High-Speed, High-Accuracy, Multi-Physics Propagator

Executive Summary Report

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1 Introduction

This is the Executive Summary Report (ESR) for the de-risk activity entitled ‘Development of a High-Speed, High-Accuracy, Multi-Physics Propagator’.

The purpose of this de-risk activity (referred to as *the present activity*) is to de-risk the development of a future high-speed, high-accuracy, multi-physics propagator to be used in Design-for-Demise (D4D).

There are existing requirements in place for space debris mitigation. It is anticipated that with the increasing number of launches and the increasing variety of launch organisation, i.e., no longer simply being restricted to national space agencies and large satellite integrators, that a new generation of high-speed, high-accuracy, and highly usable tools will be required to support D4D activities and to ensure compliance with space debris mitigation requirements.

The intention is for a future activity to develop an improved tool which offers an improved balance of accuracy and efficiency relative to the wide range of currently available tools.

However, the accuracy of these tools is not well established, and there is currently little evidence of any benefit of the more complex tools in terms of casualty risk assessment accuracy. This makes it difficult to assess even the most basic requirements for the new tool as a wide range of complexities could be considered.

The present activity de-risks the development by focusing on three key areas:

Exploration: to establish the user requirements and the potential areas of model improvement.

Investigation: to determine the improvement in accuracy and speed that can be expected; and to design an intuitive graphical user interface to investigate the user experience.

Learning: to rapidly develop and deploy, through continuous feedback and development, a new tool.

2 Current State of the Art

To understand the required future direction of development, a full assessment of the current capabilities and validation status of both historical tools and new tools was undertaken. This was particularly in the light of the recent ground test data which has been generated. The intention of this aspect of the de-risk was to provide sufficient understanding of the current knowledge base such that a roadmap towards validation of a new propagator tool could be undertaken as part of the full activity.

The modelling of destructive re-entry processes has existed for more than 25 years but, for most of this time, it has been approached as an academic study with only two known test campaigns prior to 2014. Since then, the field has changed substantially, with a range of tools of varying complexity known to be used in the assessment of ground casualty risk safety cases.

Historically, destructive re-entry tools were separated into two concepts; object-oriented and spacecraft-oriented. This was a somewhat artificial description intended to differentiate SCARAB, with its complex geometric capability, from the other available models, which were generally similar in their approach. Within the last seven years, the range of capabilities of the tools has increased greatly, and the tools are not so easily classified using this taxonomy.

The critical aspects which are required to be covered in any future destructive re-entry propagator were established, along with the key areas where the current state-of-the-art is lacking. It is noted that deficiencies in current modelling are primarily driven by lack of data. Aspects of aerothermodynamic heating and fragmentation processes are of high uncertainty, in even the highest fidelity modelling available, and this results in the use of high complexity models for destructive re-entry having little added value over simpler methodologies.

The lack of available validation data means that the generation of significant new data over the next few years is required. As this is the case, a stochastic method, accounting for the uncertainties in the physical modelling, is currently the preferred solution.

A detailed analysis of the strengths and weaknesses of the state-of-the-art tools was undertaken, including a critical assessment of the physical sub-models used, since this is relied on for the design and selection of models to make improvements.

The following state of the art tools were assessed:

- Debrisk
- SAMj
- SARA V2
- SCARAB
- PAMPERO

Key weaknesses identified as areas for potential improvement were:

- Continuum aerothermodynamics for complex shapes.
- Fragmentation modelling.
- Spacecraft representation.
- Rarefied aerothermodynamics.
- Materials modelling of composites – particularly CFRP and GFRP.

3 Requirements Capture

Requirements for a high-speed, high-accuracy, multi-physics propagator were captured in a document that collates both the technical functionality of the application and the non-functional requirements of the application such as performance, regulatory, maintainability, usability and security at both user requirement level and system requirement level. Specification of verification activities (test requirements/performance measures) were captured within a 'Measure of Effectiveness' attribute for each individual requirement.

User Requirements and System Requirements were managed using a software programme, DOORS, such that links to higher level requirements, as well as a Document Register, etc, could be maintained. DOORS is an industry standard software tool and allows the tracking and evolution of requirements during the development phases.

4 Model Design, Selection, and Results

A detailed trade study of the physical sub-models required by destructive entry codes has been undertaken to establish the physical sub-models that are likely to provide the greatest improvement to speed and accuracy.

A summary of the physical sub-models coloured by their impact on the model run-time and accuracy are given in Figure 1 and Figure 2 respectively. In these figures the arrows show the direction of dependency, for example an 'object heating' model cannot exist unless there is an 'aerothermal heating' model. Solid arrows represent essential dependencies whilst dashed arrows represent potential for significant enhancement, but not a strict dependency.

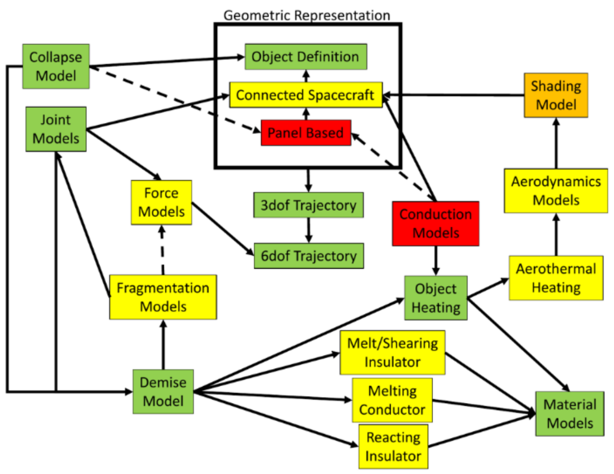

Figure 1: Impact on runtime for physical sub-models

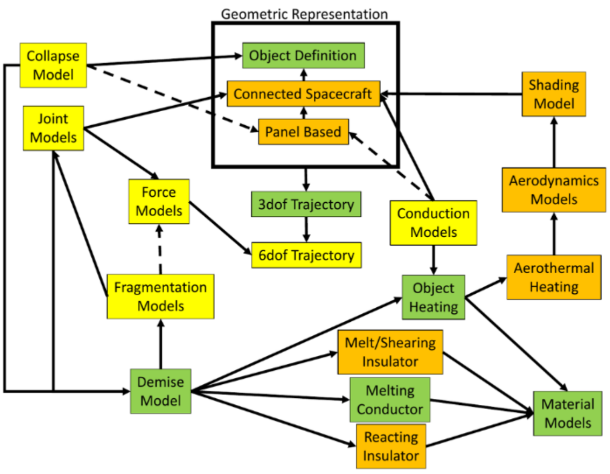

Figure 2: Impact on accuracy for physical sub-models.

Any simulation model is only as strong as the weakest sub-model within it. Therefore, it is of utmost importance to understand the main knowledge and modelling gaps which drive the uncertainties. This is critical in ensuring a good balance between ‘speed’ and ‘accuracy’ as complex high-fidelity modelling (such as a panel-based method) may lose all the accuracy benefits if the aerothermodynamics and fragmentation modelling are very simplistic and uncertain.

The selection of the aerothermodynamics and fragmentation models as examples in the previous paragraph is intentional, as these are two of the three (the other being material behaviour) critical modelling areas identified within the state-of-the-art assessment where significantly more data is required in order to build accurate models of the physical processes. This provides a natural limit to the accuracy which can be obtained using any model, no matter how complex the numerical or geometric representation. Indeed, with the uncertainties in these critical models being high, there is a significant benefit in performing the analysis in a probabilistic manner. With this being the case, this also drives towards a simpler tool implementation.

To determine the overall modelling structure and which physical sub-models should be targeted for de-risk, i.e., which physical sub-models are likely to provide the greatest improvements to speed and accuracy, then a value must be placed on a set of capabilities to manage the trade-off. To do this a set of weightings were constructed, which provides a set of sensitivities which relate the accuracy of the individual model to its importance in an accurate prediction of the casualty risk, as well as a relative accuracy and complexity. These sensitivities were determined through the work performed in PADRE. Although not direct scales of accuracy and run time, the weightings are intended to provide an indicative measure of the relative accuracy and run time of different tool types in order to perform the modelling trade-off.

The physical sub-model chosen to de-risk addressed the length scale merging aspects of aerothermal modelling. This is not considered in present component-based destructive entry tools so demonstrated an advancement on the state of the art. As currently implemented in existing tools, the lack of length scale merging presents an example of obvious pathological behaviour in applying local heating rates to primitives when they are part of a compound shape.

This is demonstrated in Figure 3, which shows a case where two cuboids are joined end-to-end. In component-based tools, the length scales of Component A and Component B are incorrectly retained whilst they are still part of the compound object, but in this case, the length scale of the compound object should be adjusted to be larger thus reducing the heating rate to the components. This type of effect is currently not known to be considered in any tool.

The effect was expected to be significant, since the heating rate calculated using the smaller length scales will be greater than using the larger length scales, this will lead to an **overprediction** of the heating rate, and consequently an **underprediction** of the ground casualty risk.

In principle, this type of pathological case could be automatically identified so that the heating to components A and B could be adjusted based on whether they are connected or not. The effort required to undertake automatic identification of such behaviour would have been many times more than the effort required to demonstrate the effect. In line with the philosophy of a de-risk, the approach of a manual identification of components making up a larger test object during the simulation setup was used. The pathological length scale assignment of these objects was then corrected based on this manual identification performed at setup. Automation of this process is considered in Section 6: Conclusions and Next Steps. It should be noted that the thermal scaling factors calculated in the de-risk are currently implemented only for box type primitives, as the effects of compound length scale can be treated exactly in the case of cuboids. Further work must be performed in order to generalise the solutions applied here for arbitrary compound shapes comprising different geometric primitives, again this is discussed in Section 6: Conclusions and Next Steps.

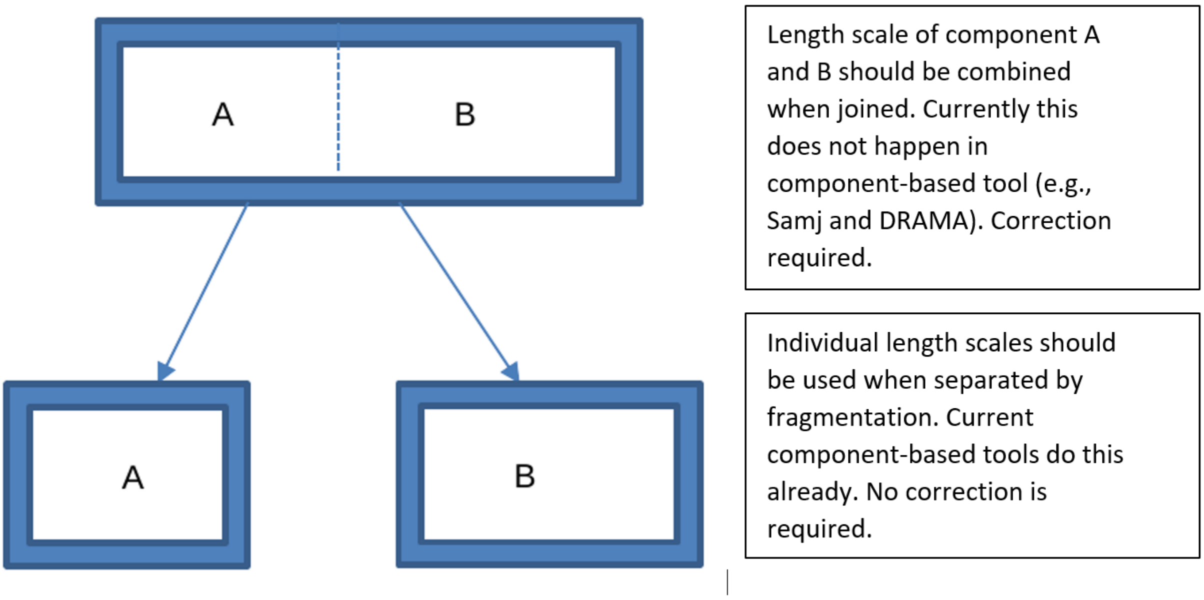

Figure 3: Incorrect assignment of length scale for joined primitives

A number of other areas for improvement in the aerothermal modelling were identified, notably changes in aerothermal heating arising from shared-shock layers and reductions in the aerothermal heating in cavity flows which are not well captured in the current state-of-the-art tools. These were out of scope for the current activity, but further investigation of them could be undertaken as part of the full activity, as discussed in Section 6: Conclusions and Next Steps.

As part of this de-risk a framework was developed to test the developed physical model. This framework has been named CRITIC. CRITIC interacts with the existing SESAM module of DRAMA, which provides the basic functionality required to demonstrate the correct functioning of the developed physical model.

A series of simulations were performed using CRITIC to determine the extent of the effect of compound length scale correction on SESAM results. All the test cases were based upon the main body of the ESA Harmony spacecraft and as such each utilised the same simplified cuboidal satellite geometry comprising a central ballistic mass (modelled as a tungsten sphere) surrounded by seven rectangular panels (modelled using box primitives).

The intent of these demonstrations was to compare the aerothermal histories of these two panels of interest with their singular counterpart on the opposite side. Figure 4 shows these basic configurations and locations of the panels of interest. The relevant dimensional nomenclature is also labelled.

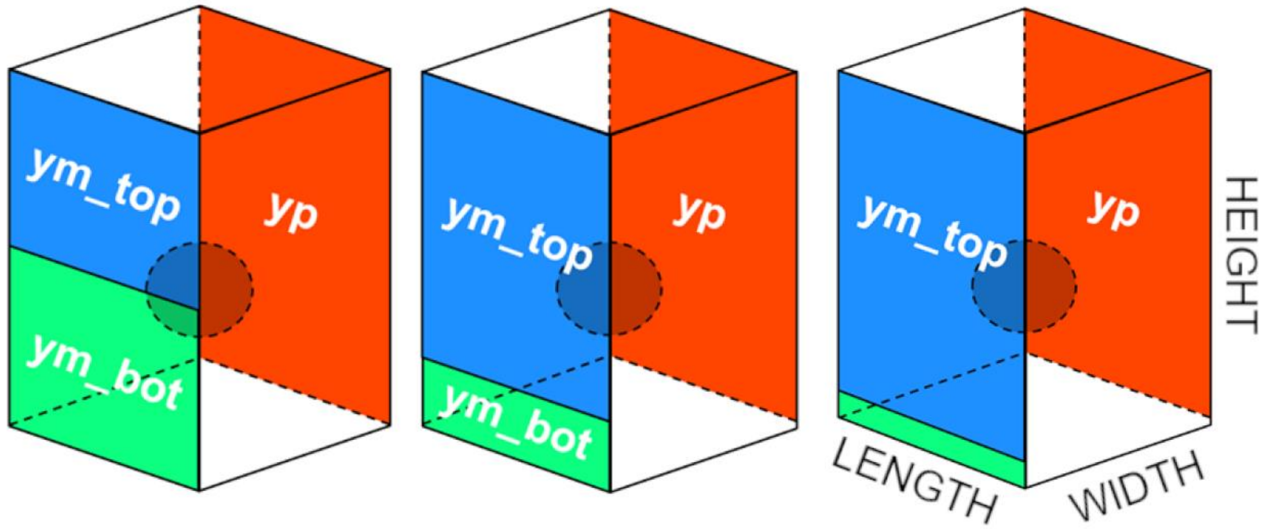

Figure 4: Model configurations evaluated during the de-risk showing the differences in the panel sizes.

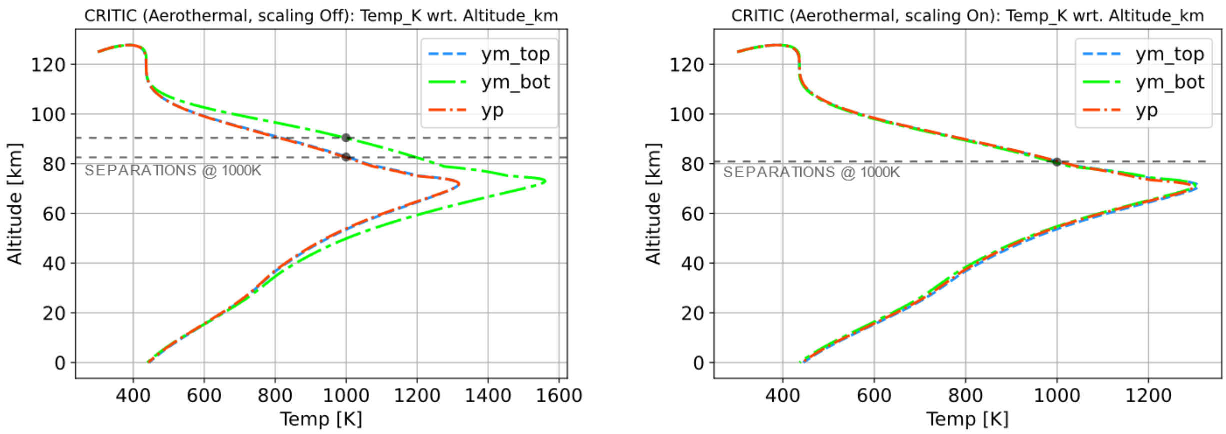

Figure 5: Temperature history with respect to altitude of panels of interest in the uneven panels case showing separation events (left: CRITIC scaling disabled, right: CRITIC scaling enabled)

Figure 5 shows the temperature history of the panels of interest for one of the test cases undertaken, with respect to altitude during re-entry. It can clearly be seen (in the left hand figure) that the temperature for the small panel differs from that of the large panel prior to separation without the application of length scale correction. Applying CRITIC scaling to the simulation improves agreement between the temperature histories of the compound panel components (ym_bot and ym_top) and their opposite neighbour (yp) significantly.

The results from a modified version of the most extreme test case (wherein additional debris items representing electrical and power system components are included) was also undertaken and this showed that including the treatment of local length scale corrections leads to significantly different results in terms of both breakup history and ground risk. In the extreme case a 112.9% difference in casualty area, 813.9% difference in total landed fragment mass, and 100% difference in the number of landed fragments was shown.

It is clear from these results that employing length scale correction can significantly affect heating calculations during re-entry simulations. As such, it is recommended that local length scale corrections be applied to all continuum heating calculations for the next generation destructive entry tool, despite the aforementioned added complexity of identifying suitable compound shapes to which individual components may be scaled.

5 Prototype Demonstrator

A prototype demonstrator has been developed which can be used by stakeholders to:

- Test the usability of the tool.
- Elicit further user requirements.
- Serve as a starting point for the development of the full activity using an Agile development approach.

6 Conclusions and Next Steps

This de-risk activity has:

- Captured the requirements of a high-speed, high-accuracy, multi-physics propagator to be developed under a future full activity.
- Established the state of the art of current D4D tools, including establishing the weaknesses in the currently available validation data and a path to, and the data required for, the validation of the full activity.
- Used the review of the current state of the art to establish where the potential improvements in accuracy and speed could be achieved.
- Developed a theoretical proposal for three physical sub-models that could be included in the full activity and contribute to the improvement in speed and accuracy.
- Implement and tested a version of one of these models and demonstrated that the effect of this phenomenon does contribute to the accuracy of the results.
- Demonstrated that, in the absence of the proposed improvement to the treatment of length scale merging, that the current state of the art tools **overpredict** the heating, and therefore **underpredict** the ground casualty risk.
- Created a prototype graphical user interface to demonstrate the workflow.

The proposed next steps are to:

- Undertake additional research to extend the proposed length scale merging model to a wider selection of shapes and develop methods to automate the calculation of the required length scales.
- Investigate further improvements to the physical sub-models that were identified during the de-risk activity, e.g., aerothermal heating arising from the formation and changing of shared-shock layers and improved treatments of aerothermal heating in cavity flows.
- Investigate in further detail how risk modelling is undertaken in the current state-of-the-art and propose improvements, for instance the application of continuous uncertainty ranges and the development of a risk dashboard allowing users to vary sources of uncertainty and see the effect on the resultant ground casualty risk.
- Undertake a programme of wind tunnel experimental runs to provide verification and validation data and revise the proposed models as appropriate.
- Include the proposed revised models into an existing tool (e.g., DRAMA).