ARIANE 5 QUALIFICATION FLIGHT: MISSION ANALYSIS DESCRIPTION AND GNC FLIGHT RESULTS

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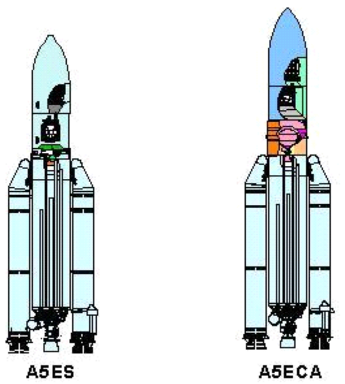
1. Return to flight of the A5ECA

1.1 History of the A5ECA launcher

The decision to develop the Ariane 5 launcher was taken in 1987 by the Council of the European Space Agency at a ministerial conference at The Hague. Performance objectives (6000 kilos in dual launch on geostationary transfer orbit) were reached in 2000. The satellite market had developed more rapidly than predicted, however, at least concerning mass, and at a ministerial conference at Toulouse in 1995 it was decided to improve the lower composite of the launcher significantly, particularly regarding the cryogenic Vulcain motor (Ariane 5 Evolution, A5E).

A ministerial conference at Brussels in May 1999 officially approved development of two new families of launcher with a view to enabling dual launches of increasingly heavy satellites while reducing production costs:

- an A5ES launcher bringing performance to 7350 kilos (with a storable propellant or EPS upper stage),
- and an A5ECA launcher capable of carrying up to 9750 kilos to geostationary transfer orbit in dual launch (with a cryogenic upper stage).



1.2 Feedback of Flight 517 experience

On 11 December 2002, the A5ECA launcher (Flight 157) took off from the ELA3 launch zone. The intended GTO orbit could not be attained owing to a failure of the Vulcain 2 engine.

The flight seemed normal until approximately H0 + 96 sec, at which time a slow fall in pressure became apparent at the hydrogen circuit outlet of the engine cooling system (a pressure drop at the dump cooling outlet). The boosters separated normally at H0 + 137.5 sec. Approximately 50 seconds later, pressure at the dump cooling outlet fell to zero. The fairing was jettisoned correctly but an abnormal movement of the launcher was noticed, associated with an absence of control of the Vulcain 2's thrust (no more gimballing). The launcher was destroyed before descending below the radio horizon, and fell back into the middle of the Atlantic Ocean.

After this setback a board of inquiry was set up by the programme authorities on 13 December 2002. The board delivered its conclusions on 6 January 2003 and stressed the following points:

- an insufficient margin of mechanical resistance in the upper part of the Vulcain 2 nozzle with respect to the manner in which axial buckling occurred under the joint influence in vacuum conditions of stress from thrust, from the steering actuators and from aerodynamic load in flight,

- an insufficiently effective nozzle cooling circuit particularly with regard to local deformation of the cooling tubes, allowing hot spots to develop.

On 27 May 2003 the Council of the European Space Agency approved a plan for return to flight of the Ariane 5 launcher, including the full range of consolidation work concerning the A5ECA version. At the same time changes were made to the organisation of the Ariane programme, in both development and production. The most important change involved entrusting all activities to a manufacturer, called the "prime contractor". To this end, two contracts were drawn up, one with EADS-ST (with a reinforced coordination between the system activities of the Industrial Architect and the stage activities of EADS-ST SAS and EADS-ST GmbH), the other with SNECMA (for Vulcain 2 and HMB7 engines). CNES was to ensure the interface function.

1.3 Overview

After the failure of 517 it was also decided to develop a new version of launcher: the A5GS. This version is similar to the A5ES version but the lower composite is adapted for a Vulcain 1 engine instead of Vulcain 2, whose nozzle was a prime cause of the failure of 517. At the same time, development of the A5ES version for the GTO mission was abandoned. Only the ATV mission for supplying the International Space Station (in Low Earth Orbit) was to be qualified.

Technically, this recovery plan dealt with qualification of A5G+ (first Ariane 5 definition), A5GS and A5ES-ATV, and of course the A5ECA consolidation phase after Flight 517. There have since been three A5G flights (L514, L515 and L516), three A5G+ flights (Rosetta L518, ANIK F2 L519 and Hélios L520) and finally the return to flight of A5ECA (L521 XTAR-SLOSHSAT).

Due to various customer priorities on Hélios, the return to flight of A5ECA, the availability of spacecrafts and also single launch qualification of the A5GS, the first A5GS flight (GTO dual launch) is now scheduled for mid-2005 and A5ES-ATV qualification is planned for mid-2006.

1.4 The qualification logic

The reference configuration of the A5ECA launcher that we are going to discuss here corresponds to the production batch known as configuration PA-1, which will apply for the 521 and later launchers.

The contribution of each of the production units concerned (engines, stages, system) terminates when the appropriate board rules that the work is "qualified". Technical reality then requires a further set of important final verifications on the integrated launcher. Launcher design assumes optimum integration and interaction between all the stages and all the fields of activity. Each individual component is developed according to the technical specifications established at the start of the programme; nevertheless, at the end, the launcher will be qualified using only the demonstrated (and not the specified) characteristics. This is why a verification phase remains mandatory even after the qualification boards for the stages and the system have completed their work, in order to verify that all the hypotheses formulated several months beforehand remain valid. The Launcher Qualification Board is responsible for this task.

The notion of generic qualification covers the flight readiness of the A5ECA launcher, in PA1 configuration, for the A5ECA (GTO) reference mission taking full account of the possible range of variation in the characteristics and performance of the different elements that make up the launch vehicle, in accordance with the hypotheses advanced at system level. System studies (concerning the work of the Industrial Architect) must of course verify flight readiness but must also quantify the launcher's robustness in terms of variations to its definition (Upper Level configuration) for each individual technical field (dynamics, general loads, thermal management, aerodynamics, guidance, control etc) and also in terms of its mission (around the reference GTO). For the stages, generic qualification means testing the readiness to answer to all the Technical Specifications.

Chronologically, final qualification of the A5ECA launcher implies the following sequence of three phases:

- a ground qualification phase, declared complete by the Launcher Qualification Board,
- level 0 of the L521 qualification flight,
- a phase made up partly of satisfying any reserves about qualification arising in previous stages, and partly of level 1 analysis of the L521 qualification flight.

1.5 Operations

Winning authorisation for operational return to flight of the launcher consisted in:

- generic qualification of the PA1 reference configuration, based on work carried out on the L517 configuration; this meant adaptations to the upper level that better satisfy commercial conditions (moving from a Long Fairing configuration - SYLDA + 1500 mm to a Medium Fairing configuration - ACY5400 + 2000 mm and SYLDA + 900 mm);
- solving the technical problems which caused the setback by letting every field of activity benefit from the experience acquired, while concentrating on the improved Vulcain 2 motor;
- consolidating demonstration conditions for those aspects of Flight 517 that remained untested - the end of the main cryogenic stage (EPC) flight, the upper cryogenic stage version A (ESCA) flight and the ballistic phase.

Performance in terms of payload mass for this return to flight configuration differs from the initial objective of 1999. Programme objectives were therefore modified accordingly.

Attention should be drawn to a significant change decided on for the return to flight programme: a system of crosschecking. This means that whenever qualification or demonstration tests are considered insufficiently representative of real flight conditions, a fully transversal crosschecking procedure comes into play at every level of the Ariane 5 industrial organisation. The manufacturers are concerned just as much as CNES in its role as qualification authority. It can be said that these crosschecking operations are an integral part of the qualification procedure.

From a Systems point of view, the most notable points concerned the validation of the EPC-ESCA interstage thermal behaviour by various tests made in French Guiana, a detailed analysis of dynamic loads on the launcher, the validation of roll control in EPC phase using observations made of Flight 517, detailed analysis of the phase between EPC extinction and ESCA firing (minimal acceleration, sloshing, thermodynamic conditions on ignition) and finalising specifications for installing the launcher on the launch site. The flight software was updated with new launcher control data (GNC, engines, etc).

Special attention was paid to the Vulcain 2 engine: optimising and mechanically reinforcing the nozzle, buffeting tests, modifying the flow of cooling and installing thermal protection. It should also be mentioned that Side Loads at ignition were carefully studied.

For the EPC, the principal activities were the adaptation of the stage to the improved Vulcain 2 and the increased robustness of the roll control.

The HM7B engine was also consolidated through extra trials (characterisation of the temperature of the injected hydrogen), by improvements to the dynamic engine simulator and the stage thermal simulator together with validation of thermal conditions on ignition.

For the ESCA, work concentrated on demonstrating the robustness of the stage in flight conditions. Several dynamic tests were carried out or reanalysed using data from the atmospheric phase of Flight 517. The purpose was to renew validation of the compatibility in the Ariane 5 environment of equipment taken from Ariane 4. It should also be mentioned that an extra helium system was installed to consolidate the design margins and that the fluid budget was re-examined with particular attention to stage residuals.

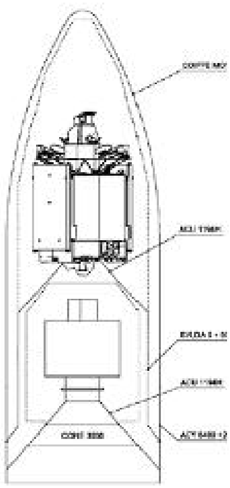
A special effort was made to verify the transient phase of EPC–ESCA separation, rendered very difficult by the numerous mechanical, fluid, thermal and environmental phenomena which come into play.

These activities led to qualification certificates being issued for each product as well as a general certificate at launcher level. Certain reserves concerning generic qualification could not be lifted in the time available or would have required an operational flight. Consequently all such reserves were waived either generically or specifically in the context of mission 521 in order that the flight might be authorised without delay.

2. Launch L521

This launch V164 / L521 is therefore the first launch of Ariane 5 with ECA in its modified version post L517 as we have just described. It is strictly identical to the generic configuration, except for the presence of technological measurements used for qualification for return to flight.

In a dual-payload configuration with a SYLDA lengthened by 900 mm under a medium fairing mounted on an ACY 5400 2 m high, the L521 launcher was to carry the XTAR-EUR communication satellite in the upper position, and the MAQSAT-B2 model carrying certain ESA experiments (including SLOSHSAT to be separated) in the lower position.



We shall now examine the Mission Analysis aspects and the results obtained in flight concerning the GNC algorithms (Guidance, Navigation and Control) and the transient phases (takeoff and separations).

2.1 Description of the mission

The mission of Flight L521 is a classic GTO Ariane mission, whose orbital parameters can be defined as follows:

Apogee	35,786 km
Perigee	250 km
Inclination	7°
Argument of perigee	178°

The performance required of the launcher for this first flight is 8300 kg (including the carrying structure). This is not the maximum performance possible for the launcher because margins were allowed for the first flight.

The trajectory calculated for releasing the payloads on this orbit is also different from the generic trajectory in order to ensure maximum safety for the flight: limited launch azimuth, slightly reduced dynamic pressure in atmospheric phase, use of the Natal tracking station instead of Fernando, longitude constraints on the ascendant node of the final orbit in order to have three hours of geometric visibility after the usual ballistic phase.

Stationing procedure for the payloads is classic, XTAR being separated stabilised on three axes and SLOSHSAT with a roll of 10°/s. It differs from a generic phase in two aspects: the MAQSAT-B2 structure (excepting SLOSHSAT) remains on the launcher to the end of flight, and there is a microgravity phase (without manoeuvres) of 300 sec after separation of SLOSHSAT.

2.2 Pre-flight tasks

Considering the progress made with generic qualification for A5ECA and the specificities of the mission that we have just described, classic mission analysis studies were carried out as well as certain complementary studies with a view to acquiring total qualification for this launcher.

<u>Mission Analysis</u>

Trajectory computation showed the feasibility of the mission with a probability of avoiding burn-out higher than 99%, while respecting all the imposed constraints (flux criteria when the fairing is jettisoned, fallback of the stages, probability of EPC and ESCA hydrogen depletion, etc.).

In ballistic phase, preparation of the control scenario and its validation by taking into account all possible perturbations (particularly the influence of propellant motion during ballistic phase, wall effects on the thrust, etc.) produced good results relative to specifications. After separation of the payloads, the passivation phase was studied particularly closely, with a special analysis coupling both launcher dynamics and propellant movement. The particular configuration of this flight (no separation of the lower payload) revealed that it was possible for longitudinal spin to decay into flat spin. But this flat spin could not prevent a successful passivation phase, however (outgazing from the tanks), as the diffusers of the pressure lines were not flooded.

No adjustments were made to the generic algorithms for navigation, guidance (apart from trajectory caracteristics linked to the mission), control and redundancy of sensors. Computation of EPC fallback required no particular adaptation.

The flight program with all its mission-adapted algorithms data was validated by component tests and Monte Carlo simulations with a very wide flight envelope relative to required domain (approximately 99.99%). Final flight projections showed a probability for mission success of 99.8% considering the latest characteristics in mass and propulsion of the L521 launcher, as far as non-burnout was concerned.

Coupled-loads analyses of both thermal and dynamic aspects terminated the analysis tasks for the mission, showing good flight readiness for the L521 launcher with the planned payloads: no thermal waiver, but specifications slightly exceeded on the Quasi Static Load during thrust decay of the EAP for XTAR, considered acceptable after the satellite qualification tests.

Complementary studies

Some thermal and dynamic aspects of the launcher were granted as a result of mission analysis calculations, in particular the thermal resistance of the EPC-ESC and Case-ESC inter-stages, and the launcher's resistance to Pressure Oscillation loads during the EAP flight. General static and dynamic loads were also validated for the specific trajectory of flight L521.

Besides, as an addition to generic qualification, all input data used in the system studies were thoroughly verified, by comparison with the final results of the qualification boards concerning stages and engines. Any deviation found was rigorously tested by specific impact studies.

The last problem to be solved before the flight concerned the resistance of the Vulcain 2 engine to side loads during the ignition sequence. A considerable amount of work lead to a fuller understanding of the phenomenon and its boundaries (calculating non-steady flow patterns during thrust stabilisation, transposing European test bench tests to the Kourou launch zone). This allowed completion of risk-reduction tasks (modifying the flight software as regards the checks to be made before ignition of the EAP stage) and a consequent verification of the launch system qualification was performed (making it compatible with the required success probability objective).

The launcher was finally transferred to its launch site on 11 February and was launched on 12 February. We shall now examine the details of its successful flight.

3. Results of flight 521 (GNC aspects)

3.1 Navigation and guidance

Deviations in orbit for the ESCA's end of flight between nominal navigation (using the nominal inertial measurement unit) and backup navigation (using the redundant inertial measurement unit) are extremely small. Orbital characteristics compare very favourably with specifications (value within 1 σ is given in brackets):

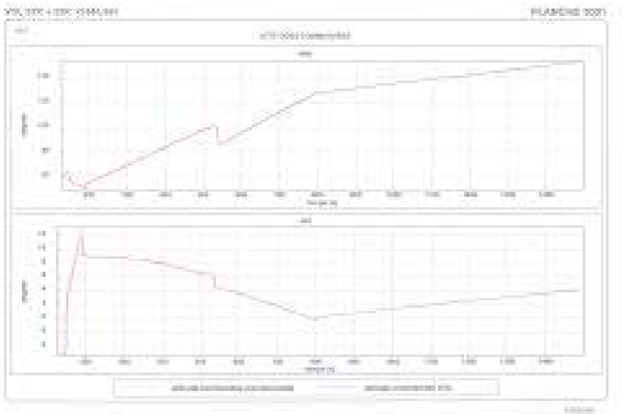
Δ Semi-major axis:	13 km *(50 km)*
Δ Eccentricity:	$1.4\text{x}10^{-4}$ *($6x10^{-4}$)*
Δ Inclination:	$1.8\text{x}10^{-2}$ ° *($3.5x10^{-2}$)*
Δ Argument of perigee:	0.21° *(0.3°)*
Δ Longitude at ascendant node:	0.20° *(0.3°)*

Orbits attained by the payloads at separation also correspond very closely to customer needs, in the same range as previously explained.

Concerning guidance during the propulsion phase, we can distinguish between: the atmospheric flight with pre-programmed guidance (interpolation of attitude laws according to relative speed) and the extra-atmospheric flight with explicit guidance, the trajectory being re-optimised after each computation cycle.

During the atmospheric (EAP) flight, slight EAP over-propulsion was noticed relative to the predicted steady state and under-propulsion during tailoff. Overall, at EAP separation, the launcher had exceeded predictions by 16 m/s (+0.8%).

In extra-atmospheric EPC flight, guidance estimates an over-propulsion of +0.5%, leading to EPC extinction 3 sec earlier than predicted. Behaviour of the demand (thrust orientation angles) and evolution at segment ends (intermediary constraints) is very close to predictions, which testifies to excellent thrust knowledge and control.

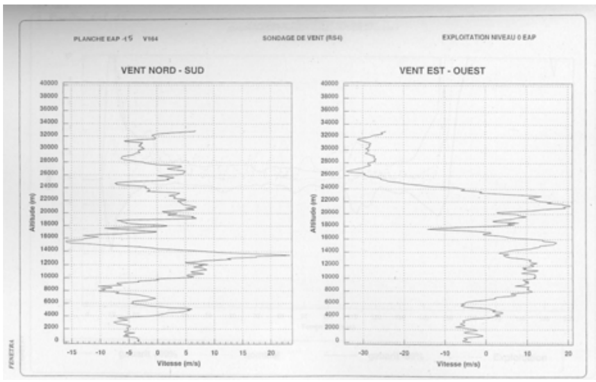


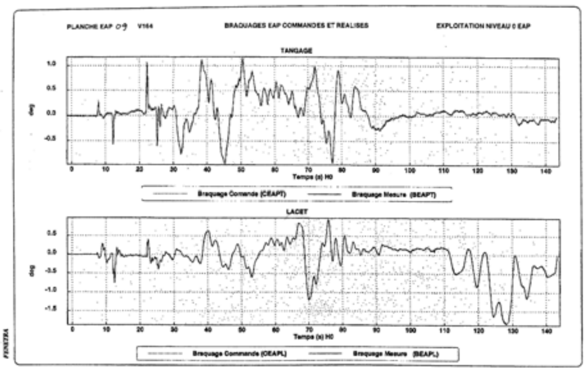
During the ESCA flight, command is also very close to prediction but guidance estimates a flow rate inferior to predictions by approximately -0.9%, which lengthens flight duration for this stage by about 9 sec. It will be necessary to find the explanation of this deviation, which would impact on the performance of future flights (equivalent to a few seconds of engine specific impulse).

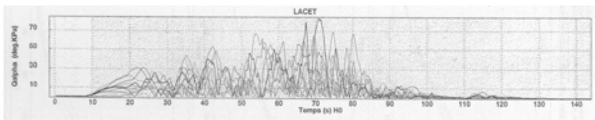
Lastly, concerning the sensors redundancy, it should be said that no warning (and of course no commutation nor inhibition) was detected either on the gyrometric units used by the EAP autopilot, or on the inertial measurement units used by the full set of algorithms.

3.2 Control in propulsion phase

During atmospheric flight, winds encountered at an altitude of about 14 kilometres apply a very strong north-south shear, affecting incidence by 2.4°, associated with 1.2° of nozzle deviation. This is linked to the month of launch, in this case February, known to be significant in matters of wind dynamics. The control algorithm, however (synthesised by the robust Hinfini method) remains well within its qualification range, even though this flight was subjected to the strongest product of "Dynamic Pressure x Angle of attack" of any Ariane 5 flight.







During EAP tailoff, dissymmetry between the two EAPs shows the same dynamics as predicted but steering levels were slightly stronger (1.8° instead of the expected 1.2°).

Consumption due to autopilot for the entire EAP flight (oil lost from the hydraulic jacks) is very low compared to the quantity carried (a margin of about 75%).

Compensation at EAP separation is completely normal, with a strong tendency to roll conforming to predictions, linked to the EAP distancing rockets on the EPC. The remainder of the flight is very calm, with little steerage and slight angular speed. The only phenomenon of note is a significant perturbation caused by roll torque, at about –1000 Nm as against predictions of –260 Nm. Although this was within the expected range (between –1600 Nm and +700 Nm) and perfectly controlled in flight by the Roll Control System, this ground/flight deviation will need to be precised.

Finally, in ESCA flight, behaviour is extremely calm with no particular incidents notified.

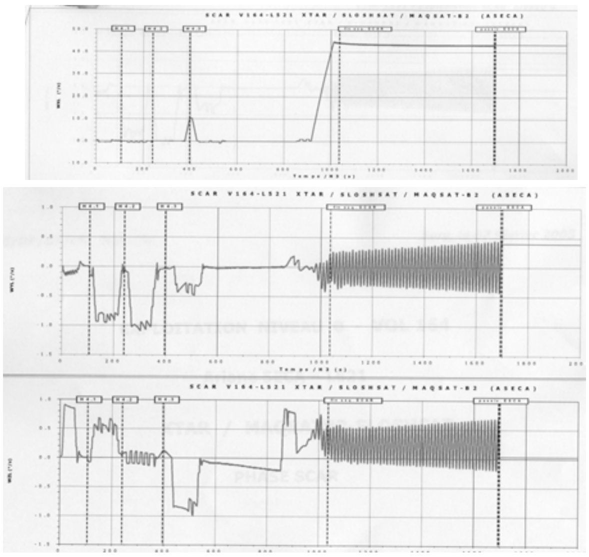
3.3 Control in ballistic phase

The sequence of 18 manoeuvres of the Attitude Control System were executed perfectly, with a very short “end over time” ratio showing the absence of any anomaly or perturbation in excess of predictions. Payload separation conditions are very good relative to specifications (shown in brackets):

	XTAR	SLOSHSAT
Roll speed	-0.16°/s *(±0.5)*	9.85°/s *(10±0.6)*
Transversal speed	0.02 °/s *(±0.1)*	0.13°/s *(no spec)*
Longit. offpointing	0.03° *(±1)*	1.2° *(no spec)*

Total duration of the phase was 30 seconds shorter than the predicted minimum (approximately 3%), due to the propulsion efficiency of the LH2 nozzles better than predictions. In-flight measurements of hydrogen and oxygen pressure were in fact considerably higher than the predicted "hot case" (L521 was a daytime launch). Pressure recovery inside the fuel tanks was particularly noticeable (change of state from cryogenic liquid into gas on contact with the walls caused by any movement of the launch vehicle).

Finally, the number of nozzle openings is within predicted range and behaviour of angular speed conform perfectly to predictions.



Concerning passivation, concerns mentioned during generic qualification and the preparation of Flight 521 were shown to be founded. Spin around the longitudinal axis (45°/s) was transferred into flat spin around the transversal axes (12 °/s), between 7000 and 8000 s.

This did not perturb behaviour at passivation, as was expected for this particular configuration, but it is an aspect to be looked after for future flights.

3.4 Transient Phases (separations)

Takeoff phase went smoothly: the acceleration, attitude and angular speed profiles are all within the predicted ranges. There was a light wind (4.3 m/sec at 35 m altitude) and lateral displacement at lift-off shows a margin of approximately 68% relative to specifications.

EAP separation also conforms perfectly to predictions, after readjustment for the plume effect of EAP acceleration rocket caused by the distancing thrusters carried out after Flight 517. Full recovery from perturbation was achieved approximately 10 seconds after separation.

For EPC-ESC separation, angular speed conditions on extinction of EPC were seen to be exactly as predicted. There was no shock during separation and acceleration just before ignition of the HM7B motor is 0.635 m/sec² (specification being for 0.2 m/sec²). Burn of the distancing thrusters was nominal but they were jettisoned slightly later than the maximum predicted limit, which will need to be corrected for the following flight. Oxygen and hydrogen pressures during the EPC passivation phase conform perfectly to predictions and show absence of any depressurisation effect which it was feared would have an impact on the stage's common bulkhead.

EPC fallback on this flight was observed from an aircraft which showed that the stage re-entered well (localisation and breakdown altitude), exactly as predicted.

3.5 Highlights on main GNC concerns

We can now review all the unresolved questions previously mentioned and consider how they should be treated for the next A5ECA flight.

- performance in ESCA flight: after updating the various dry and fluid masses in the upper composite, propellant flow rate and the mixture ratio actually used during the flight were calculated using the parameters of the engine chamber; functioning predictions were then aligned with pump input conditions and the resulting specific thrust deficit is now only 1 to 1.5 seconds, that is to say largely within the range guaranteed by the manufacturer.

Since these conditions of mixture ratio and specific thrust differ slightly from those of Ariane 4 (same engine), a justification analysis is continuing. The new values have been taken into account in the Mission Analysis for the next flight L522.

- perturbation from roll torque during EPC flight: examination of the deviation between ground and flight measurements has given rise to numerous investigations. More promising ones are a bias in the roll-measurement instrument used on Vulcain 2 or an ageing of the nozzle with unsymmetrical deformation (calculations are still under way). Since ground measurements for the next flight L522 are very close to those for L521, provisional torque has been corrected by the deviation observed on L521. This causes no problems due to the capacity of the motor's torque for countering the perturbation torque.

- late jettisoning of the acceleration rockets at the start of ESCA flight: this anomaly is linked to the problem of the temperature of the pyrotechnic delays, which were much colder than predicted. Corrective measures guaranteeing appropriate temperatures with regard to the qualification of the equipment have been decided and will be mounted on the following flight.

- transformation of longitudinal spin into flat spin during the ESCA passivation phase. The measure taken in Mission Analysis to gather telemetry data over a three-hour period provided detailed information about the behaviour of the launcher during this phase, regarding both pressure and kinematic aspects. The flat spin behaviour which started at about 8000 seconds, which had no adverse effect on the pressurisation orifices in the specific configuration of L521, was rectified for the generic flight. Firstly, the stage analysis showed a very low probability of any blocking of the outgassing orifices and that therefore passivation should function well. Secondly, from the System point of view, action was taken to increase robustness by performing a pre-passivation, involving depressurising the hydrogen tank as much as possible using the SCAR valves (immediately after separation of the last payload) before opening the main valves and carrying out passivation of the tanks themselves. This measure reduces the perturbation caused by the eccentric position of the depressurisation orifice.

4. Conclusion and perspectives

Apart from the GNC aspects described above, the entire flight was completed very satisfactorily and in full accordance with forecast. Both thermal and dynamic environments were weak, whilst predictions (computed it is true using pessimistic hypotheses) gave cause to expect higher levels. The environment encountered by the payloads conformed completely to the Ariane User Manual.

Some 50 questions were raised during preliminary exploitation of this flight, which is not excessive for a qualification flight. It was decided that 11 of these should be declared mandatory for the following flight, even though all of these questions must be solved for generic qualification. Among the most significant were validation of the roll torque in EPC flight, performance in ESCA flight and in addition precise validation of the ESCA fluid budget in respect of thermal residuals, the temperature of the ESCA separation system etc.

Specific work was undertaken in order to resolve as early as possible these questions raised concerning level 0 exploitation, with the aim of achieving authorisation for the following flight L522 before the end of June 2005. This flight will employ the same configuration as Flight 521, and will also benefit from progress made in generic qualification for A5ECA which has continued since the success of Flight 521. Since generic work has not yet been completed, Flight 522 will be authorised on similar terms to Flight 521, in the same spirit of technical thoroughness and with the same project management process.

At the same time, thanks to the successful flight which validates the "ground-qualification” approach, we hope to reach exploitation of level 1 and the end of qualification activities by December 2005, authorising full production phase of the A5ECA launcher (without any restriction) by the end of this year.

Subsequently, with a view to enlarging and consolidating the exploitation phase of the heavy European launcher, further development will open the way to consideration of an upper composite configuration with long fairing on a long SYLDA, structural rings welded onto the solid propellant thrusters and also a more robust equipment bay using Fiber Placement technology (so called PA-2 configuration). This development should be accompanied by other measures, all aiming to bring greater flexibility and robustness to this production phase, with the proposition of the ACEP programme currently being finalised by ESA.