Exploitation of ESA Flight Data: Executive Summary

E Johnstone (FGE), T Stindt (FGE), S Overend (Vorticity),
A Saunders (Vorticity)

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Fluid Gravity Engineering Ltd
The Old Coach House
1 West Street
Emsworth
PO10 7DX

Tel 01243 378614
E-mail: enquiries@fluidgravity.co.uk

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Fluid Gravity Engineering Ltd
Author: E Johnstone
Reviewer: J Merrifield

Vorticity Ltd
Author: S Overand
Reviewer: S Lingard

CONTENTS **PAGE NO**

SUMMARY

This is the final report for the “Exploitation of ESA flight data” de-risking project (ESA contract ESA 4000125309/18/NL/KML/zk). This project was a collaboration between Fluid Gravity Engineering Ltd and Vorticity Ltd.

The most effective de-risk strategy for Earth Descent and Landing (EDL) technology is to foster practical flight heritage. To this end, a Modular EDL Experiment (MEDLE) vehicle which includes a common launch interface, data collection, and, as far as practical, recovery modules would be a significant step towards enhancing the competitiveness of UK and European capability and would help mitigate the “cherry picking” of EDL technologies by other space agencies (Roscosmos, NASA and potentially Jaxa). Such a capability could also attract international research investment once flight heritage and cost efficiency are demonstrated. The first step towards establishing a reputable capability in this area should be the demonstration of an ability to adapt design uncertainties and margins policies to the available flight data. This is the subject of the present de-risking exercise carried out under this project.

In this project ESA flight data from the ExoMars Schiaparelli Descent Module and the SuperMax parachute demonstrator were utilised. A post flight analysis covering the trajectory, aerodynamics, parachute deployment and the aerothermal response has been undertaken. Vorticity were responsible for the SuperMax trajectory reconstruction and the parachute analysis. FGE were responsible for the Schiaparelli analysis and the aerothermal analysis for both vehicles. These analyses were used to critically assess the uncertainty and margins policies used in these flights and update them based on the lessons learnt.

During the analysis, it was highlighted that the aerothermal margins policy was overly conservative. In flight transition was not observed and so the transition criteria has been updated to account for this. A more realistic assumption of a fully catalytic instead of super catalytic model is also recommended. Using the updated aerothermal margin policy and a 50% increase in thermal diffusivity in the material model, to cover uncertainties here, a mass reduction of 30% can be achieved for both the ExoMars front and back heat shield. A conservative approach has still been maintained. Application of a balanced margin approach to the SuperMAX parachute would have allowed a saving of 21% of the parachute mass. Cameras that observe the parachute during inflation and flight are important to assess parachute behaviour and margin.

The consolidated lessons learnt and the updated margins policy have been encorporated into the MEDLE roadmap (generated by Vorticity). The MEDLE vehicle could be used as a flight demonstrator for inflatable and deployable aerodynamic decelerators, thermal protection systems, aerodynamics and parachutes. It has been demonstrated that using the modular approach proposed by MEDLE, a significant cost saving of 35% can be made on recurring flights (excluding launch costs).

1 INTRODUCTION

The most effective de-risk strategy for Earth Descent and Landing (EDL) technology is to foster practical flight heritage. To this end, a Modular EDL Experiment (MEDLE) vehicle which includes a common launch interface, data collection, and, as far as practical, recovery modules would be a significant step towards enhancing the competitiveness of UK and European capability and would help mitigate the “cherry picking” of EDL technologies by other space agencies (Roscosmos, NASA and potentially Jaxa). Such a capability could also attract international research investment once flight heritage and cost efficiency are demonstrated. The first step towards establishing a reputable capability in this area should be the demonstration of an ability to adapt design uncertainties and margins policies to the available flight data. This is the subject of the present de-risking exercise carried out under this project.

Under this project “Exploitation of ESA flight data” de-risking project (ESA contract ESA 4000125309/18/NL/KML/zk), the following activities have been carried out. The organisational responsibilities are also highlighted:

- Task 1.1: Entry Aerodynamics [1] – In this task, a trajectory reconstruction and aerodynamic analysis was undertaken for the ExoMars Schiaparelli Descent Module and the SuperMax Parachute Demonstrator. (FGE and Vorticity respectively)

- Task 1.2: Entry Aerothermodynamics [2] – In this task, an aerothermal analysis of the ExoMars Schiaparelli Descent Module and the SuperMax Parachute Demonstrator was undertaken. (FGE)

- Task 1.3: Parachute Dynamics [3] – In this task, the behaviour under parachute of the SuperMax vehicle was undertaken. (Vorticity)

- Task 2.1: Balanced Margins [4] – In this task, the margins policy and uncertainties used in the aerodynamic, aerothermodynamic and parachute design are reviewed in light of the post flight analyses. Key lessons learnt have also been collated. (FGE and Vorticity (parachute review))

- Task 2.2: MEDLE Roadmap [5] – In this task, a roadmap for the MEDLE vehicle is produced. A conceptual design, initial requirements, schedule and costs are produced. (Vorticity).

2 TASK 1.1: ENTRY AERODYNAMICS

This task covers the post flight trajectory analyses carried out on the ExoMars Schiaparelli descent module and the SuperMax parachute demonstration vehicle undertaken by FGE and Vorticity respectively.

The ExoMars and SuperMax aerodynamic databases were generated using very different fidelity methods. Through this analysis, it was seen that both aerodynamic databases performed well. The ExoMars database was generated using high fidelity CFD simulations and supported by ground test experiments. On the other hand, the SuperMax aerodynamic database was generated using engineering approaches, specifically Newtonian aerodynamics and literature data from Stardust. Although an extensive uncertainty quantification was made for the ExoMars database, no such uncertainties were specified for SuperMax. The effort and techniques mirrored the level of funding (orders of magnitude different) and risk associated with these two very different missions.

For both vehicles, a best estimate trajectory has been generated which best matched the available telemetry data. For ExoMars, the agreement of the best estimate trajectory was within 2% of the available aerodynamic data. The axial acceleration agreement was within 2%, the co-rotating velocity was within 1%. The normal acceleration and spin rate also agreed to within 1% pre-parachute deployment. It is important to note that at the time of writing, no data was made available for ExoMars and so all data has been taken from the open literature. Improvements to both aerodynamic databases have been made, highlighting the importance of flight data to best understand a vehicles aerodynamic behaviour. Where possible, the uncertainties used have been critiqued and improvements suggested.

The following lessons learned from both trajectory analyses are provided:

- To accurately measure the mass properties, including the cross-inertias before flight. This is important if dynamic motion or asymmetries (from ablation for example) are to be investigated.
- To ensure the instrumentation is well calibrated before flight over the entire expected measurement range.
- Although Newtonian produces a good drag approximation between Mach 3 and Mach 10, higher fidelity approaches are required below Mach 3 to capture the Reynolds number effects.
- Higher fidelity approaches, than that used to create the SuperMax aerodynamic database, are required to more accurately generate the pitch moment and normal force coefficients.
- Ensure that aerodynamic design simulations are carried out near or at the trim angle of attack, this will help scientific analysis of the flight.
- Ensure that where there is a change of computational methodology is present, enough simulations are carried out to ensure there is not a sudden step in any aerodynamic coefficients generated.
- The trajectory and aerodynamic design need to be well coupled.

3 TASK 1.2: ENTRY AEROTHERMODYNAMICS

Under this task, an analysis of existing flight data has been made to analyse the entry aerothermodynamics of the ExoMars 2016 Schiaparelli Descent module (ESDM) and the SuperMax capsule to extract lessons that can guide the development of a balanced margins policy to use for the design of the MEDLE vehicle.

The work performed provided an initial assessment of the thermal instrumentation data of the respective vehicles, comprised of in-depth temperatures in the thermal protection system (TPS). For the ESDM, the TPS is made from Norcoat® Liège (a phenolic-impregnated cork-based ablator), whilst the SuperMax capsule forebody is made from stainless steel. The telemetry data was used to perform a reconstruction of the as-flown aerothermodynamics. Updated computational fluid dynamics (CFD) analysis was performed on the best-estimate trajectories (BET) supplied from WP1.1. For both vehicles, the development of more of a performance, rather than a sizing, aerothermal database and material model has been pursued to facilitate a meaningful analysis of the flight data and inform on recommendations for future missions.

The ESDM heatshield was designed to withstand a fully turbulent heat pulse based on test results and computational analysis on a pre-flight design trajectory. Instrumentation on the flight heatshield measured relatively low in-depth temperatures which indicate the TPS fulfilled its purpose but with a considerable degree of conservatism. The removal of the dominant conservative assumptions in the aerothermal environment showed a general over-prediction of the in-depth temperatures when using the baseline Norcoat® Liège model. Therefore, to complement the inverse aerothermal analysis performed by Ariane Group [6], a more material model-focused approach was chosen. The resultant material model was found to reduce the in-depth temperature (meridian-averaged) discrepancies on the front shield to within 50K for each station apart from the nose and to within 20K across the back cover, for which inverse heat fluxes derived by Ariane Group were used. On the front shield, the steep sizing heat fluxes (turbulent, roughness augmented, super-catalytic and margined) in the same zone as the edge thermal plug were found to reach up to 6.5 times the heat flux calculated at the edge thermal plug location using best-estimated analyses (laminar and fully-catalytic). Whilst, on the back cover, a similar analysis showed the steep sizing fluxes to be 3.0 times the peak heat flux values calculated using best-estimate analysis. Data from this flight can be used to improve the margins policy used for future missions.

The SuperMax capsule aerothermal environments posed far fewer challenges to rebuild numerically than for the ESDM. The heat fluxes, particularly near the thermocouple location (positioned in the aft portion of the aeroshell's conical region), could be computed using an engineering-level approach with fidelity that closely approached that of full Navier-Stokes solutions. This permitted the use of the original laminar ATDB. The material response problem could be simplified to a thermal conduction and storage problem which placed a higher sensitivity on the accuracy of the material thermal properties and on modelling the thermal response of the interior aeroshell environment. Using the best estimate aeroshell configuration, an approximate increase of 25% of the aeroshell volumetric heat capacity, or an approximate 25% decrease of the aerothermal fluxes was required to match the in-depth temperatures measured in flight to within 5K – these are believed to be beyond realistic uncertainties. Therefore, it is expected that thermocouple calibration and/or bonding may have played a significant role.

The overarching lesson learned from this task relates to the need for a balanced approach to determining the aerothermal and material model margins.

4 TASK 1.3: PARACHUTE DYNAMICS

The intention of this task was to investigate the data from both SUPERMAX and Schiaparelli. However, since significant analysis of the Schiaparelli data has already taken place in the scope of ExoMars RSP and alternative explanations for the Schiaparelli anomaly have been proposed, it was decided to concentrate the efforts within this task on the SUPERMAX data which have been only partially exploited to date.

A brief analysis was conducted as part of the test campaign [7]. Further analyses of the SUPERMAX flight have been conducted as part of this MEDLE program. Previous analyses have investigated the phase from re-entry of the atmosphere to parachute deployment [1]. The objective of this analysis was to examine the behaviour of the vehicle and the parachute during parachute deployment, inflation and deceleration to steady descent.

The analysis was accomplished in several steps. A coherent trajectory was calculated for the parachute inflation and deceleration phase by blending the GPS and accelerometer data. This trajectory was used to calculate the evolution of the force coefficient and other parameters throughout the parachute inflation and vehicle deceleration. The deployment phase was then examined confirming that the deployment time observed in the test data is similar to that predicted.

The data were then analysed to examine the inflation phase in more detail, including comparison to the predicted inflation force-time profile. Video data were also used to examine anomalies observed in the drag coefficient data. It was found that the inflation time was close to the expected value, but the force coefficient during inflation was higher than that expected from the simulation.

The evolution of the force coefficient during the deceleration from the end of inflation at Mach 1.6 to steady descent at Mach 0.2 was examined and compared to the latest ExoMars aerodynamic database [8]. Discrepancies between the observed results and the database in the supersonic regime were found and discussed. The evolution of the force coefficient during the initial 10 second period of steady descent was also examined. It was found that there was a significant reduction in force coefficient in this period which was found to be related to the motion of the parachute.

Finally, the evolution of the angular rates was examined. The spin rate was found to have reversed soon after inflation due to riser twist. The lateral (not spin) rates observed on the test were compared to those expected from Anybody6D. The lateral rates were found to be higher immediately after inflation than those expected but similar to the simulation once they had decayed to a steady-state. It was also found that the decay to steady state observed in the test was faster than expected. The post-inflation lateral impulse model developed as part of the post Schiaparelli model updates was found to result in a model that matched the peak lateral rate. However, the decay observed in the simulation results was still slower than observed in the test.

5 TASK 2.1: BALANCED MARGINS

This task documented the key lessons learnt from the post flight analyses carried out on the ExoMars Schiaparelli descent module and the SuperMax parachute demonstration vehicle undertaken by FGE and Vorticity respectively. These are contained in §5.1. The results from the post flight analysis undertaken in task 1 have been used to propose a new margin methodology for aerothermal and aerodynamic design.

The key focus of the work performed here has been the aerothermal design margins. It was identified that this is where the biggest improvements could be made. The baseline used here is the performance heat fluxes and material model developed in WP1.2. Using these and comparing to the ATDBv5.2 design heat fluxes, the margins used were calculated. The biggest contributors to the aerothermal heat load margins were identified as the sizing trajectories and the turbulent roughness augmentation.

From the post flight analysis, transition was not observed, and an updated transition correlation is proposed. Using this transition criteria, the characterised roughness and fully catalytic fluxes, the aerothermal margins were reduced from around 300% to 90% across the front shield. This is equivalent to carrying a safety factor of approximately 2. For the back cover a conservative heat flux correlation was determined. The calculated heat load margins applied here were around 100% and so a balanced approach can be seen across the heatshield. Using these margins and a 50% increase in thermal diffusivity in the material model, to cover uncertainties here, a mass reduction of 30% can be achieved for both the ExoMars front and back heat shield. A conservative approach has still been maintained.

The parachute margin approach has been described. Margins are taken within the design of the parachute system in three stages of the design process: firstly in the parachute sizing, secondly in the derivation of design loads and finally in the detailed design. Margins must also be applied to other elements of the mission design to take account of the parachute system qualification and operation. Application of a balanced margin approach to the SuperMAX parachute would have allowed a saving of 21% of the parachute mass. Cameras that observe the parachute during inflation and flight are important to assess parachute behaviour and margin.

5.1 Consolidation of Key Lessons learnt

This section consolidates the key lessons that have been highlighted from the flight analyses and that should be taken forward for future missions.

5.1.1 Descent Module Aerodynamics

The key lessons learnt from the aerodynamic analysis of SuperMax and the ExoMars Schiaparelli Descent Probe are listed below:

- It is important to accurately measure the mass properties, including the cross-inertias before flight. This is important if dynamic motion or asymmetries (from ablation for example) are to be investigated post-flight.
- It is important to ensure the instrumentation is well calibrated before flight over the entire expected measurement range.
- Although Newtonian produces a good drag approximation between Mach 3 and Mach 10, higher fidelity approaches are required below Mach 3 to capture the Reynolds number effects.

- Higher fidelity approaches than those used to create the SuperMax aerodynamic database (Newtonian and literature results), are required to more accurately generate the pitch moment and normal force coefficients. This should include Euler simulations at angle of attack.
- It is important to ensure that aerodynamic design simulations are carried out near or at the trim angle of attack, this will help scientific analysis of the flight. To be able to do this effectively, the trajectory and aerodynamic design needs to be well coupled.
- It is important to ensure that where there is a change of computational methodology present, enough simulations are carried out to ensure there is not a sudden step in any aerodynamic coefficients generated.

5.1.2 Parachute Aerodynamics

The key lessons learnt from the analysis of the SuperMax parachute test are listed below:

- The parachute force coefficient observed on the test in the supersonic phase was higher than expected. A possible cause is the rapid deceleration (>10 g) of the vehicle which meant that the flow field around the parachute evolved rapidly and was never steady state.
- The consequence of this rapid deceleration hypothesis would be that future experiments must be designed to match the acceleration under the parachute with those expected on missions.
- The inflation time of the parachute observed on the test agreed well with the predicted value from the Vorticity parachute model. However, the force coefficient during inflation was higher than predicted. This is probably related to the high parachute force coefficient during the supersonic phase.
- It was observed on the test that the spin direction of the SuperMax vehicle reversed at inflation. This was investigated using a 2-DoF model. This analysis concluded that the phenomenon was caused by riser twist. A similar investigation was conducted for Schiaparelli and test data was well matched.
- The angular oscillation rates of SuperMax and Schiaparelli vehicles decayed at Mach 1.2. Investigations found that is the current model could not emulate this damping phenomenon and further investigation is required.

5.1.3 Aerothermodynamic and Material

A summary of the lessons learned from the reconstruction of the ESDM aerothermodynamics which can inform on the development of a margins policy are as follows:

- Overall, the aerothermal margins and subsequent material margin of the design values compared to flight were very large. As such, some improvement on the margins policy should be possible.
- The justification behind the choice of the sizing trajectories is not known but the conservatism applied here should be taken account of when considering any further margins to apply.

- For the consideration of aerothermal margins, the assumption of super-catalytic fluxes is too conservative for Martian entry (and unphysical).
- No transition was observed and so for a capsule the size and ballistic coefficient of the ESDM, turbulence and, therefore, roughness do not play a role. This transition information can be used for future missions.
- A good material model is crucial, and it is clear that the baseline material model of FGE and Ariane Group was conservative. If possible, the level of conservatism needs to be taken account of in the margins policy.
- In-situ calibration of the thermocouples is recommended.
- A physics-based probabilistic uncertainty analysis underlying the TPS margin methodology and with emphasis on material response modelling is recommended as a path forward for the design of ablating TPS. A side benefit of the probabilistic approach is that, in addition to quantifying the uncertainty of TPS sizing predictions, the technique isolates the chief sources of input uncertainty and sensitivity in the models employed.
- The uncertainty drivers in both aerothermal and material response models should be prioritised and targeted for further ground-based testing or possible flight instrumentation to maximize the return from limited research funding.

A summary of the lessons learned from the reconstruction of the SuperMax aerothermodynamics which can inform on the development of a margins policy are as follows:

- The bonding process of the thermocouples requires careful consideration relating to durability and the ability to model it accurately.
- The interior capsule design needs to be accurately modelled – A solid understanding of all potential conduction paths into highly conductive components in the vicinity of the thermocouples under the dynamic entry environment (high g, extreme vibrations) is paramount, e.g. contact of the aluminium liner.
- Pre- and post-flight in-situ calibration of the thermocouples is recommended.
- The inclusion of thermocouples at and/or close to the nose would provide useful data to validate the aerothermal models under more challenging environments and, therefore, inform on the levels of conservatism implemented in the pre-flight ATDB.
- Gold-plating was applied to the internal surface of the aeroshell due to its optical properties, however, the low temperatures reached meant that the radiation away from the surface was negligible. This is not deemed necessary for future flights.
- The thermal properties of the aeroshell need to be well characterised.

5.1.4 General

Key lessons that are not included in the previous sections are described below:

- To improve both the aerodynamic and aerothermal analysis, some data during the blackout period for the ExoMars DM would have been beneficial in determining the actual response of the vehicle. This data should have been retransmitted after blackout. The data is very significant for the Schiaparelli descent probe as peak heating and peak acceleration both occurred during the blackout period. A similar delayed transmission approach will allow more data to be transmitted for key stages of the descent phase such as parachute inflation. This would also be assisted by greater transmission bandwidth.
- Cameras with a view of the parachute are rarely flown on space missions; however, they are the only reliable method of identifying non-critical damage to a parachute. These would be highly beneficial in assessing parachute performance and determining any marginal damage.

5.1.5 Key Lessons for MEDLE

The key lessons learnt from this work which will be carried forward into the MEDLE roadmap are:

- Euler calculations (or higher fidelity) should be used to generate the aerodynamic database.
- The aerodynamic (and aerothermal) design and trajectory analysis should be well coupled to ensure that the high-fidelity calculations are focussed around the expected flight points.
- The mass properties of the vehicle need to be accurately measured before flight.
- The instrumentation should be calibrated in-situ.
- Any thermocouples used should be positioned so that the environment they are measuring is well defined and a good contact is maintained with the vehicle.
- The thermal protection and aeroshell material properties should be measured before flight.
- In defining the ATDB, a momentum thickness transition criterion of 180 should be used instead of 140 for Earth Entry.
- If a conductive aeroshell is used, a 3D thermal analysis should be carried out.
- In order to qualify the parachute, a minimum qualification load must be reached. Due to the stochastic nature of parachute inflation, it is not possible to predict the inflation load accurately so the test load target must be higher than the qualification load. As a consequence, both the parachute and other system elements which are tested at the same time must be designed to survive the maximum possible test load rather than simply the qualification load.
- For component separation, ballistic coefficient ratios are generally defined for separating elements. The ballistic coefficient is defined as the ratio between an assembly’s mass and total drag area. For release of a front shield, for example, a minimum ballistic coefficient ratio of 0.7 would normally be defined at design time in order to ensure that a positive difference in terminal velocity is always achieved. Since the parachute is usually sized using the worst-case system masses (including all design margins) and drag areas (again including all uncertainties), the

final ballistic coefficient ratio is invariably much more positive than the initial design value. Since a final ballistic coefficient ratio of anything less than 1.0 would guarantee separation, higher initial ballistic coefficient ratios could be considered in the expectation that the ratio will improve as the design matures. Often flight limit loads are estimated from early very conservative data. Therefore, flight limit loads should evolve as design proceeds in accordance with maturing analysis to allow management of margins.

- Data transmitted for key stages of the descent phase such as parachute inflation should allow full reconstruction of the EDL sequence in case of loss of mission. This would be assisted by greater transmission bandwidth. The Schiaparelli flight data indicate that the parachute inflation force was predicted very accurately; however, it should be noted that the sampling frequency of the returned data was insufficient to confirm that the peak force has been recorded. It is recommended that high frequency acceleration data is obtained during parachute inflation on any future mission.
- The angular rates measured on both SuperMax and Schiaparelli were higher than expected during the initial period after inflation. This suggests that peak rates derived from Monte-Carlo analyses should be multiplied by a factor to take into account uncertainties in the rate prediction.
- Where probe spin is important for the correct operation of a mission, this should also be modelled. No requirements were placed on Schiaparelli or SuperMax, so no margin policy was identified. A further lesson learned is that characterisation of torsional stiffness of fabric items must be made at the correct load due to non-linearity.
- Cameras with a view of the parachute are rarely flown on space missions; however, they are the only reliable method of identifying non-critical damage to a parachute. These would be highly beneficial in assessing parachute performance and determining any marginal damage.

6 TASK 2.2: MEDLE ROADMAP

This task sets out the roadmap for the Modular Entry Descent and Landing Experiment vehicle (MEDLE).

The objective of the Modular Entry Descent and Landing Experiment (MEDLE) is to produce a vehicle design that is compatible with a range of low-cost sub-orbital launchers and micro-launchers. The vehicle will be a test bed for various technologies associated with EDL i.e. parachutes, DADs/IADs, heat shields etc. in order to raise their technology readiness levels.

The three reference missions chosen for MEDLE are listed below along with a currently available launcher that could be used to enable such a mission:

1. Parachute test - VSB30/31 booster on a MAIUS type mission or an improved Orion booster, on a REXUS-type mission
2. Inflatable/Deployable aerodynamic decelerator test - VSB30/31 booster on a MAIUS type mission
3. Thermal Protection System test - VSB30/31 booster on a MASER/TEXUS-type mission

From these reference missions a set of high-level vehicle requirements were collated.

Conceptual designs were developed for all three reference missions and limitations of the approach were highlighted. The design philosophy of the MEDLE vehicle is to create a technology test bed produced from modular elements that have as many common interfaces as possible.

The common instrumentation that will be fitted to all vehicle configurations is:

- The data acquisition systems (DAS) – accelerometers, rate/barometer/magnetometer sensors, data storage and sequence control;
- GPS antenna;
- Camera(s);
- Thermocouples;
- Telemetry; and
- Pyro-mechanical activation device – for test article deployment.

The common structural modules will include:

- Forward aeroshell;
- Internal support structure –instrumentation and recovery systems;
- Ballast adjustment – for CoG attainment and spin balancing;
- Accommodation for an access panel or umbilical connector to the rocket of ground support equipment;
- A parachute recovery system; and

- Aft cover interfaces.

Some modules will be customisable. A minimal amount of re-design will be necessary in order to modify certain aspects to meet the specific requirements of the test article or associated test method. The interfaces between modules and commons parts, however, remain the same throughout. Customisable elements will include, but are not limited to:

- A mission-specific avionics control PCB (if not already covered within the DAS motherboard)
- Forward aeroshell geometry – the shape and size of the outer profile could be modified without affecting the internal structure or interfaces;
- Some parts of the internal support structure – to accommodate the test hardware associated with the specific test;
- Overall vehicle diameter and length;
- Mass and CoG position;
- Thermocouple locations;
- Parachute deployment type and size; and a
- DAD/IAD deployment system.

A schedule for the design, development and analysis has been proposed for the initial baseline flight and follow on flights. It is expected that the follow-on campaign will be around 1.5 years shorter than the initial flight.The initial development and flight will take about 3 years.

The majority of the time saved from a follow-on campaign will be in a significantly reduced time allocated to the preliminary and detailed design. Since much of the modular structural details and DAS avionics will have been designed during the baseline campaign, only the design associated with the follow-on campaign’s configuration and experiment will be required.

The time allocated to vehicle manufacture will likely remain the same between the baseline and follow-on campaigns since a completely new vehicle may have to be produced.

There will certainly be savings in the time allocated to qualification as this will depend on the technology being flown. Much of the common modular elements such as the sequence control and recovery subsystems will already have been qualified.

Finally, a cost breakdown was generated. This identifies the initial design and development costs in addition to the recurrent costs when using the vehicle design. It is expected that there will be a reduction of 35.5% on the overall costs of recurrent missions (excluding launch) by using MEDLE compared to a conventional one-off flight experiment.

7 DISTRIBUTION

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FGE Contract C899

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