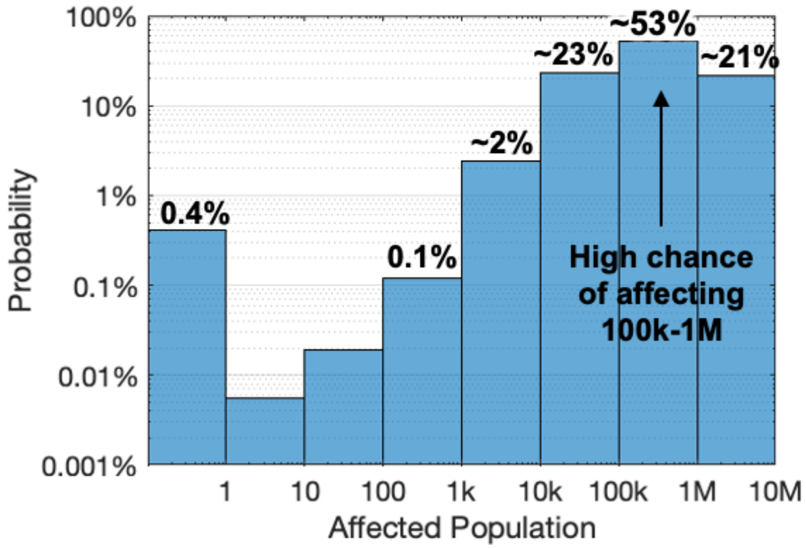
Risk Swath

Regions potentially at risk to ground damage, given ranges of potential impact locations damage sizes.

Average-sized damage footprints are shown as rings over sample cities

Hazard Summary

- Summary of potential impact hazards
- Ranges of damage sizes and severities
- How many people could be affected by the range of damage



Population Risks

Probabilities of how many people could be affected by the potential damage.

Total risk probabilities reflect likelihoods of damage ranges across all potential asteroid sizes, properties, hazards, and impact locations modeled

REFERENCES

HYPOTHETICAL EXERCISE

ATAP Impact Risk Modeling Papers

Probabilistic Asteroid Impact Risk (PAIR) Model

- **Mathias et al., 2017.** A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009
- **Stokes et al., 2017.** Update to determine the feasibility of enhancing the search and characterization of NEOs. National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/2017_neo_sdt_final_e-version.pdf
- **Wheeler & Mathias, 2018.** Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- **Rumpf et al., 2020.** Deflection driven evolution of asteroid impact risk under large uncertainties. Acta Astonautica 176, 276–286. https://doi.org/10.1016/j.actaastro.2020.05.026
- **Reddy et al., 2022.** Apophis planetary defense campaign. Planetary Science Journal, 3:123 (16pp). https://doi.org/10.3847/PSJ/ac66eb
- **Reddy et al., 2022.** Near-Earth Asteroid (66391) Moshup (1999 KW4) Observing Campaign: Results from a Global Planetary Defense Characterization Exercise. Icarus 374, 114790. https://doi.org/10.1016/j.icarus.2021.114790
- **Reddy et al., 2019.** Near-Earth Asteroid 2012 TC4 Campaign: results from a global planetary defense exercise. Icarus 326, 133–150. https://doi.org/10.1016/j.icarus.2019.02.018
- **Population data:** SEDAC GPW v4.11 gridded population counts, year 2020 (UN-adjusted values). CIESIN, Columbia University, 2016. http://dx.doi.org/10.7927/H4SF2T42

Entry & Breakup Energy Deposition Modeling

- **Wheeler et al., 2018.** Atmospheric energy deposition modeling and inference for varied meteoroid structures. Icarus 315, 79–91. https://doi.org/10.1016/j.icarus.2018.06.014
- **Wheeler et al., 2017.** A fragment-cloud model for asteroid breakup and atmospheric energy deposition. Icarus 295, 149–169. https://doi.org/10.1016/j.icarus.2017.02.011
- **Register et al., 2020.** Interactions between asteroid fragments during atmospheric entry. Icarus 337, 113468. https://doi.org/10.1016/j.icarus.2019.113468

Blast Modeling and Simulation

- **Aftosmis, et al., 2019.** Simulation-based height of burst map for asteroid airburst damage prediction. Acta Astronautica 156, 278-283. https://doi.org/10.1016/j.actaastro.2017.12.021
- **Robertson & Mathias, 2019.** Hydrocode simulations of asteroid airbursts and constraints for Tunguska. Icarus 327, 36–47. https://doi.org/10.1016/j.icarus.2018.10.017
- **Aftosmis, et al., 2016.** Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting. https://doi.org/10.2514/6.2016-0998

Thermal Radiation Modeling and Simulation

- **Johnston et al., 2021.** Simulating the Benešov bolide flowfield and spectrum at altitudes of 47 and 57 km. Icarus 354, 114037. https://doi.org/10.1016/j.icarus.2020.114037
- **Johnston & Stern, 2018.** A model for thermal radiation from the Tunguska airburst. Icarus, 327, 48–59. https://doi.org/10.1016/j.icarus.2019.01.028
- **Johnston et al., 2018.** Radiative heating of large meteoroids during atmospheric entry. Icarus 309, 25–44. https://doi.org/10.1016/j.icarus.2018.02.026

Tsunami Simulations

- **Robertson & Gisler, 2019.** Near and far-field hazards of asteroid impacts in oceans. Acta Astronautica 156, 262–277. https://doi.org/10.1016/j.actaastro.2018.09.018
- **Berger & Goodman, 2018.** Airburst-generated tsunamis. Pure Appl. Geophys. 175 (4), 1525-1543. https://doi.org/10.1007/s00024-017-1745-1
- **Berger & LeVeque, 2018.** Modeling issues in asteroid-generated tsunamis. NASA Contractor Report NASA/CR-2018-219786. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006617.pdf
- **Berger & LeVeque, 2022.** Towards Adaptive Simulations of Dispersive Tsunami Propagation from an Asteroid Impact. Proc. ICM, St. Petersburg, Russia, 2022 (submitted). https://doi.org/10.48550/arXiv.2110.01420

HYPOTHETICAL EXERCISE

Ames Research Center

Prior Related PDC 2021 Presentations

PDC 2021 presentation recordings and materials available at:

- https://www.unoosa.org/oosa/en/ourwork/topics/neos/2021/IAAPDC/index.html
- https://atpi.eventsair.com/QuickEventWebsitePortal/7th-iaa-planetary-defense-conference-2021/website/Agenda
- https://cneos.jpl.nasa.gov/pd/cs/pdc21/day1.html

PDC 2021 Impact Exercise Risk Assessment

- **Wheeler** et al., "2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk Scenario Day 1" (Day 1 Exercise Session)
- **Wheeler** et al., "2021 PDC Hypothetical Impact Exercise: Probabilistic Asteroid Impact Risk Scenario Day 3" (Day 3 Exercise Session)

Asteroid Property Inference

- **Dotson** et al., "Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios" (Impact Effects Session 9b)
- **Kelley** et al., "IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021" (Apophis Session 13)

Impact Effects – Hazard Modeling & Simulation

- **Aftosmis** et al., "High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC" (Impact Effects e-lighting talks)
- **Wheeler** et al., "Probabilistic Blast Damage Modeling Uncertainties and Sensitivities" (Impact Effects e-lighting talks)
- **Mathias** et al., "Interaction of Meteoroid Fragments During Atmospheric Entry" (Impact Effects e-lighting talks)
- **Coates** et al., "Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment" (Impact Effects e-lighting talks)
- **Berger** and LeVeque, "Towards Adaptive Simulation of Dispersive Tsunami Propagation from an Asteroid Impact" (Impact Effects Session 9b)
- **Titus** et al., "Asteroid Impacts – Downwind and Downstream Effects" (Impact Effects Session 9b)

Mitigation & Mission Design

- **Barbee** et al., "Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario" (Mission & Campaign Design Session 8b)

HYPOTHETICAL EXERCISE