

IMPROVED RANGE SAFETY ANALYSIS FOR SPACE VEHICLES USING RANGE SAFETY TEMPLATE TOOLKIT

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ABSTRACT

This paper discusses an alternative to traditional methodologies for space launch and re-entry vehicle range safety analysis using the Range Safety Template Toolkit (RSTT), developed by Australia's Defence Science and Technology Organisation (DSTO) in partnership with Aerospace Concepts Pty Ltd.

RSTT offers rapid generation of mission-specific safety templates that comply with internationally-recognised standards for range risk criteria. Compared to some traditional methods, RSTT produces more accurate assessments of risk to personnel and infrastructure. This provides range operators with greater confidence in the range safety products, enhancing their ability to rigorously manage safety on their ranges.

RSTT also offers increased precision of risk analysis and iteration of mission design allowing greater flexibility in planning range operations with rapid feedback on the safety impact of mission changes.

These concepts are explored through examples involving a suborbital sounding rocket, demonstrating how traditional range safety assumptions may be reassessed using the RSTT robust probabilistic methodology.

1. INTRODUCTION

Over the past seven 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 generation of mission-specific templates that can be combined with geospatial information, such as asset locations and population densities, to provide casualty and damage estimates for mission operational planning and safety analysis.

RSTT was originally developed for air-launched guided weapon flight safety analysis but has now been applied to two very different space applications in addition to other non-space uses:

- Risk Hazard Analysis (RHA) for 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, in future missions, flights involving hypersonic gliding and scramjet-powered air vehicles.
- Provision of independent verification services to the Australian Government in approving the return of the Japanese Aerospace Exploration Agency (JAXA) *Hayabusa* spacecraft to Woomera in June 2010. This work focused on the re-entry of the Sample Return Capsule, which successfully returned particle samples from Asteroid *Itokawa*.

Aerospace Concepts has previously presented work ([1],[2],[3],[4],[5]) describing the broad RSTT capability, theoretical underpinnings, operational user and regulatory needs and our consequent development approach.

This paper discusses an alternative to traditional methodologies for space launch and re-entry vehicle safety analysis, realising improvements through the ability to produce higher-fidelity, probabilistic risk products. Improvements in range management decision making are possible with the enhanced accuracy and precision of risk analysis products created by RSTT thus giving range operators greater confidence in mission safety and greater flexibility in range planning against applicable range safety standards.

2. SAFETY TEMPLATES

Safety templates, elsewhere variously known as 'weapon danger areas' (WDAs), 'safety traces' and 'safety footprint areas', are tools for the assessment and management of the impact 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 calculated for a particular set of mission conditions.

This paper focuses on the generation of safety templates for space vehicles specifically, using a sub-orbital two-stage sounding rocket to provide relevant examples.

3. TEMPLATE GENERATION OVERVIEW

A generic process for generating safety templates, adapted to the RSTT method, is shown in Figure 1. Many template production methods involve modelling the vehicle of interest from available technical data. The required fidelity of the model varies significantly depending on the methodology used. The model is simulated across a range of conditions and then outputs of those simulations, commonly ground impact points (GIPs), are processed to create a safety template.

Given that sounding rockets are typically unguided, traditional range safety analysis methodologies for such vehicles have been relatively simplistic. Ground impact distributions tend to be more regularly distributed than for guided vehicles and thus simpler vehicle models and processing methods have often been employed. Some methods are simplified deterministic analyses, while others involve Monte Carlo vehicle simulation or dispersion analysis techniques followed by the fitting of normal (Gaussian) distributions to produce impact risk.

These methods have merit in simpler analysis, especially when the available computing power is limited, as was the case when these methods were first developed. However, investigation of vehicle behaviour using higher fidelity models demonstrates their limitations. This is particularly true when considering realistic failure behaviour that often generates unusual impact point distributions. Analysts either attempt to include such distributions in the template by making overly conservative assumptions, resulting in large templates that are difficult to apply, or produce smaller templates using assumptions that may be difficult to defend. These limitations potentially reduce range operator confidence in the risk products, particularly given the availability of the computing power required to challenge the underlying assumptions.

RSTT improves the quality and fidelity of safety templates by increasing the sophistication of each of the stages in Figure 1. It involves the development of a six degree of freedom (6DOF) vehicle model incorporating nominal flight modes, extensive failure behaviour and parameter tolerancing. Millions of GIPs are produced by Monte Carlo simulation of initial conditions and vehicle parameters. When compared to traditional methods, this results in significantly more impact data across a wider range of flight behaviours.

Statistical processing of these impacts produces Probability Density Functions (PDFs) and subsequently impact risk contours. Critically, RSTT techniques do not assume a particular underlying impact distribution; rather, they are designed to handle the unusual random distributions generated by failure behaviour and non-linear flight effects. These improvements allow RSTT to produce more accurate and precise safety templates that are both defensible and traceable. Consequently, range operators have greater flexibility in mission planning when applying applicable standards.

The following sections delve deeper into the issues associated with some traditional template generation processes and demonstrate how RSTT overcomes them.

4. TRADITIONAL METHODS FOR SPACE LAUNCH RANGE SAFETY ANALYSIS

4.1. Categories of Analysis

As described above, traditional methods for range safety analysis take different forms. Deterministic approaches feed data describing the vehicle of interest into a kinematics-based model derived from empirical launch data for other vehicles and extensive sets of assumptions. The resultant templates are often conservative ‘worst possible case’ containment contours, commonly known as a ‘total energy area’ (TEA) or ‘maximum energy boundary’ (MEB) [6].

Other methods commonly involve simplified Monte Carlo simulations with normally distributed initial conditions. The probability of impact from events that occur at a point in time, such as jettisoning a stage, is typically derived by fitting a bivariate normal distribution to the simulated impact points. This is the common ‘N-sigma’ ellipse approach. Figure 2 is an example of a 3-sigma ellipse for a sample set of GIPs. Alternatively, the approximate bivariate normal distribution may be derived using analytical dispersion calculation techniques without Monte Carlo simulation.

Conversely, a ‘down-range corridor’ method can be used for events that occur over an extended period of time, such as a thrust failure. This method consists of a one dimensional normal distribution fitted cross-range to the Instantaneous Impact Point (IIP) trace [7]. A simple version of this method is illustrated in Figure 3. More sophisticated versions of this and related methods are described in [7].

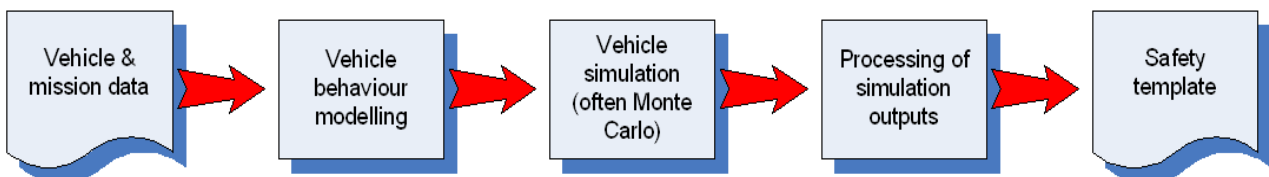


Figure 1. Overview of common safety template generation process

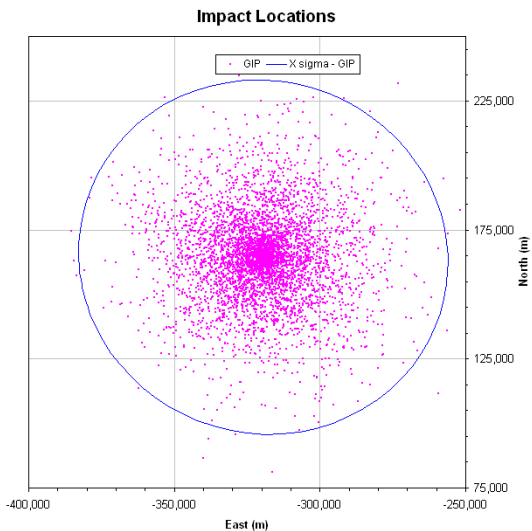


Figure 2. Sample 3-sigma ellipse fitted to impact points

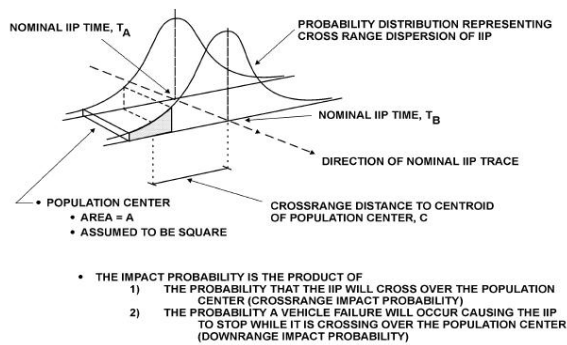


Figure 3. The 'down-range corridor' method

4.2. Limitations of Traditional Methodologies

Both traditional approaches described above require the analyst to make assumptions which can be difficult to defend, and can result in templates that are limiting because of their large size.

The maximum range used to form a TEA is often extreme, even for unguided sounding rockets given the worst failure conditions, and in reality is limited only by the imagination of the analyst. The extreme extent of such deterministic templates also requires extensive and expensive range clearing exercises by range operators and are therefore undesirable [6].

Alternatively, simplistic Monte Carlo or analytical dispersion methods can produce much smaller templates, potentially at the expense of defensibility. Firstly, all varied input parameters are assumed to be distributed normally; while this may be suitable for some parameters, others require different distributions. An example of a non-normal distribution is location-based historical wind profiles where wind speed dispersion does not follow any standard distribution.

Secondly, the methods assume that the resultant ground impact points, and thus impact probability, are normally distributed. While this may appear to be the case for some aspects of nominal flight (as shown in Figure 2), the complex non-linear behaviour of the vehicle suggests it may not be a suitable general-case solution. In particular, the effects of dispersion factors may be interdependent and one or more factors may dominate, reducing the likelihood that a normal distribution is the most appropriate fit.

Normal distributions are often inappropriate for failure cases, as demonstrated in the example in Figure 4. In this case, impacts were generated by a motor burn-through failure on the second stage of a sounding rocket and are clearly not described by a bivariate normal distribution. Even a variant of a 'down-range corridor' method would have difficulty modelling such an impact distribution as it assumes that the cross-range distribution parameters remain static while the vehicle is flying, which is clearly not the case. The poor fit of normal distributions can be even more pronounced when applied to the unusual impact footprints generated by guidance failures on guided space vehicles.

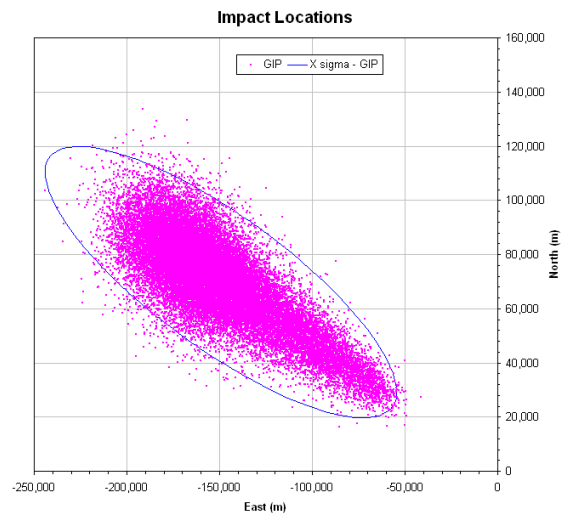


Figure 4. Inappropriate use of a 3-sigma ellipse on impact points generated by vehicle failure

Consequently, the resultant templates tend to represent risk due to nominal behaviour and dispersion rather than the risk due to failure. This can result in risk underestimation in key range areas, such as around the launch site and along the mission trajectory line. Even if multiple normal distributions are developed, such that each more closely models a real distribution of impacts, it is difficult to combine them with appropriate failure weightings while still retaining defensibility.

The extreme size of deterministic templates and the difficulty in defending the assumptions behind simple Monte Carlo approaches can make it difficult for range operators to apply such templates with confidence.

5. RSTT METHODOLOGY

5.1. Overview

As described in Section 3, RSTT implements the generic process shown in Figure 1 to produce high-fidelity probabilistic safety templates that overcome many of the issues associated with the simpler, traditional methods discussed above.

This template generation process has been explained in detail previously in [1], [2], [3], [4] and [5]. Selected aspects of the process particularly relevant to the space applications of RSTT are briefly explained below. Understanding the way in which RSTT produces safety templates aids the understanding of how it improves on traditional methodologies.

5.2. Vehicle Modelling

Development of the 6DOF aerospace vehicle model is conducted in accordance with the *Munitions Model Interface Specification for The Technical Cooperation Program (MIST)* [8]. 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. By providing a common basis from which modellers can work, significant collaboration and model re-use can occur, subsequently lowering the cost of model development, integration and maintenance over time.

A modified decomposition appropriate for a sounding rocket design is shown in Figure 5. Most components in the design are derived from existing MIST implementations with modifications to allow failure modelling, multi-stage behaviour and required parameter variation.

5.3. Failure Analysis & Failure Response Modes

An important aspect of constructing the vehicle model is understanding vehicle failure behaviour. The resultant GIPs generated by failure responses tend to drive the shape and size of the safety template.

Failure mode analysis is initially performed to identify potential failures, when in the mission they might occur, their likelihood, and their effects on the vehicle's integrity and the forces and moments that it experiences. The effectiveness and efficiency of this process is dependent on the availability of failure-related technical data and the form in which it is obtained; having limited technical information about failures requires assumptions to be made, usually by reference to comparable systems. Such assumptions, primarily relating to the probabilities of occurrence, need to be conservative and as such can result in risk overestimation. The process is considerably simplified where a Failure Mode, Effects and Criticality Analysis (FMECA) or equivalent is available.

Given the large number of possible failures in a complex space vehicle, it is useful to aggregate them into unique failure *response* modes (FRMs). Direct simulation of every identified failure mode would result in excessive modelling time and computational requirements; grouping failures that result in the same vehicle response makes the process tractable.

For example, in a liquid fuelled 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 a single 'abnormal ignition' FRM. Figure 6 shows this and some other potential FRMs for a space launch vehicle.

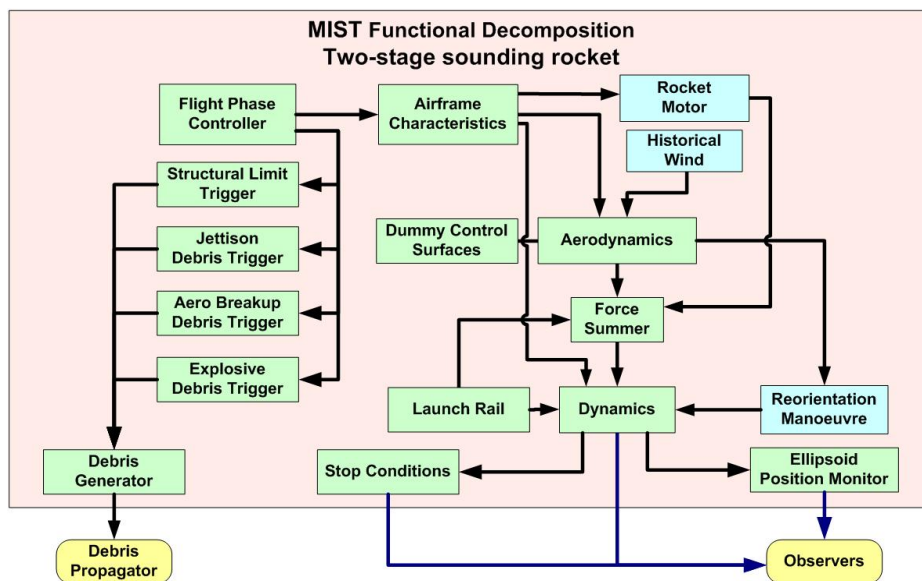


Figure 5. Modified MIST model decomposition for a sounding rocket

Many space vehicle FRMs result in the vehicle breaking into portions or fragments through explosion or aerodynamic stresses. Breakup of this nature is modelled in RSTT using a fractal fragmentation methodology and implemented with debris catalogs. Statistical techniques are used in debris generation to model the random processes present in real breakups; the methodology is described in detail in [1] and [9].

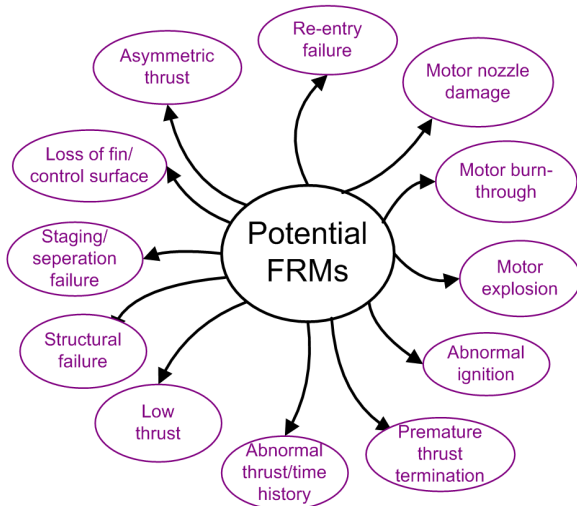


Figure 6. Potential FRMs for a space launch vehicle

5.4. Simulation

Following creation of the 6DOF model with failure response modes, the vehicle is simulated in a Monte Carlo environment to generate GIP distributions. An example is shown in Figure 7 which represents a total of 5,000 simulation runs visualised using Google Earth.

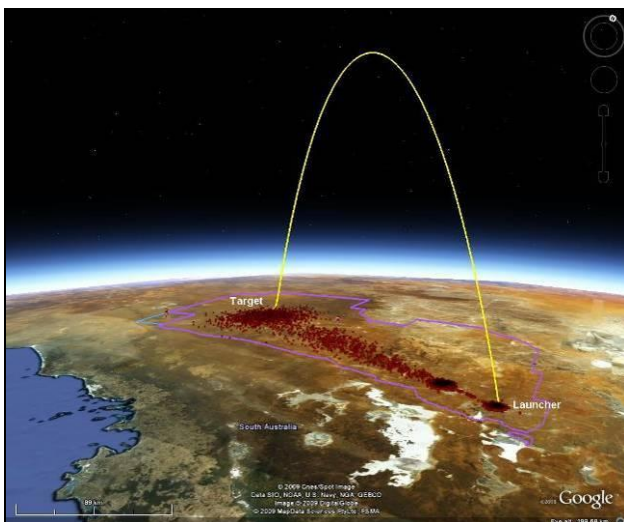


Figure 7. Ground impact points and nominal trajectory for a two-stage sub-orbital sounding rocket

The impact locations correspond to a two-stage sounding rocket displaying both nominal and one failure

behaviour. Nominal flight impacts are collected near the target, while the failure impacts resulting from a randomly-timed premature motor termination are spread downrange.

Given the unguided nature of most sounding rockets, they can suffer significant ground impact dispersion due to variation in vehicle properties such as mass. This is evident in the level of dispersion around the target location in Figure 7, even for nominal flight. The modelling of appropriate property variation is therefore a critical aspect of the RSTT simulation capability. For space vehicles, the effect of dispersions due to thrust misalignment, mass variation, aerodynamic drag scaling and wind compensation aiming error are simulated with the RSTT Monte Carlo engine.

5.5. Statistical Processing

With a large database of ground impact points (commonly several million) generated across all FRMs, the next step is to process them statistically to produce risk products. RSTT uses a Kernel Density Estimation (KDE) technique, as described in [10], to create a two-dimensional Probability Density Function (PDF) for each scenario / failure combination. Figure 8 shows a PDF derived from the data in Figure 7. This represents the probability density of impact of the vehicle and its debris for this particular combination of FRMs.

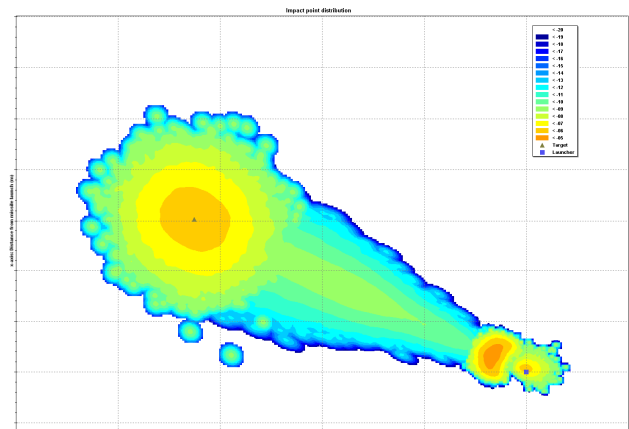


Figure 8. Probability density function generated from the impacts shown in Figure 7

All FRM PDFs are combined via appropriate probabilities of occurrence to form a total PDF for the mission. Multiple safety templates, each corresponding to different risk criteria, can then be calculated from the PDF by selecting the appropriate risk contour (or isopleth) from all contours present. This concept is discussed in more detail in Section 6.

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

RSTT primarily supports the risk criteria defined in United States Range Commanders Council (RCC) Standard 321 [11], such as the ‘one in a million’ individual casualty risk criteria for members of the general public. Importantly, it also supports the ability to calculate risk to personnel sheltered in buildings, as described in the standard.

6. RANGE MANAGEMENT OPTIONS ENABLED BY RSTT

6.1. Overview

The RSTT template generation process requires fewer assumptions compared to the traditional methods described in Section 4 and consequently is more accurate, precise and defensible. The use of a higher-fidelity vehicle model reduces the need to derive what behaviour might occur under failure conditions; instead, simulating the model directly produces this behaviour. The use of a generic PDF estimation technique reduces the inherent errors incurred by assuming a particular underlying impact distribution. This section describes in further detail the improvements to safety template quality offered by RSTT.

6.2. Accuracy

Risk to both the launcher region and area along the nominal trajectory line can be poorly estimated using traditional methods. Figure 9 shows impact points generated by RSTT for an explosive rocket failure soon after launch with a realistic historical wind profile.

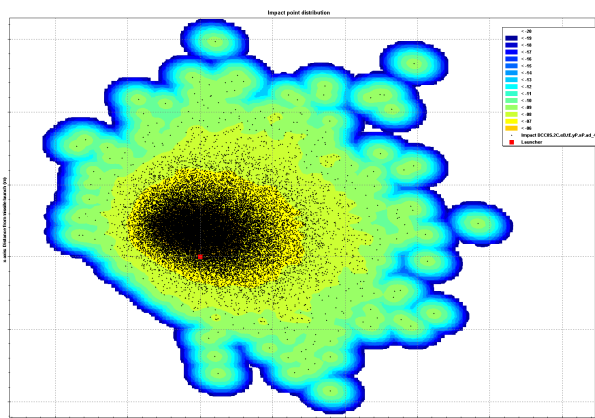


Figure 9. Impact points and PDF from an explosive rocket failure soon after launch

The impact distribution clearly does not follow an elliptical bivariate normal distribution, a result driven by the dominance of the historical wind dispersion model. Attempting to fit such a distribution would likely result in excessively large ellipses, or risk overestimation. Alternatively, such failures may not be considered to this degree of fidelity, potentially resulting in underestimation of risk to the launch infrastructure.

RSTT, however, uses the KDE mechanism to produce more accurate risk estimates in these areas.

RSTT also provides more accurate risk assessment around the nominal aim point for vehicle re-entry. Figure 10 shows an example PDF and 1×10^{-6} individual risk contour around the nominal aim point for a sounding rocket flight. While the impacts used to generate this plot were spread well out towards the edges of the PDF, the actual risk contour (as defined by the standard) is much smaller than one might expect.

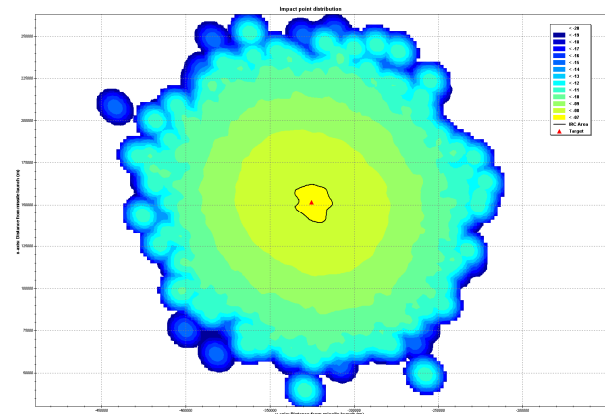


Figure 10. PDF and 1×10^{-6} risk contour around nominal aim point (1×10^{-6} contour shown in black near centre)

Attempting to fit a 3-sigma bivariate Gaussian distribution to the impacts results in larger ellipses. This potentially requires more people to be evacuated and increases the management burden on range operators.

The calculation of impact risk along and nearby the nominal trajectory is also more accurate using RSTT, particularly for risk due to failure behaviour. Figure 8 shows the probability of impact expanding cross-range when moving from launcher to aim point. This probability distribution is not well represented by a normal distribution, and a simple corridor approach, as described in Section 4.2, would inappropriately maintain a constant standard deviation along the trajectory. Accurate derivation of the impact probability in such regions is important as the associated risk can be significant in expected casualty calculations.

6.3. Precision

As described in Section 4, some traditional methods tend to produce elliptical risk contours that do not offer a high level of precision. This limits the flexibility in mission planning available to range operators when considering evacuation of the general public and placement of mission personnel and infrastructure.

By producing outputs with greater precision, range operators have greater confidence to be more targeted with the evacuation of non-essential personnel. This is particularly valuable when the range is used

simultaneously for other activities and evacuation causes significant inconvenience.

Precise risk contours also facilitate precise placement of mission essential personnel and infrastructure required for monitoring the launch. This is particularly important in the launch site region where people may need to be sheltered inside buildings to meet required risk criteria. Figure 11 shows sample risk contours around a launch site for different levels of sheltering (as per RCC Standard 321-07 [12]):

- Red: 1×10^{-6} ‘out in the open’ individual risk
- Blue: 1×10^{-6} class D building individual risk

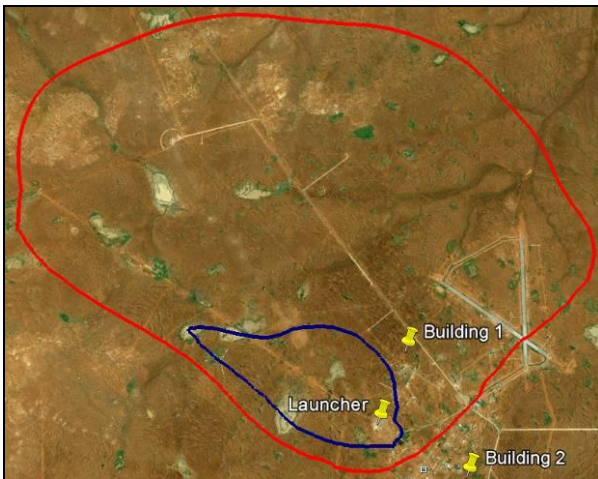


Figure 11. Risk contours around launch site for different levels of sheltering

Building 1 (labelled by the topmost pin) lies inside the red contour but outside the blue, implying that personnel may not be ‘in the open’ at that site. If the building is of class D strength or greater, however, personnel may be stationed inside.

Building 2 (bottom right), however, is outside both contours, implying that personnel may be located there ‘in the open’. These outputs from RSTT allow precise placement of mission essential assets while applying risk criteria with confidence.

6.4. Mission Design Iteration

RSTT also provides the ability to iterate mission design and receive rapid feedback on the impact that mission changes have on the safety template. Because RSTT templates are derived from detailed 6DOF modelling of the vehicle, the effect of changing mission initial conditions, launch wind and rail limits etc. can be ascertained quickly. There is no need to incorporate the changes into a complex set of assumptions, as might happen with traditional methodologies, as simply re-running the simulations and statistical processing will produce the updated template.

This feature was used extensively in development of a HIFiRE safety template. Range operators expressed concern over the allowed launch rail movement when performing wind weighting and the use of wind profiles only allowing launch during one month of the year. Adjusting launch rail and wind profile limits was a quick process, resulting in template reproduction within several days, including review. Range operators were also able to reposition personnel and infrastructure to be within allowed individual risk limits, with rapid updates to the overall collective risk estimation.

This feature of RSTT provides a flexible mechanism for overcoming mission design issues that result in unacceptable risk.

7. DESIGN ANALYSIS USING RSTT

RSTT also provides an additional tool for design analysis by developers and users; for example:

- More accurate determination of structural strength requirements based on dynamic loads during flight,
- Swapping MIST components (refer Figure 5) to assess design alternatives,
- Testing of flight software in the RSTT simulation environment (‘software in the loop’), and
- Adjusting a vehicle model to provide insight into manufacturer-proposed design changes.

Use of RSTT has previously resulted in two instances of significant insight into guided weapon behaviour not previously disclosed by the manufacturer. The first increased user understanding of weapon effectiveness and the other resulted in a safety-related launch limitation.

8. RSTT ASSURANCE

Assuring that RSTT outputs represent the actual risks to people and infrastructure as closely as practicable is fundamental to the usability of the system.

RSTT has been developed under a rigorous engineering management system including development as ‘Level C’ software in accordance with RCTA/DO-178B [13]. The design standard applied for risk criteria is RCC Standard 321-07 [11]. Furthermore, we expect that compliance with most FAA Title 14 Chapter III commercial spaceflight regulations [14] could be achieved through incorporation of minor changes to RSTT terminology and definitions (which is currently being considered) along with modification to incorporate specific characteristics of the range, launch control system and mission to achieve compliance (which has been done previously in one case).

Verification has involved appropriate derivation and specification of requirements and a range of assurance

activities to ensure that all requirements have been satisfied. In particular, critical verification issues were identified and appropriate verification measures taken.

Validation is an ongoing activity as RSTT is further developed to support new air vehicles and as other validation opportunities become available. The efforts thus far have focused on validating the HIFiRE variant of RSTT by comparing the RSTT results against radar track data and other analyses.

9. CONCLUSION

RSTT has developed into a functional and highly adaptable system for a variety of aerospace vehicles and mission types. When applied to space vehicle launch and re-entry range safety, it provides a mechanism to overcome many of the shortcomings of some traditional template generation methods. Limitations in computing power that once made the RSTT level of fidelity and complexity infeasible are no longer present. This facilitates deeper analysis of vehicle behaviour making traditional assumptions increasingly harder to justify.

The increased accuracy and precision of safety template results from RSTT give range operators more confidence in applying the template against required risk standards, and provide more flexibility when planning the location of various range assets. Given these benefits, it is expected that RSTT will continue to evolve to support the launch of other space vehicles such as suborbital space tourism flights. Furthermore, as new operational reference data becomes available the system will be further improved and revalidated.

10. ACKNOWLEDGEMENTS

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