CREATION OF DEBRIS CATALOGS USING FRACTAL FRAGMENTATION

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ABSTRACT

This paper details the approach employed in Australia by the Range Safety Template Toolkit (RSTT) for determining the fragmentation of aerospace vehicles. It outlines the development and implementation of the 'fractal fragmentation' concept and the creation of fragment lists ('debris catalogs') resulting from breakup due to both explosive and aerodynamic forces.

The approach is generic one in that it only requires an input of severity and the mass of the source object, and can be used to rapidly and inexpensively produce debris catalogs for vehicles whose exact details are not known. The inherent limitations and the overall fidelity of the approach compared to others are also discussed.

1. INTRODUCTION

Over the past several years, considerable progress has been made in the analysis of how space launch and re-entry vehicles break-up and what debris might survive.

Tools such as NASA's ORSAT (Object Re-entry Survival Analysis Tool) take an object-oriented approach that relies on assumptions about fragments (objects) and break-up altitude. The list of fragments is created by reviewing the spacecraft design and allocating major components into the fragment list. Minor components are ignored. [1]

ESA's SCARAB (Spacecraft Atmospheric Re-Entry and Aerothermal Break-Up) tool takes a spacecraft-oriented approach that involves creating geometric vehicle models and then simulating how breakup occurs in the extreme thermal and dynamic environment of launch and re-entry. [1]

By contrast, RSTT predicts vehicle fragmentation using a lower-fidelity statistical method known as 'unified fractal fragmentation' because the generation of fragments is primarily dictated by random processes which will tend towards certain distributions of fragments depending on the manner of the vehicle failure. The method is generic in that is does not require inputs relating to the vehicle construction or exact modes of failure.

RSTT is Australia's flight safety analysis system for space launch and re-entry Risk Hazard Analysis (RHA). Aerospace Concepts has previously presented work ([2],[3],[4],[5],[6]) describing the broad RSTT capability, theoretical underpinnings, operational user and regulatory needs and the development approach.

The material presented here on debris catalogs and unified fractal fragmentation is a summation of detailed internal reports ([7], [8]).

2. DEBRIS CATALOGS

Many of the failure modes of an aerospace vehicle can involve the vehicle breaking up into portions or fragments, usually through explosions or aerodynamic stresses. Thus any safety analysis of reasonably high fidelity must take into account the fragments created in such breakup events, and their effect at ground level.

The path of these fragments through the atmosphere and to the ground is greatly affected by their properties, as is the damage they may do when striking another vehicle, person, structure, etc. In RSTT, the description of these fragment properties (mass, area, ejection velocity, ballistic coefficient, etc.) is stored in debris catalogs. The fragment class properties can be thought of as the properties of a generic fragment representing all of the fragments statistically included in the class.

These catalogs are designed to provide the information required for the physical analysis each of the fragments. In RSTT such analysis is done by the 'debris propagator' tool as illustrated in Figure 1. This allows the determination of the Ground Impact Points (GIPs) and the effects of the debris, such as casualty expectation and individual risk.

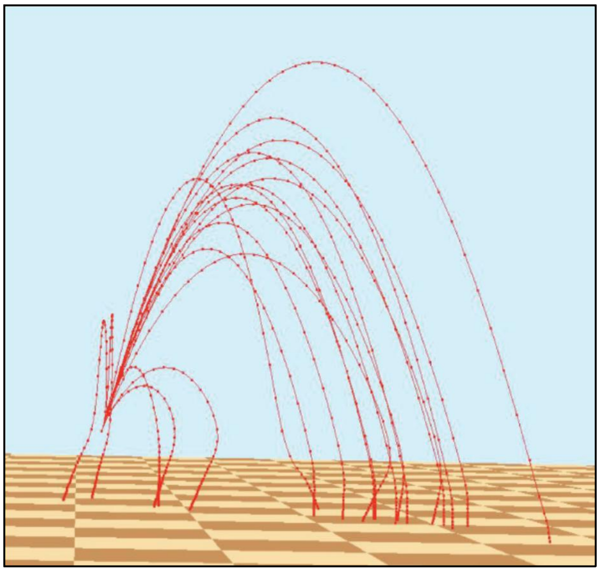

Figure 1. Possible trajectories from an inflight breakup of a launch vehicle early in ascent

Our methodology for debris catalog production enables a competent person to derive the catalogs for a particular mission for which a sufficiently detailed description exists.

The way debris catalogs are created in RSTT provides a lower fidelity but more generic approach to fragmentation than the spacecraft-oriented or object-oriented approaches used elsewhere. They are more easily derived and can be created for a class of vehicles where exact details are not known. Thus it is a less expensive and faster procedure to conduct a RHA, with massive Monte Carlo analysis providing additional confidence in the statistical significance of the results.

The severity of a breakup is estimated using the available energy, which gives a 'degree' of breakup. This, along with the mass of the source object, are the only inputs required to produce the debris catalog for that particular situation. Hence the distribution of fragments is not sensitive to the vehicle under consideration. However, provisions are made for the difference in construction between solid and liquid fuelled rocket motors.

3. RISK ANALYSIS PROCESS

Debris is defined to be any object that is generated from the main-body object during a flight and follows an unguided trajectory. As such, the motion of a debris piece, or fragment, can be predicted using 3 degrees-of-freedom (3DOF) equations of motion. This is the task of the 'debris propagator' tool as described below.

The generic process for an RHA, incorporating the use of debris catalogues, is shown in Figure 2. It involves the creation of a 6DOF model of the vehicle of interest from available technical data. This model includes both nominal and off-nominal (failure) behaviours. The model is simulated across a range of conditions using Monte Carlo analysis, where many runs are executed with random draws for each of the defined inputs. During a simulation, a vehicle may undergo a failure that leads to an explosion or aerodynamic breakup.

The debris catalogs listing all the fragments caused by an explosion or breakup are calculated *before* the vehicle simulation. A number of catalogues are derived for key times of the vehicles flight (e.g. during times of high dynamic pressure), in a way that all possible degrees of breakup will be accounted for.

During simulation, if a failure occurs, the relevant debris catalog is called upon. The fragment property descriptions from the debris catalogue, along with context data from the flight simulator (e.g. position and velocity of centre of mass), are passed to a 3DOF debris propagator. This propagator tool calculates the trajectories of the fragments from the failure position and determines the eventual Ground Impact Points (GIPs) of each debris piece. Note that parameters from the debris catalogs, such as the ejection velocity or the masses of the debris pieces, can be varied via the Monte Carlo method.

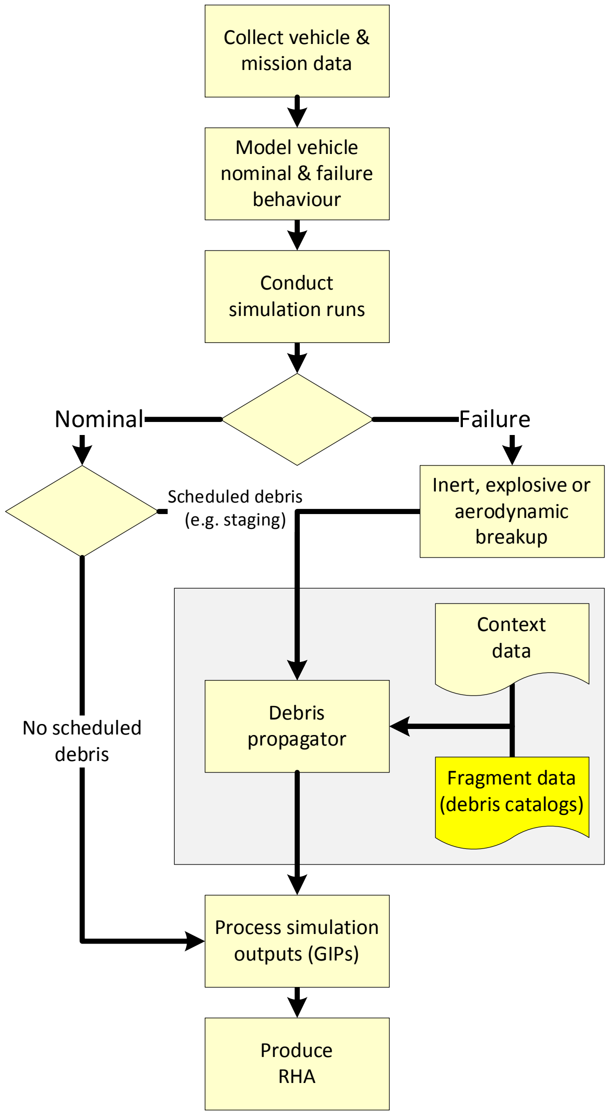

Figure 2. RHA process incorporating fragmentation

The outputs of nominal and failure simulations, that is, the GIPs, are then statistically processed to create Probability Density Functions (PDFs) of impact, as per the example in Figure 3, and from these are derived risk isopleths and, by application of risk criteria, an RHA.

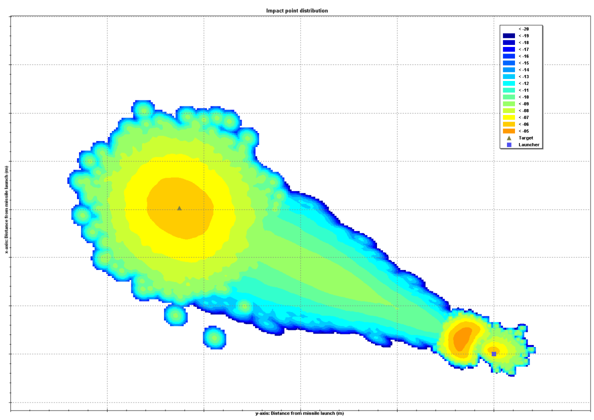

Figure 3. The PDF resulting from ground impact points of a generic sounding rocket launch

Importantly, RSTT does not assume any underlying distribution of impacts, and lets the shape of the PDF emerge from the numerous Monte Carlo simulations.

Usually for each debris class only one 'hero' debris piece is propagated, and statistical methods are used to scale the probability density for that one piece to all debris in that class, producing an appropriately conservative estimate of impact probability density for all actual debris pieces. Otherwise, every single fragment would have to be modelled and tracked individually, so considerable computing run time is saved. This assumption can be made because there is no particular reason why, with the kernel density estimation technique used, generating PDFs from scaled distributions is any different to generating them from impact points.

One simplifying assumption made by RSTT is that all debris is propagated from the centre of mass of the vehicle, with the initial velocity of the centre of mass plus the randomly-sampled ejection velocity of that debris class as specified in the debris catalogue. This will have little effect on the calculated risk on the ground as the dimensions of the vehicle are small in comparison to the effect of variation that Monte Carlo draws on ejection velocities provide in the trajectory of the fragment.

4. DEBRIS CATALOG METHODOLOGY

4.1. Introduction

This section describes the methodology for creation of debris catalogs. It refers to fragmentation in terms of 'degrees' which define the severity of breakup determined by the unified fractal fragmentation technique used by the 'fragmentation tool'.

How unified fractal fragmentation is used to derive each of the degrees in the fragmentation tool for aerodynamic and explosive breakups is described in the next section.

4.2. Inert events

Debris may be created during a nominal vehicle flight from items such as spent stages, fairings and payloads. This is known as 'scheduled debris'. Other inert events include when components fail to separate or ignite, and the debris that results. This type of debris consists of whole vehicle components rather than fragments, and is not covered in great detail in this paper. The information necessary to create debris catalogues for these objects comes easily from component design and simple empirical or computational analysis tools for things such as moments of inertia or drag to be used in the debris propagator.

4.3. Explosive breakup

Explosive breakup events (for example, a case burst in a propellant tank) are most likely to occur at specific times during a flight. Explosions of solid rocket motors can only occur when pressurised, i.e. during a burn, and are little affected by the flight environment.

The intensity of a potential explosion is estimated either from a table of known cases by similarity, or by calculation of the stored energy and casing characteristics. This results in a fragmentation degree between 0 and 6 which is passed to the fragmentation tool to create the appropriate debris catalog for the given degree. For explosive breakups, the 'explosion tool' gives an average debris velocity for each mass class – this average velocity is later used as a statistical distribution of excess debris velocity which is simulated using Monte Carlo methods in order to propagate the debris towards the ground with varying ejection velocities and directions.

4.4. Aerodynamic breakup

The occurrence of aerodynamic breakup is much more complex than explosive fragmentation. It occurs when the flight environment imposes loads in excess of the structural capacity, and thus depends on the trajectory, dynamic pressure and wind shear traces with time, as well as the vehicle attitude. For example, on a sounding rocket mission there are opportunities for loss of control or breakup when the dynamic pressure peaks at both ascent and re-entry.

The flowchart shown in Figure 4 is used to track possible aerodynamic breakup modes for a launch vehicle such as a sounding rocket.

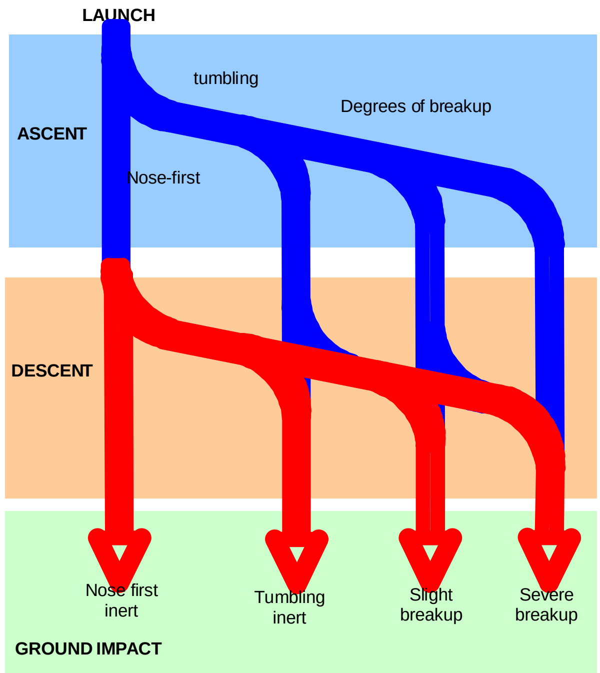

Figure 4. Flowchart for vehicle aerodynamic breakup

The attitude and dynamic pressure history are found from flight simulation for both nominal and off-nominal (failure) modes. The likely survival dynamic pressure of the vehicle is selected from the designed mission safety factors. The ratio between the actual dynamic pressure and the maximum design dynamic pressure gives the 'Over Pressure' (OP) ratio.

Thermal effects are estimated using the 'energy velocity' of the vehicle which is defined as the velocity that would prevail if the object fell in a vacuum to a reference altitude. This is a crude method of estimating the heating experienced and the effect on fragmentation. We use energy velocity because of its simplicity. It is most accurate for flat trajectories where a high velocity is sustained for minutes and hence the surface temperature can approach equilibrium.

A more accurate model for heat transfer is possible, which also uses velocity but also takes account of density, and possibly the time trace. This would require an analytical process of greater complexity than we use at present.

The OP ratio and energy velocity are input into an 'aerothermal map', shown in Figure 5, to determine whether the vehicle tumbles or not and which aerothermal breakup regime the vehicle experiences.

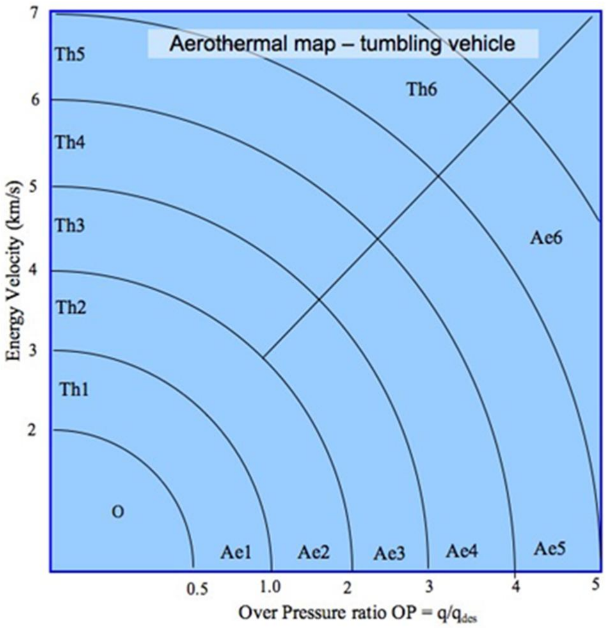

Figure 5. Aerothermal map

This regime is passed to an 'aerothermal breakup tool' is used to give the degree of fragmentation for the given situation. This degree can then be input into the fragmentation tool, in the same manner as explosive breakup. The aerothermal breakup tool also provides a description of typical fragments for known classes of vehicle, which can be used to verify the contents of the debris catalog as output by the fragmentation tool.

Note that the method currently only treats thermal effects in a crude manner and more work would be required to reasonably estimate fragmentation due to orbital re-entry.

4.5. Representative fragments

The pieces of debris in each catalog have been tuned for the respective degree of breakup according to known data (i.e. fragments found on the ground) from different breakup situations. The debris catalogs are created 'offline', and propagated directly from the point of failure to the ground with no consideration for secondary breakup. Thus the debris catalogs must be created such that the fragments in the debris catalog are representative of the fragments that would be expected to be found *on the ground* after the vehicle breakup. This has some consequences described in Section 5.5; however, one major benefit is that these pieces are the most accurate verification data sets available.

5. UNIFIED FRACTAL FRAGMENTATION

5.1. Introduction

Unified fractal fragmentation seamlessly handles explosions, aerodynamic breakup and combinations of the two and for any intensity of breakup ranging from several pieces to thousands of fragments. It has been tuned and verified against known real cases.

5.2. Concept

Unified fractal fragmentation assesses the excess energy available in an aerodynamic breakup or explosion scenario, and covers both events occurring separately or together.

The vehicle breaks into a small number of fragments with certain mass ratios, and then each fragment breaks into sub-fragments in the same ratios creating the next 'degree' of breakup as shown in Figure 6. The degree can vary from 1 to 6, depending on the excess energy available, as estimated from the explosion energy per unit mass, or the dynamic pressure and heating compared to the structural limits of the vehicle.

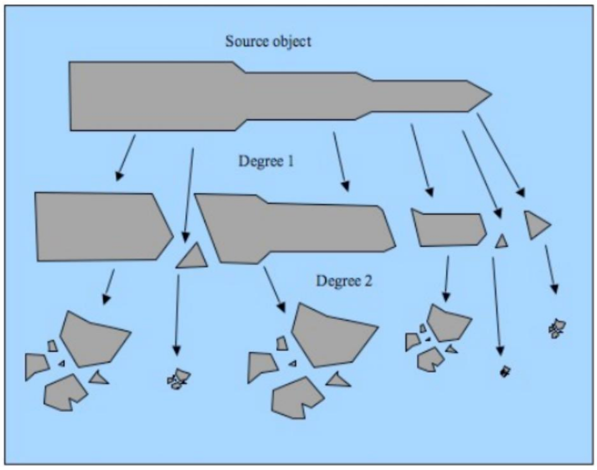

Figure 6. The principle of fractal fragmentation

The process continues until the source of energy causing breakup has dissipated sufficiently hence the name 'fractal' which means repeating successively at smaller scales. It is important to note that this is done by assessing the total energy at the 'worst case' point of flight and *not* progressively through breakup.

The theory provides a basis for the distribution of fragment counts to be tuned to match a specified degree or level of breakup. It also provides the ability to bridge gaps between known data points.

5.3. Fragment masses

Predicted fragments masses are implemented as fixed mass classes to avoid needing to track excessive numbers of fragments. These mass classes or 'bins' are created at the rate of four per decade thus for a 1000kg object there will be 6 decades and 25 mass classes.

A set of 'convolution coefficients' represents the initial breakup, the degree 1 fragments, but as a statistical model with fractional count of masses in each class. These coefficients are effectively the tool that is used to allow the 'tuning' of the degrees of breakup.

This set of convolution coefficients when applied to the source mass, gives the degree 1 fragment count distribution shown in Table 1 for a source object of mass 1000kg.

Table 1. Fractional counts for 'degree 1' convolution

Mass	1000	562	316	178	100	56.2	31.6	17.8	10
Count	0	0.85	0.8	0.7	0.7	0.8	0.5	0.5	0.49

This means the 1000 kg source object breaks into 0.85 fragments of 562 kg, 0.8 fragments of 316 kg, and so on, down to 0.49 fragments of 10 kg. The fractional counts are necessary because only certain masses (the 'bins') are available.

The degree 1 distribution is then convolved using the convolution coefficients such that every degree 1 fragment is broken in the same proportions to create the degree 2 fractional counts as shown in Table 2.

Table 2. Fractional counts for 'degree 2' convolution

Mass	> 316	316	178	100	56.2	31.6	17.8	10
Count	0	0.722	1.36	1.83	2.31	2.97	3.11	3.26

Mass	5.62	3.16	1.78	1.0	0.56	0.32	0.18	0.10
Count	3.44	2.82	2.18	1.73	1.28	0.74	0.49	0.24

This process is repeated iteratively to produce the mass distribution of fragment counts for all six degrees of breakup (or as far as is needed).

Tuning can be used to accommodate additional data sets from known cases as these become available. The convolution coefficients can be adjusted systematically, which in turn changes the resulting fragment counts in each mass bin. Through tuning, the output debris catalog is made to reflect what would be expected when comparing to a known data from a case of similar degree or severity of failure.

5.4. Ballistic coefficients

As well as a mass distribution, any fragmentation model should also predict ballistic coefficients.

A study of available data relating to high-speed re-entry of liquid rocket and satellite objects showed a quite simple relationship between mass and drag – if a fragment of any mass is regarded as a sphere with a certain density, then the cross sectional area of that sphere was a good predictor of the area of the fragment. The central value for density was 316 kg m^{-3} and the spread was from 100 kg m^{-3} to 1000 kg m^{-3}.

Thus, the best method for generating fragment densities was a random draw giving a Gaussian distribution of density. The current implementation is simpler – it splits each mass class into halves, one of density 100 kg m^{-3} and the other of density 1000 kg m^{-3}.

As shown in Figure 7, this ballistic coefficient model was found to fit fragments from the HyCAUSE mission quite well (which involved a solid rocket motor and a rugged propulsion experiment).

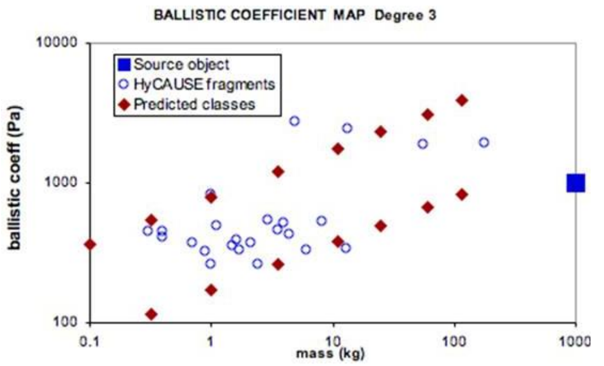

Figure 7. Ballistic coefficient versus mass for degree 3 comparison to a real case

More recently however, low-speed liquid rocket fragments were compared, and the ballistic coefficient model was found wanting. It also underestimated the basic casualty area. It needs more low-density fragments to represent the thin skins (6 mm) used. Such fragments are absent from the original high-speed data sets due to ablation and from the HyCAUSE mission which used solid-propellant rocket motors.

Thus, an interim modification is proposed for liquid fuelled vehicles – to input densities of 316 kg m^{-3} to represent heavy subsystems, and 10 kg m^{-3} to represent skin fragments. This model may be refined when sufficient data is available. In the meantime, use of unified fractal fragmentation for liquid-fuelled vehicles is currently not recommended.

5.5. Secondary breakup

Fractal fragmentation does not accommodate well the secondary breakup of debris, an occurrence predominately found in re-entry cases. This is due to the way the debris catalogs are effectively created 'offline', for a given scenario (e.g. stage 1 booster explosion late in the burn), whereby the degree for the breakup is chosen by assessing the total available energy for the failure as determined from the simulation.

Another assumption made is that the breakup is assumed to occur, and all fragments created, in an instantaneous moment. The assumption of an instantaneous release of energy is a good approximation in cases where the source of energy is dissipated within a fraction of a second (e.g. explosions). For secondary breakup to occur, a source of energy is required to continue the breakup further. Such a source can be provided during the process of re-entry by the kinetic and gravitational potential energies of a vehicle. In such situations it is aerodynamic breakup that is occurring, however the energy being dissipated by the re-entry is the energy creating further fragmentation, until the fragments are small enough that they no longer break apart or demise and eventually impact the ground.

The debris catalog used in RSTT is still able to take into account the overall energy of the breakup, and replicate the final fragments that would be found on the ground. However, because these fragments are propagated immediately from the failure position, their aerodynamic properties will be different to an object that is continually breaking into smaller fragments from one large fragment. Thus it can be seen that, while the fragments that impact the ground may have the same properties in both cases, the physical processes behind the flight are different due to the latter having changing properties with respect to time. This will lead to different dispersions of the fragments on the ground.

5.6. Verification against other tools

The fractal fragmentation method has been compared with known cases of explosion and breakup, including aluminium-skinned sounding rockets, launch vehicles, payload experiments, and satellites. It was found that with minimal and once-only tuning, the model matches known data ranging in severity from a few fragments (degree 1) to thousands of fragments (degree 4).

This is shown in Figure 8 which shows verification, against fragmentation outputs of ESA's Cloud Debris Simulator (CLDSIM). Here the distribution of fragments was tuned so that degree 4 would match the CLDSIM data.

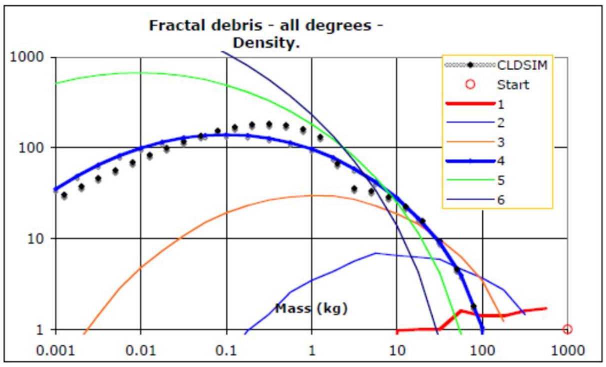

Figure 8. PDF for mass distribution of fragments

6. EXAMPLE DEBRIS CATALOGS

Two example debris catalogs are given below in Table 3 and Table 4. They show the fragment data for a 1000 kg source object after a degree 4 aerodynamic breakup and a degree 1 explosion respectively.

Table 3. Degree 4 aerodynamic breakup debris catalog for a 1000 kg source object

FRAGMENT DATA										
DEBCAT NO =	8	SOURCE OBJECT =	Stage 1 with 25% propellant		FAILURE MODE =	Case burst			DATE	17/04/2008
INPUT DATA							CALCULATED DATA			
CLASS NO	FRAGMENT COUNT	FRAGMENT MASS	AREA	EXPLOS EJECTION VELOCITY	COEFF OF DRAG (subsonic)	LIFT /DRAG (subsonic)	EQUIVALENT DIAMETER	BALLISTIC COEFFICIENT	TERMINAL VELOCITY	KINETIC ENERGY
		m av (kg)	(m2)	m/s			-	Pa	m/s	J
SOURCE	1	1000		NA	NA	NA	NA	800		
1	1	70	0.95314	0.0	0.9	0.1	1.102	800	36.2	45917
2	1	70	0.20535	0.0	0.9	0.1	0.511	3715	78.0	213128
3	4	30	0.5418	0.0	0.9	0.1	0.831	603	31.5	14837
4	4	30	0.11673	0.0	0.9	0.1	0.386	2801	67.8	68866
5	9	11.5	0.28591	0.0	0.9	0.1	0.603	438	26.8	4131
6	9	11.5	0.0616	0.0	0.9	0.1	0.280	2034	57.8	19177
7	14	5.00	0.16409	0.0	0.9	0.1	0.457	332	23.3	1361
8	14	5.00	0.03535	0.0	0.9	0.1	0.212	1541	50.3	6316
9	23	2.55	0.10474	0.0	0.9	0.1	0.365	265	20.9	554
10	23	2.55	0.02257	0.0	0.9	0.1	0.170	1231	44.9	2574
11	48	1.000	0.05612	0.0	0.9	0.1	0.267	194	17.8	159
12	48	1.000	0.01209	0.0	0.9	0.1	0.124	901	38.4	739
13	63	0.316	0.02603	0.0	0.9	0.1	0.182	132	14.7	34
14	63	0.316	0.00561	0.0	0.9	0.1	0.085	614	31.7	159
15	69	0.100	0.01209	0.0	0.9	0.1	0.124	90	12.2	7
16	69	0.100	0.0026	0.0	0.9	0.1	0.058	418	26.2	34
17	64	0.0316	0.00561	0.0	0.9	0.1	0.085	61	10.0	2
18	64	0.0316	0.00121	0.0	0.9	0.1	0.039	285	21.6	7
19	49	0.0100	0.0026	0.0	0.9	0.1	0.058	42	8.3	0
20	49	0.0100	0.00056	0.0	0.9	0.1	0.027	194	17.8	2
21	33	0.0032	0.00121	0.0	0.9	0.1	0.039	28	6.8	0
22	33	0.0032	0.00026	0.0	0.9	0.1	0.018	132	14.7	0
23	15	0.0010	0.00056	0.0	0.9	0.1	0.027	19	5.6	0
24	15	0.0010	0.00012	0.0	0.9	0.1	0.012	90	12.2	0
TOTALS	784									

Table 4. Degree 1 explosive breakup debris catalog for 1000 kg source object

FRAGMENT DATA										
DEBCAT NO =		SOURCE OBJECT =			FAILURE MODE =				DATE	
INPUT DATA							CALCULATED DATA			
CLASS NO	FRAGMENT COUNT	FRAGMENTMASS	AREA	EXPLOS EJECTION VELOCITY	COEFF OF DRAG (subsonic)	LIFT /DRAG (subsonic)	EQUIVALENT DIAMETER	BALLISTIC COEFFICIENT	TERMINAL VELOCITY	KINETIC ENERGY
		m av (kg)	(m^2)	m/s			-	Pa	m/s	J
SOURCE	1	1000		NA	NA	NA	NA	320		
1	1	540	3.72	16.1	0.9	0.1	2.177	1581	50.9	699898
2	1	255	0.49	37.1	0.9	0.1	0.787	5715	96.8	1194620
3	1	125	1.40	24.2	0.9	0.1	1.337	971	39.9	99477
4	1	50	0.16	56.4	0.9	0.1	0.457	3320	73.8	136083
5	1	25	0.48	37.3	0.9	0.1	0.782	568	30.5	11635
6	1	5	0.04	99.2	0.9	0.1	0.212	1541	50.3	6316
TOTALS	6	1000								

Each fragment class contains assigned properties ('input data'), such as count, mass and ejection velocity (explosions). Each class also contain properties derived from the debris catalog methodology and fractal fragmentation, including equivalent diameter, ballistic coefficient and kinetic energy.

7. COMPARISON OF METHODS

This paper describes the use of unified fractal fragmentation, which is in essence a statistical approach to the creation of debris catalogs that is used in conjunction with the RSTT debris propagator to determine GIP and produce RHAs.

The object-oriented approach used by, for example, NASA's ORSAT assumes the breakup of a vehicle into a number of defined shapes with assigned material properties. ORSAT analyses each of the shapes to determine whether they demise completely, partially, or impact the ground during re-entry. By tracking the progress of each piece they are able to determine the effects of the debris and hence produce a safety template.

The spacecraft-oriented approach used, for example, by ESA's SCARAB tool works in a similar manner, however a higher fidelity, very detailed model of the vehicle is created, and breakup is not assumed to occur. During re-entry every part of the vehicle is monitored, and fragmentation will occur if thermal or aerodynamic stresses overcome the applicable structural material limits. Any piece to break away from the 'parent' body is then tracked for further fragmentation, total demise, or ground impact.

These differences between the object-oriented and spacecraft-oriented approaches on the one hand and fractal fragmentation on the other make them complementary. Fractal fragmentation can benefit from tuning against debris output by the other methods. However, fractal fragmentation can also be easily tuned and verified against known cases. Hence it can provide back a simplified distributions and debris list estimates for a range of vehicle types. These can be used for verification purposes or for when money, data and time do not permit a more detailed analysis.

8. CONCLUSIONS

RSTT uses a technique called unified fractal fragmentation for determining the fragmentation behaviour of aerospace vehicles. The technique is generic and gives rise to debris catalogs where only a severity of breakup and mass of the object are required as inputs. Thus, expected distributions of fragments can be estimated for vehicle classes, or where exact details are not known. Fractal fragmentation is also easy to apply, and allows for the faster, cheaper production of debris catalogs and, hence, RHAs. Furthermore, the technique can be easily tuned to match known cases thus increasing confidence in the utility of the outputs.

Although of lower fidelity than other available tools such as ESA's SCARAB and NASA's ORSAT, and assuming the distributions of fragments are accurate for a given vehicle, the results can still be used to produce high fidelity risk assessments when used in conjunction with Monte Carlo simulation in the greater RSTT. The different methods are also complementary in that the fractal method takes the types of outputs produced by the other methods and generalises them for given vehicle configurations and failure modes.

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