SHARK-MAXUS/8 EXPERIMENT: A TECHNOLOGY DEMONSTRATOR OF RE-ENTRY DROP CAPSULE

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ABSTRACT

SHARK is a 20kg capsule launched on March the 26th 2010 from Kiruna with the European sounding rocker Maxus-8. During the ascent parabola, the capsule was released and successfully executed its 15 minutes ballistic flight and then re-entered in the atmosphere from a 700km altitude.

The capsule has been recovered on July the 1st and all data have been acquired. All the instrumentation worked nicely and the data acquisition continued even after the landing, confirming the robustness of the design.

1. INTRODUCTION

In the frame of USV program, CIRA is developing different projects aimed to develop new technologies for the future hypersonic vehicles. One of these technological projects is Sharp Hot Structures (SHS) and it is aimed to the realization of innovative thermo-structures, based on innovative material solution, able to sustain the heat loads generated during the hypersonic flight.

Because the slender configuration of the USV program vehicles, SHS is focused on sharp geometries, like sharp leading edges and sharp nose cones.

CIRA, for many years, is investigating the effectiveness of ultra high temperature ceramic materials (UHTC) by means of numerical simulations, ground testing in plasma torch and in SCIROCCO, the 70MW plasma wind tunnel (PWT) facility at CIRA.

More recently CIRA is moving the experimentation in real flight environment, boarding UHTC components on the re-entering space capsules EXPERT and SHARK. The former is a European experimental test bed boarding a couple of UHTC fins, already qualified and integrated on the vehicle.

SHARK (Sounding Hypersonic Atmospheric Re-entering 'Kapsule') is a small capsule designed and realized by CIRA. On March the 26th 2010, the European Space Agency sounding rocket MAXUS 8 was launched. During the ascent parabola, the capsule was released and successfully executed its 15 minutes ballistic flight and then re-entered in the atmosphere and landed.

The aim of the project was to prove the possibility to set up a low cost experimental space platform and execute a re-entry test flight by dropping a capsule from a sounding rocket.

Since CIRA is investigating new technologies for the re-entry and in particular new ceramic materials for sharp thermal protection systems (TPS), this flight opportunity has been chosen to test in a real flight an UHTC (Ultra High Temperature Ceramic) component, machined from scraps of previous ground tests executed in the Plasma Wind Tunnel SCIROCCO

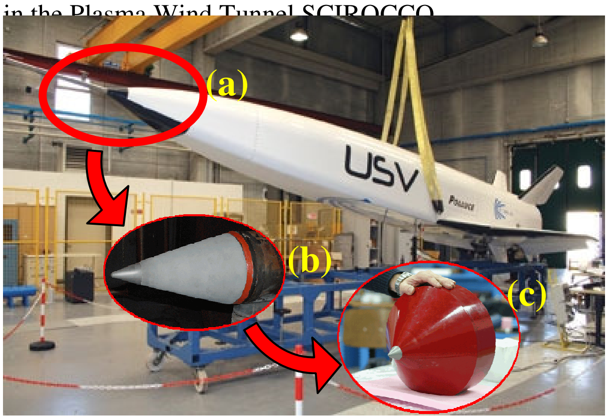

Figure 1 SHARK (c) is derived from USV supersonic vehicle (a) and real scale SCIROCCO test articles (b).

One of the most remarkable aspects of this project is the schedule. The first informal contacts occurred between CIRA and ESA at the end of July 2009. The first official commitment from ESA was transmitted in September of the same year, on the basis of a feasibility study performed by CIRA. Then the detailed design was accomplished and the procurement of all parts was activated. The final integration and functional tests were performed in three days from February 4 to 6 (including a Saturday and a local holiday). The following Wednesday, February the 10th 2010, the capsule was already in the SSC headquarter in Stockholm for the MIP. The capsule was there accepted and handed over in less then 4 months since the first official commitment.

2. SHARK MISSION OVERVIEW

The rocket has been launched at 13:43 UT from the Swedish space base ESRANGE (Kiruna). SHARK separation occurred 90s after the ignition, at a 192km altitude, when the vehicle was flying at 3km/s with an 88° flight path angle. At that time the capsule electrical systems was activated and the onboard computer started to acquire data. Acquisition continued smoothly during the ballistic flight up to 700km altitude (apogee), during the downward trip, the atmospheric re-entry and landing.

To be cheep, SHARK was not equipped with a parachute and telemetry; the survival of the data in the memory unit has been successfully achieved with a very strong design of the hull that has protected the internal systems during all the phases.

The radio beacon signal was not received by the satellite network the day of the launch, then the recovery the same day was not possible.

The capsule was then recovered in July the 1st when the localization was allowed by the melting of the snow. The metallic structure was found in very good condition, the paint on the frontal shield was totally removed by the aerodynamic heating, while it was intact on the back, proving that the re-entry attitude was nominal.

Figure 2 SHARK after the flight

The interior of the capsule was in relatively good conditions too, despite the ground impact the memory unit was in perfect condition and the downloaded data shows that the computer continued to acquire even after the landing, recording data on the cooling of the capsule in the snow.

Preliminary data analyses show that the UHTC tip has suffered damages during the re-entry, caused by the very high thermal stress. The rupture was probably triggered by small defect introduced during the machining of the component or during the last ground tests. The mechanical interface was designed to crush inside the capsule, allowing to part of the ceramic to survive the impact, offering the possibility to perform post flight analyses on the flown UHTC.

During the re-entry, the UHTC was exposed to about 9MW/m^2 heat flux and the whole capsule sustained more than 40g deceleration (data analyses are still running).

Data recorded during the flight and numerical trajectory prediction confirm that the velocity of the capsule at the impact, was about 83m/s (about 300km/h). Because the very strong structure of the capsule and because the dumping of the snow, ice and soil, the main system of the capsule survived the impact, despite this high impact velocity,

3. UHTC

The Italian scientific and industrial community owns the know-how needed for the fabrication of very high quality ceramic materials, and UHTC in particular. Italian UHTCs are characterized by very good thermal and mechanical properties. CIRA then is investigating the possible utilization of these exceptional materials for space and hypersonic vehicles. With the objective to fill the gap between the laboratory scale specimens and the real world application, CIRA is executing many tests in different conditions and with different UHTC systems and geometries, tracking the boundaries of the possible application fields.

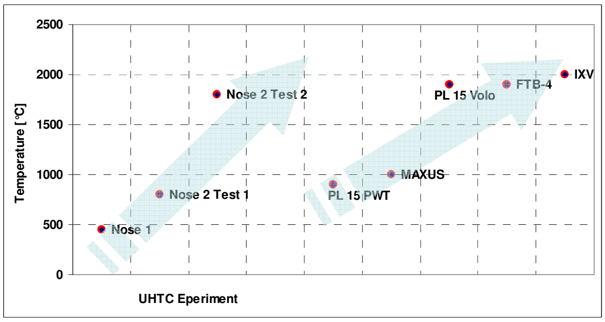

Figure 3 SHARK in the map of the CIRA UHTC activities.

The experimentation is conducted mostly on the ground, with the 70MW plasma wind tunnel SCIROCCO, but with SHARK, EXPERT, IXV and SCRAMSPACE, CIRA is moving the experimentation from the ground to the real flight environment

The image beside shows the map of the test already executed and planned on structures based on UHTC.

Nose 1 and Nose 2 are test article tested in PWT. The Nose_2 sustained also another test, designed to be the last test performed on this specimen, aimed to find the real limit of the structure. The experiment lasted 29 seconds at the highest heath flux available in the facility.

PL_15 PWT refers to the test on the EXPERT payload, aimed to evaluate the behaviour of the flight model. PL 15 'volo' refers to the real flight condition of the capsule EXPERT that shall be flown in the late 2011. FTB 4 IXV and SCARMSPAVE (not yet shown in the plot) are flight experiment still under consolidation.

4. CAPSULE DESIGN

SHARK has been conceived in the fall 2009 after some informal iteration. The first official commitment from ESA was signed in September the 30th. In order to meet the Mandatory Inspection milestone, hold in February the 10th in SSC, CIRA operated at full speed for the definition of the design, manufacturing of the structural parts, procurement of sensors, onboard data system, localization beacon, components of the power system and all the many parts that compose the 20kg of SHARK.

The design was aimed to be simple, reliable and based on COTS components with short procurement time. The mass availability, limited by the separation systems chosen, was used to build a very strong stainless steel frontal shield able to bear thermal and mechanical loads, and an aluminium rear part, that keeps the barycentre of the capsule as aft as possible, with benefits for the stability of the atmospheric part of the flight.

The data handling system was based on a flight proven, ACRA KAM 500 modular computer, able to acquire and store, on a ruggedized memory unit, all the data measured by transducers, acquired up to 8 KHz frequency

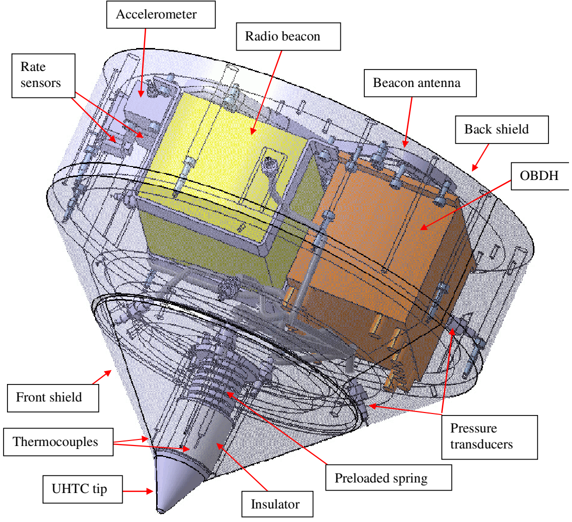

Figure 4 SHARK 3D model

The data acquisition and recording capabilities of the OBDH have been intensively used. The chosen configuration was able to acquire 15 thermocouples and 16 analogical channels. All the TC channels have been connected to K-type thermocouples, three installed inside the UHTC tip, some in the fore region, close to the external surface, aiming to measure the effect of the aero-thermal heating, and some in the inside of the vehicle, in order to evaluate the effects of the heating on the internal systems. Ten of the 26 analogical channels have been used for the 0-100mV output of the Kulite pressure transducers. The remaining six channels have been used for the -5V / +5V output of the tri-axial accelerometer and for the three rate sensors. Because the voltage output mismatch, a dedicate voltage regulator has been designed and realized.

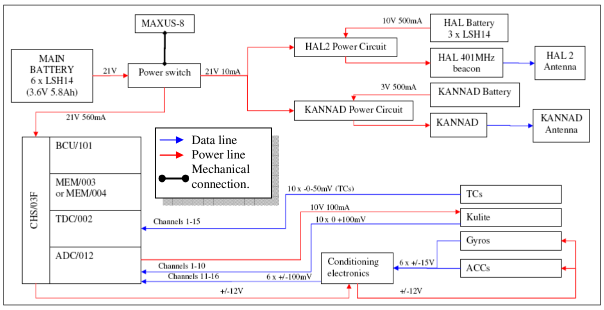

Figure 5 SHARK functional diagram

The localization of the capsule was based on a satellite emergency locator system, operating on the 406MHz, and a homing signal acquired by the recovery team at 120MHz

The power system was composed by an array of lithium primary batteries connected to the systems by a reliable safety switch, mechanically activated by the separation of the capsule from the launch vehicle. The OBDH has its own power regulation systems, so the batteries were directly connected to it. The 10V power supply, for the pressure transducers, was provided by the acquisition module. The dual power supply, for the accelerometers and rate sensors, was derived from the OBDH power supply circuit, with a dedicated board. The activation of the main switch also powered a trigger circuit that connected the radio beacon own batteries to the transmitting unit. Since the radio beacon was required to operate even after the crash landing, a very high reliability was required then the trigger circuit was designed to be independent from the main battery pack, and was able to keep the beacon transmitting, using its own batteries, even if the main battery pack was damaged at impact.

Since the activation of the capsule, at the separation from the payload stage, all the sensors have operated correctly and the data have been recorded in the main memory unit. Only one of the rate sensors was offline, but it was non operative since the delivery (it is likely that it was damaged during the transportation). The following table resumes all the data acquired during the flight:

Description	**Sensor**	**Range**	**Quant.**	**Freq. [HZ]**
Front shield temperature	K-type TC	-100 +1100°C	9	64
UHTC Temperature	K-type TC	-100 +1100°C	3	64
Back shield Temperature	K-type TC	-100 +1100°C	3	64
Computer Temperature	RTD (CJ)	-55 +125°C	1	64
Front shield pressures	Kulite	0-25 PSIa	7	512
Back shield pressures	Kulite	0-2 PSIa	3	512
Accelerations (triaxial)	SD 2430	±100 g	1	8192
Angular rates	SDG 500	±100°/s	3	512

Table 1 Sensor list, quantity and sampling frequency.

5. MEASURED TEMPERATURES

In this section are shown the temperatures measured by the 15 thermocouples.

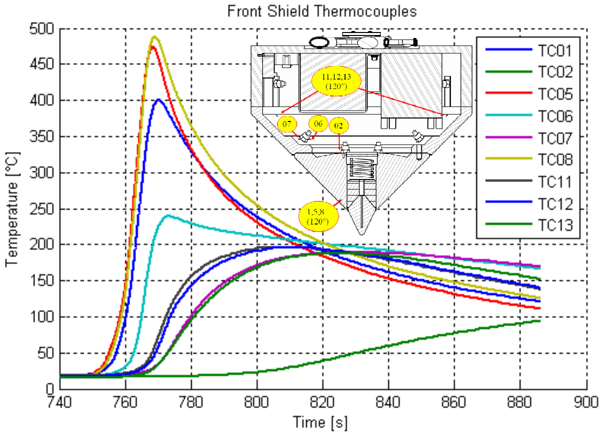

Figure 6 Front shield temperatures

All the temperatures stay almost constant for the extra atmospheric part of the flight. At re-entry interface, the temperatures rise quickly.

The TC closer to the nose (TC1, TC5 and TC8) experience higher temperatures.

The thermocouples on the back shield experience much lower temperatures. Heat is transmitted mostly by conduction through the structure of the capsule.

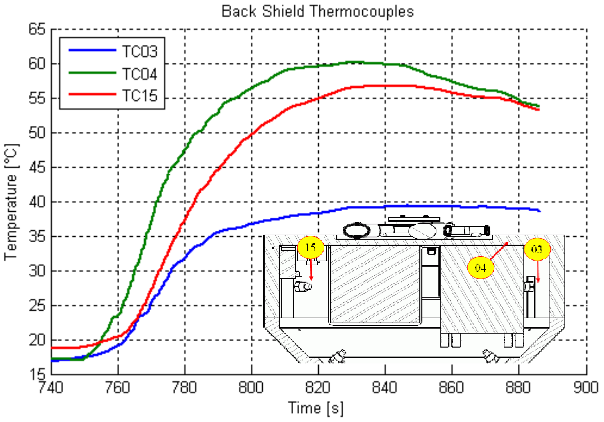

Figure 7 Back shield temperatures

The UHTC experience a very quick heating (up to 9 MW/m2). The thermo-couples are inserted and glued in a hole drilled in the UHTC Tip.

The data are lost when the tip breaks and the thermocouples get exposed to the external environment. The heating rate has to be compared with the numeric simulations. The measure permit to find the real heat flux impinging on the tip.

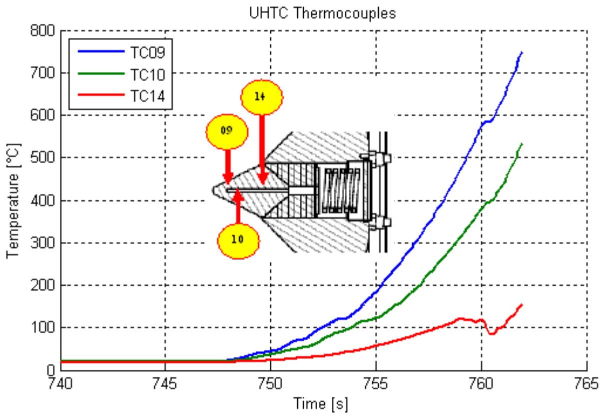

Figure 8 UHTC tip temperatures

6. PRESSURES

The pressure is zero during the extra-atmospheric part of the flight. This will permit to better correct the offset error of the transducers.

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During the atmospheric part of the flight the pressures show an oscillating behavior, indicating the oscillations of the capsule around its equilibrium attitude. Comparison the phases of the oscillations of the transducers placed in different radial positions, can give indications on the attitude.

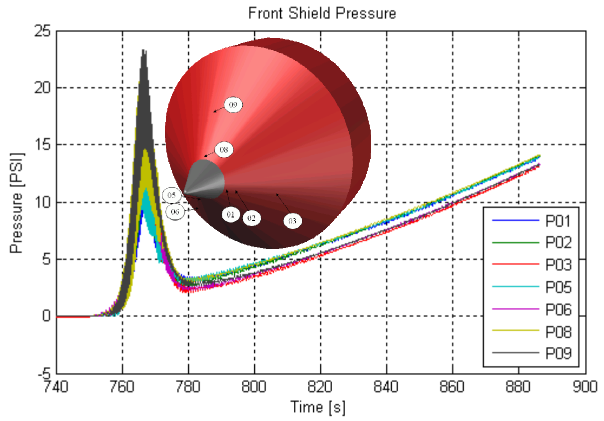

Figure 9 Front shield pressures

Transducers on the sides of the cylindrical part measure lower pressure. At 780s is the time when the deceleration stops and the capsule proceeds at constant speed.

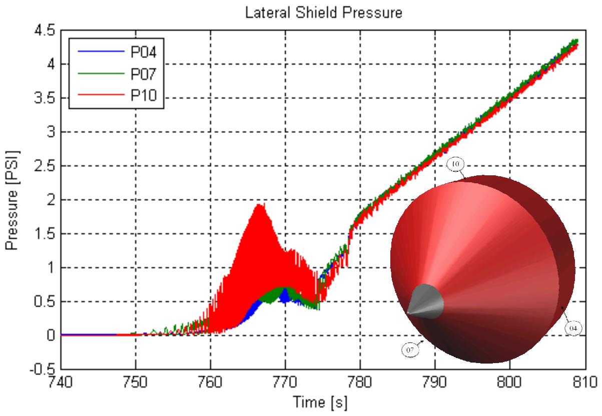

Figure 10 Back shield pressures

It is very interesting to note that these sensors between 775s and 780s sense the supersonic/subsonic transition.

7. ACCELERATIONS AND RATES.

Accelerations are negligible in the extra atmospheric phase.

This shall permit to better remove the offset errors. Such errors are introduced also by the resistances used to lower the voltage from ±5V to ±100mV. In Z direction 40g are exceeded.

The accelerations show the same oscillations of the pressures. In the steady velocity part of flight the Z acceleration is 1g higher than in the extra-atmospheric phase.

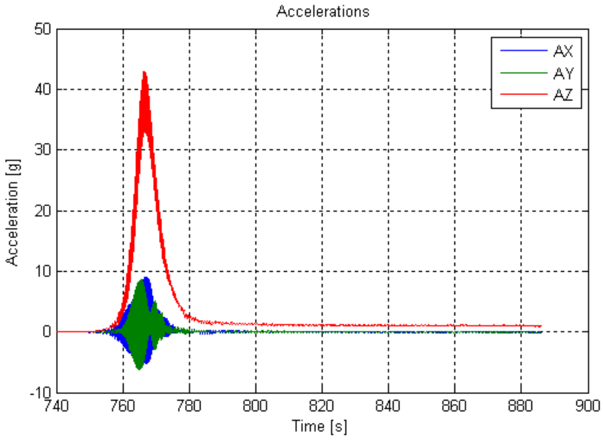

Figure 11 Accelerations

It is interesting to note that the acceleration along Z (the direction of flight) after the rough re-entry phase, get stabilized on a constant value equal to one g.

The two survivor rate sensors give indication of the motion of the capsule around the barycentre, after the separation and before the interface with the atmosphere.

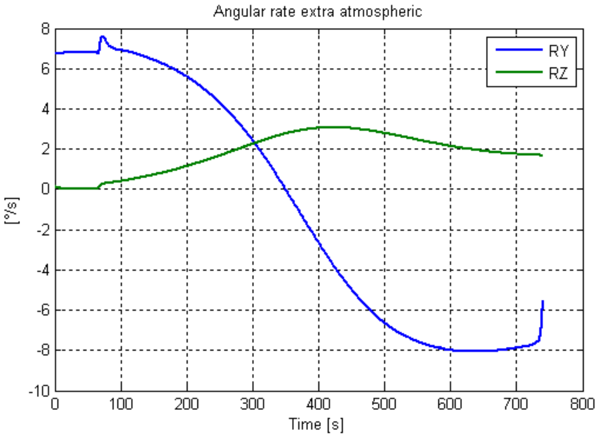

Figure 12 Angular rates outside atmosphere

The rate sensors range has been chosen to be effective in the extra-atmospheric part of the flight. The stronger oscillations in the first part of the atmospheric flight caused saturation of the rate signals.

In order to have better results, the signal has been reconstructed before proceeding with filtering.

An attempt has been made to rebuild the missing data by interpolating the available data with a spline function.

The acquired points affected by the saturation error have been removed from the original signal.

The missing points have been interpolated using the error free points.

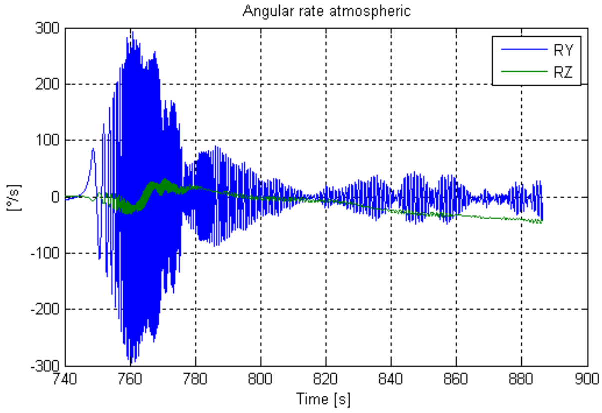

Figure 13 Angular rates in the atmosphere

The goodness of the reconstruction has been evaluated applying the same algorithm to a part of signal where there is no saturation, but an artificial saturation has been simulated. The result is in the following image.

8. CORRELATCIONS WITH THE PREDICTED TRAJECTORY

Trajectory numerical simulations have been provided by ASTOS Solutions GmbH, using their own software tools. The simulations have been proved to be very accurate, finding the capsule at about one kilometer from the expected landing point (after a flight longer than 1400km).

The ASTOS computations have proven again a very good fitting to the reality, when they have been compared with the acquired data.

The diagram below compares the calculated deceleration of the capsule after the interface, with the values acquired by the onboard instruments.

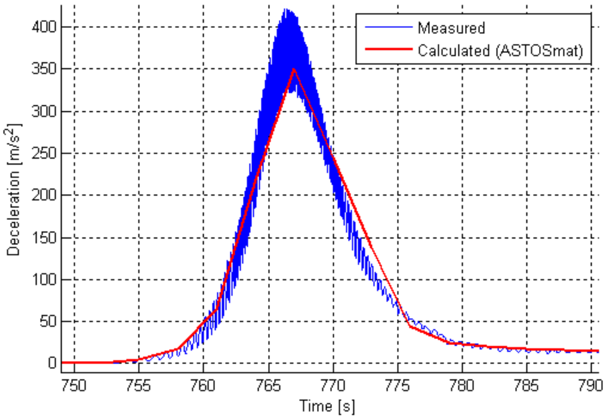

Figure 14 Comparison between measured and calculated accelerations

The time synchronization has been easily executed matching the impact instant calculated by ASTOS with the instant when the data recording was interrupted and recovered because the impact solicitations on the data acquisition system. The fitting is remarkable.

The following diagram shows, on the same chart, the Mach number as predicted by ASTOS and the pressure on the back shield. It is possible to asses that the pressure step occurs when the Mach number is equal to one, as previously stated at the end of chapter 6.

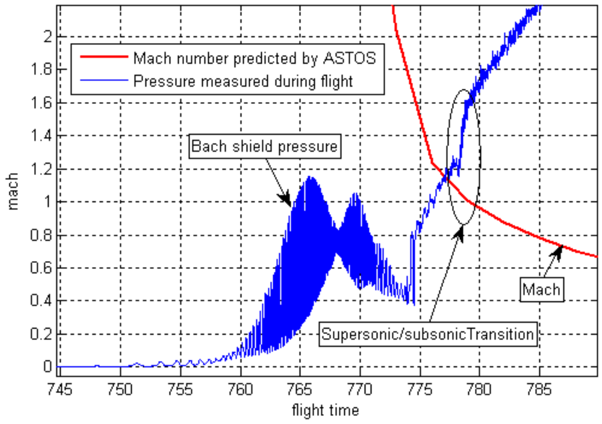

Figure 15 Effect of subsonic transition.

Once the accuracy of the numerical prediction has been assessed by comparison with the measured flight data, is possible to state that the following computed trajectory is the actual trajectory flown by SHARK.

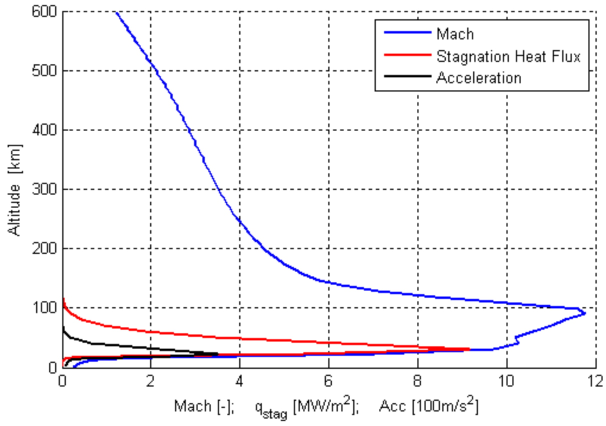

Figure 16 Re-entry trajectory.

The graph shows that the capsule entered in the atmosphere just below Mach 12 at 100km altitude. The peak heating occurred at about 30km at mach then, and the peak deceleration slightly later, at lower altitude and lower velocity.

9. PRESSURE, ALTITUDE, VELOCITY, DRAG

In the final phases of the flight, when the regime is well subsonic and the compressibility effects are fading out, the pressure sensors can be used to derive the altitude of the capsule.

A model of the atmosphere, corrected with the local barometric pressure in the flight day, has been used.

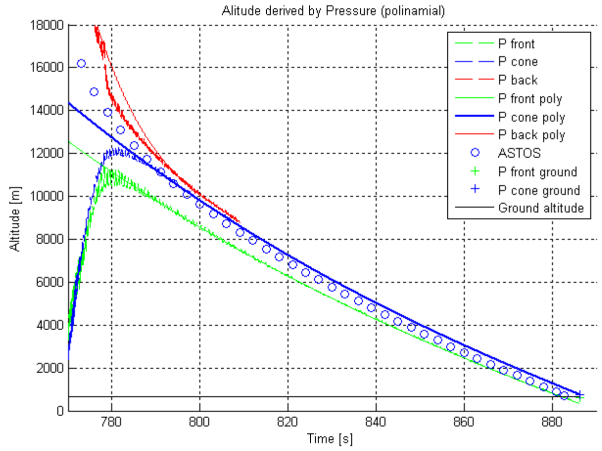

Figure 17 Measured and calculated altitude

The diagram shows that the pressures measured close the stagnation are affected by an overpressure, not sensed by the pressure ports on the cone and on the cylinder part of capsule. The latter measure a pressure closer to the static pressure, at the given altitude. This is also confirmed by the pressure measured on the ground, in static conditions.

By means of a model of the atmosphere corrected with actual pressure at the launch day, pressures are converted into altitudes and compared with the ground altitude at the impact point, and with the trajectory predictions performed by ASTOS.

The accordance between the altitude calculated by the pressure ports on the cone and the ASTOS previsions are very good.

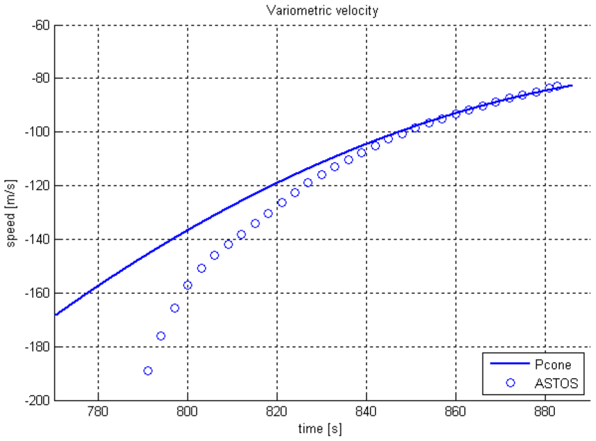

Figure 18 Measured and calculated vertical velocity

The polynomial interpolation of the measured altitude has been derived in order have a measure of the vertical velocity in the final phase of the flight.

Since the capsule flight path angle is very close to the vertical, it is possible to asses that the capsule impacted on the ground between 82 and 83 m/s.

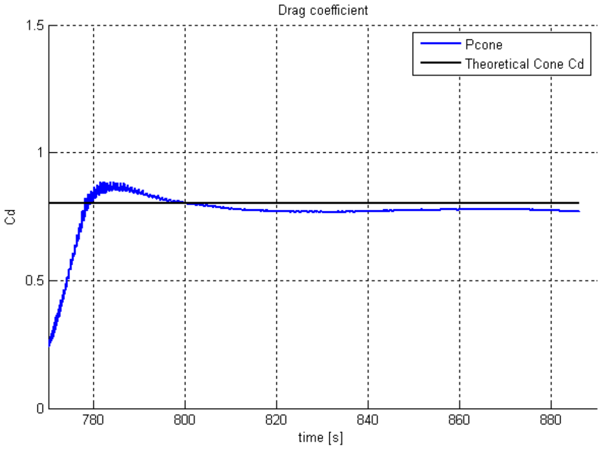

Figure 19 Drag coefficient derived from measures and theoretical value.

Once is known the deceleration of the capsule, and its mass, is known the force acting on it. Accounting the gravitational contribution (variable with altitude) the aerodynamic part can be deduced. Using the measured velocity, the drag coefficient can be evaluated.

Even in this case the accordance with the theoretical is very good.

The theoretical value has been deduced interpolating the curve reported in [3] page 3-18 Figure34.

10. CONCLUSIONS

SHARK is the first self-contained (black box) small space capsule flown in Europe. It was fully designed, realized and qualified at CIRA.

The mission was performed in nominal way. The presence of SHARK has not degraded the main mission of the rocket and has not affected the main payload experiments.

The design and all the subsystems have proven to be able to survive the launch solicitation.

All the internal systems have operated in nominal way during the flight.

The robust design allowed almost all the subsystems to survive also at the impact. The computer acquired data during the flight and for 5 hours after the landing, until the memory unit was full.

Up to 4GB of data are available for scientific investigation.

All the acquired data have a very good quality and permit to identify all the most important events of the flight.

The UHTC component was exposed to the hypersonic environment and sustained a very quick and intense heating, until a crack, probably generated by a defect introduced by the machining of the thermocouples hole, has broken the tip of the ceramic cone.

The data are actually under further investigation and comparison with numerical simulations.

11. ACKNOWLEDGMENTS

The authors would like to acknowledge Antoine Bavandi (formerly working at ESA) who was the originator of the flight opportunity and technical officer of the ESA contract, Nuno Filipe (formerly working at ESA) for his valuable support to the activity. Many people in ESA have believed in this challenging project, among them the authors would aknnowledge Simonetta Di Pippo, Antonio Verga, Guillermo Ortega, Fabio De Pascale, Giancarlo Bussu.

The work of many SSC people was absolutely remarkable, the authors would be happy to recall Gunnar Florin, Jimmy Thorstenson, Thomas Karlsson and all the people that worked very hard in ESRANGE.

Last but not least, the authors express deep appreciation for the work and the professionalism of the EADS Astrium people, leaded by Andreas Shutte.

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