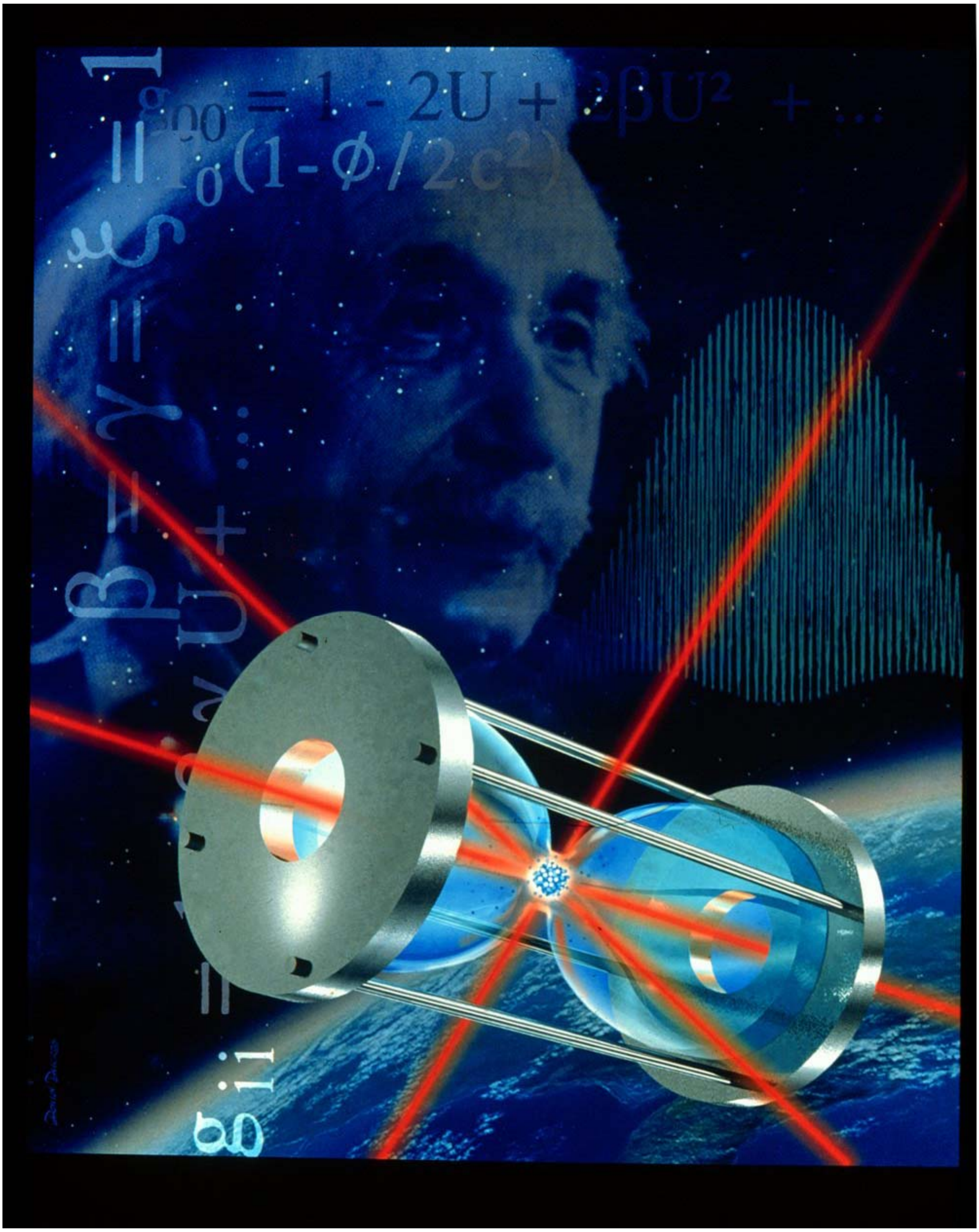
PHARAO
SYNTHESIS DOCUMENT



European Space Agency

SYNTHESIS DOCUMENT

Written by:	**PHARAO Project Team**	Date and Visa
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Summary: This document is intended to give a general description of the PHARAO instrument for the system design and architecture, the performance, the subsystem description and the development, integration and testing.		

DOCUMENT CHANGE RECORD

The modifications are listed in the Change Record section of the document.

Issue	Date	Modifications
1.0	*13/3/2000*	*Creation of the document*
2.0	*15/5/2000*	*General update for PHARAO PDR* *- chap 2 added – programmatic aspects,* *- chap 7 added – ground segment* *- chap 9 updates – verification approach* *- chap 11 updated – Product Assurance*
3.0	*8/11/2000*	*General update after PHARAO PDR (main updates : instrument budgets, UGB hardware and software description, optical architecture),*
3.1 draft	*15/6/2003*	*Document partial update for instrument risk review*
4.0	*15/5/2005*	*Document complete update for ACES mission SRR (chapters re-numbered, documentation references added)*
5.0	*01/09/2006*	*Complete update*
6.0	*21/09/2010*	*Update for Pharao CDR*

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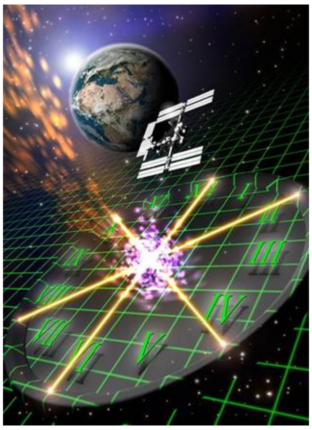
1 INTRODUCTION

Christophe SALOMON – Principal Investigator – ENS/LKB
André CLAIRON – Co-Principal Investigator – LNE/SYRTE
Didier MASSONNET – PHARAO Project Manager – CNES



The PHARAO project will develop a new generation of clocks in space. This clock takes advantage of two factors:

(1) the very low temperatures obtained by laser cooling techniques, and

(2) the micro-gravity environment of satellites in Earth orbit.

These two factors enhance the clock's performance.

In 1997, PHARAO was proposed to ESA in the framework of the ACES mission (Atomic Clock Ensemble in Space). ACES also accommodates another atomic clock, the SHM (Space Hydrogen Maser) initially developed by the Observatory of Neuchâtel (Switzerland) (now Spectratime) and a time and frequency transfer unit, the MWL (MicroWave Link) developed by Timetech and Kaiser Threde. The MWL allows time and frequency comparisons between the ACES time scale and the time scale of various ground users on Earth. The Science objectives of ACES/PHARAO will be obtained with frequency comparisons onboard ACES as well as from comparisons with the ground clocks.

This development is made in the framework of a flight onboard the ISS. The ACES payload is designed to be mounted externally on the Columbus module. The launch date is currently set to 2013 with a PHARAO delivery to ACES in spring 2012.

The objective of this synthesis document is to give the reader a global overview of the PHARAO instrument in terms of scientific and mission objectives, physics principles, design and budgets. This document is a general description for people outside the project.

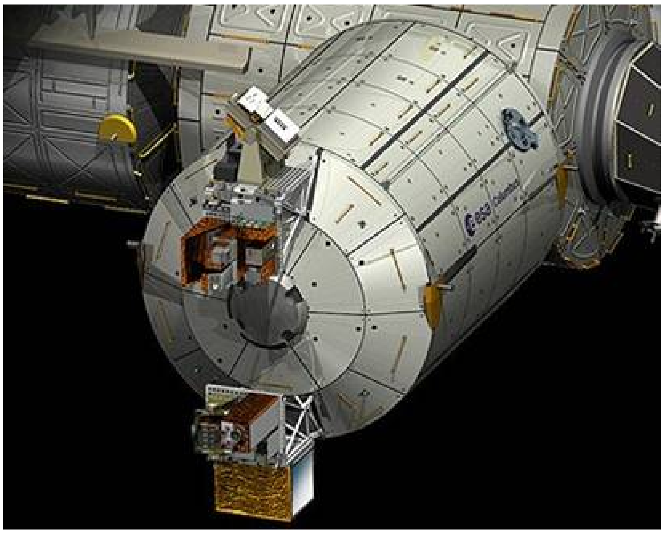


Figure 1: ACES mounted on Columbus (nadir external location)

2 PROGRAMMATIC ASPECTS

Sylvie LEON-HIRTZ – Fundamental Physics Programme Manager – CNES

The PHARAO project, initiated in the context of the Fundamental Physics scientific programme at CNES, is the result of recommendations of the Seminar of Scientific Prospective held in Saint-Malo in October 1993. The PHARAO cold atom clock was considered as a necessary step towards future Fundamental Physics space experiments. Physicists believe that the three interactions of microscopic physics (the strong, weak and electromagnetic interactions) described by the Standard Model of Particle Physics are unified at very high energy levels and that this should somehow be linked to gravitation in a single theory that includes a theory of quantum gravity. The natural way to look for evidence of these unifications is to search for deviations from the predictions of our current best theories, General Relativity and the Standard Model. These deviations are likely to be very small and must be sought in space, as it is an ideal environment for performing such experiments at the highest precision attainable. A breakdown of General Relativity predictions would signal the existence of unknown forces and "new physics" beyond the Standard Model. High performance cold atom clocks in space open the way for such new experiments. Moreover, space experiments in laser cooling will give us the opportunity to measure fundamental atomic forces and symmetries to a level which is out of reach on the ground. PHARAO is the first step in this direction. Developping the PHARAO clock has been a huge challenge due to the implied technologies. In this context, PHARAO remained a strong recommendation of the following CNES Seminars of Scientific Prospective in 1998, 2002 and 2004.

The main elements at the origin of the PHARAO project are:

- the successful method of cooling and trapping caesium atoms by laser developed at the *Laboratoire Kastler-Brossel* (LKB) of the *Ecole Normale Supérieure* in Paris (ENS), supported by CNES in the context of its science program since 1990 (Nobel Price to Claude Cohen-Tannoudji, Steven Chu et William Daniel Phillips) ;
- the application of this method to atomic fountains. The first operational primary standard based on cold caesium atoms was achieved in 1994 by the *Laboratoire des Systèmes de Référence Temps et Espace* (LNE/SYRTE) at the *Observatoire de Paris*, in cooperation with the ENS/LKB;
- the advantages of the microgravity environment for improving the performance of the clock. In June 1992, the feasibility of the cooling and trapping of atoms under microgravity was shown during a parabolic flight of the CNES Caravelle aircraft. In 1997, a complete laboratory prototype developed by SYRTE, LKB and the *Laboratoire de l'Horloge Atomique* in Orsay (LHA) was tested in the Airbus during CNES campaigns. In the same way, CNES started a R&D program on the critical technologies for the space-clock (micro-wave cavity, ultra-stable oscillator USO, laser, electro-optical components etc.), from 1993 to 1998;
- the need for ultra-accurate and ultra-stable atomic clocks in space for fundamental physics and for testing the effects of relativity. This led the laboratories LKB, SYRTE and LHA to propose the PHARAO space clock in the context of the ACES project in April 1997, in response to the ESA call for proposals for the external payloads on the International Space Station. ACES will make it possible to study the extreme limits of the clock's performance under microgravity but it also has its own scientific aims for testing relativistic effects (redshift, isotropy of light, search for a possible drift of the fundamental fine structure constant α).

A group of nine scientific proposals was received by ESA concerning the joint international ACES project. The final ACES configuration selected by the ESA peer groups in 1997 retained three scientific proposals:

- the PHARAO clock provided by CNES,
- the Hydrogen Maser SHM provided by the Observatoire de Neuchâtel,
- the Laser link T2L2 provided by CNES

plus the microwave link MWL which was added as an ESA contribution.

This configuration was submitted for approval to the Microgravity Program Board (ESA/PB-MG(97)23) and to the Manned Space Program Board (ESA/PB-MS(97)27). In 2001, the Manned Space Program Board approved the total ACES development budget (ESA/PB-MS(2001)49) and in July 2003 the overall C/D phase contract was awarded. In view of the general situation of the US Shuttle and International Space Station and of the technical challenges of the ACES project itself, major delays have occurred in the meantime. The overall situation of the ACES project was presented to the Human Spaceflight, Research and Applications Program Board in 2005 (ESA/PB-HSR(2005)18). Formal agreements will be finalised between CNES, the Swiss Space Office (SSO) and ESA in 2009 in order to confirm the delivery of the PHARAO and SHM flight models and allow the finalisation of the ESA industrial prime contract for ACES before the end of 2009.

The PHARAO project was submitted for approval to the CNES Scientific Program Committee (CPS) on various occasions:

- on 20 October 1997, to start phase A,
- on 30 April 1999, at the beginning of phase B,
- on 15 February 2001, when the laser link T2L2 and the orbitography equipment DORIS were withdrawn from ACES,
- on 8 June, 2 September and 15 October 2004 to consider the revised implementation approach and the technical difficulties encountered in the industrial development of the instrument leading to a project cost increase.
- during its June 2007 meeting, the CPS did not recommend the flight model phase due to the level of technical, financial and programmatic uncertainties, but recommended to preserve the technological base built by the project and to find a proper development plan.
- during its October 2008 meeting, considering the very significant reduction of these risks and the continuing scientific interest of the mission, the CPS recommended the completion of the PHARAO clock within the ACES framework.

The decision to start phase B of the PHARAO project was taken on 21 July 1999 (decision CNES/DG/99/125). The CNES Board of Administrators approved the start of the C/D phase on 3 May 2001 and the revision of the industrial contract on 3 December 2004. The decision to fly the PHARAO clock within the ACES project was taken by the Board of CNES on 4th December 2008.

Industrial development of the PHARAO instrument has been under way since June 2001. Following the recommendation of CPS, CNES has negotiated with industry the development of the Engineering Model of PHARAO. The last elements of the PHARAO EM model have been delivered to CNES in april 2006 and the EM is now complete at CNES for integration and performance testing. Mid 2009, the PHARAO instrument EM was delivered to ESA in order to perform integrated tests within ACES, including the maser SHM and to be integrated in ACES. These tests ended successfully in November 2009. The delivery of the Flight Model to ESA by CNES is planned for spring 2012. The last flight units (Cesium Tube and Laser Source) will be delivered to CNES for PHARAO integration in July 2011.

In 2009, ESA added the ELT (European Laser Timing) and a GNSS receiver onboard ACES. ELT is a laser link to perform time comparison between ground and space.

*For more information refer to [**96**] (reference given in the annex)*

3 SCIENTIFIC OBJECTIVES

Christophe SALOMON – Principal Investigator – ENS/LKB
André CLAIRON – Co-Principal Investigator – SYRTE

The Science objectives of ACES/PHARAO are both fundamental and technical.
The fundamental aspects concern both the physics of the cold atom clock (which will operate for the first time in conditions not accessible on Earth) and with fundamental physics tests (relativity and fundamental constants). The applied aspects are associated on the one hand with a demonstration of new technologies for SHM, PHARAO and MWL and, on the other, with a worldwide community, which will take advantage of the ACES frequency stability. These aspects will become increasingly important with future developments of navigation and positioning systems, new matter wave inertial sensors and fundamental physics tests in solar orbit. The scientific objectives are:

1) **To operate a laser cooled caesium clock in micro-gravity** with a relative frequency stability of 7-10 x 10^{-14} $\tau^{-1/2}$ where τ is the measurement time in seconds. Averaged over one day the stability will reach 2-3 x 10^{-16} and 0.7-1 x 10^{-16} averaged over 10 days. Figure 2 shows the expected PHARAO frequency stability on ISS. PHARAO will explore the domain of long interaction times made possible by the reduced gravity.

2) **To distribute by radio the optimised time scale of the combined system SHM-PHARAO, to ground users**. This time scale will be accurate to 30 picoseconds per day. Users belong to various areas of applications including: time and frequency comparisons, covering a large number of laboratories contributing to the calculation of TAI (*Temps Atomique International*), geodesy, Very Long Baseline Interferometry (VLBI), atmospheric propagation of light pulses and microwave signals etc.

3) **To perform fundamental physics experiments.** A new measurement of the redshift with an accuracy of 3x10^{-6}, a 25-fold improvement over the Gravity Probe A experiment of 1976. A search for a possible anisotropy of the speed of light at $\delta c/c$ ~2x10^{-10} will be made. A search for a possible time (or space) variation of the fine structure constant α, which is one of the fundamental constants of physics, will be investigated.

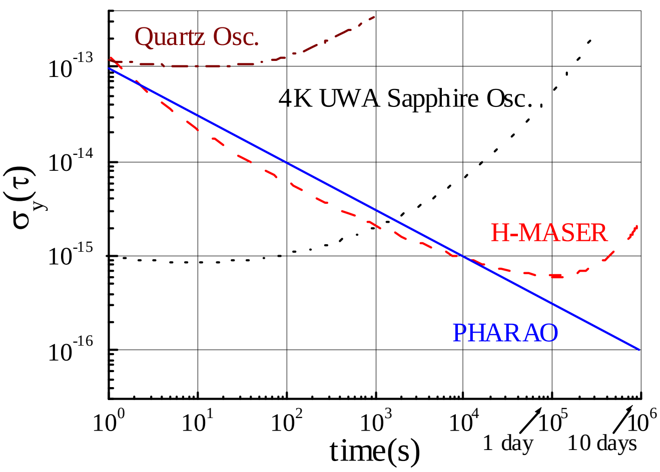


Figure 2: PHARAO frequency stability compared with quartz oscillators, SHM & cryogenic UWA oscillator

4 TECHNICAL CONCEPT AND DESCRIPTION

Christophe SALOMON – Principal Investigator – ENS/LKB
André CLAIRON – Principal Investigator – LNE/SYRTE
Philippe LAURENT – Principal Investigator – LNE/SYRTE
Pierre LEMONDE – Scientist – LNE/SYRTE
Giorgio SANTARELLI – Scientist – LNE/SYRTE

In an atomic clock, the duration of the coherent interaction between the atoms and the electromagnetic field is a fundamental limit to the resolution of the frequency measurement. This duration has been increased in the 90’s thanks to the laser cooling: the low velocity of the atoms cooled down to 1μK permits to increase the time passed in the interrogation cavity. This new type of clock was called “fountain” due to the fact that we launch the atoms upwards and that then they fall down back (see *Figure 3*). Thanks to the microgravity in space, this duration will be again increased.

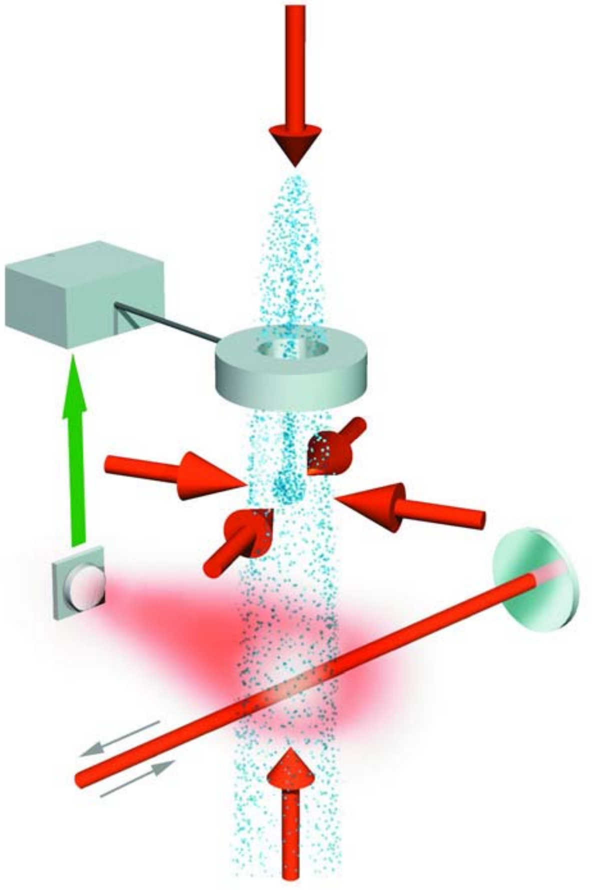


Figure 3: Atomic fountain principle

Due to gravity, this time cannot exceed 1 second for a reasonably tall fountain. By contrast, in microgravity conditions, the interaction time in PHARAO can increase up to 5-10 seconds with a simple and compact device. The principle of PHARAO is described in the following Figure 4. It looks like an optically pumped caesium beam frequency standard but, in microgravity, the atomic velocity can be reduced by a factor of 1,000!

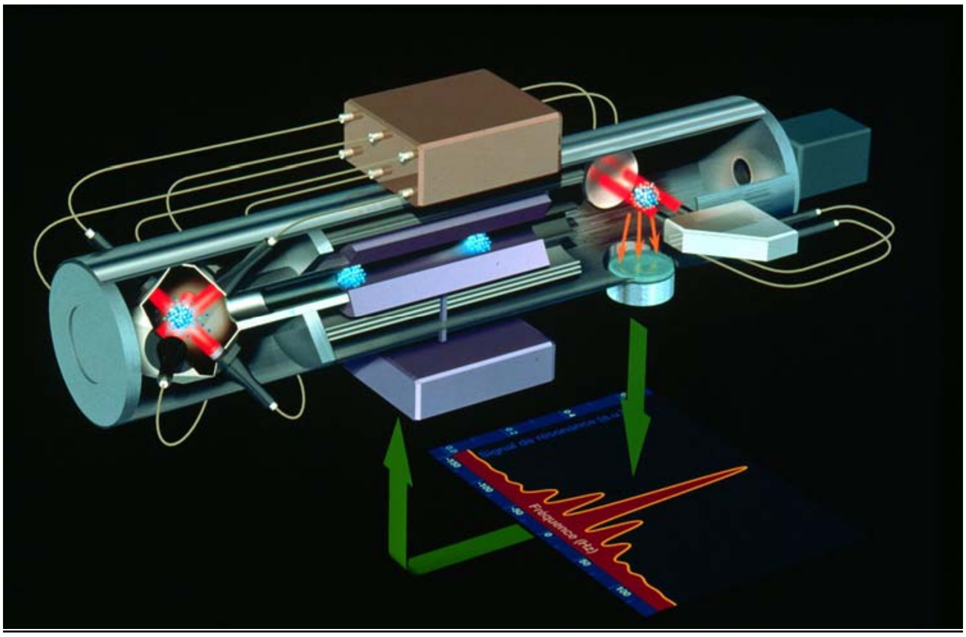


Figure 4: Atomic clock principle in microgravity

The PHARAO instrument consists of four main parts: a vacuum tube also called the caesium tube (TC), an optical bench also called Laser Source (SL), a microwave source (SH) and a control system (UGB, BEBA and flight software). The optical bench provides the laser beams for cooling, manipulating and detecting the caesium atoms. Light is delivered to the core of the device, the interaction chamber, using optical fibers. In this evacuated chamber (residual pressure below 10^{-10} Torr) a 2-zone microwave cavity is located, fed with a 9.2 GHz signal which is tuned around the caesium hyperfine transition at frequency ω_0. A static magnetic field, highly stable in time and space, is applied to the atoms with solenoid coils to control the magnetic environment and the vacuum tube is surrounded by three layers of magnetic shields to reject external magnetic perturbations.

The clock operates in a sequential mode: capture of the atoms, launch, final cooling, preparation, selection, interaction with the microwave field, detection and frequency correction. The cycle duration depends on the capture time and the launching velocity. The sequence is driven by a main computer (UGB) monitored by the ground control centre.

First, about 10^8 atoms are captured and cooled in optical molasses at the intersection of six laser beams. Using the same set of laser beams, they are launched through the tube with an adjustable velocity v. After launch, atoms are quickly cooled to 1 microKelvin (final cooling phase). Atoms in the particular quantum state F=4, with magnetic sublevel m=0 are selectively transferred to F=3, m=0 with an auxiliary microwave cavity (preparation phase). Atoms remaining in F=4 with m different from 0 are pushed sideways by radiation pressure (selection phase) so that only F=3, m=0 atoms proceed further in the tube in free flight. They interact twice with the microwave magnetic field in the two Ramsey zones separated in space. After these interactions, they enter the detection region where the transition probability from the lower quantum state to the upper one is measured by light-induced fluorescence using 2 laser beams. In the first beam, only atoms in the internal state F=4 are detected and in the second beam only atoms in state F=3. The fluorescence is collected by 2 photodiodes and the resulting signal is processed by the controlling system.

This completes one cycle of operation of PHARAO. Repeating this cycle while scanning the microwave field around the caesium resonance produces the well-known Ramsey fringe pattern: the transition probability oscillates as $\cos^2(\omega-\omega_0)T/2 = \cos^2(\omega-\omega_0)D/2v$ around the caesium hyperfine frequency ω_0. The period of the fringes is inversely proportional to the time T = D/v between the two Ramsey interactions. In microgravity this time can be made 5 to 10 times longer than in a fountain on Earth. For instance, the following figure displays the expected signal in PHARAO for v = 5 cm/s in comparison with a fountain signal and a thermal beam resonance.

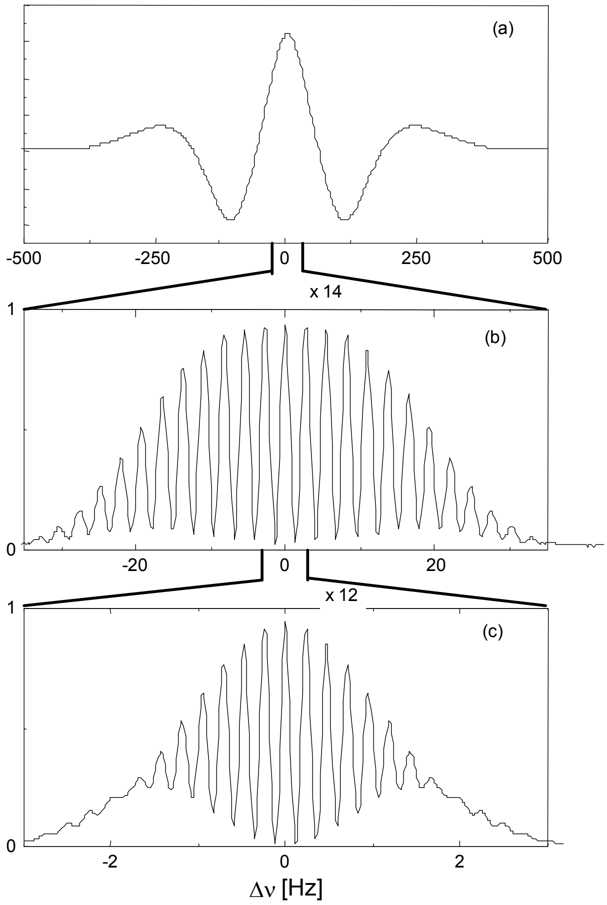


Figure 5: PHARAO expected signal versus fountain
The gain in resolution obtained in microgravity conditions
a) The resonance in thermal beam Cs clock: width 100 Hz
b) The resonance in a fountain: width 1 Hz
c) The PHARAO resonance: width 0.1 Hz for launch velocity 5 cm/s

Not only can the interaction time be longer in PHARAO but the constant atomic velocity in the instrument also brings a number of advantages with respect to the accuracy of the clock: low cavity phase shift and low collisional shift. The design parameters for PHARAO are a frequency stability of 1 (target : 0.7) $\times 10^{-13}\ \tau^{-1/2}$ where τ is the measurement time in seconds, and an accuracy of 3 (target : 1) $\times 10^{-16}$. Averaged over one day, the stability will reach $2\text{-}3\times 10^{-16}$ and about 10^{-16} over 10 days. This stability crucially depends on the performance of the interrogation oscillator (Ultra-Stable Quartz oscillator).

Laser light is provided by an all-diode laser system. The optical bench includes 4 frequency-stabilised diode lasers, some acousto-optic modulators to precisely tune the beam frequencies and control the beam intensities and mechanical shutters to turn off the light. The laser beams are injected into the ultra-vacuum tube with ten optical fibers.

The selection and the interrogation field which feed the microwave cavities are synthesised by a frequency chain. The main oscillator of the chain is a 5 MHz quartz oscillator whose frequency is multiplied and mixed with a programmable synthesiser to reach 9.192631770 GHz. It is important that the phase correlation between the two fields (preparation and interrogation) should average out at zero in the medium-term to avoid a frequency shift of the atomic resonance induced by an initial atomic coherence. The operating control system manages the operation of the clock. It provides all sequential signals, drives the power and the frequency of the synthesiser chain and processes both detection signals in order to derive the frequency correction to be applied to the programmable synthesiser of the frequency chain.

The PHARAO project is based on more than 15 years of cold atom frequency standard development in our laboratories. Three atomic fountains have been built: F01, F02 and FOM. FO1 was built in 1990 and by 1994 it was the first fountain clock operating as a frequency standard. Today FO1 and FO2 reach stabilities of $2\text{-}3\times10^{-14}\,\tau^{-1/2}$ and accuracies of 7×10^{-16}. These are the best fountains in the world. *For more information refer to [**127**] and [ref **129**].*

Transfering a laboratory-bound cold atom clock into an automated experiment suitable for Space use leads to several technical challenges. A first step towards this goal was the test of a clock prototype in the reduced gravity of the CNES ZERO G Airbus in May 1997. After this successful demonstration, the prototype was modified to an atomic fountain (the FOM fountain) in order to optimise its performance on Earth. Today this model is used as a design reference for development of the PHARAO space model and as a transportable primary standard. It is the first transportable cold atom experiment in the world. The present frequency stability is limited by the quartz oscillator at $1.2\times10^{-13}\,t^{-1/2}$ and its accuracy is 8×10^{-16}. In May 1999, February 2003 and june 2010, FOM was taken to the Max Planck Institute für Quantenoptik (MPQ) in Garching (Germany) to serve as an absolute frequency reference for the absolute frequency measurement of the 1s-2s transition in atomic hydrogen. The frequency accuracy of this transition is below 10^{-14}, an improvement of at least one order of magnitude. In June 2007 FOM was taken to the University of Innsbruck to serve as an absolute frequency reference for the absolute frequency measurement of the S-D transition in calcium ion. The frequency accuracy of this transition is $2.4\ 10^{-15}$. These measurements are currently among the most precise reference lines in the optical domain of the spectrum. The FOM fountain has also been operated in Braunsweig (Germany) for a direct comparison with the PTB (*Physikalisch Technische Bundesansalt*) Caesium fountain CSF1.

Finally the transportable fountain has been transported to Toulouse in order to characterise the performance of the PHARAO space clock.

Figure 6: PHARAO prototype in CNES ZERO G Airbus (May 1997)

The PHARAO space clock industrial development began in 2002. Engineering models of all subsystems, fully representative of the flight configuration, have been built and tested by the industry. They are now delivered to CNES for instrument integration and test.

In April 2006, the first coupling between the laser source and the caesium tube optical fibers was performed. The first cold atoms were obtained and also, with a microwave source, the first Ramsey fringes. The obtained results have shown a very satisfactory behaviour of both the laser source and the caesium tube. *For more information refer to [**161**]*

Since then, the test programm has generated many improvements and corrections to the flight software. It has also contributed greatly to a better knowledge of the instrument and was very useful for relaxing some specifications which had been proved too severe. Therefore the test program contributed greatly to the positive decision on the program. The test program will continue till the end of 2010. The EM has been formally delivered to ESA on July 2009 and was used for ACES servo-loop tests during ~~the summer~~ Autumn 2009. The EM test program will be completed in 2010 with the long term performance tests and the EMC tests.

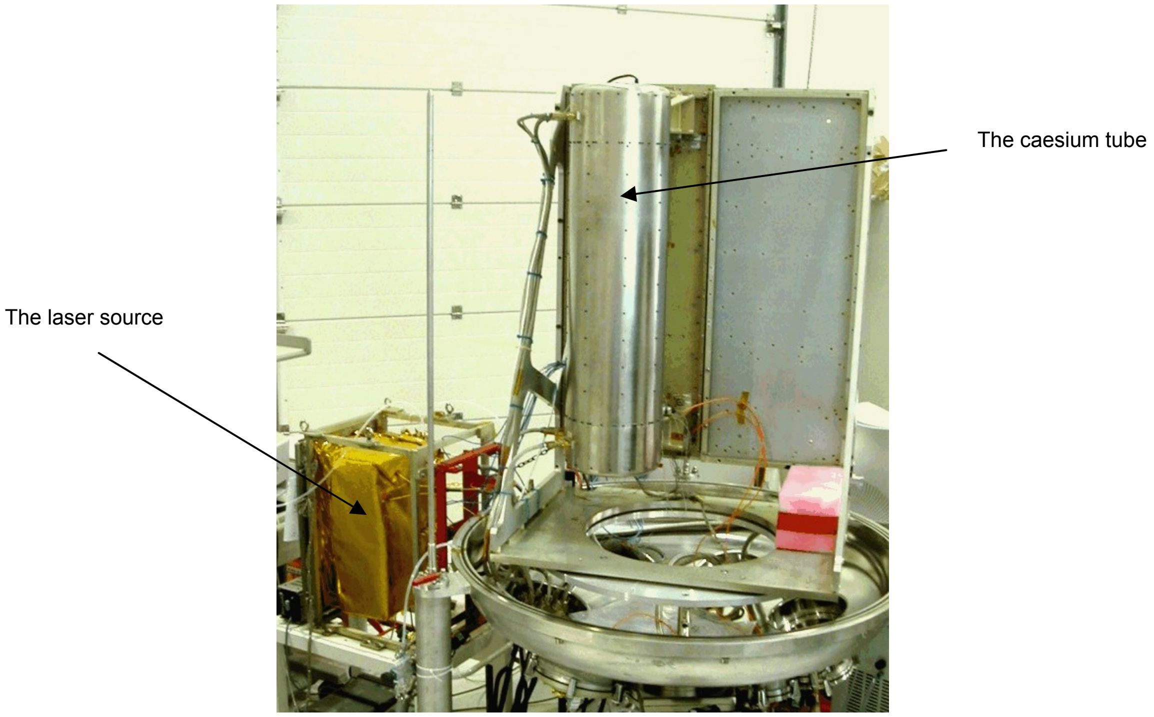


Figure 7 : Laser source and caesium tube first coupling (April 2006)

5 SYSTEM CONFIGURATION

5.1 SYSTEM DESCRIPTION & INTERFACES

Frédéric PICARD – System engineer – CNES

5.1.1 INSTRUMENT BREAKDOWN

The PHARAO instrument is made up of five separate units:

- **the caesium tube (TC)**, in which atoms are captured, launched, cooled, selected and detected after microwave interaction within a microwave cavity. The caesium tube provides ultra-vacuum conditions all along the path of the atoms and applies a constant and extremely uniform magnetic field along the atomic path, especially inside the microwave interrogation chamber. It also includes the ion pump high voltage supply (CV-THT), which is mounted separately on the ACES baseplate.
- **the laser source (SL)** provides the various laser beams necessary for the capture, launch, cooling, atomic selection and detection of atoms;
- **the microwave source (SH)** supplies 9 GHz signals to drive interrogation and preparation cavities. This unit provides the 100 MHz reference signal (called metrological signal);
- **the on board management unit (UGB)** processes the detection signal in order to command the frequency corrections to be applied to the microwave source in autonomous mode or transmitted to ACES-XPLC in the other operational modes. It also synchronises the different phases of the atomic cycle, managing the measurement acquisition and the remote control systems in order to modify the functional parameters of the instrument;
- **the BEBA electronic unit** controls the caesium tube magnetic coils and acquires the analog signals from the caesium tube.

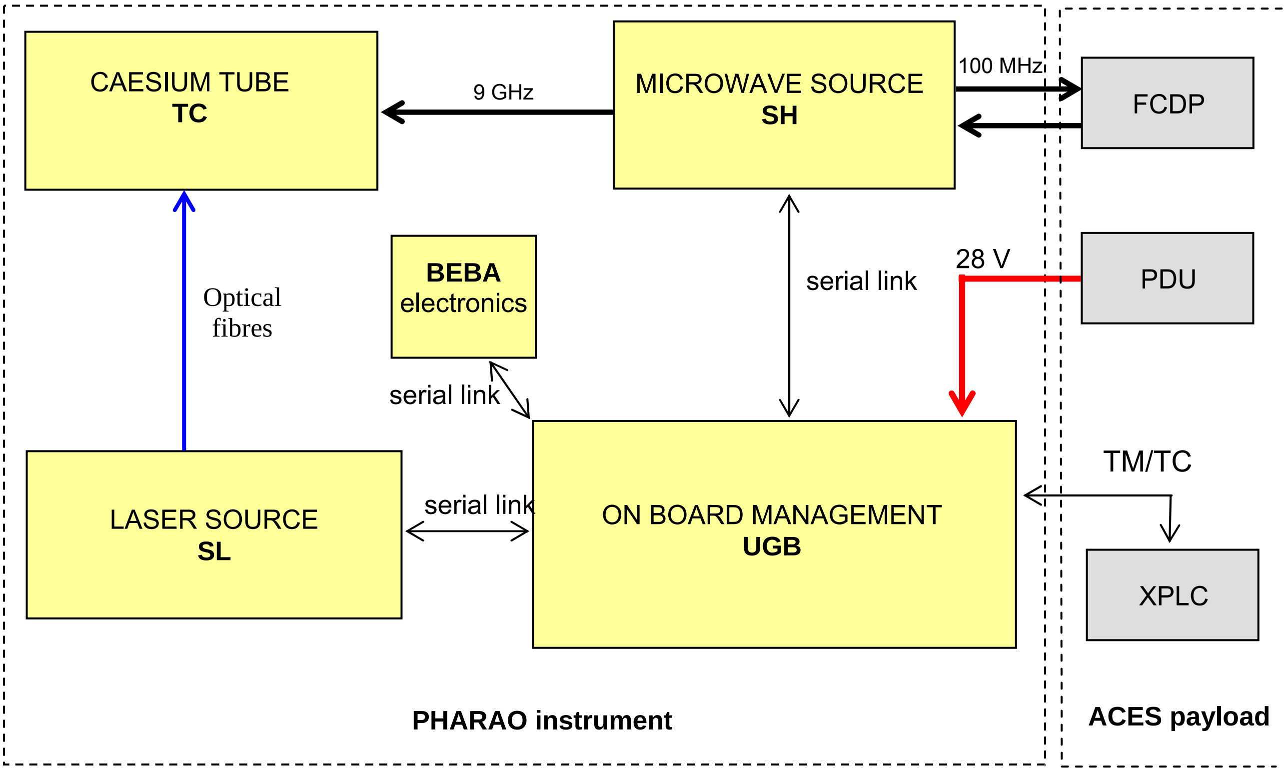


Figure 8: PHARAO instrument breakdown

5.1.2 MASS AND DIMENSIONS

The following budgets reflect the C/D phase design.

ITEM	MASS (Kg)	SIZE (L x l x h, mm)
Laser source (SL)	21.5	532 x 335 x 198
Caesium tube (TC) + CVTHT	44.8	1059 x 336 x 464
Microwave source (SH)	7	300 x 270 x 117
On board management unit (UGB)	6.3	245 x 240 x 120
BEBA	1.3	134 x 118 x 96
TOTAL (including harness, fixations and margin)	**92**	

Figure 9: PHARAO: mass, volume and units

5.1.3 POWER BUDGET

The following power budget is given for the operational modes. It gives the average power dissipation of each PHARAO unit.

ITEM	**POWER DISSIPATION** Typical (W)	**POWER DISSIPATION** Maximum (W)
Laser source (SL)	30	47.5
Caesium tube (TC)	5	5.5
Microwave source (SH)	21	26
On board management unit (UGB)	26	31
BEBA	3	4
Total	**85**	**114**

Figure 10: PHARAO power budget

5.1.4 TM / TC BUDGET

The following table shows the TM and TC data rates at the PHARAO / ACES interface. It includes the identifier and the checksum. It includes also the fillers necessary to reach the fixed packet size imposed by the ACES ⇔ PHARAO transmission protocol.

Packet	Size (bytes)	Nb of packets / ACES cycle (10 sec)	Data rate (Mbytes/day, rounded)
Frequency comparison data	6	40	2
ACES Time	18	1	0.2
Telecommands	99	0 to 1	0 to 1
Data load	370	0 to 6	0 to 20
Total TC			**2 to 23 Mbytes / day**
Housekeeping (TM-A)	372	2	6
Science (TM-P)	154	1 to 56	1 to 75
Dump (TM-D)	370	0 to 2	0 to 6
Total TM			**7 to 87 Mbytes / day**

Figure 11: PHARAO TM/TC data rates at PHARAO/ACES interface

5.1.5 FUNCTIONAL BLOCK DIAGRAM

The main functions are shown in the following diagram:

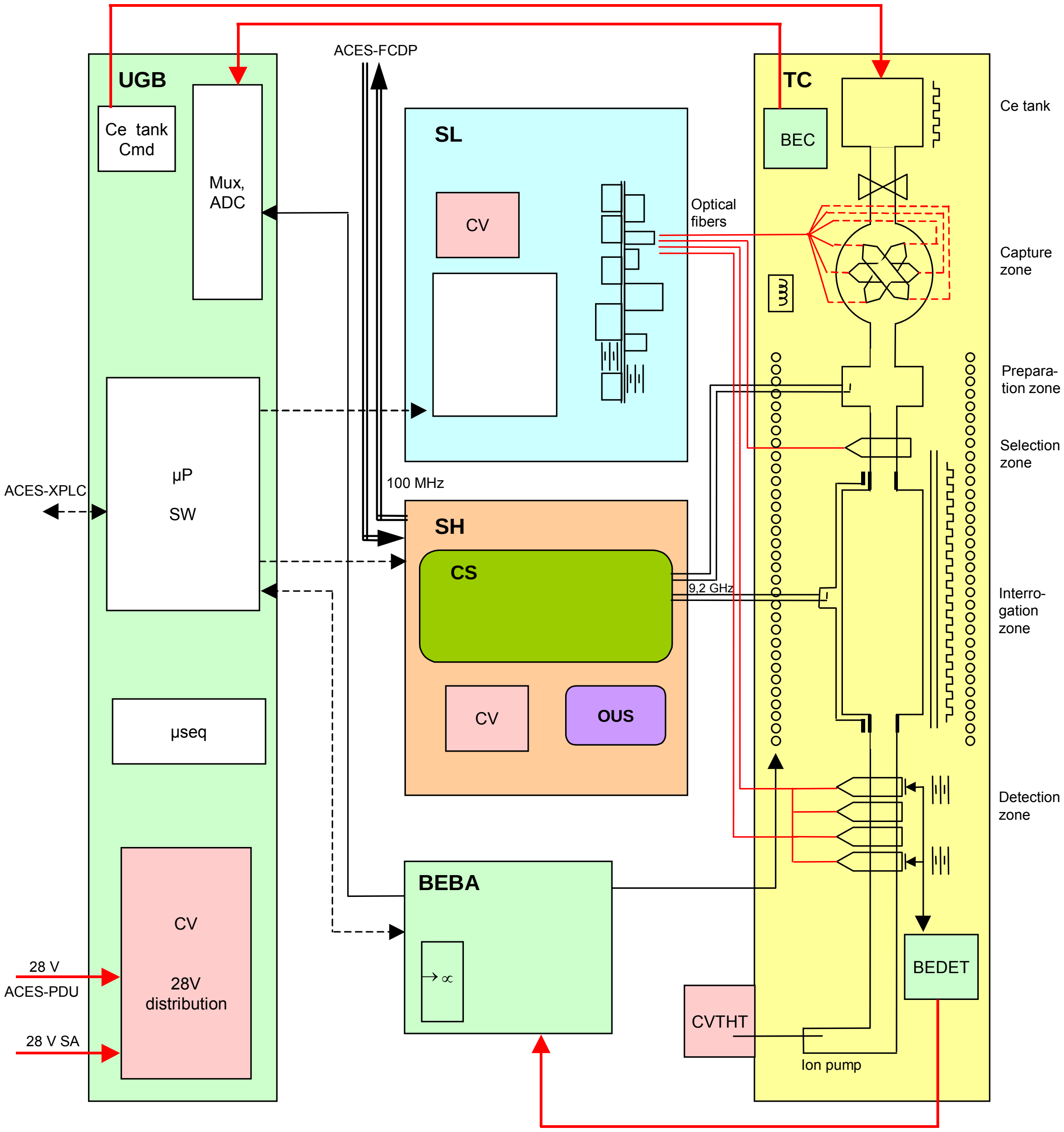


Figure 12: PHARAO functional diagram

5.2 MECHANICAL ARCHITECTURE

Fabrice BUFFE – Mechanical architect – CNES

The PHARAO instrument is composed of 5 units which form 6 boxes: TC, TC-CVTHT, SL, SH, BEBA and UGB. The instrument is accommodated in the ACES payload as shown in the following figure:

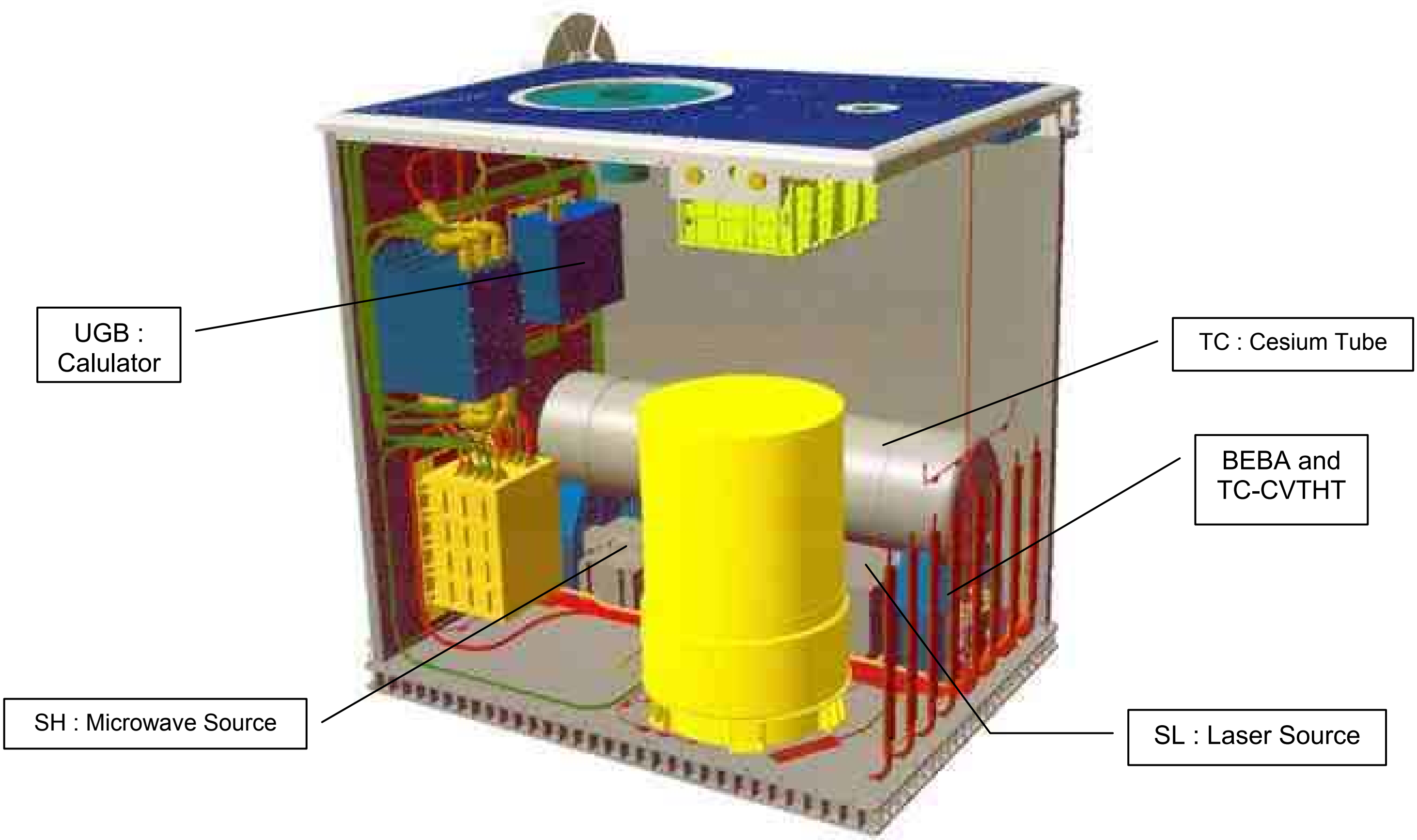


Figure 13: PHARAO in ACES layout (EADS)

All the PHARAO sub-assemblies (except UGB, onboard management unit, harness and harness bracket) are accommodated in a volume of 1059 mm x 336mm x 464 mm on the ACES baseplate. Due to ACES volume constraints, the PHARAO units are very close together.

PHARAO has no main structure. The different PHARAO units are directly mounted on the ACES baseplate (cooled with 4 heat pipes linked to the +X wall) or on the -X wall (UGB).

The PHARAO harness is made of electrical cables, but also optical fibers and microwave cables.

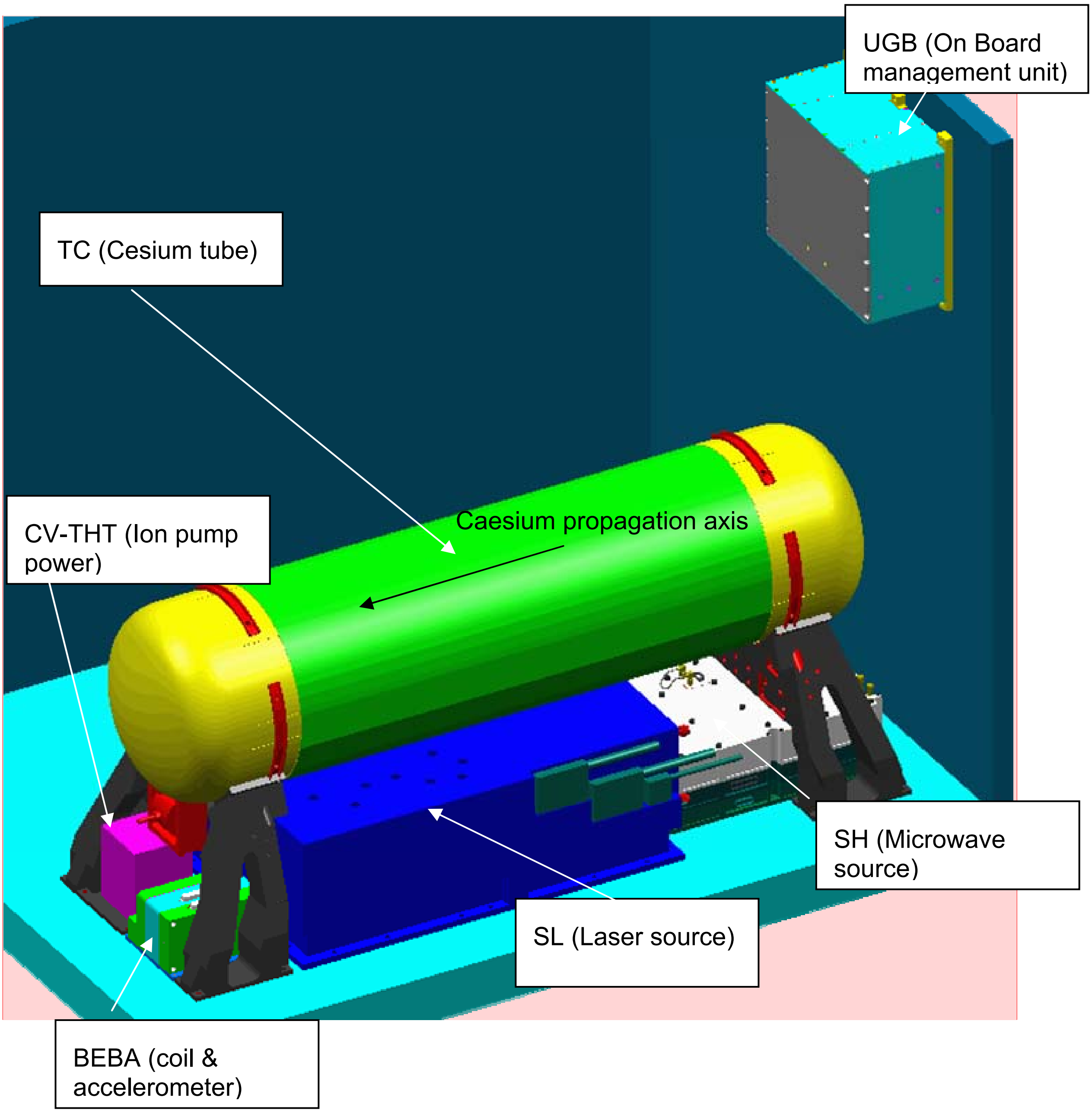


Figure 14: PHARAO sub-assemblies (MLI, harness and harness bracket not shown)

The mechanical design was made on the following requirements :

- stiffness (100Hz respected),
- quasi-static loads (30 to 35g except UGB with 42g),
- random loads (Max 11.12 gRMS except for the UGB : 13.44 gRMS)
- safety requirements (for manned flights).

The main difficulty is to make the existing PHARAO mechanical design compatible with the random load requirements. The current baseline is a HTV launch, but Space-X could be another possibility.

The mechanical qualification of PHARAO is performed at unit level for mechanical tests (sinus, quasi-static, random) with qualification or flight models (QM + FM or PFM approach) and completed at ACES level on the ACES FM (mainly for the harness).

5.3 THERMAL ARCHITECTURE

Patrizia TORRESI –Thermal architect – CNES

The objective of the thermal control is to guarantee that subsystems operate normally in the temperature range required for each device. The thermal environment of the PHARAO instrument taken into account for the design can be divided into 4 different interfaces:

Interface	Min / Max operating temperatures	Peak to peak temperature stability
Base Plate (except for TC)	10°C / 33.5°C	3°C over 1 orbite, 4°C over 20 days for SL (no guaranteed long term stability for the others equipments)
Base Plate for TC	10°C/ 31.4°C	3°C over 1 orbit, no guaranteed long term stability
-X Wall	-20°C / 43.2 °C	6°C over 1 orbit, no guaranteed long term stability
Multi-Layer Insulation	Thermal insulation from the rest of ACES, except for UGB.	

Figure 15: PHARAO thermal environment

The global design and interfaces are the following:

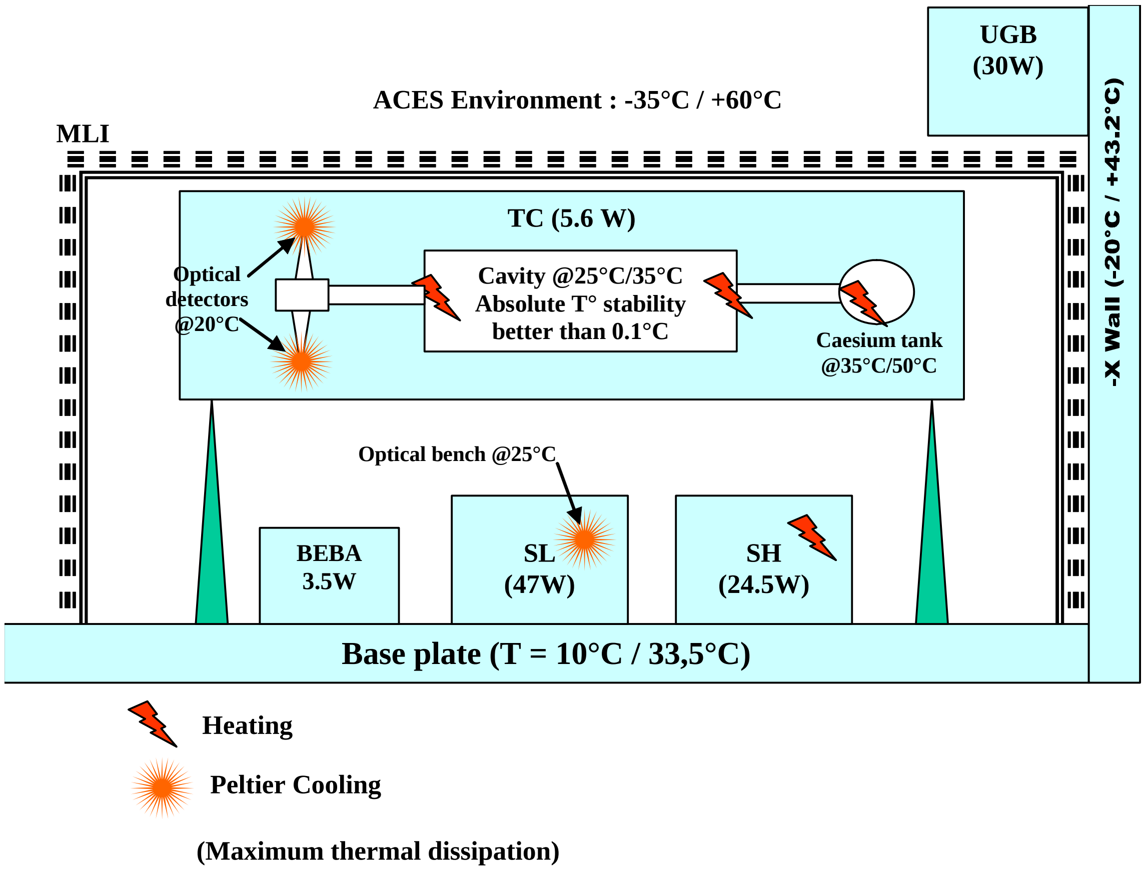


Figure 16: PHARAO thermal control

Thermal dissipations: the following table gives the thermal dissipations of each subsystem used for the thermal model, given for a Base Plate at 33.5°C (except for the TC whose TRP temperature is 31.4°C):

	Power dissipated by electrical consumption	**Thermal regulation power at 33.5°C**	**Total power (W)**
TC	2.1 W	3.5 W	5.6 W
SH	24.5 W	-	24.5 W
SL	33 W	14 W	47 W
BEBA	3.5 W	-	3.5 W
TOTAL baseplate	**63.1 W**	**17.5 W**	**80.6 W**
UGB	30 W	-	30 W
TOTAL PHARAO	**93.1 W**	**17.5 W**	**110.6 W**

Figure 17: PHARAO thermal dissipations used in the thermal model

The main challenge for the thermal control of PHARAO is to guarantee very good temperature stability for the sensitive components, mainly :

- The TC microwave cavity temperature shall be known with an absolute accuracy of 0.1°C without any possibility to measure the temperature on the cavity itself to avoid perturbations to the atoms. For that, to minimize the thermal gradients, the cavity temperature is regulated at a temperature selected in the range of 25°C to 35 °C depending on the temperature of TC TRP. This regulation has a direct impact on the accuracy performance of the clock;
- The TC detection has to be cooled in order to have an acceptable S/N ratio;
- The SL optical bench has to be regulated at 0,1 °C level in order to insure the laser flux level and the laser diodes functioning. The laser diodes have their own fine temperature regulation (0.001 °C level).
- The SH chain has to be regulated in order to limit the disturbances on the RF signals (100 MHz and 9,2 GHz). The USO has its own regulation of the oscillator at a temperature of 70°C.

Another difficulty is the large range required for the non-operational temperature (-40 / +60°C) with which some specific components cannot comply. The AOMs (Acousto Optical Modulators) of the Laser Source are limited to a maximum temperature of +40°C and cannot be replaced by any other components.

5.4 ELECTRICAL ARCHITECTURE

Frédéric PICARD – System engineer – CNES

5.4.1 PHARAO / ACES ELECTRICAL INTERFACES

The PHARAO instrument general interfaces are depicted in the following drawing. It is connected to the PDU for electrical power supply, to XPLC and XCMU for TM/TC, and FCDP for signal comparison with SHM.

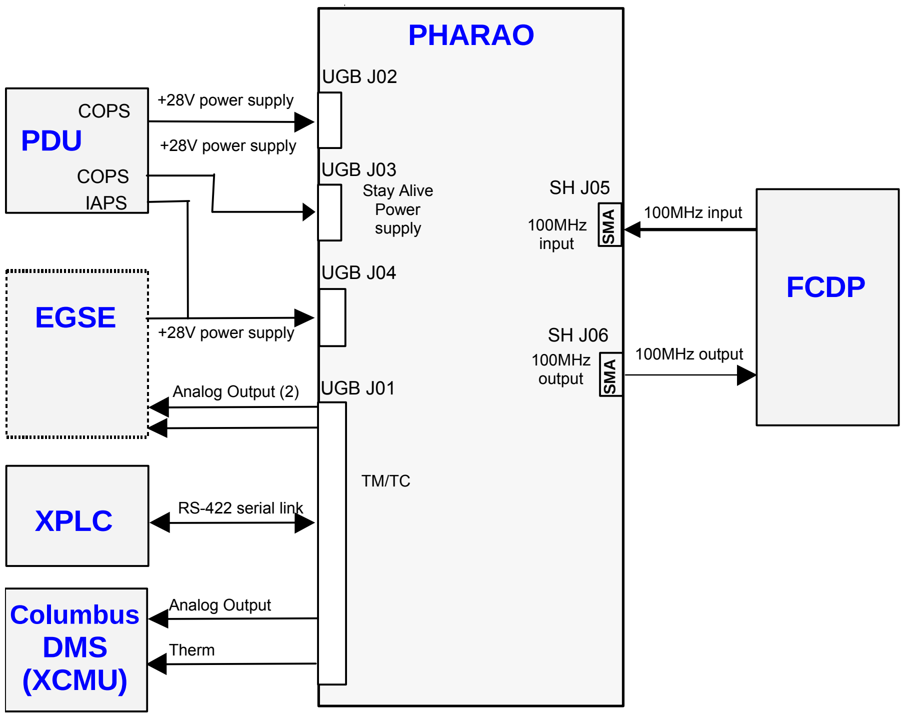


Figure 18: PHARAO electrical interface with ACES

5.4.2 PHARAO ELECTRICAL ARCHITECTURE

The PHARAO electrical block diagram is given below. PHARAO is supplied by two 28 V lines:

- A 28 V stay-alive used to power the ion pump in order to keep the vacuum in the caesium tube. This line shall never be switched off for periods longer than typically 10 days during the entire life of the TC.
- A main 28 V supply, which feeds all the electronics, the heaters and the Peltier coolers. UGB, SL and SH have their own overcurrent protection and switching capability.

The TC electronics (BEC and BEDET) and the BEBA are supplied by secondary voltages made by the UGB "external" DC/DC converter.

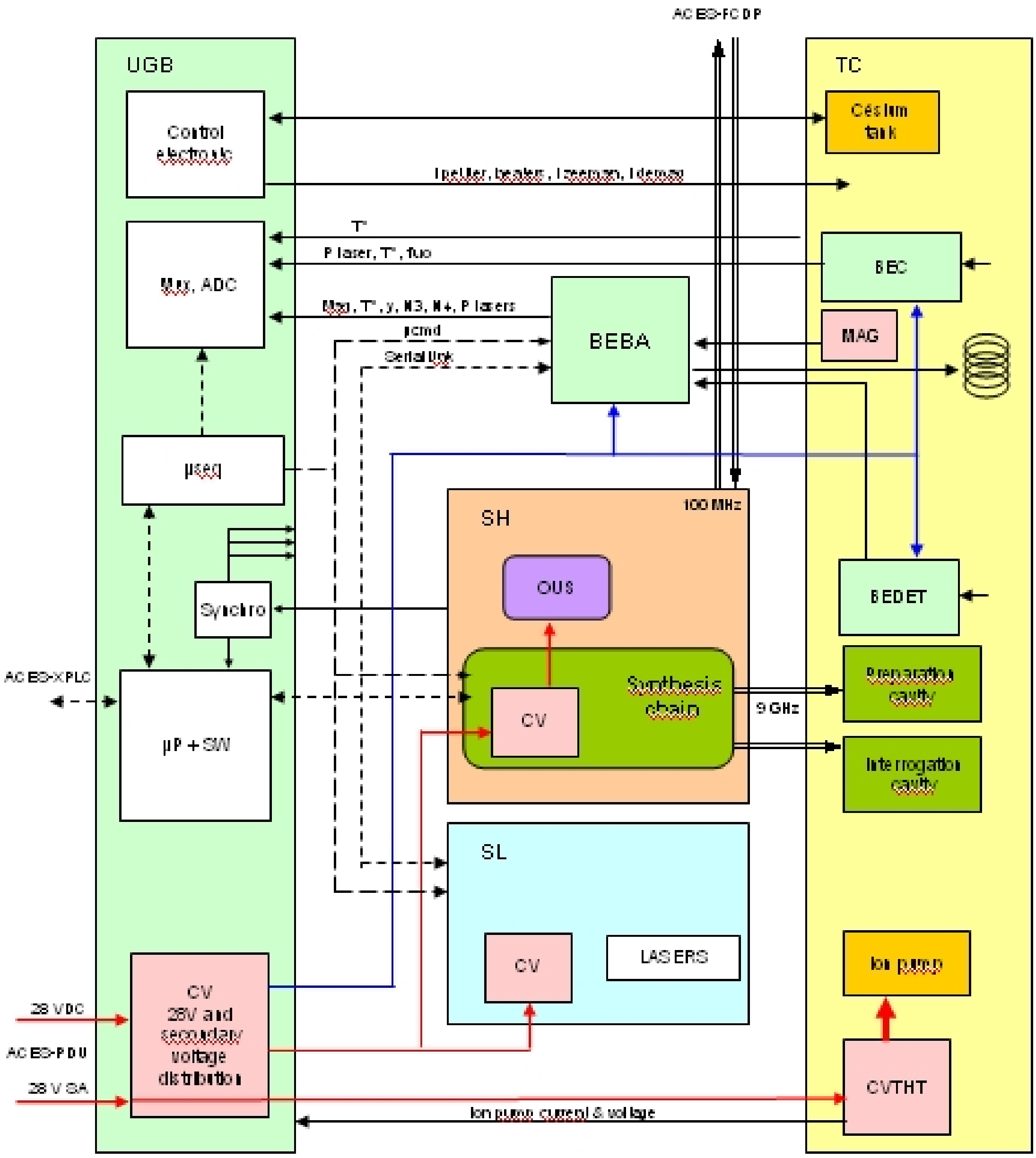


Figure 19: PHARAO electrical block diagram

All PHARAO clocks and converters are synchronised on a frequency produced by the microwave source.

- In order to synchronise all the necessary actions to be performed during each PHARAO atomic cycle with the atom cloud trajectory inside the tube, a specific function called “micro-sequencer” is implemented in the UGB. It provides 24 micro-command lines (pulses) which control the exact time for:
    - laser beams ON / OFF, power and frequency change,
    - 9 GHz microwave power and frequency change,
    - acquisition of measurements.
- The list of micro-commands to be executed during a PHARAO atomic cycle is stored in a table called the “micro-command table”. The composition of a micro-command table depends mainly on the speed required for the atoms and the usage of the instrument (operational mode, technological mode...). These tables are stored in the UGB memory and new tables can be uploaded from the ground.

There are 3 serial communication lines between PHARAO units, isolated by optocouplers:

- one from UGB to BEBA
- one from UGB to SH
- one bi-directional between UGB and SL.

5.4.3 POWER DISTRIBUTION

The following diagram shows the electric power distribution. The main features are:

- UGB receives from ACES PDU the two 28V power lines named 28 V SA and 28 V DC.
- The 28 V SA power bus is dedicated exclusively to the ion pump.
- UGB provides the following to peripheral equipment:
  - Three 28 V power lines (SL, SH and TC ion pump)
  - + 15V / - 15 V for BEBA and BEDET,
  - + 5V / - 5 V for BEBA
  - + 15V / - 15 V for BEC.

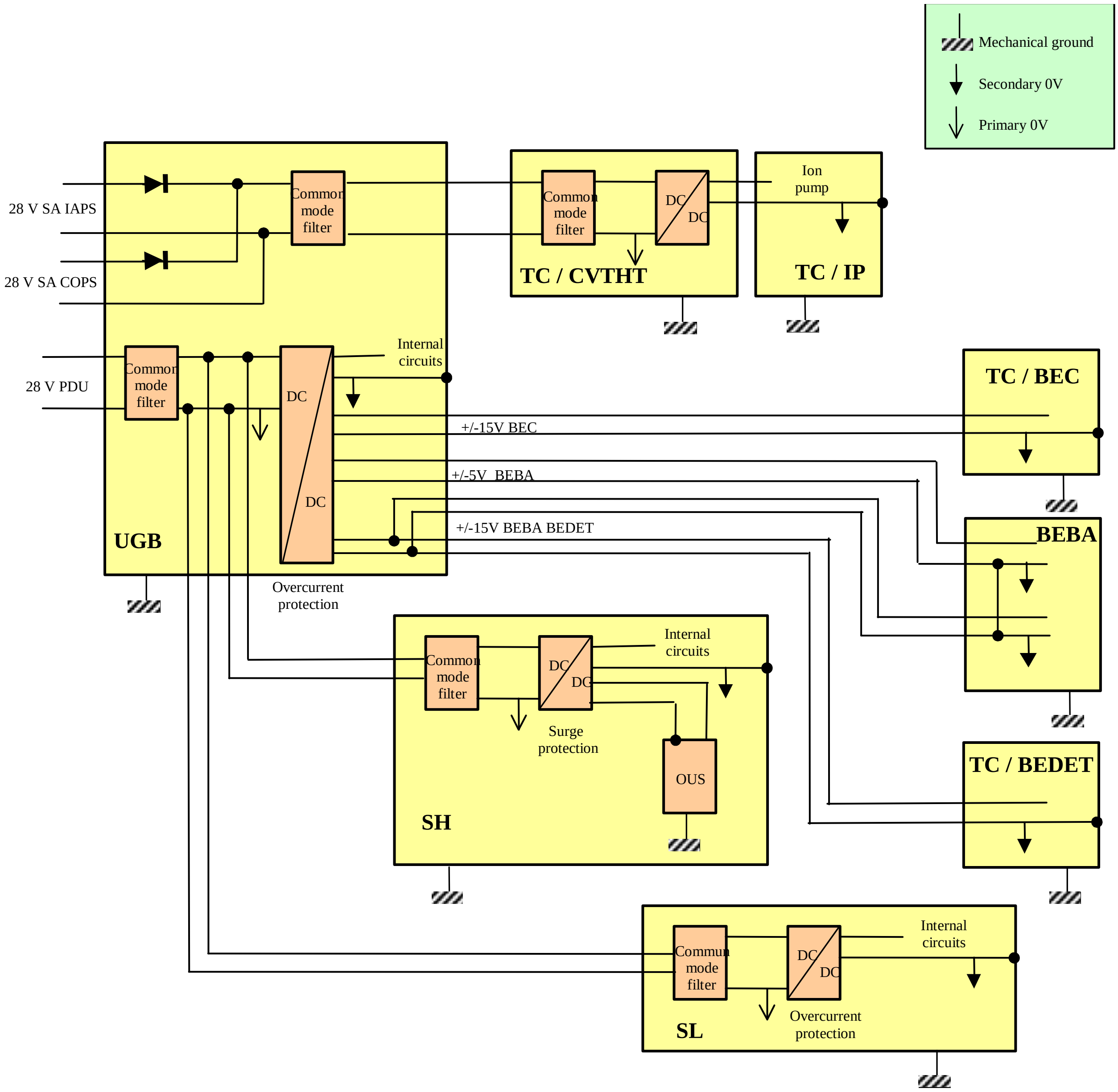


Figure 20: PHARAO electrical power distribution

5.5 OPTICAL ARCHITECTURE

Clément LUITOT – Optics architect – CNES

The main optical functions for the optical architecture of PHARAO are to:

- Generate all the laser beams needed for the optical interaction with caesium atoms (function attributed to the Laser Source).
- Capture the Caesium atoms.
- Measure the number of cold atoms.
- Cool the caesium atoms down to 1 µK
- Ensure a correct launch speed (between 0.05 to 5 m/s) for the atoms.
- Select the atoms which are in the correct magnetic sub-level before the interrogation phase.
- Divide up the atom cloud to limit its size for the lowest launching speeds.
- Check the size of the atom cloud.
- Determine the number of atoms at levels 3 and 4 after the interrogation.
- Distribute the laser beams provided by the Laser Source (SL) to the different optical parts of the Caesium Tube (TC).

These functions are performed inside two subsystems (SL and TC), which are connected by means of optical fibers. In order to obtain a high polarisation ratio, we use polarisation maintaining fibers and polarising cube beam splitters.

The SL subsystem provides and controls 10 laser beams with very precise requirements concerning frequency and power. The SL must also cut off the laser beams very precisely and respect the optical interface in terms of high efficiency for coupling into the optical fibers. The optical design of the SL aims for:

- good efficiency for the overall optical transmission
- high optical power and frequency stability
- high level of compactness
- low power consumption and low mass.

The optical functions of the TC (Caesium Tube) subsystem allow the interactions between atoms and laser beams, and the detection of fluorescence from atoms.

These interactions concern the capture (point n°1 in the figure below), selection (point n°2), detection (point n°3) and detection zones (point n°4) of the TC. To meet the PHARAO requirements, the optical system must precisely control:

- the radiometric features (radiant power, irradiance, states of polarisation, stray light level)
- the geometric features (size and alignment of the optical beams)
- the fluorescence of the atoms by illuminating a small detector in order to maximise signal-to-noise ratio.

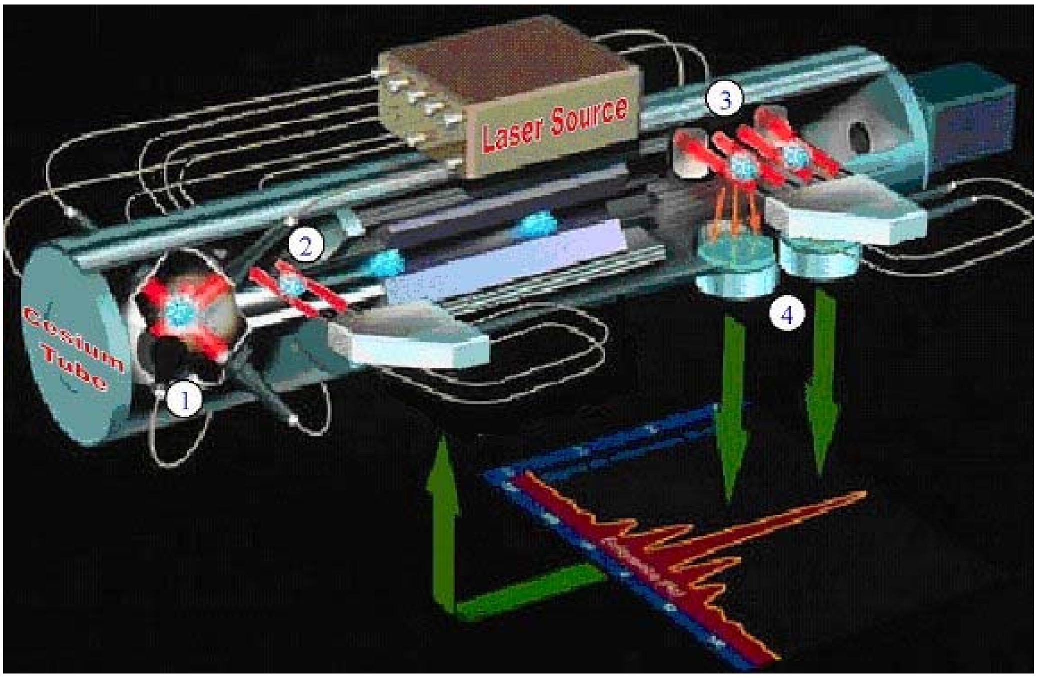


Figure 21: PHARAO diagram of optical architecture

The main challenges for the optical architecture are:

- The control of the stray light in the TC, mainly in the detection zone.
- The required high level of stability (power and frequency) for the 10 laser beams in order to achieve complete control of the atoms.
- The high degree of compactness

5.6 MICROWAVE ARCHITECTURE

Benoît Léger – Microwave Architect – CNES

The principle of an atomic clock is to lock an oscillator onto the atomic resonance frequency of 9.192631770 GHz with a very low phase noise. This signal is delivered by the ultra-stable microwave source. The principle shows that the greater the interaction time of the atoms with the radiation emitted by the oscillator, the narrower the resonance.

Two key points determine the ultimate performance of an atomic clock: a narrow resonance and a high signal-to-noise ratio. The narrow resonance is a function of the atom velocity and the cavity length: the quality of the interaction between the atoms and the cavity electromagnetic fields is very important.

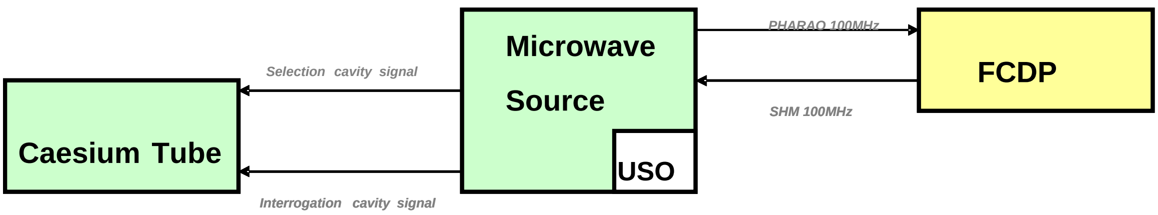
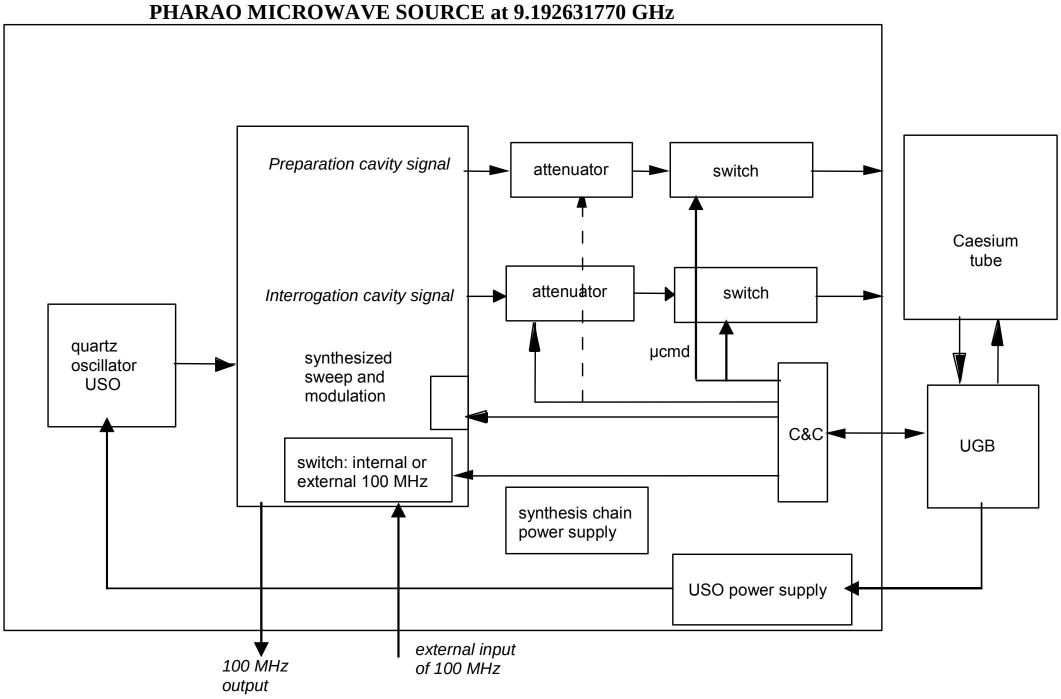


Figure 22: PHARAO microwave architecture

This microwave source is composed of an ultra-stable oscillator (USO), and a frequency synthesis chain. The main functions of this source are to provide two ultra-stable frequencies at 9.192631770 GHz from a 5 MHz reference (USO) and also to provide a 100 MHz signal for a comparison with other clocks. In case of failure of the USO, an external 100 MHz signal can be used.

PHARAO MICROWAVE SOURCE at 9.192631770 GHz



"PHARAO MICROWAVE SOURCE".

Figure 23: PHARAO Microwave Source block diagram

Two microwave signals, the preparation cavity signal and the interrogation cavity signal, are generated by the ultra-stable microwave source.

5.7 COMMAND AND CONTROL

Serge BERAUD – Control Command Architect – CNES

5.7.1 PHARAO MODES

A PHARAO mode is defined by:

- PHARAO physical electrical state (OFF, Stay Alive, Low Power, Configuration, Demagnetisation modes)
- data exchange configuration with ACES (Technological, Operational modes).

In Technological modes, PHARAO prepares its sub-assemblies and does not provide ACES with any science data (P Packets do not contain frequency correction information but contain general function processing results).

In Operational modes, PHARAO provides ACES with data depending on data received from ACES and on ACES PHARAO data management. This is the reason why four PHARAO operational modes are identified (autonomous, evaluation, nominal and back-up modes).

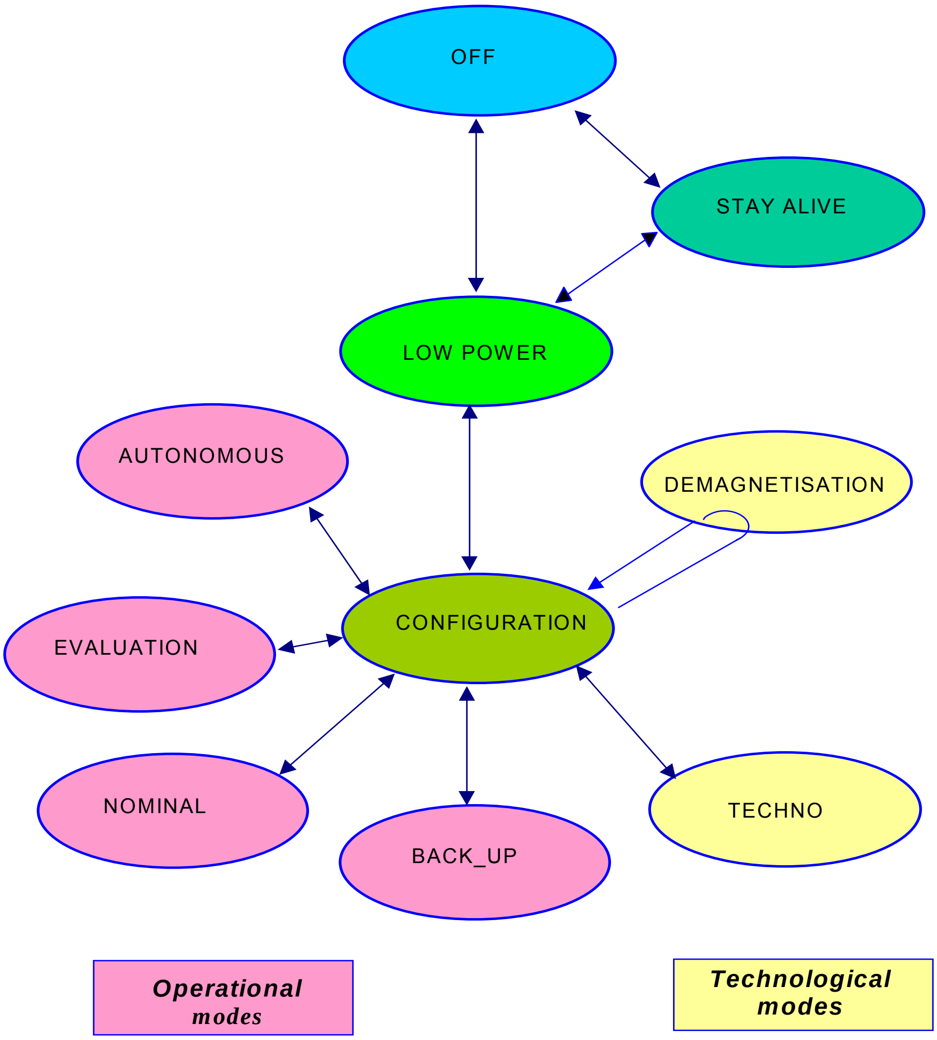


Figure 24: PHARAO modes

Each mode transition is achieved by a sequence execution. A sequence is an on-board set of software instructions.

- **Off Mode:**
  In this mode, none of the PHARAO functions is powered. As soon as UGB is powered ON by PDU (28 Volt power supply), UGB Software performs all necessary initialisations and PHARAO remains in OFF mode until the automatic Low Power mode transition is finished.
- **Stay-Alive Mode:**
  In this mode, the ion pump is powered by PDU (28 Volt stay-alive power supply) and the only function implemented in the Instrument is the vital one of maintaining the vacuum inside the Caesium Tube (TC).
- **Low Power Mode:**
  The aim of this mode is to reduce power consumption of the Instrument when ISS is not able to deliver PHARAO nominal power. It is also used in the event of anomalies detected by the PHARAO software. In this mode, the ion pump functions and the Microwave Source Ultra-Stable Oscillator (SH-OUS) and the Laser Source (SL) are in Standby Mode. All the electronic boxes (BEBA, TC with BEC and BEDET) are powered ON, to allow UGB software to perform on-board checks and to produce housekeeping telemetry.
- **Configuration Mode:**
  This mode prepares the PHARAO instrument and performs all its necessary initialisations. First of all, the Microwave Source Synthesis Chain (SH-CS) is powered ON in this mode and the 9.2 GHz signal is switched ON. The Laser Source is also powered ON in this mode and completely initialised. As a result, all PHARAO sub-assemblies are now powered ON and all permanent activities (on board checks and regulation) are operational. Full PHARAO Housekeeping telemetry is produced.
- **Technological Mode:**
  This mode is reached as soon as a technological mode general function is required by a sequence execution, and managed by UGB software. The aim of these general functions is to perform calibration or installation of PHARAO physical components.
- **Demagnetisation Mode:**
  In this mode, basic functions of the instrument are implemented but the atomic cycle is inactive. This mode is used to perform Caesium Tube demagnetisation.
- **Evaluation Mode:**
  In this mode all the functions are implemented and the atomic cycle is active. The PHARAO OUS is locked on SHM thanks to the FCDP comparison data provided by the XPLC to the Instrument. The frequency corrections provided in the PHARAO TM physical package are not used to lock the SHM long-term frequency. The PHARAO estimated corrections by Caesium atomic reference transition are directly used to modify frequencies injected into the preparation and interrogation cavities of the Caesium Tube.
- **Nominal Mode:**
  In this mode, which is the main operational mode of the Instrument, all the functions are implemented and the atomic cycle is active. The PHARAO OUS is locked on SHM thanks to the FCDP comparison data provided by the XPLC to the Instrument. The frequency corrections provided in the PHARAO Telemetry are used to lock the SHM long-term frequency (over 1,000 to 10,000 seconds).
- **Autonomous Mode:**
  In this mode, all the functions of the instrument are implemented and the atomic cycle is active. The PHARAO OUS is locked onto the Caesium Tube (TC) and not on SHM. So the frequency discrepancies estimated by PHARAO are directly used to correct PHARAO OUS. This mode is used to check the performance of PHARAO alone (when SHM and PHARAO are independent).
- **Backup Mode:**
  In this mode, an external 100 MHz signal is used instead of the PHARAO 100 MHz internal generator. This means that FCDP provides PHARAO with the SHM 100 MHz in order to drive microwave frequencies in the Caesium Tube cavities. The frequency correction estimated by

Caesium atomic reference transition is sent to the XPLC in order to correct SHM. All the other functions of the instrument are implemented and the atomic cycle is active. This mode is used as a degraded mode in case of failure of the PHARAO 100 MHz generator.

OPERATIONAL SERVICES:

In operational services, an on-board sequence is run to set PHARAO, mainly in operational mode, and periodically for a few minutes, in technological mode, to fine-tune the components.

5.7.2 TM/TC - TELECOMMAND AND TELEMETRY

The telecommands are split into five categories:

- CONTROL telecommands (operational telecommand: mode change; functional telecommands: loading parameter values, calling execution of a sequence execution, requesting variable dump, managing the flash memory),
- XPLC Time telecommand,
- FCDP data (pseudo telecommand),
- MEMORY DUMP Telecommand,
- DATA-LOAD telecommand (to load a new sequence or a new micro-command table or a memory patch).

Five kinds of telemetry packets are produced by Flight Software:

- Aces (A) packets contain Housekeeping telemetry,
- Pharao (P) packets contain science data or results of the processing of a general function (technological mode),
- Aperiodic P packets contain the final result of the processing of a general function (technological mode), the result of a non-real-time processing function, or are produced each time an off line function is called or each time a permanent activity is started on board,
- An anomaly P packet is generated when alarms are detected during execution of a real-time function,
- A Dump (D) packet contains a user-request memory dump and will be down-linked after the P packets relative to one PHARAO atomic cycle.

Mode / TM	OFF	Stay Alive	Low Power	Conf.	Operational	Technological	Demagetisation
A Packet			X	X	X	X	X
Aperiodic P Packet			X	X	X	X	X
P Packet					X	X	
Anomaly P Packet					X	X	
D Packet			X	X	X	X	X

Figure 25: PHARAO TM packets used versus modes

6 PERFORMANCE

Frédéric PICARD – System engineer – CNES
Philippe LAURENT – Instrument scientist – SYRTE

The expected PHARAO performance in flight is a frequency stability of 10^{-13} $t^{-1/2}$ and an accuracy in the order of 10^{-16}.

6.1 STABILITY

The stability performance of a cold atom clock is the combination of 4 main contributors:

$$\sigma^2 = \sigma^2_{\text{quantum proj}} + \sigma^2_{\text{detection}} + \sigma^2_{\text{SH}} + \sigma^2_{\text{TC\_}\mu\text{vib}}$$

- The quantum projection noise. It varies as the inverse square root of the number of detected atoms. It defines the ultimate limit of the clock's frequency stability.
- The detection noise. It includes the detection laser noise and the noise of the detection system.
- The microwave signal frequency noise. It is mainly determined by the OUS quartz oscillator noise. A quartz with a low sensitivity to acceleration will be used to minimise the effect of the microvibrations on this noise.
- The caesium tube microvibration noise. The microvibrations modify the transit time in the interrogation cavity from one atomic cycle to another.

These contributors also depend on the atomic velocity. The main ones have been evaluated with some simple numerical analysis and the results are summarised in the following table (in flight condition):

Contributor	**σ x 10^{13}**
Quantum projection	0.75
Detection	0.05
Microwave	0.87
Caesium tube microvibrations	0.67
Total	**1.3**

Figure 26: PHARAO stability

The microgravity environment at the PHARAO interface has been calculated for 3 typical cases:

- ISS basic operations (crew sleeping period)
- Normal crew activity (crew active but not exercising)
- Crew exercising

The microgravity environment used for the given performance prediction corresponds to normal crew activity. The performance during crew sleep is marginally better (the caesium tube vibrations contribution becomes 0.59×10^{-13}). The performance during crew exercise is very degraded (by a ratio of 3) and an algorithm is included in the flight software to flag the corrupted data in real time.

Considering the accuracy of the simulated microvibration levels at ACES payload (not better than 50%) and the non-stationary character of the fluctuations, it can be seen that the predicted PHARAO stability is within 30% of the instrument specification.

6.2 ACCURACY

The accuracy performance is based on the evaluation of the frequency shifts due to the atoms environment or due to the measurement process. For that, the effect of each disturber is amplified and measured by comparison to SHM. Then the correction to apply in nominal functioning conditions is calculated. The sources of disturbance are:

- First order Doppler effect. This effect is due to the phase shift seen by the atoms between the 2 Ramsey cavities. It depends on the speed of the atoms.
- Second order Doppler and gravitation effects. Due to the second order Doppler effect (speed of the atoms with respect to the clock) and to the Einstein effect (red shift due to gravity).
- Cold collisions. Due to the effect of the collisions between cold atoms. It depends on the density of the cold atoms.
- Background gas collisions. Due to the collisions with the residual hot atoms. It depends on the density of the cold atoms and the residual gas pressure.
- Black body radiation. Due to the interrogation cavity's thermal radiation. It depends on the interrogation cavity temperature.
- Zeeman shift. Dependant on the magnetic field, which is measured during the technological "Zeeman" mode.
- Pulling by other lines. Due to the coupling of the clock transition (F3, m=0 => F4, m=0) with atoms in other Zeeman sublevels which can be present in spite of the selection process or due to a non-stable magnetic field. It combines Rabi pulling, Ramsey pulling and Majorana transition effects.
- Microwave leaks. Concerns the effects of the microwave leaks outside the 2 Ramsey cavities.
- Microwave spectrum. Concerns the effects due to spurious signals in the microwave spectrum.

Each effect will be evaluated during ground testing and / or during flight. At the end, the expected accuracy performance is:

Effect	Applied correction in flight (10^{-16})	Uncertainty (10^{-16})
First order Doppler	$\leq$ 30	<< 1 (TBD)
Second order Doppler and gravitation	Depends on orbit	$\leq$ 0.3
Cold collision	20	1
Background gas collision	0	<< 1 (TBD)
Black body radiation	180	<< 1 (TBD)
Zeeman shift	-2000	$\leq$ 0.1
Pulling by other lines	0	<< 1 (TBD)
Microwave leaks	0	<< 1 (TBD)
Microwave spectrum	0	<< 1 (TBD)
Total 1σ uncertainty		**$\leq$ 2.6**

Figure 27: PHARAO accuracy

The most important shift is the Zeeman effect, but this is fairly easy to measure. Special care is taken with the magnetic field stability in the environment of the atoms.

The correction due to the black body radiation is based on the accurate evaluation of the absolute temperature of the interrogation cavity, from temperature measurements made outside the vacuum tube.

The cold collision shift will be evaluated continuously during the PHARAO operation.

The first order Doppler effect will be limited as a result of the quality of the results obtained with the PHARAO interrogation cavity mounted in the SYRTE fountain.

This budget will be consolidated during EM tests at unit, PHARAO and ACES integration levels.

7 PHARAO SUB-SYSTEMS

7.1 CAESIUM TUBE (TC)

Olivier GROSJEAN – Caesium Tube – CNES
Clément LUITOT – Optical systems – CNES
Christophe CASTERAS – Mechanisms – CNES

The Caesium tube is the core of the PHARAO clock where interaction occurs between microwave signals and the caesium atoms. The atomic molasses is handled and detected with 10 laser beams delivered by the Laser Source and two microwave signals delivered by the Microwave Source. The caesium tube principle can be explained with the following sequence:

- The caesium vapour is delivered from the caesium reservoir which stores the caesium in liquid phase. The quantity of caesium atoms is controlled with the valve aperture level and is fine-tuned by thermal regulation.
- The atomic cloud is cooled in the capture sphere and launched by the 6 laser beams.
- All atoms are set at the fundamental energy level (F=3 m=0) in the preparation cavity with RF excitation
- The residual atoms at level F=4 are ejected and the final cloud at level F=3 is shaped in the selection chamber by 2 laser beams.
- The cloud is subjected to the microwave signal at the frequency of the caesium reference transition in the Ramsey Cavity (interrogation cavity) in order to transfer the half of atoms from F=3 level to F=4 level.
- The fluorescence of the two energy levels of the atoms is precisely measured in the detection cavity. Atoms cloud is illuminated by 2 laser beams in two areas of the chamber to measure respectively the level F=4 and the level F=3 proportion. 2 other laser beams are needed to eject the first level atoms and to transfer the second level atoms.

The tube design has a strong impact on the clock's performance. This equipment must provide very low vacuum conditions and a very stable magnetic field and temperature in order to minimise perturbation of the atomic cloud. To avoid the consequences of the physical phenomena that occur during interaction between the microwave signal and the cold atoms, it is necessary to protect all the zones of the vacuum tube against thermal and magnetic disturbance.

To minimise collision between Caesium and other particles, a very high vacuum is necessary.

The main requirements are the following: (for the interaction zone)

- Vacuum $2x10^{-8}$ Pa ($2 x10^{-10}$ mb)
- Magnetic field stability < 0.1 nT (1 µG)
- Temperature controlled +/- 0.1° and absolute temperature calibrated
- Alignment: 1 mrad

7.1.1 DESIGN DESCRIPTION

The design of the Caesium Tube is derived from the design of the ground clocks. Development of the Caesium Tube has been contracted with SODERN

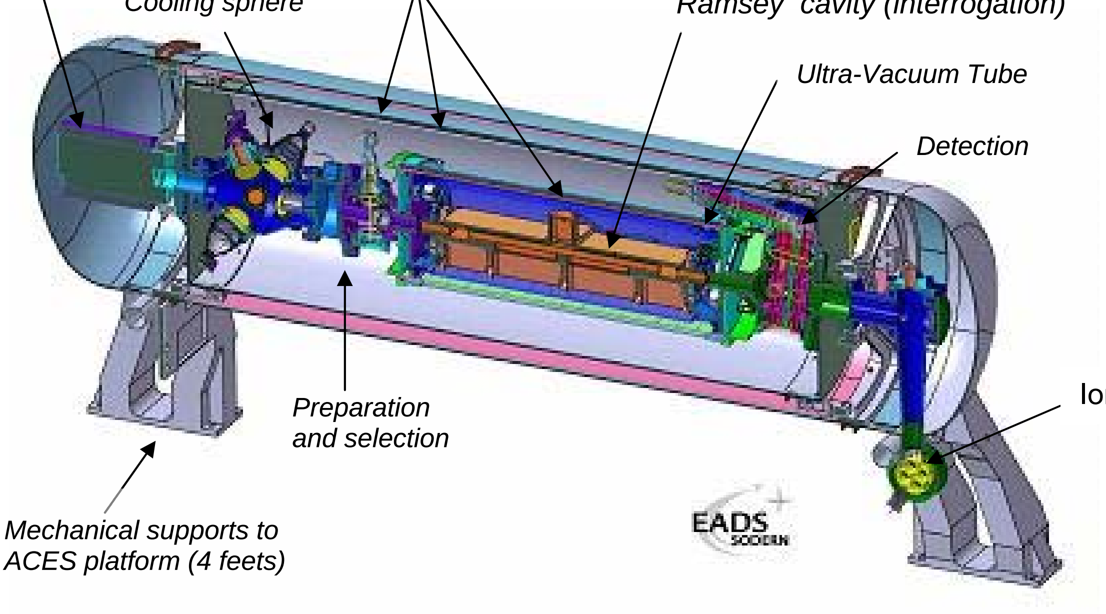


Figure 28: Caesium Tube lay-out

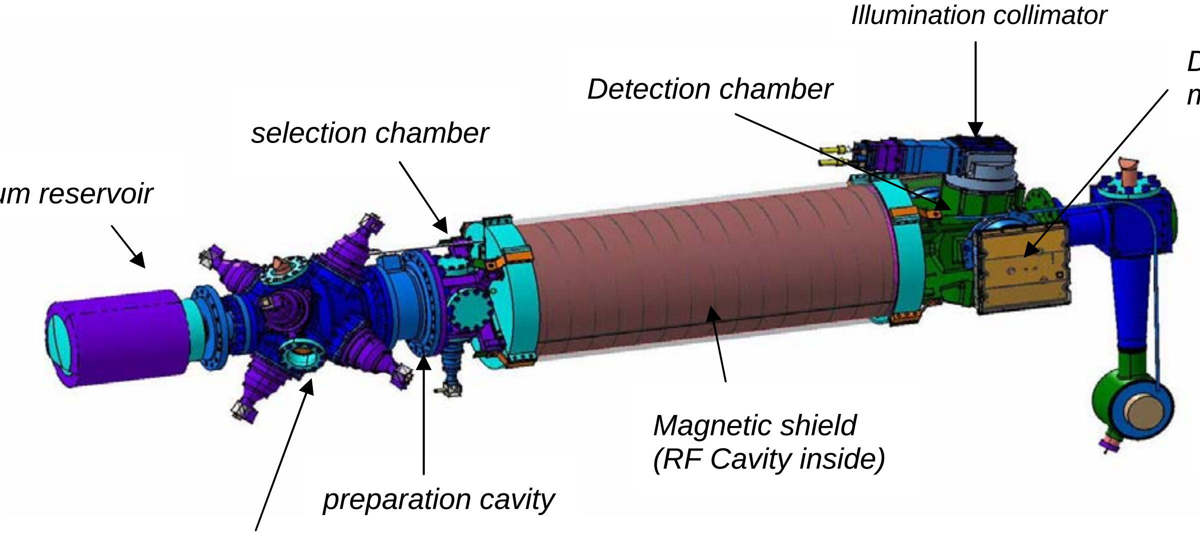


Figure 29: Ultra-Vacuum Tube lay-out

7.1.2 DESCRIPTION OF MAIN CAESIUM TUBE ITEMS

The caesium reservoir:

Its main function is to deliver a caesium vapour into the cooling sphere within the pressure range between 5 E-09 mb and 5 E-08 mb. The liquid caesium is trapped by capillarity in porous titanium matrix made of compacted micro balls. The caesium mass to be stored is about 2 grams and only caesium vapour must be able to escape from the tank. The atom density is controlled by a mechanical valve and a heater. The flux to be delivered is about 10^{+12} atoms per second.

Figure 30: Porous titanium in which the caesium is stored

The cooling zone:

The six laser beams with a 26 mm diameter are injected by collimators into the cooling zone in order to trap the caesium cloud. The spherical cloud of atoms is created at the intersection of the laser beams. In this zone the caesium atoms are captured, cooled and then launched. A photodiode monitors the fluorescent light emitted by the captured atoms. The design is driven by the allowed volume and the positioning of these collimators.

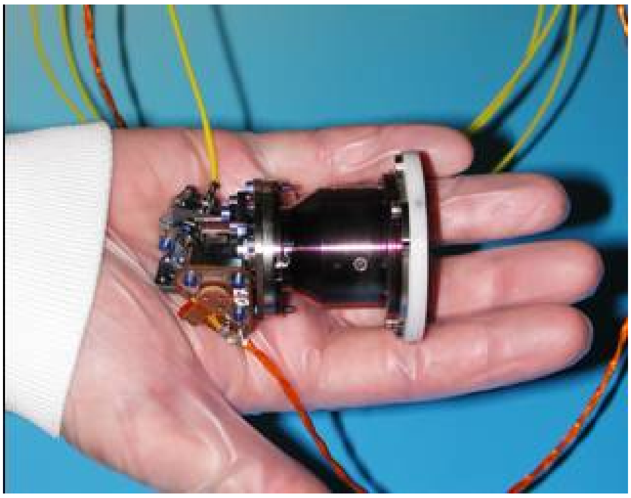


Figure 31: One capture collimator (6 units are mounted on the capture sphere)

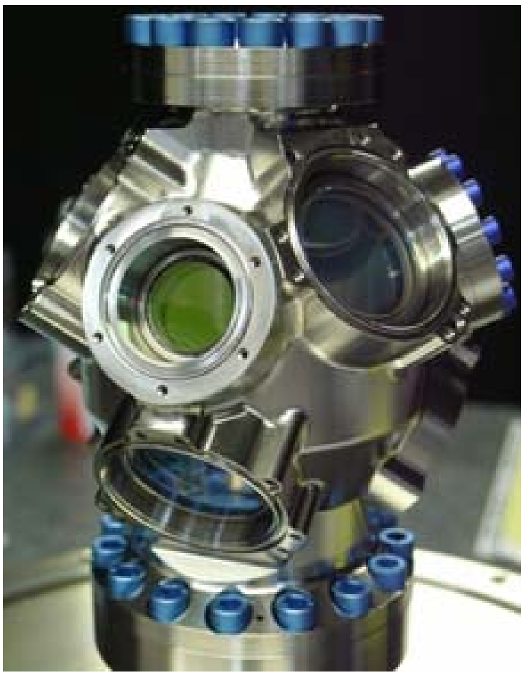


Figure 32: Cooling sphere (Flight model)

***Preparation microwave cavity*:**

The preparation microwave cavity is a TE_{011} with cylindrical shape. This cavity has a diameter of 54 mm and a length of about 24 mm

Figure 33: Preparation cavity (EM model)

Figure 34: Preparation cavity (Flight model)

***Selection chamber*:**

The selection chamber is equipped with 4 windows. RF isolation is provided by cut off pipes

Figure 35: Selection chamber (EM model)

Figure 36: Selection chamber (Flight model)

Interrogation cavity (Ramsey cavity) :

The atoms are launched to fly through the interrogation cavity where they interact with the 9.192661370 GHz microwave field which excites the hyperfine transition. The fundamental criterion is the control of the electromagnetic fields seen by the atoms. The polarisation has to be linear and parallel to the static magnetic field. The microwave magnetic field near the axis has to be parallel to the propagation direction of the atoms. The field phase variations seen by the atoms during the interaction have to be minimised. This parameter is linked to the relative accuracy of the clock frequency. For a frequency accuracy of 10^{-16} the specification in terms of the accuracy of phase variations is therefore between 2 and 3 µrad with an amplitude accuracy of 10^{-3}.

Among the different causes of uncertainty, the most important is the residual first order Doppler effect. The frequency shift depends on the cavity asymmetry, the microwave coupling and also on the variations due to the finite conductivity of the cavity material.

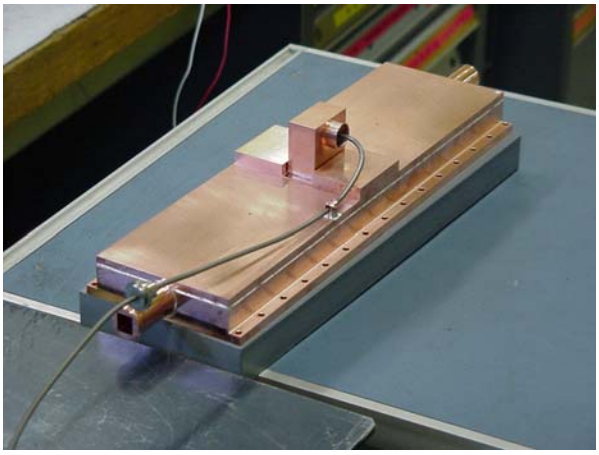


Figure 37: PHARAO Microwave interrogation cavity (FM model)

The development of the cavities was contracted with Thales TED (Velizy - F).

The cavity length is about 300 mm and it is made of 2 Kg copper. The cavity apertures are 8 mm x 9 mm in order to be under the cut-off frequency to reach an electromagnetic leakage level lower than –120 dBc.

The performance of this cavity is directly linked to the quality of the machining and welding. Furthermore, the symmetry of the cavity, the homogeneity of the electrical conductivity and the smoothness are also very important criteria.

The flight model of the cavity was tested in an atomic fountain by SYRTE. It was verified that there is no magnetic field singularity and that the end to end phase shift complies perfectly with PHARAO requirements (10^{-16}).

The cylindrical part of the vacuum tube is designed to receive the cavity. A specific AlSic structure is designed to support this ductile item.

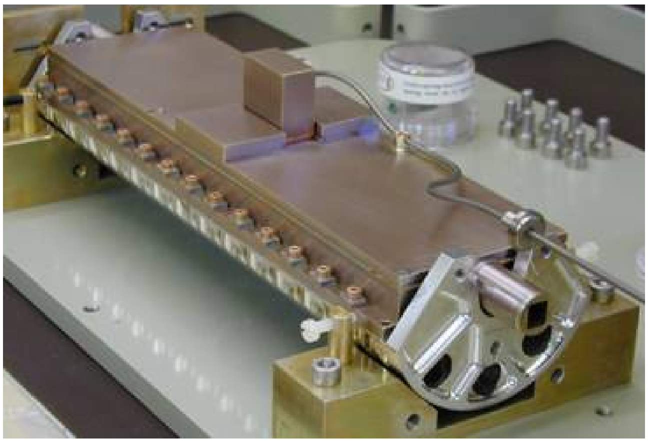


Figure 38: Microwave cavity on its supporting structure

Detection chamber :

The detection chamber is the last part where the atoms are operated, they are illuminated to induce successively the fluorescence of the two different energies population: F=3 or F=4.

The fluorescence is measured by two detection modules each amount of

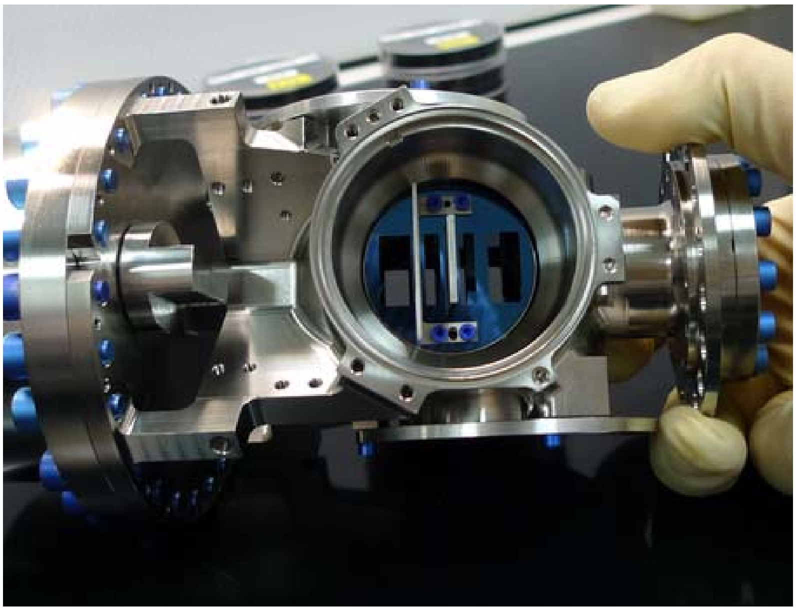


Figure 39: FM detection chamber with DALP (in blue)

Detection:

The fluorescence of each atoms population is performed by detection module using a large high sensitive photodiode. These 2 modules are mounted on the large windows of the chamber.

A dedicated internal baffle (called DALP) protects each beam from stray light

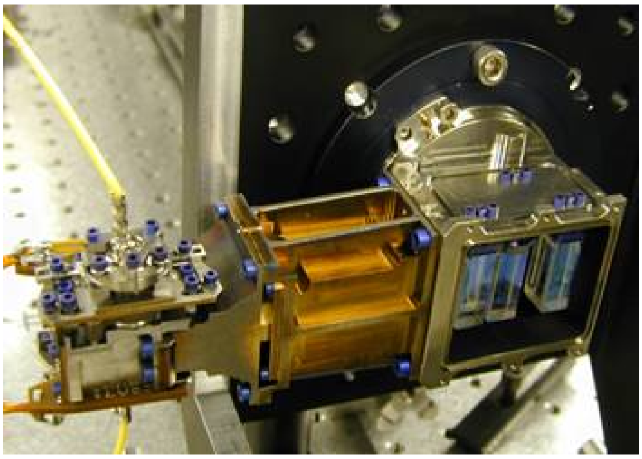


Figure 40: EM Illumination optical block during integration

Illumination:

Two laser beams are dedicated to induce fluorescence for each atoms population, two other laser beams are used to eject first population and transfer the energy level of the second one.

Vacuum:

Atom interaction phenomena require a vacuum higher than 2×10^{-8} Pa. The vacuum tube is made in several pieces screwed together with aluminium seals.

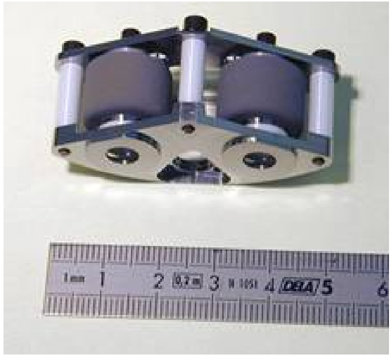


Figure 41: One getter unit

Figure 42: Ion pump mounted

Figure 43: Ion pump developed for PHARAO

The pumping system is located at the end of the vacuum tube. Pumping is ensured by a set of 6 getters distributed around the interrogation cavity and completed by a 1 l/s ion pump for noble gazes and other hydrocarbon traces.

The electronic unit provides high voltage supply at 5000 volts and also telemetries of HV and ion current which is related to internal pressure.

Magnetic:

Due to physical phenomena involved during the interaction between the microwaves and the cold atoms it is necessary to protect these zones against external magnetic disturbance. Three concentric µ-metal screens provide the magnetic shielding (about 50 % of the complete caesium tube mass). Coils provide the requested internal magnetic field.

An active compensation coil with a servo loop monitored with an internal magnetometer (DTU) provides the remainder of needed attenuation which is 400.000.

Figure 44: EM magnetic shields

7.1.3 MAIN CHALLENGES

The caesium tube uses various very specific technologies and the main challenges of this development are:

- The centre of gravity is at a significant distance from the attachment points, causing considerable mechanical forces at the junction of each part of the vacuum tube which are difficult to withstand.
- The interrogation cavity is difficult to maintain due to its low yield resistance and its thermal expansion factor. Furthermore, this cavity can only be verified in fountain or at PHARAO level.
- Background light is difficult to assess and implies specific treatment, which must be compatible with high vacuum conditions.

- Alignment of the laser beam has to be very strict for effective control of the caesium atoms capture process.
- Photodiodes are critical with regard to the required high sensitivity.
- Sealing the windows requires processes which ensure perfect tightness (range of 1 E-12 mb.l/s) and which is compatible with the optical coating.
- Metallic seals have to ensure tightness during and after vibration tests even flanges do not remain absolutely plated together.
- Ultra-high vacuum is a challenge due to the large number of windows and flanges and the limitations on baking so as to protect optical coatings.
- The ion pump and its high-voltage power supply were designed especially for PHARAO.
- The magnetic field must be homogeneous and stable despite the numerous causes of perturbation (Earth field rotation, vicinity of the MASER, electromagnetic mechanisms of PHARAO).

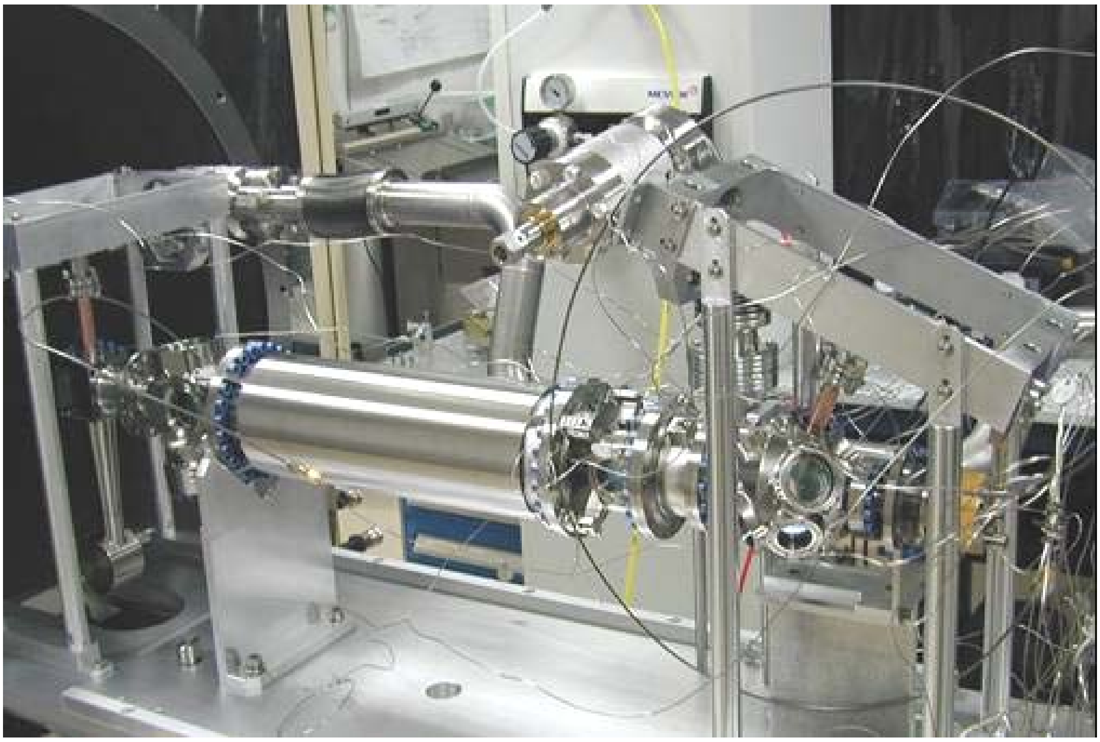


Figure 45: The Ultra-Vacuum tube in its ground support equipment

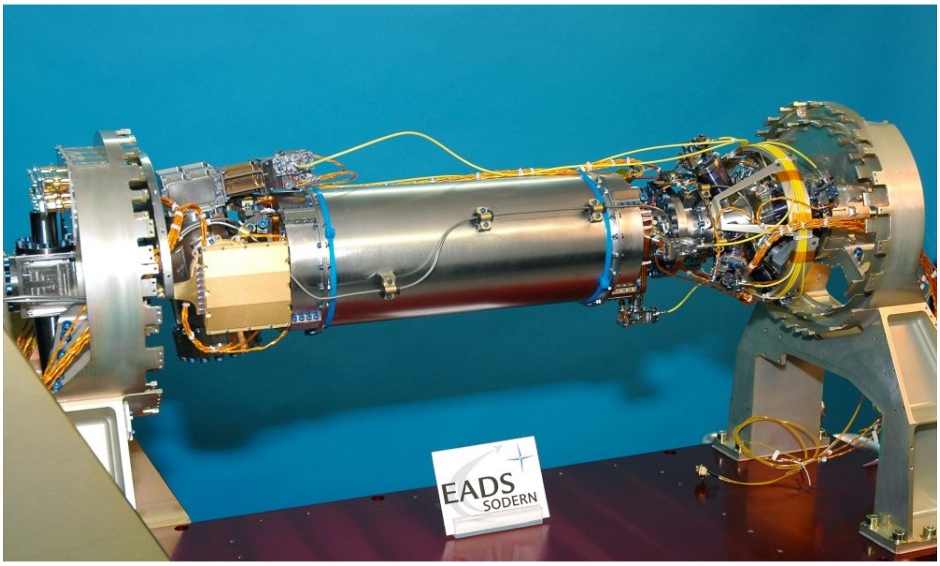


Figure 46: EM model fully integrated before closing with the magnetic shields

The situation today:
The caesium tube is fully designed and qualified.
The flight model is under construction.

Figure 47: Caesium Tube EM delivery

7.2 LASER SOURCE (SL)

Benoît FAURE – Laser Source – CNES

The Laser Source provides the laser beams for the Caesium Tube. The Laser Source provides 14 different laser signals with very precise optical frequencies, and recombines them in order to deliver the laser beams through 10 optical fibers. The Laser Source has been contracted with SODERN.

7.2.1 LASER SOURCE REQUIREMENTS

The main requirements related to the laser signals are listed in the following table:

Frequency	Power
2 precise frequencies (ν_{3-4} et ν_{4-5}) compared to saturated absorption lines of Caesium	High power (85 mW minimum at ν_{4-5} , and 5 mW minimum at ν_{3-4})
High spectral purity	High ratio of polarisation with precise polarisation
High frequency stability	High power stability
Precise frequency shifts	Difference between the power of 2 different capture laser beams lower than 2%
Precise frequency tuning (34 kHz – 3.4 MHz)	Fine power tuning
Wide frequency range (over 70 MHz)	Rapid extinction (100µs) and total extinction (120 dB)

Figure 48: Main requirements for Laser signals

7.2.2 LASER SOURCE DESIGN RATIONALE

Laser diodes are used to deliver the laser signal, but several other components (optical, opto-electronic, electronic or mechanical) are necessary to satisfy the performance requirements.

The high spectral purity is provided by 2 extended cavity laser diodes (ECLs) for the 2 main optical frequencies. ECLs have a spectral purity 10 to 100 times higher than simple laser diodes. Since an ECL delivers less laser power (about 50 mW maximum) than a single laser diode (about 150 mW), there is not sufficient laser power for the ν_{4-5} frequency.

Semiconductor amplifiers are not sufficiently reliable at a wavelength of 852 nm for a space application. So 2 slave laser sources are used (simple laser diodes delivering 150 mW each) to amplify the power of the ν_{4-5} laser. They are locked in frequency by injecting into their cavity part of the Master Laser signal issued form the ECL. They each deliver about 150 mW at the frequency emitted by the Master Laser when the injection is efficient.

In order to achieve the high frequency stability at the precise value required, each ECL-emitted frequency is compared to a caesium reference (saturated absorption line of Caesium cell) and locked onto this frequency by a servo-loop. The laser frequency is modulated by a diode current modulation (at a few 100 kHz).

A frequency change induces a differential absorption of the signal arriving in a Caesium cell (used as reference), leading to a variation of the laser power detected by a photodiode located after the cell. These changes are recorded in a synchronous detection system. Slow corrections are performed on the optical cavity length, whereas fast corrections are performed on the laser current.

The frequency of the laser beams is shifted using acousto-optical modulators (AOM) in order to optimise the interaction with the caesium atoms. The Slave Lasers follow the frequency shifts of the Master Laser.

The laser beam polarisation is controlled in order to distribute the power towards the different parts of the Laser Source and finally towards the optical fibers delivering them to the Caesium Tube (TC). The relative difference between the powers of 2 capture laser beams must be lower than 2%.

7.2.3 THE OPTICAL LAYOUT

The following figure gives the SL optical architecture diagram.

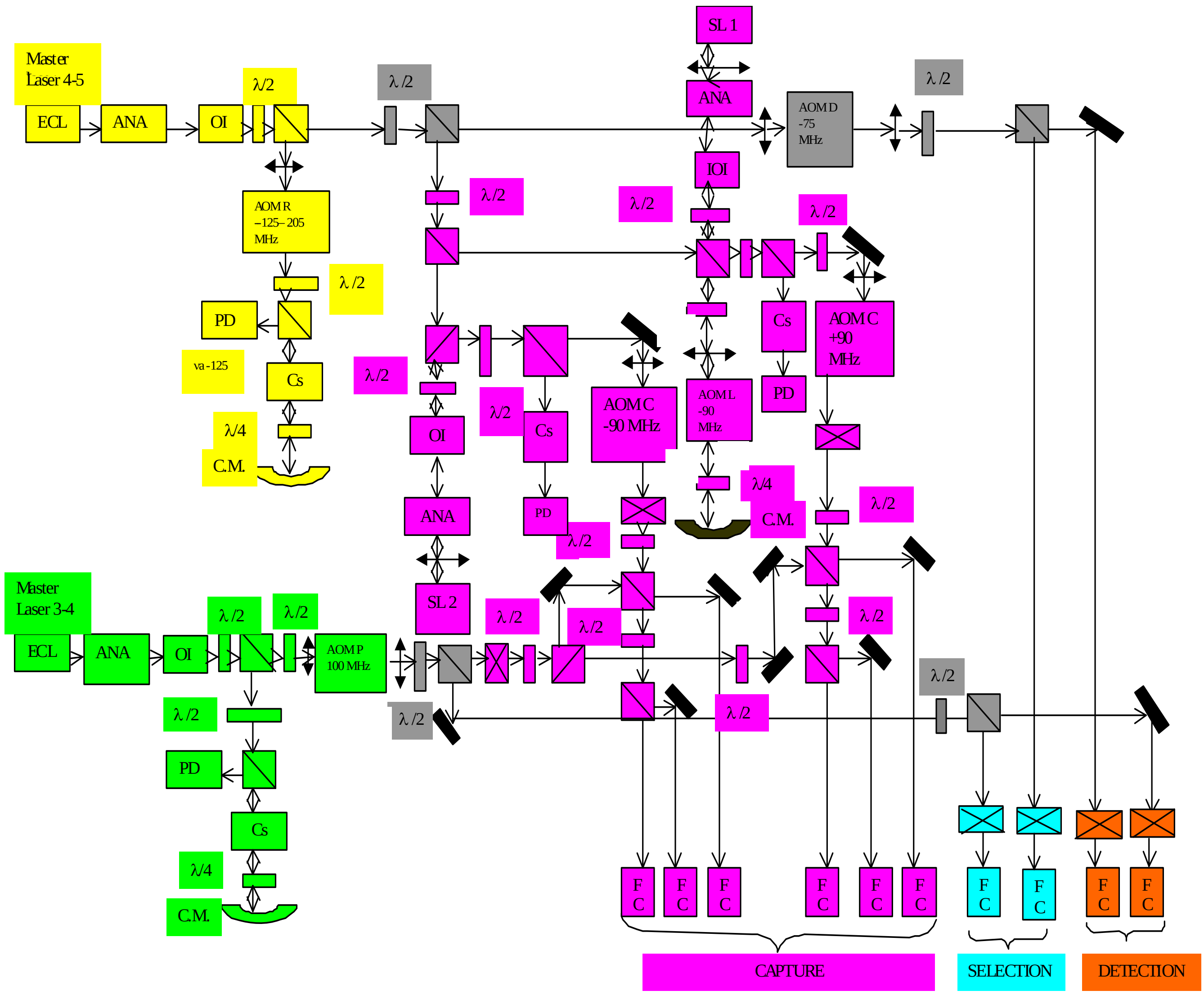


Figure 49: Laser Source optical diagram

Legend:

(crossed box)	Mechanical Shutter
ANA	Anamorphic optics
IO	Optical Isolator
AOM	Acousto-Optical Modulator
SL	Slave Laser
FC	Fiber Collimating optics
Cs	Caesium cell
(rectangle)	Retardation plates
(box with diagonal)	Polarising cube beamsplitter
ECL	External Cavity Laser
PD	Photodiode
(curved shape)	CM: Concave Mirror

7.2.4 THE OPTICAL BENCH

All the optical components are mounted on the two faces of a 400 mm x 330 mm optical bench. The main components are:

- 2 ECL delivering the 2 main frequencies, optics and frequency stabilisation electronics
- 2 slave lasers (SL) amplifying the laser power at the $\nu_{4\text{-}5}$ frequency
- 4 caesium cells: 2 for frequency stabilisation of the ECLs, 2 to verify that the Slave Lasers lock onto the correct frequency
- 6 photodiodes: 2 for approaching the right frequency for ECLs, 2 for locking the ECLs on the right frequencies, and 2 for checking the frequency locking of SLs
- 4 optical isolators (OI): 1 for each laser source, in order to protect them from optical feedback which would induce perturbations on the laser frequency
- 6 AOMs in order to obtain the different frequencies needed in the optical parts of the TC
- 7 mechanical shutters (MS) in order to switch the laser power off
- 10 polarisation maintained fibers (PM) to deliver all the beams to the different TC zones with a good polarisation ratio
- 8 rotating mirror mechanisms before injection in the optical fibers. This allows correction of the differences between the power of the 6 capture laser beams after launch and during the flight, and re-optimisation of the laser power of the selection and detection $\nu_{4\text{-}5}$ beams if needed.

Several optical components must be added to the previous list in order to adapt the laser beams and the distribution ratios, for accurate distribution of the power supplied by the 4 laser sources to the 10 different fibers: lenses, retardation plates, polarising cube beamsplitters, mirrors, etc.

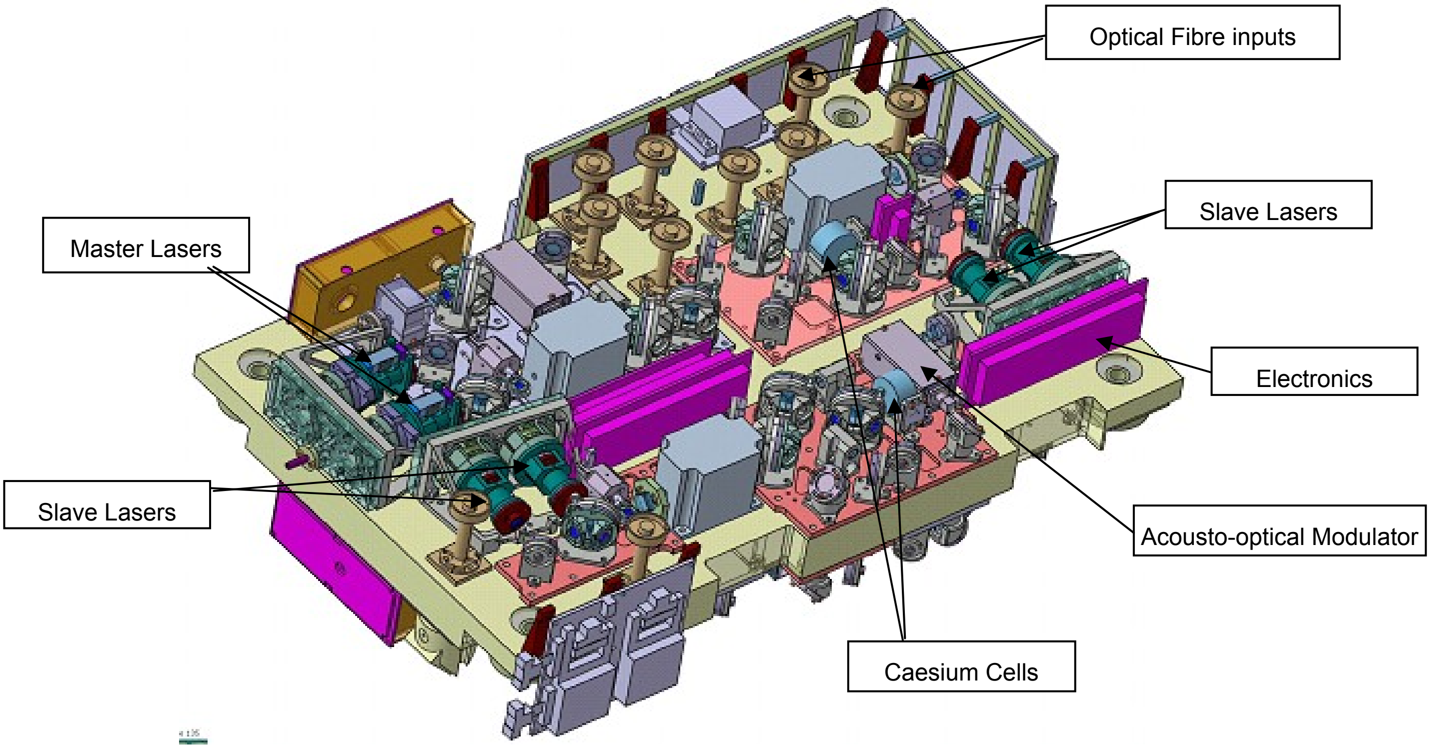


Figure 50: Laser Source optical bench - 3D CAD view

The electronics to generate and control the different parameters are located in the lower part of the laser source unit. Some temperature servoloops equipments are also implemented on the optical bench (for example to control laser diodes temperature).

The ancillary equipments of the optical bench consist of: the laser current, voltage and temperature control units, the laser frequency-locking unit, the electronics for the AOMs and the mechanisms. These equipments are located inside the SL in the lower part underneath the optical bench.

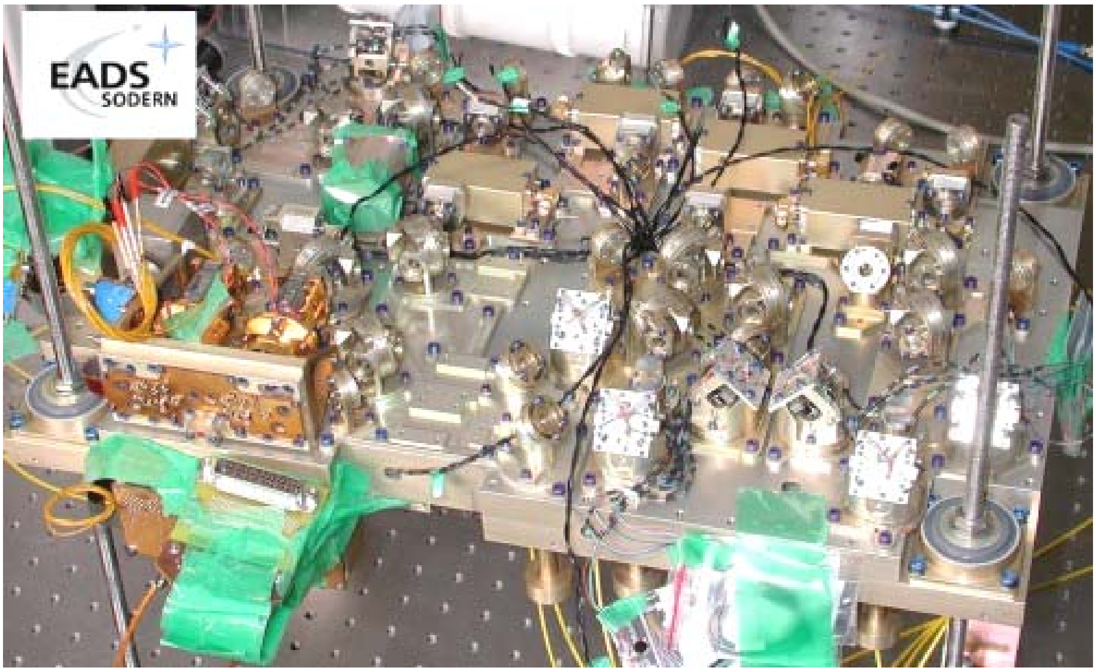


Figure 51: Laser Source optical bench - Top view

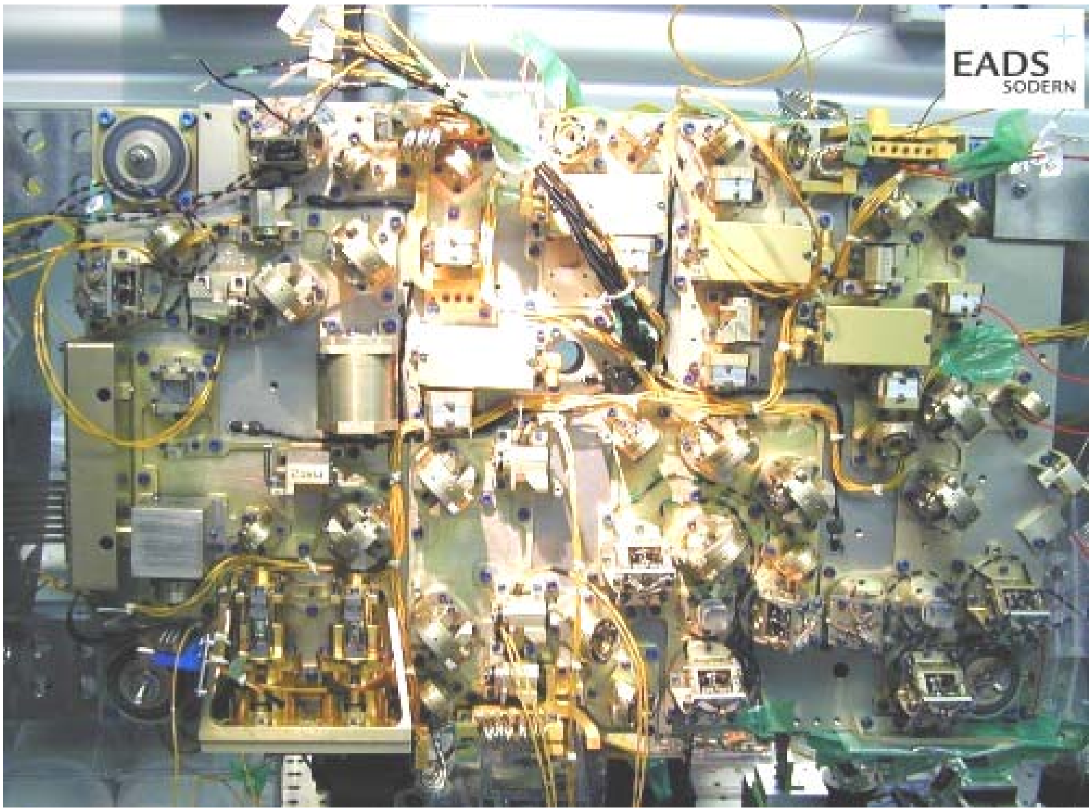


Figure 52: Laser Source optical bench - Bottom view

7.2.5 DESCRIPTION OF MAIN SL ITEMS

Laser diodes:
PHARAO uses laser diodes qualified and flown on previous SILEX and OICETS projects (same wavelength but at higher power). For Flight Model, the packaging of the diodes have been reviewed to avoid problems of Package Induced Failure (PIF).

ECL - Extended Cavity Laser:

The concept chosen is of a linear cavity containing a laser diode, a collimating lens, an anamorphic optical system to make the laser beam circular, an intracavity interference filter to obtain a high spectral selectivity, and a cat's-eye system for the output mirror in order to make it less sensitive to mechanical instabilities. The length of the extended cavity is chosen with respect to the location of the mirror which moves with a piezoelectric translator.

This design has been demonstrated by LNE-SYRTE and simulated at CNES; its industrial version for space use is manufactured by EADS-SODERN.

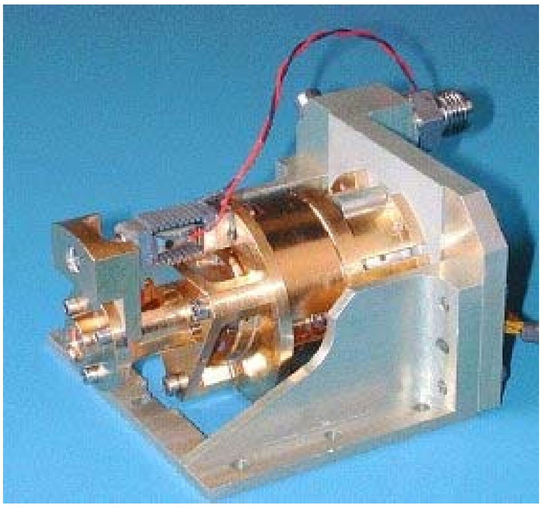


Figure 53: Laser Source ECL

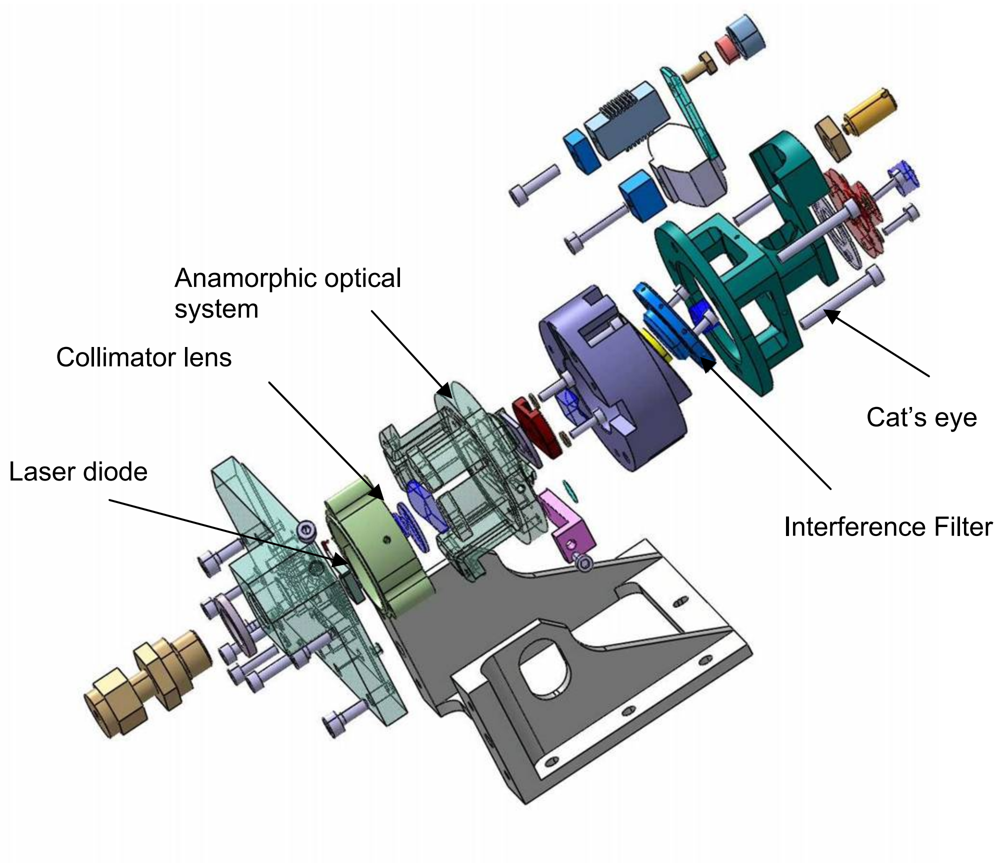


Figure 54: Laser Source ECL layout

- **AOMs:** They generate the frequency shifts needed, but also losses in laser power, and they need high electrical power (radiofrequency signal). They are optimised in order to obtain: a reduction of the power consumption, an optimisation of the diffraction efficiency and a reduction of the angles between diffracted and incident beams to less than 1° in order to simplify designing, alignment and integration of the SL.

Figure 55: AOM module

- **Optical Isolators:** These components are of commercial origin. Smaller components than those usually used by scientific laboratories have been chosen in order to reduce the overall dimensions of the SL. However, they are adapted for space utilisation and their magnetic shielding is optimised to ensure optical isolation of the lasers and to avoid magnetic perturbation on the TC.
- **Optical Polarisation Maintaining fibers:** In order to obtain a high polarisation ratio at the end of the fiber, and since polarising fibers are no longer available, we finally chose PM fibers, which are less selective in polarisation but can fill the need when combined with polarising cube beamsplitters used at their outputs, in the Caesium Tube. At the input, in the Laser Source, polarisers are placed just before the optical fibers to assure a good correlation between the polaraisation of the laser beams and the neutral axes of the fibers.

7.2.6 SL MECHANISMS

Three kinds of mechanisms are needed in the SL: ECL translators, Mechanical Shutters and Power Balancing Mechanisms.

- **ECL mechanisms:** Each ECL has a piezoelectric translator to move the end mirror of the extended cavity and select or correct the laser frequency.

- **Mechanical Shutters:** These mechanisms have to shut the laser beams totally: an extinction of 120 dB is required compared to the maximum level of power of a laser beam. They will be operated about 10^7 times during the PHARAO mission. Shutters using step-to-step motors have been designed to fulfil the need.

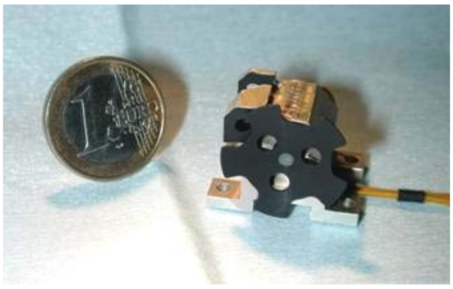


Figure 56: SL mechanical shutter

- **Power Balancing Mechanisms:** In order to balance the powers of the 6 different capture laser beams with a high precision (1%), rotating optical mirrors are necessary. Piezoelectric devices have been chosen for their performance. They also allow the injection of the laser beams into the optical fibers to be re-optimised after the launch and during the mission if necessary.

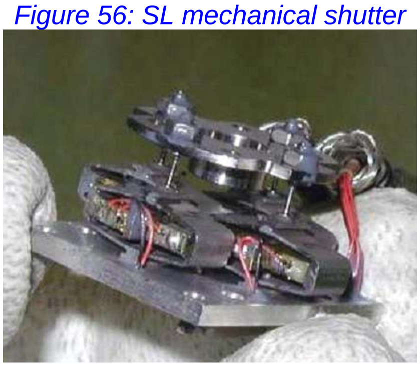


Figure 57: SL fiber optics injection mechanism

7.2.7 MAIN CHALLENGES

The main SL design challenges arise from the ACES payload accommodation constraints, which impose a high level of compactness, low electric power consumption, a wide range of storage temperature and a wide range of operating temperature, as well as the need to be operated in both air and vacuum conditions with a sufficient level of performance for testing both PHARAO and ACES.

The main constraints are:

- The dimensions: 532 mm x 335 mm x 198 mm and mass: 22 kg.
- The electrical power consumption: 47 W.
- The operating temperature: 10/33.5°C and non-operating temperature: -40/+60°C.

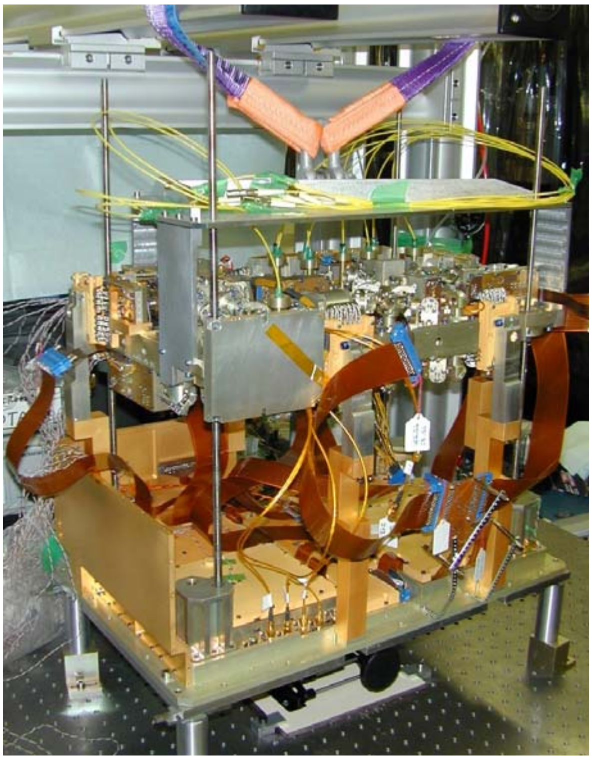


Figure 58: Complete EM model during tests

These requirements are very strict for the SL optical layout, considering the high performance and the number of functions required to reach efficient interactions between laser beams and Caesium atoms, for an optimal operation of the PHARAO clock. This requires minimising the number and size of the components, maximising their efficiency, optimising their performance on the optical bench, executing as many functions as possible while minimising the number of components, limiting the power consumption and the potential reductions in performance.

Laser diodes, ECL master lasers and the different AOMs are the most critical components from a technological point of view. They have a specific qualification program.

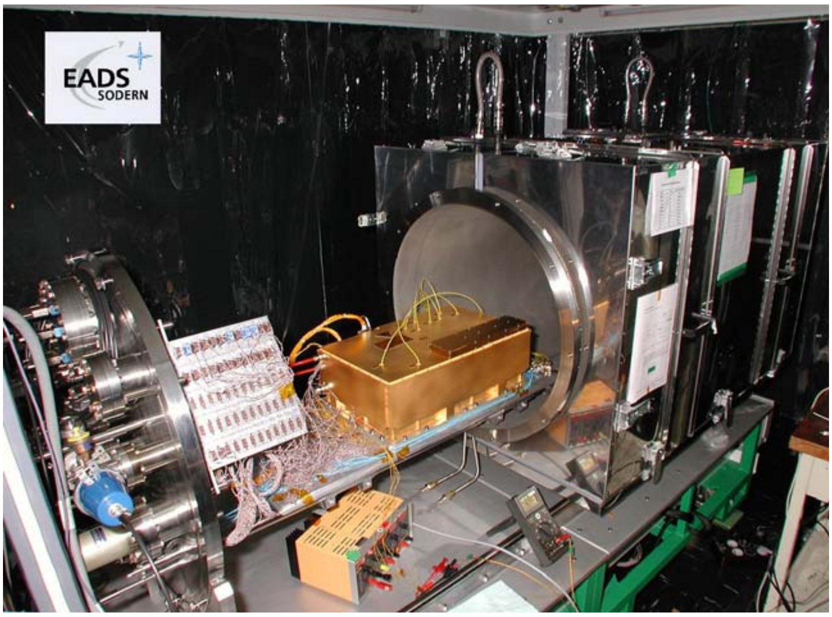


Figure 59: Laser Source EM during final test

The situation today: Definition of the Laser Source is over. Last qualification programs are on progress. The Flight Model is under construction.

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7.3 MICROWAVE SOURCE – SH

Michel CHAUBET, Benoît LEGER– Microwave source – CNES

The main characteristics of the Microwave Source are:

- a low power spectral density of the phase fluctuations
- a frequency resolution of 10^{-5} Hz
- output interrogation and selection signals: 0.01 nW to 10 mW
- less than $2x10^{-11}$ sensitivity to environment over 90 mn
- USO frequency correction via a DDS
- a synchronisation signal (100 MHz/12) to the UGB.

The Microwave Source is composed of an ultra-stable oscillator (USO) and a frequency synthesis chain. The Microwave Source has been contracted to Thales TAS (Thales Airborne Systems) and the USO to C-MAC, a Thales TAS subcontractor.

The frequency chain synthesises two signals at 9.192631770 GHz from a 5 MHz ultra-stable quartz oscillator.

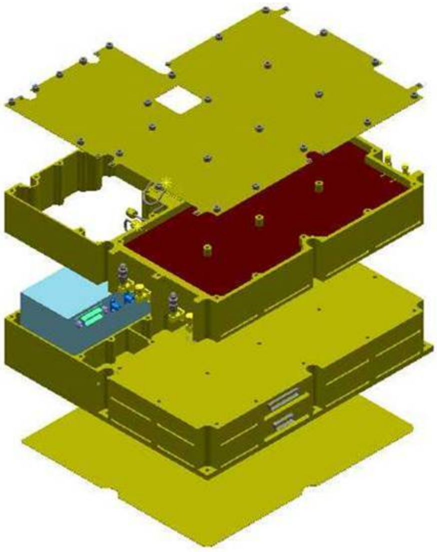


Figure 60: SH CAD model

The low-noise 9.192631770 GHz output frequency is obtained from a 5 MHz reference in two steps: phase locking a 100 MHz VCXO and phase locking a 692 MHz VCO.

The microwave source has 2 direct digital synthesisers (DDS): one is used to compensate the frequency drift of the USO, the other allows a fine frequency adjustment by steps of 10^{-5} Hz of the 9.192631770 GHz to obtain a resolution of 10^{-15} of the clock frequency.

The measured power spectral density of the phase fluctuations as a function of the Fourier frequency for the FM is:

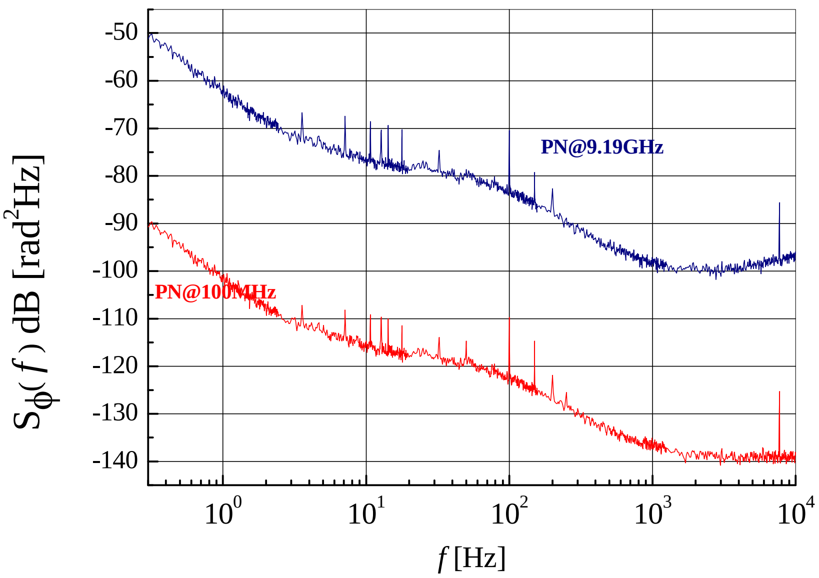


Figure 61: Microwave Source phase noise at 100 MHz (FSOUT) and 9.2 GHz (FSI)

Measurement made: FM34 against a CSO in CNES Toulouse.

The FM measured Allan Variance is: $\sigma y(\tau$=1s and 10 s)= $6x10^{-14}$

Figure 62: FM Microwave Source

Main characteristics:

- size: 270 x 300 x 103 mm^3 (8 litres)
- weight: 7.03 kg
- power consumption: 24.5 W.

The contract was awarded to Thales in 2001. The PDR was made in 10/2001 and the CDR in 05/2004. The main deliveries were the STM in 12/2002, the EQM in 02/2004 and FM in 12/2004.

Main challenges: microvibration sensitivity. The principle effect of microvibration on PHARAO's Microwave Source is degradation in microwave stability due to the USO sensitivity to microgravity.

A LSA (Low Sensitivity to Acceleration) USO FM45 has been delivered in 07/2005. The USO FM (FM34) inserted in the SH FM, found to be too sensitive, has been replaced by this LSA USO.

The situation today: *The microwave source is fully designed and qualified. All three models (STM, EQM and FM) are delivered and compliant with PHARAO specifications.*

7.4 ULTRA-STABLE OSCILLATOR (USO)

Michel BRUNET, Gilles CIBIEL– USO – CNES

PHARAO USOs must be capable of very high performance in terms of frequency stability and phase noise, but also in terms of temperature sensitivity and very low g sensitivity.

7.4.1 PHARAO DESIGN

The PHARAO USOs are based on the second generation of DORIS USOs which were designed from 1990 to 1995 and qualified in 1997 under CNES contracts to C-MAC Frequency Products, Argenteuil, France. This USO uses a very high performance quartz crystal resonator associated with an electronics unit selected to have a very low phase noise near the carrier. To have a very low thermal sensitivity in both air and vacuum, crystal and electronics (oscillator, separator, amplifier etc.) are placed in a double oven in a dewar and are temperature controlled to within 0.01 °C in the qualification temperature range. Mechanical analysis was made to assure robustness, and the qualification models EQM 25 @ 10 MHz and EQM 33 @ 5 MHz were tested at 45 g rms.

To have the best phase noise and short term stability, it was necessary to measure several resonators and transistors in noise, using a dedicated phase noise bench, and to select the best components for PHARAO. It was decided to use a 5 MHz QHS (***Q**uartz **H**aute **S**urtension*) resonator, and to select the best resonators according to several criteria (electrical parameters as well as short term stability and ageing).

7.4.2 PHARAO USOs PERFORMANCE

The following table gives the main results obtained on FM 34 and FM 35. Frequency stability for τ = 1s and 10s and phase noise were measured in air and in vacuum by C-MAC using another USO as reference, and then by LNE-SYRTE using a Cryogenic Sapphire oscillator and very low noise test bench as reference which give an absolute value for the FM USO performance.

Items	Specifications	Goals	FM 34	FM 35
Frequency stability				
τ = 1s	$\sigma_y(\tau) = 1 \times 10^{-13}$	7×10^{-14}	6×10^{-14}	7×10^{-14}
τ = 10s	$\sigma_y(\tau) = 1 \times 10^{-13}$	7×10^{-14}	6×10^{-14}	7×10^{-14}
Phase noise @ 5 MHz in dBrd^2/Hz				
Distance to the carrier				
0.1 Hz	- 98	– 101	- 102	-100
1 Hz	- 128	– 131	- 130	- 130
10 Hz	- 144	– 147	- 144	- 144
100 Hz	- 153	– 153	- 152	-152
1 kHz	- 153	– 153	- 153	- 154
Thermal sensitivity	$\leq 2.5 \times 10^{-12}$ / °C	in 0 to 48.5°C	1.9×10^{-13} / °C	1×10^{-12} / °C
G sensitivity	$\leq 1.8 \times 10^{-9}$ / g	$\leq 1.8 \times 10^{-10}$ / g	1.69×10^{-9} / g	1.87×10^{-9} / g

Figure 63: PHARAO FMs main performance

The previous table shows very good performance in phase noise and thermal sensitivity.

7.4.3 PHARAO LOW G SENSITIVITY USOS

However, due to microvibration disturbances between 0.1 Hz and 50 Hz onboard ISS, the g sensitivity of the 2 FMs was too high to obtain the PHARAO stability performance of 1×10^{-16} versus τ = 1day in a continuous measurement period of one week. It was decided to conduct studies on a QAS (BVA type self-suspended quartz) resonator at 5 MHz. A bench of several crystal QAS resonators were manufactured and measured in g sensitivity first, and then selected over all electrical and phase noise parameters.

The following table gives the results obtained on the QAS 5 MHz resonator selected for the FM 45 USO.

Items	Specifications	Goals	FM 45 resonator
Frequency stability			
τ = 1s	$\sigma_y(\tau) = 1\times10^{-13}$	7×10^{-14}	7.7×10^{-14}
τ = 10s	$\sigma_y(\tau) = 1\times10^{-13}$	7×10^{-14}	8.4×10^{-14}
G sensitivity	$\leq 1.8\times10^{-10}$ / g		1.76×10^{-10} / g

Figure 64: USO FM45 resonator performance (selected for low g sensitivity)

These results have been confirmed on the FM 45 fully integrated mid-2005, and then should be confirmed at microwave source level at 100 MHz and 9.2 GHz.

Figure 65: PHARAO USO

The situation today: *The very strict PHARAO USO performance was obtained using the DORIS-type new generation of space-qualified USO as well as crystal resonator and components specially selected for low noise emission near the carrier-wave. All goals of performances have been satisfied.*

The two first FM USO have been delivered and comply with the requirements. The upgraded FM LSA USO (Low Sensitivity to Acceleration) has been delivered in 07/2005. Following the anomaly linked to pure tin soldering (which generated "whiskers" and short-circuits), the FM LSA has been retrofitted in 2008. The microwave source has been fully re-tested after the retrofit in early 2009.

7.5 ELECTRONICS

Vivian Bernard – UGB (on board management unit) – CNES

7.5.1 MAIN FUNCTIONS

The UGB computer has been designed to perform the following hardware functions:

- ***Power supply management*** provided by the PDU (28V) and mainly:
  - ON / OFF of the PHARAO equipment,
  - Thermal regulation (heaters and Peltier coolers),
- ***Data handling protocol*** with the ACES CDHU computer using serial link (time-stamping and synchronisation with ACES),
- ***Data handling protocols*** with the PHARAO equipment,
- ***Controlling on board timing and synchronisation*** (micro sequencer),
- ***TM/TC activities*** to control analog house keeping TM and digital parameters,

The UGB has been contracted to EREMS.

7.5.2 UGB DESCRIPTION

The next picture shows UGB overall dimensions which are: 240 x 245 x 120 mm (7.3 l). The unit weight is close to 5kg and the total power consumption is less than 30W.

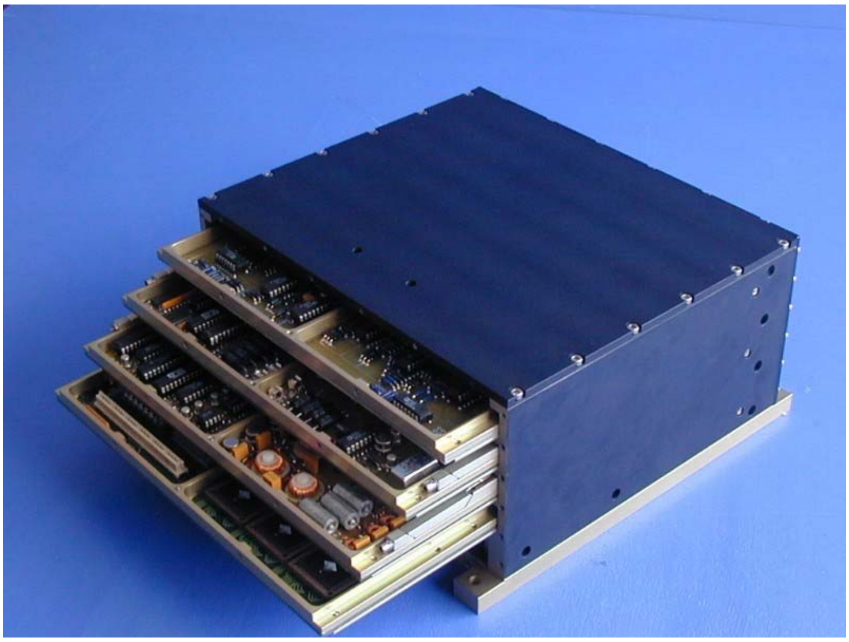


Figure 66: UGB unit

The computer is based on five boards (see diagram) connected to a back frame:

CPU board including:

- ERC32C processor (RISC 32 bit single chip) at 20MHz
- running the PHARAO flight software
- using BSP VxWORKS
- Local SRAM memory: 8Mbytes protected by EDAC
- Local Flash memory : 4Mbytes
- UART which manages all serial ports (8 channels)

- ROM memory (boot program): 512k x 8 bits

Digital board including:

- Programmable Micro Sequencer based on a PIC processor (17C756 at 10 MHz)
- Digital Data synthesiser (DDS STEL1173)
- Digital to Analog Converter (DAC 12 bits and 8 bits)

Analogue acquisition board including:

- 30 Differential inputs (±10V),
- 16 Single Ended inputs (±10V),
- all inputs are multiplexed using Harris HI546 buffer devices,
- acquisition: 12 bits / Sampling rate: 350µs,
  - Fast Burr Brown amplifier (AMP02),
  - Fast and high performance Analog to Digital 12 bits converter (ADC ADS774)

Thermal control board including:

- 3 heater lines with a power range between 0 and 2W
- 4 Peltier lines with a power range between 0 and 12W

DC/DC converter boards: The unit is powered from 28V using a DC/DC converter especially designed by the sub-contractor (EREMS).

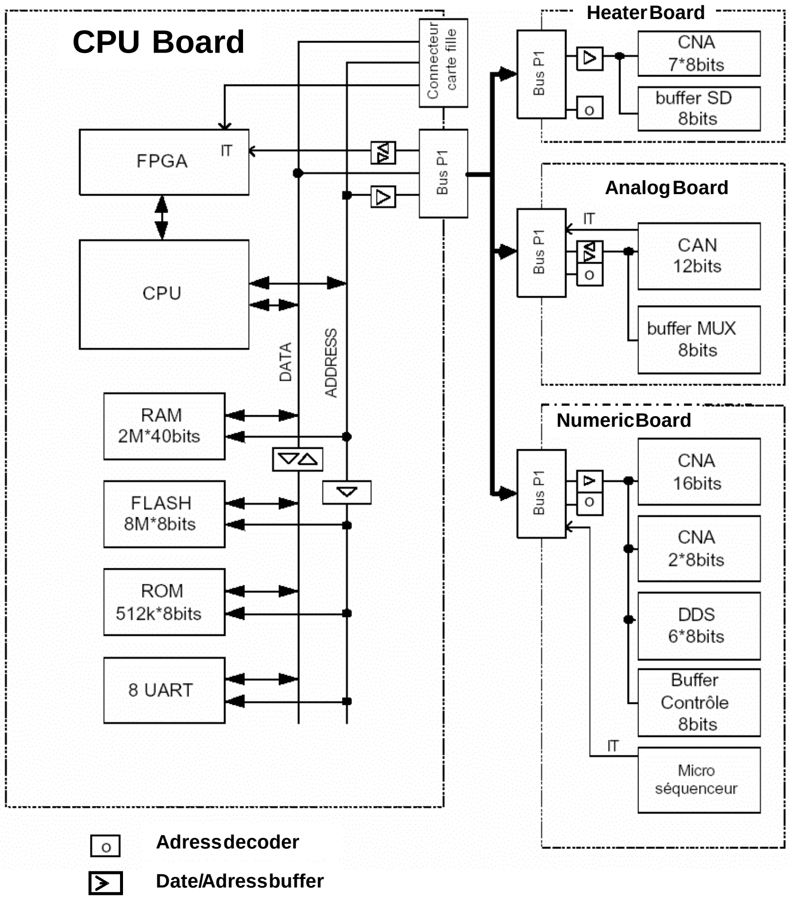


Figure 67: UGB hardware architecture

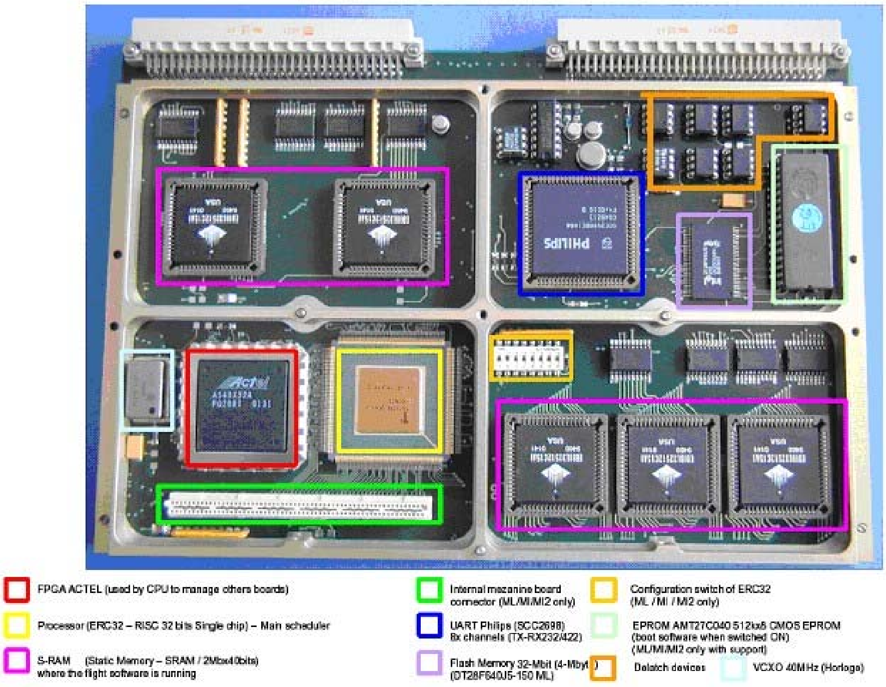


Figure 68: UGB CPU board

7.5.3 UGB POWER SUPPLY

The following diagram shows the 28V main power supply line provided by the PDU and distributed around the PHARAO instrument.

There are no active devices inside the UGB to control or to commute the 28V power supply applied to the SL and SH. ON/OFF command of SL and SH is ensured by UGB telecommand.

In the UGB, the power supply is split into two functions:

- one for to the internal DC/DC converter which includes a circuit breaker
- another for the power distribution toward the tube and the BEBA (mainly heater lines, Peltier cooler lines and secondary power supply).

Figure 69: BEBA unit

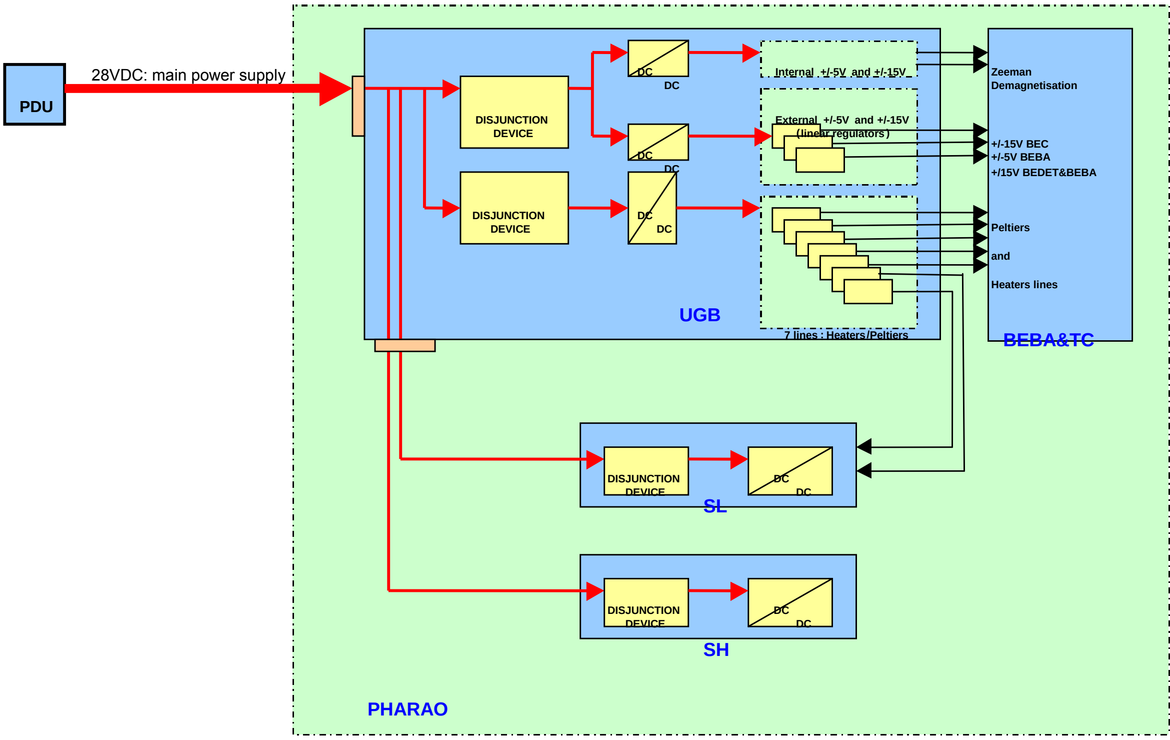


Figure 70: UGB power supply distribution

7.5.4 DATA HANDLING WITH ACES

The UGB is connected to ACES CDHU with serial link interfaces (RS422) as shown on the next figure: a data handling protocol controls the PHARAO payload.

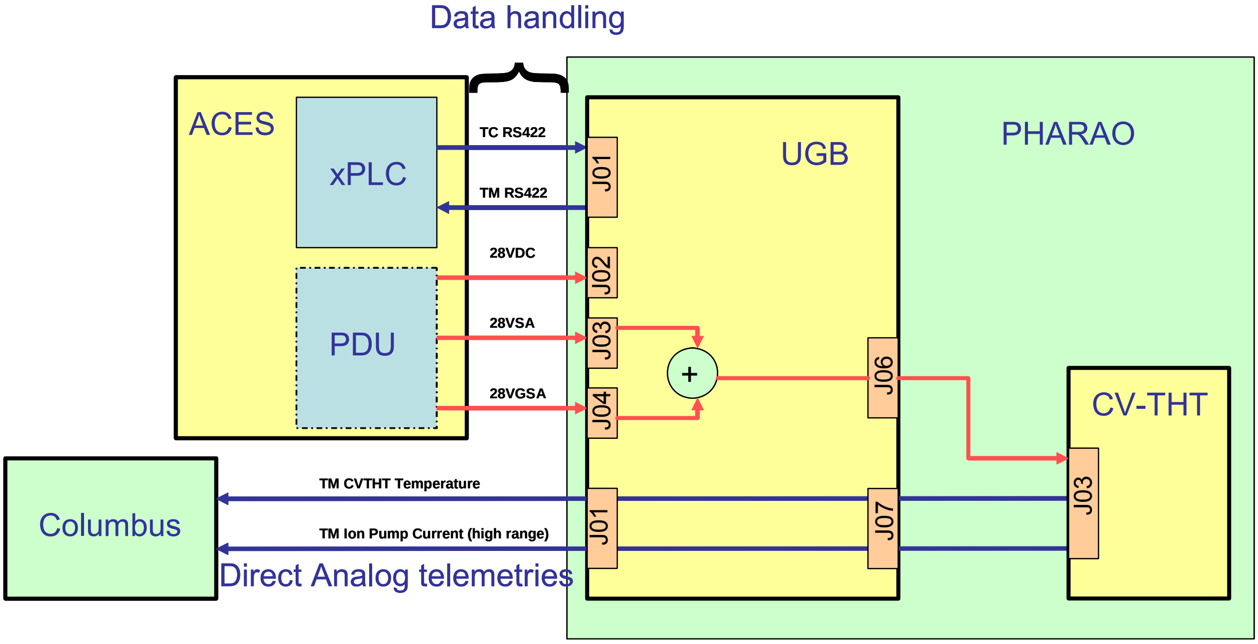


Figure 71: UGB / ACES data handling

Two dedicated links with Columbus are provided by UGB (analog telemetry data arrives from the THT converter used by the ion pump). These links are used by Columbus to monitor the converter when the payload is in OFF state.

7.5.5 UGB DATA HANDLING WITH PHARAO EQUIPMENT

The UGB is connected to all PHARAO equipment with a serial link interface (RS422) as shown in the next figure: a data handling protocol dedicated to PHARAO internal units controls the PHARAO sub-systems. The UGB manages the serial ports.

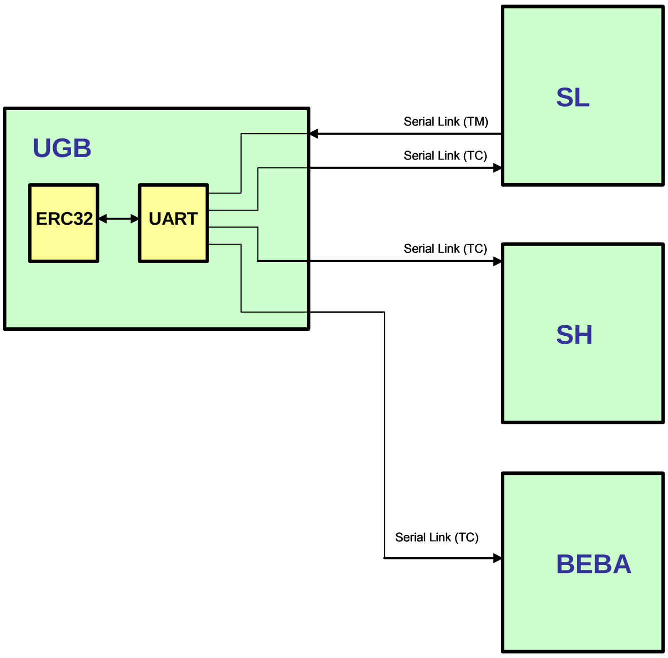


Figure 72: UGB / PHARAO internal data handling

7.5.6 UGB ONBOARD TIMING AND SYNCHRONISATION

The UGB is connected to SL and SH using specific commands called micro-commands. These commands are used to schedule SL and SH with precise timing resolution (100µs) and synchronisation. This function is provided by a Programmable Micro Sequencer using PIC. A synchronisation signal is generated by SH and distributed by the UGB to all other units.

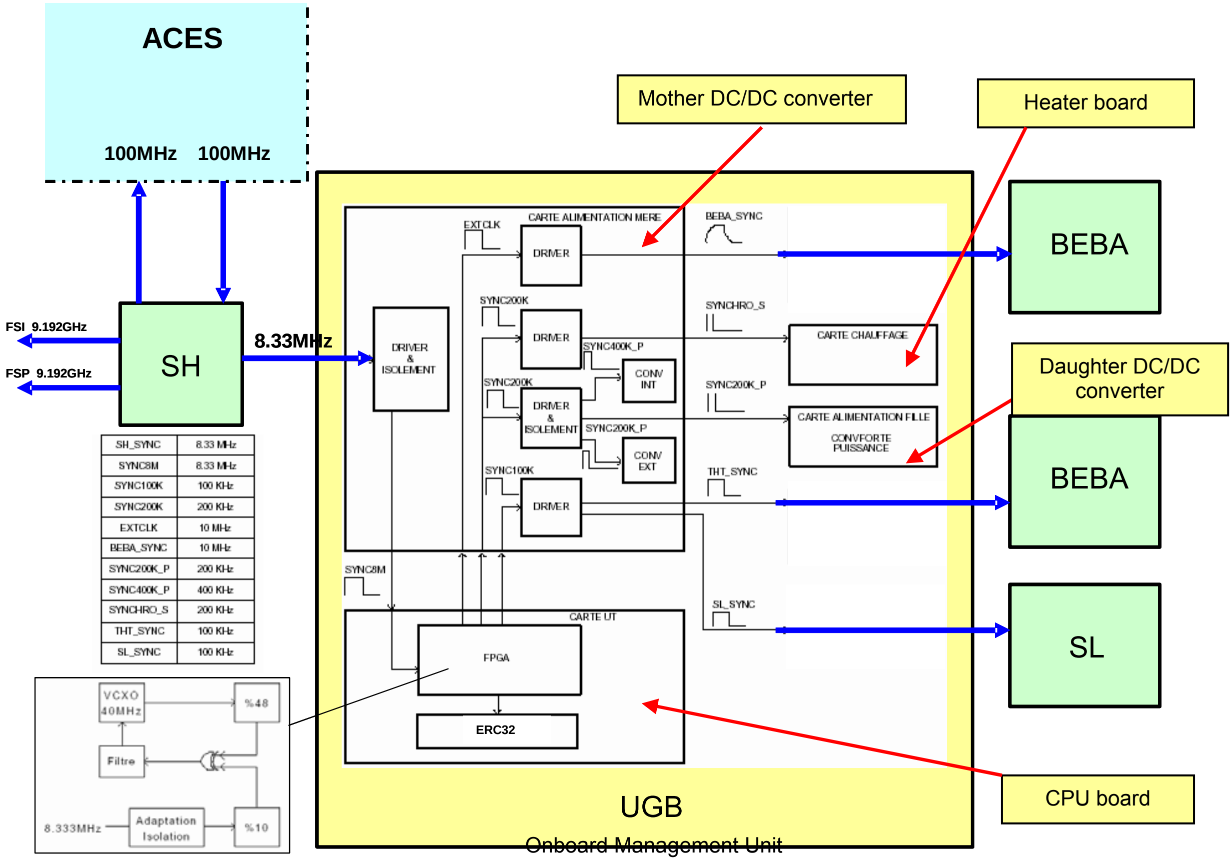


Figure 73: UGB onboard timing and synchronisation

7.5.7 TM/TC ACTIVITIES

The UGB performs analog acquisitions (house keeping telemetry) for each element of PHARAO's equipment in order to check that all PHARAO units are working correctly.

Direct telecommands to switch these units ON or OFF are performed by software in the UGB in accordance with PHARAO modes.

UGB software also controls the thermal equipment (heaters and Peltier coolers).

Scientific data (number of atoms in state F=3 and F=4) are acquired by the UGB which calculates frequency correction.

The situation today: *The UGB calculator is fully designed. Three models have been delivered. The first one is a laboratory model used for software development and now discarted. The second model delivered was an EM that was integrated and tested with microwave EQM, the software and the ground support equipment. This EM model served in PHARAO SEM (Simplified Electrical Model) which successfully tested the ACES interfaces in May 2009.*

A second EM has been delivered and integrated in the PHARAO EM. Following the observation of a bottleneck in the use of two models, a third EM will be built and delivered mid-2010. It will include the modifications filed for FM during the tests. QM and FM will then be manufactured for a delivery early in 2011.

7.6 FLIGHT SOFTWARE (LV)

Philippe LARIVIERE – Flight Software – CNES

7.6.1 PHARAO FLIGHT SOFTWARE PRINCIPLES

The context of the PHARAO project showed at the beginning (in 2002) two requirements for the PHARAO flight software: evolutivity and flexibility. The organisation and development choices of the PHARAO project lead to:

- starting the software development although the identification of all modes was not complete,
- allowing sub-system development in parallel with the software development whereas later technological choices could have a great impact on the software,
- providing the scientific and system teams with the ability to define new operational modes or treatments, with the minimum of impact on PHARAO flight software.

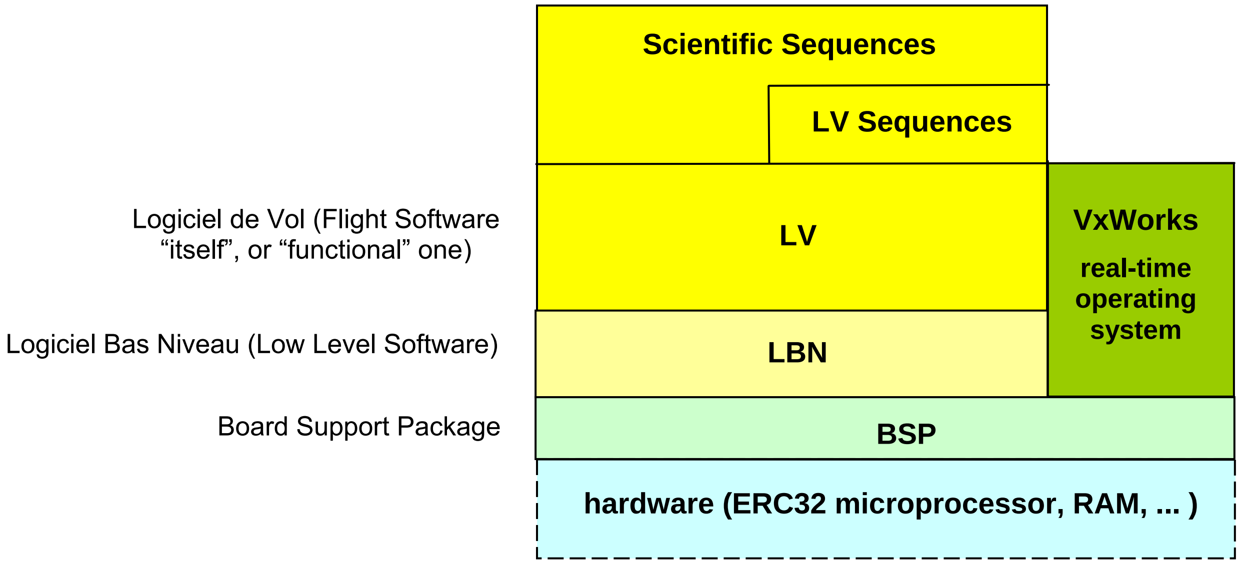
Therefore, one the main caracteristics of the PHARAO flight software is to implement an **interpreter** for the execution of “**Sequences**” defined by scientific and system teams.

7.6.2 GENERAL SOFTWARE ARCHITECTURE

The PHARAO flight software is divided into several levels:

- **Board Support Package (BSP)**: it is the first level of software, delivered with VxWorks RTOS and modified for the PHARAO UGB hardware. It offers the very low level access services to the UGB hardware.
- **Low Level Software (Logiciel Bas Niveau, LBN):** this part of the software provides a set of services for operating the PHARAO sub-systems via hardware interfaces.
- **Flight Software (Logiciel de Vol, LV)**: it is the flight software itself, which implements the functional part (TM/TC management, control and supervision, execution of Sequences, etc.) using LBN services.
- **Sequences**: a Sequence is a set of software instructions, written with a dedicated language, that the flight software has to execute with an interpreter. There are:
    - **LV Sequences** (low level Sequences), which implements, by choice of the LV developpers, LV functions.
    - **Scientific Sequences** which are defined by scientific and system teams for controlling and supervising the PHARAO sub-systems, and for the final using of the instrument.

The diagram below presents the different levels of the PHARAO flight software:



7.6.3 SEQUENCES

The Sequences and their interpreter require to have:

- a dedicated language with a set of instructions to perform acquisitions, prepare TM packets, implement algorithms, etc.,
- an execution engine into the LV, which defines the way Sequences are going to be executed,
- a Sequence decoder into the LV, with the ability to load new Sequences on board by TC.

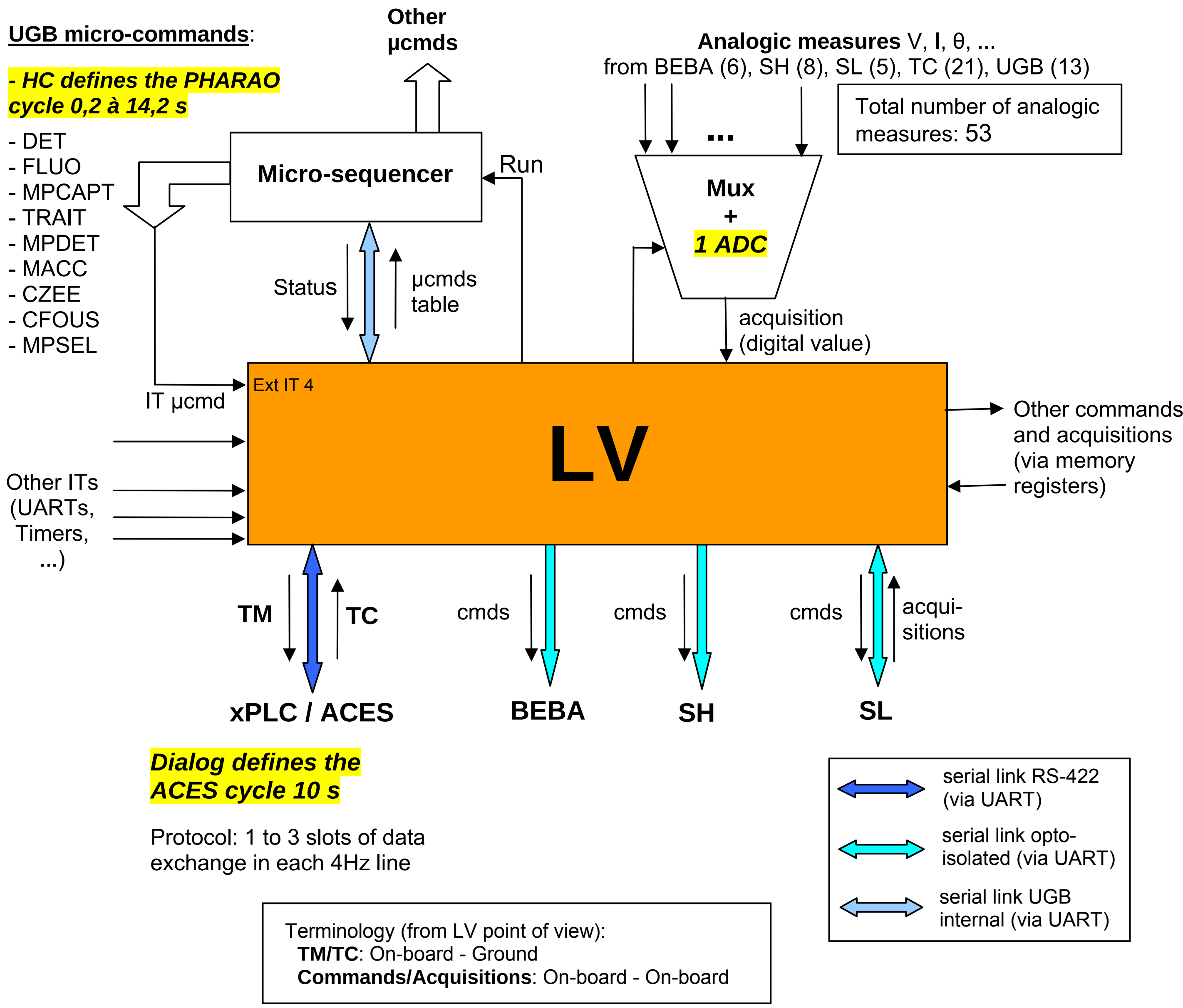
The ability to define and load on board new Sequences is useful to take into account new needs (new scientific needs, or even new equipment specifications). However, PHARAO flight software remains a real-time software, and Sequences must comply with its real-time architecture.

7.6.4 REAL-TIME ARCHITECTURE

The real-time architecture of the PHARAO flight software is based on:

- PHARAO (P) cycle: it is the main real-time part of the architecture. A cycle duration depends on the current micro-commands table, by handling the micro-sequencer interrupts; this duration can be from 0,2 to 14,2 s. Sequences can configure the treatment to be applied to the TRAIT and HC micro-commands.
- ACES cycle: it performs the permanent activities of the instrument on a 10-second cycle. For this purpose, it acquires and processes data (sub-systems supervision, control, etc.).
- Communication with ACES based on the xPLC protocol.

The diagram below summarizes the interfaces of the PHARAO flight software, and their real-time involvement (highlighted in yellow):



7.6.5 PHARAO FLIGHT SOFTWARE DEVELOPMENT

PHARAO flight software development has been contracted out to the company C-S. It is based on an incremental process. It relies on:

- Textual software specifications described through several documents (specification documents and interface documents).
- Hood method for the flight software (LV itself) design, and UML formalism for the low level software (LBN) design.
- C language (and few lines of assembly language).
- Sequences dedicated language.
- VxWorks RTOS: WindRiver multi-tasking real-time executive for the ERC32 microprocessor, with Tornado environment for development.

- Integration and validation tests performed on a specific validation environment (Banc de Validation Logiciel, BVL), providing a minimal representation of the PHARAO sub-system's behaviour.
- The development of several ground software tools associated to the LV. The BVL is an example, and also PHASM (PHARAO Sequence Manager) to compile the source code of Sequences.

The budget for the PHARAO flight software is (LV2-1.1, august 2009):

- BSP: 4400 lines of C code, 500 lines of assembly code
- LBN: 8700 lines of C code
- LV: 26000 lines of C code
- Sequences:
    - 335 Sequences (76 LV Sequences, 259 scientific Sequences)
    - 12000 lines of source code

The situation today: *The last delivered PHARAO LV is identified as LV2-1.1. It was delivered in august 2009 (for the EM PHARAO instrument). It is a complete and stable version with very few known SPR. The definition of the flight software modifications for the FM PHARAO instrument, is in progress. The work has to take into account the needed renewal of tools as software design tools (TOPCASED is considered). The development of the FM PHARAO flight software shall begin by the fourth quarter of 2010.*

8 ASSEMBLY, INTEGRATION AND VERIFICATION

Claude ESCANDE – AIV Manager – CNES
Philippe LAURENT – Project scientist – LNE/SYRTE
Benoit LEGER – T&F engineer - CNES

PHARAO Assembly, Integration and Verification takes into account the mechanical and electrical integration of the subsystems as well as the associated validation tests. PHARAO AIV is performed in 2 phases for EM and FM:

AIV 1 : The first AIV phase consists :

- in demonstrating that PHARAO works correctly
- in detecting all doubts related to the sub-assemblies.

For the EM, AIV1 is intended to validate the general design in order to authorise the manufacturing of the flight sub-assemblies.

AIV 2 : The second test campaign phase consists in verifying the performance of the PHARAO clock in configurations close or identical to ACES conditions.

The AIV plan details the assembly, validation and tests sequence from the delivery of the accepted subsystems until the end of the EM or FM AIV corresponding to the delivery to the ACES prime contractor.

Figure 74: The clean room and vacuum chamber dedicated to Pharao AIV phase

PHARAO FM AIV is performed following the process validated on EM with a shorter AIV1 phase. The AIV2 phase characterises the performance of PHARAO FM on the ground.

8.1 AIV PREPARATION

The integration and test activities are carried out on formally accepted components (test bench, structure, active equipment, harness, simulators) whose mechanical, optical and electrical interfaces have been checked with regard to definition drawings, the ICD and ground test facilities developed specifically for the project.

All the items will be delivered with an associated documentation (logbook in particular) and with the planned specific ground support equipment. The acceptance tests for delivery and for the supply of associated equipment are defined in the STB (requirements) and the contract of each sub-system procurement.

After instrument AIV activities, it is planned to use the EM model:

- First, to check ACES interfaces.
- Secondly, after a possible refurbishment, as a ground clock during the operational life of the FM for instrument troubleshooting during commissioning or to validate specific sequences before implementation in flight.

The AIV campaign requires that all the following points have been fulfilled during a preliminary phase:

- All Ground Support Equipment (GSE) has been designed, developed, manufactured, delivered and accepted by CNES.
- All GSE has been integrated, tested and validated in clean-room and operational conditions.
- Procedures related to GSE have been written and validated. Procedures are ready for EM testing to be carried out. After the EM campaign they will be updated for testing on the FM.

Figure 75: The mobile atomic fountain

Figure 76: Cryogenic oscillator from UWA

The preliminary phase started in June 2002 with the procurement of the CCGSE (Time and Frequency GSE), vacuum chamber and support structure.

8.2 AIV1 – VALIDATION PHASE

The first AIV phase called the **VALIDATION** campaign (or AIV1) checked the coherence of the sub-systems (overall interfaces and operation):

- EM AIV1 will authorise integration of the FM sub-systems.
- FM AIV1 will validate the FM instrument.

For this phase, the instrument is in an AUTONOMOUS operational configuration. All the validation tests are performed in a software configuration adapted to the test target. At the same time, all the mechanical and electrical integration procedures, as well as the test procedures, are validated.

AIT Incoming Acceptance Test: After delivery to CNES, each subsystem goes through an internal acceptance procedure to check its integrity after transport and before integration. This is a simple functional checking made up of some "good health" tests with the sub-contractor’s ground support equipment.

Hardware Interface Validation: This validation phase is composed of the simplest tasks of the Integration Plan. After CNES reception, the equipment is connected to the UGB:

- Mechanical integration of each item on the mechanical interface base plate while using and validating the dedicated mechanical integration procedures.
- Harness connection of each item while using and validating the dedicated electrical integration procedures.
- Validation of TM/TC signals transmission.

Functional Chain Validation: The functional chain validation checks the correct working of each sub-system connected to the UGB. This validation is performed by activating the elementary software functions.

PHARAO Functions Validation: PHARAO functions validation is performed with complete hardware and the flight software. The instrument must perform an accurate action of measurement, of calibration or of adjustment.

EMI-EMC Verification: These tests, either specific (noise measurements) or carried out on characteristic instrument functions, measure the sensitivity of the instrument to the different environments as well as the disturbances produced by the instrument itself.

Good health sequence: At the end of the "AIV1" phase, a good-health test sequence has been defined and validated. It involves all the PHARAO subsystems in order to characterise the good health of the system as quickly as possible. This sequence will be used at every step of AIV on EM and FM, in vacuum conditions as well as under ambient pressure for traceability and non-regression checking.

PHARAO FM AIV1 will be performed following the process validated on EM with a shorter AIV1 phase.

8.3 AIV2 - DETAILED CHECKING PHASE

The **DETAILED CHECKING** campaign (AIV2) validated:

- Command / control procedures (hardware + software).
- ACES timing imposed by XPLC.
- Validation, after longer testing, of the real-time functioning and the performance of the PHARAO clock. Operational configurations tested will be NOMINAL and BACK UP (configurations close or similar to ACES configuration).

The last step is the longest and concerns the clock frequency accuracy measurements.

The accuracy of PHARAO in microgravity environment will be in the order of 10^{-16}. On ground its accuracy is limited to 10^{-15}.

In this AIV2 phase we evaluate each systematic effect which disturbs the atoms (such as magnetic shift, Blackbody shift, collisional shift, …). And in order to minimize the time to evaluate this accuracy, we replace the USO by a Cryogenic Sapphire Oscillator (CSO) whose very low phase noise permits to obtain a stability of PHARAO of $2.10^{-13}\ \tau^{-1/2}$.

In parallel, we use the mobile fountain (FOM) comming from SYRTE to verify the calculated accuracy of PHARAO.

The goal of the EM AIV2 campaign is to demonstrate the functioning of PHARAO and to validate the measurement process. FM AIV2 is to verify the instrument performance before flight.

9 DEVELOPMENT

Christophe DELAROCHE – PHARAO development – CNES

The instrument architecture is derived from the ground clocks available in laboratories. One challenge for PHARAO is that there is no industrial background directly applicable. For this reason CNES has to act as the instrument development prime contractor with strong support from the scientists.

9.1 DEVELOPMENT PHASES

PHARAO phase A started in April 1998 and the decision to proceed to phase B was taken in July 1999. During Phase B numerous actions were performed in French industry.

The Instrument Phase B was closed with the PDR in June 2000. The instrument was divided into subsystems according to an architecture derived from the ground clocks.

For each subsystem, the RFP (Request For Proposal) was sent to the industry in order to select subcontractors. Due to the technical complexity, a 6-month competitive industrial phase B was scheduled for most of the subsystems (TC, SL & SH). The full industrialisation phase lasted about one year, from instrument PDR in June 2000 until selection of all the subcontractors in June 2001. All the industrial C/D phases were started in industry by mid 2001 and the contracts were finalised in the autumn of 2001.

EM (Engineering Model) subsystems has been delivered from 2004 to 2006, integrated at CNES and tested until mid 2010.

FM (Flight Model) SH has been delivered in January 2005 but re-open to retrofit the OUS which could be degraded in flight after apparition of pure tin whiskers. The last delivery has occurred in March 2009. Others FM are planned to be delivered mid 2011.

The main subcontractors chosen are:

Main items	Sub-Contractor
Caesium Tube (TC)	SODERN
Caesium reservoir	AER
Microwave Cavity	THALES ELECTRONICS DEVICES (TED)
Laser Source (SL)	SODERN
Microwave Source (SH)	THALES AIRBORNE SYSTEMS (TAS)
USO (OUS)	C-MAC (now RAKON)
Onboard calculator (UGB)	EREMS
Software (LV)	CS-SI
Harness	STEEL
Integration engineering support	ALTEN
Electric and command / control eng. support	ALTRAN
PHARAO simulator (micro-command tables)	SYNTEGRA

Figure 77: Main PHARAO subcontractors

9.2 MODEL POLICY AND QUALIFICATION

The model policy take into account the need to produce two PHARAO models:

- an Engineering Model (EM) to verify the compatibility of the subsystem interfaces, validate the command and control, the functionning and verify the EMC autocompatibility.
- a Flight Model (FM), able to stand the space constraints and to reach the performance.

These two models are delivered to ESA to be integrated into ACES.

EM and FM PHARAO models are made up of EM and FM subassemblies respectively. Qualification with regard to the spatial environment is tested on PFM or QM or on dedicated Structural and Thermal Models (STM) according to the best compromise between efficiency, cost and time.

Due to technological differences, each subassembly has its own model policy.

PHARAO Models	TC	SL	SH	UGB
-	STM	STM	-	-
EM	EM	EM	EQM	EM
PFM*	PFM	PFM	FM	PFM

Figure 78: Model policy / PHARAO model composition

*At PHARAO level, only functional and electrical qualification will be performed on FM. As PHARAO is made of separate subassemblies, mechanical and thermal qualification will only be totally reached through the ACES PFM qualification campaign.

9.3 ASSEMBLY SCHEDULE

Due to the technical challenges, PHARAO development encountered numerous technical difficulties which significantly delayed the PHARAO integration activities. The biggest problems occurred on Caesium Tube and Laser Source mainly due to the lifetime difficulties of the laser diodes in vacuum and the mechanical structure of the high vacuum tube.

These delays retarded the subassembly model delivery schedule and modified the integration program of PHARAO models. Originally, all the sub-systems were planned to be delivered at the same time. As a consequence, the AIV sequence was rebuilt several times in order to perform previous tests in advance and to consolidate the ground facilities. Another consequence is that PHARAO assembly will be made step by step using simulators to replace delayed equipment.

9.4 AUTO-COMPATIBILITY TESTS

Before delivery to the ACES prime contractor, PHARAO will be tested with regard to SHM in the same vacuum chamber to check EMC and magnetic compatibility. These tests are under the responsibility of the ACES PI.

CNES will also test the servo loops which control the frequency stability of the ACES signal, involving the signals from both PHARAO and SHM.

10 MISSION SCENARIO

Philippe LAURENT – Project scientist – SYRTE
Frédéric PICARD – System engineer – CNES

At PHARAO level, the mission is made up of 3 phases:

1. **Phase 1 - in-orbit acceptance phase:** During this phase the instrument is powered up, its good health is verified and a full functional test will be performed: every functionality will be tested, and a first tuning of the instrument parameters will be performed. The duration of this phase is about 1 month. A frequent (i.e. permanent or at least once per orbit) TC link with the instrument is necessary.

2. **Phase 2 - characterization phase** (about 4 months): During this phase, the instrument will be optimised and its performance will be evaluated for several physical parameter sets (such as the launch speed of the atoms, atom density etc.). For this purpose, the instrument needs to have TC access four times every day for modifying the clock's parameters in order to measure and calibrate the physical effects with accuracy at the 10^{-16} level.

3. **Phase 3 - operational phase:** In this phase, PHARAO will be set in its optimal configuration, as determined during the characterisation phase. The stability and the accuracy of PHARAO will be evaluated at a level of 10^{-16}. The PHARAO instrument needs to have a TC access every day. Each measurement session for one instrument configuration will last 10 to 20 days in a noise-free environment (microgravity, EMC).

11 PRODUCT ASSURANCE

Sabine JULIEN – PHARAO AP Manager – Logiqual for CNES

PHARAO PA requirements have been established in 2001 by tailoring of ECSS and/or CNES standards.

A comparison between PHARAO and ACES PA Plan showed up some discrepancies or comments, see §7.8 of ICD PHARAO of reference PH-CI-1130-39-CNS issue 3.2 of 12/05/2009:

- No reliability assessment will be performed at PHARAO level but numerical reliability assessments will be performed in conceptual and trade-off studies. NCR on this topic, if any, will be considered as minor ones.
- DPL will be available but not submitted to ESA for approval.
- Outgassing criteria TML and VCM are replaced by RML and CVCM.
- On PHARAO, we consider a mission lifetime of 3 years without the 1.5 design margin. A shielding of 1 mm can not be demonstrated for the optical fibers (worst case on PHARAO). A preliminary radiation analysis on these fibers leads to a total dose of 10.5 Krads for a mission lifetime of 3 years, which is fully compatible with PHARAO need.

Analysis of material and EEE parts lists shows that outgassing requirements are met except on some polymers. The situation is the same for flammability requirements, with a lack of data on some materials.

The situation today:

1. The DML and DPL of UGB FM are not yet available.
2. The DML and DPL of laser source and cesium tube have been discussed between SODERN and CNES and they have to be updated to take into account the CNES comments.
3. The DCL of all equipments have been discussed between CNES and industrials. The DCL have to be updated to take into account the CNES comments.
4. Radiations analysis has been led for the components of laser source and cesium tube and radiations tests have been performed with success. Radiations tests shall be performed for some components of UGB and BEBA.
5. RFA shall be written for materials which do not meet requirements
    - of flammability and for which the mass is more than 5g
    - of outgassing.

ANNEX 1 - ACRONYMS

ACES	Atomic Clock Ensemble in Space
AOM	Acoustic Optic Modulator
BEBA	Electronic calculator in the vicinity of the Caesium Tube (coils and magnetometer)
BEC	Caesium Tube electronics for capture zone
BEDET	Caesium Tube electronics for detection zone
BIPM	*Bureau International des Poids et Mesures*, Sèvres (France)
LNE/SYRTE	*Bureau National de Métrologie – Laboratoire des Systèmes Temps et Espace*, Paris (F)
CAD	Computer Assisted Drawing/Design
CNES	*Centre National d'Etudes Spatiales*
CNRS-LHA	*Centre National de la Recherche Scientifique – Laboratoire de l'Horloge Atomique*, Orsay (F)
Cs	Caesium
ECL	Extended Cavity Laser (in Laser Source)
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
ENS/LKB	*Ecole Normale Supérieure – Laboratoire Kastler-Brossel*, Paris (France)
FCDP	Frequency Comparison and Distribution Package
FM	Flight Model
FRC	Facility Response Centre
ICD	Interface Configuration Document
IRD	Instrument Requirements Document
ISS	International Space Station
LCEP	*Laboratoire de chronométrie, d'Electronique et de Piezzoélectricité* (Besançon)
MMS	Matra Marconi Space
MWL	Microwave Link
OCA	*Observatoire de la Côte d'Azur*, Grasse (France)
OI	Optical Isolator
OUS	*Oscillateur Ultra-Stable* (Ultra-Stable Oscillator)
PDU	Power Distribution Unit
PIC	Programmable Integrated Circuit
PHARAO	Projet d'Horloge Atomique à Refroidissement d'Atomes en Orbite
SH	Microwave source
SHM	Space Hydrogen Maser
SL	Optical Laser Source
TBC	To Be Confirmed
TBD	To Be Defined
TC	Caesium Tube Resonator
T2L2	Time Transfer by Laser Link
T/F	Time and Frequency
TM/TC	Telemetry/Telecommand
UGB	*Unité Gestion Bord* (Onboard management unit)
XPLC	eXpress Pallet Calculator

ANNEX 2 - REFERENCES

The following table gives the list of the main publications about, or of interest to, PHARAO.

N°	Title
1	**Ramsey resonance in a Zacharias fountain** *A. Clairon, C. Salomon, S. Guellati, W. Phillips; Euro. Phys. Lett. 1991*
2	**Ultra cold atoms and microgravity clocks** C. Salomon, A. Clairon, P. Laurent, G. Santarelli, S.Ghezali, M. Bahoura, P. Lemonde, J. Reichel, A. Michaud, Radio Science Bulletin 276, 33 (1996).
3	**A simple and compact source of cold atoms for caesium fountains and microgravity clocks** Clairon A., Laurent P., Nadir A., Drewsen M., Grison D., Lounis B., Salomon C., Proc. of the 6th Frequency and Time Forum (ESA-SP), 340 (1992) p. 27
4	**Atomes Refroidis par Laser: vers une horloge ultra stable** Salomon C., Lounis B., Reichel J., Clairon A., Laurent Ph., Nadir A. Revue scientifique de la défense 1993-3 p 113/119
5	**Laser cooling and trapping of atoms: New tools for ultra-stable caesium clocks** *S. N. Lea, A. Clairon, C. Salomon, P. Laurent, B. Lounis, J. Reichel, A. Nadir, G. Santarelli. Physica Scripta, 1994*
6	**T2L2 Time Transfer by Laser Link** Veillet C., Fridelance P. Pages 443/453
7	**3D Cooling of Caesium Atoms with Isotropic Laser Light** N. Dimarcq, E. Aucouturier, G. Champagne, M. Tchagaspanian, proc. of the 5th Symposium on Frequency Standards and Metrology. Woods Hole, Massachusetts, Etats-Unis, October 1995, (ed.) James C. Bergquist, World Scientific, p. 115-120.
8	**Preliminary accuracy evaluation of a caesium fountain frequency standard.** *A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, S.N. Lea, M. Bahoura, E. Simon, S. Weyers and K. Szymaniec. Proceedings of the fifth Symposium on frequency standards and metrology. (1995)*
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10	**A caesium fountain frequency standard: recent results** *A. Clairon, P. laurent, G. Santarelli, S. Ghezali, S.N. Lea, M. Bahoura. IEEE Trans. Inst. and Meas. (1995)*
11	**A Space Frequency Standard Using Cold Atoms: the PHARAO project,** Laurent Ph., NPL: Next generation GNSS & Frontiers of Time and Frequency Measurement
12	**PHARAO: a cold atom clock in microgravity** *C. Salomon, P. Lemonde, P. Laurent, E. Simon, G. Santarelli, A. Clairon, N. Dimarq, P. Petit, C. Audouin, F. Gonzales, F. Jamin-Changeart, ESA Symposium Proceedings on 'Space Station Utilisation', ESOC, Darmstadt (December 96) , ESA special publication SP 385, p289 (1997).*
13	**PHARAO: a space clock with cold caesium atoms.** Ph. Laurent, E. Simon, G. Santarelli, A. Clairon, Ch. Salomon, P. Lemonde, P. Petit, N. Dimarcq, C. Audoin, F. Gonzalez, F. Jamin-Changeart, 26 th Precise Time and Time Interval, Washington, USA (1996). (PTTI - 06-28-477)
14	**Toward a space clock using cold caesium atoms: The PHARAO project** Ph. Laurent, E. Simon, G. Santarelli, A. Clairon, P. Petit, N. Dimarcq, C. Audoin, P. Lemonde, Ch. Salomon, F. Gonzalez, F. Jamin-Changeart, Conference on Precision Electromagnetic Measurements, Braunschweig, Germany (1996). (Invited paper).
15	**PHARAO: Une horloge à atomes froids dans l'espace** C. Salomon, P. Laurent, E. Simon, G. Santarelli, A. Clairon, P. Lemonde, P. Petit, N. Dimarcq, C. Audoin, F. Gonzalez, F. Jamin-Changeart, Journées internationales sur les vols paraboliques, Bordeaux (1996).
16	**PHARAO: a space clock with cold caesium atoms.** C. Salomon, P. Laurent, E. Simon, G. Santarelli, A. Clairon, P. Lemonde, P. Petit, N. Dimarcq, C. Audoin, F. Gonzalez, F. Jamin-Changeart, NASA-NSF workshop on laser cooling and atomic physics in space (1996). (Invited paper).
17	**Ultra cold atoms and microgravity clocks** *C. Salomon, A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, M. Bahoura, P. Lemonde, J. Reichel, A. Michaud* *Radio Science Bulletin 276, 33 (1996).*
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146	**Evaluation and Space Qualification of laser diodes for ATV-Videometer and PHARAO projects.** *S Minec-Dube - Sodern Workshop Laser Diodes in Space - CNES Toulouse 11/12 May 2006*
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152	**The Atomic Clock Ensemble in Space (ACES) Experiment** *Mr. Giuseppe Reibaldi, Mr. Rosario Nasca, European Space Agency, Noordwijk, Netherlands, Mr. Philippe Goudy, 'Mr. Christian Sirmain, CNES, 31055 Toulouse Cedex, France, IAF 2006 (IAC-06-A2.1.03) Valencia, 29 Oct - 6 nov 2008*
153	**PHARAO's Cesium Tube** *Mr Stephane Thomin, Mr Christian Mace, Mr Salem Belmana, EADS-Sodern, Limeil-Brévannes, France* *Mr Olivier Grosjean,CNES , Toulouse, France, IAF 2006 (IAC-06-A2.1.04) Valencia, 29 Oct - 6 nov 2008*
154	**REVIEW Experiments in Fundamental Physics scheduled and in development for the ISS** *C. Lämmerzahl1, G. Ahlers2, N. Ashby3, M. Barmatz4, P.L. Biermann5, H. Dittus1, V. Dohm6, R. Duncan7, K. Gibble8, J. Lipa9, N. Lockerbie10, N. Mulders11, C. Salomon12, General Relativity and Gravitation, Vol. 36, No. 3, March 2004 (C° 2004)*
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156	**MINIATURE PIEZO MECHANISMS FOR OPTICAL AND SPACE APPLICATIONS** *R. Le Letty(1), F. Barillot(1), H. Fabbro(1), F. Claeyssen(1), Ph. Guay(2), L. Cadiergues(2)* *(1) CEDRAT TECHNOLOGIES, 10 ch. de Pré Carré, ZIRST, F-38246 Meylan Cedex,* *(2) CNES/DTS/TV/MS, 18 Av. E. Belin, F-31041 Toulouse Cedex 9, philippe.guay@cnes.fr* *ACTUATOR 2004, 9th International Conference on New Actuators, 23-26 March 2004 Bremen Germany*
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Gestion Filière ISS		Serieys G.	74523	2513					
Documentation/Configuration		Ekis Clairis	74084	2212					
AQ Projet ACES/PHARAO	**X**	**Julien S. (Logiqual)**	73110	2931	**DCT/AQ**		**Saunier P.**	73376	1411
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AQ Intégration		Catala R.	73229	1415	DCT/AQ/GP		Etienne JP.	73817	2513
					DCT/AQ/QP		Dorleac G.	74696	1415
		Gasc Philippe	83049	1415	DCT/AQ/SF		Laulheret R. (web)	74719	1413
Sécurité		Faure Julien	82689	2513					
Système PHARAO	**X**	**Picard Frédéric**	81586	2212	**DCT/PS**		**Behal B.**	73396	1321
Architecte C/C		Béraud Serge	73242	2214	DCT/PS/SGE		Pasquier H.	73681	1504
Architecte Electrique		Ratsimandresy A. (Altran)	73453	2532	**DCT/RF**		**JP. Aguttes.**	74128	2512
Architecte mécanique		Buffe Fabrice	82861	1714	DCT/RF/HT		Carayon Guy	81857	2013
Architecte optique		Luitot Clément	82279	3601	**DCT/SB**		**Marchal Ph.**	74456	1421
Architecte thermique		TORESSI P.	73341	1716	DCT/SB/CC		Pouliquen C.	73298	2214
Support mécanismes		Casteras C.	82138	1715	DCT/SB/LV		Arberet P .	82367	2214
Support EMC		Panh J.	74734	2213	DCT/SB/OR		Van Troostenberghe P.	83423	1323
Développement PHARAO	**X**	**Delaroche Ch.**	74471	2212					
Source Laser		Faure B.	81960	3601	**DCT/SI**		**Valorge C.**	73572	1711
Tube Césium		Grosjean O.	74151	2212	DCT/SI/IN		Costeraste J	74223	3601
Source Hyperfréquence		Leger B.	74861	2013	DCT/SI/OP		Berthon J.	81948	3601
OUS		Cibiel G.	73767	2013					
					DCT/TV		**Boloh L.**	81401	1416
UGB & BEBA		Bernard V.	81548	1412	DCT/TV/AV		Vincendet C.	73693	1713
Logiciel de vol		Larivière Philippe	82048	2214	DCT/TV/EL		Tastet P.	74666	2213
					DCT/TV/IN		Le Meur P.	81625	1713
					DCT/TV/MS		Guay Ph.	82620	1715
AIV PHARAO		**Escande Claude**	**73049**	**2212**	DCT/TV/TH		Briet R.	82322	1716
AIV informatique		Ayache Liesse (Sogeti)	74677		DCT/TV/RI		Dubourg V.	73733	2212
AIV Informatique et SEM		De Graeve C.M. (Sogeti)	73930	2212	DCT/TV/2I		Chamontin E.	75048	2213
AIV électrique		Chatard Philippe (Sogeti)	74069	2212	DCT/TV/MT		Bricout J.N.	81320	1714
AIV électrique		Bousquet F.	73964	2212	DCT/TV/SM		Gangloff D.	82638	1714
Harnais		Fauveau M.M.	73769	1421					
AIV mécanique		Paillet A.	73406	2212					
AIV TF		Léger B.	74861	2013	**DSP/E2U**		Bonneville R.	67638	213
Banc sol		Fonta Lionel (Alten)	74133		DSP/EU		Hirtz-Leon S.	67802	Paris
		Figueiredo JP (Alten)	82102		DSP/EU		Casoli F.	67859	Paris

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	PS ACES	Dimarcq N.		
ESA	Coord. ACES	Nasca R.		
	Payload ACES	Feltham S.		
	Resp. Scientifique	CACCIAPUOTTI L.		
	Resp. Instr. ACES	Much R.		
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