esa publications

Innovative Technologies from Science Fiction for Space Applications

By D. Raitt, P. Gyger & A. Woods

The idea that perhaps science-fiction (SF) literature contained innovative technological ideas that could possibly be brought to the point of development with either today's technology or technology that is just around the corner was the driving force behind a recent European Space Agency (ESA) study entitled "Innovative Technologies from Science Fiction" (ITSF).

The main objectives of the study were to review the past and present science-fiction literature, artwork and films in order to identify and assess innovative technologies and concepts described therein which could possibly be developed further for space applications. In addition, it was hoped to garner imaginative ideas, potentially viable for long-term development by the European space sector, which could help in predicting the course of future space technologies and their impact.

ESA BR-176
Price: 10 Euros

Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk,
The Netherlands
Tel. (31) 71 565 3405 - Fax (31) 71 565 5433

ORDER FORM INSIDE BACK COVER

The Mission and Post-flight Analysis of the Atmospheric Re-entry Demonstrator (ARD)

A. Thirkettle, M. Steinkopf & E. Joseph-Gabriel
ESA Directorate of Manned Spaceflight and Microgravity,
ESTEC, Noordwijk, The Netherlands

The ARD was flown in October 1998. Its purpose was to achieve a controlled sub-orbital flight, from separation through atmospheric re-entry to splashdown. It carried an instrumentation and data-acquisition payload so that the actual flight parameters could be compared with those predicted mathematically. The post-flight analysis was therefore an integral part of the overall project.

Introduction

The Atmospheric Re-entry Demonstrator (ARD) was launched on 12 October 1998 on Ariane-503, the third Ariane-5 qualification flight. The ARD performed a sub-orbital flight with a maximum altitude of 830 km, and landed in the Pacific Ocean, with a splashdown point within 5 km of the predicted touchdown zone. The mission profile in Figure 1 shows the trajectory, the re-entry profile, the flight communication system, and the splashdown. The Demonstrator itself is shown in Figure 2.

During the mission, key data (including pressures, temperatures, vibrations, etc.) were recorded on more than 200 measurement channels distributed over the vehicle. These measurements were stored on two recorders and also transmitted to ground and airborne telemetry stations: the Libreville ground station for ARD status data after Ariane-5 separation, and the Aria-1 and Aria-2 aircraft-based stations for data prior to and after the blackout phase.

Project objectives

The main technical objectives with ARD were to:

- test and qualify re-entry technologies and flight-control algorithms under actual flight conditions
- achieve in-flight validation of design concepts, hardware and system capability to manage compromises between various technologies
- validate the aerothermodynamic predictions

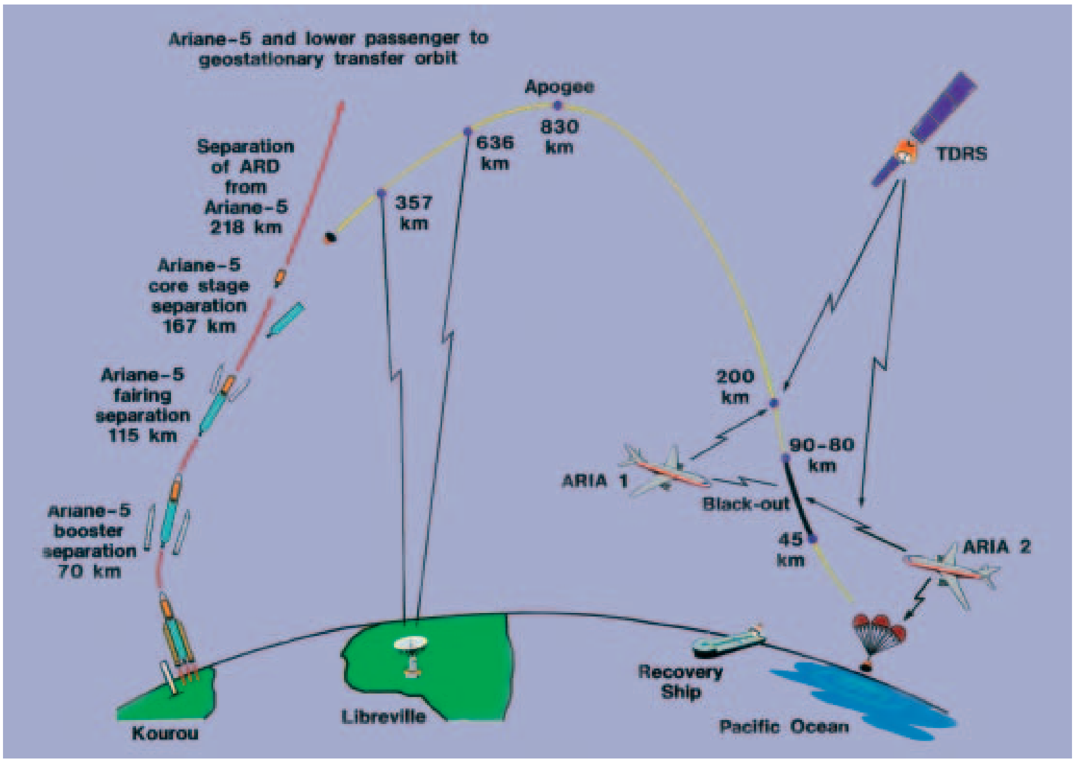


Figure 1. The Atmospheric Re-entry Demonstrator (ARD) mission profile

- qualify the design and the materials of the thermal-protection system
- assess the performance of the navigation, guidance and control system
- assess the performance of the parachute and recovery system
- study the radio communications during atmospheric re-entry
- demonstrate industrial capability within a tight schedule and with a limited budget.

The main management objectives were based on:
- a small ESA management team
- a high degree of autonomy assigned to the industrial consortium
- a direct review/acceptance approach
- an efficient development and cost schedule, as shown in Figure 3.

Project organisation

Development

Twenty-seven companies participated in the realisation of the ARD, under the lead of the then Aerospatiale, now EADS-LV:
- Belgium: ETCA (functional control bench), Sabca and Sonaca (structure), Trasys (software development)
- Denmark: Alcatel
- France: EADS-LV (Prime Contractor, TPS, GN&C, AIV, antennas), Astrium (functional electronics), Sextant Avionique, Intertechnique, ONERA
- Germany: Astrium (reaction control system)
- Italy: Alenia (descent and landing system)
- Spain: CRISA
- Sweden: Saab.

Post-flight analysis

The Agency set up a small team of experts in order to monitor the industrial activities. Under the Prime Contractorship of EADS LV (F), the following companies/institutions were involved in the post-flight analysis:
- Belgium: Von Karman Institute (CFD analyses)
- France: EADS-LV (Prime Contractor), ONERA (wind-tunnel tests), SEP (CMC sample analyses), Astrium (GPS analyses)
- Germany: MAN-T (CMC sample analyses), Astrium (FEI sample analyses), DLR (CFD analyses and wind-tunnel tests)
- Italy: Alenia Spazio (parachute analyses)
- Netherlands: Fokker (trajectory analyses)
- Switzerland: CFS (CFD analyses).

The post-flight-analysis methodology was articulated as follows (Fig. 4):

Level-0 activities: October 1998/Spring 1999
- Recovery and inspection
- Evaluation of data availability (real time, recorded)
- Initial comparison with predictions.

Phase-A evaluation: Spring 1999/Spring 2000
- Detailed data evaluation
- Correction of flight parameters and correlation with predictions.

Figure 2. The ARD vehicle

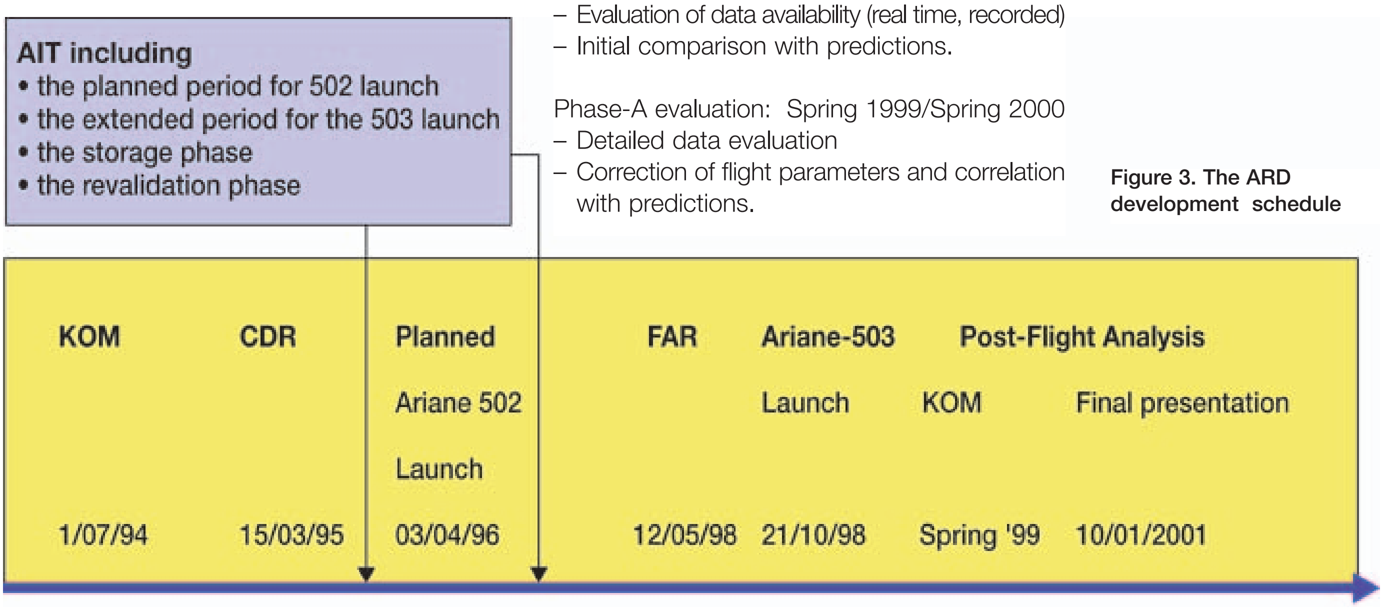


Figure 3. The ARD development schedule

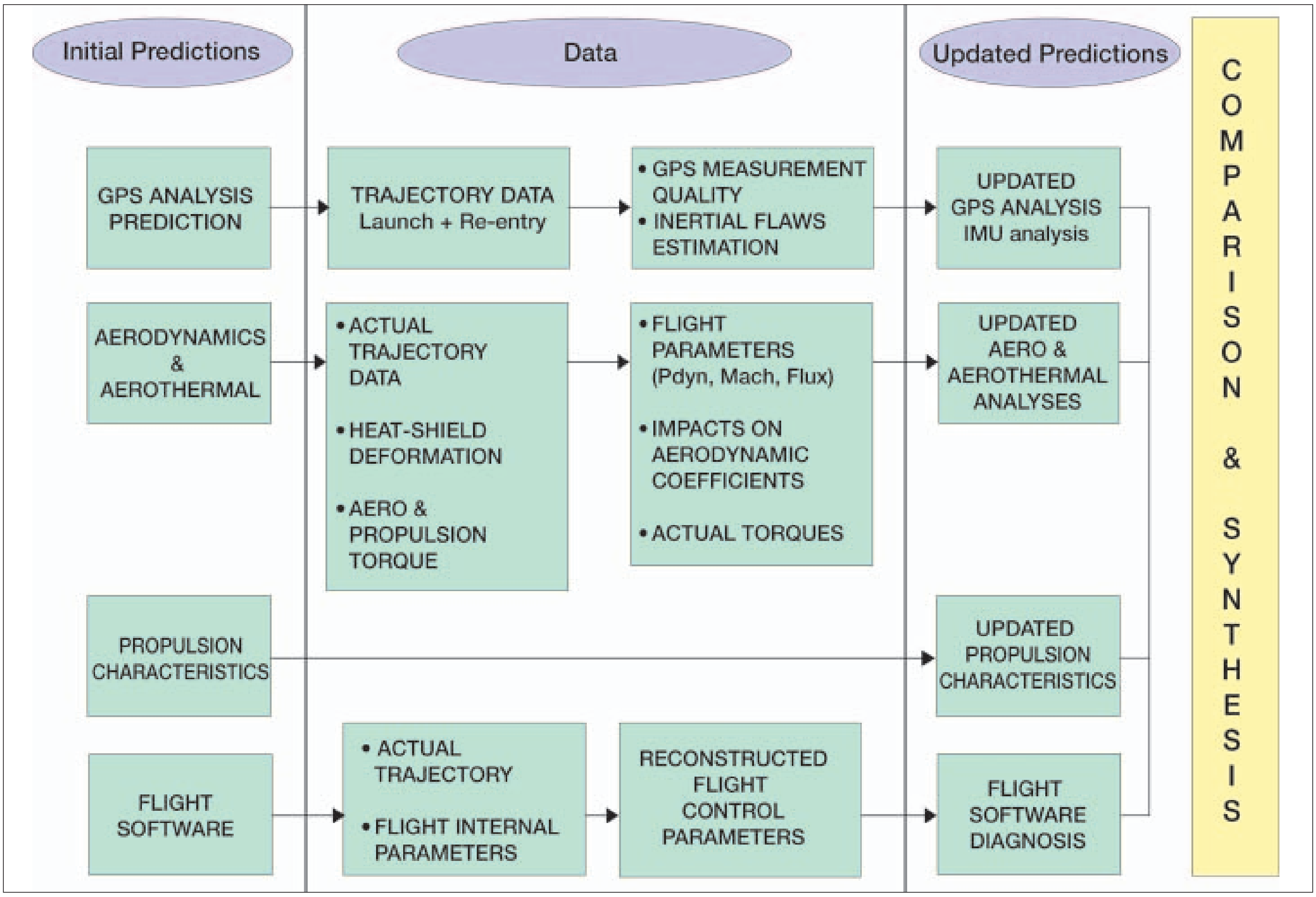


Figure 4. The post-flight-analysis work flow

Table 1. ARD post-flight analysis major events

EVENT	PREDICTION (time from H0)	FLIGHT Measurement (time from H0)
Ariane-5 separation	00 : 12 : 00 218 km	00 : 12 : 00 216 km
Injection orbit	Semi-major axis: 6798.5 km Inclination: 5.753 deg	Semi-major axis: 6802,4 km Inclination: 5,754 deg
Libreville visibility	00 : 17 : 09 to 00 : 27 : 39	00 : 17 : 38 to 00 : 29 : 20
TDRS signal received	1 : 08 : 34	1 : 09 : 10
ARIA-1 visibility	1 : 15 : 42 to 1 : 20 : 30	1 : 15 : 34 to 1 : 23 : 25
Start or reentry	1 : 18 : 58	4746 s - 1 : 19 : 06 gap in longitude : 60 km
Acceleration (max.)	3.2 g	3.7 g
Trim	22 deg	20 deg
Roll angle command (max.)	105 deg	110 deg
Black-out	Between 90 & 42 km	Between 90 & 43 km
Cross-range	68 km	67 km
ARIA-2 visibility	1 : 22 : 05	1 : 25 : 02
Parachutes opening	1 : 28 : 14 altitude 14 km	5280s - 1 : 28 : 00 altitude 14 km horizontal acc. 3 km
Splash down	1 : 42 : 55 vertical velocity: 6.7 m/s impact: 7g	6079 s - 1 : 41 : 19 vertical velocity: 7 m/s impact: 7.3 g accuracy: 4.9 km
End of mission	1 : 47 : 55	1 : 46 : 23
Recovery		9 hours

Final phase: Spring 2000/January 2001
- Updated flight predictions, flight measurements and correlations
- Synthesis of conclusions and lessons learnt.

Flight events and actual versus expected major results

Table 1 shows the predicted events timeline and major orbital parameters, and those actually achieved during the mission. It can be seen that the trajectory was very close to prediction, but that some discrete variations did occur, which had an effect on the predicted performance. However, overall the profile was very accurate and capsule recovery (Fig. 5) was achieved within five hours of splashdown.

Aerodynamics/Aerothermodynamics

In terms of aerodynamics and aero-thermo-dynamics, the analysis was supported by CFD (Computational Fluid Dynamics), computations (Euler and Navier-Stokes) and tests in the high-enthalpy F4 (ONERA) and HEG (DLR) wind tunnels.

The analysis of the hypersonic trim behaviour was consistent with a Centre of Gravity (CoG) offset during the flight of the order of 3–4 mm. This could be explained by propellant consumption and heat-shield pyrolysis. CFD calculations confirmed the overall Angle of Attack (AoA) evaluation during the flight, whereas the pre-flight data underestimated the impact of real gas effects. The systematic flight-data analysis of the relative pressure data led to the conclusion that real gas effects were also observed below Mach 10. The same trend was confirmed by the additional CFD analysis carried out during the post-flight study.

The atmospheric sensitivity analysis based on the pressure density confirmed the flight-prediction values and is coherent within the applicable uncertainty band (predictive model CIRA 86).

The heating rates were difficult to assess due to a malfunction in the thermocouple measurements, but the temperatures closest to the surface appeared to be in the 700–800°C range. However, the predicted peak heating values could be correlated with the usable flight data if chemical non-equilibrium is assumed, because for the low heating rates non-catalytic predictions are confirmed by flight data. These trends have been well-reproduced by CFD and other engineering methods. The low catalytic effects at high altitude have been confirmed, whereas the occurrence of pyrolysis effects close to peak heating inhibits the low catalytic behaviour, resulting in heating rates closer to chemical-equilibrium conditions.

Another example of surprising phenomena is the rear cone section, for which the flight data differed from those predicted. The observed overheating cannot be reproduced by current CFD analysis, for which two interpretations have been proposed. The first is the occurrence of a transitional regime that cannot be correctly described by current turbulence models, and the second is inadequate finite rate chemistry modelling.

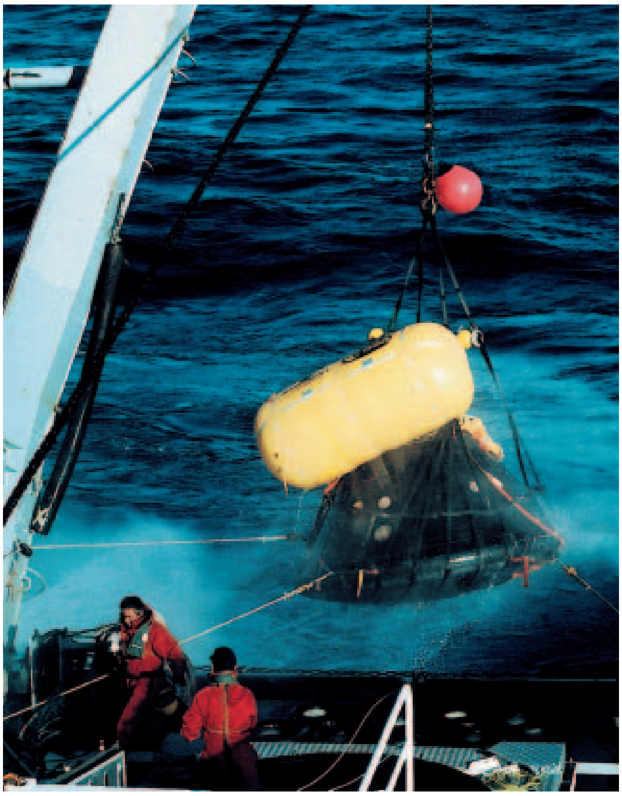


Figure 5. ARD capsule recovery

Thermal Protection System (TPS)

Several different types of TPS were applied to ARD, as shown in Figure 6:
- Aleastrasil (a compound containing randomly oriented silica fibres impregnated with phenolic resin) on the main heat shield
- Norcoat (composed mainly of cork powder and phenolic resin) for the cone section
- Samples of Flexible External Insulation (FEI) and Ceramic Matrix Composite (CMC).

A comparison of the ARD heat shield's state before and after flight is shown in Figure 7. The basic heat shield was a classical ablative, which had the function of protecting the demonstrator throughout the re-entry.

The Aleastrasil sample examination after coring confirmed the expected low surface recession

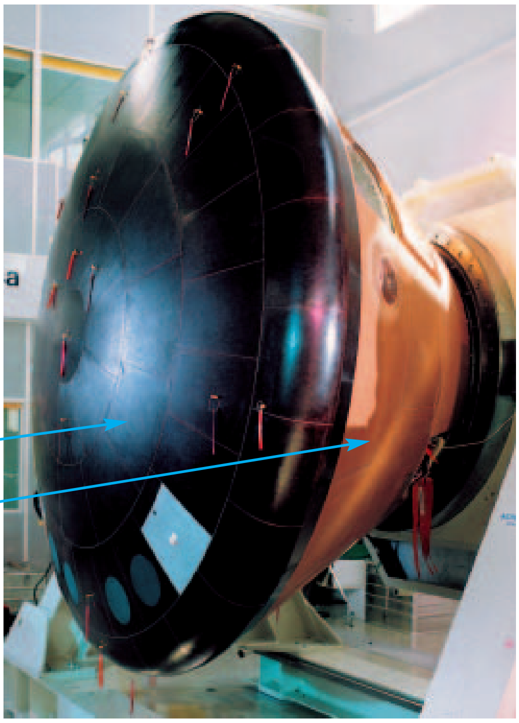
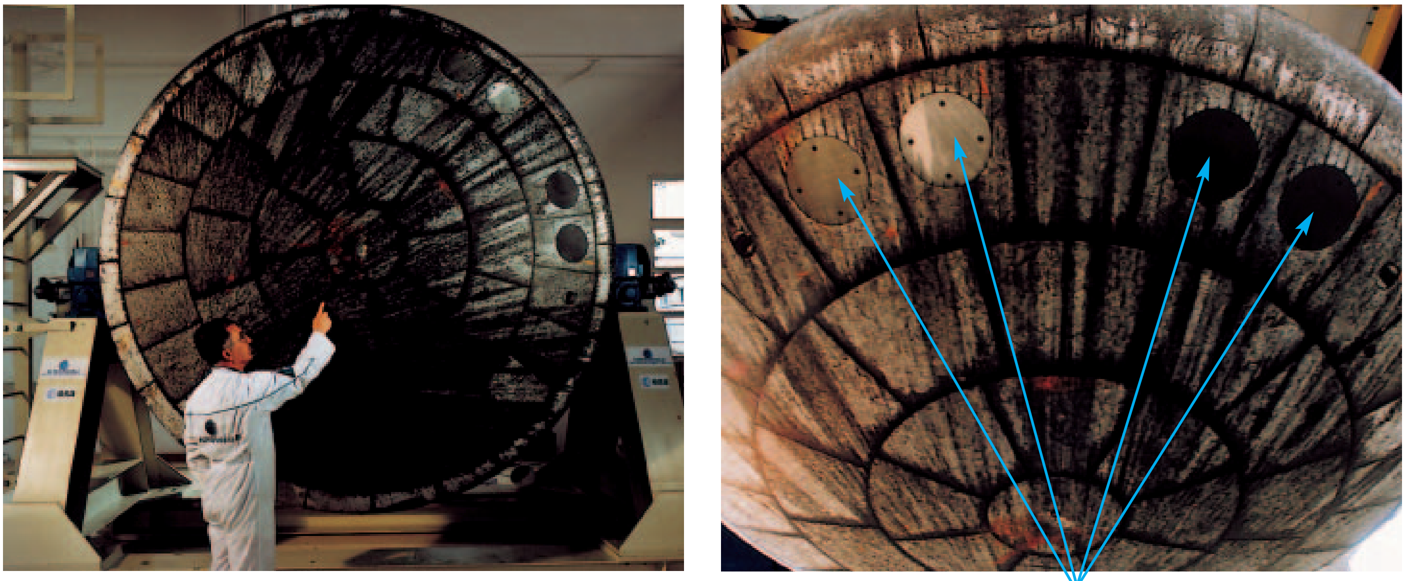


Figure 6. The ARD thermal-protection system

Figure 7. Comparison of the ARD TPS before (a) and after flight (b and c)


(a)


(b) (c) CMC samples

(0.1 to 0.3 mm) and provided an update to the thermal-properties data set, including measurement uncertainties to be taken into account for revised heat-flux reconstruction.

The other TPS materials are reusable, and one major test objective of the TPS flight experiment was their potential application to future re-usable re-entry vehicles.

Each material has been visually inspected, demounted and processed through further mechanical tests, and finally the measured temperature values have been analysed and compared with design loads. The results were as follows:

– The FEI experiment did not show any degradation or damage due to the flight thermal environment. The thermal loads on the leeward side of ARD were significantly lower than expected, and therefore the thermal stresses on the FEI were far below its performance limit. During the recovery procedure, some severe damage was caused to the FEI by the hoisting device. Local rigid reinforcing would prevent this. Only a limited demonstration of the reusability of the FEI TPS on capsules is possible due to the severe landing conditions compared to winged RLVs.

– The CMC sample examination showed no degradation of the material's surface due to ablator contamination or the sea-water impact, and it was therefore a successful demonstration of this combination of CMC and ablator. However, due to the relatively low re-entry temperature level (the two thermocouples on the inner side registered about 900°C) only a limited performance demonstration was possible. Concerning lift-off and landing loads, no damage to either the samples themselves or the attachment bolts was apparent. The surface morphology and oxidation protection layer remained unchanged. No signs of oxidation attack were apparent, but some slight increases in mechanical properties had occurred (explained by the witness sample manufacturing process). The maximum measured surface temperatures were around 940°C. In summary, it can be said that for all CMC samples the following applies:

- no material or oxidation damage
- no seal degradation, no carbon-fibre damage
- oxidation products probably coming from Aleastrasil pyrolysis
- no loss of mechanical properties by the samples after either the qualification test or the flight.

Another interesting experiment that was flown is the C/SiC screw. Here again, no damage has been observed on overloaded areas. The ratio of damaged thread tips is the same as that observed on virgin screws, and only a slight decrease in tensile rupture load can be observed.

The Norcoat performed as expected.

Flight control and GNC

The flight guidance, navigation and control hardware, as can be seen in Figure 8, consisted of:

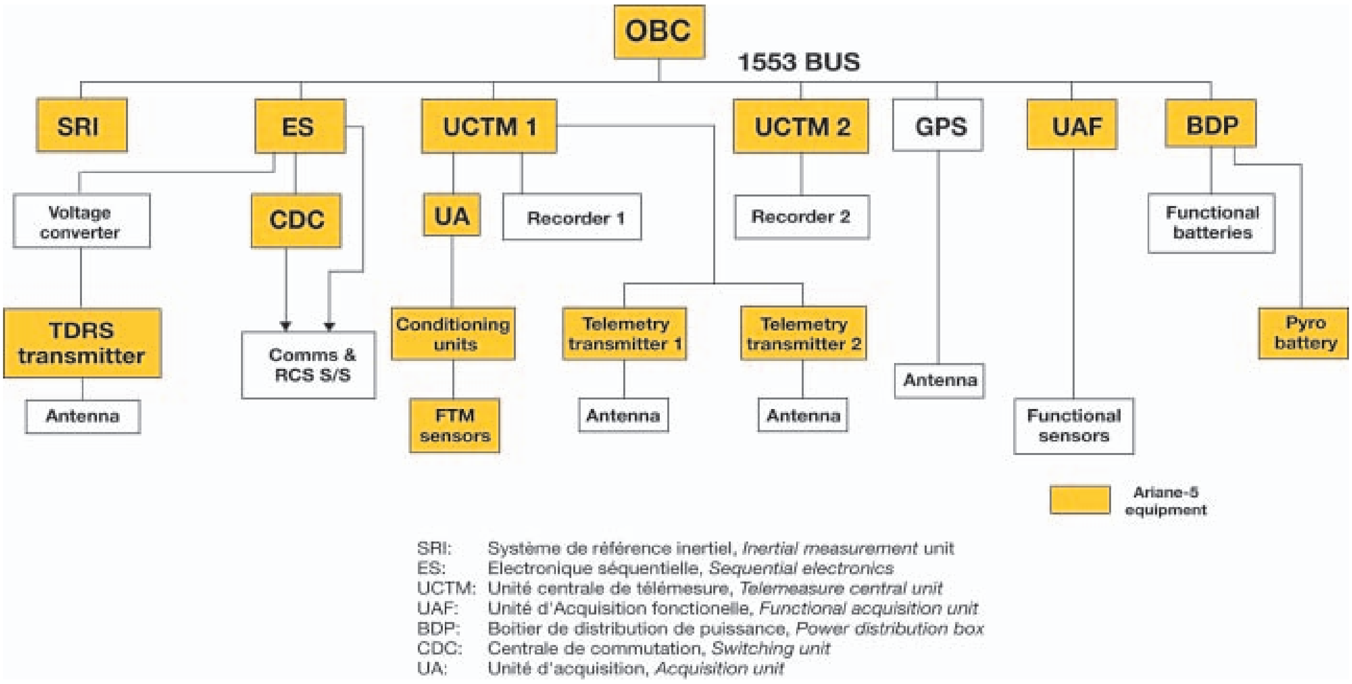
- a Global Positioning System (GPS) receiver
- an inertial navigation system
- a flight computer.

Examination of the trajectory accuracy showed that there was an attitude offset (time shift of bank-angle manoeuvre and a higher bank-angle value), including a higher load factor. These discrepancies could been explained by uncertainties in the atmospheric density model and the Mass Centering and Inertial (MCI) model. After updating these models with the CoG location, as well as the normal and axial force coefficients, the restored flight simulation was coherent with the flight data. Analysis of the propulsion model showed a higher fuel consumption than initially expected. This was due to an ARD jettisoning perturbation (CoG offset), which resulted in greater Reaction Control System (RCS) activation to reduce the range during re-entry and to cope with wind perturbations. Most of the velocity errors and hence also position errors were accumulated between 12 and 11 km altitude, due to large uncertainties in north-south wind gradients. Improvement of the atmospheric model, particularly the density element, is necessary.

The recorded Inertial Measurement Unit (IMU) and radar data were examined to establish the best-estimate reference trajectory. The ARD inertial navigation showed rather good performance. The errors at injection into orbit were lower than predicted and better than their specified value of one sigma. The ARD IMU behaved nominally during launch,during which 20 parameters were measured (biases, scale factors, misalignments, etc.). Weak residual inertial flaws were observed, but all stayed below their specified one sigma value.

The main contributors to navigation errors were the longitudinal accelerometer scale factor and IMU alignment error in trajectory characteristic data. This resulted in an updating of the IMU model for further trajectory analysis.

Figure 8. ARD functional block diagram



SRI: Système de référence inertiel, *Inertial measurement unit*
ES: Electronique séquentielle, *Sequential electronics*
UCTM: Unité centrale de télémesure, *Telemeasure central unit*
UAF: Unité d'Acquisition fonctionelle, *Functional acquisition unit*
BDP: Boitier de distribution de puissance, *Power distribution box*
CDC: Centrale de commutation, *Switching unit*
UA: Unité d'acquisition, *Acquisition unit*

Plasma and communications

Drag friction during re-entry creates a plasma (ionised gas) that can disturb the communications links. The ARD was specially equipped with eight dedicated skin antennas to prevent data loss in the TDRS and GPS satellite and Aria aircraft links (Fig. 8):

- 6 dedicated to the telemetry link
- 1 to the TDRS link
- 1 to the GPS link.

For the first time, the GPS flight data covered the launch conditions, orbital motion, and re-entry of a vehicle. The new 'code-only' mode that had been developed to enhance fast acquisition and robust tracking was successfully validated in flight. Quasi-permanent tracking of nine satellites with a single patch antenna during all accessible flight domains (except the black-out period) was demonstrated, and even the vehicle's rotating motion during the parachute phase was clearly indicated.

The analysis of the GPS data has contributed significantly to our understanding of plasma formation and its effects, which included:

- very unsymmetrical attenuation effects, lasting from 180 to 300 seconds
- forefront satellites disappeared first and reappeared last
- partial reacquisition.

The post-flight plasma analysis activities showed:

- the usefulness of axi-symmetric calculations on the windward side for studying the different effects and guiding modelling selection for 3-D calculations
- the relatively good agreement between calculations and measurements at altitudes of 85 and 46 km
- the calculated plasma frequencies and TDRS link attenuations are clearly greater than the measured ones at an altitude of 61.5 km.

The communication analysis results showed:

- blackout for GPS links on the leading edge from 92 to 28 km altitude
- blackout for GPS links on the trailing edge
- from 87 to 41 km altitude
- attenuation due to plasma for the TDRS link from 86 to 44 km altitude (no complete black-out)
- attenuation due to plasma for the Aria-1 telemetry links (backward side) from 84 to 77 km altitude
- blackout for the Aria-2 telemetry links from 70 km (beginning of recording) to 42 km altitude
- plasma measured by reflectometer (on the shield) from 100 to 42 km altitude.

The visibility picture for the between Aria-1and -2 links is summarised in Figure 9.

Parachutes

The overall study consisted of modelling using DCAP (Dynamics and Control Analysis Package) software, flight-data analysis and correlation of the two (Fig. 10).

The main results of the study confirmed:

- the suitability of the drag-area growth formulas for inflation loads
- 80% is the appropriate scaling factor to be applied for the descent-rate/drag-area calibration for the 20% porosity conical ribbon drogue chutes in capsule wake fields

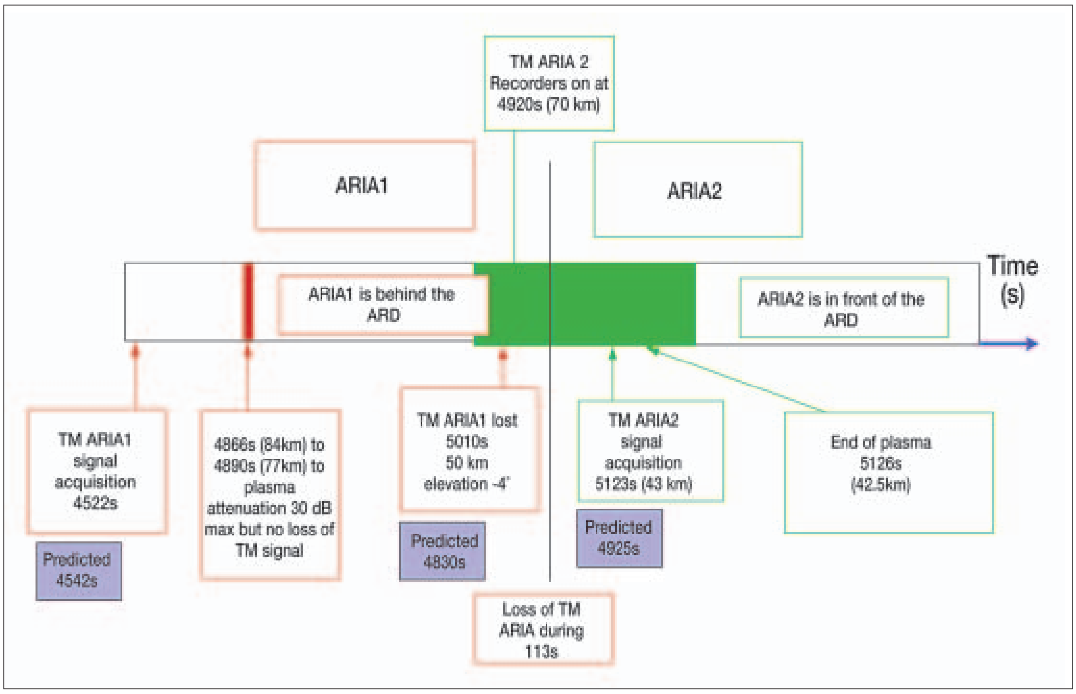


Figure 9. Visibility window with Aria-1 and Aria-2

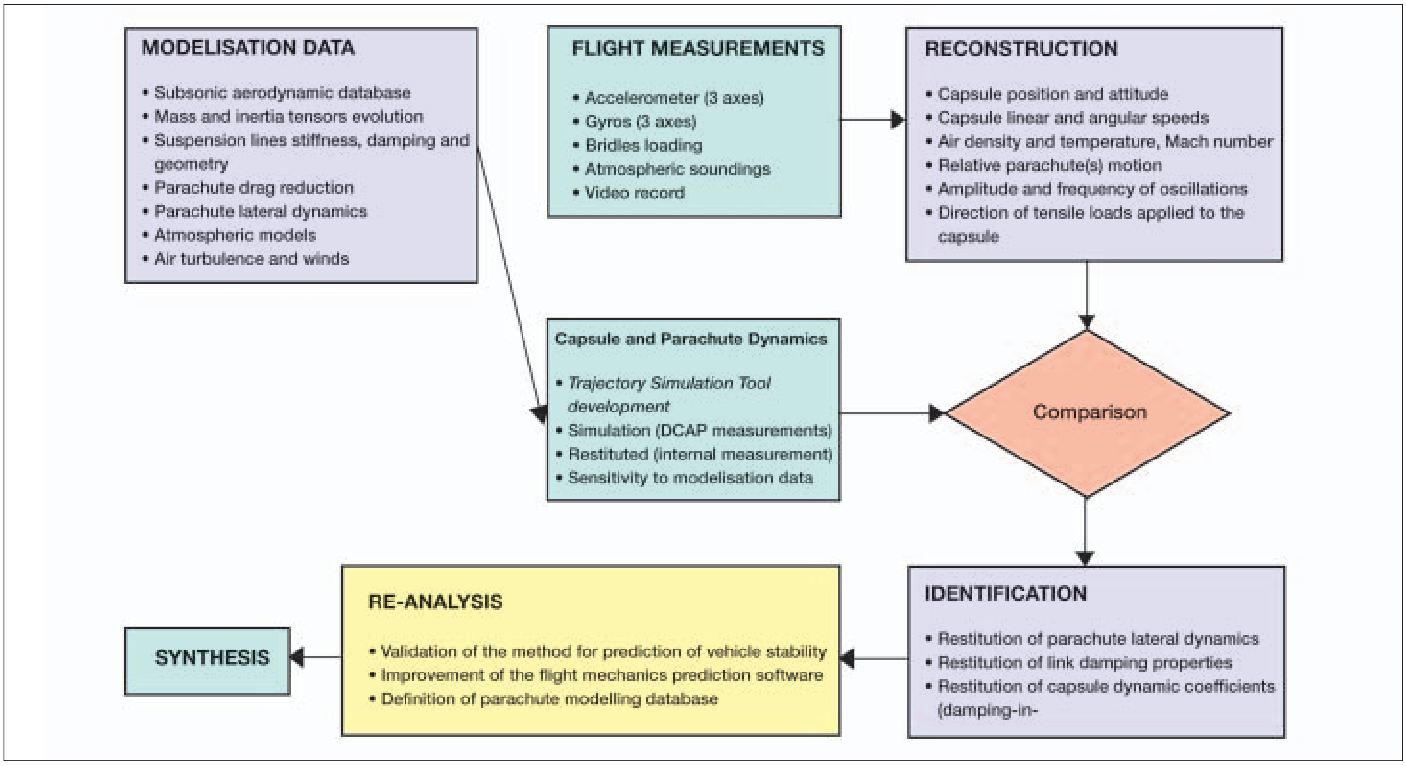


Figure 10. The parachute study elements

- simplified 1-D codes (two-body system) are fully applicable for the deployment analyses, with a safety factor of 10% for the estimation of stretch velocity and snatch force
- the suitability of the simulator for stability prediction in 2-D (pitch) analysis.

Lessons learned

In general, it can be said that the ARD flight was successful and the initial demonstration objectives set for it were fully achieved. Despite the protoflight nature of the approach applied, the initial flight-data analysis has already confirmed the following major achievements:

- demonstration of Europe's ability to master re-entry technologies
- successful overall mission control from launch to recovery
- splash-down in the Pacific less than 5 km from the expected position
- nominal behaviour of all main equipment and functions
- demonstration of Ariane-5's ability to service complex missions
- demonstration of European industry's ability to manage such a project under tight financial and planning constraints.

Nevertheless, it has to be said that complete mastery of re-entry technology is still quite a challenge. The ARD has a simple shape, and yet there were some significant discrepancies between actual and predicted results. Most could be explained, understood and corrected a posteriori, but more complex shapes can be expected to generate greater discrepancies. The flying of real hardware is therefore mandatory in a stepped approach to accumulate sufficient expertise in mastering re-entry systems. The need for flying prototypes before progressing to operational vehicles is clear.

Conclusions

This first European post-flight analysis of the complete mission scenario for a re-entry vehicle, covering its launch, orbit, re-entry and landing, has greatly improved our knowledge of the real flight environment. Europe's ability to manage a complete mission of this type, including recovery, has been successfully demonstrated. Further experience with instrumented experimental flight vehicles is mandatory to improve Europe's mastery of future space-transportation missions involving re-entry vehicles, and the results of the unique ARD flight will certainly help greatly in the preparation of future flight demonstrators (X-38/V201 and others).

Programmatically speaking, the hands-off management approach adopted by the Agency with ARD, delegating responsibility for the major development effort to Industry, proved to work well and greatly reduced the number of contract changes required. The use of non-high-reliability and off-the-shelf hardware was also shown to be perfectly adequate, with the simplified Critical Design Review and Flight Acceptance Review that were conducted.

Acknowledgement

The support and expertise of R. Molina, A. Pradier and R. Bonhomme is gratefully acknowledged.