

IAC-11-D6.1.2

RISK HAZARD ANALYSIS FOR COMMERCIAL SPACEFLIGHT ACTIVITIES USING RANGE SAFETY TEMPLATE TOOLKIT

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Australia has recently introduced a new capability into service for space launch and re-entry Risk Hazard Analysis (RHA). This capability, called the Range Safety Template Toolkit (RSTT), was originally developed for air-launched guided weapons but has now been successfully applied to a broad range of air and space flight missions and is being adapted to help meet the needs of the commercial spaceflight community.

RSTT offers rapid generation of mission-specific safety templates which comply with common standards for range risk criteria, as well as a suite of analytical tools that enable the templates to be combined with geospatial information, such as asset locations and population densities, to provide casualty and damage estimates for operational planning and safety analysis of the mission.

With a diverse range of missions and vehicles already analysed using RSTT, the system already has the capability to meet the technical and regulatory needs of commercial space flight operators.

I. 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 which 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.

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

We have also presented at a previous IAC [5] about RSTT being used in two very different space safety applications. The first was (and continues to be) the HIFiRE joint US / Australia hypersonic flight research program involving a series of suborbital launches and controlled hypersonic flights from Woomera, South Australia. The second

was the return to Earth in mid-2010 of the Japanese Hayabusa spacecraft.

This paper discusses how RSTT could be used to meet end user and regulatory requirements for risk analysis on commercial spaceflight missions. With a diverse range of missions and vehicles already analysed using RSTT, the system already has the capability to meet the technical and regulatory requirements of commercial space flight operators.

II. RSTT BACKGROUND & METHODOLOGY

Safety templates, otherwise variously known as 'weapon danger areas' (WDAs), '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. A safety template is one form of 'risk product' which can be produced using RSTT, and the foundation for deeper level analysis which can produce risk products to support range operations and assessments for liability and insurance.

A generic process for generating safety templates is shown in Fig 1. Many template production methods involve the modelling the vehicle of interest from available technical data.

The 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 called ground impact points (GIPs), are processed to create a safety template and other risk products such as liability assessments.

Traditional range safety analysis methodologies for such vehicles have been relatively simplistic, as a mature and trusted system for producing higher fidelity results had not been available, and the vehicles under study were also relatively simple – unguided sounding rockets as an example. Ground impact distributions tend to be more regularly distributed for unguided than for guided or human-controlled vehicles and thus simpler vehicle models and processing methods were employed. Some methods are deterministic, based on empirical evidence from previous launches and many simplifying assumptions. Others involve Monte Carlo simulation of the vehicle model followed by the fitting of normal (Gaussian) distributions to the resultant impacts (such as the typical “three sigma” ellipse). Events that occur at a “point” in time, such as a jettisoned stage, are typically bivariate normal

RSTT improves the quality and fidelity of safety templates by increasing the sophistication of each of the stages in Fig 1. It involves the development of a six degree of freedom (6DOF) vehicle model consisting of nominal flight, extensive failure behaviour and parameter tolerancing. Millions of ground impact points are produced by Monte Carlo simulation of initial conditions and vehicle parameters. When compared to traditional methods, this results in significantly more data across a wider range of flight behaviours from which to develop templates. RSTT processes and techniques have been explained in detail previously in other papers [1], [2], [3], [4] and [5].

The statistical processing of these impacts produces Probability Density Functions (PDFs) and subsequently risk contours. Critically, these 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 defensible and traceable. Consequently, range operators have greater flexibility in mission planning when applying safety standards, regulators can trust the output, and insurers have a firm basis for assessing policy premiums.

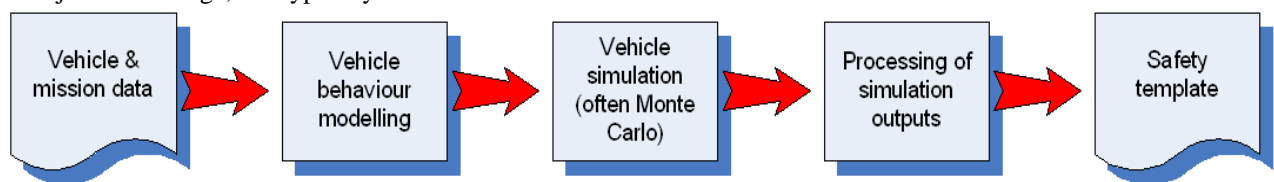


Fig 1. Overview of common safety template generation process.

(Gaussian) distributions. Conversely, for events that can occur over an extended period of time, such as a thrust failure, a “down range corridor” consisting of a one dimensional normal distribution fitted cross range to the Instantaneous Impact Point (IIP) trace is a typical method [6].

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

Furthermore, RSTT is unencumbered by some of the challenges associated with ITAR, although it is governed by the Australian equivalent. The component structure of modelling in RSTT under the MIST standard allows different components of the vehicle to be handled independently using encapsulation. This supports an ‘ITAR-flexible’ approach to development meaning that almost all elements of the RSTT system can be adapted to suit the export control registrations required by the user. Some vehicle and missions could be analysed by RSTT free of all ITAR restrictions, other missions where just some components of the simulated vehicle are governed under ITAR or finally where the entire model is ITAR-affected.

III. USER NEEDS FOR COMMERCIAL SPACEFLIGHT RISK ANALYSIS

A. Overview

Commercial space flight is a rapidly emerging industry which is leading the development of unique and innovative methods of accessing space for the purposes of tourism, supporting research activities, rapid global transportation, satellite launch, space station resupply and debris mitigation. With these rapid changes and advancements in spaceflight concepts, regulatory systems and range managers face challenges in adapting their policies and procedures to ensure the safety of the general public, mission personnel and range infrastructure.

Commercial spaceflight actors need a cost-effective system which can support their novel concepts, meet regulatory requirements and produce risk products with sufficient precision to allow for flexible range operations. Furthermore, a quantitative risk assessment methodology is needed to assess the potential liability for novel missions to support appropriate insurance applications. This section describes some of the unique user needs which apply to commercial spaceflight risk analyses and how RSTT can meet those needs. The following section expands on this work to describe how the analyses previously completed using RSTT have helped to create a system which is capable of assessing the mission concepts likely to be required by commercial space flight actors.

B. Assurance under stringent regulatory environments

The regulatory environment for commercial spaceflight is developing over time as operators and regulators each develop concepts for dealing with the uncertainty and risk of new missions. One of the driving needs behind the development of RSTT was a robust system which could produce assured risk products under the Australian space and defence regulatory environments. Risk analyses products developed using RSTT for space flight applications have recently been accepted for use under the both the Australian civil and military regulatory systems demonstrating that RSTT is fit for purpose as a capability. 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. The design standard applied for risk criteria is RCC Standard 321-07. Compliance with most FAA Title 14 Chapter III commercial spaceflight regulations could likely be achieved through incorporation of very minor changes to RSTT terminology and definitions (which is currently being considered).

However, in the case of remaining regulations, RSTT can be modified in collaboration with the launch service provider to incorporate specific characteristics of the range, launch control system and mission to achieve compliance.

Verification of RSTT 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 using flight data and other simulation sources is an ongoing activity as RSTT is further developed to support new air vehicles and as other validation opportunities become available.

C. Support of novel concepts

Commercial spaceflight is characterised by the development of novel concepts for accessing space. These innovative approaches are intended to give a company a competitive edge in their chosen market and will help drive lower costs and more reliable space systems. Novel mission concepts need a system to support risk analyses which can be applied across a wide range of ideas. Simpler analysis methodologies need to make broad assumptions about the performance of vehicles whereas RSTT is able to quantify risk for complex new vehicles and mission profiles with the same level of precision as traditional missions.

D. Export control flexibility

Commercial spaceflight operators are intending to operate at various locations around the world, each with their own unique regulatory and operational environment. With many space and launch technologies regulated by export control frameworks, such as the US International Traffic in Arms Regulations (ITAR), flight analysis systems need to be flexible to work within these regimes. With US-based companies currently leading much of the commercial space flight vehicle development, some elements of their systems will be directly governed by ITAR and will definitely limit the flexibility of working in other countries. RSTT supports an 'ITAR-flexible' approach to development, meaning that almost all elements of the RSTT system can be adapted to suit the export control regime required by the user. Some vehicle and missions could be analysed by RSTT free of all ITAR restrictions, other missions where just some components of the simulated vehicle are governed under ITAR or finally where the entire model is ITAR-affected.

E. Use of existing ranges and launch facilities

Commercial spaceflight will operate from existing or modified ranges and launch facilities that present additional challenges, and rigorous analysis requirements. These facilities are close to

populated areas, other critical infrastructure and are tightly coupled with management of the airspace – this leads to the need for precise and flexible range operations. The increased accuracy and precision of safety template results from RSTT gives range operators more confidence in applying the template against required risk standards, and provides more flexibility when planning the mission and selecting the location of various range assets.

F. Distribution and training

Aerospace Concepts has developed a configuration control system and training package to distribute RSTT to other organisations and rapidly train new users. This system will allow commercial spaceflight operators need to be able to undertake their own analysis in order to better evaluate their own systems, rapidly adjust their mission profiles to satisfy range requirements and to meet commercial security requirements. This distribution and training system has been recently been deployed with two organisations – Advatech Pacific, Inc., a US-based partner who will lead risk analysis on US military systems; and to students at the University of Adelaide, to introduce them to aerospace simulation and modelling techniques.

IV. APPLICABILITY OF PREVIOUS RSTT ANALYSES TO COMMERCIAL SPACEFLIGHT

A. Overview

A preliminary analysis into how RSTT could be applied to commercial spaceflight operations has been undertaken in order to assess the level of effort required to modify RSTT for new users. Through its application on previous projects, RSTT already has satisfied the user needs of a solution for risk analysis for commercial human space flight, or could be easily adapted to do so. The following sections describe how the recent analyses of HIFiRE, Hayabusa, JASSM, ASRAAM, Javelin and Unmanned Aerial System (UAS) missions, as well as work into dynamic airspace management, have all contributed to creating a system which is ready for application to commercial spaceflight.

B. HIFiRE

Since 2007 Aerospace Concepts has been engaged by the Defence Science and Technology Organisation (DSTO) to assist with the development of RSTT and apply it in the production of Risk Hazard Analyses (RHAs) for vehicles launched by the US/Australia HIFiRE hypersonics flight research program being conducted from Woomera, South Australia.

There is a broad range of mission concepts planned for the HIFiRE program overall and these requirements have driven the development of a

system which can support a wide range of space driving the work includes ballistic launch and re-entry as well as missions involving hypersonic gliding and scramjet-powered air vehicles.

This work has significantly increased the capabilities of RSTT including support of mission elements central for commercial spaceflight missions, including:

- Modelling of multi-stage vehicles, of which each stage can be of a different vehicle type including rockets, gliders, UAS and satellites;
- Methodologies for identifying and modelling high-fidelity failure modes;
- Introduction of hypersonic aerodynamics and control modelling;
- Modelling of many classes of debris following a catastrophic failure; and
- High-precision risk assessments near the launch area to assist with range management options.

C. Hayabusa SRC

Aerospace Concepts was engaged to provide analytical support to the Australian Government in overseeing the return of the Japanese Aerospace Exploration Agency's (JAXA) *Hayabusa* spacecraft to Woomera in mid-2010. This work focused on independent analysis of the Sample Return Capsule (SRC) which successfully returned samples from Asteroid *Itokawa*.

The scope of work included modelling, Monte-Carlo simulation and analysis of the Hayabusa return trajectory using RSTT and comparison against trajectory predictions provided in the return safety plan.

This work introduced new capabilities to RSTT applicable to commercial spaceflight including:

- Improved fidelity for a the simulation environment of a Curved Rotating Earth with a WGS84 Earth model, as per NIMA TR8350.2, an oblate ellipsoid shape, ellipsoid gravity model and rotation rate;
- Improved fidelity of high atmosphere models;
- Direct integration with current GIS mapping applications and GPS;
- 'Dynamic starts' for vehicles which allows for commencing the simulation with a vehicle model that has an existing dynamic state including velocity, rates of acceleration, fuel condition, damage and failures; and
- Consideration of extremely high speed aerodynamics, upwards of Mach 40.

D. ASRAAM and JASSM

The heritage of RSTT is firmly based in the development of risk assessment products for the ASRAAM and JASSM missiles recently acquired

by the Royal Australian Air Force. This effort has been led by the Defence Science and Technology Organisation since 2005 and has recently culminated in the acceptance new JASSM safety templates for operational use.

The complexity of these systems has significantly influenced the development of RSTT and has introduced capabilities to handle mission concepts directly applicable to commercial spaceflight missions including:

- GPS guidance systems, including missions with multiple and dynamic way points;
- Flight termination systems;
- Statistical processing capability to handle large datasets in a robust manner; and
- Multi-waypoint following guidance.

E. Javelin

In mid-2010, the Australian Department of Defence tasked Aerospace Concepts to undertake modelling and simulation of the Javelin Block 1 missile in order to verify the safety templates supplied by the weapon system manufacturer.

Through this work Aerospace Concepts modelled the Javelin missile failure response modes, aerodynamics, propulsion, gravimetrics, guidance and control and flight profile characteristics.

Undertaking risk analysis on Javelin greatly project has significantly increased the capabilities of RSTT for modelling dynamic flight control for multiple mission profiles, which is directly applicable to commercial space flight vehicles.

One of the most surprising findings of this project was how the Monte-Carlo analysis approach uncovered a low-probability but very high consequence hazard – commonly known as a ‘black swan’ event – which was unknown to the Department of Defence at the time. The high-fidelity Monte-Carlo techniques uncovered a vulnerability of the Javelin missile to cross winds at launch. As a result, this hazard has now been mitigated through limitations on firing conditions disseminated to Army through visible warnings on the endorsed range safety template.

This finding illustrates an important concept for systems safety analysis in general – complex systems exhibit emergent behaviours, some of which can have major implications to safety, and some of these can likely only be uncovered through statistical analysis. By undertaking a very large number of simulations across the mission envelope, probabilistic risk analysis can greatly assist with establishing an understanding of vehicle behaviour. This approach complements other system safety analysis techniques, such as FMECA and Fault Tree Analysis, which are less likely to uncover low-probability, but high-consequence ‘black swan events’.

F. Unmanned Aerial Systems

RSTT is planned to be applied to UAS hazard analysis, including its implications on airspace operations.

RSTT is being extended to support the production of high fidelity, quantitative, probabilistic risk estimates due to failures of the UAS that can be used by airworthiness authorities to assess risk to Mission Essential Personnel, the general public, range infrastructure and public sites as well as quantitative analyses of scenarios such as airspace incursions/excursions and separation distances from other aircraft.

The quantitative nature of the risk analysis produced by RSTT provides UAS operators with greater confidence in estimating mission hazards. It also enables airworthiness authorities to quantitatively assess the airworthiness of UAS within an operational environment and in a manner which closely aligns with UAS technical airworthiness regulations currently being developed by the Australian military airworthiness regulator. These assessments are assured of their provenance as RSTT is developed within a formal engineering framework and is compliant with applicable software lifecycle standards and international range safety criteria standards.

In an operational context, RSTT also offers increased precision of risk analysis, allowing greater flexibility in planning of UAS missions. This assessment of risk allows UAS operators to consider a broader set of options for the placement of flight paths, mission-essential personnel, and critical ground infrastructure. These concepts can also be readily applied to commercial space flight operations.

The primary benefit to UAS operators of using RSTT is the ability to iterate mission design with rapid feedback on the impact of mission profile changes on flight safety. This then provides a practical mechanism for overcoming mission design safety issues that may result in risk exceeding acceptable criteria.

G. 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 Next Generation Air Transport Program (NextGen) in combination with concepts and tools for dynamic airspace management for Operationally Responsive Space (ORS)⁷ and, perhaps, RSTT, offer a way to improve airspace management through better use of simulation and other computer-based safety assurance techniques.

V. CONCLUSION

The development of RSTT against a wide range of vehicles and mission profiles over many years has led to a system which is able to support risk hazard analysis of almost any new aerospace system. Ballistic rockets, re-entry capsules, guided weapons and UASs have all contributed their own requirements to the development of the capability, meaning there is now a very broad base on which to build for novel vehicles and future mission concepts.

From this preliminary analysis, RSTT appears to be ideally suited to supporting commercial spaceflight missions in the very near future with little additional development required.

Aerospace Concepts now intends to conduct a small pilot study from publically available data of an upcoming commercial mission to further test its systems and provide an indication of the level of effort required to support commercial spaceflight.

ACKNOWLEDGMENTS

The authors thank the Australian Defence Science and Technology Organisation (DSTO) for its permission to publish this work.

We also thank the Australian Department of Defence, the joint US/Australia HIFiRE Program and the Australian Space Licensing and Safety Office (SLASO) for funding contributions, ideas and critical review throughout the development program.

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