IAC-14-D6.1.4

CONSIDERATIONS FOR THE SAFE CONTROLLED TARGETED DE-ORBIT OF LARGE SPACE VEHICLES

Michael Brett
Aerospace Concepts Pty Ltd, Australia, support@concepts.aero

Dr Mark Bateup, Chris Butt & Shaun Wilson of Aerospace Concepts

The International Space Station (ISS) is likely to be de-orbited sometime around 2025. The ISS will need to be safely retired, either in whole or as major segments. A controlled, targeted de-orbiting manoeuvre is the most likely scenario for disposal and due to the orbital design and geography, any break-up is likely to occur over mainland Australia. Building on experience modelling the Hayabusa re-entry in 2009, recent improvements to Australia's space situational awareness capabilities and updates to space policy, this paper investigates considerations for ensuring the retirement of the ISS is safe. This paper builds on the approach employed by Aerospace Concepts in determining break-up of experimental vehicles, Failure Response Mode probabilities and dispersions in aerospace vehicles in applying Australia's Range Safety Template Toolkit (RSTT), specialised software for determining probabilistic safety outcomes of space vehicles.

I. THE DE-ORBIT CHALLENGE

The International Space Station (ISS) will need to safely de-orbit at its end of life (EOL) as alternative options are not viable. System reliability and multi-body gravity effects will limit the viable lifetime, and there is no available vehicle to support disassembly and return to Earth. There is insufficient propellant to boost ISS to a higher orbit. Orbital decay to a random re-entry is expected to result in a casualty risk that is too high. The challenge is to control the ISS EOL de-orbit in a manner that results in an acceptable level of risk [1].

The NASA Safety Guideline [2] acceptable casualty risk limit is 1 chance in 10,000 of single casualty, which is a less stringent criterion than the RCC STD-321-10 [3] criterion of 1 chance in a million. Of satellites that re-enter, approximately 10% to 40% of the mass of the object is likely to reach the surface of the Earth [4].

For any re-entry of the ISS, an overflight of Australia to land in the Pacific Ocean is likely, so what is the risk to the public, both on the ground and flying in aircraft?

Based on historical precedent, there is clearly a need to assess the risk. When Skylab re-entered from an uncontrolled EOL de-orbit in 1979, it spread debris across Australia damaging several buildings and killing a cow. Fortunately there was no loss of human life. Similarly, in 1991 Salyut 7 underwent an uncontrolled re-entry over Argentina, scattering much of its debris over the town of Capitan Bermudez [5]. While ISS shall be a controlled re-entry, there is much uncertainty over its profile and the risk to the public shall be non-trivial. A means to assess the residual risk to the general population is necessary.

II. ABOUT RSTT

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.

Aerospace Concepts has presented work at previous IAC symposiums about the RSTT capability and its use in space safety applications [6,7]. Of particular relevance to the ISS EOL de-orbit is the analysis of the Japanese *Hayabusa* spacecraft return to Earth in mid-2010.

The RSTT process for generating or verifying range safety templates involves creation of a six degrees-of-freedom (6DOF) model of the vehicle from available technical data. This model includes both nominal and off-nominal (failure) behaviours. The typically large number of failure behaviours are lumped together in a smaller set of failure response modes (FRMs). The use of FRMs allow the scope of the model to remain computationally manageable. The model is simulated across a range of conditions using Monte-Carlo analysis, where many runs are executed with random draws for each of the defined inputs.

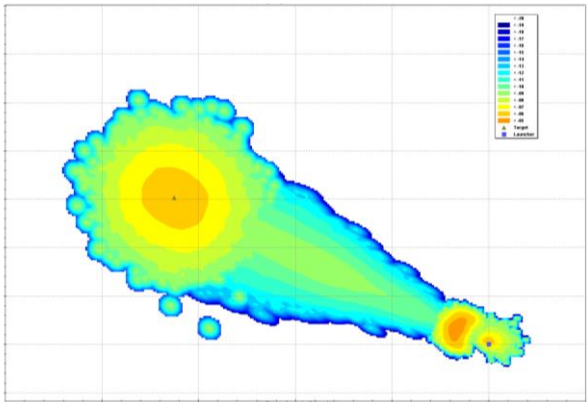

Fig. 1: PDF generated from ground impacts.

The outputs of those simulations, referred to as Ground Impact Points (GIPs), are statistically processed to create Probability Density Functions (PDFs), as shown in Fig. 1, and further processed into range safety templates. Importantly, RSTT does not assume any underlying distribution of impacts, and lets the shape of the PDF emerge from intensive Monte-Carlo simulation [8]. The final output is a probabilistic assessment of risk measured against an accepted risk-threshold based on an impact energy criteria.

III. TECHNICAL CHALLENGES

Given the need to assess the safety of this activity, the question is whether RSTT could accurately create a valid safety template for the ISS re-entry. There are many technical challenges with this approach including:

1. Uncertainty of the starting conditions, possibly due to the availability of tracking assets to monitor orbit decay and to time the various manoeuvres and final de-orbit burn,
2. Uncertainty on the altitude where attitude control authority may be lost, and
3. Uncertainty in vehicle state changes as modules break-off and the vessel ruptures.

Furthermore, the predicted long, shallow re-entry means a relatively long dwell time below 120 km altitude. A higher fidelity atmospheric model would be required within RSTT for this region given that most vehicles transit this region very quickly during ascent and descent and aircraft traffic does not fly this high.

There is also uncertainty in the heating effects caused by atmospheric density and aero-thermal heating for various ISS modules during transition from free-molecular to continuum flow, etc. Modelling the aerodynamics would be challenging owing to the ISS's large, complex shape with little available verification data. Vehicle breakup is a naturally random process, and combined with all of these uncertainties, there is a demonstrable need for a comprehensive probabilistic risk analysis.

IV. MODELLING

The RSTT modelling framework can model any aerospace vehicle at any scale. It can apply probabilistic analysis to any significant areas of uncertainty, both in vehicle design and behaviour.

The major improvement required to the modelling framework would be a more comprehensive atmospheric model than that used to analyse the Japanese *Hayabusa* asteroid explorer re-entry in 2010. Models exist for the heterosphere [9,10], and are being augmented by additional re-entry research data [11]. Critically such models are needed to assess uncertainties in upper atmospheric density, though they should also account for external influence from solar and geomagnetic activity. The dominant atmospheric influence on re-entry bodies through the homosphere, below 90km altitude, is covered by verified data sets [9, 10,12].

A detailed understanding or analysis of what, when and how the ISS would transform to debris pieces as it breaks up is a necessary input to the RSTT process. Whilst RSTT incorporates a validated, general-purpose 'fractal fragmentation' model, shown in Fig. 2, this is intended for launch vehicles and would likely produce poor results for the ISS re-entry without appropriate validation data from a detailed study. Far more detailed break-up behaviour information, such as that provided by a panelised modelling tool such as SCARAB (Spacecraft Atmospheric Re-entry and Aero-thermal Breakup) used by ESA [13], would be needed to create the appropriate debris catalogues.

A dedicated fault-tree analysis of the planned re-entry, such as that discussed by Duncan [1], would provide a method for assessing the likelihood of nominal and off-nominal re-entry mechanics. Such analysis would provide a reasonable coverage of the uncertainty against the initial conditions described above, and provide a good qualification on the degree of spread on the inputs to RSTT.

If such data was made available, RSTT could be tuned to do, perhaps with some modifications, the entire simulation and Monte-Carlo analysis for all debris propagated to Earth including an assessment of the debris impact energy. This would allow sheltered and unsheltered individual and collective casualty and fatality estimates to be made.

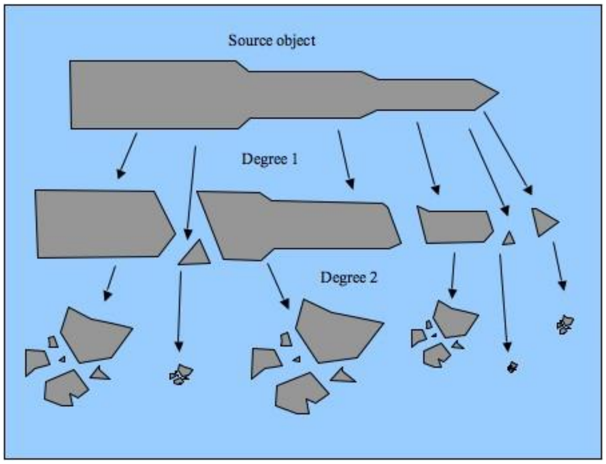

Fig. 2: RSTT fractal fragmentation model.

V. FRM PROBABILITY ALLOCATION

The end effect of any nominal or off-nominal event during the ISS de-orbit process may be rolled into two possible FRMs which capture the resultant behaviour of interest. Those FRMs are: variations in the properties of the debris pieces resulting from breakup (debris catalogues), and variations in the state-vector of the vehicle as it re-enters.

Probabilities could be allocated to the primary FRMs as per Table 1 and thus allow for variation in the weighting of debris catalogues and re-entry state severity. Here each FRM is the combination of a defined debris catalogue and vehicle state severity level.

The exemplar probability spread shown here is for a situation where the least severe case is also the most likely. Note that the values sum to 100%. The combinations would be assigned in an appropriate manner, along with applied weightings, which would come out of the primary analysis of vehicle breakup emphasised above. Note that the values of probability assigned to each FRM combination is relative. This means there is a need to apply a global probability to scale them (this may be assigned according to an analysis of the form described by Duncan [1]).

VI. VALIDATION DATA

It is important to have a valid data set to show the model is accurate. The sources of such data are challenging.

Validating the small mass components of the simulation engine may be done using data from the Hayabusa re-entry. Aerospace Concepts already have the simulations for this analysis, along with trajectory data for comparison from other missions.

		Debris catalogue severity Less				More
		I	II	III	IV	V
Re-entry state severity: Less	I	26	13	6.5	3.5	1.9
	II	13	6.5	3.5	1.9	0.8
	III	6.5	3.5	1.9	0.8	0.4
	IV	3.5	1.9	0.8	0.4	0.2
More	V	1.9	0.8	0.4	0.2	0.1

Table 1: Exemplar FRM probabilities.

A unique source of validation data could be sourced from the Australian Desert Fireball Network, led by Professor Phil Bland at Curtin University, to correlate meteorite tracking data with ground truth data. An image from the Desert Fireball Network is shown in Fig. 3.

Validating the break up models may be done with re-entry data from studies of other large re-entry vehicles such as ISS re-supply vehicle ATV-5, Starlight and others.

Fig. 3: Desert Fireball Network captures the Perth green fireball on 4 August 2014 just before dawn [14].

VII. CONCLUSIONS

Given the need to assess the safety of the ISS EOL re-entry activity, RSTT could be used to estimate public risk across a broad ground swathe. There is likely to be a level of uncertainty in the debris generated upon re-entry, but the RSTT approach is tractable assuming access to break-up and validation data.

The outputs from RSTT may be used to inform the overall risk plan for the re-entry activity, and may be used by mission planners to assess the residual risk of ground impact. A follow-up question to be answered is whether the Australian Government will require this analysis to be done given the proximity of the planned re-entry corridor.

VIII. REFERENCES

1. Duncan, G., '*International Space Station End-of-Life Probabilistic Risk Assessment*', 12th International Probabilistic Safety Assessment and Management Conference, Honolulu, HI., (2014).
2. Anon., '*Handbook for Limiting Orbital Debris'*, NASA Handbook 8719.14, Office of Safety and Mission Assurance, NASA Headquarters, 2008.
3. United States Range Commanders Council, '*Common Risk Criteria Standards for National Test Ranges'*, RCC Standard 321-10, Secretariat Range Commanders Council, White Sands Missile Range, New Mexico, USA (2010). [and associated supplement]
4. The Aerospace Corporation, '*How much material from a satellite will survive re-entry?'*, The Aerospace Corporation, 2310 E. El Segundo Blvd. El Segundo, CA, USA, (2014).
5 Messerschmid, E. W. and Renk, F., '*Space Stations. Encyclopedia of Aerospace Engineering*'. 424, (2010).
6. Brett, M., Wilson, S.A., Vuletich, I.J., Tisato, J., Williams, W., '*Risk Hazard Analysis for Commercial Spaceflight Activities Using Range Safety Template Toolkit*', 62nd International Astronautical Congress (IAC), Cape Town, Sth Africa, (2011).
7. Wilson, S.A., Vuletich, I.J., Bryce I.R., Brett, M.S., Williams, W.R., Fletcher, D.J., Jokic, M.D. & Cooper, N., '*Space Launch & Re-entry Risk Hazard Analysis – A New Capability*', 60th International Astronautical Congress (IAC), Daejeon, Korea, (2009).
8. Tisato, Vuletich, Brett, Williams & Wilson, '*Improved Range Safety Analysis for Space Vehicles using Range Safety Template Toolkit'*, 5th International Association for the Advancement of Space Safety Conference (IAASS), Versailles, France, (2011).
9. Klinkrad, H., '*On the Use of Atmospheric Models in Re-Entry Predictions*', ESA Symposium Proceedings on Environment Modelling for Spacebased Applications, Noordwijk, NL, (1996).
10. Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin, '*NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues'*, J. Geophys. Res., 107(A12), 1468, (2002).
11. Asma, C.O., Naviaux, J., Kerschen, G., Reinhard, R., Muylaert, J., '*Orbital Dynamics Characteristics of a QB50 CubeSat Performing Atmospheric Re-entry*', AIAA Atmospheric Flight Mechanics Conference, Ontario, Canada, (2010).
12. NASA, US. "*Standard atmosphere, 1976*." National Oceanic and Atmospheric Administration, National Aeronautic and Space Administration, United States Air Force, Washington, DC (1976).
13 Lips, T., Fritsche, B., 2005, *A comparison of commonly used re-entry analysis tools*, Acta Astronautica 57, pp 312 – 323.
14 Courtesy of Desert Fireball Network (DFN) website at www.fireballsinthesky.com.au.