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A Ground Footprint Eccentricity Model For Asteroid Airbursts

Michael J. Aftosmis*, Marian Nemec*, and Lorien Wheeler†

** NASA Ames Research Center, Mail Stop 258-5, Moffett Field CA 94035, United States*

† RedLine Performance Solutions, NASA Ames Research Center, MS 258-6, Moffett Field, CA 94035, United States

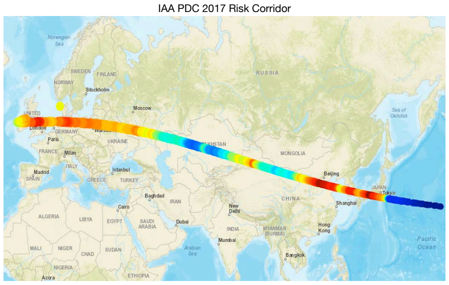
Overview

Uncertainties in early observations of potentially hazardous asteroids result in preliminary impact corridors that can stretch across large portions of the Earth's surface. At this early stage of detection, the corridor width and potential for damage are typically estimated using techniques from nuclear weapons research. These estimates often employ spherical blast assumptions resulting in a constant width impact corridor (Aftosmis, 2017). In actuality, however, the ground damage footprint of obliquely entering asteroids is generally roughly elliptical or "butterfly" shaped, with the major axis extending in the cross range direction and the minor axis aligned with ground-track of the meteoroid. Since actual ground footprints for oblique entries may have aspect ratios greater than two or three, the assumption of a circular blast may significantly underestimate the area of the impact swath and the at-risk population. This work develops an engineering model that can be used to quickly estimate the eccentricity of the ground footprint as a function of local impact parameters. This yields vastly improved local estimates of the corridor width and can significantly enhance the accuracy of risk analysis.

1 Improving the Risk Corridor

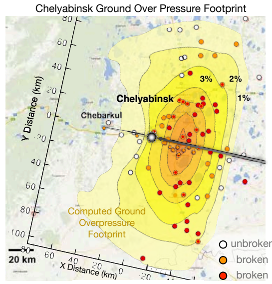
- Uncertainties in observations lead to preliminary impact corridors that extend over large portions of the earth's surface
- When based on spherical blast approximations, these corridors are often nearly constant width and do not capture the eccentricity of oblique asteroid entries.

IAA PDC 2017 Risk Corridor



Risk corridor for the 2017 IAA Planetary Defense Conference threat exercise colored by local affected population. Corridor width determined by spherical blast methods. (Mathias, 2017)

Chelyabinsk Ground Over Pressure Footprint



High-fidelity simulation and glass breakage data showing the ground footprint of the 2013 Chelyabinsk meteor (Aftosmis, 2016).

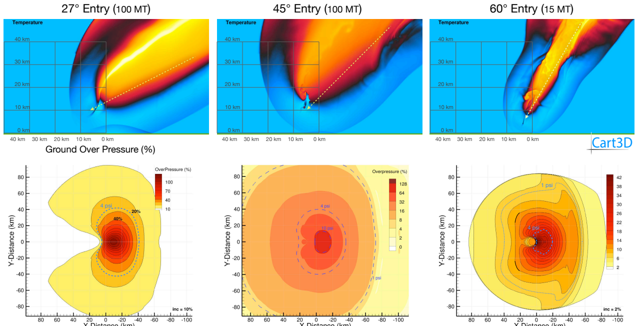
2 Approach - Numerical Parametric Studies

- Performed parametric study of large-scale 3D airburst simulations to gain insight into key entry parameters driving footprint eccentricity with the entry simulation approach of Aftosmis (2016)
- Examined ground footprint of 40 meteoroid airbursts varying entry angle, θ, aerodynamic strength, s, and kinetic energy at atmospheric entry interface, y, ("yield"); these parameters spanned:

  entry angles: $20° \le \theta \le 90°$, aero. strength: $0.01 \le s \le 20$ MPa, entry KE: $0 \le y \le 250$ MT
- Collected data & extracted aspect ratio of footprint focusing on 4 & 10 psi contours (when they exist)
- Developed an empirical analytic fit of ground footprint eccentricity as a function of entry parameters that can be used in fast-running codes used to generate ground risk corridors

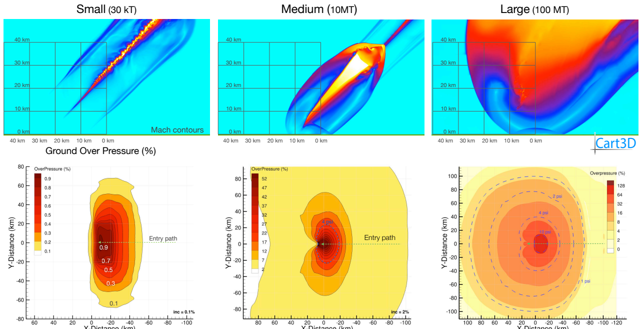
2.1 Increasing Entry Angle

(Rounder footprint)



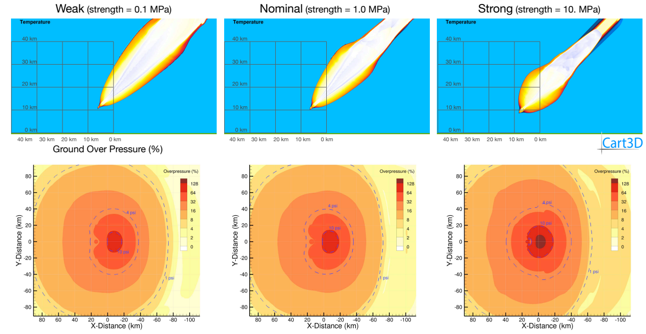
2.2 Increasing Kinetic Energy at Entry Interface (aero. str. = 1.0 MPa @ ∠45°)

(Rounder footprint)



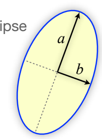
2.3 Increasing Aerodynamic Strength (KE = 100MT @ ∠45°)

(Rounder footprint)



3 Observations and Discussion

- **Entry angle is the main driver.** Low angles produce the highest eccentricity and the footprint becomes increasingly circular as entry angle approaches vertical.
- Objects with **higher aerodynamic strengths** result in more sudden airbursts, resulting in rounder footprints with lower aspect ratios.
- **Higher kinetic energy** at entry interface leads to rounder footprints. Since the blast radius scales with the yield, energy acts as a proxy for the shape of the blast wave, varying from cylindrical (low energy) to round (higher energy). Lower yields give the most eccentric footprints – consistent with intuition that smaller objects tend to produce more cylindrically dominated blasts
- Numerical experiments showed that footprint eccentricity is relatively **insensitive to burst height**. This allows us to seek an empirical model with only three input parameters (angle, strength & energy).
- For an ellipse



with a := Semi-major axis, b := Semi-minor axis

eccentricity, e, is defined

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

the aspect ratio, AR, is

$$AR = a/b$$

AR is the *shape of the rectangle that contains the ellipse.*

- Since they are all oblique entries, all of the simulations were conducted in three dimensions and used computational meshes with 200-300M cells using NASA's Cart3D simulation tool (Aftosmis, 2016).

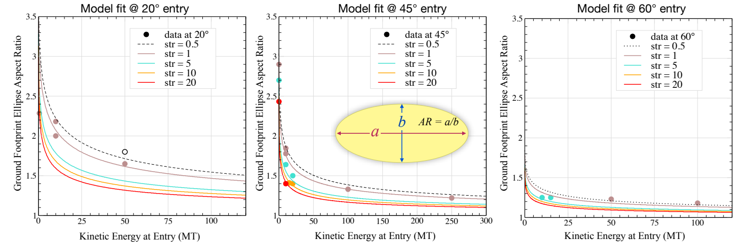
4 An Analytic Footprint Eccentricity Model

$$\theta' = \min(\max(\theta, 25), 80)$$

$$\Phi = 0.7065(1 + \cos((\theta' - 25)\frac{\pi}{55}))$$

$$\mathrm{AR}(y, s, \Phi) = 1 + \frac{\Phi}{\frac{s^{0.1}}{1.9} + 0.33276\, s^{0.25}\sqrt{y}}$$

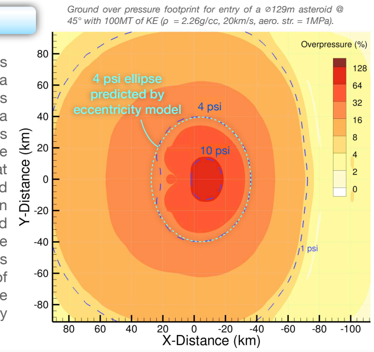
The model provides an analytic prediction of AR as a function of entry angle, yield, and strength, $AR(y, s, \Phi)$. The figure shows a slice through this three-parameter space at three entry angles, θ. Data from the calibration set are presented as filled symbols. Lines on the plots show the model predictions for AR as a function of yield.



5 Outcome

The plot at the right gives a view of the model's predictive performance through comparison with a full 3-dimensional entry simulation. The figure shows peak ground overpressure contours for 45° entry of a chondritic asteroid at 20 km/s. Density was nominally 2.26 g/cc. The FCM entry modeling code (Wheeler, 2017) predicted peak energy deposition at 17.5 km altitude. The contour plot shows the ground footprint for maximum overpressure expressed in percent of sea level pressure. Contours at 1, 4 and 10 psi are shown with dark blue dashed lines. The 4 psi ellipse predicted by the model (AR=1.26) is shown in cyan (dotted line) and does a good job of overlaying the corresponding contour from the simulation. Predicted aspect ratios are typically within 10% of those from full simulation.

Ground over pressure footprint for entry of a ⌀129m asteroid @ 45° with 100MT of KE (ρ = 2.26g/cc, 20km/s, aero. str. = 1MPa).



Acknowledgements

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