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SPACE LAUNCH & RE-ENTRY RISK HAZARD ANALYSIS – A NEW CAPABILITY

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Australia has recently introduced a new capability for space launch and re-entry Risk Hazard Analysis (RHA) into service. This capability, called the Range Safety Template Toolkit (RSTT), was originally developed for air-launched guided weapons but is now being applied to two very different space safety applications. The first is the US/Australia HIFiRE hypersonics research program and the other is the return to Earth of the Japanese Aerospace Exploration Agency (JAXA) *Hayabusa* spacecraft in mid-2010. RSTT offers rapid (minutes to hours) generation of mission-specific safety templates. The templates can be combined with geospatial information, such as asset locations and population densities, to provide casualty and damage estimates for operational planning and safety analysis. The templates are generated from a set of ground impact points generated specifically for the mission. Creation of the ground impact point database for a mission is a computationally-intensive activity that simulates all (reasonably) possible failures and trajectories using a Six-Degree-of-Freedom (6-DOF) model of the vehicle system including Failure Response Modes (FRMs). RSTT is able to support experimental vehicle design by including design parameter tolerances as part of the launch envelope thus eliminating the need to 'lock down' design before producing an RHA. It also includes a new methodology for predicting the breakup of vehicles called 'fractal fragmentation'. This estimates the distribution of fragments based on successive breakup into smaller fragments, the 'degree' being dependent on the excess energy available. It seamlessly handles explosions, aerodynamic breakup, and combined events.

I. INTRODUCTION

Over the past five years, the Australian Defence Science and Technology Organisation (DSTO) and industry partners, including Aerospace Concepts Pty Ltd and the University of Adelaide, have developed a new capability for the flight safety analysis of aerospace vehicles. This capability, called the Range Safety Template Toolkit (RSTT), offers rapid (minutes to hours) generation of mission-specific templates which can be combined with geospatial information, such as asset locations and population densities, to provide casualty and damage estimates for operational planning and safety analysis.

RSTT was originally developed for air-launched guided weapon flight safety analysis but is now supporting two very different space applications (and other non-space uses).

The first space application is analysing whole-of-flight safety of vehicles launched by the US/Australia HIFiRE hypersonics flight research program being conducted from Woomera, South Australia. This includes ballistic launch and re-entry missions and, later, missions involving hypersonic gliding and scramjet-powered air vehicles.

The second application, which we have only recently commenced, is providing analytical support to the Australian Government in overseeing the ballistic return of the Japanese Aerospace Exploration Agency (JAXA) *Hayabusa* spacecraft to Woomera in mid-2010. This work focuses on the Sample Return Capsule (SRC) that is intended to return samples from Asteroid *Itokawa*.

We have previously presented our work[1,2,3,4,5] focusing on the broad RSTT capability, investment rationale, theoretical underpinnings, operational user and regulatory needs and our consequent development approach. The intent of this paper for the 60th International Astronautical Congress is to describe the RSTT from a space mission analysis perspective using our work with HIFiRE as an example.

II. SAFETY TEMPLATES

Safety templates, otherwise variously known as 'weapon danger areas', 'safety traces' and 'safety footprint areas', are tools for the assessment and management of the risk associated with the operation of aerospace vehicles including space launch vehicles, returning spacecraft, and various forms of guided and unguided munitions. A safety template is defined for a particular set of mission conditions.

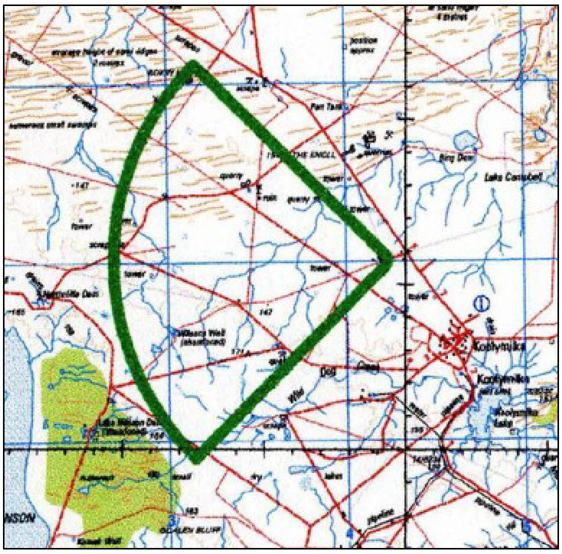

Fig 1. Safety template for ballistic sounding rocket operations at the Woomera Test Range, South Australia.[6]

A safety template can take a number of forms, including:

- A boundary enclosing an area within which the vehicle, or debris from the vehicle, might land with a specific probability;
- A contour plot representing different regions of ground impact probabilities or regions of risk such as injury or fatality risk for people or risk of damage to facilities, equipment or vehicles.

These boundaries or plots are overlaid on maps of the intended launch or landing area, as illustrated in Fig 1, are used to assess the level of risk to people and/or infrastructure. The results of the risk assessment can lead to the conditions of the launch being changed. For example, if the curve representing an impact area with a probability of 1×10^{-6} lies outside the firing range boundary the launch plan might be adjusted for a lower altitude or a different location.

The template in Fig 1 has been calculated from a Monte Carlo simulation of vehicle nominal and failure behaviours with the final shape then conservatively adjusted for ease of operational use on the test range.

III. TEMPLATE GENERATION

An overview of how templates are generated using RSTT is shown in Fig 2. This process typically involves considerable engineering analysis to construct a reasonable Six-Degree-of-Freedom (6-DOF) model of the vehicle system including both nominal and failure behaviours. Monte Carlo flight simulation is then used to create a database of ground impact points. This database is then processed via statistical algorithms to calculate the probabilities of impact in the form of Probability Density Functions (PDF). From these a template is created.

As noted above, this generic process has been explained in detail previously.[1,2,3,4,5] Selected aspects of this process particularly relevant to the space applications of RSTT are explained below.

IV. VEHICLE BEHAVIOUR MODELLING

A. Model Architecture

Development of the aerospace vehicle model is done in accordance with the *Munitions Model Interface Specification for The Technical Cooperation Program (MIST).*[7] As shown in Fig 3, this specification provides a functional decomposition of a generic guided weapon, a specification of the signals passed between model components and a modelling architecture blueprint.

Although MIST has been developed for guided weapons, its inherent flexibility allows ready adaptation to civil space applications through tailoring-out of weapon-specific components.

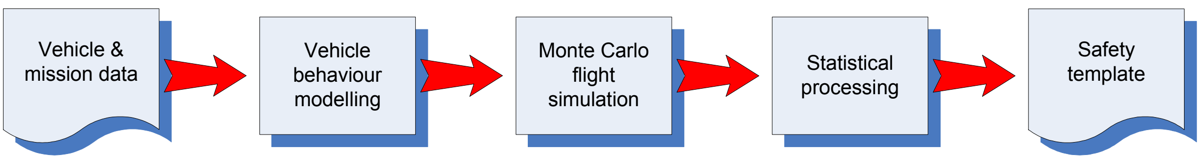

Fig 2. Overview of safety template generation process using RSTT.

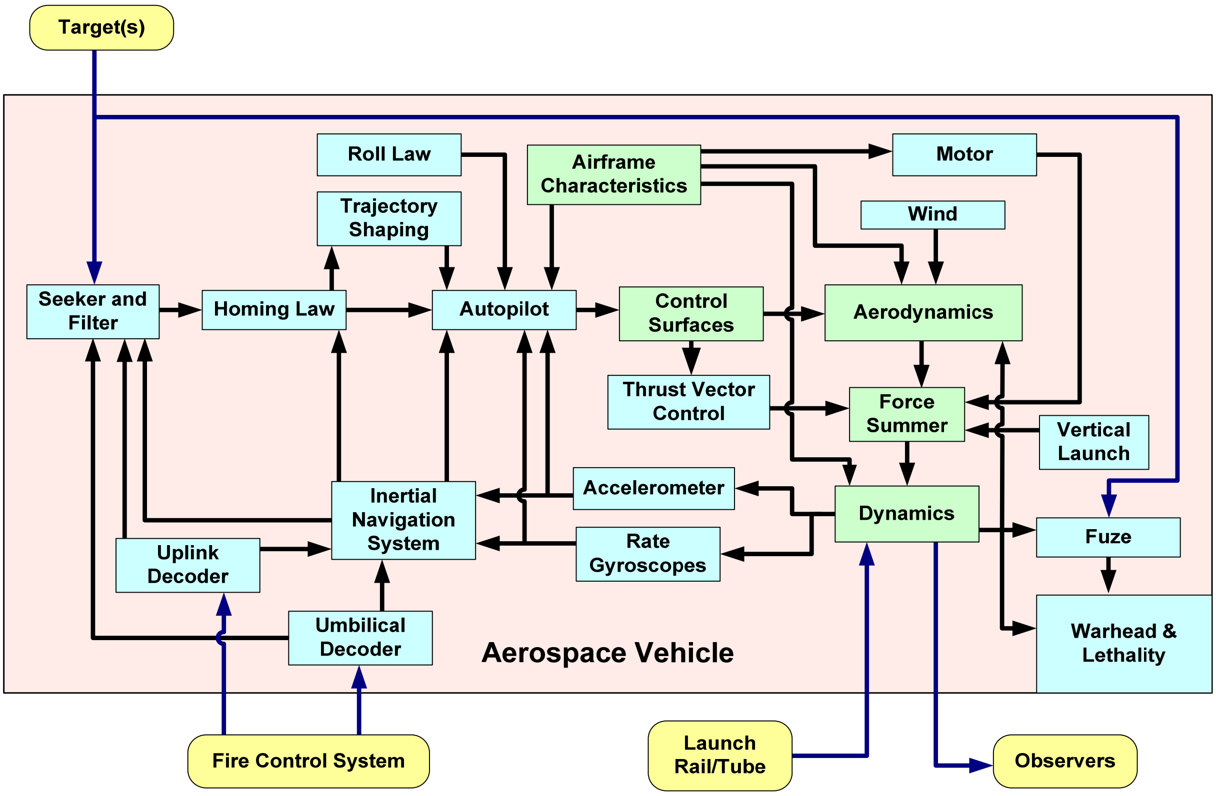

Fig 3. MIST baseline weapon / air vehicle components.[7]

All of the aerospace vehicles addressed to date have been modelled using a combination of standard MIST components and vehicle-specific variants. For example, an existing MIST-compliant 'motor' component was modified to support the multi-stage launch vehicles being used in the HIFiRE Program.

Munition-specific components such as the fuze and warhead are removed for space applications. Furthermore, specific component models are created or modified to represent failure behaviours such as motor case burn-through or jammed control surface actuators.

B. Failure Analysis

Failure analysis identifies potential failures, when in the mission they might occur, their likelihood and effects on vehicle trajectory and integrity. Clearly, the effectiveness and efficiency of this process is dependent on both the availability of failure-related technical data and the form in which it is obtained; for example, where only minimal technical information about the vehicle is available, many assumptions must be made, usually by reference to comparable systems. The process is considerably simplified where a Failure Model Effects and Criticality Analysis (FMECA) or equivalent is available.

Failures such as software logic errors are included either by accurately describing them and assigning probabilities of occurrence or by conservatively assuming a wide range of possible effects of such failures, and assigning a relatively high probability of occurrence.

C. Failure Response Modes

Much can go wrong with complex space vehicle hence the list of potential failures is typically extensive. Directly simulating each of these failures would not only impose a considerable effort in simulation model development but would likely make the computation times far too long to be acceptable.

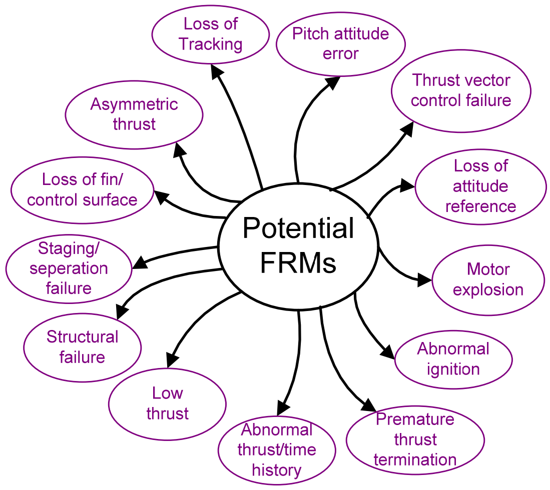

Fig 4. Potential FRMs for a space launch vehicle.

The key to making the failure analysis process tractable, and computation times acceptably short, is the Failure Response Mode (FRM) concept which recognises that many failures often result in the same overall system behaviour.

For example, in a liquid rocket engine, a failure in the igniter, or a valve, or the turbo pump assembly can all cause the engine ignition process to fail, with potentially catastrophic results. This is a case of three failures giving rise to an 'abnormal ignition' FRM. Fig 4 shows this and some other potential FRMs for a space launch vehicle.

A matrix is used to map the list of possible failures to the possible responses. This mapping will typically vary according to the phases of the mission. Generic mappings for types of vehicle may be used to speed up the process.

D. Debris Catalogs

Many failure modes involve the vehicle breaking into portions or fragments, usually through explosion or aerodynamic stresses. The mass, shape, size and material of the fragments affects their path through the atmosphere and also their effect on assets on the ground, at sea or in the air. The description of such fragments is called a debris catalog. As real breakups involve random processes, statistical modelling, often Monte Carlo, is used to generate fragments.

A methodology[8] has been developed for deriving debris catalogs. This contains complete and detailed instructions for the derivation of debris catalogs for a particular mission for which a adequate description exists. The methodology includes a number of software tools and charts.

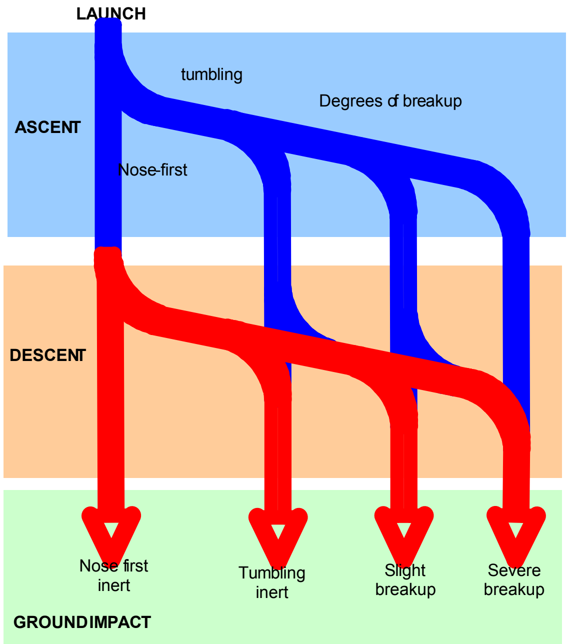

Fig 5. Flowchart for tracking sounding rocket attitude modes and degree of breakup.

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 to show the relevant stressors for various failure modes at flight phases – selected from thrust, mass, dynamic pressure, heat input, velocity, altitude. For each of the 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 computation load – the example mission used 14 debris catalogs.

Two examples of the timing of failure will be discussed here. Explosions of solid rocket motors can only occur when pressurized, that is during the burn, and are little affected by the flight environment. Two debris catalogs might be assigned for such an explosion, representing the mass of propellant at ignition and at 75% consumed. The failure probability trace would have peak at ignition and maintain a steady value until burnout regardless of flight environment.

The occurrence of aerodynamic breakup is much more complex. This occurs when the flight loads exceed structural strength and thus depends on the trajectory, dynamic pressure and wind shear traces with respect to time, as well as the vehicle attitude. A flowchart is used to track attitude and breakup modes as shown in Fig 5.

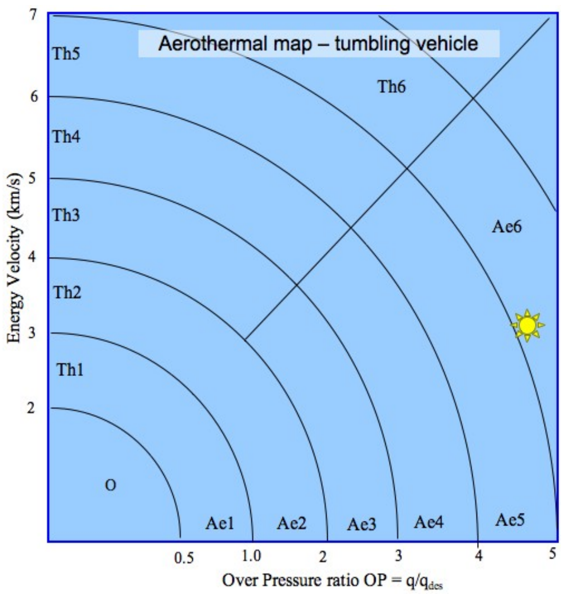

Fig 6. Aerothermal map used to predict degree of vehicle breakup.

The attitude and dynamic pressure history are generated from the flight simulation. For relevant configurations the likely survival dynamic pressure is estimated from the designed mission and safety factors. The ratio of these is the overpressure factor. Weakening by heating at high velocities is also estimated. These two factors are input to an ‘aerothermal map’, such as shown in Fig 6, which then predicts a ‘degree of breakup’.

This degree is passed to the fractal fragmentation model as described in the next section. It will derive the description of fragments accordingly, and will in turn pass the debris catalog back into a more detailed flight simulation, which includes the trajectories of the fragments, as shown in the example in Fig 7. This is further discussed under ‘multi-object simulation’ below.

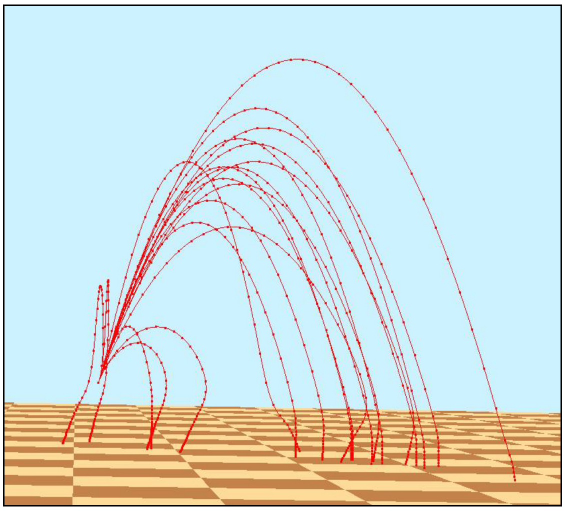

Fig 7. Trajectory trace of debris resulting from an in-flight fragmentation.

V. FRACTAL FRAGMENTATION

A. Principle of Fractal Fragmentation

The path of fragments through the atmosphere and to the ground is greatly affected by their properties, as illustrated by the range of trajectories present in Fig 7, as is the damage they may do when striking another vehicle, person, structure, etc.

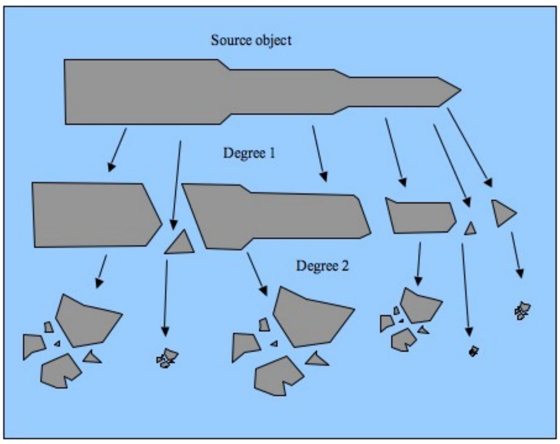

Fig 8. Principle of fractal fragmentation.

The statistical descriptions of these fragment properties are called debris catalogs. 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 a known case and perhaps adjust it to the subject vehicle and failure mode.

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

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. The principle is ‘fractal fragmentation’ whereby the vehicle first breaks into, say, six fragments with a certain distribution. Then if sufficient energy remains, each fragment breaks into six more fragments in similar proportions – and so on, to any degree (even fractional). This principle is shown in Fig 8.

B. Development

A trial set of fragments in fixed mass bins was identified, and numerical convolution used to repeat the breakup from one to six times. The basic breakup was tuned so that higher degrees provided statistical matches to known cases where fragments were recovered and measured.

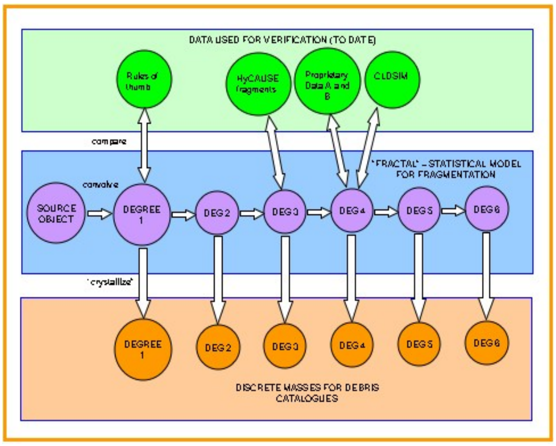

Fig 9. Mathematical implementation of fractal fragmentation.

It was found that eight basic fragments were sufficient per degree. However the numbers in each bin are non-integer. This is the ‘core’ calculation, as shown in Fig 9.

C. Implementation

To be useful in a methodology, further processing is required. For each degree, the many and fractional masses were converted to equivalent whole fragments. For each of about eight mass classes, two effective aerodynamic areas or ballistic coefficients were assigned. This gives the simplest output and is of medium fidelity. Such a prediction is compared to a known case in Fig 10.

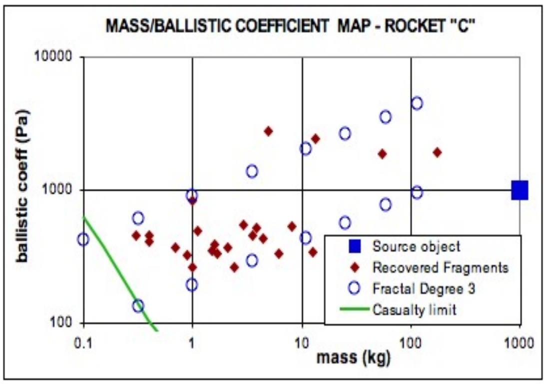

Fig 10. Mass versus ballistic coefficient map for degree 3 compared to a real case.

In a higher fidelity environment (including RSTT), the core mass distribution (for each degree) is approximated by a series of trapezoids. RSTT selects the appropriate degree and generates fragment masses and areas using Monte Carlo techniques.

D. Determining the Degree

The degree of fragmentation is determined by the energy available to cause breakup. In the case of an explosion, this is affected by the internal pressure and hence the stored energy, as well as the characteristics of the casing.

The methodology includes a listing of many examples of explosion causes, such as a pressurized gas tank rupture, and a suggested degree for each. For a real case the user can select a similar example or perform some analysis. The methodology also includes guidelines for the effect of an explosion on other stages, either side-by-side or in line.

In the case of aerodynamic breakup, the source of energy is the excess dynamic pressure, over and above that which the vehicle is designed to withstand, and taking account of the attitude mode or angle of attack as described previously.

There are many cases where the event is a combination of explosion and aerodynamic breakup, such as the Indian GSLV loss in July 2006 due to the failure of one of the four liquid-propellant strap-on stages and the Space Shuttle Challenger disaster in 1986. The model is seamless, and works by estimating the degree for both cases and then taking whichever value is higher.

E. Verification

The model has been tuned and tested against known cases of explosion and breakup, mainly for aluminium-skinned sounding rockets, launch vehicles, payload experiments, and satellites. It was found that with minimal tuning, the one model would match known cases as shown in Fig 10. For breakup, these cases include a few fragments (degree 1) to a known breakup case of degree 3 and two re-entry cases of degree 4. For explosions the best benchmark is the space fragmentation model CLDSIM[9] developed for the Italian space agency and adopted by ESA. An explosion generates thousands of fragments and is estimated as degree 4 on average.

Further refinement can occur when more data is obtained from known cases. Extension to collisions may also be fruitful.

VI. SIMULATION

A. Overview

This description is based around generating a safety template for a sub-orbital sounding rocket such as those used in the HIFiRE Program; however, this same process would apply to any sub-orbital or orbital launch vehicle. This section describes the ‘simulation’ and subsequent steps in the process illustrated in Fig 2.

We use a medium fidelity 6-DOF model of the launch vehicle, which includes the assessed FRMs, within a Monte Carlo simulation environment to generate ground impact distributions. An example of a ground impact distribution is presented in Fig 11. This represents a total of 5,000 simulation runs visualised using Google Earth™.

The impact locations correspond to a generic two stage sub-orbital sounding rocket, showing both the nominal mission and a selection of FRMs. In this example, we have modelled the nominal flight and also allowed both the first and second stage motor thrust to prematurely terminate at random times during flight. A representative trajectory from the nominal mission is also shown. We use a computer farm to complete the Monte Carlo simulations in a reasonable time.

RSTT uses a Kernel Density Estimation (KDE) technique[10,11,12] to create a smooth two-dimensional Probability Density Function (PDF) for each scenario / failure combination. Fig 12 shows a PDF derived from the data in Fig 11.

We turn the resulting probability map into a safety template corresponding to designated risk criteria by drawing an appropriate contour or risk isopleth. This is illustrated by the black curve in Fig 12, which has been smoother and made conservative by use of a convex hull algorithm and represents a $1{\times}10^{-6}$ probability of escape (that is, impacts have less than $1{\times}10^{-6}$ probability of occurring outside this boundary).

The ground impact PDF map can also be combined with population demographics and debris energy characteristics to calculate an expected casualty estimate. This is typically done using a Geospatial Information System (GIS).

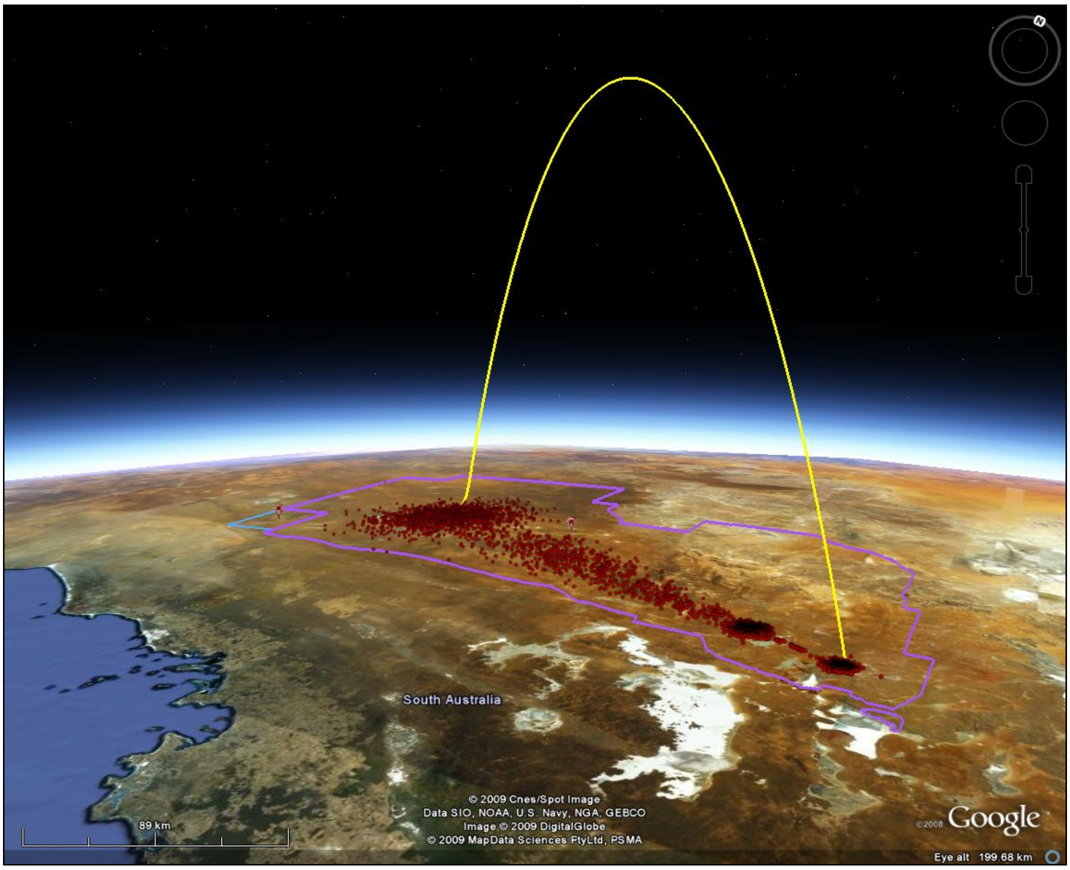

Fig 11. 5,000 ground impact points and nominal trajectory for a two stage sub-orbital sounding rocket.

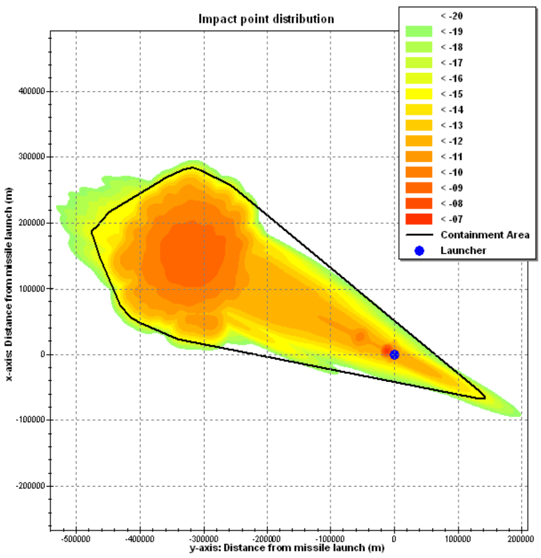

Fig 12. Ground impact PDF ($\log_{10}$ scale), with weighting 98% nominal, 2% failure. Boundary is $1{\times}10^{-6}$ probability of escape.

B. Dealing with Uncertainty

Combining the PDFs for each FRM, given the probability of occurrence extracted from the failure analysis, and then defining a template is quite straightforward. The problem is that this produces a safety template valid only for a point in the operational envelope of the vehicle. In a sounding rocket, for example, this safety template would only be valid for a single launch rail elevation, which due to weather conditions might have to be varied at the time of launch.

A further complication for experimental programs, such as those typically utilising sounding rockets is that the exact configuration of the integrated launcher and payload stack may not be precisely known until very late in the program. So the final safety template must be valid for a user-selected *region* of the envelope, where this envelope also includes tolerances on the vehicle design parameters.

For vehicles such as sounding rockets, the process of combining PDFs is implemented via a technique that combines a carefully selected combination of 'Broad Focus' (BF) and 'Fine Focus' (FF) scenarios, which is referred to as the direct simulation technique.[13]

Using the direct simulation technique a, single BF scenario is defined and a number of FF scenarios are selected to cover the scenario envelope. The BF scenario has its parameter tolerances selected to cover the full range of possible values of the scenario parameters (e.g. launch rail elevation, payload mass etc.). These tolerances define the valid operational envelope of the safety template (that is, the extent of the mission and vehicle design parameters). Tolerances are influenced by the maturity of the design and the uncertainty inherent in the available data. The process of defining the BF scenario and hence generating the safety template can be carried out well in advance of the planned launch date.

Once the BF scenario has been defined, a set of FF scenarios are generated from it. The first step in this process is to determine the reasonable minimum tolerances of the scenario and design parameters based on acceptable measurement techniques and appropriate engineering judgement.

As an example, early in the design stage the mass of the payload may only be definitively known to ±40kg, which is taken as the payload mass tolerance in the BF scenario. However, the reasonable expected payload mass tolerance might well be ±0.1kg, which will be the payload mass tolerance for the FF scenarios. An FF tolerance of zero is conservative.

Once the FF parameter tolerances are determined, FF scenarios are generated by randomly picking a centre value within the BF tolerances for each parameter and applying the FF tolerances around each centre value to specify statistical distributions for each parameter. These are then recorded as Monte Carlo variables of the FF scenario definition.

One BF and many FF scenarios are then simulated and the ground impact points are converted into PDFs using the KDE technique. These PDFs are then combined using an anti-dilution PDF scaling technique, which combines the 'expanse' of PDFs from BF scenario with the 'peaks' of the FF scenarios. That is, the BF PDF can be visualised as a broad gently sloping hill while FF PDFs are steep, compact mountains.

Without this (or an alternative) anti-dilution scaling technique involving multiple tolerances and both BF and FF scenarios, the safety template for a planned mission would actually shrink if the vehicle and mission design was broadened to cover a wider range of possible launches. Such a non-conservative outcome is not acceptable, particularly given the potential for manipulation; hence the complexity that the anti-dilution scaling technique adds is justified.

C. Multi-object Simulation

Most flight simulation is concerned with nominal flight and usually does not consider vehicle break-up and the resulting debris. By contrast, the RSTT modelling and simulation environment[14] is able to simulate both the 'main vehicle', using the 6-DOF vehicle simulation model, and any debris generated using a 3-DOF debris propagator model.

For a multi-stage launch vehicle the production of debris will be either the result of a failure or of nominal events such as staging. During a flight the main vehicle will change configuration several times as shown in Fig 13.

Alongside the main vehicle, a 3-DOF debris propagator model handles the spent stages and other items expended during the flight, as well as any debris resulting from failures. Each of these debris pieces generates additional ground impact points as illustrated in Fig 7.

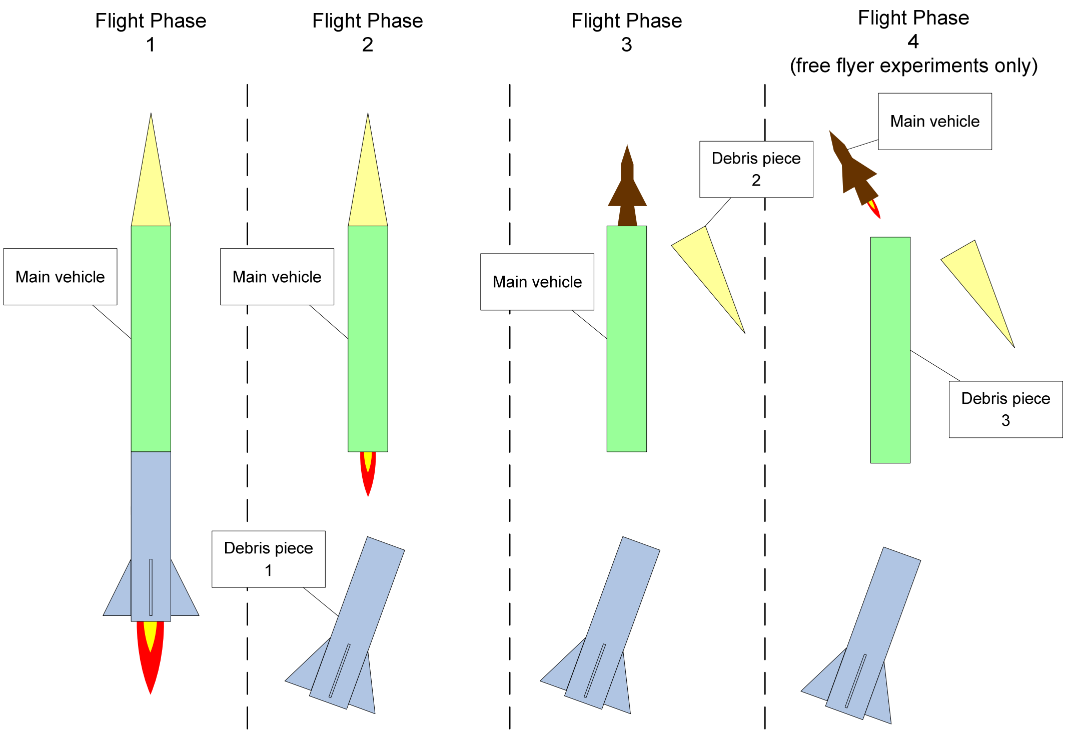

Fig 13. HIFiRE configurations during flight, illustrating the 'main vehicle' concept.

In order to simplify the handling of debris from failure events and from nominal events such as staging, debris catalogs are used to define the debris resulting from both sources. However, whereas failure events use the debris catalog methodology discussed above, nominal events such as staging are analysed directly from design data.

D. Template Verification for *Hayabusa* Sample Return Capsule (SRC)

Verification of the templates supplied by JAXA for the *Hayabusa* SRC return to Earth is similar to the process described above. The process is simplified by the ballistic trajectory and the almost monolithic nature of the SRC itself.

Hayabusa will re-enter the Earth's atmosphere at 12 km/sec hence we must deal with the very high speed aerodynamics involved. This requires an aerodynamic database of sufficient accuracy covering free molecular, hypersonic, supersonic and subsonic aerodynamics.

In this particular case the approach has been to apply the available JAXA aerodynamic data for the *Hayabusa* SRC with the verification approach based on a comparison of aerodynamics with other Earth return vehicles of similar external shape and mission profiles.

E. Templates for Other Space Vehicles

As noted in the introduction, RSTT was originally developed for guided air weapons, specifically the ASRAAM air-to-air missile and the AGM-158 JASSM cruise missile.

Although the techniques developed for modelling these vehicles are described elsewhere[1,2] and well beyond the scope of the present paper, the techniques developed for an air-to-air missile like ASRAAM could be applied to an air launched space vehicle like Orbital Science's Pegasus or Virgin Galactic's Space Ship Two.

Similarly, the techniques developed for a waypoint following cruise missile like JASSM could be applied to re-entry vehicles designed for runway landings such as JAXA's HSFD or, again, Space Ship Two.

VII. ASSURANCE

A. Overview

Assuring that RSTT outputs represent the actual risks to people and infrastructure as closely as practicable is fundamental to the usability of the system. Ideally, this assurance would be in the form of statistically-meaningful comparisons with actual flight data for the weapons and air vehicles concerned. However, given that launch vehicles are not tested in statistically-meaningful quantities and that experimental vehicles, such as HIFiRE are, by their nature, unique or near-unique, we have addressed assurance in other ways.

B. Engineering Assurance

RSTT has been developed under an engineering management system that meets the requirements of the Australian Department of Defence airworthiness regulatory framework. This engineering management system addresses requirements management and verification, organisational competence, personnel qualification and experience, development processes, models, tools, data and assumptions. Furthermore, given that RSTT is a safety-related software-intensive system, it has been developed as 'Level C' software under RCTA/DO-178B.[15]

This development approach was not without challenges of its own given that the effort in creating this engineering management system within what is essentially a research and development organisation demanded significant cultural changes within DSTO and its relationship with military airworthiness regulatory authorities. However, after several years of effort and consultation, this engineering management system has been endorsed as being valid and indeed, will likely be used for other activities.

C. Verification and Validation

As a new capability with few, if any, direct 'peers', verification and validation of RSTT outputs posed a challenge particularly due to the lack of statistically-meaningful flight data.

Verification has involved strict application of our engineering management system to ensure appropriate derivation and specification of requirements and that all requirements have been satisfied. In particular, critical verification issues were identified and appropriate verification measures taken. For example, third-party independent review of the KDE algorithms was undertaken to establish the validity of the method and correct implementation within RSTT.

Validation will, of course, be an ongoing activity as RSTT is further developed to support new weapons and air vehicles and as other validation opportunities become available. Our efforts thus far have focused on validating the HIFiRE variant of RSTT via comparison of:

- Flight simulation outputs against radar track data from similar flights, and analytical pre-mission analysis; and
- Ground impact point sets against those generated by other means.

In both cases RSTT was validated against HyShot 2, a previous hypersonic flight experiment conducted in 2002 at the Woomera Test Range in South Australia.[16] HyShot 2 involved a two-stage sounding rocket with the same general configuration as that planned for early HIFiRE flights.

The HyShot 2 launch vehicle and payload was modelled in the RSTT environment. The HyShot 2 flight was then simulated and compared against the actual flight telemetry and radar tracking data. Finally, ground impact points for the nominal flight and several representative FRMs were generated and then converted to a PDF, as shown in Fig 14 and Fig 15. This PDF was compared to the range safety template generated by a third party for the HyShot 2 launch approval process.

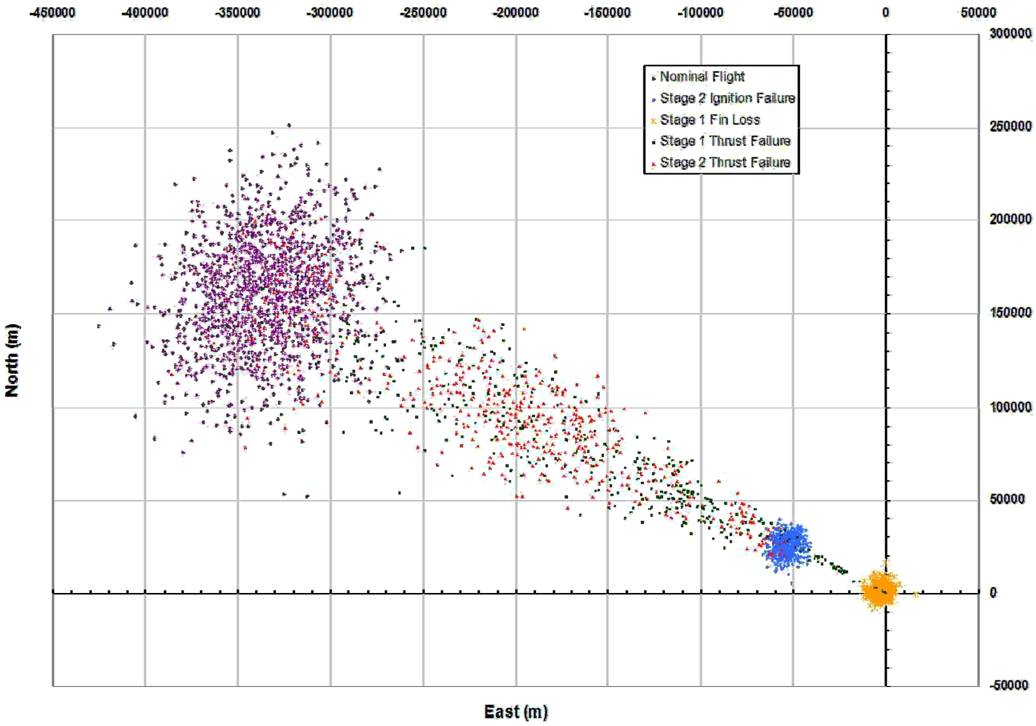

Fig 14. Ground impact points generated for validation against HyShot 2.

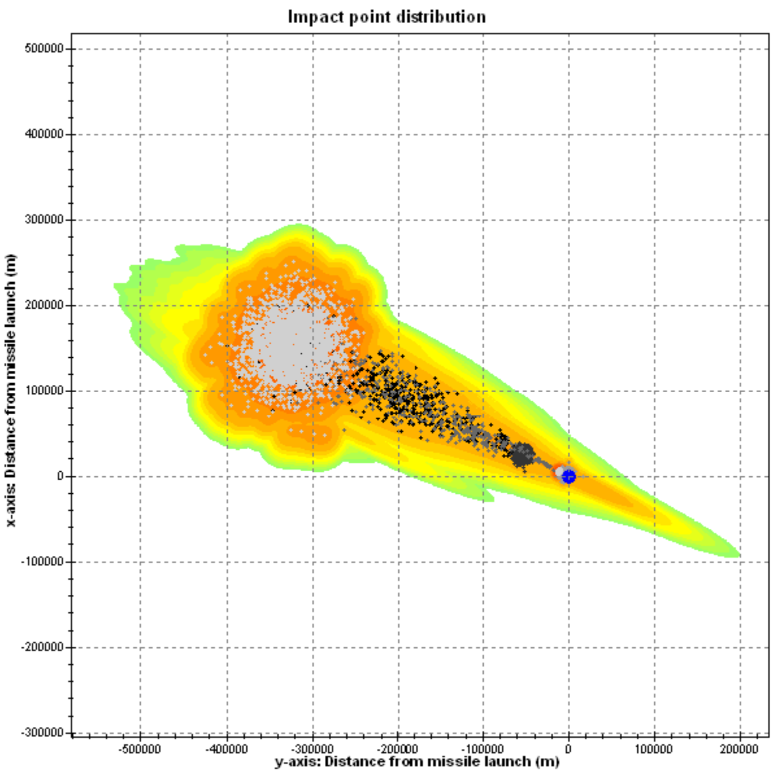

Fig 15. Ground impact point distribution and PDF (per m²), generated for validation against HyShot 2 (98% nominal, 2% failure).

Fig 16. Validation against HyShot 2 vehicle acceleration telemetry data (telemetry in red; RSTT in blue).

RSTT outputs closely matched both the radar track data, as shown in Fig 16, and the safety template accepted for the mission.

The differences between the plots can be accounted for by known discrepancies in the source data. For example, in Fig 16, we had to use publicly available thrust curves, which did not account for possible ageing and performance tolerances. Furthermore, the reference altitude for the data was unknown so we had to make a pragmatic estimate.

The result was that thrust produced in the RSTT model was lower than the measured thrust in the second stage thus accounting for differences in the trajectory later in the simulation.

D. Operational Assurance

To assure the output of a tool such as RSTT, the tool must be properly employed. In much the same way that airworthiness encompasses both the technical and operational aspects, RSTT employment encompasses not only the tool itself but the environment in which it is 'operated'.

This operational environment must satisfy requirements which broadly mirror those for RSTT development relating to organisational competence, qualifications and experience of personnel, adherence to defined processes, provenance of source data, and identification of assumptions.

VIII. NON-SPACE APPLICATIONS

A. Guided Air Weapons

RSTT was initially developed for safety analysis of guided air weapons (the ASRAAM and JASSM missiles) and we expect that RSTT will be adopted for other weapons as they enter Australian service. Particularly where the Total Energy Area (TEA) / Maximum Energy Boundary (MEB) is too big for the traditional exclusion, or 'keep it on the range', approach, or where existing users of the same vehicle control launch risk using significant range infrastructure and flight termination-support systems that Australia cannot afford to replicate.

B. Safety of Unmanned Aerial Systems

In additional to its current guided weapon and space applications, RSTT also has the potential to aid in the safety management of other aerospace vehicles such Unmanned Aerial Systems (UAS).

UAS are not conceptually much different to long-range missiles such as JASSM. In this context, similar challenges exist in the safety management of airspace and ground-based infrastructure such as troops, vehicle convoys and buildings in peacetime operations.

In particular, the Australian Department of Defence sees a strong future in the application of UAS in future joint operations which involve the sharing of military airspace with other users, as well as close-in troop support operations such as convey over-watch, convoy following, and a variety of Intelligence, Surveillance and Reconnaissance (ISR) missions. These operations have the potential to expose troops, assets on the ground, other military airspace users, and non-military bystanders to risks and hazards as a result of loss of control or failure of the UAS.

C. Dynamic Airspace Management

The ever-increasing density of commercial air traffic in many regions of the World, particularly in North America and Europe, is placing pressure on the use of restricted airspace for military exercises and tests and for space launch operations. Specifically, the long-standing practice of restricting airspace via Notice to Airmen (NOTAM) action for periods of hours or days to cover a test or launch event lasting only minutes is looking increasingly untenable. Furthermore, the likely sustained rise in the cost of aviation fuel and the recognition of the apparent impact of aviation on climate change further strengthens the case against airspace users being able to impose blanket restrictions on other users for extended periods of time.

Because RSTT offer rapid (minutes to hours) generation of mission-specific safety templates and templates, it has the potential to play a role in a more dynamic approach to airspace management in which restrictions would be in place for only as long as needed to assure safety and, ultimately, restrictions and re-routing could be achieved in near real-time. Programs such as the US Federal Aviation Administration (FAA) Next Generation Air Transport Program (NextGen) in combination with concepts and tools for dynamic airspace management for Operationally Responsive Space (ORS)[17] and, perhaps, RSTT, offer a way to improve airspace management through better use of simulation and other computer-based safety assurance techniques.

IX. CONCLUSION

RSTT is now a functional and highly adaptable system for a variety of air vehicles and mission types. The development of RSTT has led to the resolution of a number of operational and development challenges, which have improved the understanding and importance of range safety in the Australian Department of Defence.

The architecture of RSTT can be readily used for new weapons systems, space launch vehicles and other applications such as air traffic management. As RSTT is put into operational use we expect the system will continue to evolve, based on feedback from end users and the exploration of new concepts by the wider user community.

Further, as new reference data from operations becomes available, particularly from HIFiRE, the system can be assessed, adapted and revalidated. We expect RSTT will evolve into a reliable, mature capability and will be well placed to support advanced weapons and flight vehicles in the future.

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