

Building a Tool to Predict Damage Patterns from Meteoroid Airbursts

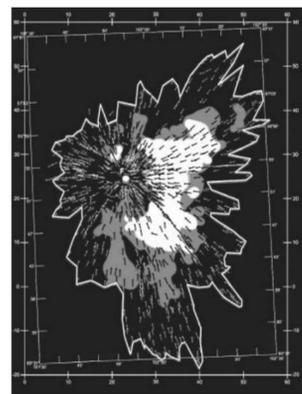
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Abstract

Most meteoroids do not reach the ground fully intact, they explode mid-air. These airbursts produce a shockwave that propagates to the ground and creates a damage pattern, typically in the shape of a butterfly for oblique entry angles and more oval or circular for steep impacts. The shape varies due to the height of the airburst, impact angle, and impact velocity. My goal is to create a web-based airburst simulator. The first step is determining the relationship between the airburst parameters and the shape of the contours representing the area affected by the meteoroid. This browser would include a GUI interface with sliders or knobs to control the bolide's size, entry angle, speed, and height of burst. The output will be a contour map of damage at Earth's surface at locations specified from a risk corridor, such as those calculated by JPL CNEOS for potentially hazardous objects, output as a Google Earth kml file or similar. So far, I have represented the contours using a Fourier series. The next step is to find a relationship between the parameters and the Fourier series.



Left: Bolide entering Earth's atmosphere Image: Thomas Grau, via Wikimedia Commons (Public Domain)



Right: Map of treefall from the Tunguska airburst

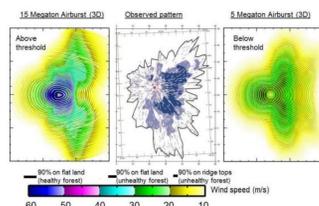
Adapted from "A new unified catalogue and a new map of the 1908 tree fall in the site of the Tunguska Cosmic Body explosion" (Vasilyev et al., 2013). Used here for educational and research purposes under fair use.

Background

Bolides are space rocks that enter Earth's atmosphere at high speeds. Most of them explode in mid-air because the intense pressure and heat from the air erode and weaken them as they travel through the atmosphere. These explosions are called airbursts. The airbursts create a shockwave that travels faster than the speed of sound, because the surrounding air is suddenly heated, compressed, and rapidly pushed outward. This creates damage on the ground in a circular or elliptical shape when the impact angle is steep. For shallower impact angles, it creates damage on the ground in a distinctive butterfly-shaped pattern. Small bolide airbursts happen every few years on Earth. However, most do not cause much damage because they occur over the ocean or in remote areas. Larger airbursts, which can cause serious damage, are much rarer and may happen only once every few decades or centuries. Two of the most famous examples are the Tunguska event in 1908 and the Chelyabinsk airburst in 2013. The Tunguska event occurred in Siberia in 1908 and flattened over 2,000 square kilometers of forest. It is the largest known impact-related airburst in recorded history. The Chelyabinsk event occurred in Russia in 2013 and caused thousands of injuries, mostly from broken glass, as well as damage to over 7,000 buildings. Unlike Tunguska, it was well-documented with videos and scientific instruments.

Wind speed contours from asteroid airburst simulations

Left and right: Modeled wind patterns for 15 and 5 megaton airbursts from the "FEMA Asteroid Impact Tabletop Exercise Simulations" (Boslough et al., 2015). Center: Observed forest damage pattern used for comparison. The green contour on the left was recreated manually in Desmos for this project.

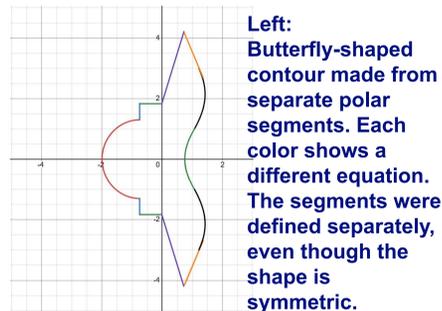


Project Goals

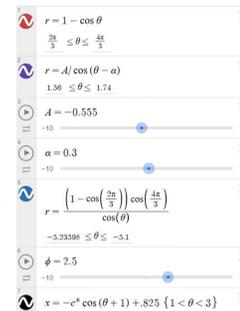
The goal of this project is to create a web tool that helps scientists quickly estimate the damage area from a meteor airburst. By entering key properties of the bolide, such as burst altitude, impact angle, and velocity, users can predict the likely extent of ground level shock. The tool is built around a scaling relationship that was derived from real world events, including Chelyabinsk and Tunguska, which helps ground the model in observed physical behavior. This is useful because large airbursts are rare, and real-world data is limited, so researchers rely on models to explore possible outcomes. Unlike full physics simulations, which require time and computing power, this tool gives quick, approximate results that can be used directly in a browser. This makes it more accessible for early-stage analysis, planning, or emergency response.

Progress So Far

I began by fitting the butterfly-shaped damage pattern using a Fourier approximation. I first created a manual, piecewise polar function in MATLAB to trace the shock contour, using trial and error to approximate the shape. Although this was not a Fourier series, it helped me understand the overall geometry. After verifying the shape, I translated the function into Python and exported the plot as a KML file for geographic visualization. The resulting contour looked realistic and matched the expected pattern.



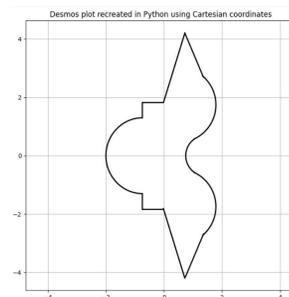
Left: Butterfly-shaped contour made from separate polar segments. Each color shows a different equation. The segments were defined separately, even though the shape is symmetric.



Right: Example equations used to build the butterfly shape. Each segment was defined using a different polar or piecewise function. Some include sliders for easier tuning by trial and error. Not all equations are shown here.

I used the findContours function in Python to automatically detect the Tunguska treefall pattern from a map image. The input included features like arrows and crosshairs, which made it difficult to isolate just the dashed contour lines. The program identified the general shape well but also picked up unwanted segments. I manually cleaned the results by erasing those extra pieces and connecting the valid segments to form a complete and continuous outline. Once I had the cleaned contour, I used the Fast Fourier Transform (FFT) function to calculate a set of Fourier coefficients that describe the shape. This gave me a more systematic and mathematical way to represent the butterfly geometry, making it easier to study how the shape changes with different input parameters. Next I used Cursor.ai's AI tools to make my work more efficient. I provided the equations I had used in Desmos, and Cursor helped me convert them to Cartesian coordinates and plot them in Python. I also imported the Tunguska damage map into the environment. Cursor helped me automatically extract the contour and implement the Fourier fit.

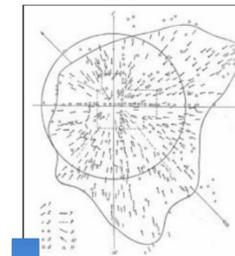
Left: Equations originally written in polar coordinates in Desmos were converted to Cartesian form for plotting in Python.



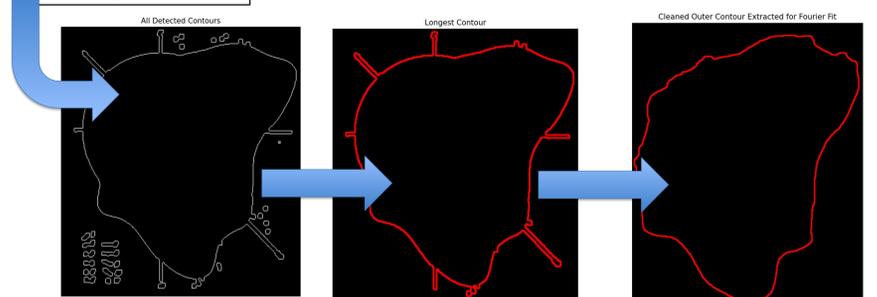
Right: Butterfly contour plotted in Google Earth using KML export. The manually defined butterfly shape was exported as a KML file and overlaid on real geography for visualization. This example shows the contour centered over Mountain View, California.



Result



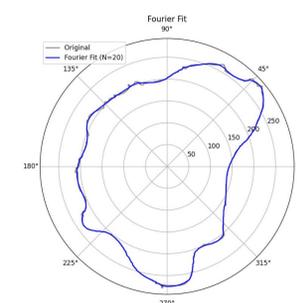
Top Left: Tunguska damage map used for contour extraction and Fourier fitting. This map shows observed treefall directions and blast extent from the 1908 airburst. It was originally published by K.P. Florenskii (1963) and reproduced in later works, including Vasilyev et al. (2013). The contour was traced, cleaned, and used as input for Fourier analysis in this project. Used here under fair use for educational purposes.



Python-detected contours

Longest contour detected

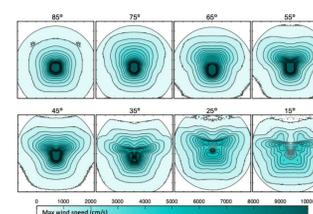
Manually edited



Fourier fit using 20 terms

Next Steps

The next steps are to parameterize the butterfly-shaped contours produced by running the model with different input values, such as burst altitude, impact angle, and velocity. For each case, we will extract the best-fit Fourier coefficients that describe the shape of the damage pattern. By studying how these coefficients vary with the input parameters, we can build an interpolated scaling relationship. This will allow the final tool to generate smooth, accurate contours for any combination of inputs selected by the user, using sliders in the interface. Finally, these contours will be exported to a KML file so users can view the predicted damage footprint in mapping programs like Google Earth.



Wind speed contours from 3D airburst simulations. Contours from 3D simulations showing blast patterns for asteroid airbursts at various entry angles. Adapted from Boslough et al. (2025), these patterns help in understanding how entry angle affects the shape of the damaged region. This data serves as a basis for identifying mathematical relationships between input parameters and contour geometry, and for interpolating shapes across a range of angles.

