Spectroscopic Response of Break-up Fragments to the Re-entry Environment – Executive Summary

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EXECUTIVE SUMMARY

Understanding the processes by which spacecraft demise during re-entry of the Earth's, or other planet's for that matter, atmosphere has become an important subject in recent years. The need to clean up space in the immediate vicinity of Earth and reduce the risk from falling debris to acceptable levels is now vital. To design spacecraft that will demise as completely as possible requires a good working knowledge of what happens during re-entry. One way to improve this knowledge is to carefully observe what happens when existing spacecraft re-enter the atmosphere. Realistically this cannot be done in close proximity unless the spacecraft is pre-instrumented for the purpose. This has been attempted and further missions of this form are planned for the near future. This leaves remote observation and to maximise the results from this it makes sense to exploit spectral techniques. To make this effective requires a good repository of relevant data and this was the purpose of this project.

The "Spectroscopic Response of Break-up Fragments to the Re-entry Environment" project was setup to answer the question: Can we use spectroscopic data to unambiguously identify what is happening during re-entry demise? To address this, four tasks were undertaken:

1. Review spectroscopic observations, ground tests and modelling applied to understanding demise processes.
2. Carry out ground tests to establish verification data for numerical radiation prediction models, based on materials expected to be involved in destructive re-entries.
3. Develop a software package to predict spectroscopic emissions from re-entry trajectories and expected demise events (melting, breaking off etc.).
4. Apply the modelling capability to the upcoming re-entries of four ESA Cluster-II spacecraft between 2024 and 2026 and develop a roadmap for an observation campaign.

Development of the predictive software has not been attempted before, as far as we know, and is a challenging task. To be able to make sensible predictions of the likely radiation requires quite detailed knowledge of the flow characteristics around complex shapes. This is not practical due to the run times required so alternative approximations are needed.

Based on a review of recent observational campaigns for objects (e.g. ATV) re-entering the Earth's atmosphere, recommendations of instrumentation have been provided. One of the problems is distinguishing between overlapping lines below 550 nm (above this there the lines happen to be easier to separate) so high resolution (better than 1 nm) spectroscopy can help.

An analysis of the various materials typically used in spacecraft construction has identified a group of spectral signatures that would be good to target in observational campaigns. Combined with a knowledge of the spacecraft construction, this can be a strong indicator of what is actually happening during the descent. An initial survey of the construction of the Cluster II spacecraft has identified signatures of note.

One of the remaining questions concerns the mechanisms by which the spectral features of interest are generated. Understanding these allows the observation of the lines to be properly interpreted. Some lines are well understood but others are not so further ground testing is required to identify the important mechanisms.

A review of previous tests carried out in wind tunnels has identified that some features are not fully understood have not been tested at all airflow conditions of relevance to Earth re-entry demise. TiO is a typical example which has not been clearly seen but would be expected given the common usage of titanium in spacecraft. Such gaps in knowledge are noted for the campaign within this project as well as future programmes. Another area of uncertainty is where the spectral features are quite congested. Careful experimentation in this context can help to unravel these observations. One other observed feature is sudden and short brightenings. These are likely to correspond to events of significance so a better understanding of these would be useful. In this project we have put forward the idea that these brightenings are the result of opening up of the spacecraft causing shock interactions that produce hotter and brighter regions and this will be tested.

The details of the flow around such openings must be ignored when building the software for predicting the spectral signatures along the trajectory. Computation of any form of flow field will take too long for the software to give predictions in a reasonable time. We are not aware of any similar attempt at a predictive tool of this nature – this is a very difficult problem. The approach adopted is like that of the observations and ground tests, to focus on the mechanisms by which the various spectral features are generated. The model is based on destructive re-entry tools which take a spacecraft model and give predictions of the timing of breakup for the various components based on the given trajectory. Correlations with higher fidelity methods and understanding of the processes of breakup and demise are used to generate the models that are of a suitable form for the software as well as being quick enough to run. The output of these models is the emission generating environment that can be used by codes such as PARADE to generate spectra.

The final element is the spectral predictions themselves. PARADE is able to do this and is well suited to work within the proposed package. Other, more recent software could do this more efficiently but, for practical reasons, is not usable in this context. The only aspect of PARADE that is missing is coverage of the species of interest. The species identified as part of the observational review and the experimental work have been added by taking NIST data and data sourced elsewhere for multi-atom species.

These various elements go into the PRODUCERS software for predicting spectra during destructive re-entry. They are linked together by management software with takes a description of the spacecraft components in PADRE format (a format developed for a previous ESA project on destructive re-entry) along with description of the analysis required and the trajectory. The management software then generates input files for the destructive re-entry code (e.g. DRAMA) which generates a history of breakup which is fed back into our system. This is combined with the physical models to generate the emission creating parameters in the gas and solid materials. PARADE uses this to determine the emissions at various altitudes through the trajectory.

An extensive test campaign was carried out to improve understanding of the emission mechanisms. This consisted of three phases: A) basic material tests using “coupons” (small discs) of the materials of interest such as Titanium, CFRP etc.; B) sub-systems of Cluster I spacecraft recovered from the launch failure and C) a splitter probe which suddenly separates during the experiment to simulate the spacecraft breakup. Two test conditions were established in the wind tunnel to represent maximum enthalpy (Max-H) flow conditions for most of the Cluster II re-entries and a Fast condition representative of Cluster II, Spacecraft 1 which has a faster re-entry than the others and hence a different demise sequence. During the tests a third condition, Max-Q, was added to be representative of the extreme of heat flux for Spacecraft 1.

The tests were recorded with visual and infra-red cameras as well as two spectrometer systems with different resolutions and set to record over different ranges according to what was expected in each test. The testing of the coupons provides baseline data that will assist in understanding of the spectra production mechanisms. These have been seen in the demise of the various sub-systems (Type B) tests. Of interest here is that we usually saw flare-ups of emissions usually associated with a component breaking off or just splitting apart. This often releases other materials and these sometimes generate distinctive flashes. In contrast the splitter probe (Type C) tests did not generate significant enhancements in emission. This suggests that the brightenings that have been seen are due to material release rather than changes in the flow-field. The data generated here has been used, along with some other test cases, to examine how effective the PRODUCERS software is at predicting spectral features of demise.

A careful programme of validation of the PRODUCERS software has been carried out by comparing with the experimental data as well as other sources. High fidelity simulations that are used as input to PARADE have been used as a second source of comparisons. Finally, a much simplified model of the well observed ATV re-entry has been carried out. From these comparisons, it was concluded that PRODUCERS has operated as intended during and is capable of identifying and reproducing calibrated spectra when being used to analyse the output of DRAMA debris demise simulations. As is to be expected from post-processing methods such as PRODUCERS, the accuracy of the underlying demise trajectories, mass/melt histories, and spectral data are of significant importance when considering the overall accuracy and appropriateness of a simulation.

As well as demonstrating the use of the software and establishing the input parameters for some of the species of interest, the validation work was also an effective “beta-test” activity. Some code fixes and model adjustments were made as a result of this work and this has improved performance. It is most likely that further adjustments to the models will be desirable in future.

The PRODUCERS software has been used to make predictions about the spectral signatures that can be expected during an observation campaign for the Cluster II spacecraft re-entries. The spectra were consistent with the markers configured for the analysis and suggested that radiative emission would typically be dominated by that originating from particles stripped from fragments rather than their main body. However, this result is strongly driven by the assumptions made in the definition of the spectral markers so care is required and other data should be sought to increase confidence levels. The spectra also highlighted the sensitivity of the results to the input data, and specifically the value of ψ used to evaluate the proportion of demising material that becomes gaseous.

The modelling also highlighted an issue with the small components of the model with multiple instances. This may require the removal of the DRAMA constraint that prevents connected components having multiple instances, although it is recognised that this also has implications for regular ground casualty risk assessments.

In conclusion,

- Reviews of previous work in observation, ground tests and modelling have identified gaps in our knowledge but also informed the test programme and software construction within this project.

- Ground tests with spacecraft sub-systems have been useful in identifying some of the issues with interpreting re-entry spectral data and relating it to particular component demise. The process is complex and includes many species, some demising suddenly and others over periods of seconds or even tens of seconds. The identification of spectral lines is often difficult due to the and there can be some species that emit strongly and swamp out other. Nonetheless, there were clear aspects of the spectral data that could be linked to events and processes of interest so that the ultimate aim of the project is seen as feasible if difficult.

- A software package, PRODUCERS, has been developed that is able to produce useful predictions. There are inevitable compromises but the software verification process has indicated that the software performs better than was expected at the outset. The software must be used with care and the analysis will still be difficult. There are various avenues for improvement, in particular the derivation of ψ values for species and the underprediction of spectra compared to CFD results, that could be investigated in future projects.

- An analysis of the expected Cluster II re-entry has been carried out based on the predictions of the trajectories that have been calculated elsewhere. These seem reasonable but the PRODUCERS analysis highlighted an issue with the demise of composite materials and some incompatibilities between the spectral analysis and the break-up predictions. Some work is required to address these issues but the prediction provided as part of this project is a good basis on which to build forecasts that have greater confidence levels.

A development programme for ground tests, observation campaigns and modelling methods that can be used in PRODUCERS has been described. The forthcoming Cluster II spacecraft re-entries will be an excellent test bed for the software and for use as a tool to help define the observation campaign.