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Guided Weapon Danger Area & Safety Template Generation – A New Capability

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The Australian Department of Defence will shortly introduce a new capability for the generation of guided Weapon Danger Areas and launch vehicle range safety templates into service. This Australian-developed capability, called the Range Safety Template Toolkit (RSTT), will initially support operations of the ASRAAM air-to-air missile, AGM-158 JASSM cruise missile and the joint US/Australia HIFiRE hypersonic flight research program being conducted from the Woomera range in South Australia. Support for future guided air weapons operated by Australia's armed forces will be introduced as these weapons enter service. Future uses for RSTT could potentially include broader mission analysis tasks, operational safety assessment for Unmanned Air Systems (UAS), and reducing the time and volume of airspace needed to be restricted for weapon tests and space launch operations thus facilitating more dynamic management of airspace to reduce air traffic congestion.

I. Introduction

Over the past four years, the Australian Defence Science and Technology Organisation (DSTO) and industry partners have been developing a new capability for the generation of Weapon Danger Areas (WDA) for guided air weapons and other aerospace vehicles. This capability, known as the Range Safety Template Toolkit (RSTT), is shortly to be introduced into service for the ASRAAM air-to-air missile, the AGM-158 JASSM cruise missile and the US/Australia HIFiRE hypersonics flight research program being conducted from Woomera, South Australia. In the longer term, we expect that RSTT will become the standard for guided air vehicle WDA and safety template generation within Australia.

Development of RSTT has involved both public and private organisations under the sponsorship of the Royal Australian Air Force (RAAF) and the Defence Materiel Organisation (DMO). The RSTT development team was led

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by DSTO, part of the Australian Department of Defence, with specialist support throughout development from industry and academia, including Aerospace Concepts Pty Ltd and the University of Adelaide. RSTT is wholly-owned Commonwealth of Australia intellectual property, though it leverages certain generic missile models sourced through international government-to-government collaborative arrangements. Commercialisation licenses are currently being negotiated.

We have previously presented our work to the AIAA[1] and elsewhere[2-4] focusing on the theory underpinning the capability, operational user and regulatory needs and our consequent development approach. The intent of this paper is to describe the resulting capability, how it will be employed and potential future uses.

II. Weapon Danger Areas and Safety Templates

Weapon Danger Areas (WDA), otherwise variously known as 'range safety templates', 'safety traces' and 'safety footprint areas', are tools for the assessment of risk associated with air weapon and other aerospace vehicles.

A WDA can take a number of forms, including:

- A curve representing an enclosed area where the weapon might land with a specific probability, or
- A contour plot representing different regions of ground impact probabilities.

These plots are overlayed on maps of the intended launch area and used to assess if there is an acceptable risk of the launch affecting the safety of 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. A WDA is defined for a specified firing envelope and a defined set of launch conditions.

In this paper WDA is used interchangeably with 'template' due to RSTT being used for both guided air weapons and non-weapon (e.g. HIFiRE) rocket launches. Furthermore, the terms 'weapon' and 'air vehicle' will also be used interchangeably, as from a range safety perspective there is little difference between the two.

III. How RSTT Works

A. Overview

The RSTT offers rapid (minutes to hours) generation of mission-specific WDAs that are valid for a launch event undertaken anywhere in a user-specified envelope. The WDAs 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 pre-calculated ground impact distribution database. There are two processes for creating the impact database, selected depending on the number of independent variables that influence the ground impact point. For systems with few independent variables, such as ASRAAM, creation of the impact database for the air weapon type is a once-off, computationally-intensive activity that simulates all (reasonably) possible failures and trajectories over a grid of independent variable values. For one-off systems or systems with many independent variables, such as HIFiRE or JASSM, creation of the impact database is a per-mission, computationally-intensive activity that simulates the mission with suitably selected tolerances on the independent variables. Both processes require a fit-for-purpose model of the weapon system, usually Six-Degree-of-Freedom (6-DOF), which includes modelling of Failure Response Modes (FRMs). Calculating these databases typically takes calendar months in the first process and days to weeks in the second process, on a 'farm' of more than 100 high-end computers. The impact database, along with client software, is then used by operational planning or range safety specialists who then generate mission-specific templates in minutes to hours on a small farm of five or more high-end computers.

The remainder of this section discusses how a WDA or template is generated, beginning with failure analysis which is common to all weapon / vehicle variants covered. Each weapon offers unique challenges due to the very different mission characteristics that need to be considered:

- For an air-to-air weapon such as ASRAAM, the kinematics of the launch (velocity, altitude) and of the (probably manoeuvring) target can vary greatly.
- A waypoint-following weapon such as JASSM has variability in the route for each mission and may be capable of dynamically rerouting during flight.
- An experimental program such as HIFiRE may involve changing vehicle designs and mission parameters from launch to launch. Also, the experimental nature of each launch means that some design data, is simply not produced and hence, the template must reasonably incorporate this inherent design uncertainty.

B. Failure Analysis

As noted in our previous AIAA paper,[1] WDA generation begins with failure analysis of the weapon or air vehicle of interest. The failure analysis provides information about potential failures, their likelihood and effects, and a measure of how critical the failure is to system operation. Certain individual sub-system failures often result in the same system behaviour. The behaviour of such a group of failures is referred to as a Failure Response Mode (FRM).

For example, failures in the actuator frame components, or the power supply, or the PCB assembly can all cause the fins to drive to their end-stops. This is a case of three failures giving rise to one FRM. Figure 1 shows some potential FRMs for an air-to-air weapon.

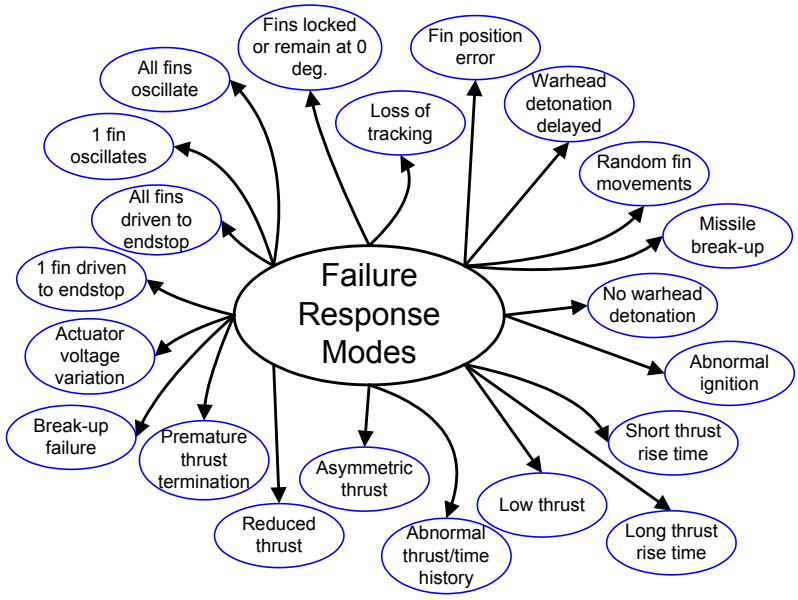

Figure 1. Possible FRMs for an air-to-air weapon.

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

C. WDA Generation for Air-to-air Weapons

This description is based around generating a WDA for an air-to-air missile such as ASRAAM; however, this same process would likely apply to any shorter-range direct-to-target (non waypoint-following) guided weapon such as a surface-to-air missile or an anti-armour missile. This section describes the first process outlined above.

We use a medium fidelity Six-Degree-of-Freedom (6-DOF) model of the air vehicle or weapon, which includes models of the FRMs, within a Monte Carlo simulation environment to generate ground-impact distributions. An example of a ground impact distribution is presented in Figure 2, which represents a total of 50,000 simulation runs. The impact locations correspond to a fictitious air-to-air missile and a single set of initial launcher and target conditions. In this example, we have allowed the fins to lock to zero degree deflection at a random time during the missile's flight. The trajectories for a successful target engagement are also shown. We use a computer farm to complete the Monte Carlo simulations in a reasonable time.

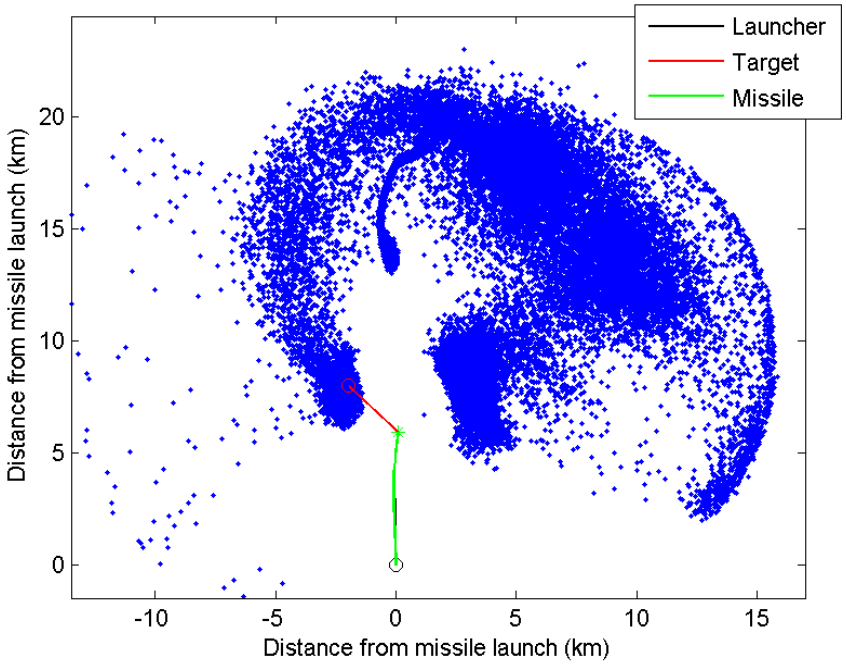

Figure 2. 50,000 ground-impact locations for a fictitious guided weapon with fins locking to zero degree deflection at random times.

We have selected a Kernel Density Estimation technique[5-7] to create a smooth two-dimensional Probability Density Function (PDF) for each scenario/failure combination. Figure 3 shows an example PDF derived from the scenario represented in Figure 2.

Combining the PDFs for each FRM, given the probability of occurrence extracted from the failure analysis, is quite straightforward. The problem is that this produces a WDA valid only for a point in the operational envelope of the weapon. In an air-to-air engagement for example, even a test pilot would be hard pressed to take the shot when travelling at exactly 210 knots with the target exactly 5.3 nautical miles away. So the final WDA must be valid for a user-selected *region* of the envelope.

We achieve this by establishing ground impact data (or PDFs) at the corners and other critical points of the firing envelope from scenarios in the ground impact database. In ASRAAM-style cases it will be necessary to generate the corners and critical points of the user-selected region via a conservative interpolation technique. Figure 3 illustrates what a PDF might look like at a critical point in the user-selected *region* of the envelope.

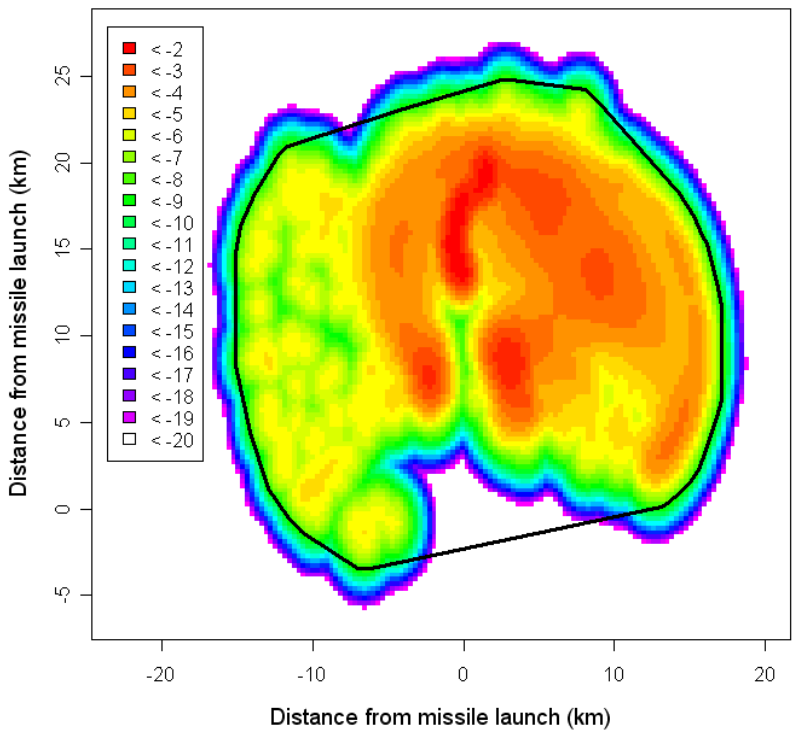

Figure 3. Ground impact PDF ($\log_{10}$ scale) with boundary representing 1×10^{-6} probability of escape.

To produce the WDA we overlay the PDFs for each of the corners (and other critical points) in the user-specified firing envelope and apply a convex-hull algorithm to account for the middle of the envelope. We set the probability-density-of-impact for any grid-square on the ground to be the maximum probability density at the corresponding grid squares of all the overlayed PDFs. The resulting PDF is 'smeared' to account for launch location errors, heading errors and wind. This produces a conservative ground impact probability map that is valid for a shot taken anywhere in the user-selected envelope. We turn the probability map into a WDA corresponding to an acceptable risk threshold by drawing the appropriate contour or risk isopleth, as illustrated by the black curve in Figure 3. The ground impact probability map can also be used with population demographics and debris energy characteristics to calculate an expected casualty estimate.

D. WDA Generation for Waypoint-following Weapons

The WDA generation process for waypoint-following vehicles such as AGM-158 JASSM also begins by constructing a 6-DOF model of the vehicle including its FRMs. The 6-DOF model is used to populate the WDS with ground-impact distributions for each of the FRMs initiated at specific vehicle dynamic states (i.e. altitude, speed etc.). For each FRM simulation the ground impact point and a coarse history of the trajectory are recorded. JASSM also requires the generation of ground impact distributions corresponding to debris created by the activation of a Flight Termination System (FTS).

The generation of a trial-specific WDA can be done iteratively. First, waypoints corresponding to the intended mission are overlaid on a range map, as illustrated in Figure 4; this can be done via some form of mission planning software or manually.

We then run Monte Carlo simulations of the planned mission using the 6-DOF model, as shown in Figure 5, where the trajectories are shown in black. These simulations eliminate the need to pre-calculate the off-nominal weapon behaviour for all possible missions. In practice, hundreds of simulations will be needed to characterise the dynamic state of the system at points along the nominal mission, which will be recorded for the next stage.

Next, the dynamic states recorded by the 6-DOF model are used to access the ground impact distributions in the WDS and generate a combined, whole-of-mission ground impact PDF. This PDF will then have a convex hull WDA boundary applied to it, which is illustrated in Figure 6 (PDF shown in red, WDA boundary in blue).

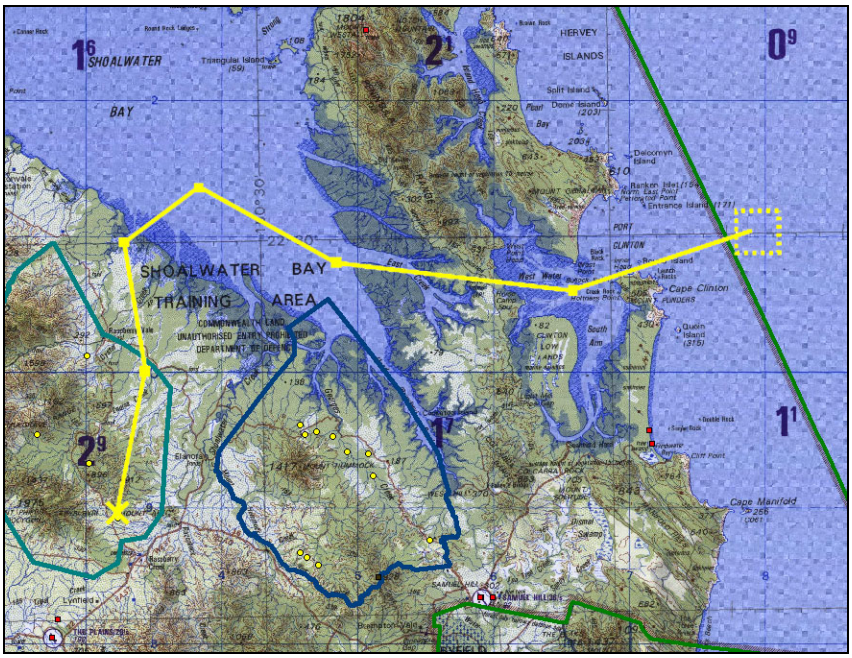

Figure 4. Mission waypoints overlaid on a range map (illustration only).

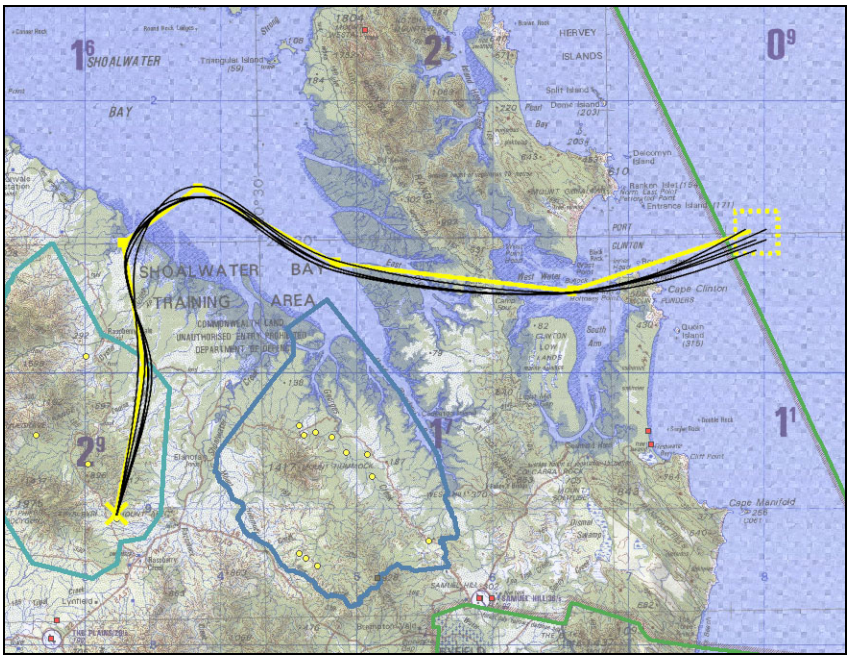

Figure 5. Possible trajectories simulated by RSTT (illustration only).

In some situations, an Area of Critical Concern (ACC), such as a valuable piece of range infrastructure, could lie within the WDA boundary and may therefore be subjected to an unacceptably high level of risk. This risk could be mitigated by using an FTS to 'protect' the ACC. Specifying FTS cut-down lines around the ACC, with consideration given to the reliability of the FTS and supporting systems, can reduce the risk to which the ACC is exposed. This situation is illustrated in Figure 6, where the ACC is represented by a blue dot, the FTS cut-down lines are indicated in green, and the debris impact area in red.

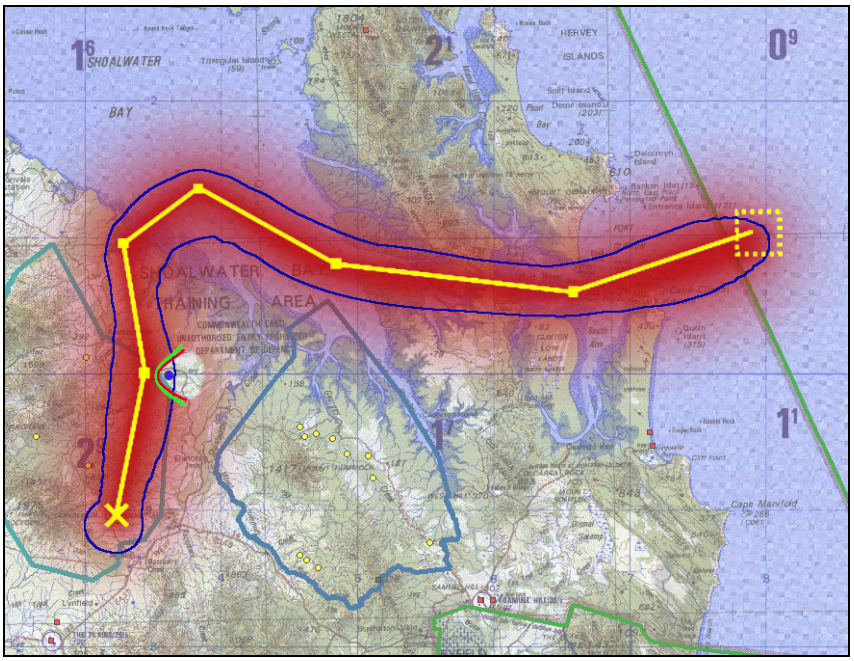

Figure 6. PDF with WDA boundary, showing reduced risk to an ACC through use of an FTS (illustration only).

E. Template Generation for HIFiRE and Other Launch Vehicles

In contrast to ASRAAM and JASSM, the generation of safety templates (WDAs for non-weapons) for HIFiRE and similar vehicles is relatively straightforward. A HIFiRE launch can be thought of as an ASRAAM launch in which the launch point and target are fixed. Therefore, the generation of a HIFiRE template can follow a simple path from the vehicle modelling, to the generation of ground impact points and PDFs, similar to ASRAAM, but with the complication of tolerances in the vehicle design replacing the complication of the ASRAAM firing envelope.

IV. RSTT Architecture

A. Overview

The RSTT has been developed within the Australian Defence Science and Technology Organisation's mature, flexible and standards-based *Mars* and *SimFramework*[8] modelling and simulation environment from standard component models that comply with an internationally-accepted standard. Consequently, new weapons or vehicles can be quickly added to the system (assuming sufficient weapon technical data is available) and the resulting model used for many other purposes besides generation of range safety templates. For example, we expect that RSTT will play some role in the technical and mission design of several HIFiRE research launches which include sustained horizontal flight of a scramjet-powered aircraft.

B. High-level System Architecture

The RSTT high-level system architecture, shown in Figure 7, consists of two segments and a data store:

- The 'Back End RSTT' (BERSTT) is a set of libraries and applications ('tools') used to model and simulate the air vehicle to produce ground impact sets, where each ground impact set corresponds to a particular weapon or vehicle, mission and FRM combination. Within each ground impact set there may be sets of ground impacts for each class of debris that is generated by a given FRM. This ground impact data are then stored in a weapon-specific Weapon Data Store (WDS).
- The 'Front End RSTT' (FERSTT) includes an application that enables generation of PDFs from the ground impact data set in the WDS, subsequent creation of WDAs and analysis of the range-safety related aspects.

Although the computer farm is shown in the BERSTT segment, the shear number of interpolation and KDE operations required for WDA generation also needs computer farm capabilities, albeit on a smaller scale. For systems such as JASSM and HIFiRE, some mission-specific information is required to be input to FERSTT. To simplify the user experience, in some cases such data can be entered into FERSTT, which will then drive BERSTT on the user's behalf.

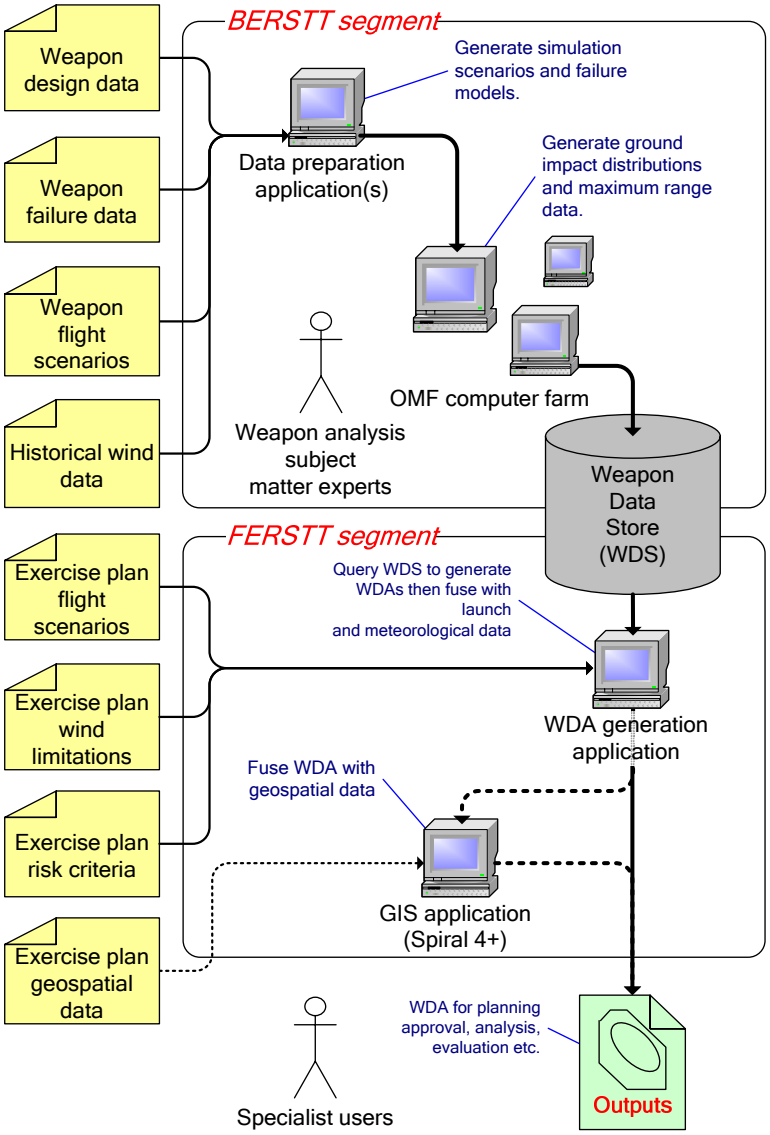

Figure 7. High-level system architecture.

C. Model Architecture

Development of weapon (and other air vehicle) models is accomplished using the *Munitions Model Interface Specification for The Technical Cooperation Program (MIST)*.[9] This specification provides a functional decomposition of guided weapon systems, as show in Figure 8, a specification of the signals passed between model components and a modelling architecture blueprint.

Each of the three vehicles addressed to date (ASRAAM, JASSM and HIFiRE) have been modelled using a combination of standard MIST components that have been used as-is and others that have been modified. For example, an existing MIST compliant 'Motor' component was modified to support multi-stage launch vehicles such as will be used in the HIFiRE Program. Furthermore, component models have been created or modified to represent failure behaviours such as motor case burn-through or jammed control surface actuators.

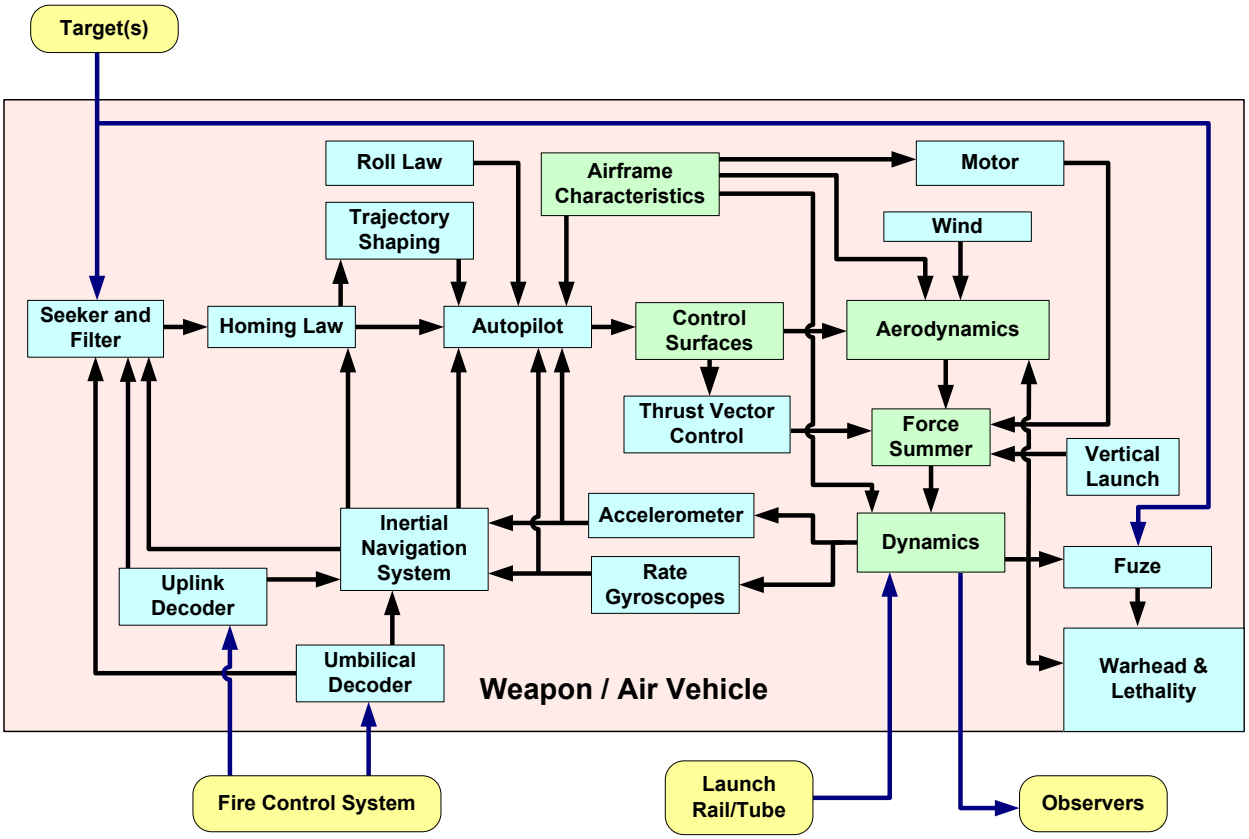

Figure 8. MIST baseline weapon / air vehicle components.[9]

D. Simulation Architecture

An integral part of DSTO's philosophy of reuse and multinational interoperability is the evolving simulation architecture known as *SimFramework*. This architecture is consistent with MIST and allows development of component-based models air vehicles that interact with other component-based models such as aircraft and terrain in a portable hierarchy. Figure 9 illustrates such a hierarchy of models, each of which can be developed independently.

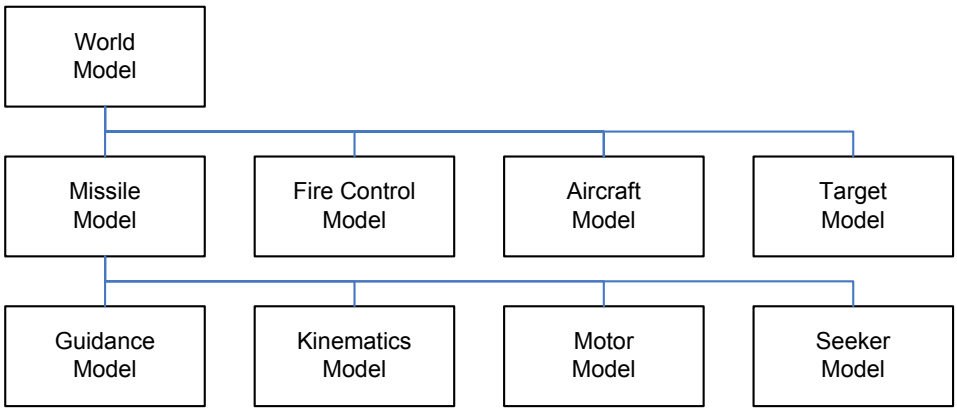

Figure 9. A single *SimFramework* simulation combining different system models.[8]

V. RSTT Development

A. Development Challenges

Because the RSTT capability represents a new approach to WDA and template creation, both in Australia and (we understand) internationally, we faced a number of distinct development challenges:

- **End-user needs.** End-user needs were not clear and were thus be elicited on an ongoing basis, initially using prototyping within a spiral development approach.
- **Policy issues.** The policy framework that governs the ability of the Australian Department of Defence to conduct potentially-hazardous flight test activities was found to be somewhat dated and significant effort has been expended in supporting changes such as a broad acceptance of probabilistic approaches to range safety management.
- **Data availability.** The engineering practicality of the conceptual solution was not guaranteed in that sufficient data to adequately model the weapons (and other air vehicles) might not be available. Addressing this required some minor changes to Australian Department of Defence acquisition processes, particularly the creation of a Data Item Description (DID) with which to capture relevant design information, and the development of a risk-based approach to addressing deficiencies in the eventual input data set.
- **Multi-object simulation.** Noting that most flight simulation is concerned with nominal flight and usually does not consider vehicle break-up and where the resulting debris might fall, it was necessary to adapt the DSTO modelling and simulation environment to simultaneously simulate the 'main vehicle' and any debris generated. This is described below.
- **Vehicle behaviours.** The very different nature of the first three air vehicles to be modelled (ASRAAM, JASSM and the HIFiRE vehicles) meant that our design has had to incorporate a broad range of vehicle behaviours, ranging from air-to-air engagement of moving targets, through to waypoint-following and exoatmospheric flight.
- **Vehicle design variability.** The experimental nature of the HIFiRE vehicles demands that RSTT be able to accommodate significant vehicle design changes and uncertainty between flights. This diversity of behaviours required several advances in modelling techniques, including development of a unified method of modelling vehicle break-up and fragmentation.[10] How this design variability was addressed is discussed in some detail below.
- **Mathematical practicality.** The mathematical practicality of the statistical analysis techniques used RSTT was also not guaranteed; indeed, considerable work in adapting statistical techniques, such as Kernel Density Estimation (KDE), to treat the large simulation data sets was needed.
- **Computational tractability.** The computational requirement of the design was significantly higher than past WDA generation methodologies; that is, meeting the required time constraints required significantly more computing power than a small handful of servers could provide. Solving this has required the development of a 'farm' of computers, made available over secure networks and the development of specialised distributed simulation job management software.
- **Assurance.** Finally, assuring that RSTT outputs represent the actual risks to people and infrastructure as closely as practicable is fundamental to the usability of the system given the trust that decision-makers will be placing in RSTT. Our assurance efforts, including validation approaches, are described in the next section.

B. Multi-object Simulation

As noted previously, most flight simulation undertaken by DSTO is concerned with nominal flight and usually does not consider vehicle break-up and the resulting debris. Consequently, it was necessary to upgrade the modelling and simulation environment to simulate both the 'main vehicle', using the central 6-DOF vehicle simulation model, and any debris generated using a 3-DOF debris propagator model.

For guided weapons, the production of debris is usually the result of a failure (excepting drop-off boosters, sub-munitions, etc) whereas for space launch vehicles, such as will be used by HIFiRE, the production of some debris classes is a nominal event. Consequently, most of our work in multi-object simulation has been oriented towards space launch as explained below.

During a flight, the main vehicle will change configuration several times as shown in Figure 10. In contrast to the main vehicle, a 3-DOF debris propagator model handles the spent stages and other items expended during the flight. Each of these debris pieces generates a ground impact point in addition to the main vehicle.

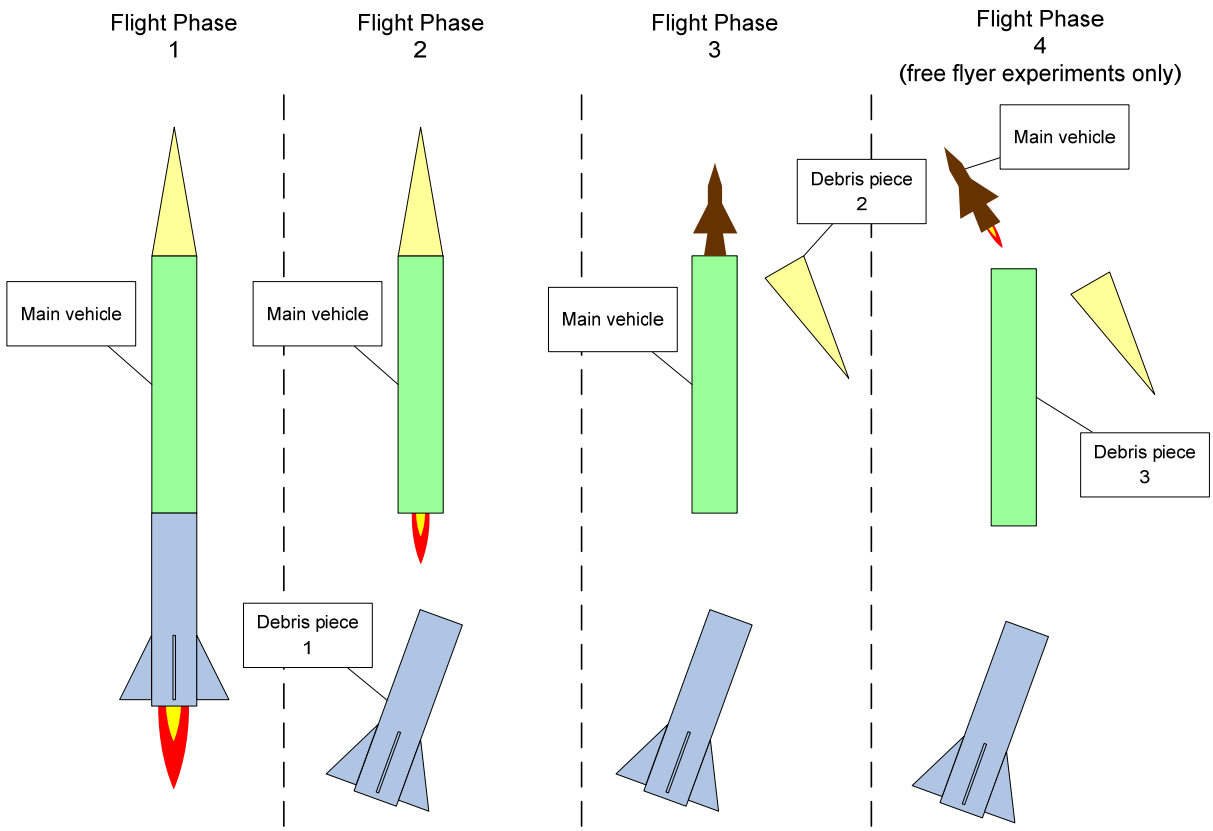

Figure 10. HIFiRE configurations during flight, illustrating the 'main vehicle' concept.

Due to the high velocities required by the HIFiRE program (up to Mach 10) and consequently the large amount of propellant required by the HIFiRE launch vehicles to reach these velocities, many of the FRMs can result in the aerodynamic or explosive fragmentation of the vehicle. Even the nominal mission can end in the break up of the main vehicle due to aerodynamic heating as was experienced during the HyShot and HyCAUSE Programs. These break ups can lead to the generation of tens to hundreds of debris pieces in the case of aerodynamic fragmentation, through to hundreds to thousands of pieces in the case of explosive fragmentation. Debris generated by aerodynamic or explosive fragmentation is handled by the same 3-DOF debris propagator model that simulates spent stages.

To make the problem of simulating the trajectories of such a large number of pieces of debris computationally tractable, a debris catalog approach is employed, in which the debris are grouped into a reasonable number of classes which are formed into catalogs representing the debris resulting from a given FRM.

In order to allow the generation of debris catalogs covering the envelope of both relevant FRMs and flight conditions and also to cope with a likely lack of suitable data, a methodology for generating debris catalogs has been developed. This methodology utilises a new fragmentation model which unifies the current treatments of aerodynamic and explosive fragmentation.[10] This fragmentation model has been calibrated against actual debris from previous hypersonic flight tests and the foremost in-space explosive fragmentation model. We expect to perform further validation of this new model and methodology over the coming months and, depending on progress, to publish our results at this conference in 2009.

C. Vehicle Design Variability

RSTT had its beginnings with ASRAAM, an 'off the shelf' weapon with a fixed and known configuration and performance. Our more recent move to support the experimental programs such as HIFiRE presents a different challenge to supporting military weapons for two main reasons: Firstly, experimental vehicles will not have a fixed configuration unlike an 'off the shelf' weapon. Secondly, there is a very real risk that model data with a sufficient level of provenance will not be available. Therefore, the RSTT ground-impact generation process (outlined in Section III, above) has been developed to handle uncertainty in model data by incorporating a level of tolerance.

The method for allowing tolerance in the model design and mission parameters without invalidating the template is threefold:

1. The data management system was developed to manage uncertain or unavailable data. The response to and uncertainty in, data with low provenance is managed and recorded.
2. The existing parameter manager tool, used for assigning Monte Carlo figures to mission and vehicle parameters, was upgraded to support specification of a percentage tolerance on any value including physical parameters such as aerodynamics, moments of inertia and thrust profiles.
3. We included techniques to demonstrably not underestimate the risk anywhere within the ground impact zone. This has been achieved by first running a scenario at full tolerance, then arbitrarily picking a battery of additional scenarios with a tighter tolerance range. The wide tolerance PDF is 'scaled up' so as to not underestimate risk compared to the results of the tight tolerance range. That is, the risk floor is raised to the highest 'tight tolerance' PDF.

VI. RSTT 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 given the trust that decision-makers will be placing in RSTT. 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 guided air weapons are not usually tested in statistically-meaningful quantities and that experimental vehicles are, by their nature, unique or near-unique, we have addressed assurance in other, more subtle, 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.[11]

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 accepted as being valid and indeed, will likely be used for other activities.

C. Validation

As a new capability with few, if any, direct 'peers', validation of RSTT outputs posed a problem particularly due to the lack of statistically-meaningful flight data as discussed above. Validation will, of course, be an ongoing activity as RSTT is further developed to support new weapons and air vehicles and as 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
- 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 by the University of Queensland and its partners on 30 July 2002 at the Woomera test range in South Australia.[12]

HyShot 2 involved a two-stage sounding rocket with the same general configuration as that planned for the early HIFiRE flights. We first obtained the vehicle data and used it to model the vehicle within RSTT, using the data management processes outlined above. The HyShot 2 flight was then simulated and compared against the actual flight telemetry and radar tracking data. Finally, we generated ground impact points for the nominal flight and several representative FRMs and converted those impact points to a PDF, as shown in Figure 11 and Figure 12. This was then compared to the actual range safety template that was generated some years ago by a third party and approved for the HyShot 2 flight.

RSTT outputs closely matched both the radar track data (when corrections for certain known differences were applied) and the safety template generated for the mission.

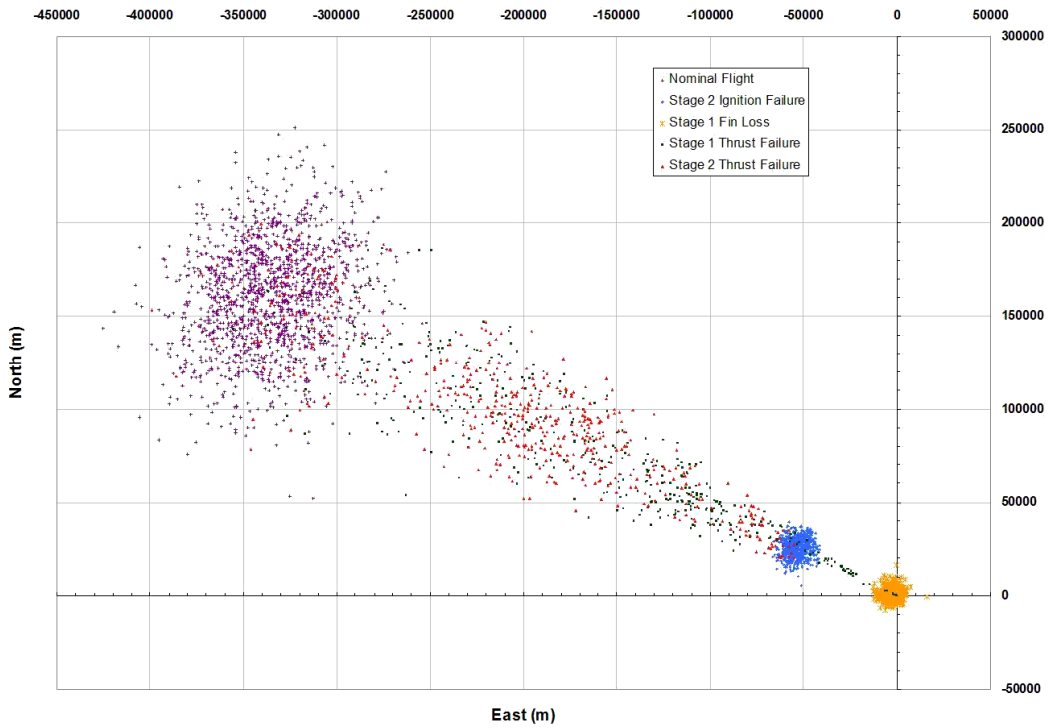

Figure 11. Ground impact points generated for HIFiRE validation against HyShot 2.

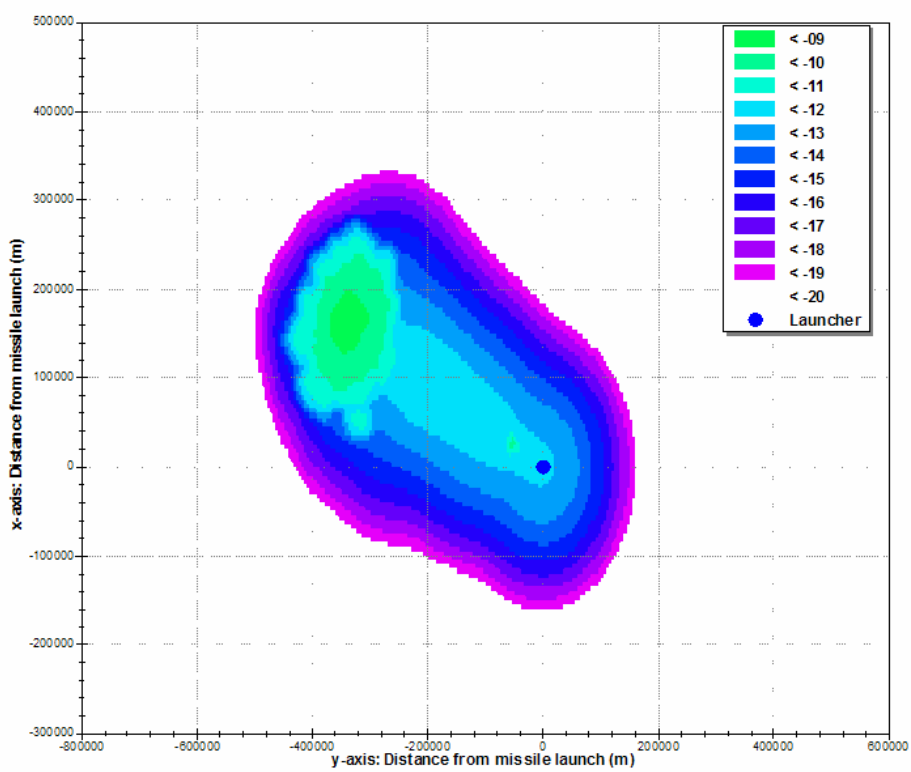

Figure 12. PDF (per m²), generated for HIFiRE validation against HyShot 2 (98% nominal, 2% failure).

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'. Consequently, organizations operating RSTT (within the Australian Department of Defence context) to generate WDAs and templates must satisfy requirements which broadly mirror those for RSTT development relating to organisational competence, personnel, processes, data and assumptions.

VII. RSTT Applications

A. Core use for WDA Generation

RSTT variants for ASRAAM and JASSM are in the final stages of development and will be introduced into service with the Australian military over the coming months. Most development risks have either been retired or are being treated and introduction-into-service activities, such as policy adjustments, publications and training are well-advanced.

An initial-capability RSTT variant to support the HIFiRE Program was completed in June and now awaits tasking as the HIFiRE Program progresses. We expect to create additional component models for HIFiRE as the program introduces novel designs for hypersonic flight; for example, the form of the scramjet-powered 'flyer' intended to be flown later in the program is not yet determined and is likely to use novel control techniques. Certainly, we expect to adjust the component models for hypersonic aerodynamics as the concepts and data for each mission are finalised.

As noted previously, 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 Management of Unmanned Aerial Systems

Aside from the application of RSTT to weapons or vehicles similar to those already supported (as covered in the rest of this paper), RSTT also has the ability to manage risk and hazards of other air vehicles such an Unmanned Aerial Systems (UAS), which in fact are not conceptually very much different to long-range missiles such as JASSM. In this context, similar challenges exist in the 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 conducted as peacetime exercises 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.

Furthermore, the technical airworthiness of UAS currently operated by the Australian Department of Defence typically do not comply to any accepted design standards, and as such are managed through imposing operational restrictions through an accepted system of operational airworthiness. This system of airworthiness management, whilst adequate for the short term, can be overly restrictive and therefore limit the capability to train UAS crew to the full potential of the UAS capability. RSTT has the ability to manage the technical data, or rather lack of technical data, associated with current UAS. It can apply tolerances to manage these uncertainties through the data management system processes as discussed earlier.

Therefore, RSTT can provide a technical airworthiness authority the ability to apply a structured and verifiable approach in managing mixed airspace and the associated ground-based risks and hazards. This RSTT-based approach to technical airworthiness will not replace military technical airworthiness regulatory framework but rather works within it as a source of assurance. It can provide a means to adequately manage UAS risks and hazards to ensure that UAS can be operated to their fullest capability within peacetime operations.

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 WDAs 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)[13] and, perhaps, RSTT, offer a way to improve airspace management through better use of simulation and other computer-based safety assurance techniques.

VIII. 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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References

[1]Fletcher, D.J., Wilson, S.A., Jokic, M.D., and Vuletich, I.J., "Guided Weapon Safety Trace Generation – Implementing a Probabilistic Approach," *AIAA Atmospheric Flight Mechanics Conference*, Keystone, Colorado, 2006.

[2]Fletcher, D.J., Wilson, S.A., Jokic, M.D. and Vuletich, I.J., "Guided Weapon Safety Template Generation – A Probabilistic Approach," *Systems Engineering / Test and Evaluation Conference (SETE)*, Brisbane, Australia, 2005.

[3]Jokic, M.D, White, T., Fletcher, D.J., Wilson, S.A. and Vuletich, I.J., "Guided Weapon Danger Area Generation – Australian Capability Development," *International Range Safety Advisory Group*, Amsterdam, The Netherlands, 2007.

[4]Fletcher, D.J., Jokic, M.D. and Graham, R.F., "DSTO Approach to Standoff Weapon Danger Area Generation", *International Range Safety Advisory Group*, Amsterdam, The Netherlands, 2007.

[5]Silverman, B.W., *Density Estimation for Statistics and Data Analysis*, Chapman and Hall, 1986.

[6]Silverman, B.W., "Kernel Density Estimation using the Fast Fourier Transform," *Applied Statistics*, Vol. 31, 1982, pp. 93-99.

[7]Staniford, T., Glonek, G., and Rumsewicz, M., "Investigation of Appropriate Size of Datasets, Resolution of Kernel Density Estimates and the Generation of Kernel Density Estimates Between Input Scenarios Using Interpolation," Adstat Solutions, Adelaide, Australia, 2006.

[8]Fletcher, D.J., Luckman, N., and Hodson, M., "Principles of Simulation Architecture-Independent Model Development", *Simulation Technology and Training (SimTecT) Conference*, Sydney, Australia, 2005.

[9]Fletcher, D.J., *et al*, "MIST Interface Specification Version 1.0," TR-WPN-7/1-2006, TTCP, Edinburgh, Australia, 2006.

[10]Bryce, I.R., "Development of a Debris Catalog Methodology Incorporating a Unified Fragmentation Model," Springside Engineering, Sydney, Australia, 2008.

[11]"Software Considerations in Airborne Systems and Equipment Certification," RCTA/DO-178B, RTCA, Inc., Washington, DC, 1992.

[12]Smart, M.K., Hass, N.E. and Paull, A., "Flight data analysis of the HyShot 2 scramjet flight experiment." *AIAA Journal*, Vol. 44, No. 10, 2006, pp. 2366-2375.

[13]Torres, J., Rohl, P.J, Krozel, J. and Thompson, T., "A Dynamic Air Traffic Management Approach for Operationally Responsive Space," *AIAA Atmospheric Flight Mechanics Conference*, Hilton Head, South Carolina, 2007.