SUPERSONIC PARACHUTE TESTING USING A MAXUS SOUNDING ROCKET PIGGY-BACK PAYLOAD

J. Stephen Lingard (1), Arrun Saunders (1), Jim Merrifield (2), Jamie Caldwell (2), José Longo (3), Luca Ferracina (4)

(1) Vorticity Ltd, Chalgrove, Oxfordshire, OX44 7RW, UK, Email: steve.lingard@vorticity-systems.com
(2) Fluid Gravity Engineering Ltd, Emsworth, Hampshire, PO10 7DX, UK, Email: jam@fluidgravity.co.uk
(3) European Space Agency, Noordwijk, The Netherlands, Email: jose.longo@esa.int
(4) ATG Europe B.V. on behalf of the European Space Agency, Noordwijk, Netherlands, Email: luca.ferracina@esa.int

ABSTRACT

A feasibility study has been performed under European Space Agency funding to produce a preliminary design of a re-entry vehicle that can be used as a test bed for supersonic parachutes. An opportunity in 2016 has been identified that would allow the vehicle to be launched aboard a MAXUS sounding rocket from the Swedish Space Corporation’s facility, Esrange, in Kiruna, Sweden.

Supersonic tests in large wind tunnel facilities are costly. Moreover, since the mothballing of the AEDC 16S facility, parachute testing has been limited, by tunnel blockage, to articles with diameters <0.83 m or to modest Mach numbers. Full-scale supersonic parachute testing is also expensive, of the order of tens of millions of Euros for a series of tests. Therefore, a test technique that allows representative supersonic testing of parachutes at modest cost is required. The preliminary design MAXUS piggyback capsule capable of allowing such testing is presented here.

1. OVERVIEW

The objective of this mission is to test the inflation and flight of a small test parachute deploying at Mach 2.0 in a low density atmosphere. In order to do this, a small parachute test vehicle will be added to the underside of the MAXUS upper stage.

The MAXUS flight is launched from the Swedish Space Centre’s (SSC) ESRANGE facility in Kiruna, Sweden. The vehicle replaces a ballast mass on the MAXUS launcher. It can have a mass up to 15 kg and a maximum diameter of 0.29 m. The vehicle will remain passive during the MAXUS launch up to release from the MAXUS upper stage following booster separation. Release of the capsule occurs at 90 seconds after ignition at an altitude of 192 km with a velocity of 3 km/s and at a flight path angle (FPA) of 88°. At deployment the spin rate is 12 °/s.

The piggy-back vehicle will then continue on a ballistic trajectory up to an apogee of ~710 km before descending and starting its re-entry. Prior to atmospheric interface the vehicle will be travelling at approximately Mach 12. The vehicle is stabilised by a low spin rate in the exo-atmospheric phase of flight and by aerodynamic stability during the re-entry.

At Mach 2.0, a test parachute is deployed rearward from the test vehicle by means of two pyrotechnic actuators. The vehicle then descends under the parachute until it reaches the ground.

Data will be recorded throughout the flight from release until landing using an on-board data acquisition system. Additionally, limited engineering and positional data will be broadcast to the ground in order to aid retrieval.

The capsule will be retrieved by helicopter following landing and the data retrieved for post-test analysis. Figure 1 shows the mission sequence.

![Figure 1 MAXUS piggy-back mission sequence](image)

2. SUPERSONIC PARACHUTE TEST CAPABILITIES ON MAXUS

To obtain useful data from sub-scale parachute tests, in addition to accurately scaling the model, it is necessary to match the relevant test parameters: Mach number, parachute model porosity, parachute stiffness, forebody Reynolds number. Therefore, the selected trajectory must provide deployment conditions allowing these parameters to be matched as closely as possible.

Mach number has a strong influence on parachute performance (both drag and stability) and must be matched. As Mach number increases above 1.0 parachute drag coefficient varies significantly and eventually above Mach 1.5 starts to reduce significantly. This is caused by the forebody wake interacting with the bow shock ahead of the canopy causing bow shock to
move forward and distort and the pressure in the canopy to change. This in turn causes the canopy shape to change and thus influence the position of the bow shock resulting in cyclical motion. As Mach number increases the motion becomes more severe. Figure 2 shows the variation of drag coefficient with Mach number for a Huygens/ExoMars type parachute.

Figure 2 Drag coefficient for Huygens/ExoMars DGB parachute

The effect of the material stiffness on the dynamics of the parachute is dependent not only on the material stiffness itself but also the force acting upon the parachute. Increasing the force (i.e. the dynamic pressure) will make a stiffer material deform more easily. Since the dynamic pressures expected in wind tunnels are generally higher than those expected in space missions, the increased dynamic pressure will, to some extent, offset the increased stiffness resulting from small model parachutes.

This effect can be quantified using a Stiffness Index derived from the material mechanical properties, the parachute size, and the dynamic pressure during the test. The stiffness index is defined as:

$$\xi = \frac{E}{\rho V_s^3 (1 - \nu^3)} \left( \frac{\delta}{D_0} \right)^3$$

where $E$ is Young’s modulus for the canopy fabric, $\rho$ is the air density, $V_s$ is the flow velocity, $\nu$ is Poisson’s ratio for the material, $\delta$ is the canopy fabric thickness and $D_0$ is the canopy reference diameter.

The performance of a parachute is affected by the total porosity of the canopy, both geometric and fabric. The geometric porosity of the parachute (the proportion of the canopy which comprises gaps in material) scales with size (dependent on Reynolds number to some extent). The porosity of permeable fabric, however, increases significantly with Reynolds number per m. The fabric porosity in a low level Earth test will be significantly greater than that of the same fabric used for a Mars entry.

Fabric porosity can be allowed for in the design of test parachutes by using fabric of a different permeability than that of the flight parachutes. However, the best approach is to obviate the problem by using imporous material in the prototype and model and relying only on geometric porosity.

The performance of a parachute is inextricably linked with the payload behind which it flies due to the payload wake.

The payload wake has several effects on the parachute performance. Firstly, the parachute drag reduces due to the momentum deficit in the wake. For large parachutes and small payloads, the reduction in drag of the parachute from this mechanism is approximately equal to the drag of the payload. Secondly, the unsteady wake of the payload causes a non-uniform pressure distribution across the mouth of the parachute canopy. This causes flying shape of the canopy to change and thus the drag to change. This effect is particularly marked in supersonic flow. The wake from the payload interacts with the bow shock of the parachute canopy and the shock moves axially. Since Reynolds number modifies the wake characteristics it should be matched if possible.

3. PERFORMANCE ASSESSMENT AND TRADES

Initially a trade of the vehicle shape was conducted. Two candidate shapes were identified. The first was that of the Mars Microprobe vehicle that had a 45° sphere cone nose geometry and a hemispherical aft surface. The second candidate shape was that of the Stardust vehicle that had a 60° sphere cone nose and truncated conical aft surface. The former has better stability but the latter provides a lower ballistic coefficient for the same mass and hence lower peak heating. The deciding factor was the maximum dynamic pressure at Mach 2 for the two shapes. For the 45° sphere cone with the maximum mass of 15 kg the nominal dynamic pressure at parachute deployment is 21 kPa compared with 15.7 kPa for the 60° sphere cone. This increase in dynamic pressure necessitates the use of a heavier canopy fabric for the parachute increasing the stiffness index and making the canopy less representative of mission parameters. Thus a 60° sphere cone nose was selected. It then became necessary to demonstrate that a vehicle that is stable down to Mach 2 could be achieved.

The nominal trajectory for the mission is shown below in Table 1.
Perform a perfectly scaled model test, aeroelastic coefficients (Cn) and pitching moment were used for the test conditions for AOIs up to 10°. For AOIs greater than 10° in the continuum regime, the deployment conditions in terms of Stiffness index (SI) are normally required when testing in wind tunnels.

The achievable deployment conditions in terms of SI and Reynolds number at similar supersonic Mach numbers are achieved by using a MAXUS Piggy-Back payload. MAXUS testing will provide high-quality data by allowing suitably flexible parachutes manufactured from off-the-shelf materials to be tested.

### 4. Aerodynamic Database Generation

Since the interface requirements of the piggy-back vehicle with the MAXUS rocket is most easily achieved with a cylindrical aft body with a flat aft face, neither the aerodynamic database of the Stardust nor Mars Microprobe vehicle was suitably representative. Therefore, an aerodynamic database for the specific geometry of the piggy-back vehicle was created in order to investigate the vehicle’s flight dynamics.

Continuum and free molecular aerodynamic coefficients were generated for the MAXUS piggy-back capsule: axial force coefficient (Ca), normal force coefficient (Cn) and pitching moment coefficient (Cm) were computed. The AErodynamic DataBase (AEDB) was designed for flight conditions preceding parachute deployment at Mach 2.

Free molecular coefficients are calculated by the method of Schaaf from the capsule geometry itself using a panel inclination method. The Stardust bridging function is used to bridge between the free molecular and continuum aerodynamic coefficients.

High hypersonic coefficients can be calculated using Newtonian theory with reasonable reliability. However, further action is necessary at lower Mach numbers. This first iteration of the AEDB was generated by comparison with the Stardust aerodynamic coefficients [1] due to the similar forebody geometry. The Mach number and angle of incidence (AOI) dependence of the AEDB was generated by scaling the present capsule’s Newtonian coefficients by the proportional difference between the actual Stardust AEDB and the Stardust Newtonian values. The published Stardust AEDB only provides information for AOIs up to 10°. For AOI above 10°, the proportional difference at 10° is used for scaling purposes. This is not expected to lead to significant issues since the capsule is not anticipated to achieve AOIs greater than 10° in the continuum regime. Pitch damping coefficients are taken from the Huygens AEDB. The present capsule has a flat-based geometry that is known to be non-optimal for dynamic stability. As such, the Huygens dynamic stability database is used since it is thought to be reasonably conservative.

3D Euler simulations were conducted at Mach 10 using the FGE in-house code ANITA to compare against the scaling technique used to generate the initial AEDB and gain further understanding of the aerodynamic behaviour at large AOI. A half body mesh was used for the computations as illustrated in Fig.3. Fig. 4 presents the comparison between the AEDB and 3D Euler results. The results support the AEDB for small AOI, validating the methodology used. Large AOI show larger differences, particularly for Ca. These discrepancies will make little difference to the capsule.

#### Table 1: Nominal mission trajectory

<table>
<thead>
<tr>
<th>Event</th>
<th>Time from release (s)</th>
<th>Altitude (km)</th>
<th>Vel (m/s)</th>
<th>Mach</th>
<th>q (Pa)</th>
<th>Accel (m/s²)</th>
<th>Heat flux (MW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launcher ignition</td>
<td>-91</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1st Stage burn-out</td>
<td>-27</td>
<td>75</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1st Stage sepn</td>
<td>-5</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Capsule release</td>
<td>0.00</td>
<td>192.0</td>
<td>3,000</td>
<td>5.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Apogee</td>
<td>357.9</td>
<td>713.1</td>
<td>242</td>
<td>N/A</td>
<td>0.0</td>
<td>0.0</td>
<td>0.000</td>
</tr>
<tr>
<td>Max heat flux</td>
<td>765.6</td>
<td>33.0</td>
<td>2,856</td>
<td>9.47</td>
<td>37,341</td>
<td>232.2</td>
<td>1.375</td>
</tr>
<tr>
<td>Max q</td>
<td>768.2</td>
<td>26.5</td>
<td>2,051</td>
<td>7.08</td>
<td>57,354</td>
<td>360.2</td>
<td>0.884</td>
</tr>
<tr>
<td>Chute deployed</td>
<td>774.7</td>
<td>19.3</td>
<td>576</td>
<td>2.00</td>
<td>15,773</td>
<td>103.4</td>
<td>0.037</td>
</tr>
<tr>
<td>Chute inflation max force</td>
<td>774.8</td>
<td>19.0</td>
<td>567</td>
<td>1.97</td>
<td>15,295</td>
<td>989.0</td>
<td>0.035</td>
</tr>
<tr>
<td>Tunnel</td>
<td>SI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AEDC 16S</td>
<td>2.0</td>
<td>4.9x4.9</td>
<td>5,000</td>
<td>1.60</td>
<td>4.3x10⁻³</td>
<td>5.0x10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>NASA Glenn</td>
<td>2.0</td>
<td>3.1x3.1</td>
<td>5,000</td>
<td>0.83</td>
<td>2.6x10⁻³</td>
<td>3.6x10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>CNRC Trisonic</td>
<td>2.0</td>
<td>1.5x1.5</td>
<td>68,000</td>
<td>0.34</td>
<td>2.7x10⁻³</td>
<td>3.0x10⁻⁴</td>
<td></td>
</tr>
<tr>
<td>MAXUS</td>
<td>2.0</td>
<td>Free flight</td>
<td>15,773</td>
<td>1.25</td>
<td>1.2x10⁻²</td>
<td>2.6x10⁻²</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 2: Some wind tunnel facilities for supersonic parachute testing

Maxus provides a lower, and hence more representative, stiffness index than any tunnel currently operating. Only AEDC 16S is better but this tunnel is not in use.

The achievable deployment conditions for a MAXUS flight was compared with those for past and future missions. It was shown that there are many cases where the deployment conditions in terms of SI and Reynolds number at similar supersonic Mach numbers are achieved by using a MAXUS Piggy-Back payload. MAXUS testing will provide high-quality data.

#### Table 2: Nominal mission trajectory

The use of a MAXUS Piggy-Back payload can reduce the compromises normally required for a wind tunnel campaign. Small diameter parachutes are necessary to avoid excessive blockage of currently operating tunnels. Small parachutes are too stiff to accurately emulate parachute inflation parameters. They over predict C_D, over predict inflation load and under predict inflation time.

Since all the parameters discussed in section 2 need to be matched to perform a perfectly scaled model test, a compromise is normally required when testing in wind tunnels.

Table 2 below compares Maxus with wind tunnel testing in the best available tunnels.

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Mach</th>
<th>Size (m)</th>
<th>q (Pa)</th>
<th>Chute max D_c (m)</th>
<th>Re</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEDC 16S</td>
<td>2.0</td>
<td>4.9x4.9</td>
<td>5,000</td>
<td>1.60</td>
<td>4.3x10⁻³</td>
<td>5.0x10⁻⁵</td>
</tr>
<tr>
<td>NASA Glenn</td>
<td>2.0</td>
<td>3.1x3.1</td>
<td>5,000</td>
<td>0.83</td>
<td>2.6x10⁻³</td>
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</tr>
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<td>CNRC Trisonic</td>
<td>2.0</td>
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<tr>
<td>MAXUS</td>
<td>2.0</td>
<td>Free flight</td>
<td>15,773</td>
<td>1.25</td>
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<td>2.6x10⁻²</td>
</tr>
</tbody>
</table>
trajectory calculations since only small AOI are expected in the continuum regime. The main purpose of generating continuum coefficients at large AOI is to provide a realistic continuum anchor for the bridging function in the transitional regime. Note, although the present capsule does fly backwards for some of its trajectory (i.e. in ascent), this portion is highly rarefied and thus does not depend on the continuum coefficients.

The AeroThermal DataBase (ATDB) for the capsule was constructed using the Euler boundary layer capability within the FGE in-house code SMACH (Shape changing Modular Aerothermal Code for Hypersonics). A 2D simulation was performed using the FGE in-house code TINA (Thermochemical Implicit Non-equilibrium Algorithm) at one trajectory location in order to investigate base heat fluxes. The sensitivity of the convective heating to AOI was also investigated using SMACH.

Augmentation along the windward ray is generally greater on the conic section than on the cone (where some regions actually see a small decrease) and is greater for laminar than turbulent fluxes.

5.2. Base Heating Investigation

An estimate of the base heating on the Maxus capsule is an important issue since the necessity for an aft TPS and the shielding of sensitive components needs to be evaluated. SMACH automatically generates a heat flux profile on the base of the vehicle after Bulmer. The heating in the centre of the base (highest base heating due to the rearward stagnation point) is provided in Fig. 5. The characteristic “double hump” distribution for base heating is recovered with the first peak occurring just after peak laminar heating and the second occurring just after peak dynamic pressure. The temporal resolution of the SMACH simulations is not sufficient to accurately identify the timing of these peaks, but the plot is illustrative of what should be expected.
A Navier-Stokes simulation was performed at peak base heating to compare with the results from the correlation. The simulation was performed with TINA. Afterbody heating correlations should be considered rule-of-thumb for design since the correlating data generally has a very large scatter associated with it. As such, comparison with a higher fidelity method is of utmost importance. The heat fluxes to the base of the vehicle, as computed using Bulmer’s correlation, are compared with the TINA results in Fig. 6. It is seen that the Bulmer correlation under predicts the aft stagnation point heating but the linear interpolation assumed over the base region over-predicts the heating towards the outer circumference of the vehicle. Indeed, if one calculates the total transmitted power to the circular base, Bulmer’s method provides an estimate that is 25% greater than the Navier Stokes calculations. As such, design level conservatism is retained.

6. VEHICLE PERFORMANCE

6.1. Trajectory

Initiation of the parachute deployment is determined by an accelerometer trigger. This has been tested by Monte Carlo analyses and the performance at parachute inflation is shown in Figure 7 below. The scatter is low and acceptable.

A transient thermal analysis of the vehicle was performed using the thermal solver within LS-DYNA. The stagnation point heat flux was taken from the 3-dof trajectory simulations. Stagnation point heating is calculated using the Sutton-Graves correlation and heat distribution was defined by the Aerothermal Database described in section 5. Some results for front shield temperature are shown in Fig 10.
The addition of 2 mm of syntactic foam to the inside of the heat shield was beneficial in delaying the temperature rise on the back face.

Further evolution of the heatshield design and internal insulation will take place in the next phase.

7. VEHICLE DESIGN

7.1. Mechanical Design

A preliminary design of the piggy-back vehicle has been created so that the vehicle will be aligned with the flow, able to accommodate the significant peak (kinetic) heat flux along with the total heat load and withstand aerodynamic forces as well as accommodating the test parachute and instrumentation.

The principal design parameters of the entry capsule are given below in Table 3 and shown in Figure 7.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Diameter (D)</td>
<td>290.0 mm</td>
</tr>
<tr>
<td>Nose Radius</td>
<td>72.5 mm (0.250xD)</td>
</tr>
<tr>
<td>Aeroshell cone half-angle</td>
<td>60°</td>
</tr>
<tr>
<td>Mass exc. Margin</td>
<td>12.363 kg</td>
</tr>
<tr>
<td>Mass inc. Margin</td>
<td>14.702 kg</td>
</tr>
<tr>
<td>Shoulder Radius</td>
<td>7.25 mm (0.025 D)</td>
</tr>
<tr>
<td>Body Length</td>
<td>177.00 mm</td>
</tr>
<tr>
<td>Centre of mass from nose</td>
<td>63.80 mm</td>
</tr>
</tbody>
</table>

Table 3: The principal design parameters for the capsule

The forward aeroshell is manufactured from stainless steel. The parachute bridle attachments are fastened directly to the aeroshell.

There is a cylindrical volume of $1.085 \times 10^{-4} \text{ m}^3$ in the centre of the forward aeroshell to accommodate a heavy-metal ballast mass. The ballast mass is assumed to be Tungsten ($\rho = 19,273 \text{ kg/m}^3$) in order to ensure a forward Centre of Mass (CoM) position.

The Data Acquisition System (DAS) is mounted above the ballast and fixed to the aeroshell. The position was selected in order to place the accelerometers as close to the CoM as possible; to reduce errors from capsule rotation. The capsule contains 12 x AA batteries. The batteries are mounted adjacent to the DAS.

An instrument support structure is then mounted above the DAS and fixed directly to the aeroshell. The structure supports a high-speed camera, low speed camera, the parachute canister and two pyrotechnic actuators as well as providing part of the load path from the MAXUS launch vehicle separation mechanism. The high-speed camera is positioned directly below the parachute on the axis of the riser with the camera lens protruding through the base of the parachute canister. The low-speed camera runs from vehicle separation.

The test parachute is housed in a cuboid fibreglass canister. The parachute canister has sufficient volume to contain a parachute of up to 0.5 kg at a packing density of 300 kg/m$^3$.

A radio antenna is packed with the test parachute. The antenna will be a flexible "bazooka"-dipole attached to the parachute riser. It is deployed and able to transmit data effectively once the parachute has been deployed.

As an option, there may be an array of approximately 10 temperature sensors mounted directly on the aeroshell. The data they gather will be used to derive entry heat flux.

The capsule break-out patch (BoP) in the back cover of the vehicle is fixed in place using Nylon screws. It is ejected by the two pyrotechnic actuators.

Eight aluminium pillars are mounted on the forward aeroshell to connect the back plate to the forward aeroshell. These pillars transmit the loads induced by
the launch vehicle via the back plate to the forward aeroshell. The cylindrical casing that forms the side walls of the capsule sits in a groove machined on the forward aeroshell and the back plate and is clamped when the back plate is fixed to the aluminium pillars. The casing will either be made from carbon fibre or from Duroid.

The aluminium back plate is fixed to the aluminium pillars and conforms to the requirement of a flat top surface of the capsule. An additional requirement for the MAXUS launch vehicle is the provision of mounting holes for the MAXUS attachment anchors.

Aft-surface aerodynamic heating requires that the top surface instrumentation be protected. The low-speed camera lens is protected by a heat-resistance plate of Pyrex glass. The GPS antenna and separation detection micro-switch are protected by heat-shrunk polymer.

Figure 13 shows the fully assembled capsule with back plate top surface components.

Figure 13: The external configuration of the capsule

The reference point for the position of CoM and associated moment is the intersection of the capsule axis of symmetry and the outer surface of the front aeroshell. The CoM position is at 63.80 mm from the nose, which is 22% of the capsule diameter. The total mass including margin is calculated to be 14.7 kg, which leaves 0.3 kg for optimising the mass distribution and spin stabilisation.

7.2. Avionics Design

The recorded data will include high- and low-speed video, GPS position and velocity, 3-axis accelerations, 3-axis rates and vehicle body temperatures from up to 10 thermocouples positioned at selected points within the vehicle’s nose and adjacent surfaces. The recorded data will enable deployment and flight analysis of the parachute from the supersonic regime through transonic to subsonic. The measurement of capsule heating will provide in-situ re-entry aerothermal data. Finally, the accelerometer and rate gyros will provide flight stability data that can be used to correlate CFD modelling.

The schematic for the avionics is shown in Figure 11 and the prototype system in Figure 12. It measures only 65 mm across octagon flats.

7.3. Test Parachute Design

The parachute that will be tested on this mission will be a 1.25 m nominal diameter Huygens heritage Disk-Gap-Band. It was selected since the background knowledge of this type of parachute is relatively extensive allowing a good assessment of the quality of the data derived from the piggy-back test methodology. The configuration is illustrated below.
8. CONCLUSIONS

The preliminary design of a parachute test vehicle to be flown as a piggy-back on MAXUS has been achieved. The study found no show-stoppers.

The vehicle concepts could be enhanced to provide a test bed for:

- Inflatable aerodynamic decelerators
- Deployable aerodynamic decelerators
- TPS systems
- Provide aerothermal data
- Capsule flight stability

9. REFERENCES