Probabilistic Blast Damage Modeling Uncertainties and Sensitivities

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Abstract

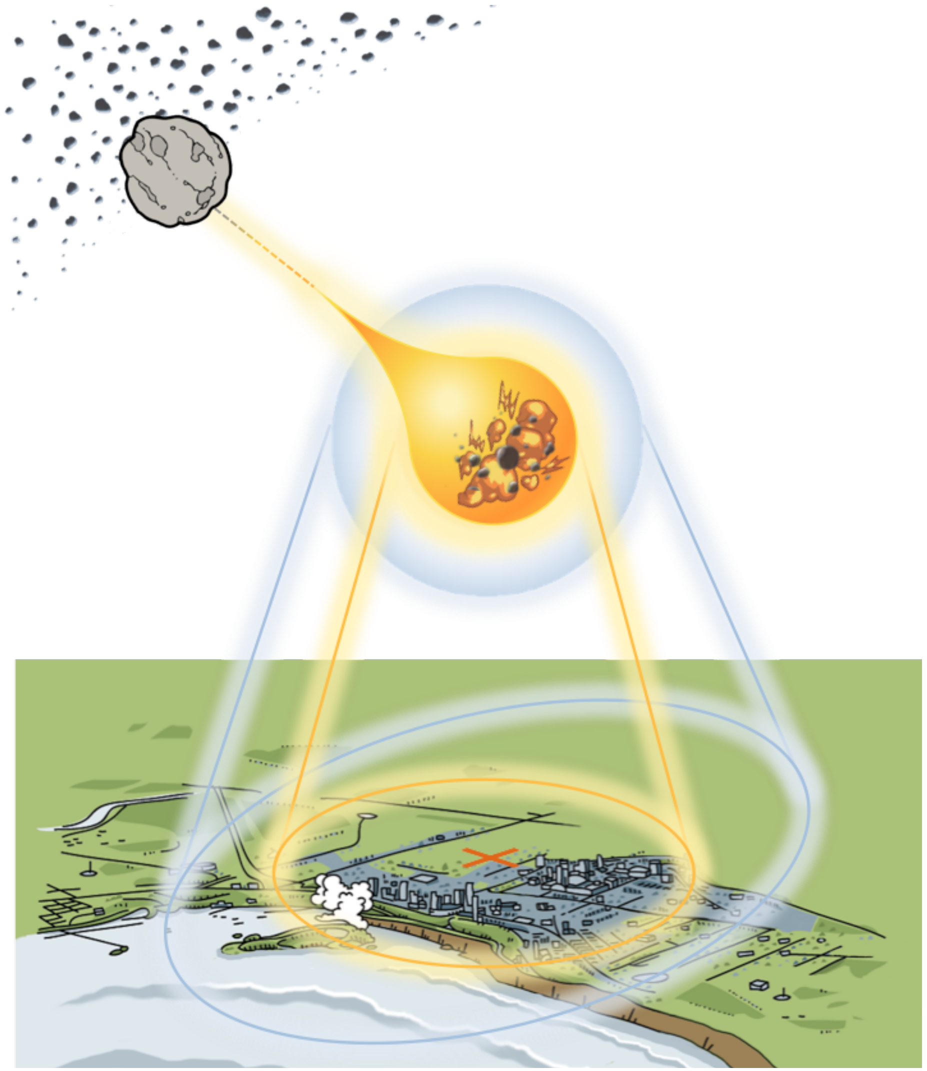
Blast overpressure is the predominant source of ground damage posed by potentially hazardous asteroid strikes. Estimates of the extent, severity, and likelihoods of potential blast damage regions will be one of the key metrics needed to mount civil defense or disaster response plans in the face of an impending impact. However, there are many inherent sources of uncertainty in evaluating the damage, both in characterizing the properties of the incoming object and in the approaches used to model the entry/impact and resulting damage, which make it difficult to produce a single 'accurate' or 'best guess' prediction of ground damage. The current 2021 PDC hypothetical impact scenario poses a particular challenge due to its short warning time. The need for rapid disaster response to prepare for an immanent impact, combined with lack of observational opportunities to refine basic knowledge about the object's basic size and properties, make understanding the range and relative likelihood of consequences particularly critical.

The potential damage caused by these blasts can be evaluated using a range of modeling and simulation approaches and levels of fidelity. Fast-running engineering-level models can be used to run large numbers of probabilistically sampled cases covering wide variations of uncertain properties or parameters. High-fidelity simulations, on the other hand, can capture more detailed/accurate blast physics, but can only be performed for a small selection of specific cases, requiring many assumptions to be made about the initial object and its unpredictable entry/breakup characteristics. In order to provide a more complete picture of the potential threat for effective disaster response, both types of analysis need to be employed together. In this approach, high-fidelity simulations are used to refine and anchor engineering models, and the probabilistic engineering models are used to evaluate broad parameters spaces and guide selection of the most pertinent simulation cases for a given scenario.

This presentation expands upon the probabilistic asteroid impact risk assessments being performed as part of the 2021 PDC hypothetical impact exercise, focusing on key aspects of blast damage modeling uncertainties and sensitivities. We review the current modeling and simulation approaches employed in the current assessment, compare the relative levels of uncertainty stemming from each main element of the problem (i.e., knowledge of the asteroid properties, modeling of the atmospheric entry/breakup and airburst, and estimates of the ground damage from the resulting blasts waves), and highlight any notable trends and sensitivities for the current scenario case.

HYPOTHETICAL EXERCISE

Overview



- Performed Probabilistic Asteroid Impact Risk (PAIR) modeling for the 2021 PDC hypothetical impact exercise
  - Primary risk assessment results and impact scenario details are presented in the impact exercise sessions for the Day 1 and Day 3 injects
  - https://cneos.jpl.nasa.gov/pd/cs/pdc21/
- This presentation highlights key blast damage factors and trends for the 2021 PDC scenario risk assessment
  - Shows the range of airburst and blast damage results for the scenario's potential impactor sizes and properties
  - Investigates blast damage probabilities and trends as a function of impactor energy
  - Highlights key factors influencing total blast damage areas, severities, and risks

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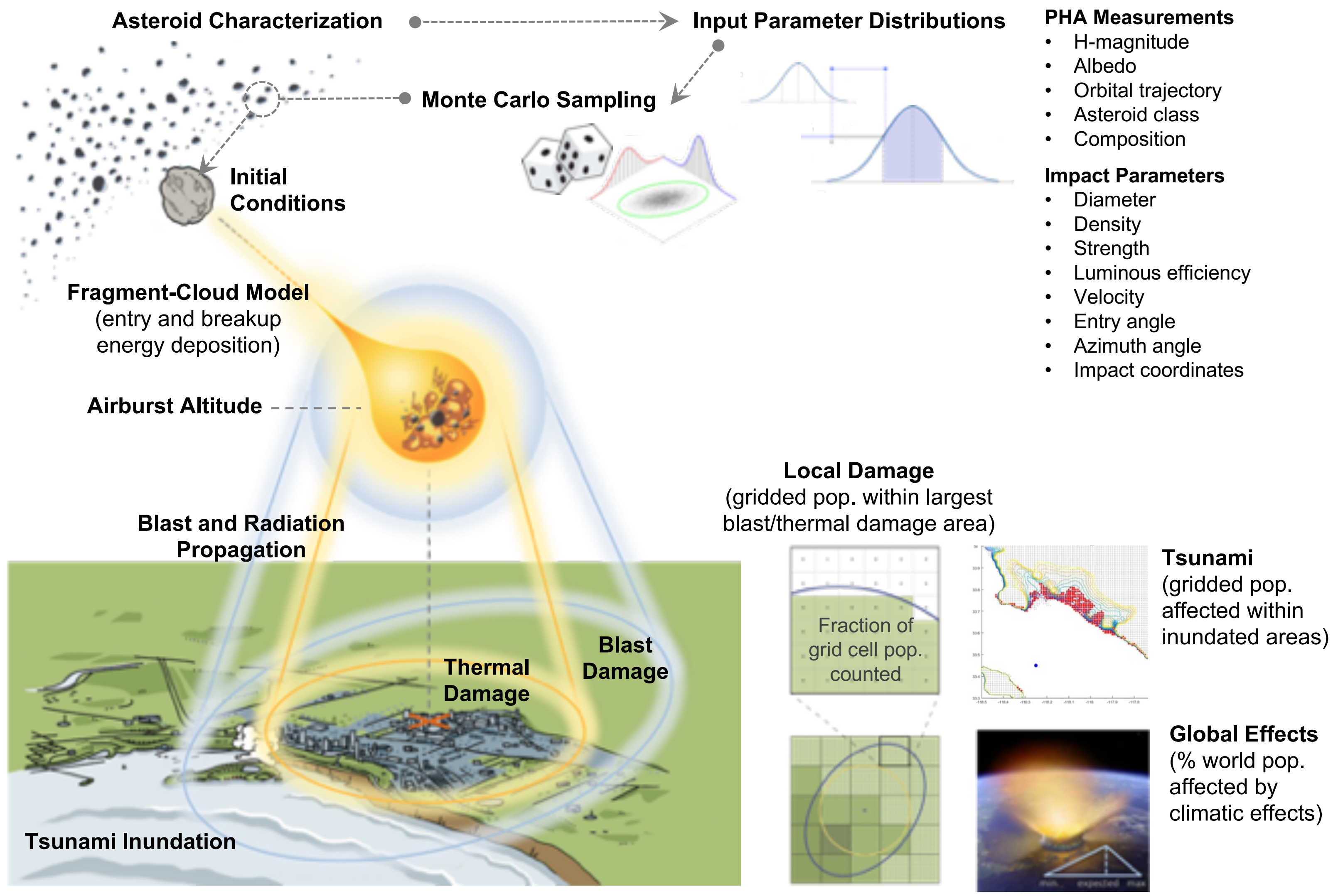
Probabilistic Asteroid Impact Risk (PAIR) Model

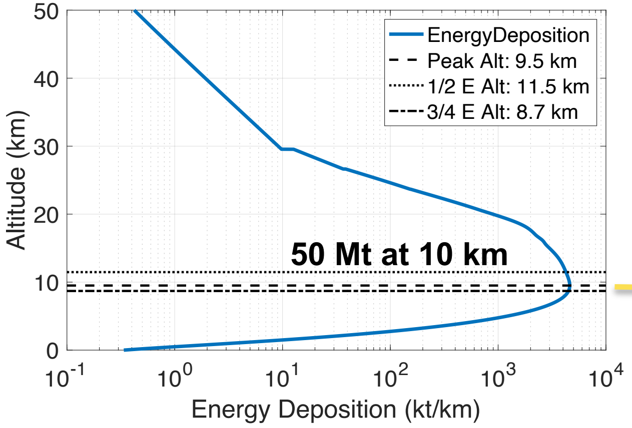


- PAIR uses fast-running engineering models of asteroid entry and damage to assess impact risk for millions of sampled asteroid impact cases with uncertain properties (Mathias et al., 2017)
- Asteroid properties are sampled using inference model based on current knowledge of general asteroid populations and any specific observational data for a given impact scenario (J. Dotson, PDC 2021)
- Entry parameters and locations are determined from orbital propagation models (P. Chodas, CNEOS/JPL)
- Modeling parameters are sampled over uncertainty ranges to represent model uncertainties or variability of entry/damage outcomes

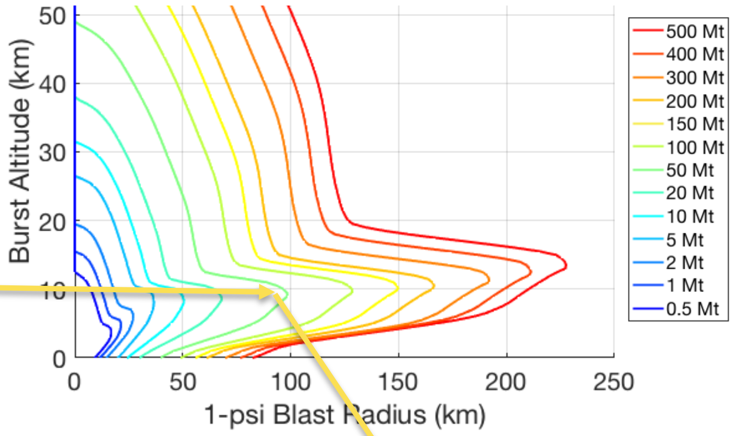
PAIR Blast Damage Modeling Overview

PAIR evaluates blast damage at four severity levels, and each level affects different fractions of the population within that region

Atmospheric Energy Deposition

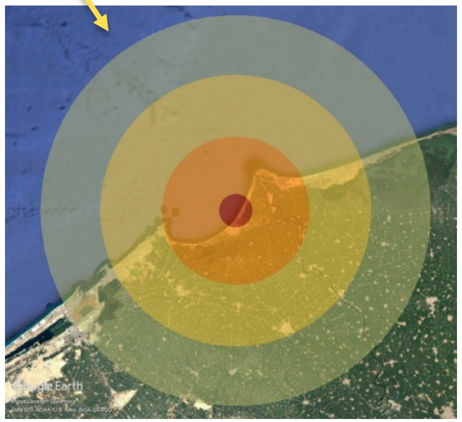


Height-of-Burst (HOB) Map



PAIR Blast Damage Severity Levels (Stokes et al., 2017)

Damage Level	Overpressure Threshold	Population Fraction	Damage Severity
Serious	1 psi	10%	Window breakage, some structure damage
Severe	2 psi	30%	Widespread structural damage
Critical	4 psi	60%	Most residential structures collapse
Unsurvivable	10 psi	100%	Complete devastation



- Fragment-Cloud Model (FCM) is used to model atmospheric entry and breakup of each probabilistic impact case
- Entry/breakup depend on sampled size, density, strength, entry velocity and angle, and breakup modeling parameters
- Effective burst altitudes or ground impact are determined from FCM energy deposition peak or energy fraction (peak used here)
- Height-of-burst (HOB) maps are used to estimate blast footprint sizes based on impactor energy and effective burst altitude

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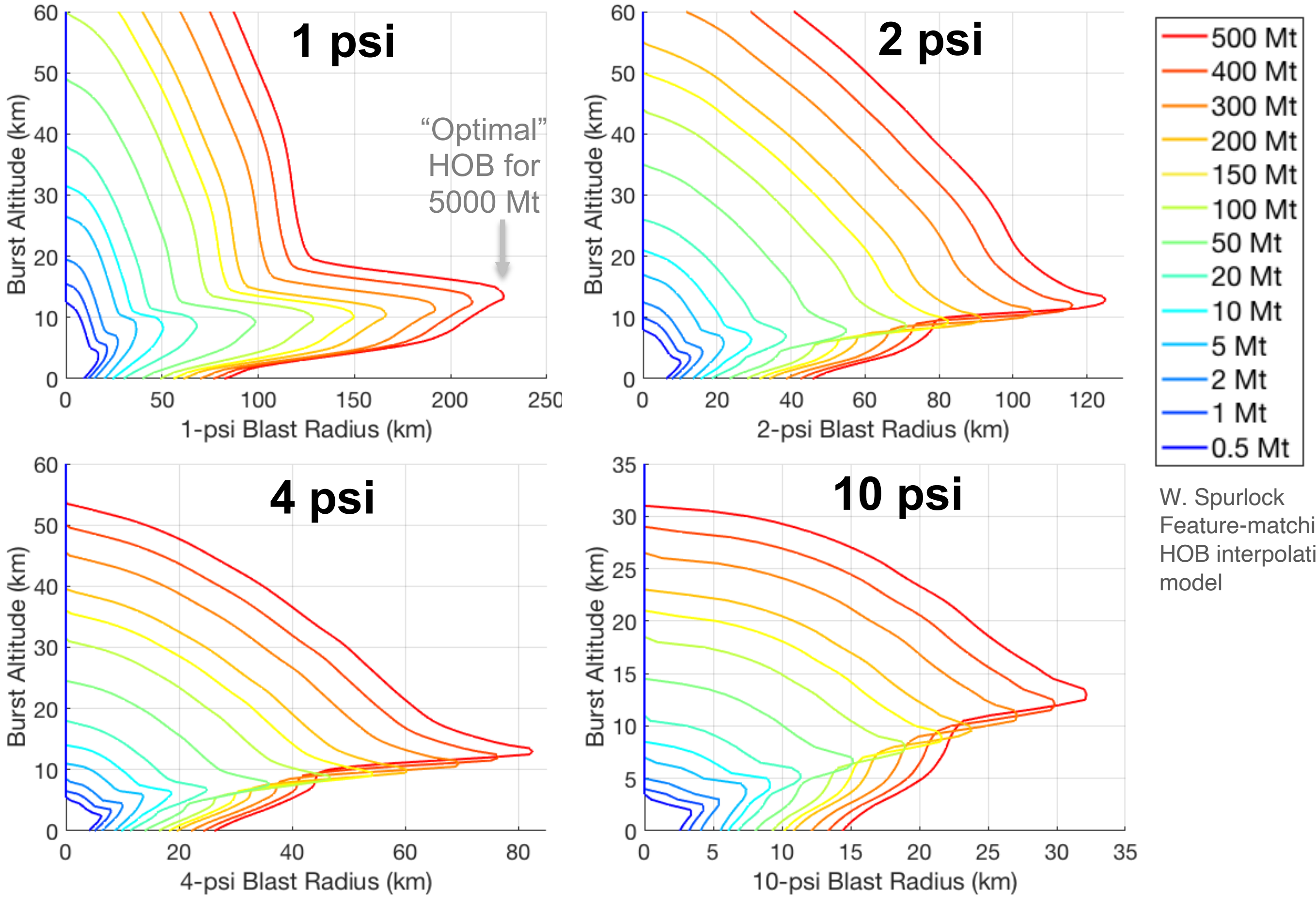
PAIR Simulation-Enhanced HOB Maps

HOB maps provide an efficient (simplified) approach for estimating blast damage radii as a function of energy (yield) and effective burst altitude.

PAIR HOB maps for four overpressure levels from various yields



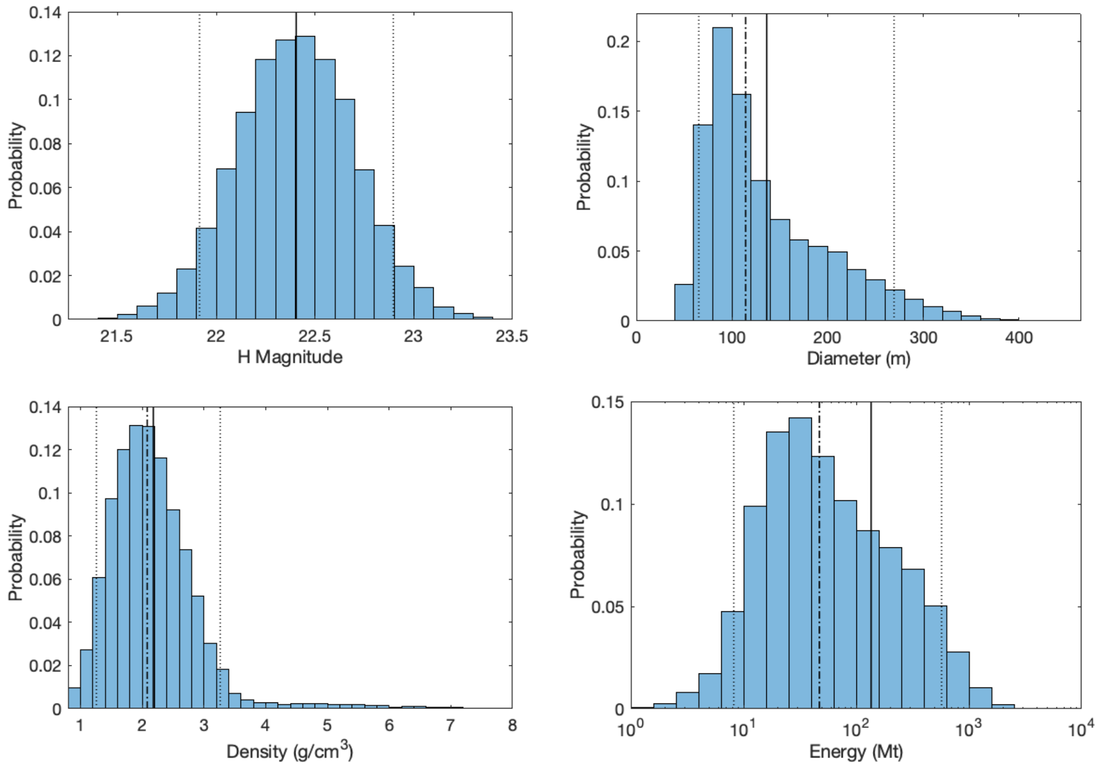
W. Spurlock Feature-matching HOB interpolation model

- Nuclear-based HOB maps are often used, but are based on small yields that cannot scale accurately to large asteroids
- PAIR uses simulation-enhanced HOB maps based on CFD simulations of 250 Mt asteroid blasts (Aftosmis et al., 2019)
- PAIR uses nuclear curves for E < 5 Mt, uses simulation curves for E > 250 Mt, and interpolates between them for intermediate energies
- For a given yield and overpressure level, there is an “optimal” burst altitude that produces the largest ground damage radius
- Simulation-based HOB curves have lower optimal burst altitudes for large energies than the scaled nuclear curves, which affects damage trends for large impactors
- Comparisons of PAIR HOB model and CFD simulations presented in M. Aftosmis, PDC 2021

HYPOTHETICAL EXERCISE

PDC 2021 Scenario Properties Modeled

Distributions of asteroid impact properties modeled



	Range	Mean
Diameter (m)	30 – 420	135
Density (kg/m^3)	800 – 9000	2200
Energy (Mt)	<1 – 1000	120
Strength (MPa)	0.1 – 10	2
Strength scaling	0.1 – 0.3	0.2
Ablation (kg/J)	3.5e-10 – 7e-8	1.3e-8

- PAIR probabilistic asteroid impact cases generated using Bayesian property inference model
  - See J. Dotson, PDC 2021 presentation on inference model
- Highly uncertain asteroid size and properties, based on 2021 PDC Scenario Day 3 Inject:
  - H 22.4±0.3 (1-σ), unknown albedo, minor upper-size constraint
  - Type and density unknown
- Fixed entry velocity of 15.2 km/s and entry angle of 52°
  - Fixed entry parameters to focus on blast trends due to asteroid property uncertainties
  - Represents scenario impact point near central Europe
- Entry modeling parameter uncertainties for aerodynamic strength, strength scaling, and ablation parameters
- Evaluated impactor cases with energies up to 1000 Mt

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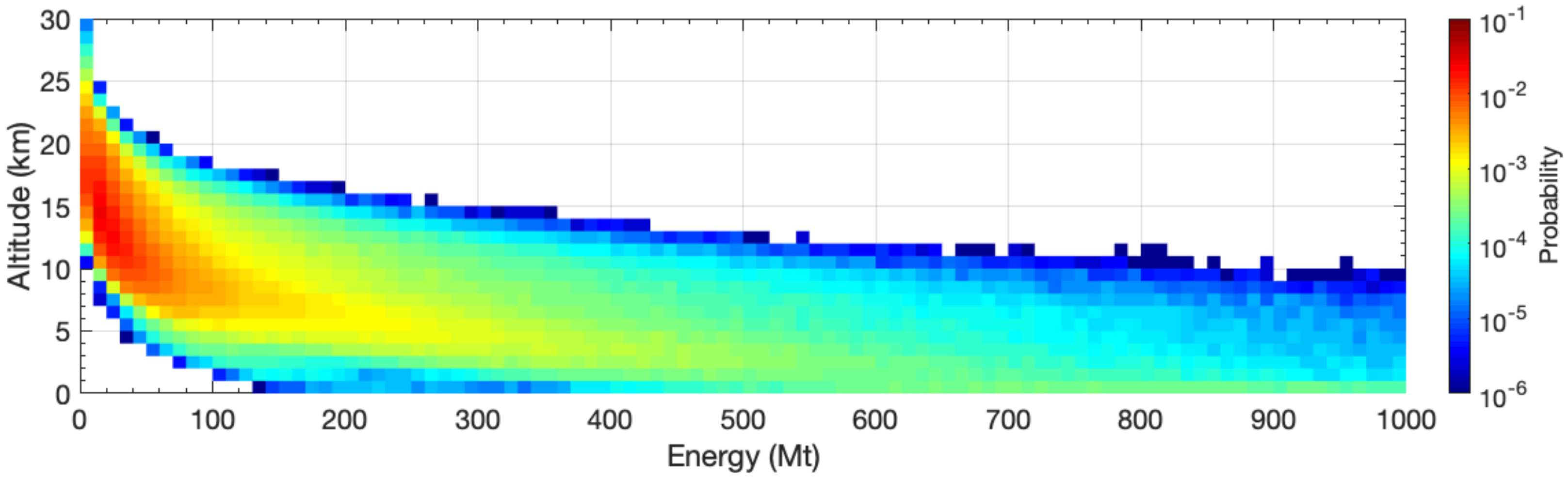
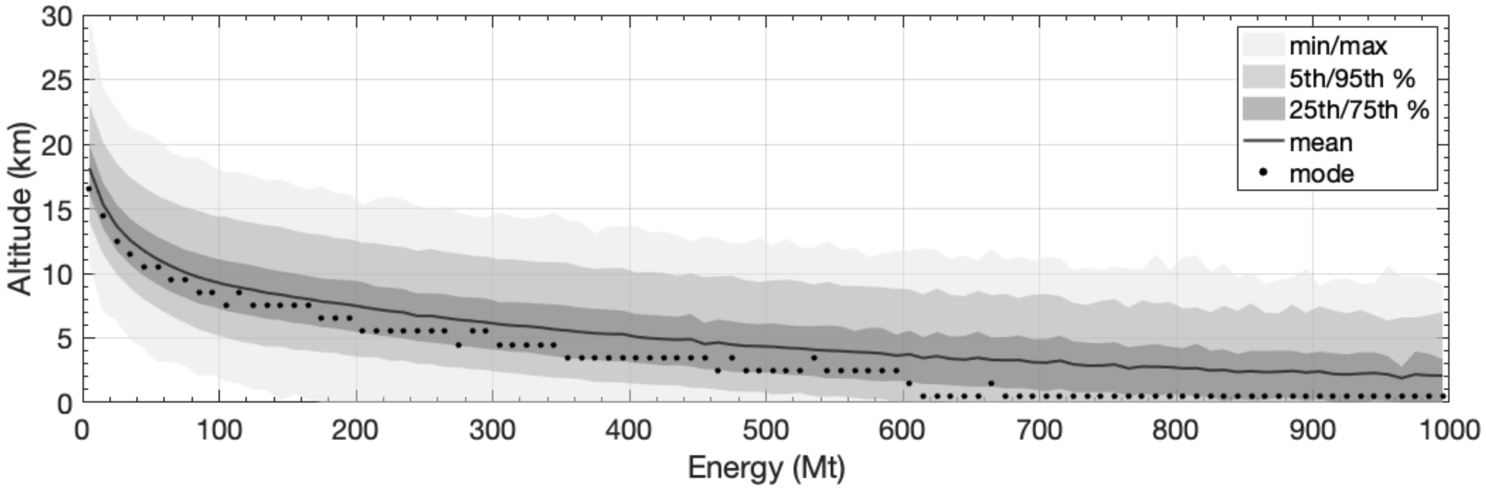
Burst Altitude Ranges and Probabilities

Relative burst energy/altitude probabilities across full impactor set



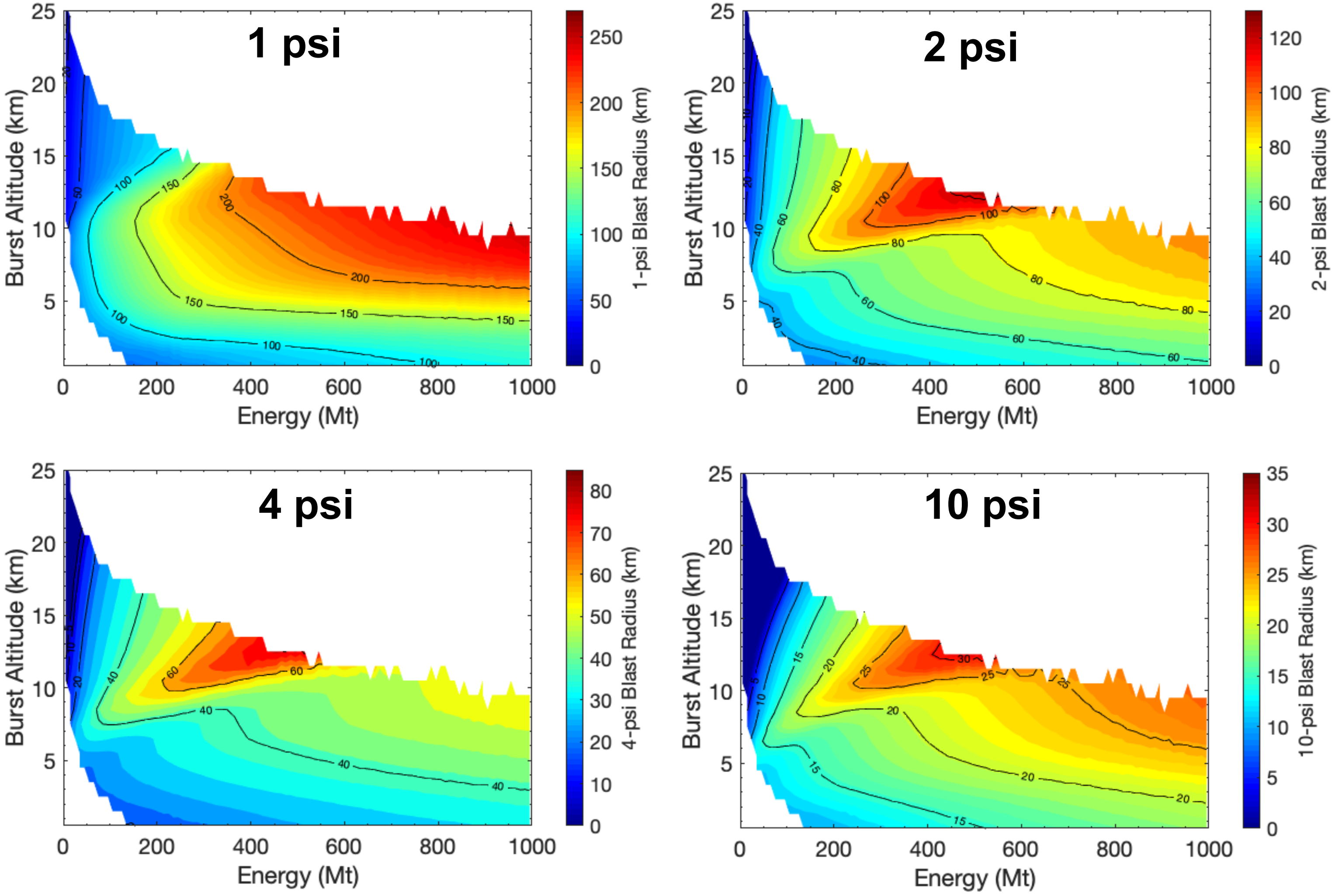
Burst altitude distributions by energy bin (10-Mt bins)



- Probabilistic impact risk approach captures broad potential range and relative likelihoods of potential impact scenarios
- For a given energy, burst altitudes depend on property variations (size, density, strength, ablation)
- Blast risk depends on likelihood and resulting damage severity of bursts at different energy/altitude combinations

Blast Radii vs Burst Altitude and Energy

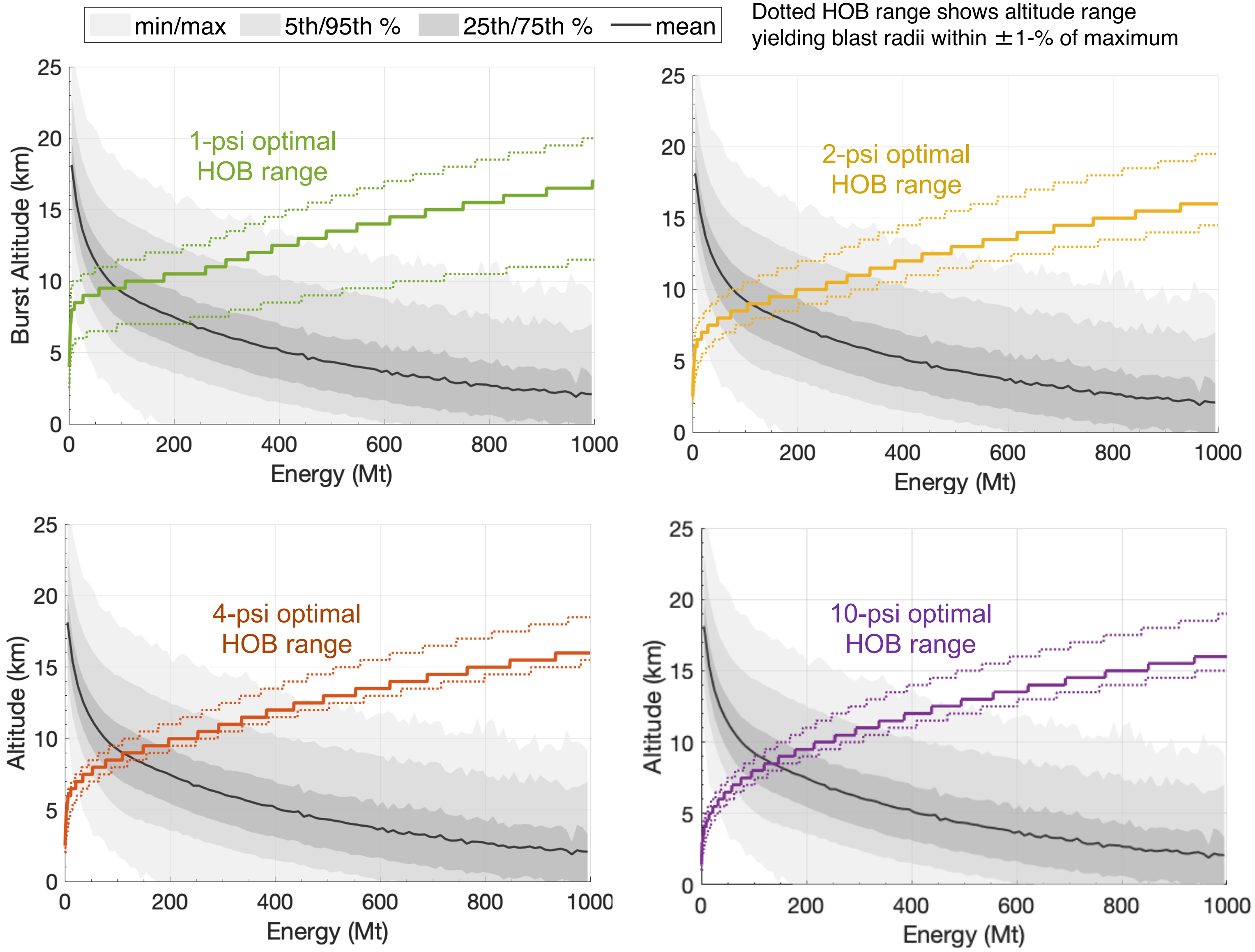
PAIR blast radii results as a function of impactor energy and effective burst altitude for the modeled impact scenario cases



- Higher-altitude breakup/energy deposition produces worst blast damage among the current scenario cases
- Damage trends differ among blast levels due to different forms of their HOB curves
- Largest 1-psi damage radii are produced by a broader range of larger energies at their highest possible burst altitudes
- Largest 2, 4, and 10 psi damage radii occur for energies ~500 Mt near their highest burst altitudes, and are smaller for larger energies

HYPOTHETICAL EXERCISE

Burst Altitudes vs Optimal HOB



- Blast damage is driven by two competing factors:
  - Increases in blast yield
  - Distance from optimal HOB
- Smaller/lower-energy objects tend to burst above their optimal HOB, making lower bursts worse
- Larger/higher-energy objects tend to over-penetrate below their optimal HOB, making higher bursts worse
- Airburst sensitivities and trends depend on crossover between the likely burst altitudes and the “optimal” HOB as larger objects penetrate lower in atmosphere

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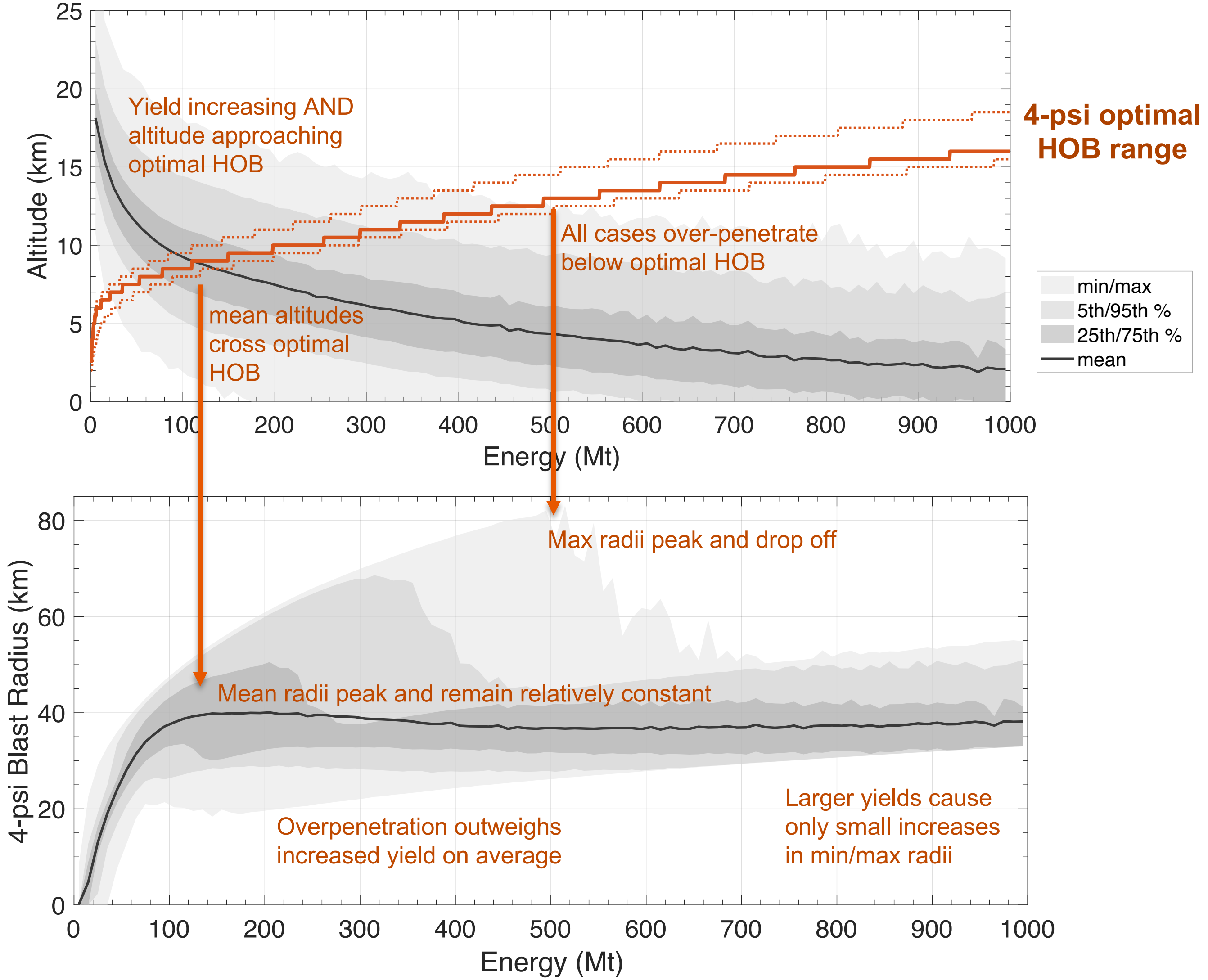
Effects of HOB on Blast Damage Trends (4-psi)

NASA

Comparison of burst altitudes and 4-psi blast radius ranges as a function of impactor energy

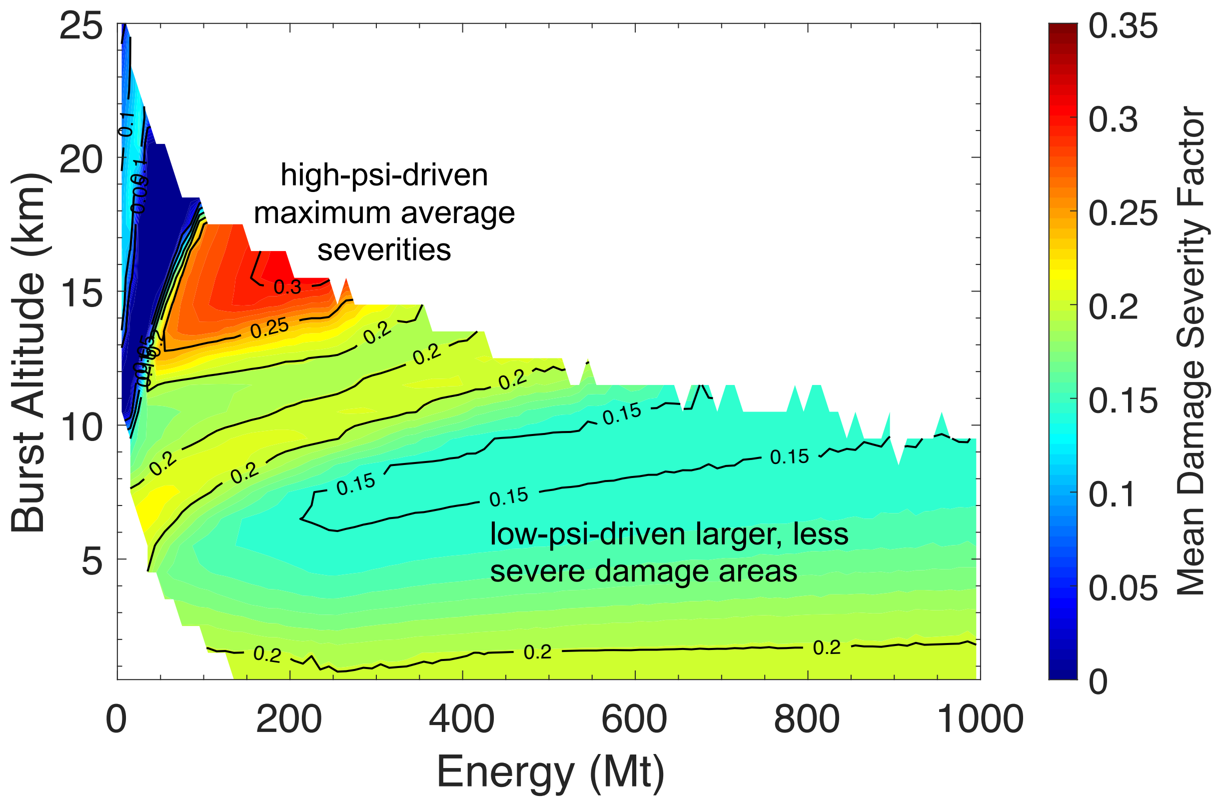


- Damage radii increase rapidly over smaller size ranges where both yield is increasing and decreasing burst altitude is approaching optimal HOB
- Mean radii peak where mean burst altitude crosses optimal HOB (~120 Mt for this scenario)
- Max radii peak and drop off significantly beyond energies at which all cases over-penetrate below optimal HOB (~500 Mt for this scenario)
- Blast radii become much less sensitive to further increases in impactor energy once most cases over-penetrate or impact ground

Combined Total Blast Damage & Severities

Total blast damage depends on the combined relative sizes and severities of all blast overpressure levels within the damage regions. Here we compare the average severity levels and total effective ground damage.

Average damage severity as a function of burst energy and altitude



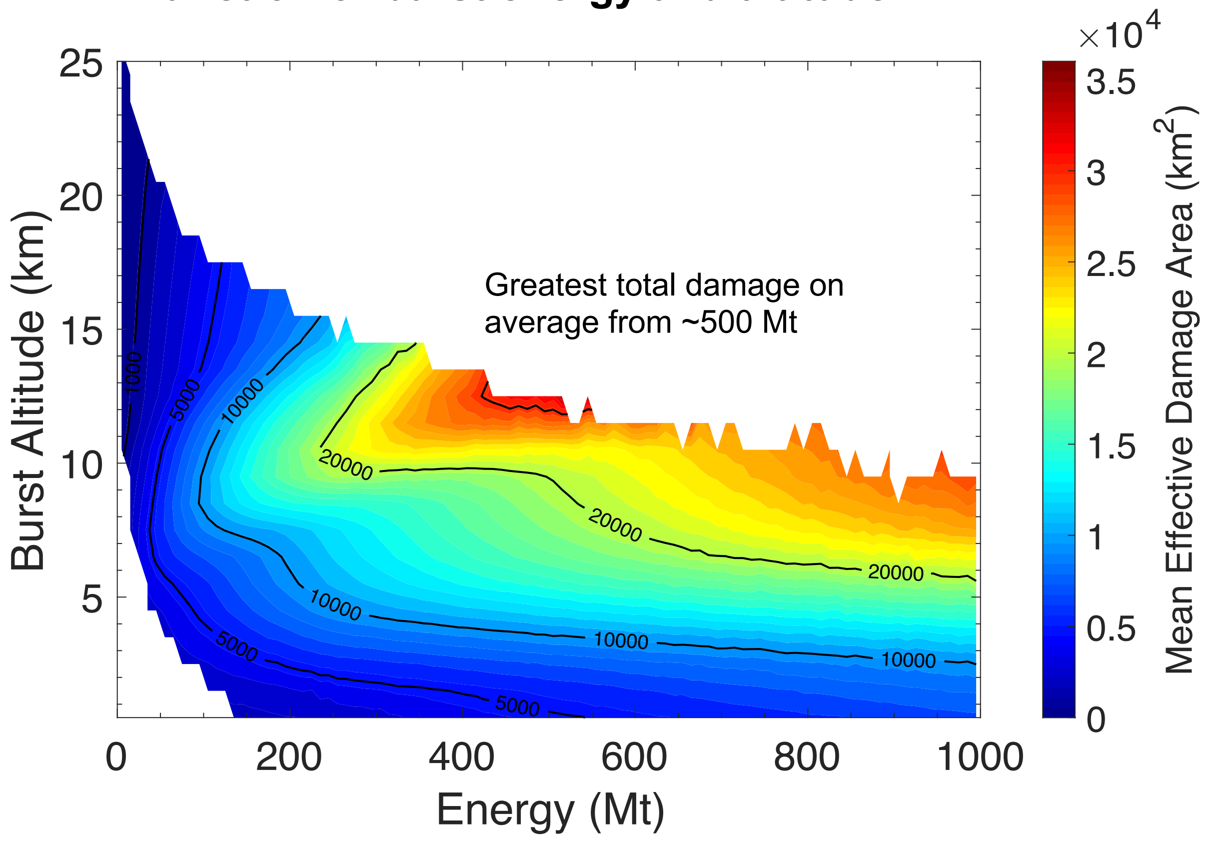
- Damage severity levels:
  - 10% damage in 1-psi area, 30% damage in 2-psi area, 60% damage in 4-psi area, 100% damage in 10-psi area
- Average damage severity factor:
  - Represents the area-weighted average severity of the four modeled overpressure levels within the total area
  - Does not reflect total footprint size, just average severity
- Damage severity trends
  - On average, highest damage severities are caused by ~200-Mt bursts at their highest altitude range ~15 km
  - For larger/lower blasts, lower-psi damage areas grow more than higher-psi areas, leading to lower average severities

HYPOTHETICAL EXERCISE

Combined Total Blast Damage & Severities

Total blast damage depends on the combined relative sizes and severities of all blast overpressure levels within the damage regions. Here we compare the average severity levels and total effective ground damage.

Average effective damage areas as a function of burst energy and altitude

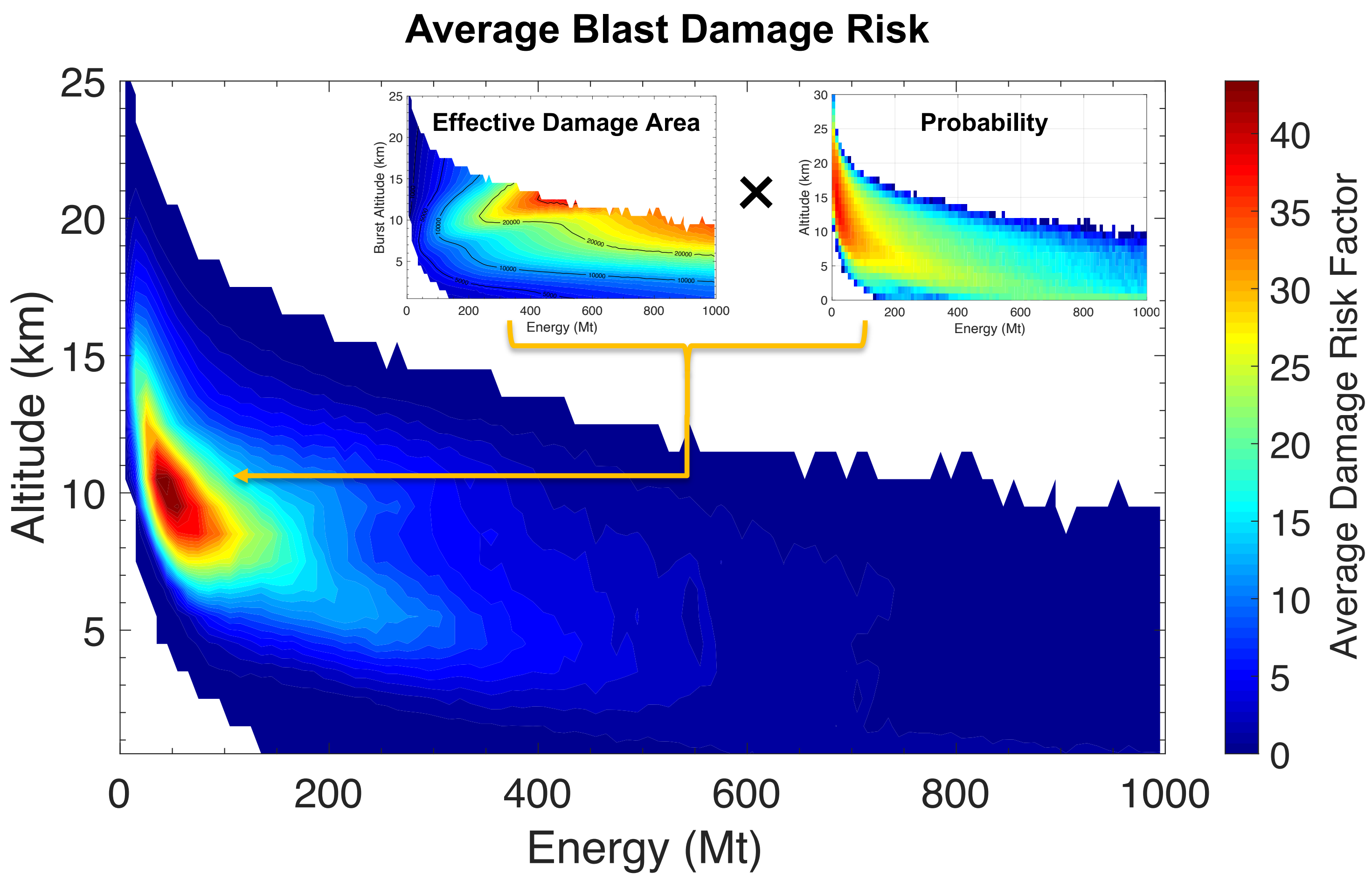


- Damage severity levels:
  - 10% damage in 1-psi area, 30% damage in 2-psi area, 60% damage in 4-psi area, 100% damage in 10-psi area
- Effective damage area:
  - Represents each case's aggregate total amount of ground damage from all fractional damage levels
  - Equivalent 100% damage area (sum of each damage level area scaled by its relative damage fraction)
  - Given a uniform population density, then this would be the area that would contain the total affected population
- Effective damage area trends:
  - On average, mid-range energies can cause greater total damage than larger ground impacts if they breakup high
  - Greatest average effective damage ~500 Mt at ~12 km
  - However, these maximal burst altitudes are also unlikely for large asteroids in that energy range

HYPOTHETICAL EXERCISE

Combined Total Blast Damage & Severities

Blast damage ***risk*** posed by various bursts/impacts depends both on the amount of damage and the probability. Here we compare the average risks from blasts of each energy and altitude, accounting for their relative probability.



- Average blast damage risk:
  - Average effective damage area multiplied by the relative probability
  - Plot shows average risk (average damage x probability) for each energy/altitude bin
- Effective damage area trends:
  - When relative probabilities are included, greatest blast damage risk is posed by objects in the median ~50 Mt energy range bursting near average altitudes ~10 km
  - These objects produce less damage, but are much more likely to occur than rare high bursts of rare large impactors
  - Damage risk driven more by likelihood than highest potential damage severities

Summary

- Blast damage trends in the current HOB modeling approach depend on the interplay between breakup altitude ranges and optimal burst heights for different energies and overpressure levels
  - Small lower-energy impactors tend to burst above their low optimal HOB, while higher-energy impactors tend to penetrate below their higher optimal HOB, reducing their damage potential
  - Sensitive regions occur where likely burst altitudes cross optimal HOB ranges for a given energy
- For large impactor sizes, the weakest, highest-breakup cases cause greater damage than larger, lower bursts or ground impacts
- High-energy/high-altitude regimes causing worst blast damage also tend to be at the lower-probability edges of the potential size and breakup ranges for this scenario
- Blast damage radii can become much less sensitive to further increases in impactor energy once most cases over-penetrate below optimal HOB or impact ground—maximum or mean damage levels can decrease or remain relatively constant across large impactor energies
- Low 1-psi damage areas grow more than higher-psi damage areas as energies increase, resulting in greater average severity within smaller damage regions and lower relative severity within larger regions
- Overall average blast risk levels are driven more by likeliness than by maximum damage potential

HYPOTHETICAL EXERCISE

References

Probabilistic Asteroid Impact Risk (PAIR) Model

- Mathias, D.L., Wheeler, L.F., Dotson J.L., 2017. A probabilistic asteroid impact risk model: assessment of sub-300m impacts. Icarus 289, 106–119. https://doi.org/10.1016/j.icarus.2017.02.009
- Wheeler, L.F., Mathias, D.L., 2018. Probabilistic assessment of Tunguska-scale asteroid impacts. Icarus, 327, 83–9. https://doi.org/10.1016/j.icarus.2018.12.017
- Stokes, G., 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

Fragment-Cloud Model (FCM)

- Wheeler, L.F., Mathias, D.L., Stokan, E., Brown, P.G., 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, L.F., 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

CFD Blast Simulations and HOB Model

- Aftosmis, M.J., Mathias, D.L., Tarano, A.M., 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
- Aftosmis, M.J., et al., 2016. Numerical simulation of bolide entry with ground footprint prediction. 54th AIAA Aerospace Sciences Meeting SciTech Forum, (AIAA 2016-0998). https://doi.org/10.2514/6.2016-0998

Related ATAP PDC 2021 Talks:

- “High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2021 PDC,” M. Aftosmis et al.
- “Bayesian Inference of Asteroid Physical Properties: Application to Impact Scenarios,” J. Dotson et al.
- “Interaction of Meteoroid Fragments During Atmospheric Entry” D. Mathias et al.
- “Comparison of Thermal Radiation Damage Models and Parameters for Impact Risk Assessment,” A. Coates et al.
- “Airburst Consequence Modeling Using Artificial Ablation” M. Boslough
- “Risk-Informed Spacecraft Mission Design for the 2021 PDC Hypothetical Asteroid Impact Scenario” B. Barbee et al.
- “IAWN Planetary Defense Exercise: Apophis Observing Campaign 2020-2021” M. Kelley et al.
- “Tsunami with dispersion and mesh adaptation,” M.J. Berger and R.J. LeVeque
- “Asteroid Impacts – Downwind and Downstream Effects” T. Titus et al.

HYPOTHETICAL EXERCISE

BACKUP

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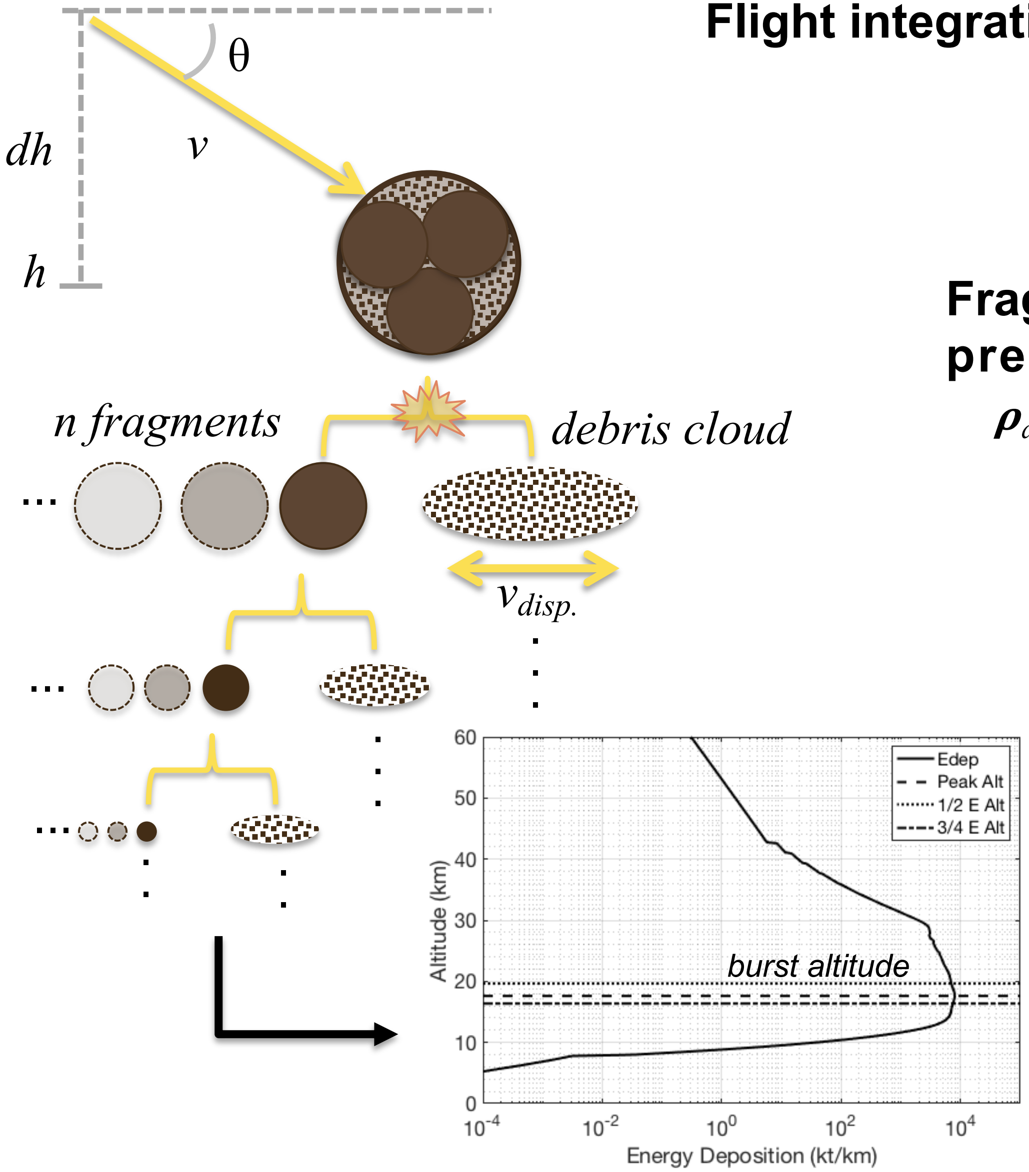
Fragment-Cloud Model (FCM)



Flight integration:

$$dm/dt = -0.5\rho_{air}v^3A\sigma$$
$$dv/dt = \rho_{air}v^2AC_D/m - g\sin\theta$$
$$d\theta/dt = (v/(R_E+h) - g/v)\cos\theta$$
$$dh/dt = v\sin\theta$$

Fragmentation occurs when stagnation pressure exceeds strength

$$\rho_{air}v^2 > Strength\ (S)$$

Fragment strengths increase with decreased size

$$S_1 = S_0(m_0/m_1)^{\alpha}$$

Debris clouds broaden and slow under common bow shock

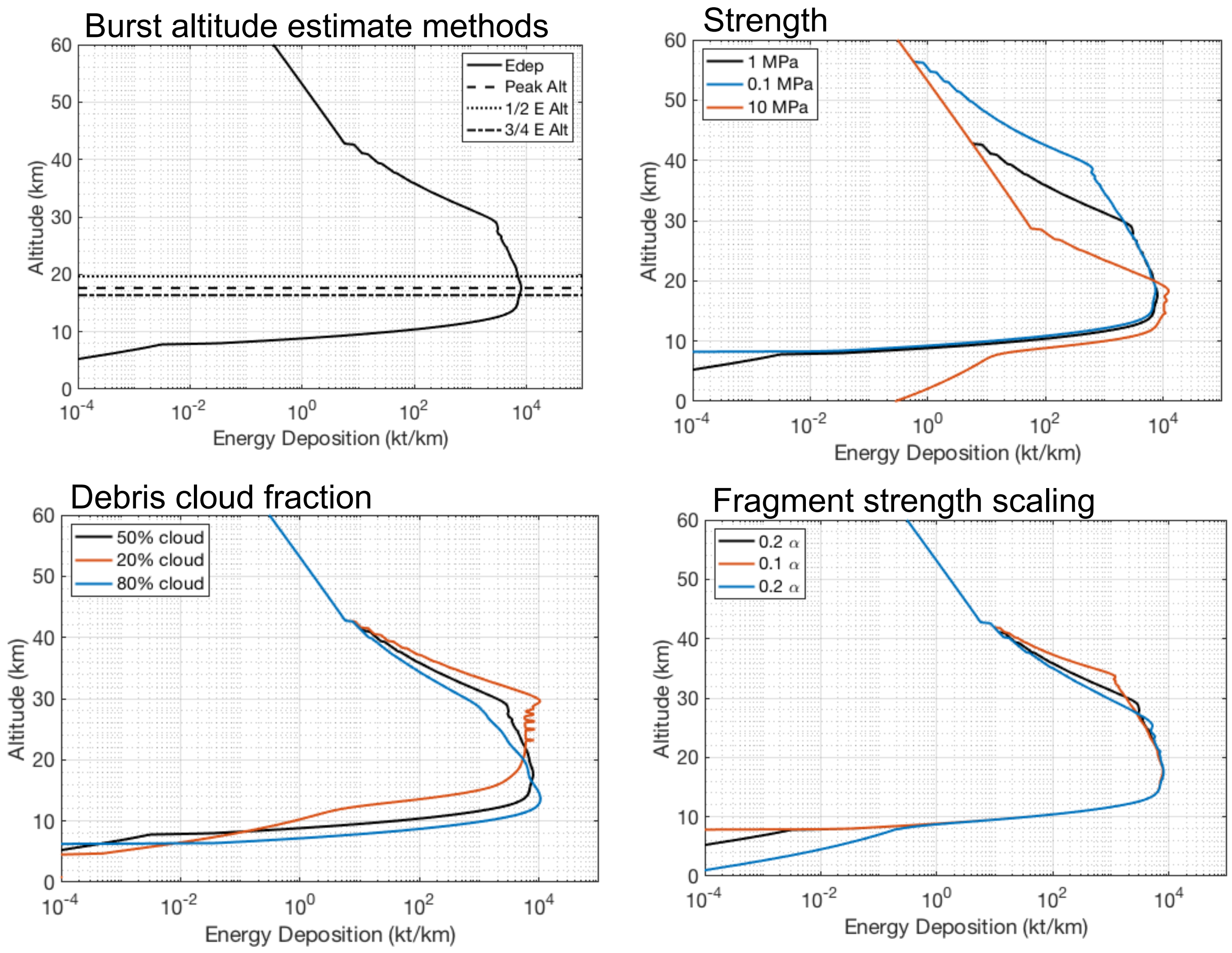
$$v_{disp.} = v_{cloud}(C_{disp}A\rho_{air}/\rho_{debris})^{1/2}$$

Atmospheric energy deposition rates used to estimate effective airburst altitude

HYPOTHETICAL EXERCISE

Burst Altitude Uncertainty Modeling in FCM

100 Mt, 120 m diameter, stony type asteroid, entering at 20 km/s and 45°



- Model provides varied energy deposition curves that can represent uncertainties in breakup behavior and effective burst altitudes.
- Effective burst altitudes can be based on peak energy deposition or deposition of a bulk fraction of the total energy

HYPOTHETICAL EXERCISE