The PHARAO SPACE CLOCK

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INTRODUCTION : Since 2001, CNES has funded the realisation phase of the PHARAO program. The first step is the construction and the performances evaluation of an engineering model of a space clock using cold cesium atoms. The clock is made of four main sub-systems and their procurement is contracted in industry l subsystems will be finally assembled at CNES in Toulouse, for tests and validations. The flight model, will then be constructed to be assembled on the ACES payload. The ACES mission, managed by the European Space Agency, has two main objectives: the study of the physic of the cold atom clock and to perform fundame comparing the space clock signal with ground based clocks via a two way link. An H-maser developed by Observatoire Cantonal de Neuchâtel is the second ACES clock and will be used as a stable frequency reference for mid term duration

PHARAO OBJECTIVES :

High accuracy laser cooled Cesium clock in space for :

Fundamental physics
- Relativity theory tests
- Search for drift of fundamental physical constants

Delivering a world-wide reference time frequency signal for navigation, positioning,,…

PERFORMANCES :

- Cesium atoms launch velocity : from 5 cm/s to 5 m/s
- Stability : $10^{-13}\,\tau^{-1/2}$, 3×10^{-16} @ $\tau = 1$ day
  1×10^{-16} @ $\tau = 10$ day
- Accuracy : at the level of 10^{-16}
- 91 Kg, 114 W

FLIGHT : ACES is to be launch with the Shuttle and accommodated on an Columbus external pallet onboard ISS

DEVELOPMENT :

- PHARAO is a CNES funded project,
- The engineering model is under construction,
- A strong collaboration between CNES, ENS & SYRTE

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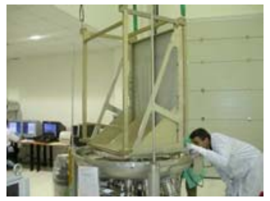
Integration


SYRTE mobile fountain


UWA cryogenic oscillator

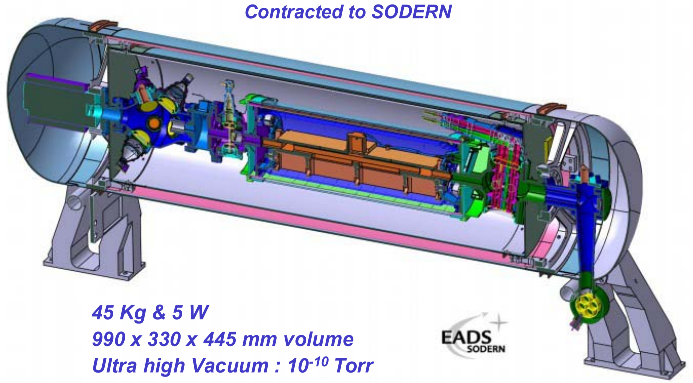

Microwave FM integration


Thermal regulated baseplate

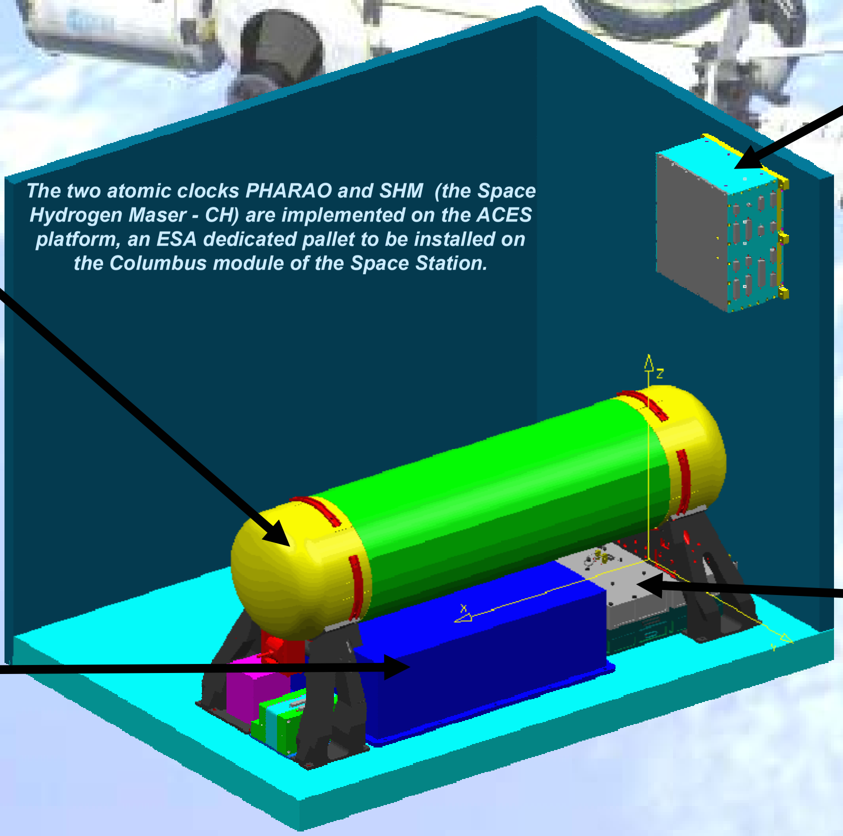

Vacuum chamber before closing

Cesium Tube

Contracted to SODERN



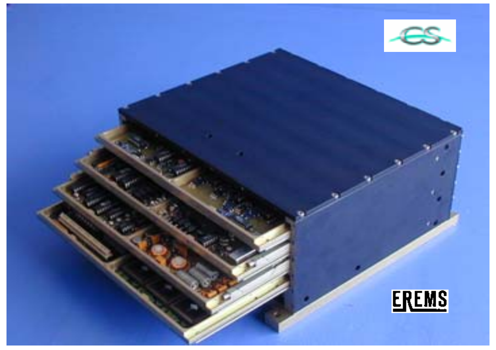
45 Kg & 5 W
990 x 330 x 445 mm volume
Ultra high Vacuum : 10^{-10} Torr
Magnetic shielding : 10^{-10} Tesla
Optics for atomic cooling, selection & detection
Microwave Ramsey cavity



The two atomic clocks PHARAO and SHM (the Space Hydrogen Maser - CH) are implemented on the ACES platform, an ESA dedicated pallet to be installed on the Columbus module of the Space Station.

On board computer

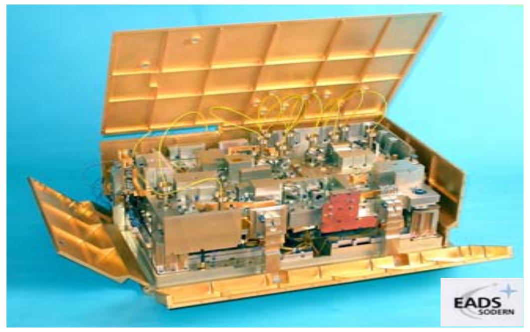
Contracted to EREMS (hardware) and CS (software)



6 Kg & 26 W
240 x 245 x 120 mm volume
VxWORKS Real Time Software
20 MHz ERC32SC processor
Ethernet link for software development

Laser Source

Contracted to SODERN



20 Kg & 40 W (including electronics)
530 x 330 x 180 mm
Frequency stabilised laser diodes $\Delta\nu < 200$ kHz
14 lasers beams delivered with 10 optical fibers
Output power active control : $\Delta P/P = 1$ %

Microwave Source

Contracted to Thales TAS

7 Kg, 25 W
270 x 300 x 100 mm (including USO)
Provides the 9.192631770 GHz microwave signal (atomic resonance)
Ultra Stable Oscillator USO : 6 10^{-14} (1-30s frequency stability)
Reference output signal : 100 MHz for clocks comparison

PHARAO Cesium Tube

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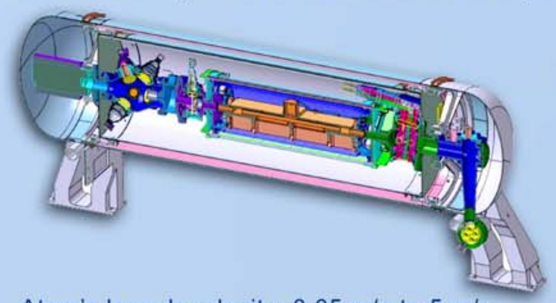
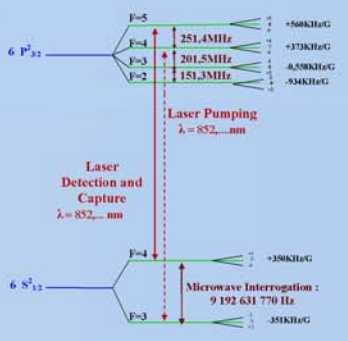
Philippe LAURENT, André CLAIRON, Pierre LEMONDE : BNM-SYRTE Paris, France, Christophe SALOMON : ENS-LKB
Christian MACE, Stéphane THOMIN: EADS-SODERN, France
Microwave cavity; Michel CHAUBET: CNES, André CLAIRON: SYRTE, Muriel ANDRE: Thales Electronic Device

CESIUM TUBE description

The Cesium Tube is the heart of PHARAO, where interactions between cold cesium atoms, microwaves and lasers take place

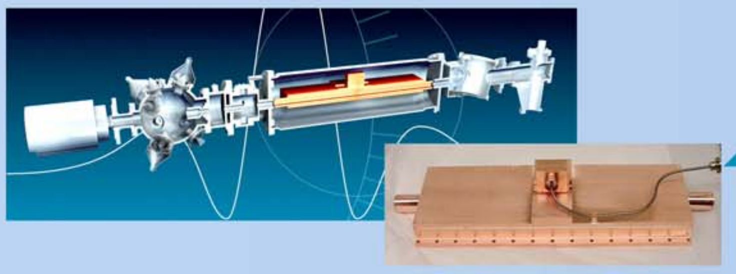




Atom's launch velocity: 0,05 m/s to 5 m/s
Interaction time : 0,5 to 5 seconds

The microwave Cavity

- The microwave cavity is the heart of the Cesium Tube where cesium atoms are submitted to the microwave signal at the frequency cesium atoms



RF input from microwave source

The microwave Cavity
THALES

Development :

Cesium Tube milestones

July 2001: industrial development contracted with EADS/Sodern
May 2002: TCs (Cs tube) PDR
July 2003: Detailed design
Sept 2003: EM integration
Mars 2004: Vacuum validation
February 2005: EM Pumping and outgassing : vacuum level < 2.10^{-9} Torr
August 2005 : Cesium tank Opening

Cesium Tube Magnetic subsystem

Seven coils generate an homogeneous and stable DC magnetic field on the atoms' trajectory.
The cesium Tube features an original active compensation coil and servo-loop with a magnetometer in order to minimize the residual induction in the rotating Earth magnetic field in orbit, by a factor of 10 at least.
All Tube components must have a low residual magnetic induction below 10 µG. This is verified by using a dedicated work-bench.
The performances of this subsystem are verified with a specific mock-up using the Engineering Model's shields and coils.

magnetic work-bench

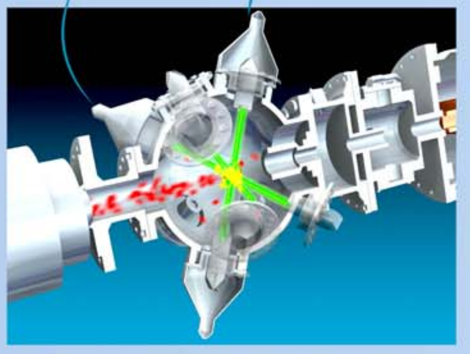
Three concentric cylindrical magnetic shields attenuate the outer magnetic field by a factor of 20000.

integrated shielding

magnetic schields

Cesium Tube Main characteristics

- 45 Kg & 5 W
- 990 x 330 x 445 mm^3
- cesium reservoir (3 grams of Cs)
- Ultra-High-Vacuum : 1.5 10^{-10} Torr
- Ion Pump 3 l/s + getters
- Laser beams, Ramsey Cavity, Magnetic shielding



fibers from Laser Source

Capture and cooling of cesium atoms
T = 1 µK, Vrms = 7 mm/s

Cesium Tube Main Challenges

The main challenges in the development of the cesium Tube:

- low mass budget : a total budget of 45 kg was allocated to the cesium Tube, 50 % of mass is shielding)
- development of specific innovative components and technologies compatible with amagnetism, ultra-high vacuum and space environment
- design of optical windows, flanges, collimators with respect to space environment (mechanical and thermal).

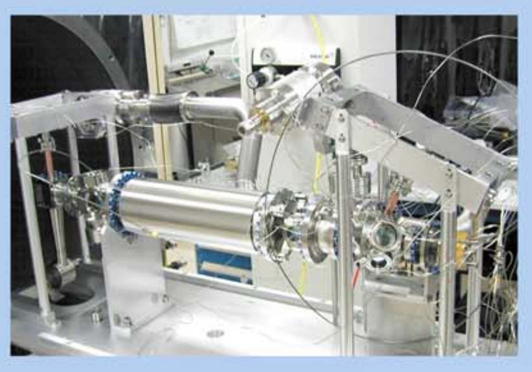
Cesium Tube Ultra-High Vacuum and pumping means

The vacuum tube is pumped by 3 pairs of SAES St171-16-10-NP getters. Due to the presence of interrogation copper cavity and flanges close to the getter supports, a specific thermal activation sequence has been determined.

Getters

Since getters do not pump rare gases and hydrocarbides (CH4,...), a specific 3 l/s ion pump was also developed. This pump is a diode-type pump, with a titanium body, directly welded on the vacuum tube, with a 5 kV power supply.

Ion pump

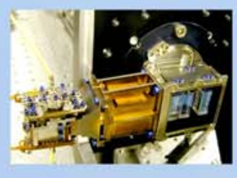


UHV Tube of the Engineering Model

Optical and detection subsystems

The optical subsystem contains 10 collimators fixed to the Ultra-High Vacuum tube and equipped with optical fibers for laser injection. Precise positioning of the laser beams is obtained by adjusting rotation and translation wedges on top of each collimator. The six degrees of freedom of each optical fiber are adjusted independently on each collimator.
Two cooled (15 °C) detection modules measure the fluorescence signals of the atoms during the detection process. The development of the detection modules needed a high level of simultaneous engineering since all disciplines involved in the cesium Tube development had to be taken into account: thermal control, optics, electronic performance, but also microwave and magnetism.

One of the six Engineering Model's Capture Collimators



The Engineering Model's Illumination Collimator

PHARAO Laser Source

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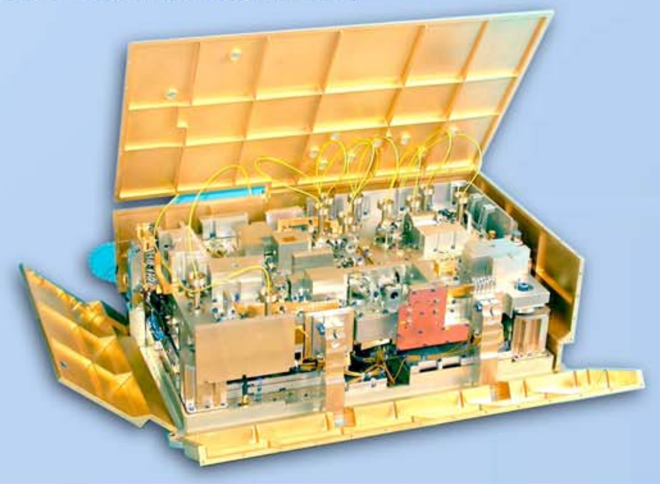
Christian MACE, Jean-Pierre LELAY : EADS SODERN, Limeil Brévannes, France

Laser Source STM model



Laser Source Main Performances

➤ 2 precise reference frequencies (4-5 et 3-4 saturated absorption lines of Cs) and precise frequency shifts	
➤ Frequency tuning from :	3 kHz to 80 MHz by AOMs
➤ High spectral stability :	< 10^7 Hz²/Hz below 100 Hz 10^4 Hz²/Hz above 100 Hz
➤ High spectral purity :	$\Delta\nu = 200$ kHz
➤ Low Relative Intensity Noise :	< 2.10^{-10} Hz^{-1} above 100 Hz <10^{-7} Hz^{-1} below 100 Hz
➤ High optical power :	~ 120 mW (for the 14 signals)
➤ High polarization ratio	(99:1)
➤ Active stabilisation of optical power :	DP/P = 1 %

piezoelectric mechanism
for laser beam
intensity balance

High density of
optical components

Laser beam
Shutter mechanism

Electronics
cards integrated

Acousto-Optical
Modulator

- High efficiency > 85%
- Low power consumption ***< 0.2 W***

Development status

Contracted to EADS-SODERN.

- 3 SL models :
STM delivered in september 2005
EM delivery in december 2005
FM delivery in 2007

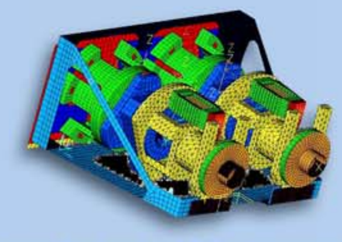
- Main difficulties encountered :
- Laser Diodes lifetime in vacuum
- Compromise between volume/mass/power allocation.
- Laser power budget
- Extended Cavity Laser Diodes qualification

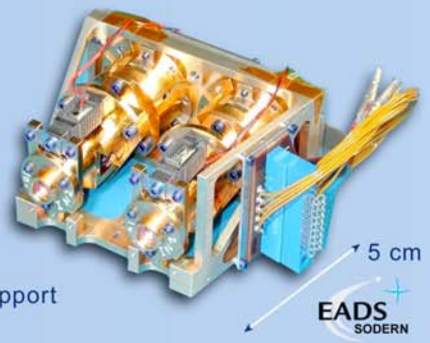
Main Characteristics

- 20 Kg & 40 W (electronics included)
- 530 x 330 x 180 mm³
- 14 lasers signals delivered in 10 optical PM fibers
  - Capture and cooling of cesium atoms : 15 mW per beam
  - Selection and detection : 3mW per beam
- Laser diode redundancy

Extended Cavity Laser Diode

- High spectral purity +/- 100 kHz
- Encapsulated laser diodes for air /vacuum operation





Main and Redundant ECL integrated in support

The ECL development was a real challenge now fully perational

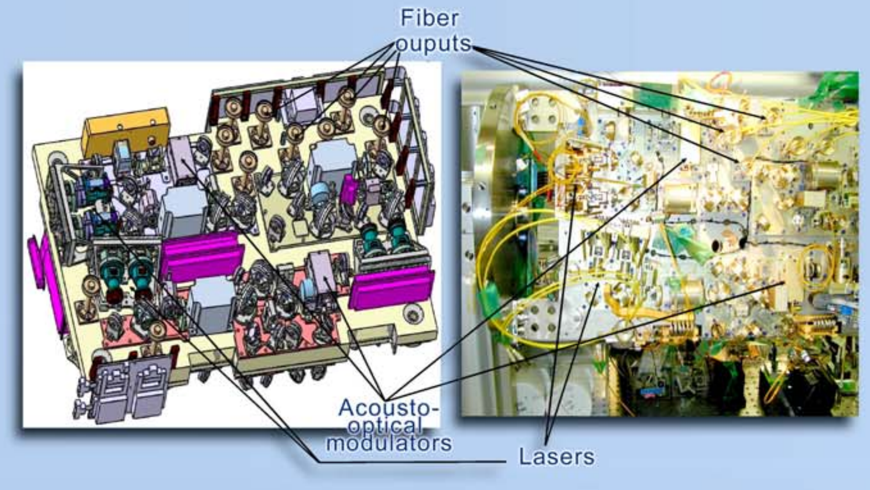
• Extended Cavity Laser Diode with :

- Frequency selectivity: tilted filter,
- Frequency stabilisation using Cesium saturated absorption,
- High optical stability : PZT on output mirror in cat's eye geometry.

• Concept demonstrated by SYRTE

Spacialization by Sodern :
- performances measured in vacuum & air
- servo-loop stability tested over 20 days

Upper side of the optical bench



Laser Source Status

- A challenge was the accomodation in the allocated volume
- Design is finished, main perfomances in accordance with requirements
- EM to be delivered end 2005
- On going EM thermal verification

PHARAO Microwave Source

A short term frequency stability of 6. 10^{-14} at 1 Hz.

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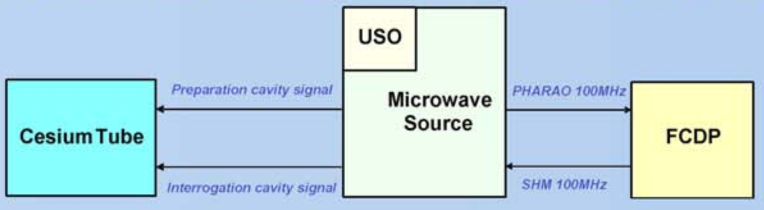
Thierry POTIER, Yohann COSSARD : Thales Airborne Systems, Elancourt, France.
Patrice CANZIAN, Vincent CANDELIER : C-MAC, Argenteuil, France.

SH Flight Model

Microwave Source Main functions

- **To provide 2 ultrastable frequencies at 9.192631770 GHz from a 5 MHz reference (USO) to supply the microwave cavities inside the Cesium Tube.**
- **To provide a metrological 100 MHz signal for the comparison with MASER (SHM) via the Frequency Comparator and Distributor Package (FCDP of ACES).**



-To switch off and to replace the internal SH 100 MHz signal by external 100 MHz signal.
-To drive the synthesized frequency to measure interference fringes.
-To control the power of the 9.192631770 GHz output signals.

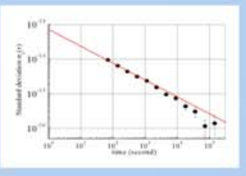
Development :

- **Contracted to Thales Airborne Systems.**
- **Development duration : 43 months.**
- **3 SH models :**
  STM delivered in december 2002
  EQM delivered in february 2004
  FM delivered in december 2004
- **USO models :**
  FM35 integrated inside SH EQM
  FM34 integrated inside SH FM
  FM45 for the SH FM retrofit in relation with microvibration level increase
- **Main difficulties encountered :**
  Compromise between volume/mass/power allowed.
  Susceptibility to radiated magnetic field
  Phase noise and phase shifts.

DC-DC converter and the USO fixed on

Microwave Source Characterisations

- TAS : comparison between two sources
- SYRTE : comparison with an Atomic Fountain
  The SH EQM short term frequency stability : $\sigma_y(\tau=1s) = 7\ 10^{-14}$
- CNES : SH FM measurements with an ultra low phase noise Cryogenic Oscillator.



(See : 'The PHARAO time and frequency performance verification system',Ph. Guillemot and al., Frequency Control Symposium, Montreal, 2004).

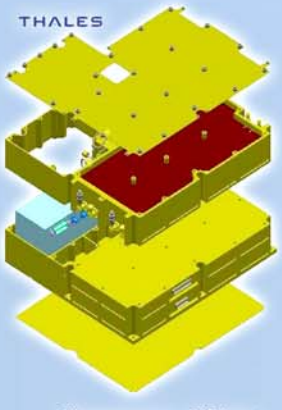
Preparation of SH characterisation in Thermal Vacuum. During SH AIV in CNES.

SH Flight Model under tests

SH FM and SH Prototype in Tests (TAS facilities)

Microwave Source Main Challenges

- Extremely stable signals at 100 MHz and at 9.192 GHz
  Very low phase noise : -60 dBrad²/Hz @ 1 Hz at 9.192 GHz
- The USO frequency fine tuning : correction via a DDS (Direct Digitally Synthesizer)
- Electromagnetic leakage level : -70 dBc.
- 100 MHz VCXO phase noise performances.
- SH volume accommodation for the USO and its power supply.
- Compromise between volume/mass/power allowed.
- To withstand space environment.
- USO performances very stringent : a dedicated USO developed.



Microwave source - CAD layout

Microwave Source Main characteristics

- 270 x 300 x 100 mm³ (8.3 L) & 7 kg & 24.5 W
- Operational temp. range 10°C to 33.5°C
- Output levels at 100 MHz (0 dBm) and at 9.192 GHz (-80 dBm to -20 dBm)
- Output power resolution : 0.02 dB
- Level integral linearity error < 0.01 dB
- Tuning frequency range +/- 100 kHz around 9.192 GHz
- Frequency resolution at 100 MHz (86 nHz) and at 9.192 GHz (0.12 µHz)

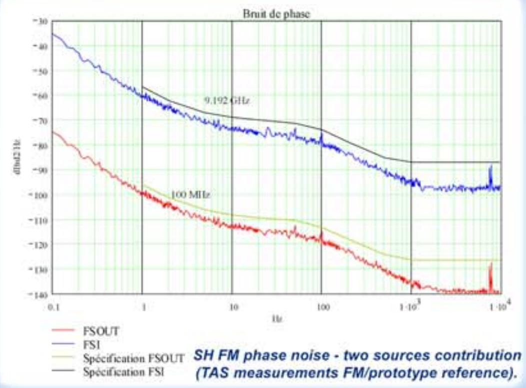
USO - Ultra Stable Oscillator (CMAC : Thales subcontractor)

- USO frequency 5 MHz
- 1.2 Kg & 2.2 W
- 80 x 130 x 85 mm³
- FM short term frequency stability (characterised by **SYRTE** with cryogenic oscillator):
  $\sigma_y(\tau=1s \text{ and } 10s) = \mathbf{6 \text{ to } 7.\ 10^{-14}}$
- Difficult point : sensitivity to microgravity level
- A new USO FM developed under CNES contract : to withstand ISS microvibration level increase

$\sigma_y(10\ s) = \mathbf{8.4\ 10^{-14}}$ and microgravity sensitivity : $\mathbf{1.8\ 10^{-10}/g}$

FM34 PHARAO USO curently in SH MV

Microwave Source FM Phase noise (Thales Airborne Systems)



SH FM phase noise - two sources contribution (TAS measurements FM/prototype reference).

Short term frequency stability Requirement :
$\sigma y(\tau=1s \text{ and } 10s) = 10.\ 10^{-14}$

Measurements :
$\sigma_y(\tau=1s) < 6\ 10^{-14}$
$\sigma_y(\tau=10s) < 5\ 10^{-14}$

The challenge is reached :

- PHARAO requirements fullfilled,
- Development finished,
- Microvibration environment solved,
- PHARAO AIV in progress

A 6. 10^{-14} short term frequency stability at 1 Hz.

It is the best result with a source based on an USO