Asteroid Impact Risk Assessment Damage Maps for the 2023 PDC Hypothetical Impact Scenario

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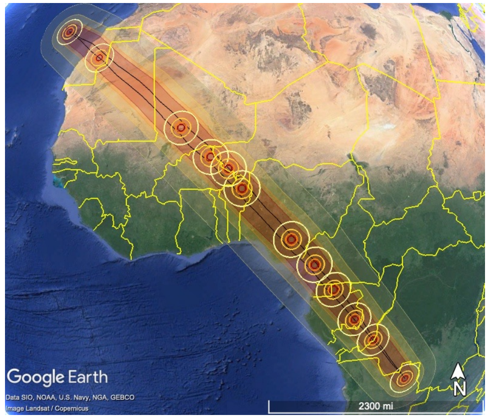
Google Earth Damage Region Maps

- Interactive maps of potential ground damage regions modeled for the 2023 PDC hypothetical asteroid impact scenario risk assessment are available as Google Earth .KMZ files
  - The Google Earth .KMZ map files include damage risk region swaths and sample damage footprints representing the estimated range of potential damage sizes, severities, and locations modeled.
  - These .KMZ files can be downloaded from the CNEOS 2023 PDC scenario website and viewed using the freely available desktop or web app versions of Google Earth
- This presentation gives an overview of the Google Earth .KMZ contents for the 2023 PDC scenario epochs:
  - Local ground damage types and severity levels
  - Risk region swaths key
  - Damage footprints and sample damage sizes
  - .KMZ file contents and navigation
- Background information on 2023 PDC scenario and the probabilistic asteroid impact risk modeling can be found on the CNEOS 2023 PDC scenario website

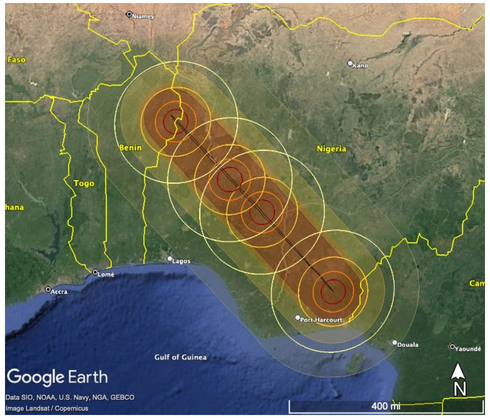
Google Earth Damage Map Snapshots and Hyperlinks for the 2023 PDC Scenario Epochs

Epoch 1

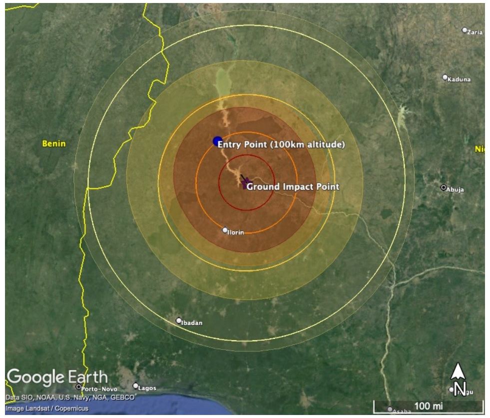
Epoch 2



Epoch 3



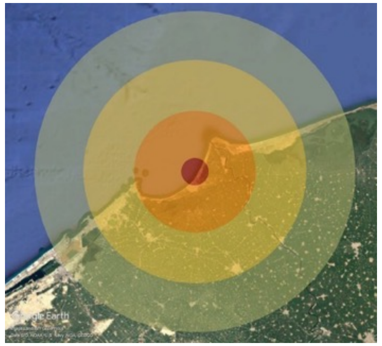
Epoch 4



HYPOTHETICAL EXERCISE

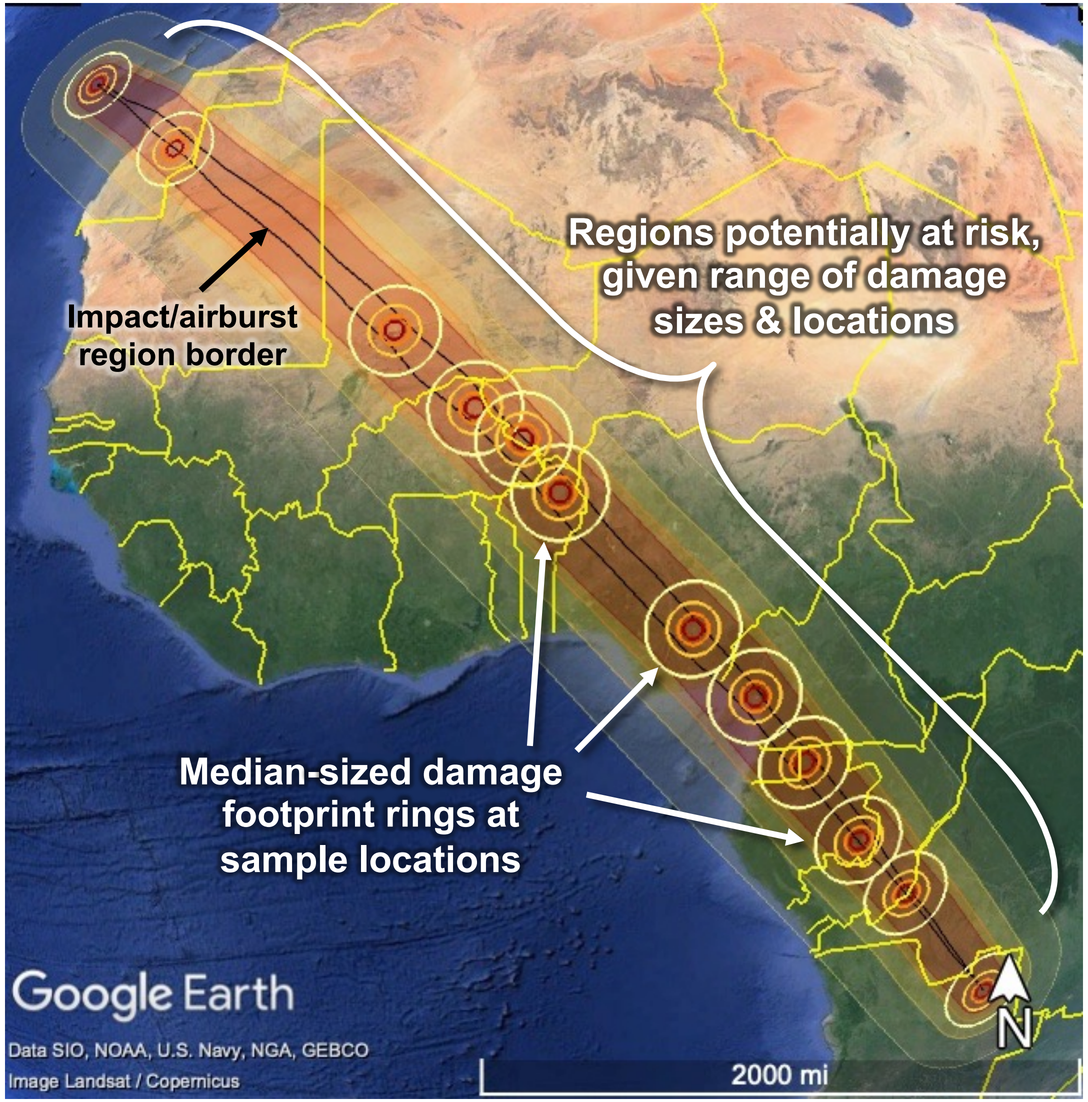
Local Blast & Thermal Ground Damage Key

- Large impacts or airbursts 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 and combines the largest of each level to represent the overall local ground damage areas for each case
  - "Local damage" regions represent the *larger* of *either* the equivalent blast *or* thermal damage area for each severity level, *not* necessarily the occurrence of both effects within the entire region
  - "Blast damage" and "Thermal damage" regions represent the extent of each hazard separately
  - Affected population estimates within each region are scaled by the relative severity of each damage level
- Blast vs thermal damage sizes:
  - Blast tends to be larger and more severe than the thermal damage in most cases, and usually defines 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	2^{nd} degree burns
Severe	30%	Widespread structural damage	3^{rd} degree burns
Critical	60%	Most residential structures collapse	Clothing ignites
Unsurvivable	100%	Complete devastation	Structures ignite, incineration

Risk Region Swath Map Key



Example from 2023 PDC Epoch 2 Swath

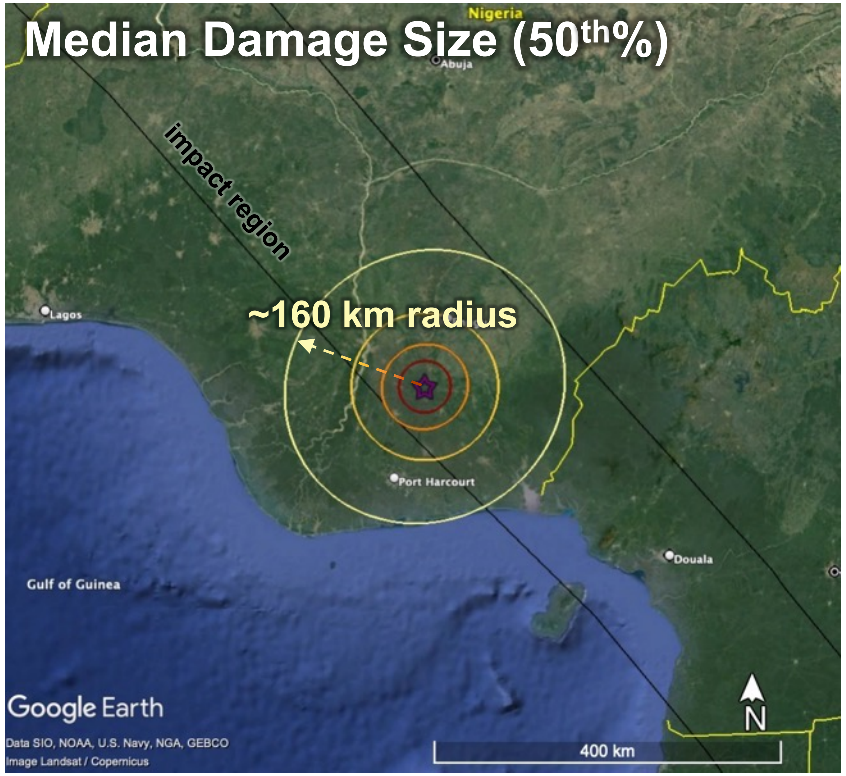
Risk Swaths show range of regions ***potentially*** at risk to local ground damage, including range of possible damage sizes and locations

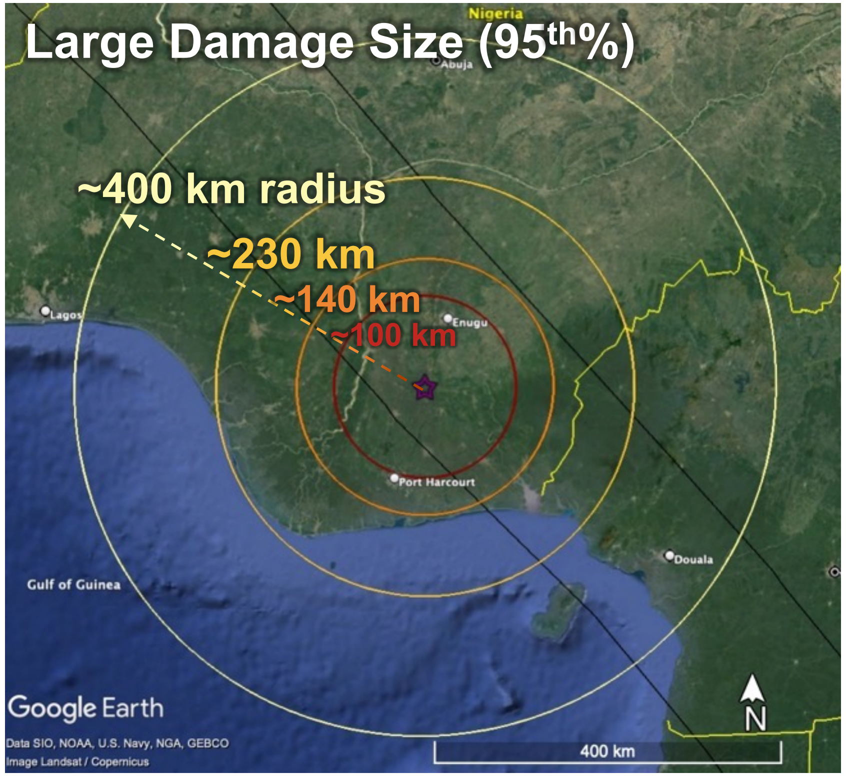
- Black outline shows boundary of potential impact locations (damage center points) depending on orbit and entry trajectory
- Shaded areas show potential at-risk regions given range of damage sizes around the possible locations
- Rings show sample damage footprint sizes at various sample locations within the swath

Damage Level	Description
Serious	Windows shatter, minor structure damage, or 2nd degree burns
Severe	Widespread structure damage, or 3rd degree burns
Critical	Residential structures collapse, or clothing ignites
Unsurvivable	Devastation, structures flattened or burned

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

Damage Footprints and Damage Sizes





Local Ground Damage Radius Sizes (km / mi)

Damage Level	Mean	25th %	50th %	75th %	95th %
Serious	190 km (120 mi)	120 km (75 mi)	**160** km (100 mi)	220 km (140 mi)	**400** km (250 mi)
Severe	110 km (70 mi)	70 km (45 mi)	**90** km (55 mi)	120 km (75 mi)	**230** km (150 mi)
Critical	65 km (40 mi)	40 km (25 mi)	**50** km (30 mi)	75 km (45 mi)	**140** km (90 mi)
Unsurvivable	40 km (25 mi)	20 km (15 mi)	**30** km (20 mi)	50 km (30 mi)	**100** km (60 mi)

Damage footprints show damage sizes around sample impact locations along the swath

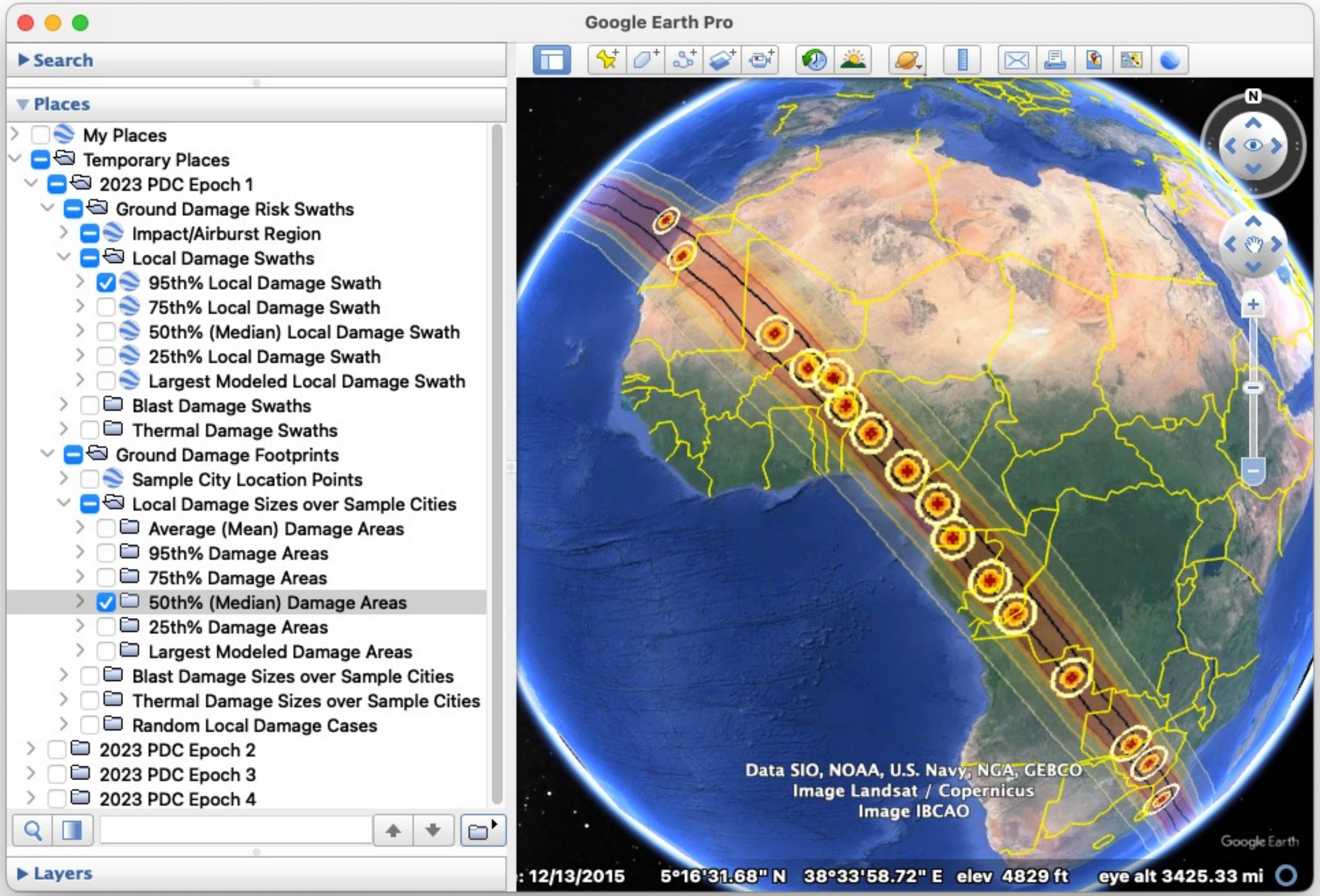
- Damage size percentiles give the chance that the damage could be up to the given size or smaller (i.e., % of modeled cases that are smaller)
- For example, the 95th% footprint size means there is a 95% chance that the damage could be smaller and a 5% chance that it could be larger than the region shown
- Percentile sizes are computed for each damage severity level across all cases modeled (do not represent a specific single impact case)

HYPOTHETICAL EXERCISE

Viewing & Navigating Google Earth Damage Risk Maps

- The .KMZ files include several folders with different damage swath and damage footprint sizes
- The file tree in the 'places' folder navigation panel on the left allows you to **select or hide which swaths or footprint sets to show**
- Parent folders can be selected at the top level to show all their elements, or can be expanded to select particular items
- You can **rotate, pan, or zoom the map** to see different regions, either by dragging and clicking or using the navigation buttons in the map pane.

Snapshot of Google Earth KMZ Contents and Maps for 2023 PDC Epoch 1



HYPOTHETICAL EXERCISE

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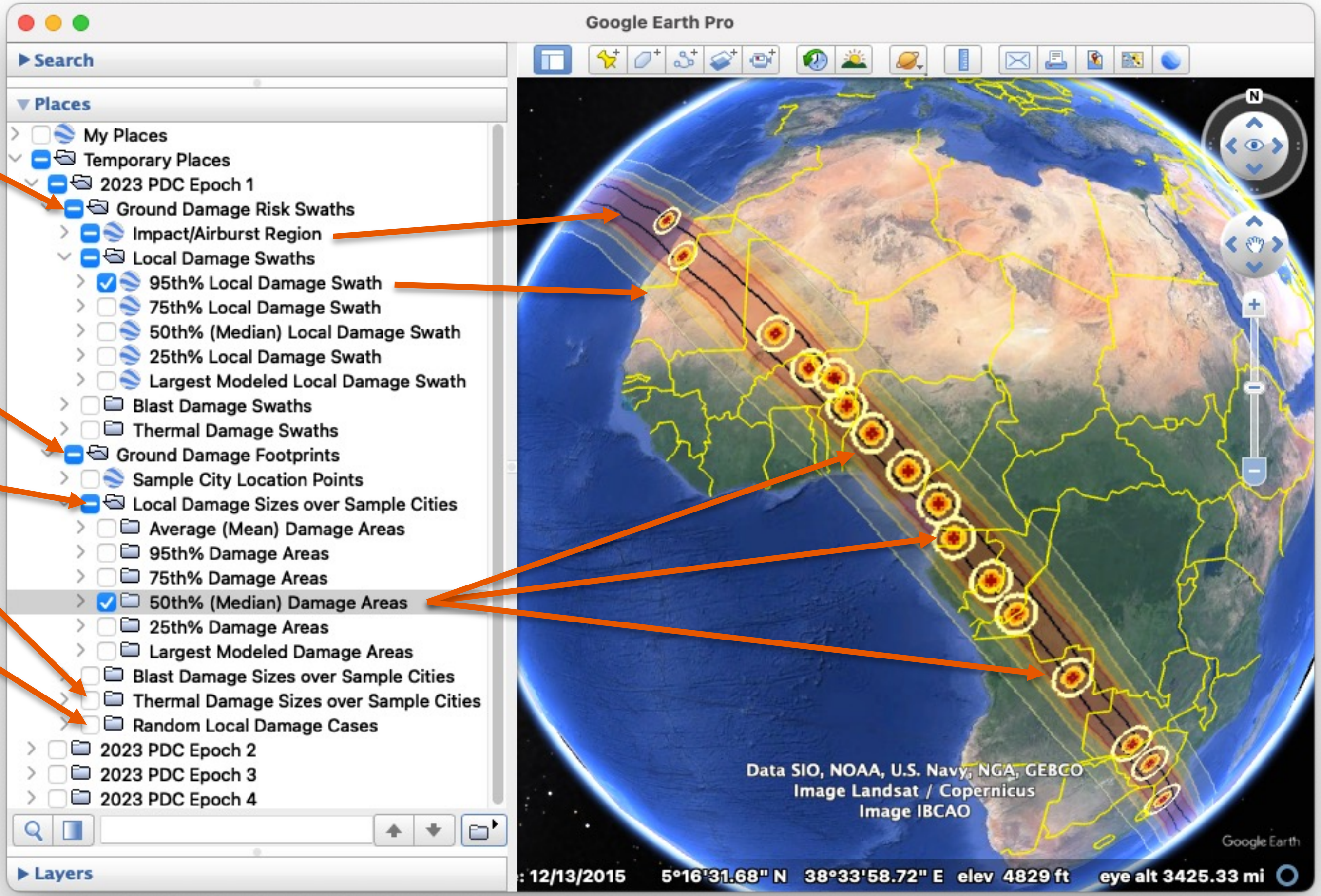
2023 PDC Damage Risk Map File Contents

NASA

- **Damage swath and footprint sets** are included for different hazard types and sizes:
  - **Local ground damage hazard types**: overall ***local*** *blast/thermal* damage, ***blast*** *damage*, and ***thermal*** *damage*
  - **Statistical damage sizes:** e.g., 50th%, 75th%, 95th%, average, largest modeled
- ***Damage Risk Region Swaths*** folder:
  - Contains damage risk swaths for each ground hazard type and sample damage sizes
- ***Ground Damage Footprints*** folder:
  - Contains sets of sample damage footprints for each ground hazard type and damage size
  - ***Footprint sizes over sample cities*** show statistical damage size ranges over various selected cities or regions along the swath
  - ***Random local damage footprint cases*** show randomly selected examples of specific asteroid impact cases modeled to demonstrate the variety of potential outcomes



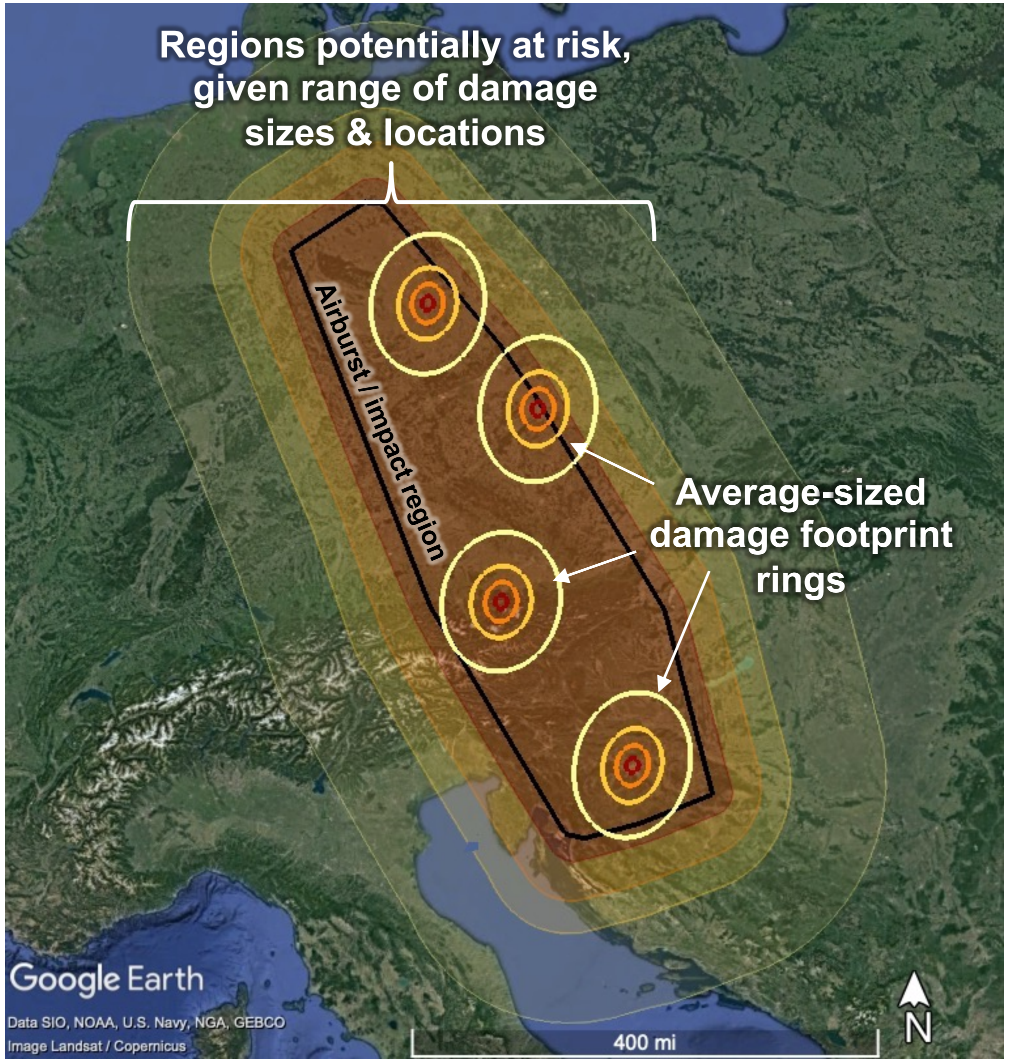
HYPOTHETICAL EXERCISE

RISK REGION SWATH EXAMPLE

Example swath build-up demonstrating how the damage risk swaths are constructed from the individual modeled impact cases with ranges of different damage sizes and locations (using example images from prior 2021 PDC hypothetical scenario)

HYPOTHETICAL EXERCISE

Risk Region Swath Maps



Example from 2021 Planetary Defense Conference Exercise

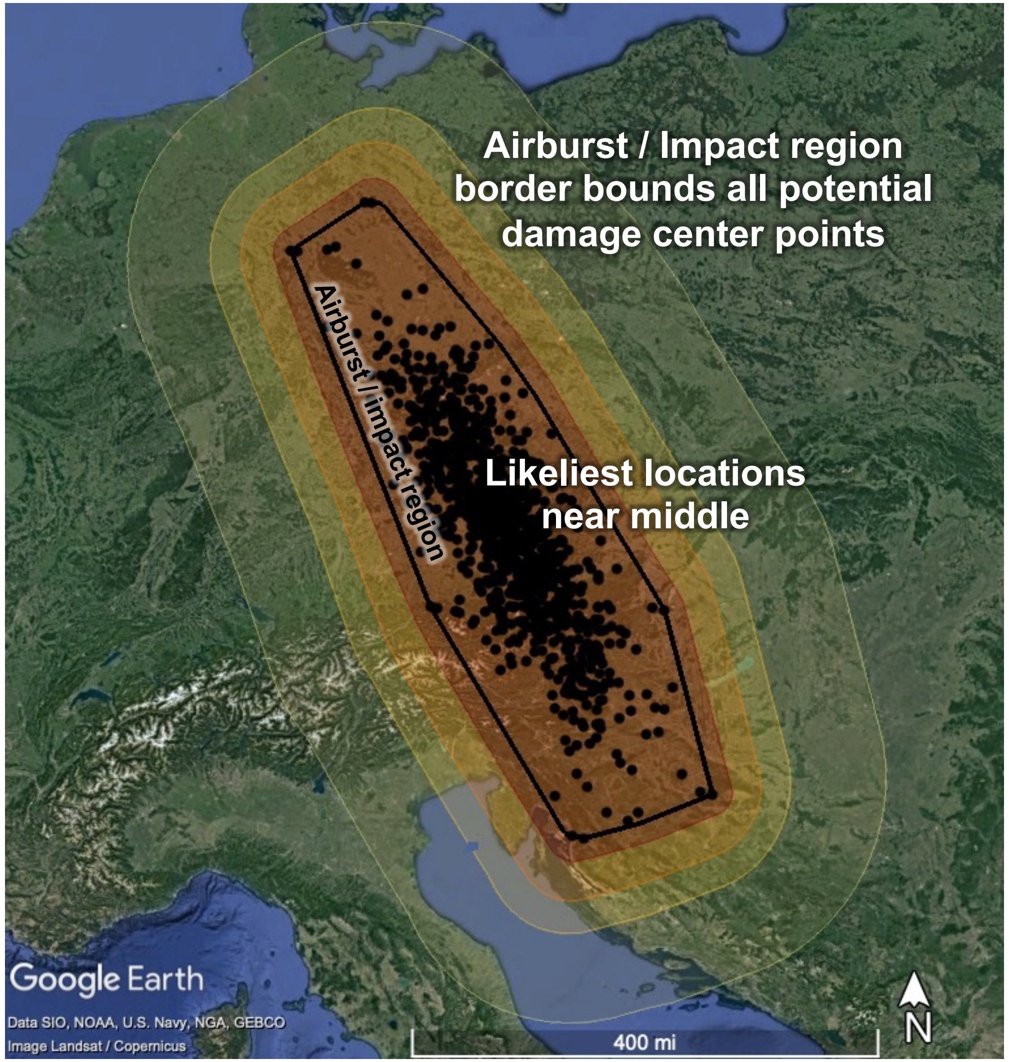
Risk swaths show range of regions ***potentially*** at risk to local ground damage, including range of possible damage sizes* and locations

- Black outline shows boundary of potential impact locations (damage-center points) depending on orbit and entry trajectory
- 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 risk to tsunami or global effects.

Risk Region Swath Maps

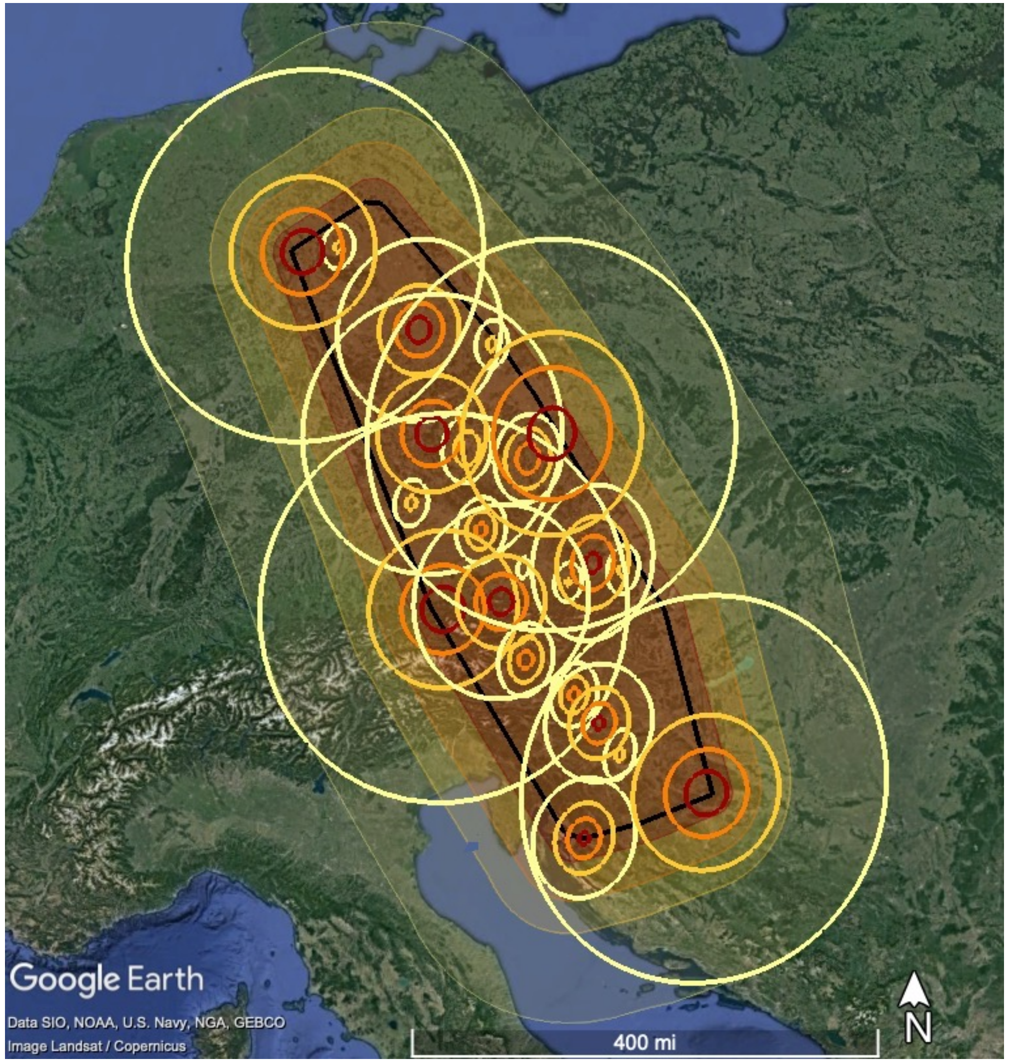


Example from 2021 Planetary Defense Conference Exercise

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

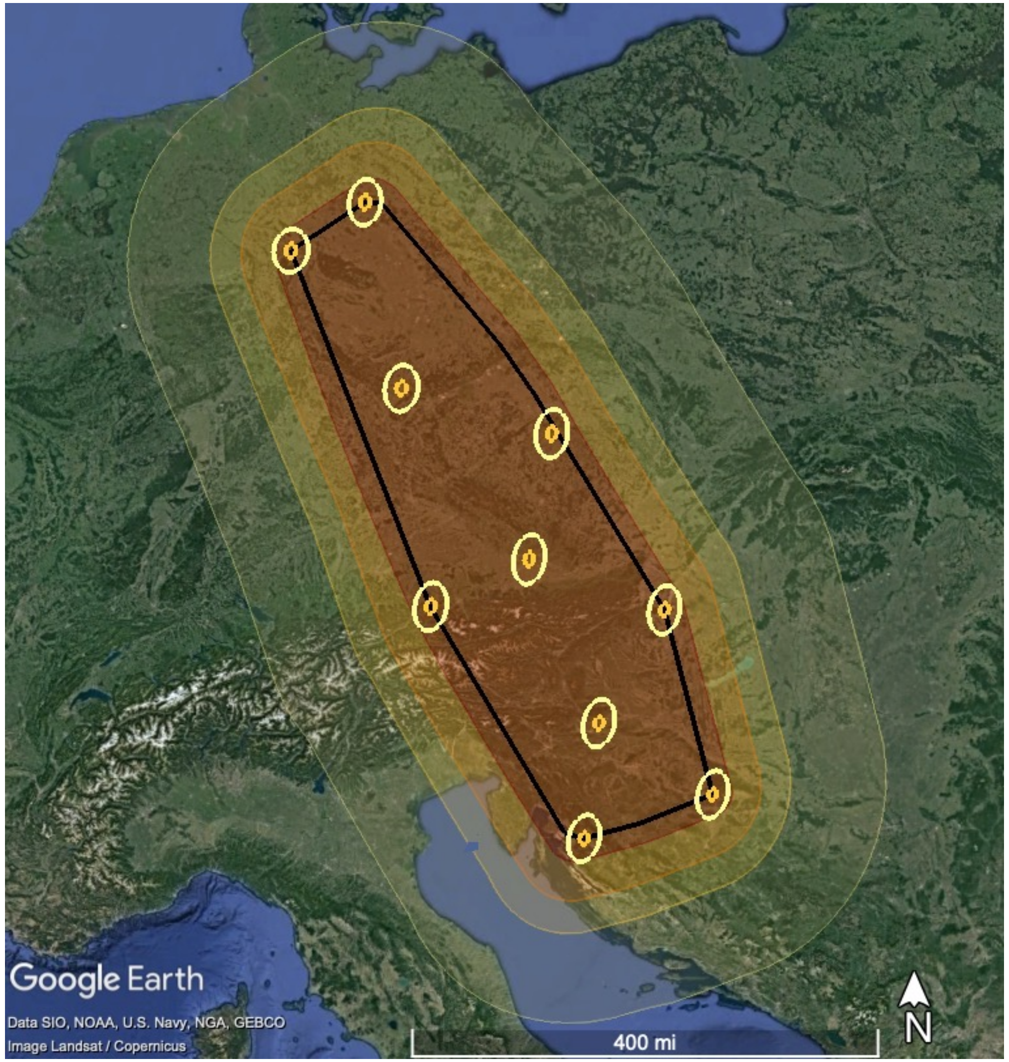


Example from 2021 Planetary Defense Conference Exercise

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

Risk Region Swath Maps



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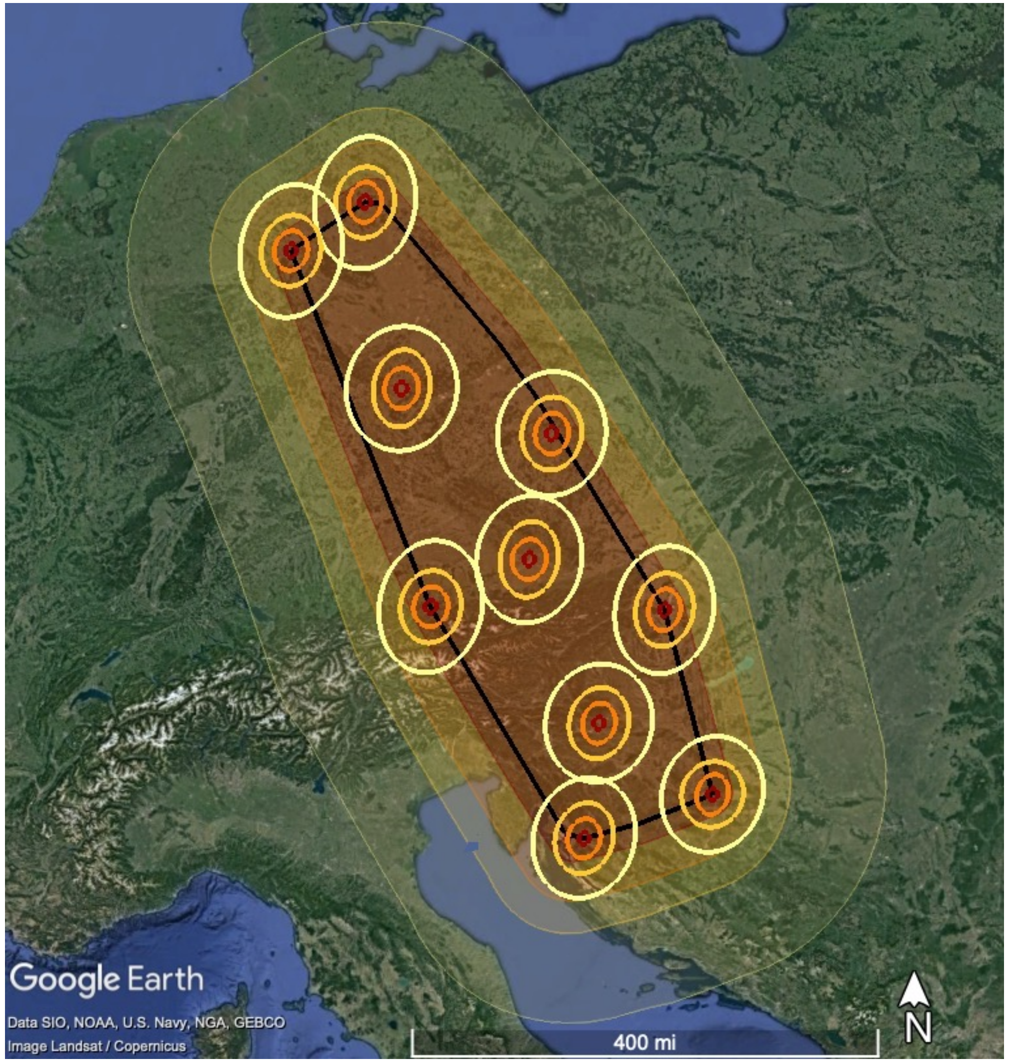
  - Smaller regions with only lower severity levels

Risk Region Swath Maps



Example from 2021 Planetary Defense Conference Exercise

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

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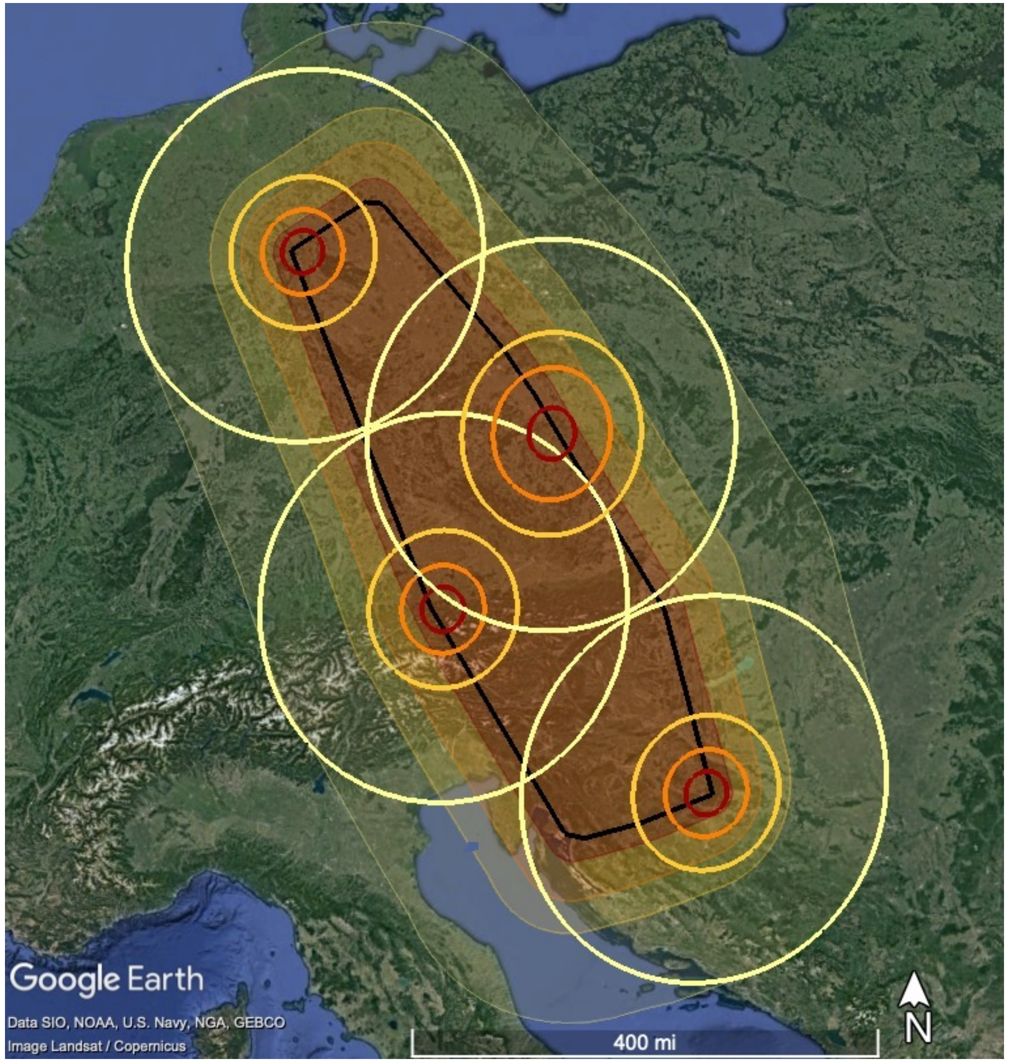
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)

Risk Region Swath Maps

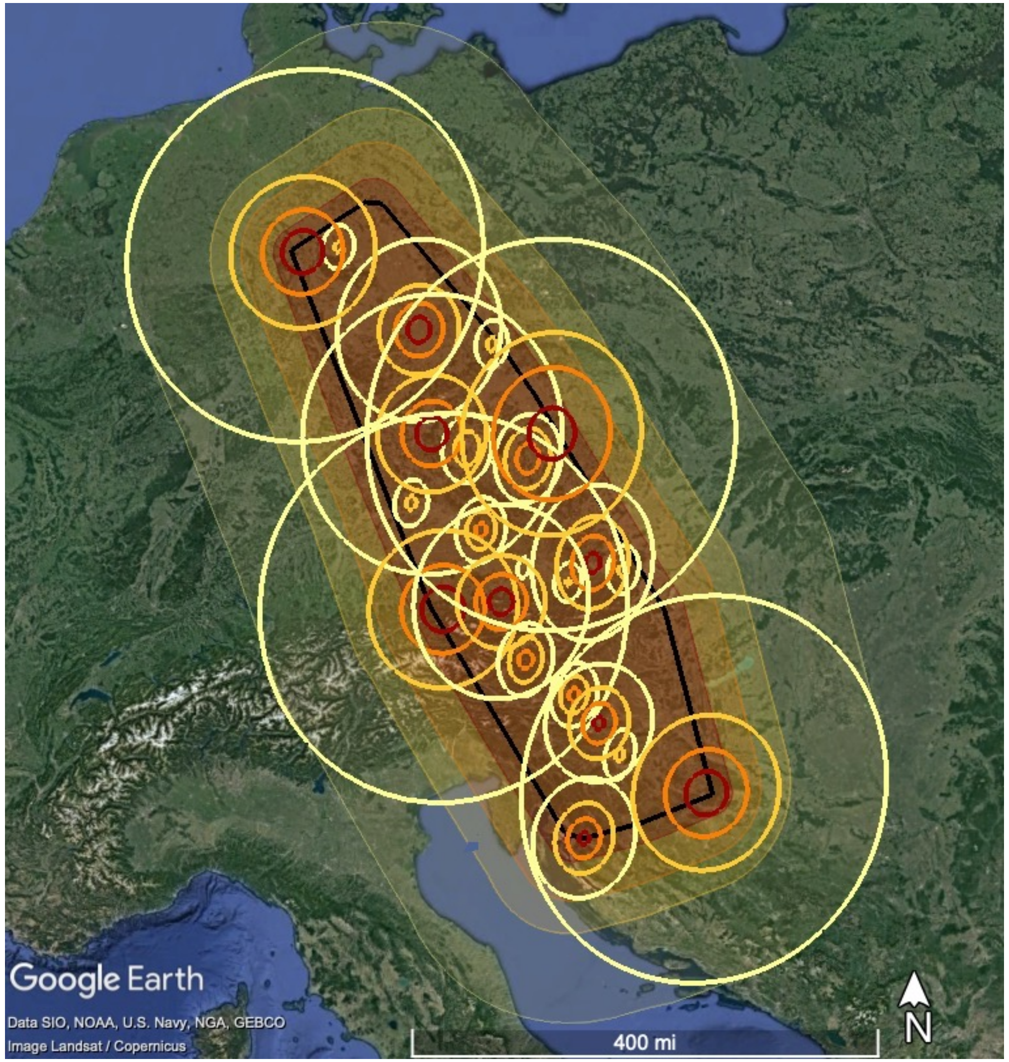


Example from 2021 Planetary Defense Conference Exercise

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



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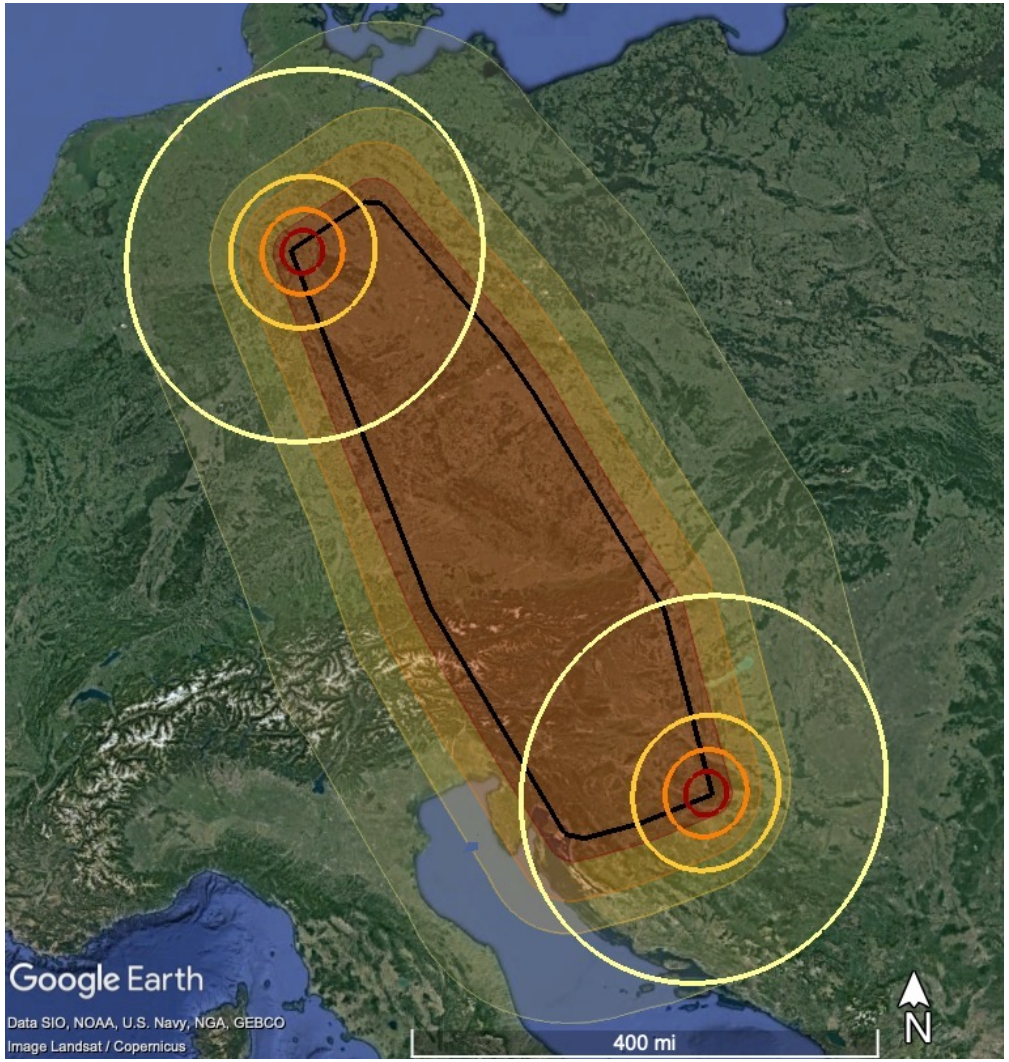
  - Smaller regions with only lower severity levels
  - Mid-range, average areas (from the likelier asteroid sizes/properties)
  - Very large but unlikely areas (from the largest, least-likely possible impact sizes)
  - And everything in between….

HYPOTHETICAL EXERCISE

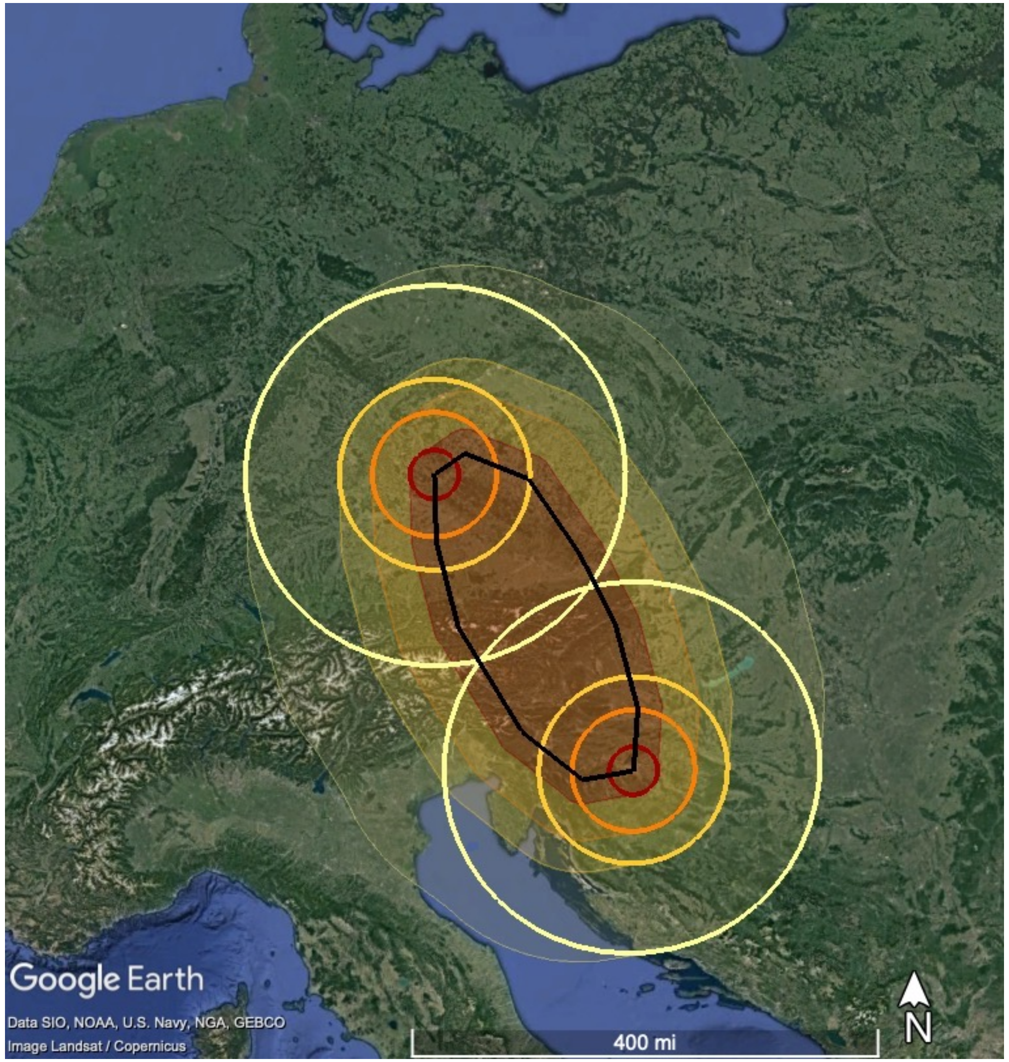
Risk Region Refinement Over Time



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

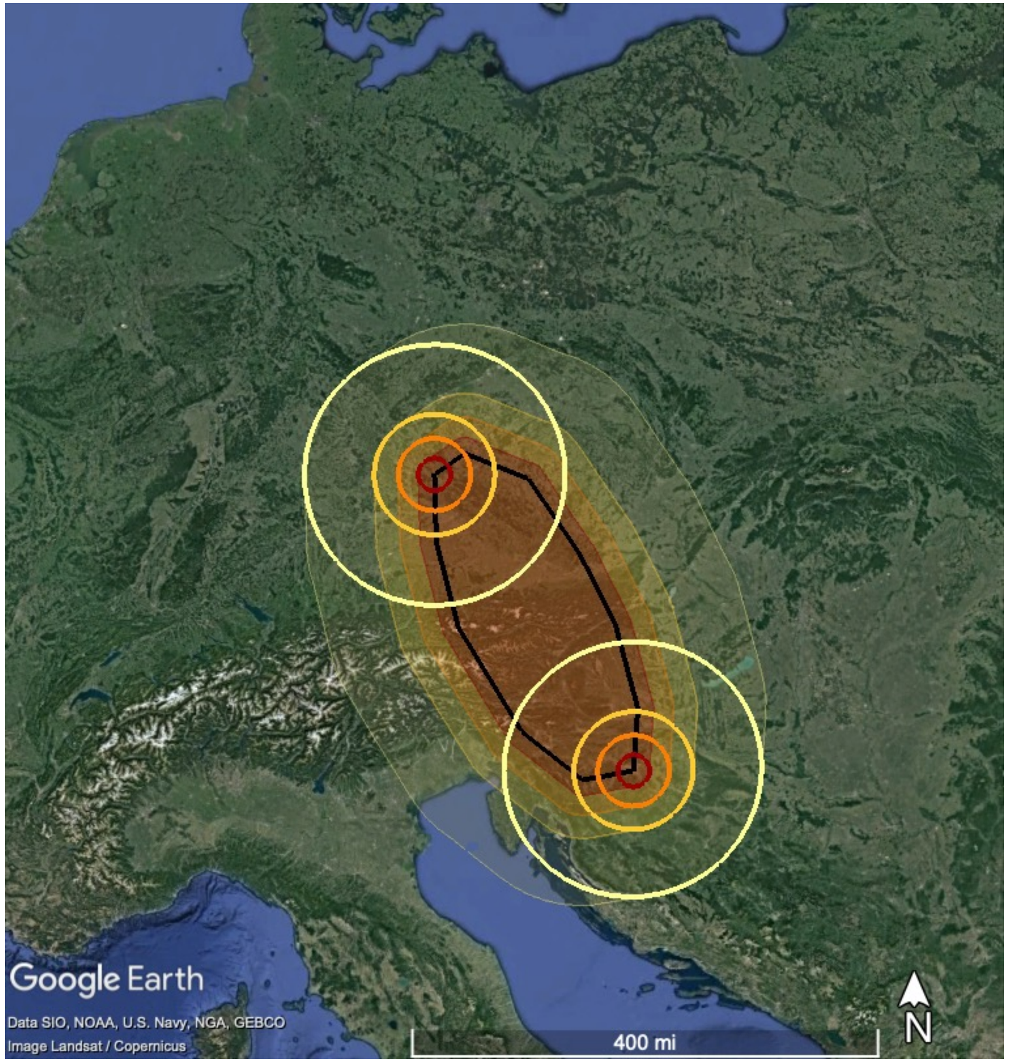


Example from 2021 Planetary Defense Conference Exercise

- 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 size range may remain large for longer due to asteroid size/property uncertainties through much of the approach

HYPOTHETICAL EXERCISE

Risk Region Refinement Over Time



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  - Largest damage estimates may also shrink if observations can refine asteroid size range

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  - Impact region will continue to shrink

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  - 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

HYPOTHETICAL EXERCISE

Risk Region Refinement Over Time

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  - 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

HYPOTHETICAL EXERCISE

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REFERENCES

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
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- **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

Related PDC 2023 Presentations

PDC 2023 presentation materials, webcast recordings, and impact exercise details available at:

- https://www.unoosa.org/oosa/en/ourwork/topics/neos/2023/IAAPDC/index.html
- https://atpi.eventsair.com/QuickEventWebsitePortal/23a01---8th-planetary-defense-conference/programme-website/Agenda
- https://cneos.jpl.nasa.gov/pd/cs/pdc23/

PDC 2023 Hypothetical Asteroid Impact Exercise Session (3 April 2023)

- **Wheeler** et al., "Impact Risk Assessment Briefing: 2023 PDC Hypothetical Asteroid Impact Exercise Epoch 1"
- **Chodas** et al., "The 2023 PDC Hypothetical Impact Scenario: Epoch 1 Summary"
- **Barbee** et al., "PDC 2023 Simulated Impact Threat Scenario SMPAG Mission Option Analysis"

Impact Effects (Session 7, 6 April 2023)

- **Wheeler** et al., "Asteroid Impact Risk Across Transitional Hazard Regimes"
- **Dotson** et al., "Consequences of Asteroid Characterization on the State of Knowledge about Inferred Physical Properties and Impact Risk"
- **Coates** et al., "Sensitivity Study of Impact Risk Model Results to Thermal Radiation Damage Model for Large Objects"
- **Chomette** et al., "Machine learning for the prediction of local asteroid damages"
- **Stern** et al., "Advances in Entry Modeling for Impact Risk Assessment"
- **Aftosmis** et al., "High-fidelity Blast Propagation Modeling for Hypothetical Asteroid 2023 PDC"
- **Titus** et al., "Asteroid Impacts and Cascading Hazards"

Disaster Management & Impact Response (Session 8, 6 April 2023)

- **Robertson** et al., "Evacuation and Shelter Plans for Asteroid Impacts"

Space Mission & Campaign Design Session (Session 6, 5 April 2023)

- **Barbee** et al., "Planetary Defense Mission Campaign Design for the 2023 PDC Hypothetical Asteroid Impact Scenario"