Development and Analysis of the Automated Object Reentry Survival Analysis Tool Parametric Study Wrapper

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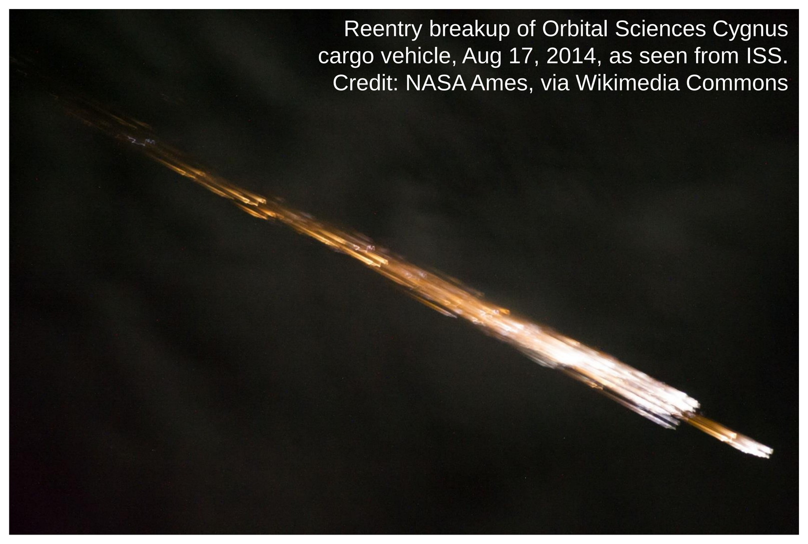
Introduction

The NASA Orbital Debris Program Office (ODPO) studies all aspects of spacecraft end-of-life and orbital debris measurement, modeling, and mitigation. The reentry safety group within the ODPO uses the Object Reentry Survival Analysis Tool (ORSAT) to calculate the casualty risk due to reentry of spacecraft and other types of orbital debris. ORSAT models spacecraft as a collection of fragments that break apart from the parent object at a pre-defined "breakup altitude." It then calculates the trajectory and aero-heating of these fragments to determine which fragments are completely destroyed and which survive to the ground and pose a risk to human population. Because of the historically high computational cost of these calculations, many simplifying assumptions have been made in the traditional calculation and analysis process used by the ODPO, some of which have been shown by recent research by the ODPO and others to be incorrect. Improvements to the ORSAT code and advancements in computer technology have vastly decreased the program's processing time, and have allowed the ODPO to develop a capability for large-scale parametric studies and Monte Carlo reentry simulations that can aid in both the initial spacecraft design and provide more detailed and accurate risk analysis to spacecraft operators.

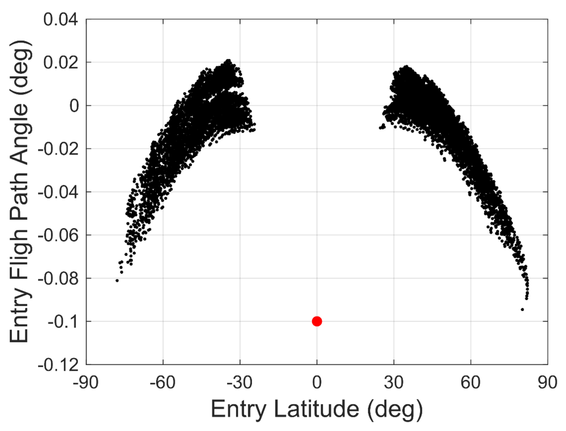
Key Topics

NASA ODPO	ORSAT	AutoORSAT	Parametric Risk Study
Spacecraft Reentry	Monte-Carlo Risk Analysis	Design for Demise	Demisability Database



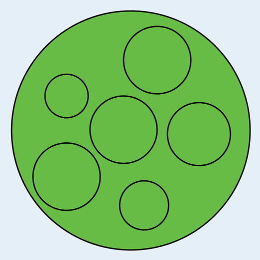
Reentry breakup of Orbital Sciences Cygnus cargo vehicle, Aug 17, 2014, as seen from ISS. Credit: NASA Ames, via Wikimedia Commons

Spread of possible reentry initial conditions for a spacecraft with a ballistic number of 80 and an orbital inclination of 90°.

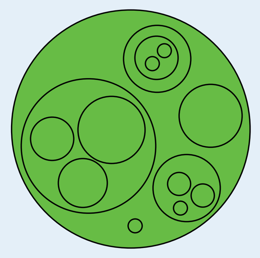


Modeling Spacecraft Reentry

- A reentering spacecraft is modeled as a collection of components that are released when the spacecraft breaks apart due to aerodynamic forces.
- Sometimes, a component may contain other components that are shielded from aero-heating until the parent component is destroyed.
- Traditionally, ORSAT has only modeled un-nested fragments due to limitations of original code. AutoORSAT adds the capability of easily simulating complex nesting of components.
- Exact entry conditions for the spacecraft are impossible to predict, so traditionally, ORSAT is run with a single entry condition that is assumed to be representative of many possible entry conditions. Monte-Carlo analysis is often used when the starting conditions are uncertain, and AutoORSAT adds this capability to the ODPO's processing toolchain.



Un-nested Fragments
All pieces of the spacecraft are released at the same time at the breakup altitude



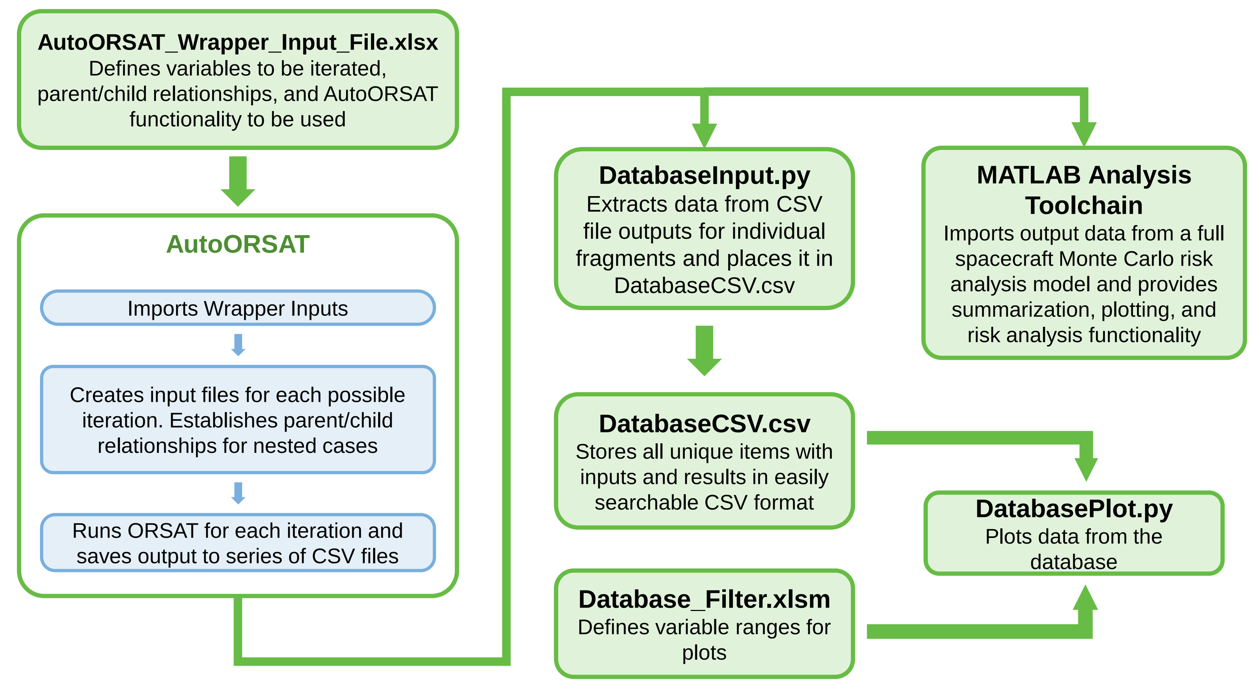
Complex Nesting
Some fragments are fully contained within larger fragments and are only exposed to aero-heating when the parent component demises

Designing for Spacecraft End-of-Life: Design for Demise (D4D)

Most spacecraft placed in a low-Earth orbit will eventually reenter the atmosphere on a random orbit decay path, potentially posing a casualty risk to ground populations. The goal of the D4D concept is complete vaporization of the spacecraft in the upper atmosphere, leaving no surviving fragments to cause potential harm on the ground. Whether the end of mission plan for the spacecraft includes a targeted entry or a random decay reentry, the ground casualty risk can be significantly reduced by including component demisability in the initial spacecraft design.

To meet this goal of complete demise of the spacecraft, designers need access to information on component desmisability early in the design process in order to make informed component and material selections.

AutoORSAT Process Flow



Automating Reentry Simulations

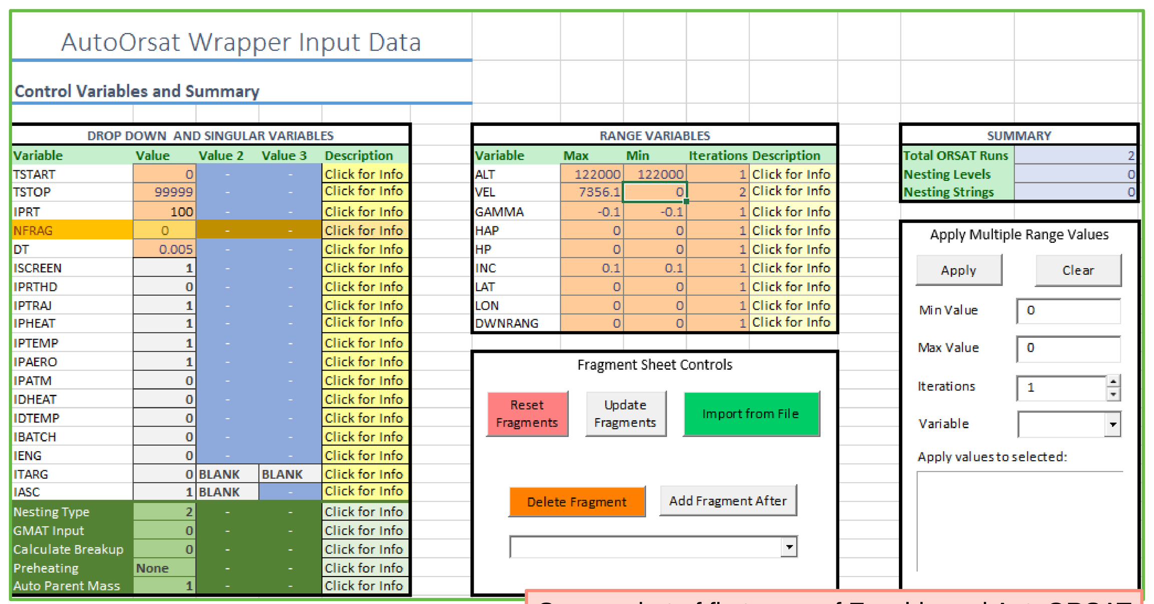
Because the initial setup for each ORSAT calculation typically involves a large amount of manual editing of the text-based simulation definition file, performing large scale parametric studies of reentry conditions has always been a prohibitively time-consuming task and therefore limited to a small number of conditions in cases where the results of a given simulation were ambiguous. Therefore, the main purpose of the AutoORSAT wrapper was to automate the generation of individual simulation definition files.

The AutoORSAT wrapper is a command-line tool written in Python that can read an easy-to-edit Excel-based input file with value ranges for each variable and output thousands of ORSAT input files to be individually processed by parallel ORSAT instances.

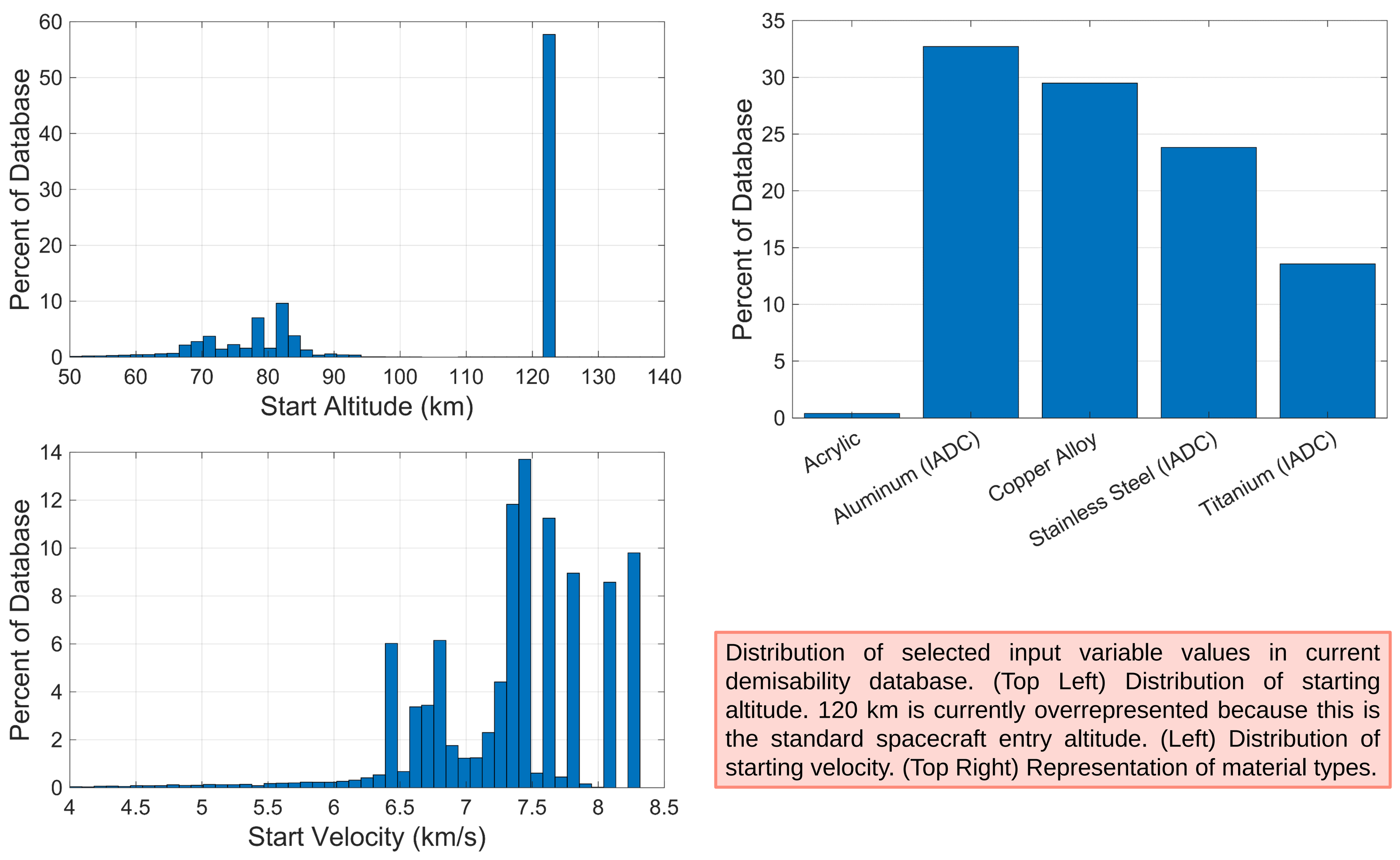
AutoORSAT Performance

AutoORSAT uses the Python multiprocessing module to run an arbitrary number of parallel ORSAT instances. Typically, an ORSAT run for a single fragment takes about 1 to 5 seconds of computation time depending on whether and how quickly the fragment demises. Using a single node of the ODPO computing cluster with 16 cores and 32 parallel threads, up to 126,000 ORSAT runs per hour have been achieved, with a typical run computing about 72,000 ORSAT runs per hour on average.

For a spacecraft with 150 modeled components, this computation speed enables a Monte Carlo parametric study of the full range of reentry starting conditions with 8,000 starting points to be completed in ~12 hours.



Screen shot of first page of Excel-based AutoORSAT input file. Variables are defined by value ranges, and VBA scripts automate several common input tasks.

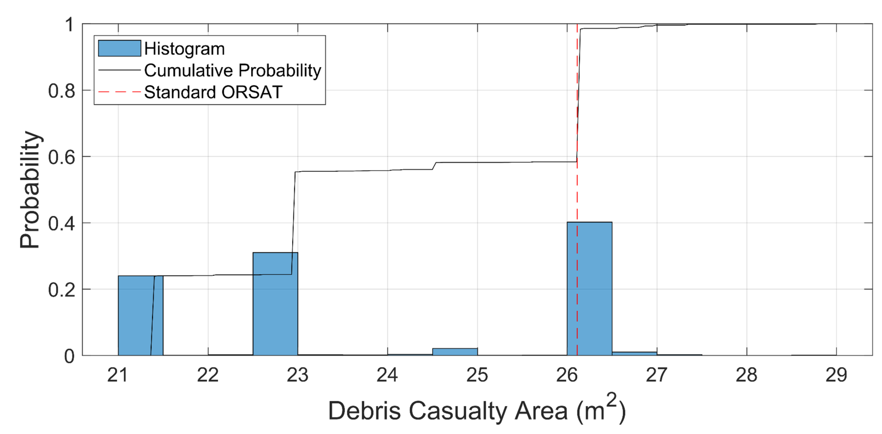


Distribution of selected input variable values in current demisability database. (Top Left) Distribution of starting altitude. 120 km is currently overrepresented because this is the standard spacecraft entry altitude. (Left) Distribution of starting velocity. (Top Right) Representation of material types.

Demisability Database

An important goal of D4D is to make it easier for spacecraft designers to incorporate demisability into their trade studies early in the design process. Because simulating reentry demisability requires somewhat specialized knowledge, and running the number of reentry simulations to build a good model for the demisability range of a potential component can be computationally intensive, having a large database of precomputed fragment trajectories covering a broad range of possible materials, fragment shapes, release altitudes, and velocities could be invaluable to a design team. Using such a precomputed database, a designer could instantly produce a report of the demisability of a preliminary component design by searching the database for similarly shaped objects.

Using the new capabilities of AutoORSAT, the ODPO is currently building such a demisability database, which currently exists as a comma-separated value text file containing the input conditions and final state of each fragment scenario. As the number of fragment scenarios calculated increases, this method of data storage becomes increasingly cumbersome. Work is ongoing to implement the database in SQLite, which will improve searchability, data storage efficiency, and portability.



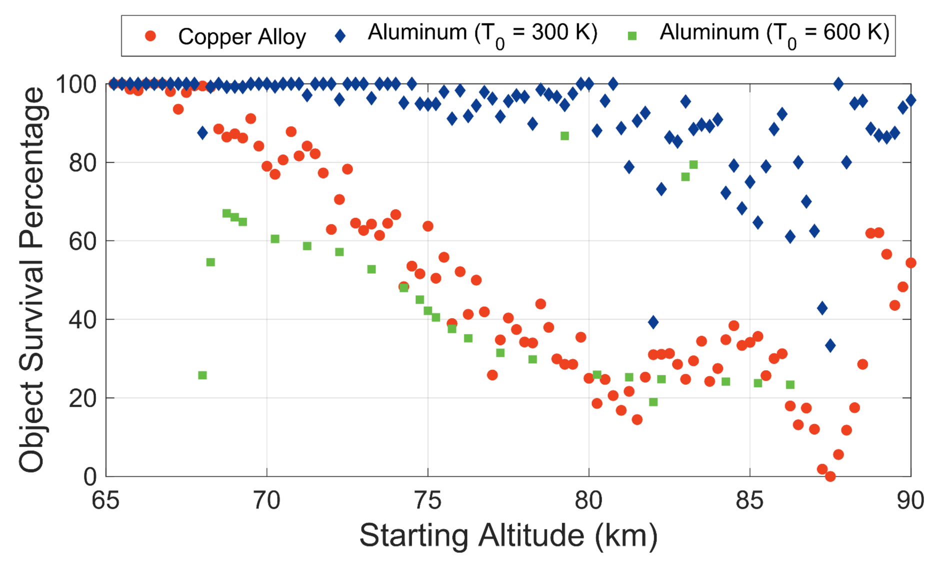
Example histogram of possible values of total spacecraft debris casualty area (DCA) from a realistic range of possible entry conditions. The discrete nature of the histogram is due to the fact that the minimum possible DCA of a single fragment is approximately 0.35 m^2.

Monte Carlo Risk Analysis

Traditionally, ORSAT is run on a single case basis, using a set of standard inputs, to determine a value for the ground casualty risk of a given spacecraft. Some variation in input parameters can be studied either by using the limited built-in parametric study feature of ORSAT 6.0 or by manually editing the input text file each time to run multiple cases. This is a tedious process and only allows for simple one- or two-variable parametric studies for a small number of spacecraft fragments. These sorts of parametric studies therefore are used only when something in the risk model is marginal and needs more study to solidify the ORSAT analyst's confidence in the model.

Using the AutoORSAT wrapper, large parametric studies of spacecraft demisability models can be implemented and run in only a few hours. This vast increase in capability has allowed the ODPO to investigate the use of Monte Carlo analysis to obtain a clearer and more accurate picture of the real ground casualty risk of a reentering spacecraft. Rather than using a single standard entry assumption, AutoORSAT can use a realistic statistical model of the entry conditions to calculate a ground casualty risk that can automatically incorporate uncertainty and small biases. The ODPO is currently developing appropriate statistical models for inputs to the Monte Carlo analysis and ways to meaningfully interpret the output of the analysis.

Preliminary results of database query, showing the demisability of solid copper and aluminum spheres vs. release altitude. As the release altitude decreases, the probability of survival increases, with nearly all objects released below 65 km surviving to the ground.



Preliminary Results

Though the extent of the database is currently very limited, a general trend of fragment demisability vs starting altitude can be extracted for fragments made of copper and aluminum, shown in the plot to the right. As expected, the demisability of a fragment made of either material decreases as the release altitude decreases, with very few fragments demising when released below 70 km. However, the figures show that copper fragments demise more readily than aluminum fragments of comparable size. A possible explanation for this effect is the high density of copper. This increases the ballistic coefficient, and therefore the length of time the fragment is exposed to peak heating. These are also very large fragments (0.5 m), which may skew the results somewhat.

Summary and Future Work

The NASA Orbital Debris Program Office (ODPO) has created AutoORSAT, a python-based parallelized parametric wrapper for ORSAT. The new wrapper can perform tens of thousands of ORSAT runs per hour, allowing the ODPO to perform massive parametric studies on both full spacecraft models (enabling the application of Monte Carlo analysis to spacecraft reentry risk), and on individual fragments to create a database of fragment demisability for use in design for demise. Work has begun on both of these possible applications of AutoORSAT, but much remains be done. The demisability database will be re-implemented as an SQLite database to improve searchability and data storage efficiency. Monte Carlo analysis requires a good understanding of the range and probability distribution of possible input values, and work is ongoing to develop that understanding and apply it to spacecraft risk assessment.