SHARK – MAXUS 8 EXPERIMENT. A TECHNOLOGY DEMONSTRATOR FOR RE-ENTRY DROP CAPSULE

Roberto Gardi[(1)], Antonio del Vecchio[(1)], Gennaro Russo[(1)], Sven Weikert[(2)], Francesco Cremaschi[(2)], Guillermo Ortega[(3)], Antonio Rinalducci, Alvaro Martinez Barrio[(3)]

[(1)] *C.I.R.A. Italian Aerospace Research Centre, Via Maiorise snc, 81043 Capua (CE), Italy*
r.gardi@cira.it, a.delvecchio@cira.it, g.russo@cira.it

[(2)]*Astos Solutions GmbH, Grund 1, 78089 Unterkirnach, Germany.*
sven.weikert@astos.de, francesco.cremaschi@astos.de

[(3)] *European Space Agency, ESA-ESTEC. Keplerlaan 1, Noordwijk 2200 AG, The Netherlands.*
guillermo.ortega@esa.int, antonio.rinalducci@esa.int, alvaro.martinez.barrio@esa.int,

ABSTRACT

SHARK (Sounding Hypersonic Atmospheric Re-entering 'Kapsule') is a small capsule designed and realized at CIRA under ESA contract. The aim of the project is to prove the feasibility to set up a low cost experimental space platform and execute a reentry test flight by dropping a capsule from a sounding rocket. The main payload of SHARK is a UHTC (Ultra High Temperature Ceramic) component, machined from scraps of previous ground tests executed in the CIRA Plasma Wind Tunnel *SCIROCCO*.
SHARK was successfully launched on March the 26th 2010, by the European sounding rocket MAXUS 8. The separation occurred nominally during the ascent parabola and successfully executed its 15 minutes ballistic flight (achieving more than 700 *km* altitude) and then re-entered the atmosphere and landed. The capsule was recovered on the 1st of July 2010 and the data retrieved from the memory unit.
This paper will present a mission overview, with particular details on the safety and operational aspects.

1. SHARK CAPSULE DESIGN OVERVIEW

SHARK was conceived in the fall 2009 after some informal iteration with ESA. The first official commitment from ESA was signed on September the 30th, 2009. In order to meet the Mandatory Inspection milestone, hold on February 2010 at the Swedish Space Corporation (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 composing the 20 *kg* 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 8KHZ frequency

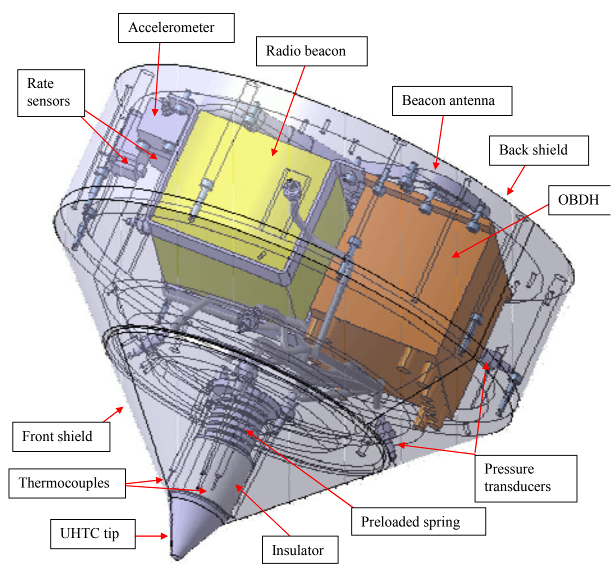

Figure 1 SHARK 3D model

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.

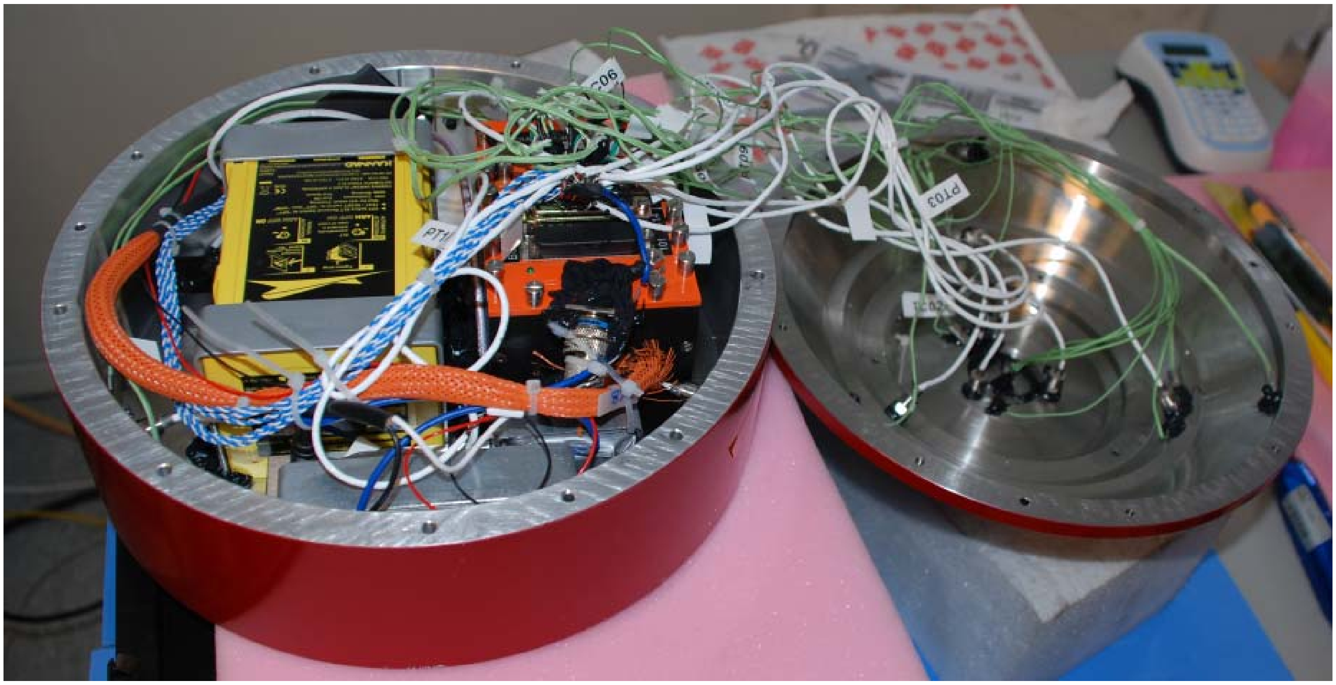

Figure 2 SHARK during the final integration

.

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 manufactured.
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 had 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.
SHARK was not equipped with a parachute and telemetry; the survival of the data in the memory unit was successfully achieved by means of a very strong design of the hull that protected the internal systems during all the phases.
After recovery, the metallic structure was found in very good conditions, 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 3 Fully integrated SHARK capsule.

2. PRE-FLIGHT SAFETY ANALYSIS

As any other flying component, safety aspects have been analyzed and safety requirements have been imposed by the launch authority.

The following points have been addressed:

- People safety during the pre-launch and launch operation.
- People safety during the flight and post flight phases.
- Safety for the main mission in the pre-flight and flight phases.

2.1 People safety during pre-launch and launch operation

Once integrated in CIRA the capsule has been handled by the SSC personnel and their safety has been accounted realizing the capsule with safe materials, no harmful shapes and providing detailed documentation and user manuals for handling and integration. All the documentation and the capsule itself have been inspected and accepted by ESA, SSC, and ASTRIUM.

At the hand over milestone a fit-check has been executed, simulating the vehicle-capsule mating and de-mating. The capsule has also been opened and the internal parts have been inspected in order to guarantee the compliance with the design.

The most critical pre-launch phase occurs when the booster stage is loaded with propellants and the pyrotechnic devices are installed. In this phase any unexpected electromagnetic emission could accidentally ignite a pyrotechnic and seriously jeopardize the safety of the personnel involved in the vehicle preparation.

During the pre-launch activities it is absolutely mandatory to have no electromagnetic emission from any boarded payload.

This stringent requirement has been met keeping all the electrical systems of the capsule powered off by means of a mechanical switch.

Figure 4 shows the functional diagram of the capsule subsystems. The main batteries are connected to a mechanical switch only, highlighted in green, and activated by the vehicle/capsule separation. Other subsystems batteries (radio beacons) were connected to the subsystem trough a power circuit designed to keep the power off until it is activated by the main batteries.

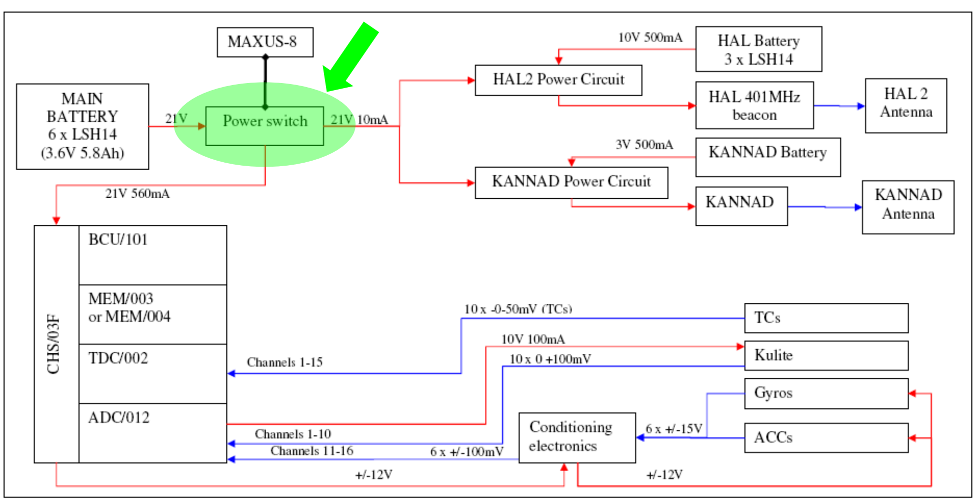

Figure 4 SHARK functional diagram.

For the activation of the capsule a Honeywell micro safety switch has been used.

Figure 5 Honeywell GKM safety switch and activation key.

The switch was mounted in the capsule, while the key has been bolted to the payload stage. The switch gets active when the capsule is separated from the vehicle and the key is removed from the switch body.

2.2 People safety during flight and post flight phases

In order to proceed with the mission, two independent assessments of the foot print of the capsule have been required, one analysis has been executed by ESA and one by CIRA. In the CIRA analysis the Coriolis effect and the separation speed have been accounted and the worst possible wind pattern has been supposed.
Because of the ballistic coefficient of the capsule, it was easy to prove that the capsule would have always fallen within the range limits. Figure 6 shows some ground dispersion for different wind conditions.

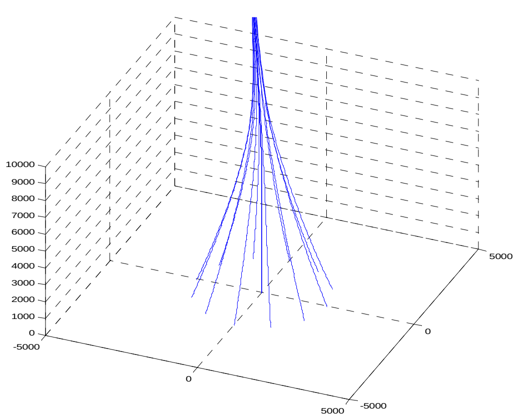

Figure 6 Ground dispersion due to wind calculated by CIRA

2.3 Safety for the main mission in pre-flight and flight phases

SHARK is a low cost experiment, boarded on the most expensive European sounding rocket. Assessed the safety for the humans, the main concern is the safety of the main mission, and then the safety for SHARK mission.
Neither electrical nor mechanical interference between SHARK and the main mission can be accepted, both before and after the separation from the launcher.
In order to prevent any electrical interference between the capsule and the main system, no connections have been realized. The capsule was fully autonomous, for what concerns power, data acquisition, data handling, and recovery.
In order to reduce the impact of SHARK on the vehicle also umbilical has not been used for connecting the capsule to any ground system, mostly because the capsule is located inside the interstage, and access is difficult. This implied however that neither health monitoring nor power supply were possible after integration on the launcher.
For what concerns mechanical interference, the major concerns consisted in either a possible failure of the release system or a structural failure of the capsule itself, when the system undergoes the loads generated by the thrust of the main engine. Such a failure would leave the capsule free to move inside the interstage, jeopardizing the whole mission.
In order to prevent this possibility, CIRA realized the capsule with wide structural margin of safety. More over, SSC and ASTRIUM have designed and realized a metallic structure, attached to the motor stage that, by means of a metallic ring, engaged the conical part of the capsule, preventing any motion even if the release system fails.
Finally, it was mandatory to have a correct separation of the capsule from the MAXUS payload stage. In case of off-nominal separation, the attitude of the payload stage could have been modified, with the possible consequence to affect the micro-gravity environment for the main payloads. Any off-nominal separation would also affect the payload stage attitude at re-entry, jeopardizing the recovery.
In order to increase the confidence in a correct separation the following actions have been taken:

- A very reliable, flight proven, separation system has been chosen and CIRA designed a capsule compatible with this mechanism.

- Much earlier than the delivery of the flight model, CIRA provided a model of the capsule representative of the mass, CoG and fully representative of all the mechanical interfaces with the vehicle.
- SSC executed integration and separation tests with the dummy model, using the real flight hardware.

The correct implementation of the exposed procedures during the design, the realization and the operations of the capsule, allowed a successful accomplishment of the SHARK experiment, with no impact on the main mission of the other primary payloads of the MAXUS-8 sounding rocket.

3. FLIGHT AND RECOVERY OPERATIONS

MAXUS-8 rocket carrying SHARK onboard was launched on March 26th, 2010, at 13:43 UT, from ESRANGE space base, near Kiruna, in the far north of Sweden.
SHARK separation occurred 90s after the ignition, at a 192 km altitude, when the vehicle was flying at approx. 3 km/s with a 88° flight path angle. At that time the capsule electrical systems were activated and the onboard computer started to acquire data. Acquisition continued smoothly during the ballistic flight over 700 km altitude, during the downward trip, the atmospheric re-entry, and landing.
Due to the deep snow in the landing area it was not probable that SHARK would be visible from the recovery helicopter, especially because it was not equipped with a parachute. Therefore signal of the emergency locator was foreseen to be triangulated in order to narrow down the potential impact area. Then, by means of the homing signal, the helicopter crew should have been able to find SHARK even under snow. Unfortunately no signal was received from SHARK.
For that incident a trajectory reconstruction was performed with the ASTOS optimization, simulation and analysis software, directly after MAXUS 8 telemetry data were made available. The trajectory of SHARK and the main payload was very similar during their flight outside the atmosphere. The initial separation impulse resulted in distances of just a few meters. Therefore it was possible to use the telemetry data of the main payload also for the SHARK capsule. From the telemetry data a trajectory was identified that fit the initial conditions after separation, the apogee location and the re-entry conditions at 130 km altitude. From this nominal re-entry point Monte Carlo simulations were performed to determine the impact foot print. The latest HIRLAM wind prediction was used for these simulations. Wind forecast and telemetry data were received from SSC/ESRANGE.
Fig. 7 shows the result of the Monte Carlo analysis as yellow crosses as well as the location were SHARK was finally found (red box). The blue box of trapezoidal shape was the defined search area based on the Monte Carlo analysis. The tip of this arrow-shaped box marks the re-entry prediction without wind. It is noticeable that the main driver for the impact uncertainty is the wind velocity, partly due to the large uncertainty (1σ=25%) assumed for the wind velocity.

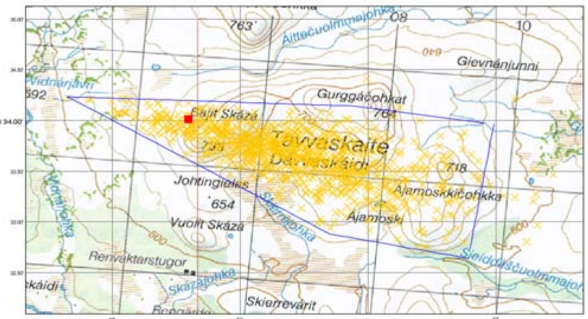

Figure 7 Monte-Carlo simulation results

Still with this information the helicopter crew was not able to find SHARK and it was decided to wait until the snow melted but also the second helicopter mission was not successful and was also not able to cover the whole impact prediction area (due to time constraints).
The missing part of that zone was some weeks later covered by a UAV campaign operated by a joint team of Astos Solutions GmbH and the Institute of Flight Mechanics and Control of the University of Stuttgart. During this proof-of-concept mission, high-resolution photos were taken from the remaining area. The UAV system comprised two 1.3k UAVs (one as backup) and a ground station. The ground station was used to monitor the flights and to define way points. The UAVs were following these way points autonomously, taken pictures every 1.5s. The used camera provided a resolution of 12.1 million pixels. Together with data from the IMU and GPS the time of each snapshot was recorded. This information was used later on to derive the covered area of the single images and to verify the total coverage of the impact zone. An elevation model was considered in this analysis to cope with the terrain. To avoid larger differences in altitude the way points were adjusted to follow the terrain altitude.
Since it was expected that the backside of SHARK was still painted red, color filters were applied to the images before they were inspected on site. This inspection was done manually by the UAV operators.

The UAV campaign covered the missing part of the impact zone (see fig. 7) but due to time and weather constraints it was not possible to cover again the parts already searched by the helicopter.
Finally, the capsule was found by a further helicopter flight that was not dedicated to SHARK in the area already searched by the first helicopter.

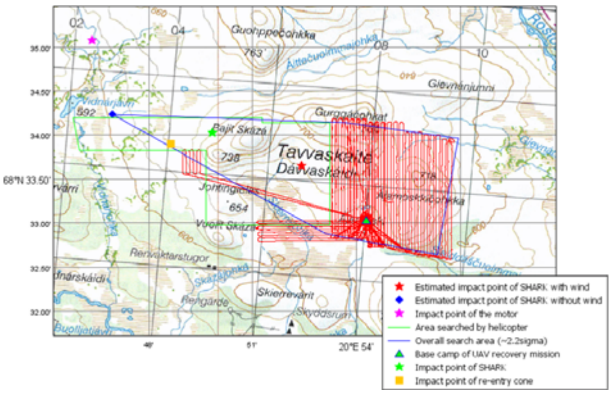

Figure 8 UAV flight paths and search area

4. POST-FLIGHT ANALYSIS

Once recovered, the capsule was disassembled and the data contained in the memory unit (still in perfect conditions) showed that all the sensors worked as expected not only during the flight, but also after the landing.

Figure 9 SHARK as found on July 1st 2010

Temperatures, pressure, accelerations, and angular rates were downloaded, converted in engineering units, filtered, and data were made available for aero-dynamic and aero-thermo rebuilding.
Preliminary analyses showed that the UHTC tip suffered damages during 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 9 *MW/m2* heat flux and the whole capsule sustained more than 40 g's deceleration.
The diagram below compares the calculated deceleration of the capsule after the interface, with the values acquired by the onboard instruments.

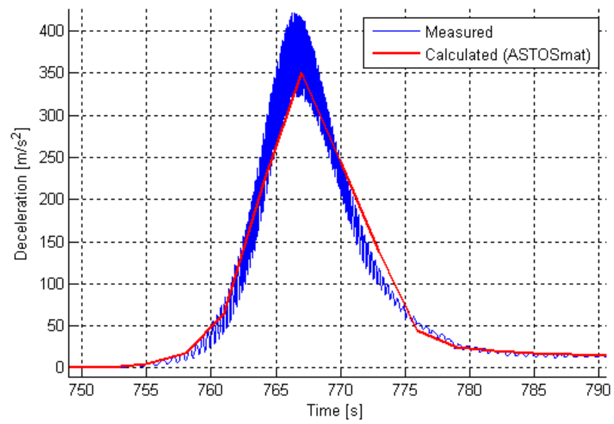

Figure 10 Comparison between measured and calculated accelerations

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 (fig. 11) shows, on the same chart, the Mach number as predicted by ASTOS and the pressure on the back shield of the capsule.
It is possible to assess that the pressure step due to the supersonic/subsonic transition (circled in the diagram) occurs when the predicted Mach number is equal to one.
This is another big proof of the consistency of the measured data with the predicted trajectory.

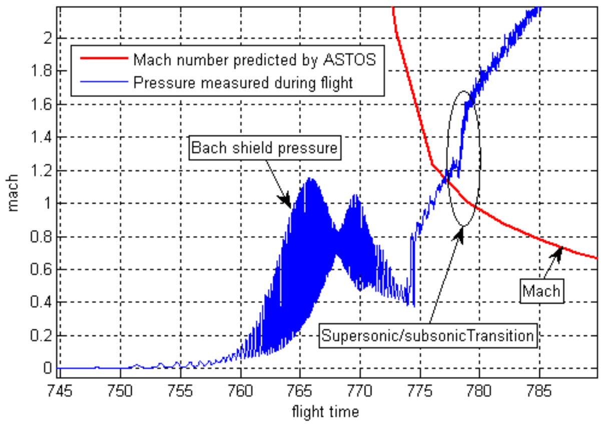

Figure 11 Effect of subsonic transition.

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.

The computed nominal impact point (at 68°33.871'N 20°50.298'W), is located only a few meters away from the real impact point.

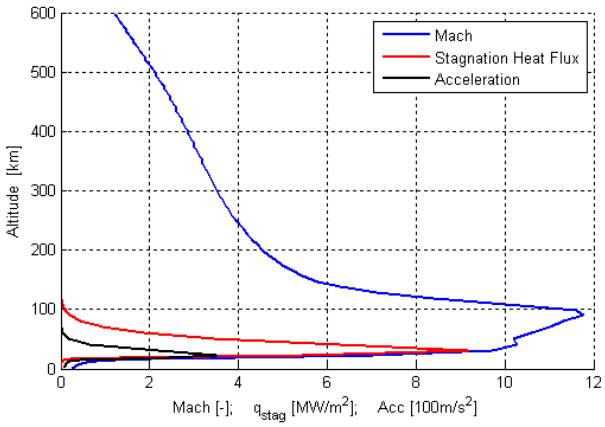

Figure 12 Re-entry trajectory.

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

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.

The diagram shows that the pressure values 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 measures 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.

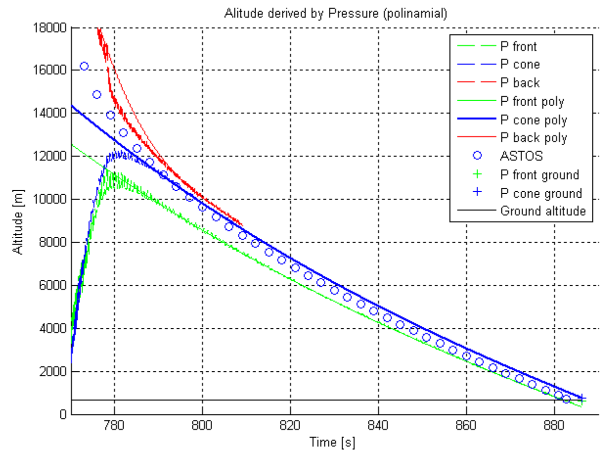

Figure 13 Measured and calculated altitude

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

The polynomial interpolation of the measured altitude has been derived in order to 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 at between 82 and 83 m/s.

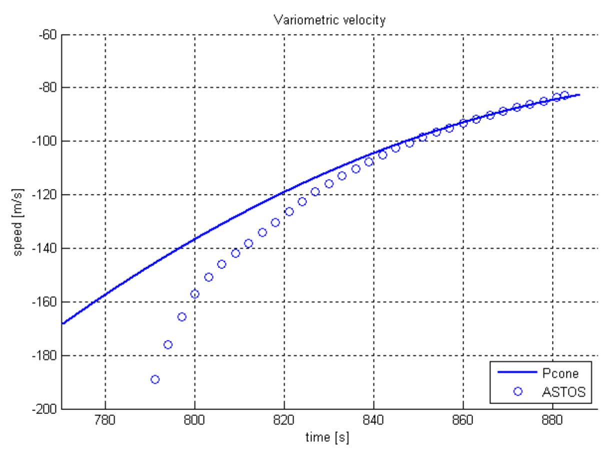

Figure 14 Measured and calculated vertical velocity

Once the deceleration of the capsule is known, the force acting on it can be calculated by means of its mass. 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 computations is very good.

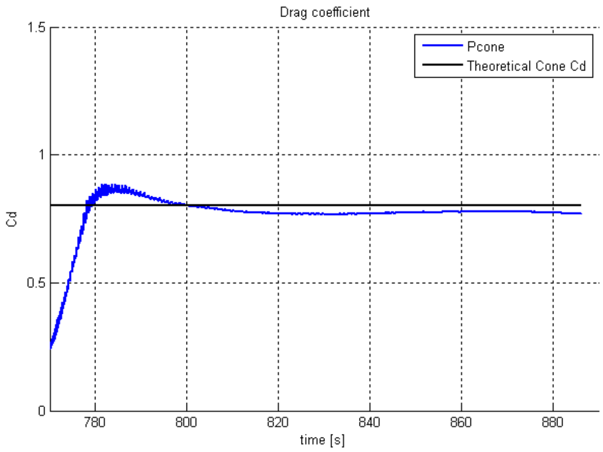

Figure 15 Drag coefficient derived from measures and theoretical value.

5. CONCLUSIONS

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

The mission was performed in nominal way. The presence of SHARK has not degraded the main mission of the rocket nor 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 were made available for scientific investigation. All the acquired data have a very good quality and allowed 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, broke the tip of the ceramic cone.

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

6. ACKNOWLEDGMENTS

The authors would like to acknowledge Antoine Bavandi (formerly working at ESA) who was the originator of the idea and technical officer of the ESA contract. The authors would also like to acknowledge Nuno Filipe (formerly working at ESA) for his valuable support to the activity.

7. ABBREVIATIONS AND ACRONYMS

ASTOS	Aerospace Trajectory Optimization Software
CIRA	Centro Italiano Ricerche Aerospaziali
COTS	Commercial Off-The-Shelf
ESA	European Space Agency
OBDH	On Board Data Handling
SHARK	Sounding Hypersonic Atmospheric Re-entering 'Kapsule'
SSC	Swedish Space Corporation
UAV	Unmanned Aerial Vehicle
UHTC	Ultra High Temperature Ceramic

8. REFERENCES

1. R. Gardi, A. Del Vecchio, G. Marino, G. Russo "SHARK: Flying a self-contained capsule with an UHTC-based experimental nose" 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. San Francisco CA 11-14 April 2011
2. R. Gardi; G. Pezzella; A. Del Vecchio; G. Marino; G. Russo. "Sounding Hypersonic Atmospheric Reentry Capsule Shark. Design Realization Flight And Data Interpretation." 3rd International ARA Days. 2-4 May 2011 Arcachon France.
3. R.Gardi; A. Del Vecchio; G.Russo, "SHARK-MAXUS/8 EXPERIMENT. A TECHNOLOGY DEMONSTRATOR OF RE-ENTRY DROP CAPSULE." 20th Symposium on European Rocket and Balloon Programmes and related research
4. A. Del Vecchio, R. Gardi, G. Russo. "SHARK: Flight Results of an UHTC-based Nose related to USV Hot Structures" 7th Aerothermodynamics Symposium Bruges, Belgium, 9 - 12 May 2011
5. R. Gardi, D. Alfano, A. Ferrigno, A. Del Vecchio, L. Scatteia. "Fractographic Analysis of a Flying Test Bed UHTC Nose Tip" International Astronautic Congress 2011.