Probabilistic Assessment of Asteroid and Entry Properties Producing Tunguska-Like Airbursts

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Overview

• ATAP team has developed fast-running models to assess the potential threat from asteroid strikes on Earth
  • Probabilistic Asteroid Impact Risk (PAIR) model: models millions of impact cases to assess damage and risk probabilities.
  • Fragment-Cloud Model (FCM): models asteroid entry and breakup to estimate atmospheric energy deposition and airburst altitudes.
• We’ve used these models to do a ‘big picture’ probabilistic assessment of what asteroid/entry properties produce Tunguska-like cases
  • Model millions of Tunguska-scale impact cases, covering full range of probabilistically sampled asteroid and entry properties
  • Determine what property ranges are most likely to produce Tunguska-like airbursts and ground damage
Probabilistic Asteroid Impact Risk (PAIR) Model

Asteroid Characterization → Input Parameter Distributions

Monte Carlo Sampling

Initial Conditions

Entry & Breakup Modeling

Airburst Altitude & Surface Impact Energy

Blast Overpressure

Thermal Radiation

Tsunami

Risk Assessment Results

Damage Consequence + Likelihood → Risk

Risk = min\$ \times max\$ \times \text{expected}$

- Diameter
- Density
- Strength
- Velocity
- Entry angles
- Impact coordinates
- Uncertain modeling parameters

Casualties and Affected Populations

Local Blast/Thermal

Tsunami Inundation

Global Effects

January 16, 2018

L. Wheeler
Fragment-Cloud Model (FCM)

Flight integration:
\[
\begin{align*}
\frac{dm}{dt} &= -0.5 \rho_{\text{air}} v^3 A \sigma \\
\frac{dv}{dt} &= \rho_{\text{air}} v^2 A C_D/m - g \sin \theta \\
\frac{d\theta}{dt} &= \frac{v}{(R_E + h)} - g/v \cos \theta \\
\frac{dh}{dt} &= v \sin \theta
\end{align*}
\]

Fragmentation condition:
\[
\rho_{\text{air}} v^2 > \text{Strength (S)}
\]

Fragment strengths increase with decreased size
\[
S_{\text{child}} = S_{\text{parent}} \left(\frac{m_{\text{parent}}}{m_{\text{child}}}\right)\alpha
\]

Clouds broaden and slow under common bow shock
\[
\nu_{\text{disp.}} = \nu_{\text{cloud}} \left(\frac{C_{\text{disp}} A \rho_{\text{air}}}{\rho_{\text{debris}}}\right)^{1/2}
\]
(Hills & Goda pancake approach)

Result: total energy deposited per unit of altitude (kt/km)
Validation & Inference from Observed Meteor Modeling

- FCM matches to observed meteors provide model validation and help determine appropriate fragmentation parameter ranges for our risk model

Chelyabinsk (~20 m, ~500 kt)

Tagish Lake (~4.5 m, ~2 kt)

Inference for large flares like Chelyabinsk:
- Moderately high debris cloud fractions ~80%
- Lower ablation and debris cloud spread rates
- Strengths of primary flares ~1–4 MPa
- Earlier minor disruptions at <0.1–1 MPa
- Some stronger fragments persisting to ~15 MPa
- Strength scaling exponents 0.1–0.3
Tunguska-Scale Energy Deposition for Damage Assessment

- Sample energy deposition curves for Tunguska-like strong stone airburst, modeled with FCM parameters based on Chelyabinsk matching and simulations

- Asteroid parameters:
  - 15 Mt, 71 m diameter
  - 15 km/s, 45°
  - 3 g/cm²
  - 5 MPa

- Fragmentation parameters:
  - 80% debris cloud fraction
  - 2 even fragments/split
  - Strength scaling $\alpha = 0.1$
  - Ablation $\sigma \sim 1e^{-9}$ kg/J (based on simulations by C. Johnston & E. Stern)

- Velocity variation (~4 km altitude range)
- Entry angle variation (~5 km altitude range)
- Density variation (~2 km altitude range)
- Strength variation (~2 km altitude range)
Blast Overpressure Damage

- Ground damage radii are estimated from energy and burst altitude using yield scaling and height-of-burst (HOB) maps

- Nuclear-based HOB maps (Glasstone & Dolan, 1977)
  + Simulation-based HOB maps that account for buoyancy effects in larger bursts (Aftosmis et al., 2017)

- Optimal burst altitude that causes the largest damage area.
Probabilistic Assessment of Tunguska-Like Airburst and Damage

- 10 million cases 10-200 m diameters (uniform), focusing on impact energies ≤ 50 Mt
- Parameter distributions from Mathias et al. (2017, Icarus)
  - Density: meteorite densities combined with porosity distributions (J. Dotson)
  - Velocity distribution based on Greenstreet et al. (2012)
  - Entry angle: 0-90° cosine distribution around 45°
  - Strength: Logarithmic distribution from 0.1-10 MPa (Popova et al., 2011)
  - Ablation coefficient: Logarithmic distribution over large uncertainty range: 3.5e-10 – 7e-8 kg/J
  - Strength Scaling: \( \alpha \) 0.1-0.3 (uniform)
- Modeled breakup using 80% debris cloud fraction based on FCM matches to Chelyabinsk etc.
Result Approach (Plot Primer)

• Investigate what asteroid/entry parameters produce Tunguska-like cases by showing:
  • Energy-Altitude airburst trends for each parameter
  • Probability distributions of parameters values meeting various Tunguska-like criteria

• Tunguska-like criteria
  • 5-20 Mt energy and 5-15 km burst altitude ranges from prior published estimates
  • 4 psi blast radius ~25 km tree-fall radius
    – 4 psi overpressures roughly correlating with tree-fall wind speeds ~48-50 m/s
    – Based on M. Nemec & M. Aftosmis’s simulation results and Glasstone & Dolan wind speeds
    – 10-40 km radius range used, given uncertainties in tree strengths and analytic blast model

[Graphs showing airburst trends and probability distributions for Tunguska-like criteria]
Blast Radius Airburst Trends

- 4 psi ground damage radius as a function of impact energy and burst altitude
- Distinct jump in ground damage across optimal burst altitude for a given energy
Blast Radius Probability Trends

- Max blast radii
  - 22 km for $E \leq 20$ Mt
  - 29 km for $E \leq 50$ Mt
- No 4-psi damage most likely
  - (lower overpressure levels would still cause damage)
- Energy and altitude criteria give
  - Blast radius means 1.3-16 km
  - Secondary peaks at 7-16 km (among damage-causing cases).
- Dip in distribution due to jumps near optimal burst altitudes

<table>
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<tr>
<th>Criteria Set</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Peak</th>
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<td>4psi 10-40km</td>
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<tr>
<td>$E \leq 20$Mt &amp; 4psi $\geq 20$km</td>
<td>20</td>
<td>22</td>
<td>21</td>
<td>20</td>
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</table>
Burst Altitude Probability Trends

- 5-20 Mt impactors burst at 4-50 km altitude (mean 20 km, peak 17 km)
- Blast radius range is caused by burst between 1-21 km altitude (mean/peak ~12-13 km)
- Impactors ≤ 20 Mt must burst at:
  - 4-14 km to get blast radii ≥ 10 km,
  - 5-10 km to get blast radii ≥ 20 km.
- Most likely burst altitude range 8-13 km for Tunguska-like ground damage areas.

<table>
<thead>
<tr>
<th>Criteria Set</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Peak</th>
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<tbody>
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<tr>
<td>4psi 10-40km</td>
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<td>12–13</td>
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<td>E 5-20Mt &amp; Alt 5-15km</td>
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<td>E ≤ 20Mt &amp; 4psi ≥ 10km</td>
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<td>14.0</td>
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<td>11–12</td>
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<tr>
<td>E ≤ 20Mt &amp; 4psi ≥ 20km</td>
<td>5.7</td>
<td>9.8</td>
<td>8.7</td>
<td>8–9</td>
</tr>
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</table>
Impact Frequencies by Energy

- Density and velocity distributions used to compute impact frequencies and periods as a function of energy from diameter-based frequency estimates of A. Harris.
- When velocity and density distributions are accounted for, impacts for a given energy threshold are more frequent than diameter-based approximations using mean density and velocity (2.26 g/cc, 20.5 km/s).
- For $E \geq 20$ Mt, impact period decreases by $\sim 1000$ years compared to mean estimate.

Frequency data from Al Harris: Stokes et al. 2017, NEO SDT Report

Frequency data from Al Harris: Harris 2015, Icarus
Frequency-Scaled Impact Energy

- Normalized probabilities scaled by the relative impact frequency of each energy bin (2017 freqs)
- Even when scaled by relative impact frequencies, blast damage criteria are more likely met by higher energies
  - For blast radii 10-40 km, most likely energy is ~20 Mt, with mean ~14 Mt.
  - Min energy 7 Mt for >10 km damage, min 16 Mt for >20 km
- Burst altitudes more likely met by lowest energies when impact frequency is included, but skew slightly more toward higher energies compared to base distribution.
Frequency-Scaled Diameters

- Expected trend of larger penetrating lower through most of the altitude range
- Smaller sizes with highest (iron) densities yield the very lowest burst altitudes
- Diameter ranges 18-175m with means ~20-60m to meet various Tunguska-like criteria.
- Most likely (peak) diameter ranges 40-90m
  - 40-50 m for energy criteria
  - 50-60 m for altitude criteria,
  - 60-90 m for blast radius criteria,
Density Trends

- Highest densities cause the very lowest bursts, but otherwise the range is fairly agnostic across stony density ranges (< 3.5 g/cc)
- Full range of densities can fulfill all criteria
- Altitude criteria and combined criteria skew slightly toward higher densities (means 2.3-3.1 vs 2.26)
- Most likely ranges for meeting Tunguska criteria: 2–2.75 g/cc (input mode ~2.2)
• Clear tendency for lower bursts to be from slower objects.
• Lower velocities (<17 km/s) more conducive to meeting Tunguska-like criteria, with most likely values between 12-14 km/s.
• Full velocity range able to meet single criteria
• Upper velocity bound reduced from 43 to 22-37 km/s when combining energy with altitude or damage restrictions.
Entry Angle Trends

- Initial entry angle, measured from horizontal
- Clear tendency for lower bursts to be from steeper entries.
- Steeper entries better able to meet Tunguska criteria:
  - Means and peaks shift up to 52–70°
  - Minimum angle of 22–37° for impacts ≤ 20 Mt to cause damage radii ≥10-20 km
- Shallower entry angle estimates from historical records (~30°) are within bounds of most criteria, but are much less likely.

<table>
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<tr>
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<th>Max</th>
<th>Mean</th>
<th>Peak</th>
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<td>All 10-200m ≤ 50 Mt</td>
<td>0</td>
<td>90</td>
<td>45</td>
<td>45</td>
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<tr>
<td>E 5-20Mt</td>
<td>0</td>
<td>90</td>
<td>45</td>
<td>45</td>
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<td>Alt 5-15km</td>
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<td>90</td>
<td>58</td>
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<tr>
<td>4psi 10-40km</td>
<td>1</td>
<td>90</td>
<td>52</td>
<td>50–60</td>
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<td>E 5-20Mt &amp; Alt 5-15km</td>
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<td>90</td>
<td>61</td>
<td>60–65</td>
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<tr>
<td>E ≤ 20Mt &amp; 4psi ≥ 10km</td>
<td>22</td>
<td>90</td>
<td>64</td>
<td>60–65</td>
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<tr>
<td>E ≤ 20Mt &amp; 4psi ≥ 20km</td>
<td>37</td>
<td>90</td>
<td>70</td>
<td>70–75</td>
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</tbody>
</table>
Strength Trends

- Only slight tendency for highest strengths to produce very lowest burst altitudes
  - Trend is fairly weak
  - Moderate strength increases tend to compress the width of the flare more than lower the peak max
- Distribution covers estimated range, but does not reflect meaningful probabilities
- Higher strengths generally more likely to meet criteria compared to input distribution
- Full strength range able to meet all criteria

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<th>Peak</th>
</tr>
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<td>2.2</td>
<td>n/a</td>
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<tr>
<td>All 10-200m ≤ 50 Mt</td>
<td>0.1</td>
<td>10</td>
<td>2.2</td>
<td>n/a</td>
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<tr>
<td>E 5-20Mt</td>
<td>0.1</td>
<td>10</td>
<td>2.2</td>
<td>n/a</td>
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<td>Alt 5-15km</td>
<td>0.1</td>
<td>10</td>
<td>2.6</td>
<td>max</td>
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<td>4psi 10-40km</td>
<td>0.1</td>
<td>10</td>
<td>2.4</td>
<td>max</td>
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<td>E 5-20Mt &amp; Alt 5-15km</td>
<td>0.1</td>
<td>10</td>
<td>2.8</td>
<td>max</td>
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<td>E ≤ 20Mt &amp; 4psi ≥ 10km</td>
<td>0.1</td>
<td>10</td>
<td>3.0</td>
<td>max</td>
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<tr>
<td>E ≤ 20Mt &amp; 4psi ≥ 20km</td>
<td>0.1</td>
<td>10</td>
<td>4.2</td>
<td>max</td>
</tr>
</tbody>
</table>
Strength Scaling $\alpha$ Trends

- Fragment strength scaling:
  \[ S_{\text{child}} = S_{\text{parent}} \left( \frac{m_{\text{parent}}}{m_{\text{child}}} \right)^\alpha \]
- Airburst results fairly agnostic to this $\alpha$ range
- Full $\alpha$ range able to meet all criteria
- Slight preference for lower $\alpha$ at very lowest burst altitudes
- $\alpha < 0.2$ slightly more able to meet Tunguska-like criteria, but not significantly
Ablation Coefficient Trends

- Ablation coefficient $\sigma = CH/Q$
- Clear trend for lower ablation rates yielding lower burst altitudes
- Full range able to meet all but strictest criteria, which reduces upper limit slightly
- Lower ablation rates more likely to meet Tunguska-like criteria
  - Means decrease to 2e-9 – 8.5e-9 (vs 1.3 input)
- $\sigma \sim 1e-9$ is similar to using variable $C_H$ values from E. Stern and C. Johnston’s simulations
- Hills & Goda model used $\sigma \sim 1e-8$ kg/J

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<th>Max</th>
<th>Mean</th>
<th>Peak</th>
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<td>Input Distribution (Log)</td>
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<td>3.5E-10</td>
<td>7E-8</td>
<td>1.3E-8</td>
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<tr>
<td>E 5-20Mt</td>
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<td>7E-8</td>
<td>1.3E-8</td>
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<td>Alt 5-15km</td>
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<td>7E-8</td>
<td>5.7E-9</td>
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<td>8.5E-9</td>
<td>3.5E-10</td>
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<td>3.5E-10</td>
<td>7E-8</td>
<td>4.3E-9</td>
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<td>5.3E-8</td>
<td>2.0E-9</td>
<td>3.5E-10</td>
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</table>
Conclusions

- **Blast Damage:** Full 25 km observed blast damage radius is difficult for energies <20 Mt to meet (given 4 psi tree-fall assumption, current models, and input distributions).

- **Burst Altitude:** To meet the damage range, impactors <20 Mt must burst between 4-14 km, with most likely altitudes 8-13 km.

- **Energy Frequencies:** Expected impact periods for Tunguska-scale energies are reduced compared to mean estimates when accounting for parameter distributions.

- **Impactor Size:** Even when size frequencies are accounted, blast damage criteria are more likely met by higher energies and larger diameters.
  - 20 Mt energies most likely (means 14-18 Mt)
  - 70-90 m diameters most likely (means 46-57 m)

- **Summary of most likely impact parameter ranges for Tunguska-like criteria:**

<table>
<thead>
<tr>
<th>Criteria Set</th>
<th>Blast Radius (km)</th>
<th>Altitude (km)</th>
<th>Energy (Mt)</th>
<th>Diameter (m)</th>
<th>Density (g/cc)</th>
<th>Velocity (km/s)</th>
<th>Angle (deg)</th>
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<td>19–20</td>
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<td>2.5–2.75</td>
<td>12–13</td>
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BACKUP
Blast Overpressure Damage

- Ground damage radii are estimated from energy and burst altitude using yield scaling and height-of-burst (HOB) maps.
- Nuclear HOB maps (Glasstone & Dolan, 1977) are reasonable for small impact energies, but not for E >100 Mt.
- Aftosmis et al. performed CFD simulations of 250 Mt bursts at a range of altitudes to produce more faithful curves for large energies.
- PAIR model uses nuclear GD curves for energies <5Mt, uses simulation-based curves for energies >250Mt, and interpolates between the two for intermediate energies.
- For a given energy and overpressure, there is an optimal burst altitude that causes the largest damage area.
Comparison with Chyba et al.

- Chyba modeling assumed higher breakup strength criteria, slightly higher ablation, cylindrical shape and drag coefficient.
- FCM matches Chyba altitudes when using analogous inputs.
- When using FCM parameters similar to Chelyabinsk models, FCM gives altitudes 9-13 km for 45° entry with a range of strengths 1-20 MPa.
Impact Period & Ec Estimates

- Impact periods and expected casualty (Ec) rates for Tunguska-like ranges and thresholds
- Colors = Harris 2017 frequencies, black outlines = Harris 2015 frequencies.