

A Fractal Fragmentation Model for Breakup of Aerospace Vehicles

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Summary: When space launches, missile tests and weapons trials are held, a comprehensive range safety analysis is required, in order to protect personnel, assets and the general public. In such cases, many of the failure modes of the vehicle result in the explosion or aerodynamic breakup of a portion of the vehicle.

To date there has been no unified method of estimating the fragment properties resulting from such breakups. The fractal fragmentation model uses an iterative fractal method – in the first degree the vehicle breaks into small number of fragments with certain mass ratios, and then each fragment breaks into sub-fragments in the same ratios, and so on. 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 actual dynamic pressure and heating compared to the structural limits of the vehicle. The one model seamlessly handles explosions, aerodynamic breakup and combinations of the two, for any intensity. It has been tuned and verified against known real cases.

Keywords: aerospace vehicle, fragmentation, aerodynamic breakup, explosion, debris catalog, fragments, ballistic coefficient, range safety.

Introduction

Flight safety analysis is required in order to estimate risk to the uninvolved public, involved personnel, other vehicles, and to property, from space launches, missile tests, etc. The flight safety analysis system to which this paper refers is the Range Safety Template Toolkit (RSTT), which has been described previously at several conferences [Ref 1,2]. RSTT was developed by the Defence Science and Technology Organisation (DSTO). It is for use with international projects such as the HIFiRE scramjet tests [3,4,5,6], weapons trials, and for the space licensing by SLASO [7].

Such a system needs to consider all credible malfunctions and also nominal events in order to evaluate risk (both probability and severity). Most such failure modes involve the vehicle fragmenting (breaking into pieces), usually through explosion or aerodynamic stresses. The statistical descriptions of these fragment properties are called debris catalogs.

The path of these fragments through the atmosphere and to the ground is greatly affected by their properties, as illustrated in Figure 1.

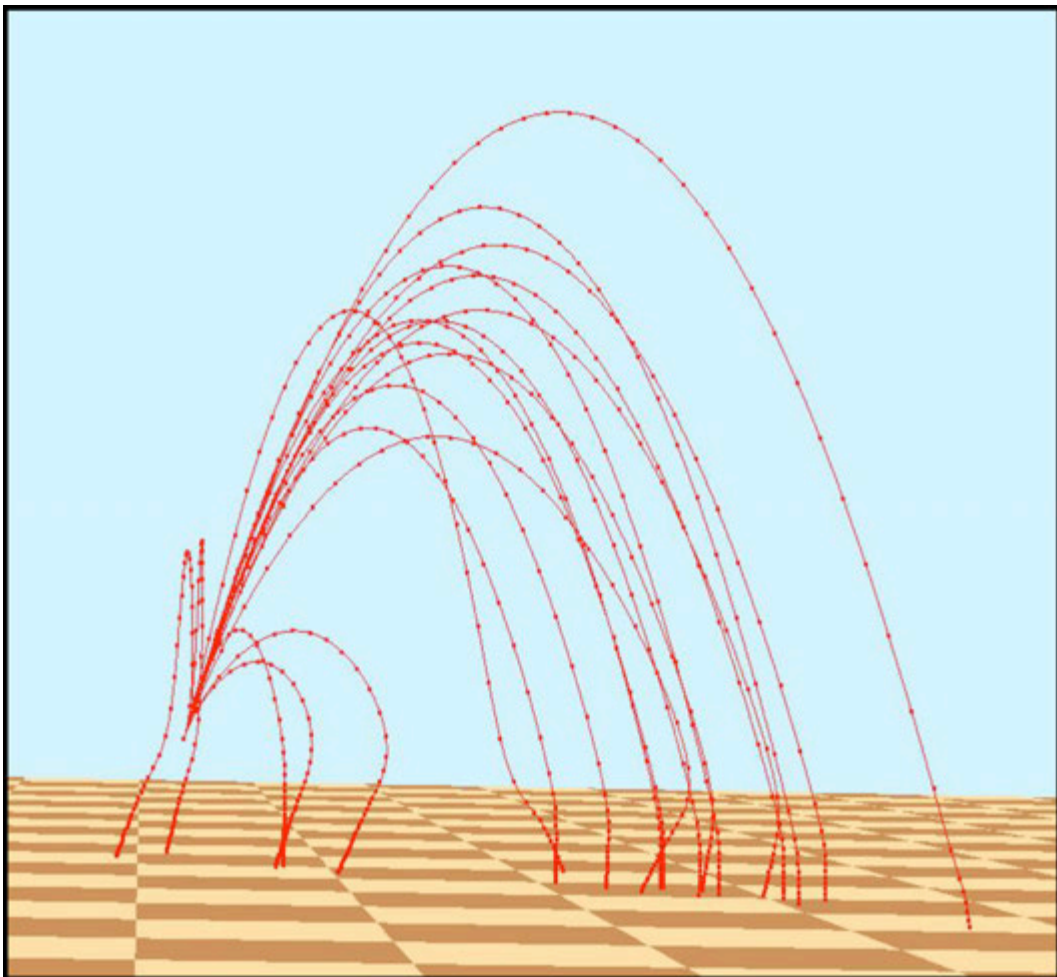


Figure 1: Possible fragment trajectories for an inflight breakup of a rocket.

The potential damage when fragments strike the ground, a person or an asset also depends on their mass, area, reactivity (ability to burn or explode), and the like. Existing methods of estimating the fragments [4,5,12] appear to rely on finding the most similar known case. Given that the number of fragments varies from 2 to 10,000, this does not provide a general method.

Debris Catalog Methodology

A Methodology has been developed [9,10,11] by the lead author, which contains complete and detailed instructions to enable a competent person to derive the debris catalogs for a particular mission for which a sufficiently detailed description exists. The Methodology includes a number of software tools and charts.

The types of failure that can occur during the flight are identified, along with the time windows when this is possible. 'Flight maps' are constructed – selected from thrust, mass, dynamic pressure, heat input, velocity, altitude - to show the relevant stressors for various failure modes during the various flight phases. For inert, explosive and aerodynamic failures, several distinct at-risk conditions or times are identified, at which debris catalogs will be generated. Guidelines are given to be sufficiently representative of the whole flight while not imposing too onerous a computational load – a mission might require 10 to 20 debris catalogs.

Explosive fragmentation

Two examples of the timing of failure are discussed. Explosions of solid rocket motors can only occur when pressurized, i.e. during the burn, and are little affected by the flight environment. Two debris catalogs might be assigned, representing the mass of propellant at ignition and at 75% consumed. The failure probability trace would have an impulse at ignition and then a steady value until burnout – without depending on external factors.

The range of possible explosions is indicated in Figure 2.

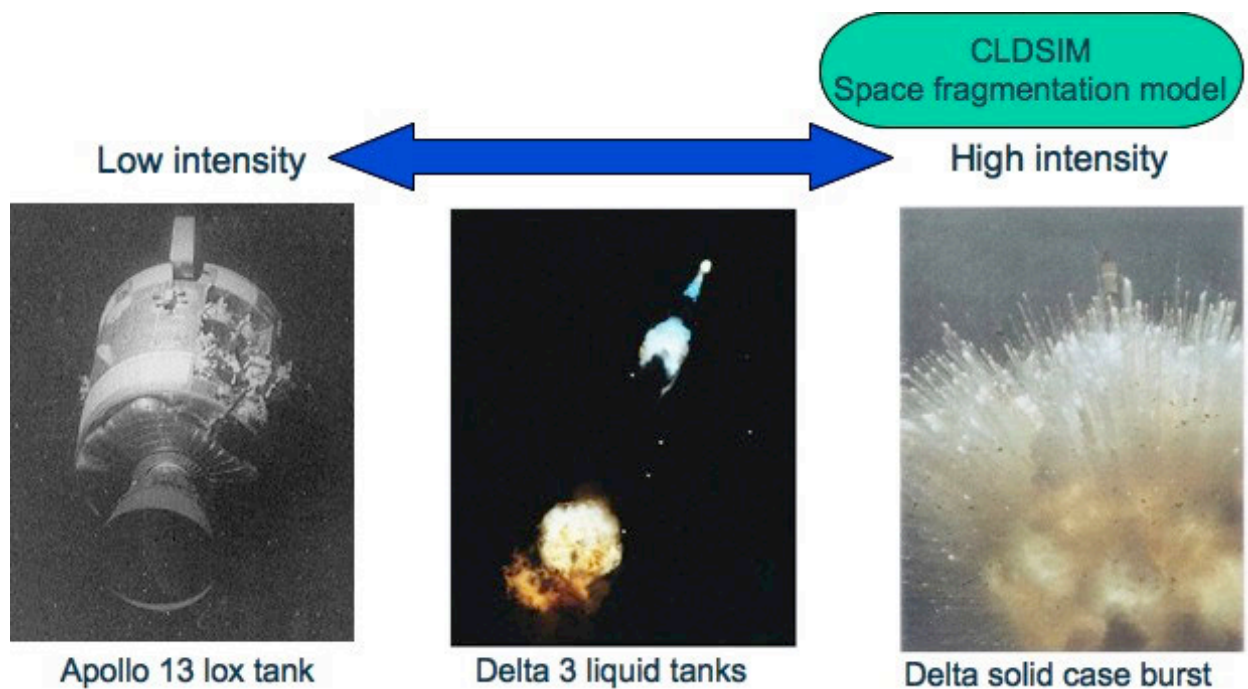


Figure 2: A range of possible explosions of flight vehicles.

In this Methodology, the intensity of a potential explosion is estimated using the *explosion tool* - 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*. Also included is guidance on how an exploding stage is likely to affect adjacent side-by-side or in-line stages.

The green box refers to a known benchmark used for calibration – the CLDSIM model of space fragmentation managed by the Italian space agency and adopted by ESA [7].

Vehicle Attitude History

The occurrence of aerodynamic breakup is much more complex. It occurs when the flight environment imposes loads in excess of the structure's capacity, and thus depends on the trajectory, dynamic pressure and wind shear traces with time, as well as the vehicle attitude. A flowchart is used to track attitude and breakup modes as shown in Figure 3.

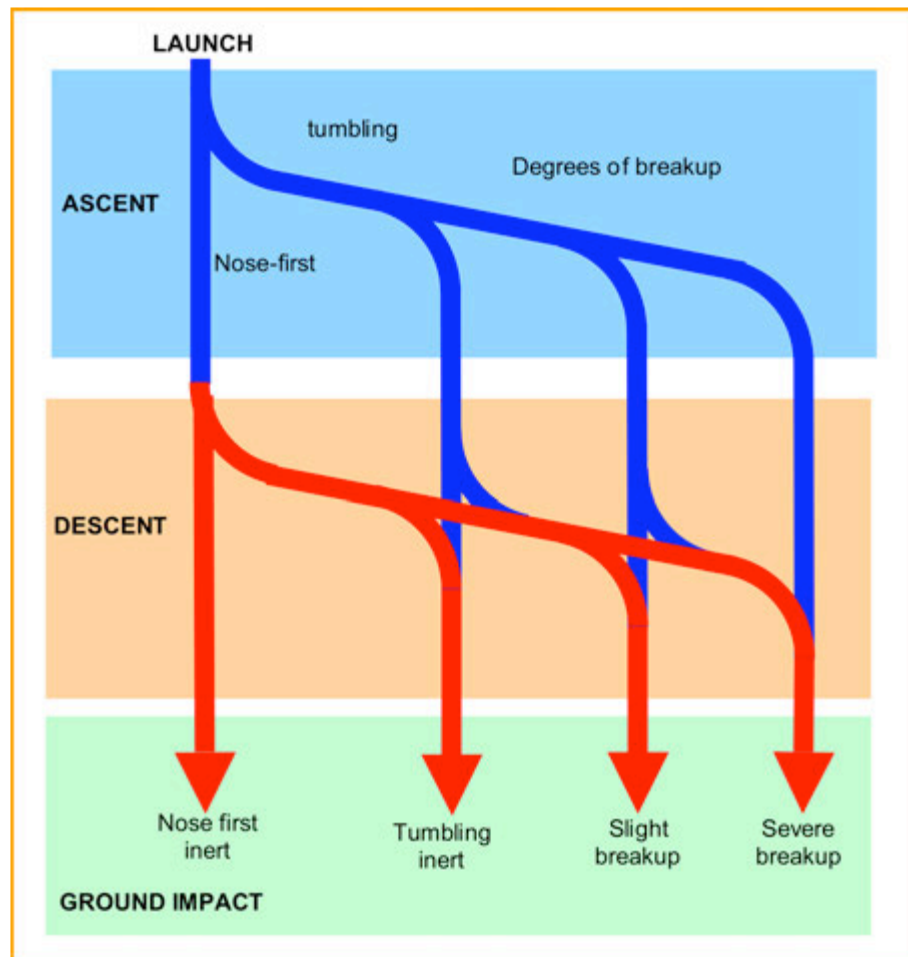


Figure 3: Flowchart for tracking sounding rocket attitude modes and degree of breakup.

For such a sounding rocket mission there are opportunities for loss of control or breakup when the dynamic pressure peaks at both ascent and re-entry.

Aerothermal Overstress

The attitude and dynamic pressure history are found from flight simulation, including the failure behaviour, if applicable. For relevant configurations the likely survival dynamic pressure is estimated from the designed mission and safety factors. The ratio of these is the overstress factor. Weakening by heating at high velocities is also estimated.

These two factors are input to one of several “aerothermal maps”, such as Figure 4, which then predicts a thermal or aerodynamic *regime*, indicating the severity and type of overstress.

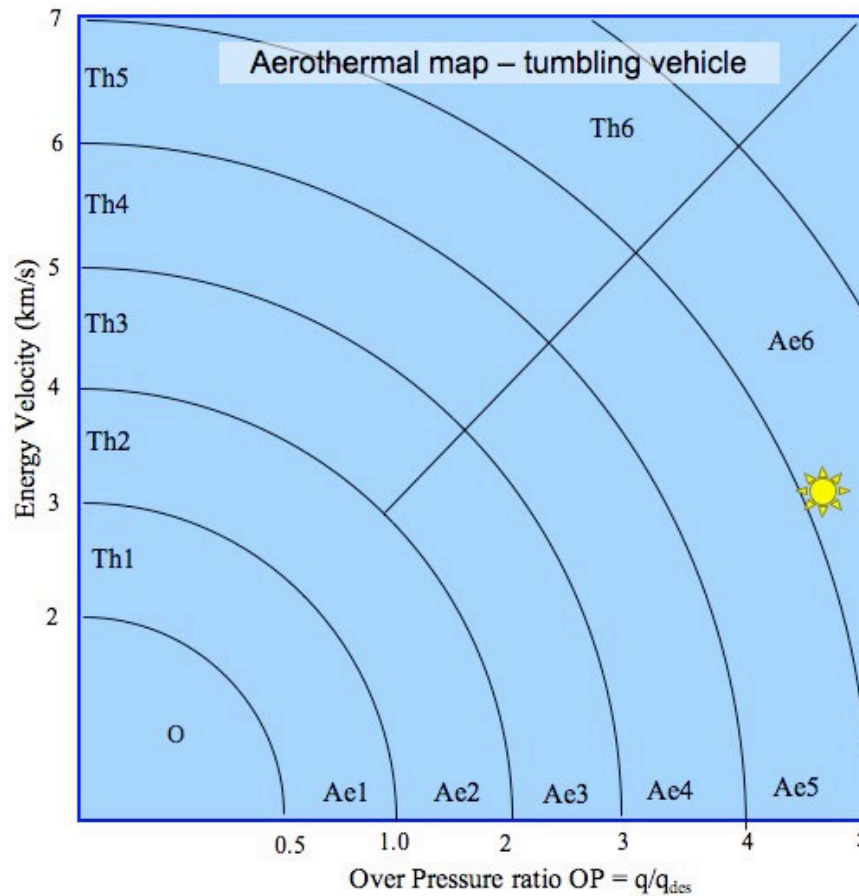


Figure 4: Aerothermal Map used to predict degree of breakup.

This regime is passed to the *breakup tool*, in which a table is used to output a *degree*, for passing to the *fragmentation tool*. The tool also provides a description of typical fragments for known classes of vehicle, such as conventional aluminium-skinned launch vehicles, or hypersonic propulsion experiments.

A range of possible breakups is illustrated in Figure 5. The green boxes are again known cases which are used for calibration and verification. The rule of thumb refers to a simple observation by the US consultancy ACTA [4], whereby first breakup may often be typified by fragments in the ratio $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{6}$. A Degree 1 fragmentation, which is discussed in the next section, matches this rule well.

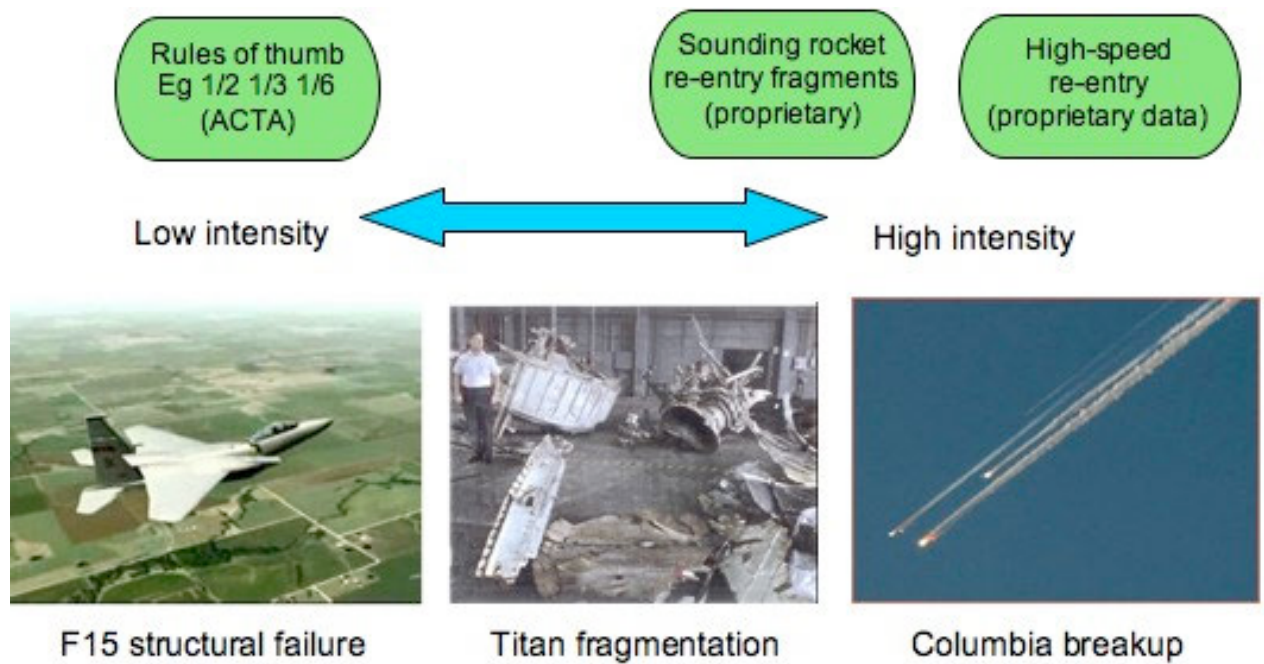


Figure 5: A range of possible aerodynamic breakups.

Using this and other tools, a list of candidate failure modes is derived, associated with their probability timeline and degree of breakup. Associated with each is of course the vehicle configuration, position and velocity. This data set is then passed to the Fractal Fragmentation Model which is described in the next section.

Fractal Fragmentation

The Principle

The path of 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 the past there has been no comprehensive method for predicting the fragmentation of vehicles in flight. Instead, the practice has generally been to select the most similar known case and perhaps adjust it to the current situation.

A fragmentation model was sought which would have some theoretical basis and also be capable of being tuned to match known cases. The model should also cover all degrees of fragmentation, from several pieces to thousands. This was achieved using a fractal method. As a bonus, it seamlessly covers explosion and aerodynamic breakup, and everything in between.

The model is based on the fact that energy is required for the breakup, and may come from an internal explosion, or from excess dynamic pressure perhaps in combination with heating. The theory is 'fractal fragmentation' whereby the vehicle first breaks into, say, six fragments with a certain distribution. Then if sufficient energy (in the form of gas flows) remains, each fragment independently breaks again into six more fragments in similar proportions, and so on, to any 'degree' (which can even be fractional). The concept of this process is illustrated in Figure 6.

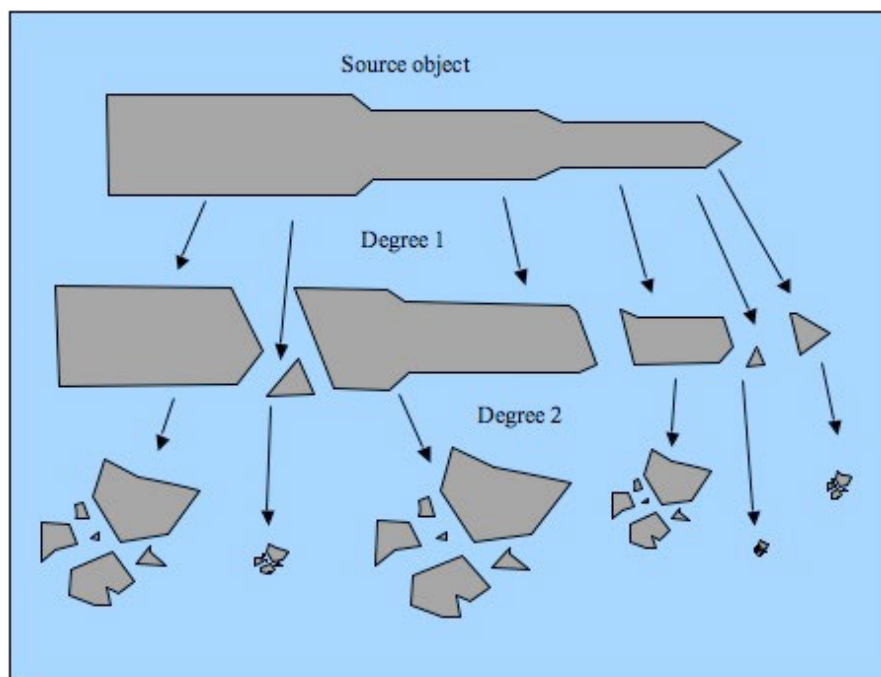


Figure 6: The principle of fractal fragmentation.

Development

Implementation of the fractal fragmentation model required a once-only development process, as shown in Figure 7.

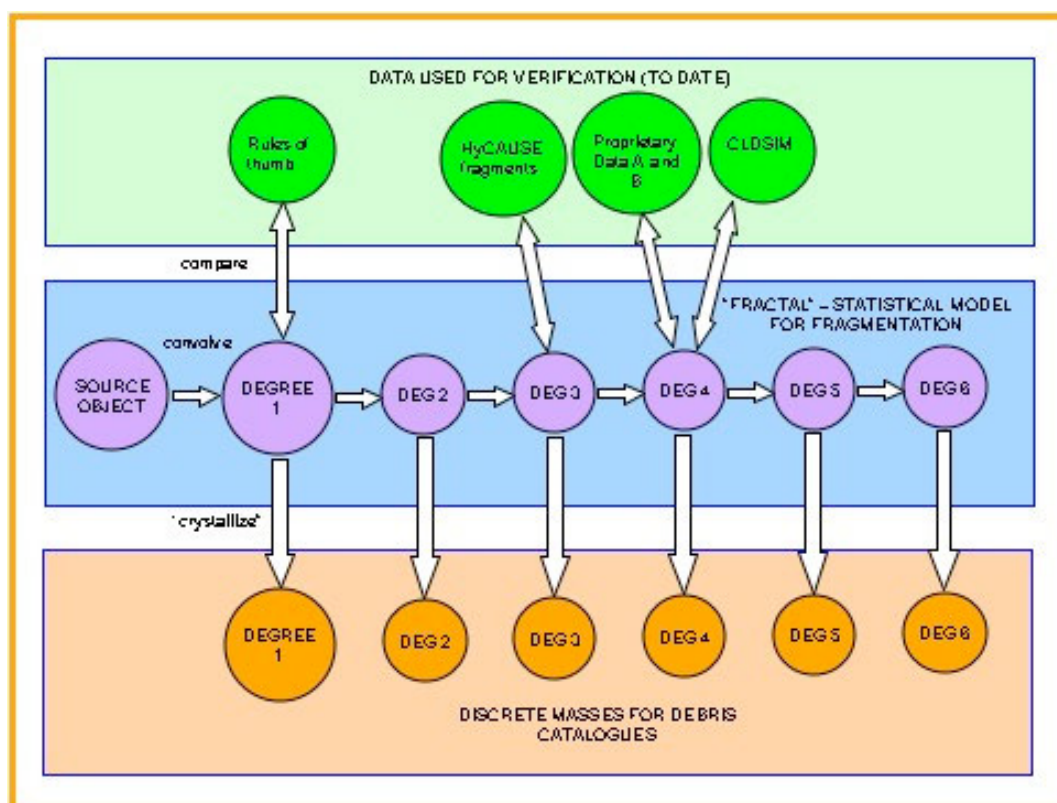


Figure 7: Mathematical implementation of Fractal Fragmentation.

A trial set of fragments in fixed mass bins was identified, and numerical convolution used to automatically repeat the breakup 1 to 6 times. The basic breakup (equivalent to Degree 1) was tuned such that higher degrees provided statistical matches to known cases where

fragments were recovered and measured. It was found that 8 basic fragments for each degree were sufficient. However, the numbers in each bin were not integers, so additional processing was required.

The resulting probability density function for the mass distribution of the resulting fragments is shown in Figure 8 for Degrees 1 to 6.

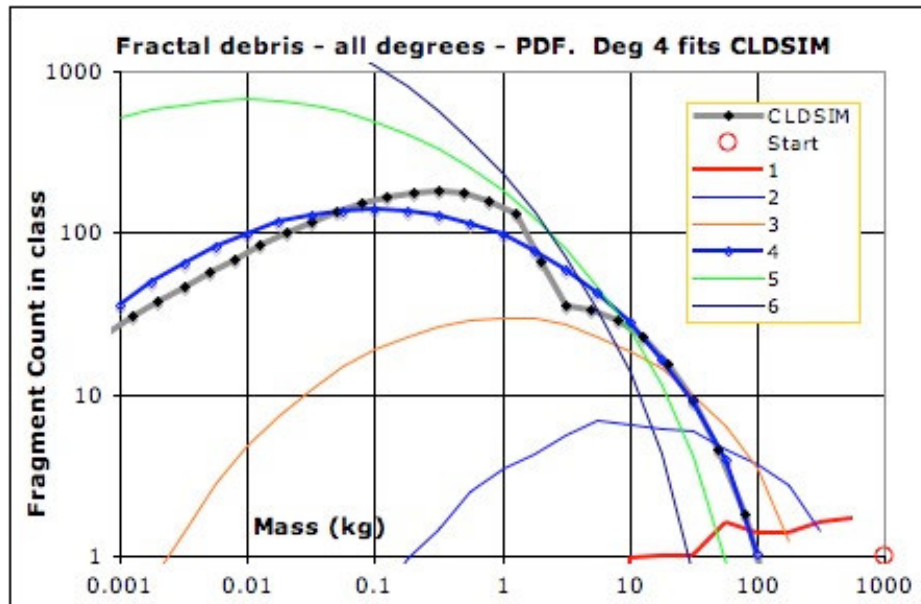


Figure 8: PDF for mass distribution of fragments.

Also shown in Figure 8 is the PDF for CLDSIM - the ESA standard for space debris. The model's Degree 4 fragmentation is a very good fit to CLDSIM, after tuning as described above. Note that the dip in CLDSIM is acknowledged to be a mathematical artefact and should not be there. This could indicate that our new model provides a superior description of the underlying fragmentation process.

Note also that CLDSIM represents many real space debris cases rolled into one ensemble, which is only one population, whereas our model provides for varying intensity and varying source object mass.

Implementation in the Methodology – Medium fidelity

For the fractal fragmentation model to be useful in a Debris Catalog Methodology, further processing is required. For basic applications this was as follows. For each degree, the many fractional masses were converted to tables of equivalent whole fragments, of non-uniform mass distribution, which more closely resembles real cases. Figure 9 gives part of such a tabular Debris Catalog.

DEBCAT NO =	8	SOURCE OBJECT =	Stage 1 with 25% propellant	FAILURE MODE =	Case burst	
INPUT DATA						
CLASS NO	FRAG- MENT COUNT	FRAGMENT MASS	AREA	EXPLOS EJECTION VELOCITY	COEFF OF DRAG (subsonic)	LIFT /DRAG (subsonic)
		m av (kg)	(m2)	m/s		
SOURCE	1	1000		NA	NA	NA
1	1	70	0.95	28.3	0.9	0.1
2	1	70	0.21	51.8	0.9	0.1
3	4	30	0.54	35.5	0.9	0.1
4	4	30	0.12	64.2	0.9	0.1
5	9	11.5	0.29	45.6	0.9	0.1
6	9	11.5	0.062	81.2	0.9	0.1
7	14	5.00	0.164	56.4	0.9	0.1
8	14	5.00	0.035	99.2	0.9	0.1
9	23	2.55	0.105	66.8	0.9	0.1
10	23	2.55	0.0226	116.3	0.9	0.1

Figure 9: Portion of a tabular Debris Catalog.

For each of approximately 7 masses, two areas or ballistic coefficients were assigned. This gives the simplest output (specific fragments) and is of medium fidelity. Such a prediction is compared to a known case in Figure 10.

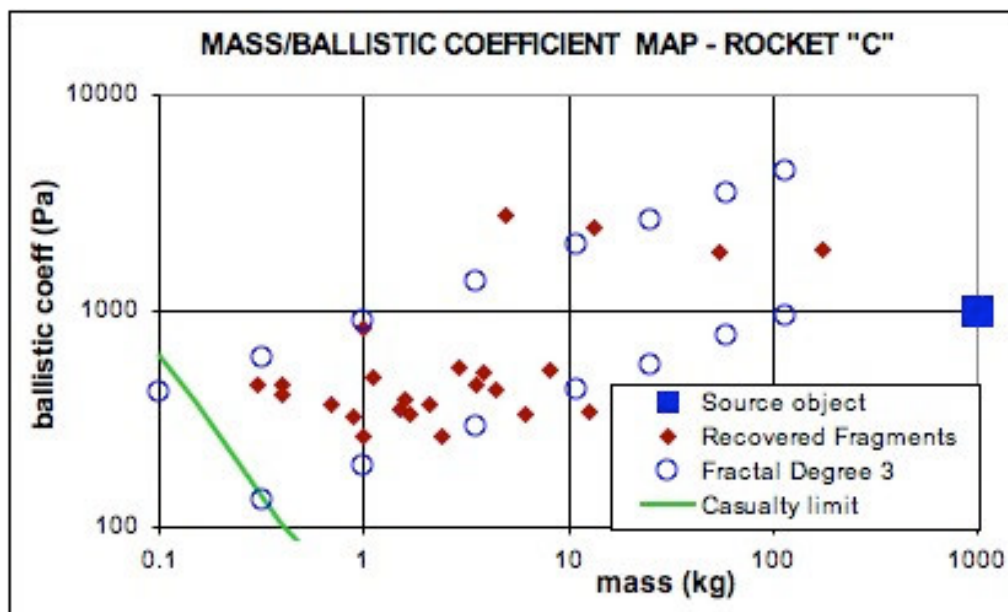


Figure 10: Mass/Ballistic Coefficient Map for Degree 3 compared to a real case.

Implementation in the Methodology – High fidelity

In a higher fidelity environment (such as RSTT), the underlying continuous mass distribution, generated by the fractal fragmentation process, for a given degree, is approximated by a series of trapezoids, as shown in Figure 11.

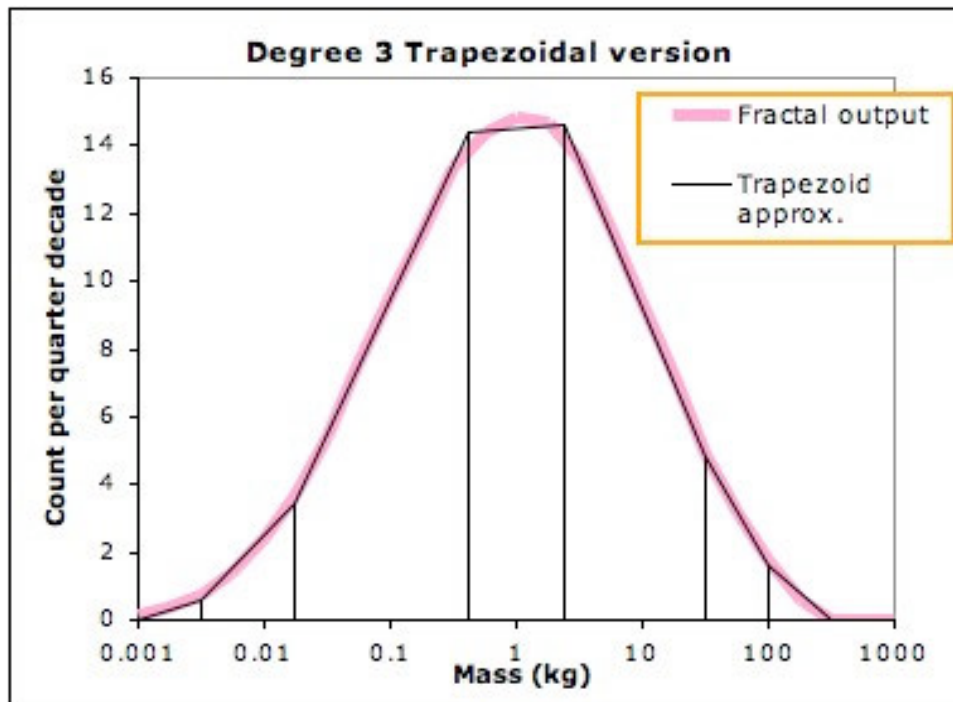


Figure 11: Seven trapezoids approximate the mass PDF for Degree 3.

The *debris generator* sub-system implemented in RSTT is sent trapezoid descriptions for the selected degree, and generates random fragment masses using Monte Carlo techniques, as well as areas and hence ballistic coefficients. Thus two separate Monte Carlo runs will generate fragments with different characteristics.

Mixed breakup modes

There are many cases where the event is a combination of explosion and aerodynamic breakup, such as the Indian GSLV and Challenger accidents, as illustrated in Figure 12.



Figure 12: Several examples of mixed aerodynamic breakup and explosion.

Our fractal model is seamless, so the Methodology estimates the degree for both cases and takes the higher value.

Verification

The fractal fragmentation model 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 one model matches known data ranging in severity from a few fragments (degree 1) to thousands of fragments (CLDSIM, degree 4) as described above.

A further comparison is shown in Figure 13.

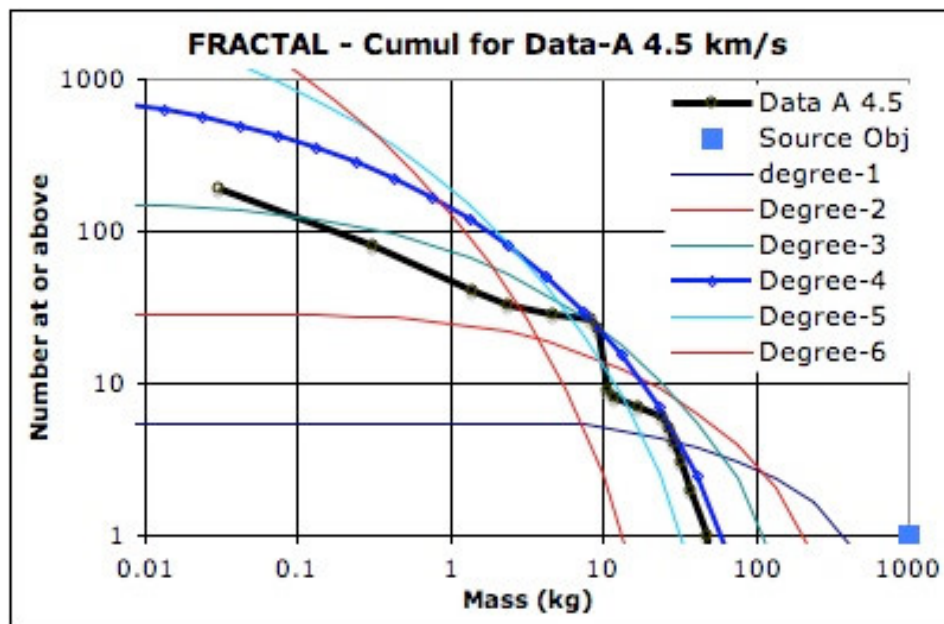


Figure 13: Verification against a case of medium speed re-entry.

Degree 4 matches the fragments in the source data quite well, above about 7 kg. Lighter fragments would be expected to burn up to some degree, accounting for the apparent shortfall.

Further refinement and extension of the fractal fragmentation model could be undertaken when more data is obtained from known cases. Extension of the model to collisions is also possible.

Conclusion

As part of a larger range safety system, a Debris Catalog Methodology has been developed, incorporating a set of tools which enables a knowledgeable person to generate lists of fragments (i.e. a debris catalog) for vehicles breaking up in flight.

This Methodology includes a Fractal Fragmentation Model, in which each degree adds a stage of successively finer fragments. There is some theoretical justification for such a model.

The Fractal Fragmentation Model has been tuned and verified against known cases of breakup. It seamlessly covers explosions and aerodynamic breakup of all degrees, from a few fragments to thousands.

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