Guided Weapon Danger Area Generation – Implementing a Probabilistic Approach

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In this paper, we outline an approach for the generation of guided Weapon Danger Areas via probabilistic means. This approach involves the calculation of a ground impact distribution database for each weapon via Monte Carlo simulations performed on a 'farm' of computers. A Weapon Danger Area specific to a user-defined firing envelope is then generated. The Weapon Danger Area is derived from a probability density function of the ground impacts for the specified firing parameters. We are currently building a two-part system to provide this capability to the Australian Department of Defence for weapon test and evaluation purposes. The first part is a data preparation process that weapon experts can use to produce the weapon-specific ground impact distribution databases. The second part of the system is a software tool intended for operational users and range managers. This tool references the weapon database to generate a Weapon Danger Area for a specific firing envelope. We intend that the system be accepted for general use by the Department of Defence; hence, we are building it in accordance with departmental quality assurance requirements for complex aerospace systems.

I. Introduction

A Weapon Danger Area (WDA) is an important tool for the assessment of risk associated with weapon launches. The WDA can take a number of forms, including:

- A curve representing an area where the weapon might land with a specific probability
- 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 equipment. 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 might be planned for a lower altitude or a different location. The WDA is defined for a specified firing envelope and a defined set of launch conditions.

Various organisations within the Australian Department of Defence have produced and used WDAs over many years. However, there is no broadly-accepted methodology to generate the WDAs. Each weapon has been dealt with on an ad hoc basis by the organisation with responsibility for developing and/or authorising WDAs for that

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particular weapon. In response, the Defence Science and Technology Organisation has proposed a generic Range Safety Template Toolkit (RSTT).

The initial RSTT was a functional prototype designed both to generate WDAs for the ASRAAM air-to-air missile within a limited firing envelope, and to serve as a risk reduction exercise for the full RSTT, which will be capable of broad use.

Our main justifications for development of the 'full' RSTT are as follows:

- A need exists to generate probabilistic WDAs for ASRAAM.
- The current approach to WDA development and approval is ad hoc; there is no 'system' as such.
- There is not adequate support for longer-range weapons, particularly for future ground-based air defence and, possibly, ballistic missile defence applications.

This paper presents an updated description of the developing RSTT beyond that provided to the SETE 2005 conference.[1]

II. Range Safety Requirements

We derived a number of RSTT requirements by canvassing all elements of Defence with potential interest in range safety. The following sections summarize the requirements of the evolving RSTT.

A. Air Weapon Types

The RSTT must provide WDAs and associated outputs for 'legacy' air weapons, weapons under procurement and future air weapon developments/acquisitions.

The RSTT could also be used for unguided weapons, such as iron bombs, if necessary since unguided weapons are a less-complex subset of guided weapons.

Additionally, the RSTT could support foreign and commercial use of Australian test ranges. The processes and techniques developed for the RSTT will meet the requirements of a number of aerodyne systems and commercial applications. Space vehicle launch and re-entry are examples that could take advantage of the RSTT with minimal changes.

B. Weapon Lifecycle

The RSTT must support the testing of air weapons in all stages of the lifecycle from experimental/conceptual development through to in-service exercises and to life-of-type extension validation.

C. Users and Usage

The following are potential users of, and uses for, the RSTT:

- Operational staff (aircrew and ship's crew) to support trials planning and other operationally-focused activities.
- Technical staff to support analysis, flight trials, and the development of operating procedures and similar.
- Requirements development staff to support development of capability requirements; for example, whether or not a given weapon needs a flight termination system based on likely operating areas.

D. Useability

All identified classes of user must be able to use the RSTT. Furthermore, the information generated by the RSTT should be easily understandable by operational and technical staff and relevant outside parties; for example, legal advisers and public officials.

The RSTT must provide 'quick look' results to aid rapid assessment of options for operational planning and also provide more detailed results to support technical assessments and similar activities.

The range safety software must be useable in standard computing environments likely to be found in Australian Defence agencies.

E. Policy

The RSTT must conform to applicable Australian Department of Defence policy.

The list of policy documents (and their impact on the RSTT) must continue to be updated throughout the project to ensure that policy requirements have been properly captured.

F. Economy

The RSTT should only demand as much user input, and consume as much computational resource, as is necessary to satisfy the particular WDA generation requirement being addressed. For example, one of the most obvious and conservative ways to obtain a WDA is to compute the Total Energy Area (TEA), which is the maximum distance a missile can fly after launch. Hence, the first step in using the RSTT process should be the calculation of a TEA:

- If the TEA falls within the range boundary then no further assessment is necessary.
- If, however, the TEA falls outside the range boundary, then a probabilistic approach should be employed to calculate a smaller boundary that is within specified safety limits.

G. Confidence

The RSTT must be able to produce WDAs and associated outputs in which there is a sufficient degree of confidence to support safety-of-life safety case decisions defensible in a court of law.

This need assumes, of course, that there is sufficient information about a given weapon and employment scenario with which to calculate high-confidence WDAs and associated outputs.

Consequently, the RSTT must be able to provide some indication of the level of confidence in calculated WDAs and associated outputs as a function of quality or completeness of inputted information.

H. Assurance

The apparent need for a ‘legal standard’ of confidence in the results implies that the RSTT may need to meet yet-to-be-specified assurance requirements to ensure that the:

- Mathematical theory upon which the WDAs are generated is valid (correct design),
- Implementation of this mathematical theory into processes and software is correct (correct build),
- Generated weapon data-set accurately represents weapon behaviour (correct model),
- Correct weapon data set is used to generate WDAs (correct weapon), and
- Scenario/engagement envelope selection is correct (correct scenario).

These assurance requirements may, in turn, affect the RSTT development process by, for example, demanding that development be done in accordance with a particular software development standard or that specific verification and validation techniques be employed.

In addition to the development requirements, service-specific assurance regimes also need to be accommodated to support the introduction of new weapons within RSTT.

I. Robustness

A full set of WDA-related weapon information is not always available. This is because of the varied nature of the weapons to be supported by the RSTT and the need to support testing of air weapons in all stages of the lifecycle:

- **In-service weapons.** Obtaining WDA-related information for in-service weapons is often problematic. The reason for this is that a major motivation for supplying detailed technical information (the promise of a major acquisition contract) is lacking and there may be no residual contractual right to the required information.
- **To-be-acquired weapons.** WDA-related information for to-be-acquired weapons is usually obtained from the Original Equipment Manufacturer via the contracting process. This means that there is a reasonable likelihood that sufficient WDA-related data can be obtained as necessary.
- **Experimental and developmental weapons.** For those that are not mature enough to have undergone detailed engineering analysis, such as Failure Mode Effects and Criticality Analysis (FMECA), WDA-related information may not exist.

Consequently, the RSTT must be able to calculate WDAs in the absence of full weapon technical information, albeit with a potentially-degraded level of confidence in the WDAs and associated outputs.

J. Traceability

The RSTT should provide insight into the effect of air weapon failure modes, or design features, on range safety; for example:

- ‘The reason the TEA transgresses a particular range boundary is due to a guidance system failure at 10 seconds into the flight.’

- ‘The reason that debris lands within 500m of the road is that the weapon was at 1500ft when an engine failure occurred 15 seconds after launch.’

The RSTT should, as far as is practicable, provide traceability right from initial failure modes and flight paths through to effects on the ground.

K. Geographical Situation

The RSTT must be useable for activities contained entirely within land and sea test ranges and, for those weapons that demand it, for activities conducted beyond established range boundaries.

In all cases, the RSTT must take account of the placement of roads, range boundaries, buildings, technical equipment and other nominated places and objects. Example constraints that the RSTT must be able to accommodate might be as follows:

- ‘The TEA shall not be within 500m of the range boundary.’
- ‘The probability of any debris impacting within 500m of any road or railway shall be less than 10^{-5}.’
- ‘The maximum individual risk to any member of the general public shall be less than 10^{-7}.’

The RSTT is designed to be flexible enough to accommodate range safety requirements arising during use rather than prescribing them all during RSTT development.

Finally, consideration will be given to having the RSTT produce Weapon Danger Zones as an aid to airspace management.

III. The Functional RSTT

A. System Concept

Our Range Safety Template Toolkit consists of two sub-systems linked by an impact distribution/TEA database (Weapon Data Store) as shown in Figure 1.

The data preparation sub-system is used by subject matter experts to produce the weapon-specific Weapon Data Stores. We prepare data through simulations, weapon-specific information and statistical analysis. Both TEA and probabilistic methodologies will be supported.

The WDA generation sub-system is a user-friendly software tool that produces a WDA from a user’s flight envelope selections. We plan to create the WDAs through careful application of selection, mixing and plotting algorithms to the impact distribution/TEA databases. The front-end tool will be integrated with a Geospatial Information System (GIS) to allow the WDAs to be compared with range boundaries, allow for calculation of expected casualty estimates and so on.

B. Weapon Danger Areas

Probabilistic WDA generation for the RSTT is more resource and-time intensive than calculating a Total Energy Area. Therefore, we identified it as the highest technical risk to the RSTT project. We have adopted a methodology that allows simulated and recorded impact data to be turned into probabilistic WDAs. While we focus on probabilistic techniques in this paper, the TEA is an important element of the RSTT. The TEA has previously been found by searching for the trajectory of the guided weapon that will achieve maximum ground impact distance (with conservative assumptions). Current work is aimed at identifying a TEA based on scenarios that are sufficiently conservative without being extremely improbable.

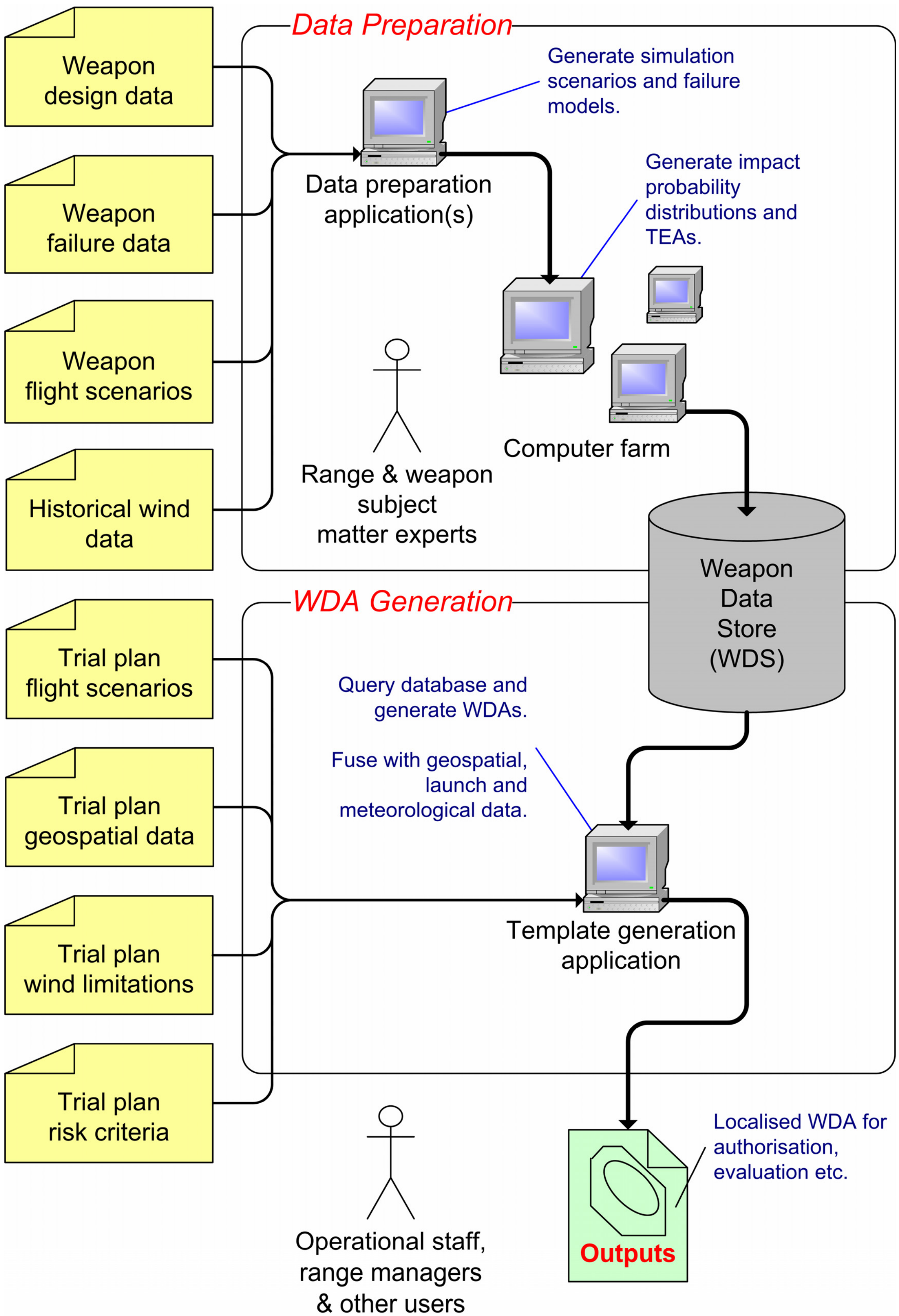

Figure 1. Schematic of the Range Safety Template Toolkit.

Our process begins with failure analysis, such as a FMECA, of the weapon system 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. This information is gathered by the manufacturer from rigorous testing of the missile systems in accordance with industry standards. Certain individual 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 endstops. This is a case of three failure modes giving rise to one FRM. Figure 2 shows some potential FRMs. Systematic failures, such as software and guidance failures, are included if they can be accurately described and assigned probabilities of occurrence. If failures of this type cannot be quantified, the TEA must be considered.

We use a medium fidelity Six-Degree-of-Freedom (6DOF) model of the weapon system, which includes models of the FRMs, to generate ground-impact distributions. For specified launch/release conditions and particular target profiles we do Monte Carlo simulations to determine where the weapon might land for each potential FRM occurring at a random time of flight. Sufficient information is recorded so that the simulation associated with each ground impact location can be recreated and viewed for a detailed inspection of the weapon's behaviour. This functionality has been included to address the traceability requirement discussed previously. An example of a ground impact distribution is presented in Figure 3, which represents a total of 50000 simulation runs. The impact locations correspond to a fictitious guided weapon 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.

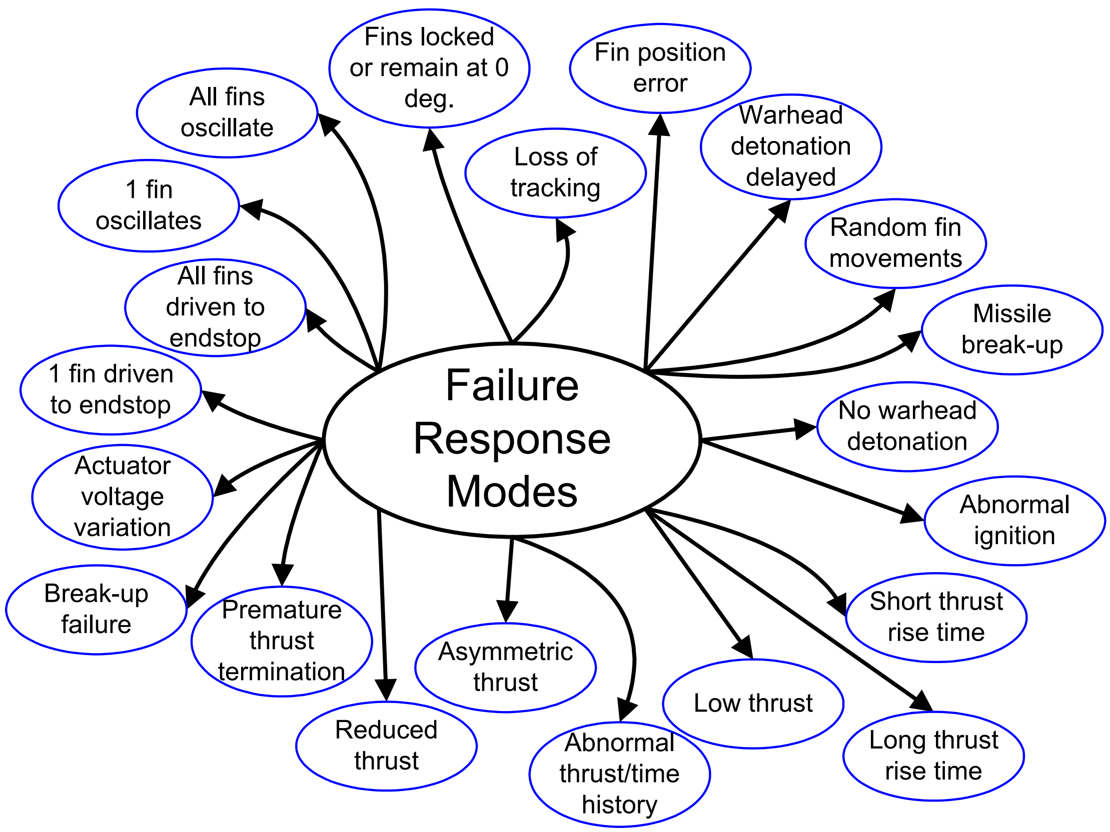

Figure 2. Possible Failure Response Modes for guided weapons.

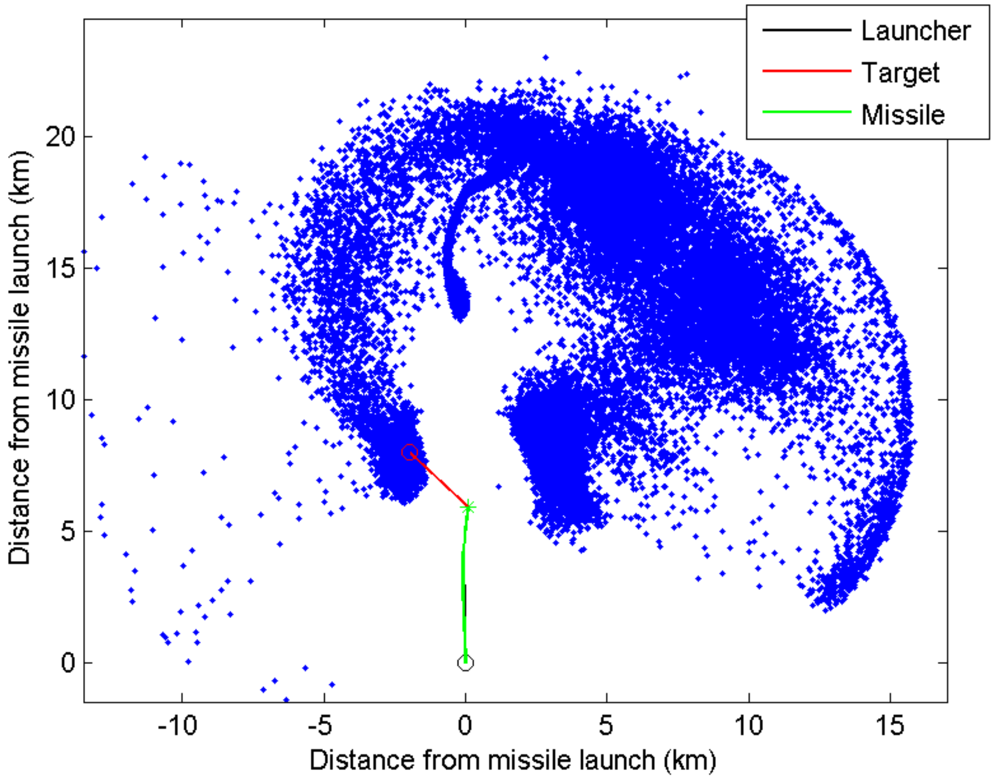

Figure 3. 50000 ground-impact locations for a fictitious guided weapon with fins locking to zero degree deflection at random times.

We have selected a Kernel Density Estimation technique[2,3] to create a smooth two-dimensional Probability Density Function (PDF) for each scenario/failure combination. Figure 4 shows an example PDF derived from the scenario represented in Figure 3.

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 Weapon Danger Area 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 Weapon Data Store (WDS). Figure 5 illustrates the calculation of a ground impact data set for a critical point of the user-selected region via conservative interpolation. Impact data from three different scenarios stored in the WDS has been used as input to the interpolation algorithm. This technique allows the user to specify a region or firing envelope that does not necessarily match database scenarios.

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. The ground impact probability map can also be used with population demographics and debris energy characteristics to calculate an expected casualty estimate.

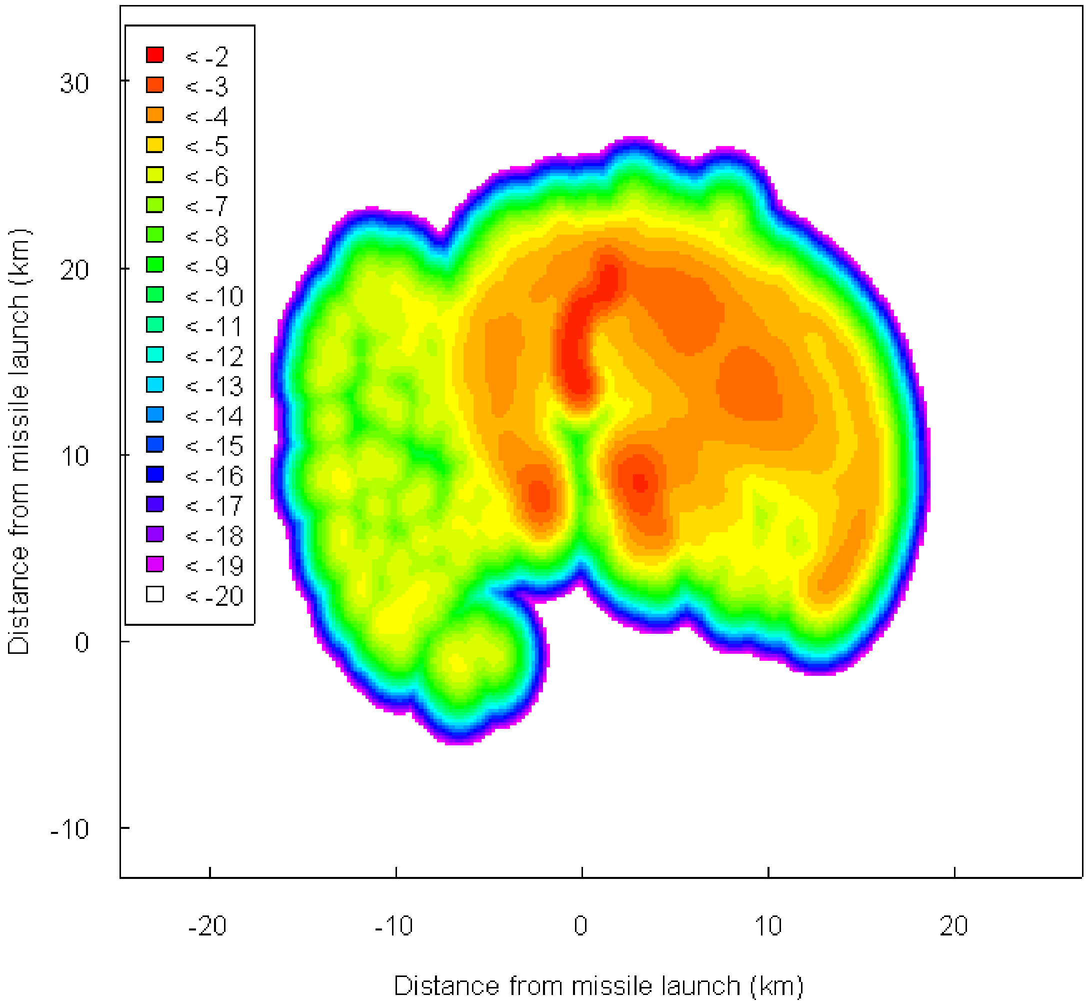

Figure 4. Ground impact Probability Density Function ($\log_{10}$ scale) for a fictitious guided weapon with fins locking to zero degree deflection at random times.

C. Implementation Considerations

We currently envisage the RSTT as a stand alone system that will not be integrated with other hardware and/or software systems. There will not be any direct 'feeds' into or out of weapon computers or mission planning systems. The RSTT front-end software is expected to run on standard Defence computing infrastructure.

Our RSTT requires data from a number of sources/agencies external to the RSTT system. These include:

- Meteorological data
    - Required for trial planning
    - Must only be from authorised sources (e.g. Bureau of Meteorology)
- Air-weapon technical data
    - Required for WDA generation
    - Must be certified by weapon manufacturers
- Trial scenario data
    - Required for trial planning
    - Must be authorised by operations unit commanders
- Geospatial data
    - Required for trial planning
    - Must be authorised by range authorities

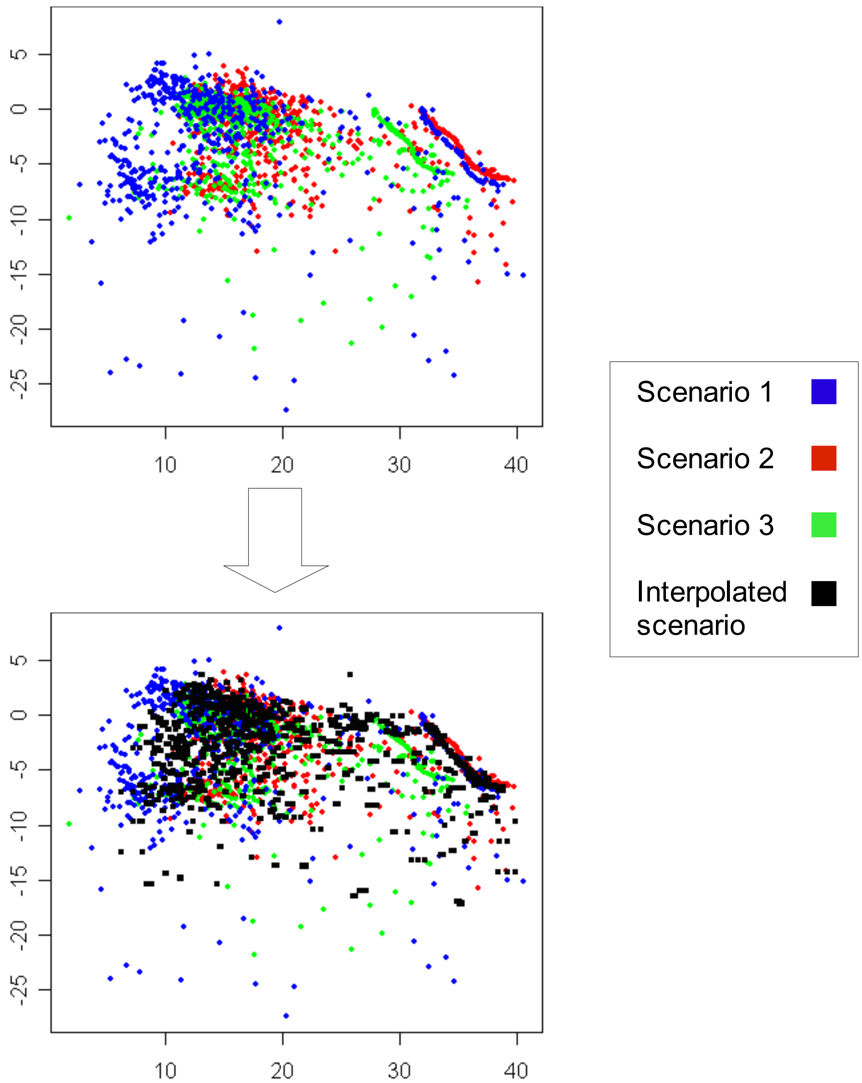

Figure 5. Interpolating impact data from 3 different scenarios.[4]

IV. Range Safety Assurance

A major issue in providing advice to the acceptance authority (who will authorise the system's output for operational use) is ensuring that all facets of the RSTT system are correct. For example, if the process by which the WDA is generated is flawed (i.e. the input data is incorrect, the software malfunctions or the user misinterprets the output) then safety will likely be compromised.

In summary, the Australian Department of Defence's aerospace design acceptance process for WDAs is:

- **Specification of requirement**. Ensure the definition of the launch conditions and the requirements of the WDA are complete and acceptable.
- **Determination of competence**. Verify the competence of the organisation developing the WDA.
- **Verification of requirement satisfaction**. Verify that the WDA is acceptable to the Australian government.
- **Certification of requirement satisfaction**. Certification by the organisation that the WDA satisfies the requirements of the launch conditions.

Using the current framework, a network of personnel from a variety of Defence areas will be used to develop and review the WDA generating tools.

V. Intended Application

The information used to generate WDAs supplied with weapon systems may not be available due to legal restrictions on suppliers, such as the US International Traffic in Arms Regulations (ITAR). This can hinder the certification of the WDAs for use by the Australian Department of Defence. In addition, we can rarely modify the supplied WDA for Australia's needs. If limited data is available on a particular weapon the local generation of a WDA might not be possible. In this situation the Australian Department of Defence can prescribe the methodologies of the RSTT as the required standard. This will ensure that all Departmental legal and technical requirements are met by the organisation supplying the weapon and WDA. Therefore, one of the elements of the RSTT is a data item description for use with the Australian Department of Defence's standard acquisition contracting template. A weapon manufacturer will be required to:

- Enable the Australian Department of Defence to generate a WDA from raw data about the weapon, or
- Provide the complete (or large elements of) the weapon database to link directly with the mature RSTT front end.

VI. Conclusions

We are in the process of developing a robust, comprehensive and flexible Range Safety Template Toolkit capable of meeting the diverse requirements of guided Weapon Danger Area generation. Our data preparation process and front-end software tool will be capable of providing Weapon Danger Areas containing both Total Energy Area and ground-impact probability information. Range safety will be addressed with the appropriate level of assurance through weapon manufacturers and/or defence organisations adopting the processes and methodologies of the proposed system. For the Australian Department of Defence, the Range Safety Template Toolkit will be a valuable asset for the assessment and safe testing of existing and future weapon systems.

VII. References

[1]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, 2005.

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

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

[4]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, July 2006.