Operational and Technical Updates to the Object Reentry Survival Analysis Tool

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ABSTRACT

The Object Reentry Survival Analysis Tool (ORSAT) has been used in the NASA Orbital Debris Program Office for over 25 years to estimate risk due to uncontrolled reentry of spacecraft and rocket bodies. Development over the last 3 years has included: a major change to the treatment of carbon fiber- and glass fiber-reinforced plastics (CFRP and GFRP, respectively); an updated atmospheric model; a new model for computing casualty area around an impacting debris object; and a newly-implemented scheme to determine the breakup altitude of a reentry object. Software also was written to automatically perform parameter sweeps in ORSAT to allow for uncertainty quantification and sensitivity analysis for components with borderline demisability.

These updates have improved the speed and fidelity of the reentry analysis performed using ORSAT, and have allowed for improved engineering understanding by estimating the uncertainty for each component's survivability. A statistical model for initial conditions captures the latitude bias in population density, a large improvement over the previous inclination-based latitude-averaged models. A sample spacecraft has been analyzed with standard techniques using ORSAT 6.2.1 and again using all the updated models; we will demonstrate the variation in the total debris casualty area and overall expectation of casualty.

1 INTRODUCTION

The Object Reentry Survival Analysis Tool (ORSAT), version 6.0 was released in 2005 for use by analysts in the NASA Orbital Debris Program Office (ODPO) [1]. Since the release of that version, analysts at the ODPO have continued the development of ORSAT, resulting in versions 6.1, 6.2, and 6.2.1. These later versions have included numerous minor changes to the numerical algorithms, drag and heating models, material models, and even to the way analysts interact with the ORSAT software.

2 MODEL UPDATES

2.1 Carbon Fiber- and Glass Fiber-Reinforced Plastics

There have been a series of news reports over the last decade indicating that composite-overwrapped pressure vessels (COPV) survive reentry to impact the ground [2], [3], [4]. Research conducted by many groups (as well as an improved understanding of the manufacture of some thermal protection materials) has also indicated that thick pieces of composites may not completely demise during reentry [5], [6]. To address this challenge, the ODPO has undertaken a new series of tests at the University of Texas at Austin's Inductively-Coupled Plasma Facility. Phase I tests were completed in the spring of 2018 and provided a sufficient qualitative understanding of the behavior of composite materials to develop a transitional model for immediate application in ORSAT [7], [8]. A supporting statement was also made by Fritsche in [9] that the overwrap on composite-overwrapped pressure vessels (COPV) is not likely to demise if it is thicker than about 1 mm.

The details of this model can be seen in [8]. Briefly: fiber-reinforced plastics thicker than 1 mm are treated as a heterogeneous material, with a layer of epoxy on top of a layer of refractory material, both with custom material

properties. The epoxy layer currently is assumed to have a thickness of 5% the total thickness of the material (since it was observed that the objects under test in the plasma torch did not significantly change in volume). The ORSAT analyst must supply an approximate epoxy fraction (i.e., the fraction of the total mass of the composite that is epoxy); all this mass is located in the outer 5% of the object. A simple depiction of this model (on a hollow, thick CFRP cylinder) can be seen in Fig. 1, where the outer blue area is the epoxy phase and the inner black area is the refractory carbon phase.

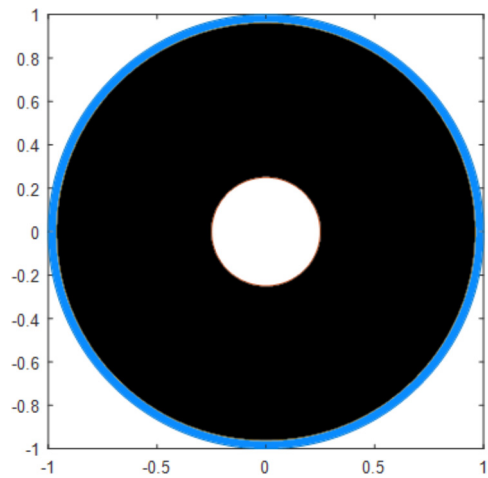

Figure 1. Visualization of two-material CFRP model.

This new model predicts that more CFRP and GFRP objects will survive reentry, which will increase the total impacting debris area (though it is difficult to estimate the effects on casualty area). Material strength of these composites is also an area of high interest, as epoxy-less composites may show low strength, breaking either into smaller pieces that have less than 15 joules of impact kinetic energy, or in a worst-case scenario, breaking into many pieces with each having the potential to cause casualty.

2.2 Entry Conditions

Previous publications by Matney, Lips, and Bacon have challenged the assertion that reentries are equally likely to happen at any point in time during an orbit; in fact, there appears to be a much higher likelihood that objects reenter near the equator, not at the poles [10], [11], [12], [13]. The variation of reentry locations, especially around an ellipsoidal Earth, implies that the entry conditions will also differ: speed relative to the atmosphere and flight path angle (FPA) both change as a function of argument of latitude; see Fig. 2 for a geometric depiction of FPA (reproduced from [13]).

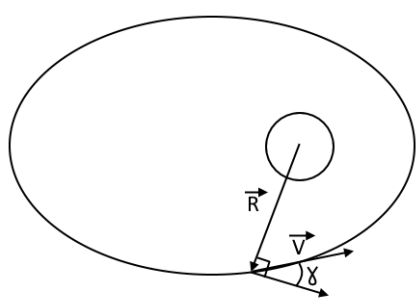

Figure 2. Geometric depiction of flight path angle (γ).

This research indicates that for certain combinations of orbit inclination and latitude at entry interface (typically defined as 122 km altitude for ORSAT analysis), the assumed FPA of 0.1° is not possible. In addition, the "wall of air" effect that produces the statistical variation in entry conditions also produces latitude bands where reentries are nearly impossible to occur. Both these phenomena can be seen in Fig. 3 (reproduced from [13]): the left plot shows that no simulated decay trajectory produces an initial FPA as steep as 0.1° (and this trend carries until approximately

60° inclination), while the right plot shows both the trajectories that produce steeper than 0.1° FPA as well as the gap in predicted entry latitudes around the equator.

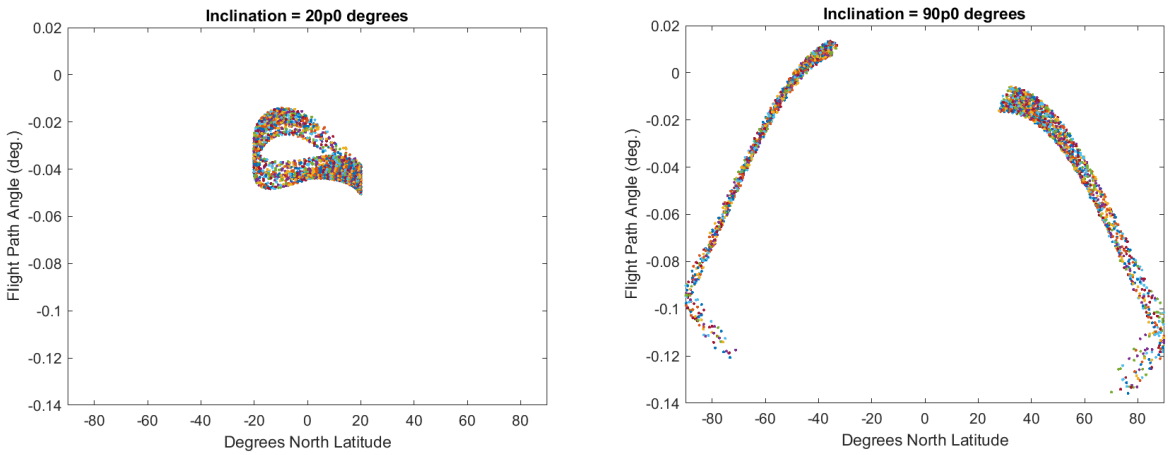

Figure 3. Latitude variation of FPA; Inclination = 20° (left), Inclination = 90° (right).

These entry conditions (latitude, longitude, speed, and FPA) are generated using NASA's General Mission Analysis Tool (GMAT) starting from a near-circular orbit at 200 km altitude and propagating until the object crosses 122 km. This process is performed for each spacecraft or rocket body analyzed by the ODPO team of analysts. Incorporating this change allows the analysis to better capture the heat load experienced by the reentry object across all orbit inclinations. This new model also allows for an improved computation of expectation of casualty: instead of using the inclination-based, latitude-averaged (or sub-satellite) population density, analysts can use the population density of the latitude bands in which any surviving debris fragments land, then compute the average over all trajectories.

2.3 Breakup Altitude

Standard ORSAT analysis has assumed breakup to occur at 78 km (originally 42 nmi) altitude, regardless of spacecraft mass, shape, or size. This assumption was derived from [14], written in support of the Office of Commercial Space Transportation. It is stated, explicitly:

> *Magnesium/aluminum structure consistently exhibits catastrophic failure at 42 nmi altitude.* [Page C-8]

The report continues, however, to explain that structural breakup of space vehicles is determined by the radiation equilibrium surface temperature of the vehicle. Since the heating rate (and thus equilibrium surface temperature) varies with altitude and as a function of ballistic coefficient of the space vehicle (see Fig. 3 below, reproduced from [14]), it may be introducing bias into standard ORSAT analysis to always use 78 km as the final altitude of the parent body.

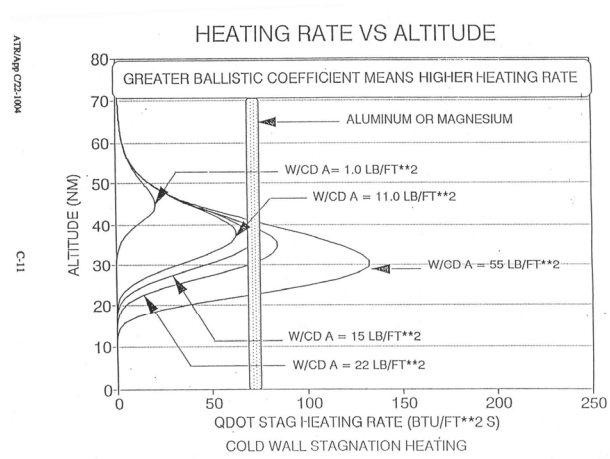

Figure 4. Heating rate profiles as a function of ballistic number.

To improve on this assumption, a new model to predict the breakup altitude of the parent body in ORSAT simulations is now in use. First, ORSAT users will determine the appropriate ballistic coefficient, using the projected area for the parent body shape and tumbling motion type (i.e., fixed, spinning, 2-axis tumbling, or 3-axis tumbling). Then, the user will produce a set of breakup altitudes corresponding to each unique entry condition determined above; these altitudes are where the radiative equilibrium surface temperature is equal to the melting point temperature of the parent body material. Thus, some parent objects, such as CubeSats, will have higher breakup altitudes than 78 km, by dint of their very low ballistic numbers, while denser spacecraft such as ISS cargo vehicles will have lower breakup altitudes than the assumed 78 km.

2.4 Radiation Heat Transfer Correlations

In addition to the Jones-Park correlation already in ORSAT, the Tauber-Sutton correlation [15] was added to the code. The Tauber-Sutton correlation also predicts the stagnation radiation heat transfer due to re-entry heating. The correlation has the form seen in Eq. 1, where a, b, and C are constants relating to the entry speed and composition of the atmosphere, ρ is the atmospheric density, and V is the entry speed. The equation is valid for velocities from 10 km/s to 16 km/s and for free-stream densities from 6.66E-5 kg/m^{3}to 6.31E-4 kg/m^3 or altitudes of 54 km to 72 km. It is also restricted to nose radii from 0.3 m to 3 m and values of $a \leq 1$.

$$\dot{q} = Cr^a \rho^b f(V) \qquad \text{(Eq. 1)}$$

The second method incorporated is the QRAD code and is now a subroutine of ORSAT. This code is based on Page's 4-band model [16] for equilibrium radiation. Nonequilibrium radiation is computed in the code by binary scaling methods, with collision limiting applied at high altitudes. Details of the code can be found in [17].

2.5 NRLMSISE-00

The 2000 Naval Research Lab Mass Spectrometer and Incoherent Scattering – Extended (NRLMSISE-00) atmosphere model [18] has been incorporated into the ORSAT code, replacing the 1990 version of that model (MSISE-90). Major changes in this model include new data from orbital decay of satellites, updated temperature and number density models, and spacecraft onboard accelerometer data. This model requires current altitude, latitude, longitude, solar flux, geomagnetic index, and other inputs that analysts may not have reasonable values for, considering a reentry that could be decades in the future. As such, this model is reserved for use in examining controlled reentries of spacecraft and rocket bodies, like the previously-implemented MSISE-90 and GRAM-99 models. Natural decay reentry trajectories are simulated using the 1976 US Standard Atmosphere.

2.6 Source Code Changes

The ORSAT software was originally written in Fortran 77; over the last 25 years of its development, features and external source codes have been added with different code standards. For the update to version 6.2.1, a major effort was undertaken to update the code base to Fortran 95 for maintainability and other algorithmic improvements. Concurrent with the development and implementation of the AutoORSAT python wrapper [20] (also see Section 3), the parametric functionality within ORSAT was removed, both to simplify the main ORSAT routine, as well as remove redundant code. Version 6.2.1 also introduces a new "speed mode" for running on a compute cluster, in which all output is directed to the command line. This reduces file input and output, improving the runtime, as well as improving the integration with the AutoORSAT tool. In addition to this new mode, some changes were implemented in how timesteps are computed in the thermal and trajectory routines, allowing a nearly 100-fold improvement in speed.

2.7 Updates to the Debris Casualty Area Calculation

ORSAT version 6.2.1 implements the Opiela-Matney formula for computing debris casualty area (DCA), first proposed in 2003 (see Eq. 2). [19] Since then, the ODPO has conducted more sophisticated Monte Carlo studies of the interaction between simple convex shapes (such as triangles, squares, and circles) and more realistic models of human shape. These studies indicate that it is possible to further simplify this formula to remove the explicit dependence on object perimeter (see Eq. 3 – all units in meters). The new model matches all simulations with 1% higher accuracy (root-mean-square) than the prior model, and is simpler to implement in a reentry code, while allowing for complex shapes.

$$DCA = 0.278 + A_{obj} + 0.3 * P_{obj} \qquad \text{(Eq. 2)}$$

$$DCA = 0.278 + A_{obj} + 1.39 * \sqrt{A_{obj}} \qquad \text{(Eq. 3)}$$

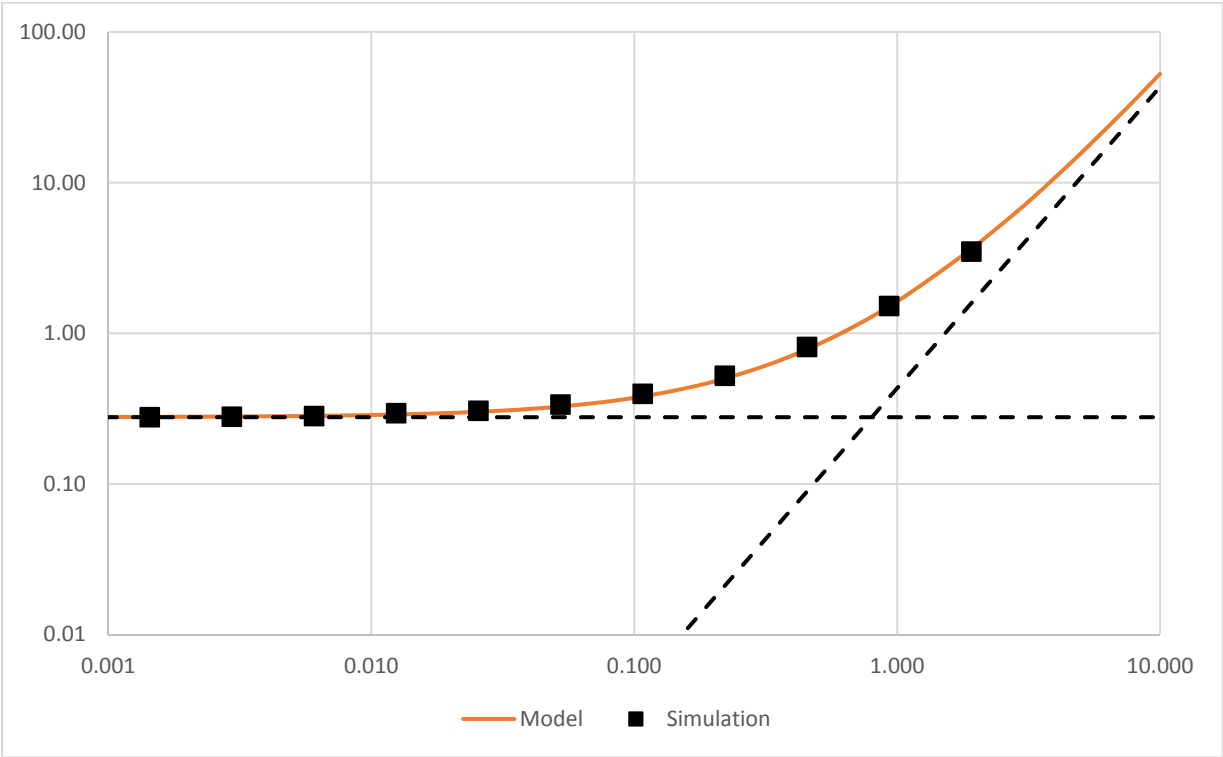

Figure 5. Comparison of Monte Carlo and model estimates of triangular debris casualty area.

3 AutoORSAT PARAMETRIC WRAPPER

Previous versions of ORSAT (before 6.2.1) could perform parametric studies in a single variable. Analysts looking to assess the effect of multiple variables at once (such as breakup altitude and initial temperature, or number of nodes and oxidation efficiency) had to manually create a matrix of test points for examination. Analysts at the ODPO have recently developed the AutoORSAT wrapper, a new tool that greatly expands the ability to assess uncertainty in reentry survivability. AutoORSAT is written in Python 3.6 and allows for parallel processing of up to 48 ORSAT simulations at a time, and as many as 100,000 simulated reentry trajectories per hour. [20] In addition to handling the multi-parametric spread in ORSAT simulations, AutoORSAT also performs all the information transfer between parent and child objects (for an arbitrary level of nesting complexity), including initial temperature for child objects, and the new trajectory's initial state.

This new ability to automatically generate and run thousands of cases has enabled analysts to improve their confidence in the survivability of components (whether they are expected to never demise, partially demise, or always demise). Work is ongoing on the development of a database of standard objects (such as ballast masses, battery and computer boxes, and reaction wheels, among many others) and their expected survivability (i.e., an expected DCA for surviving objects, or an expected demise altitude, depending on initial conditions). [20]

4 SATELLITE TEST CASE

To demonstrate the effects of the changes over the last three versions of ORSAT, we have constructed a sample satellite test case of approximately 1100 kg mass (and containing over 150 unique components with varying levels of nesting) in a near-polar orbit (98.0° inclination). GMAT was used to simulate 8640 trajectories to generate a statistically valid sample of initial conditions (varying the initial right ascension of ascending node, season of the year, and a dither factor on mass following the method of [11]). For the purposes of this comparison study, the breakup altitude for all cases was set to 78 km (the "standard ORSAT assumption"). All cases used an initial altitude of 122 km above the WGS84 ellipsoidal Earth; higher altitudes could be used, but no significant heating is expected above that altitude.

A total of over 1.25 million ORSAT cases were run to complete this comparison study, one of which was done by hand with "standard ORSAT assumptions" of initial conditions: initial FPA of -0.1° and traveling northbound at the equator at entry interface. Simulations that used AutoORSAT as the driver used initial states computed from GMAT; combinations of the FPA and latitude at entry interface can be seen in Fig 6.

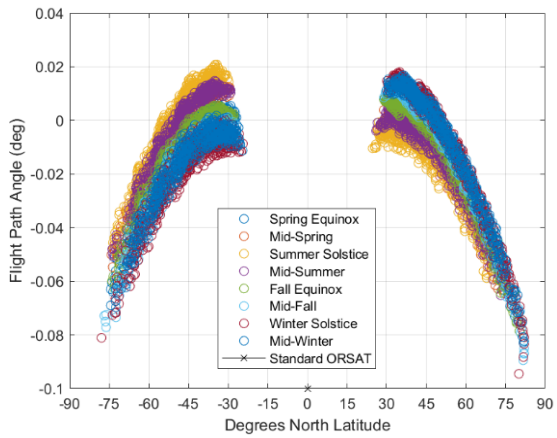

Figure 6. Variation of FPA with latitude at entry interface.

This sample satellite test case resulted in 43 surviving components (including multiples), with a total of 26 m^2 of DCA, under the standard ORSAT assumptions. Using the inclination-based, latitude-averaged population density for a 2051 reentry at 98.0° orbital inclination, this results in an expectation of casualty, E_c, of 1:2700. Analysis from AutoORSAT indicates that the DCA can vary between 21 m^2 to 29 m^2, depending on initial conditions. For these parametrically varied trajectories, we only use the latitude bands in which each component lands, which then yields a distribution like that seen in the right-hand plot of Fig. 7. It is important to note that while the DCA predicted by ORSAT is higher than 57% of the AutoORSAT cases, the E_c produced by the combination of the standard ORSAT analysis process and the sub-satellite population density is very near the mean of the large sample, an original goal of the development of ORSAT. The second important feature to note is that the E_c for the sample may be 1:3300, but a single trajectory may be up to 6 times worse than this; future research in design-for-demise strategies and implementing a targeted reentry at end of mission may be warranted to reduce the risk from these low-probability events.

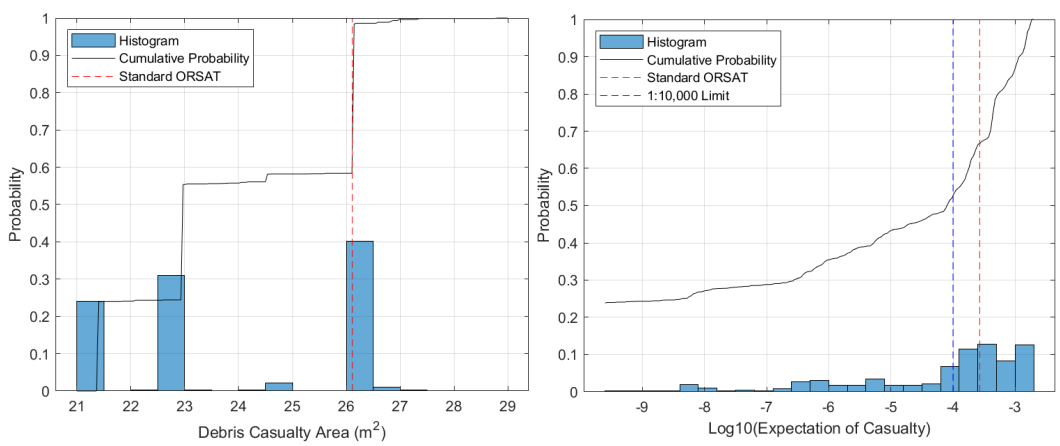

Figure 7. Histogram and cumulative distribution of DCA (left). Histogram and cumulative distribution of Ec (right)

5 CONCLUSIONS AND FUTURE WORK

This paper has presented the improvements to the ORSAT software suite from versions 6.0 through 6.2.1. These changes allow the feasible study of a wider range of parameters than previously possible. The new ORSAT analysis process allows ODPO analysts to better understand the risk envelope due to an uncontrolled reentry; analysis

indicates that the prior method of computing average risk from DCA, orbit inclination, and reentry year provided an accurate estimate, but the new method using AutoORSAT can capture both the best- and worst-case risk values.

In the future, routines will be written to allow for: spatially-varying heating distribution, conduction, and ablation; improved handling of aerodynamics and heating for hollow objects; improved composite material models that incorporate charring ablation and material strength; and a new model for heating and drag coefficients based on rarefied gas dynamics simulations.

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