« Gravitational Waves and Experimental Gravity »

Status of the ACES mission

The ACES system

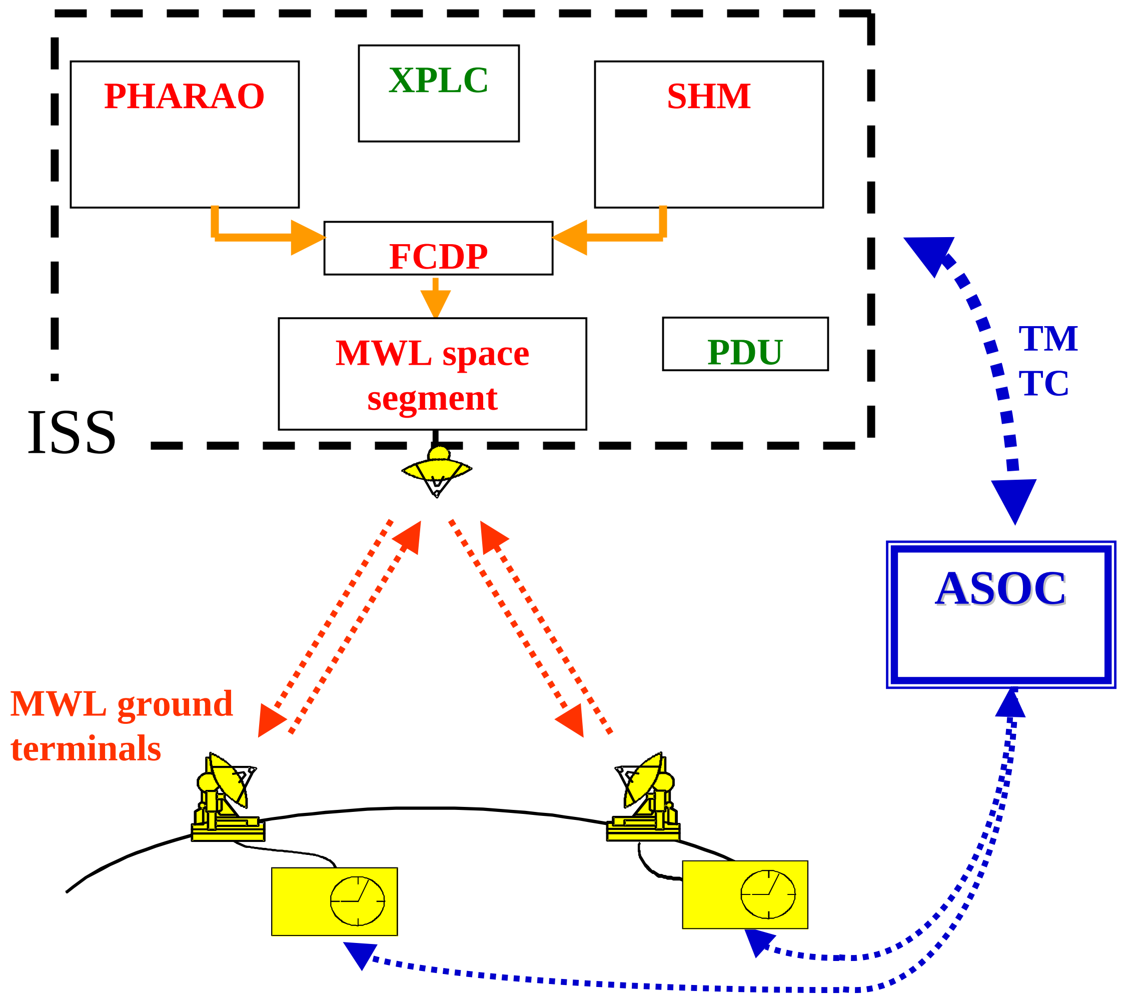
The ACES payload :

- space clocks : PHARAO and SHM
- on-board comparisons
- space-ground clocks comparisons with the microwave link MWL

ISS orbit determination

The operations and coordination of ACES ground users

The ACES system



PHARAO : Cold Cs atoms clock

SHM : Space Hydrogen Maser

FCDP : Frequency Comparison and Distribution Package

XPLC : External payload computer

PDU : Power distribution unit

MWL : Microwave Link

ASOC : ACES control and mission center

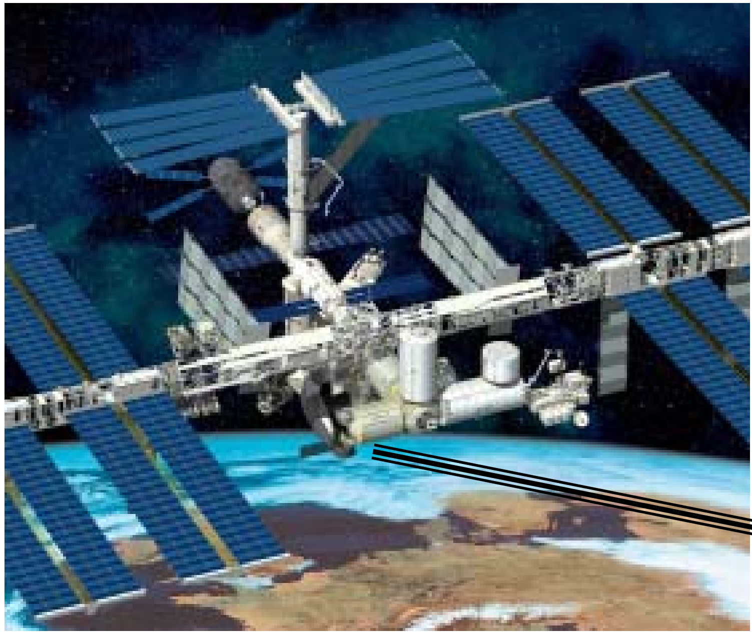
Specific needs :

Precise ISS orbit determination

ACES payload microvibrations level

The ACES payload

ACES on ISS



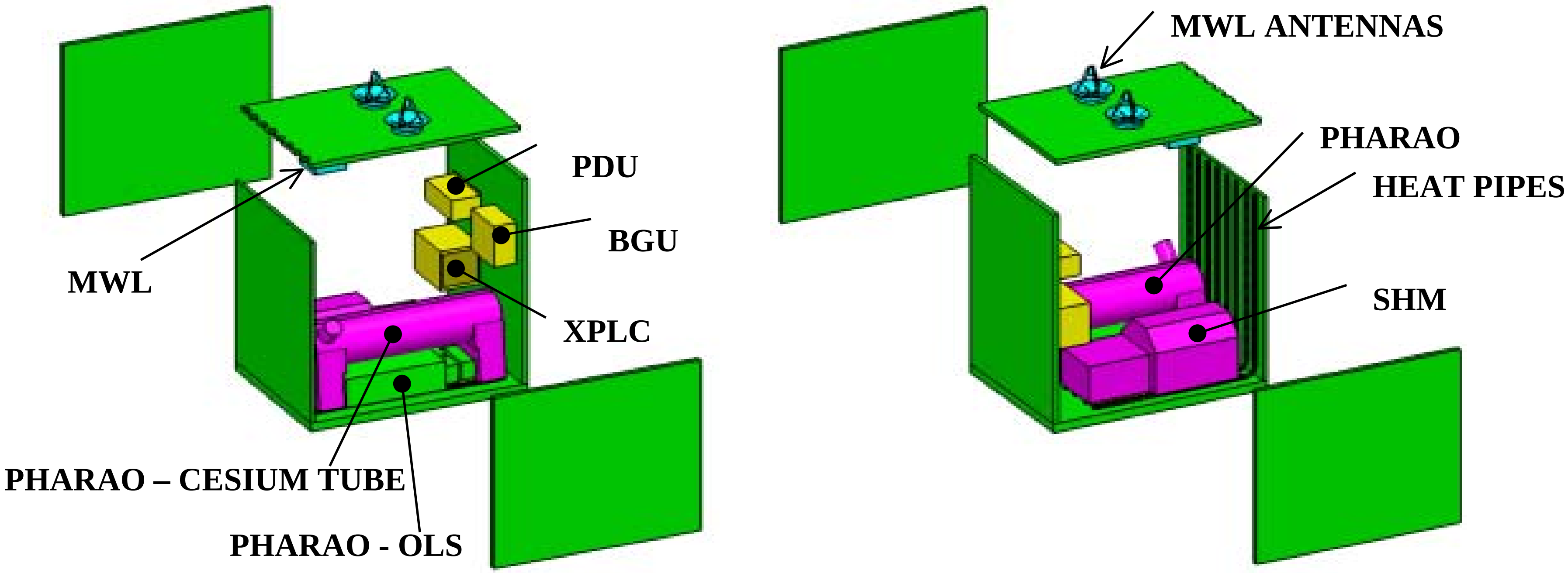
Launch ULF-3 end of 2006

COLUMBUS module

Express Pallets

ACES LOCATION

ACES PAYLOAD
(Astrium, France and Germany)



Volume ≈ 1 m³ **Mass ≈ 225 kg** **Power ≈ 400 W**

ACES SPACE CLOCKS : PHARAO & SHM

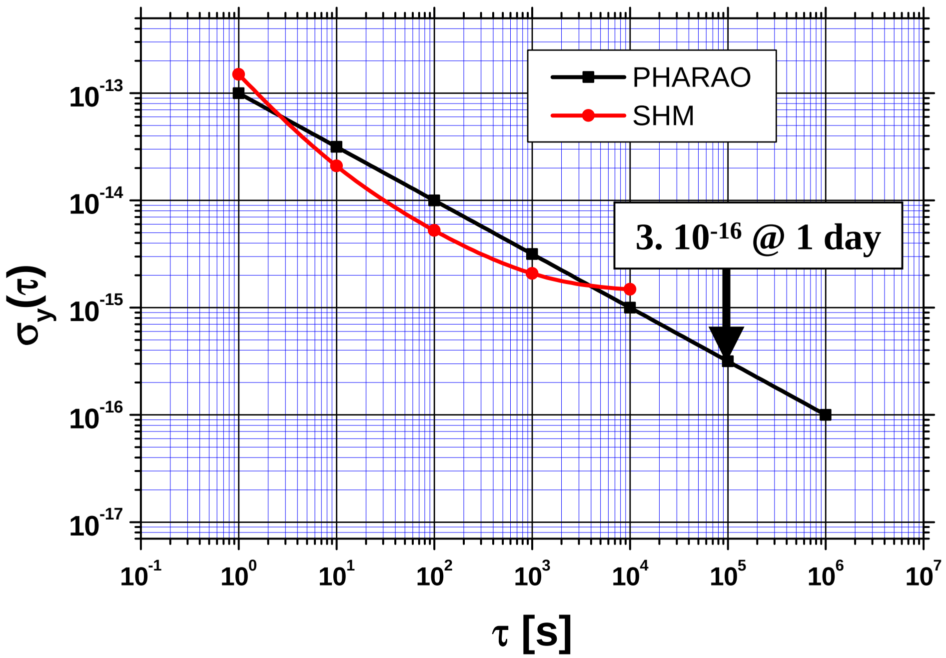
ACES space clocks performance

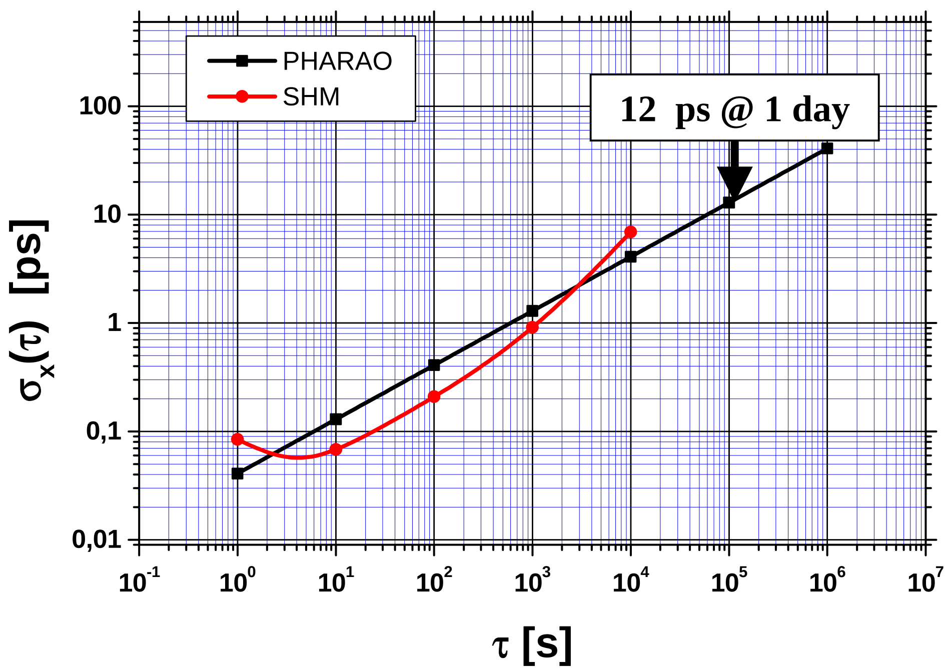
PHARAO stability better than $\sigma_y(\tau) = 10^{-13}.\tau^{-1/2}$ (in frequency)

$\sigma_x(\tau) = 4.1\ 10^{-14}.\tau^{+1/2}$ (in time)

PHARAO accuracy target : 10^{-16}

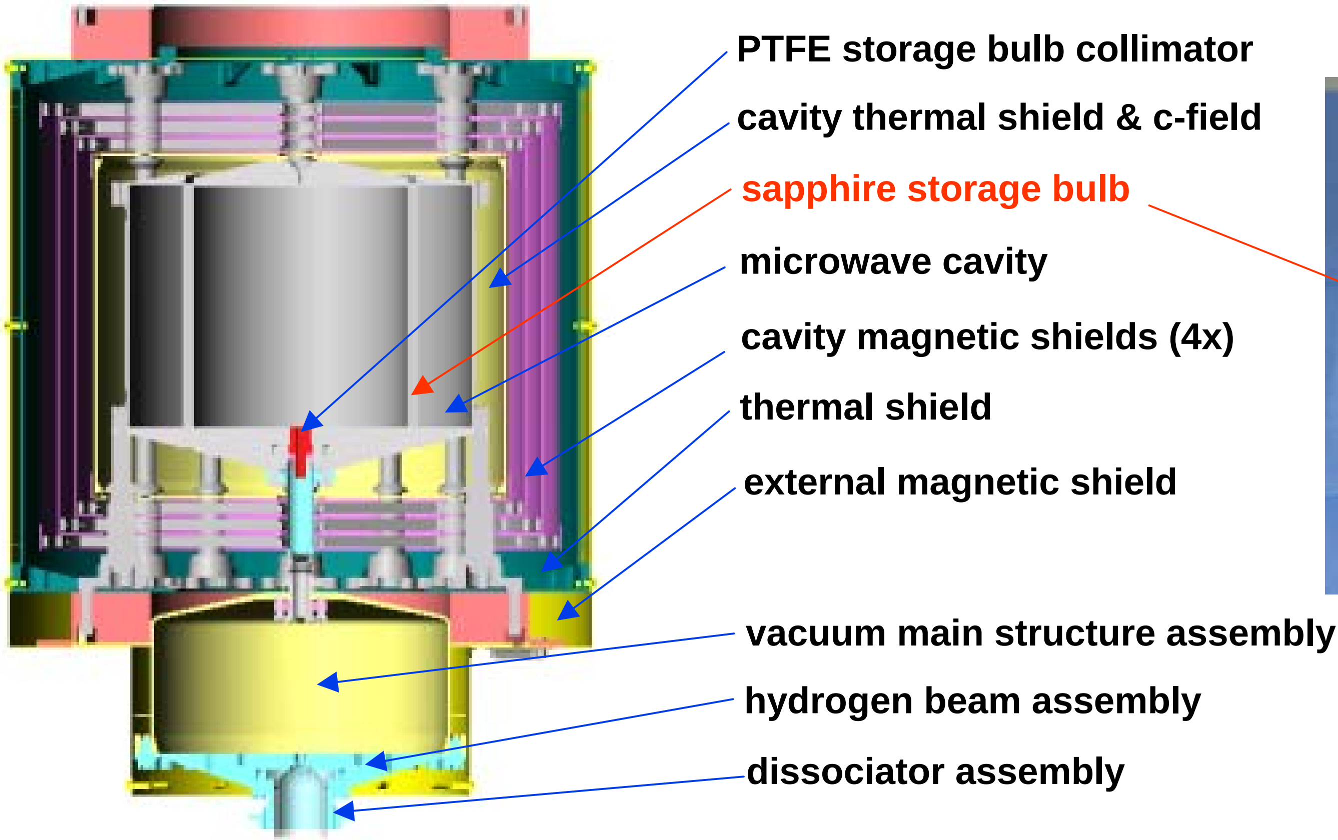
SHM stability better than PHARAO stability for mid-term

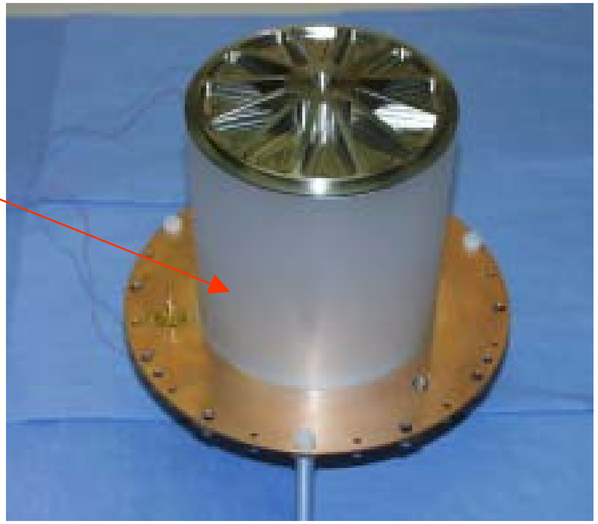




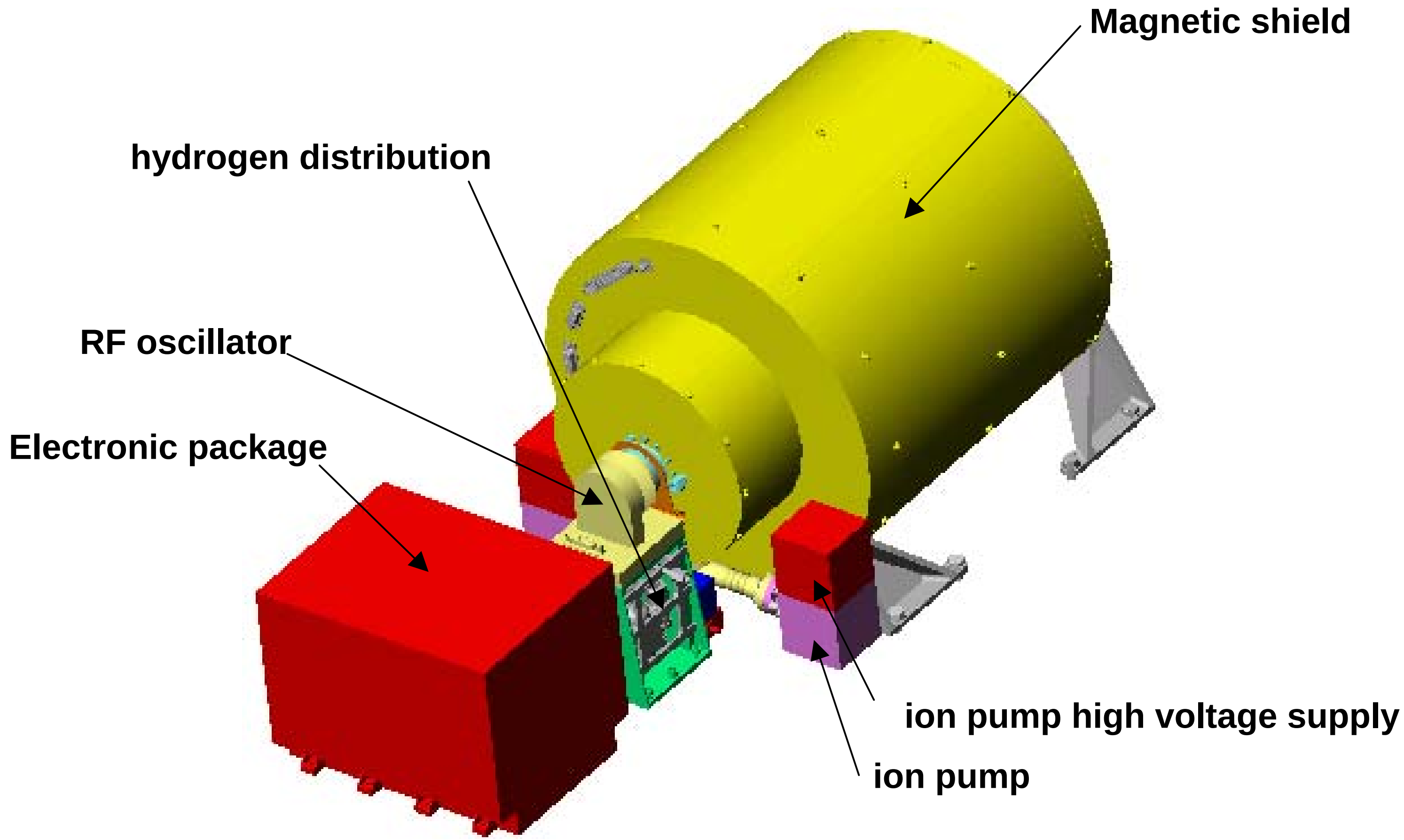
SHM PHYSICS PACKAGE
(Neuchâtel Observatory, Switzerland)

physics package cut view



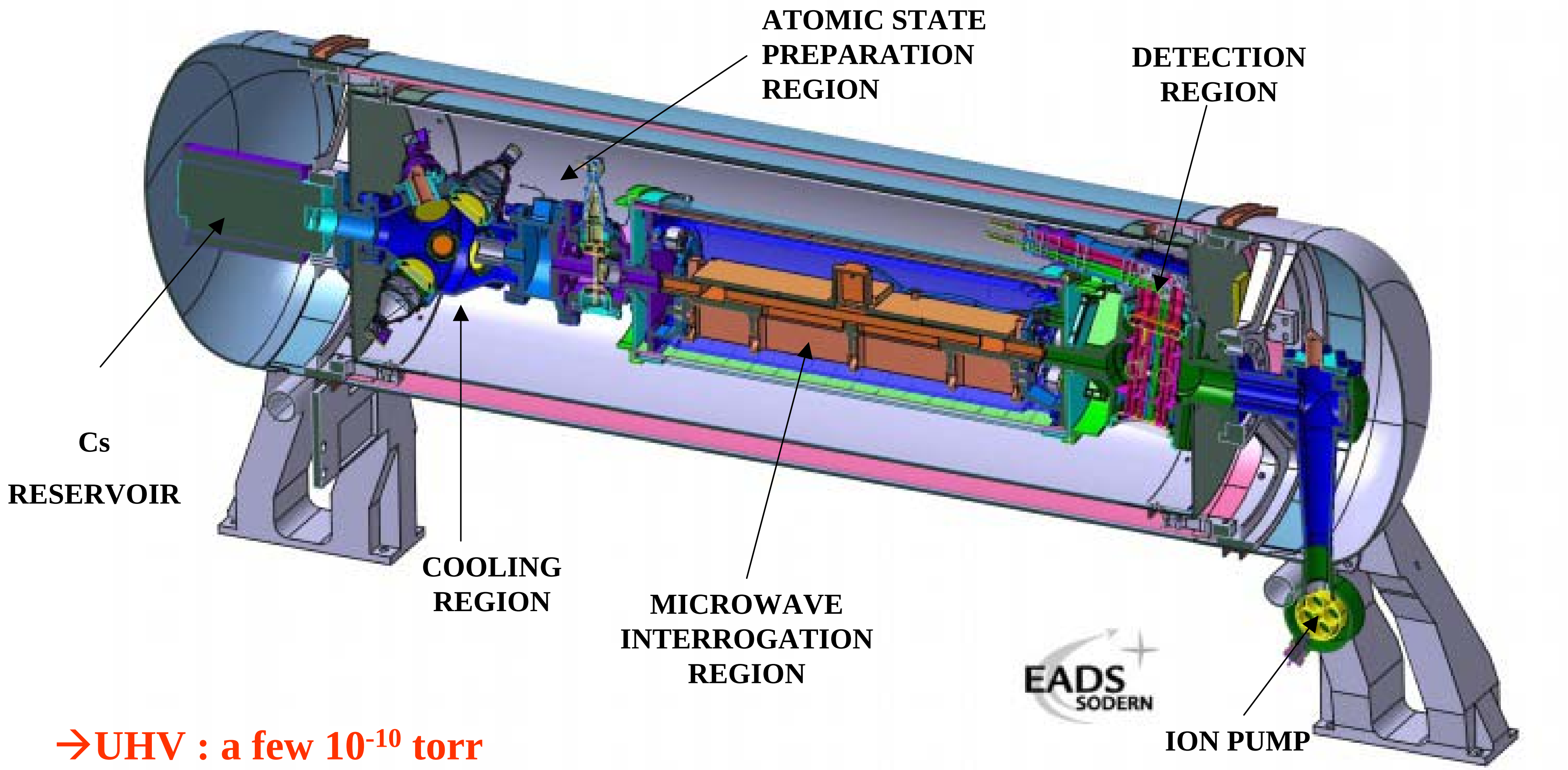


SHM DESIGN



→ Thermal sensitivity ($\Delta f/f \approx 10^{-15}$ per °C), magnetic control ($\approx 1\ \mu G \approx 0.1$ nT)

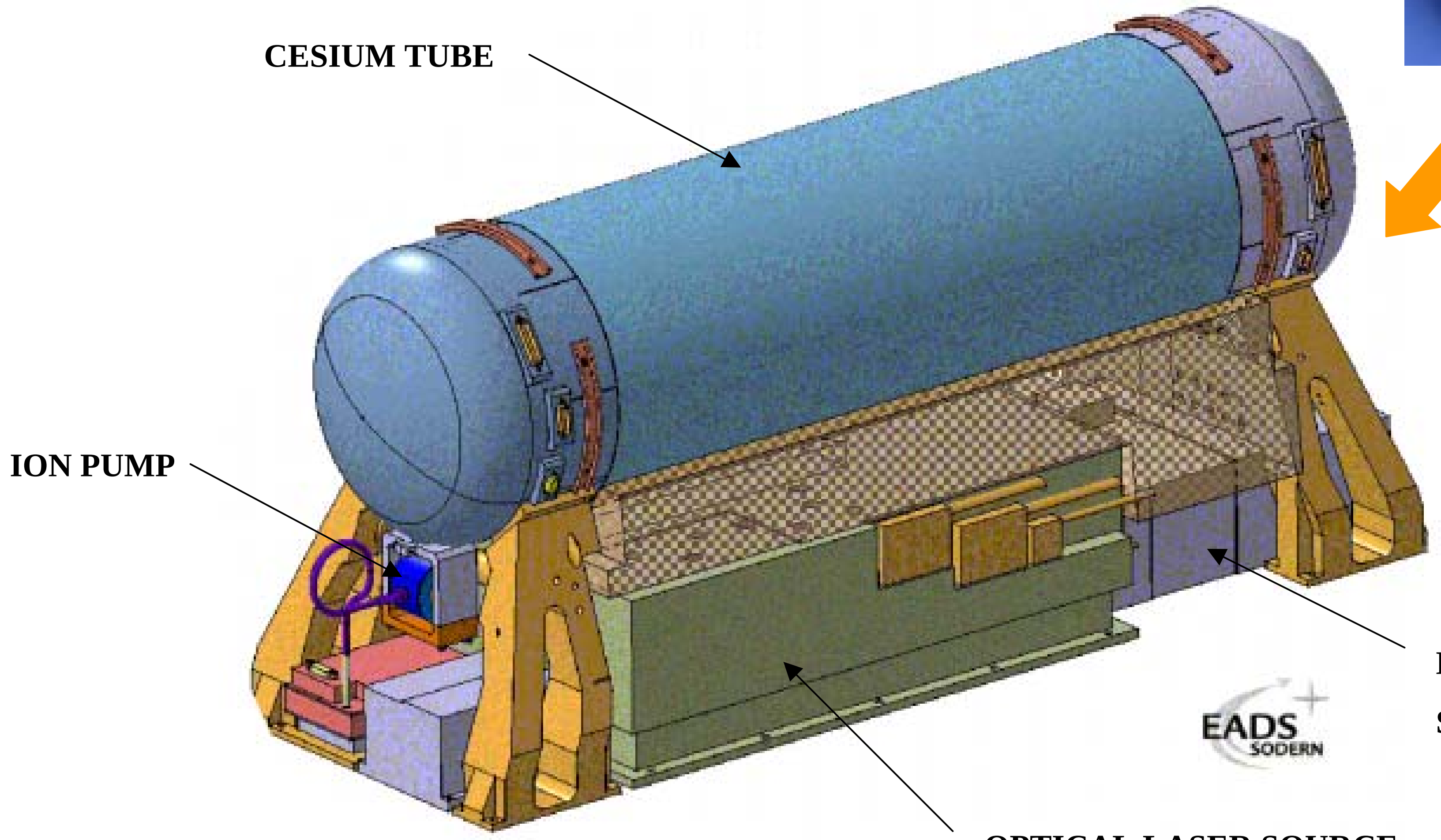
PHARAO CESIUM TUBE DESIGN
(SODERN, France)



→UHV : a few 10^{-10} torr

→Cavity temperature control (0.1 °C), magnetic control (< 1 µG ≈ 0.1 nT)

PHARAO DESIGN



PHARAO COMPUTER

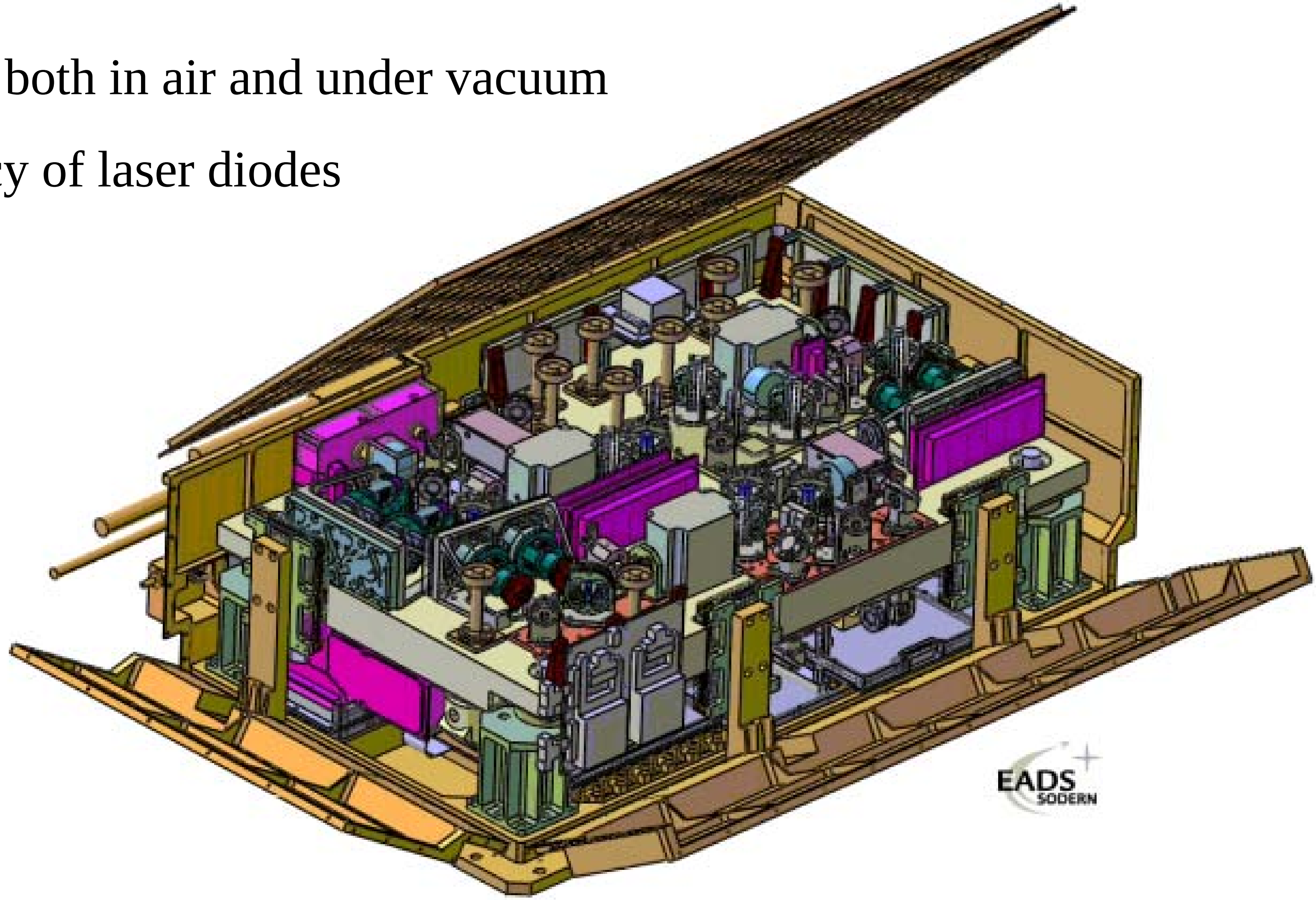
(EREMS)

OPTICAL LASER SOURCE DESIGN

(SODERN, France)

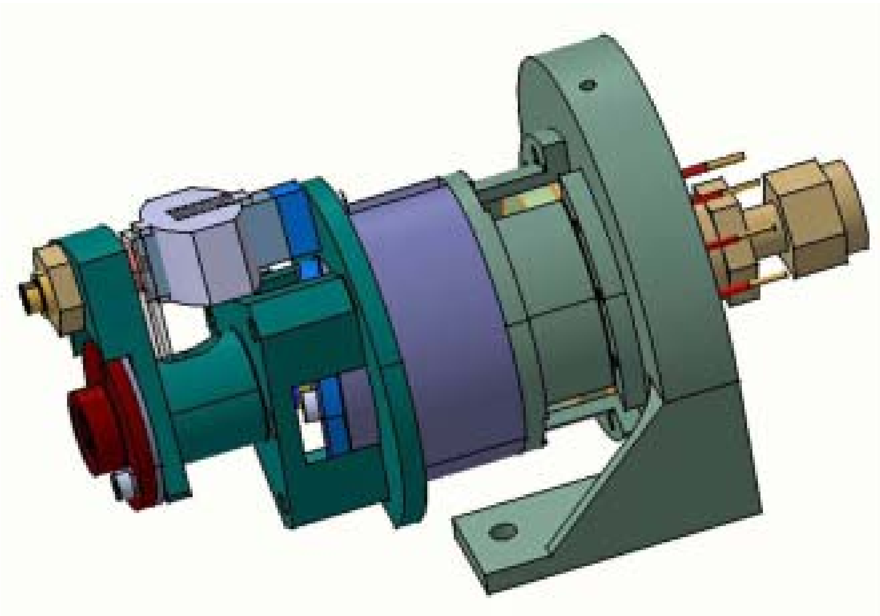
Alignment both in air and under vacuum

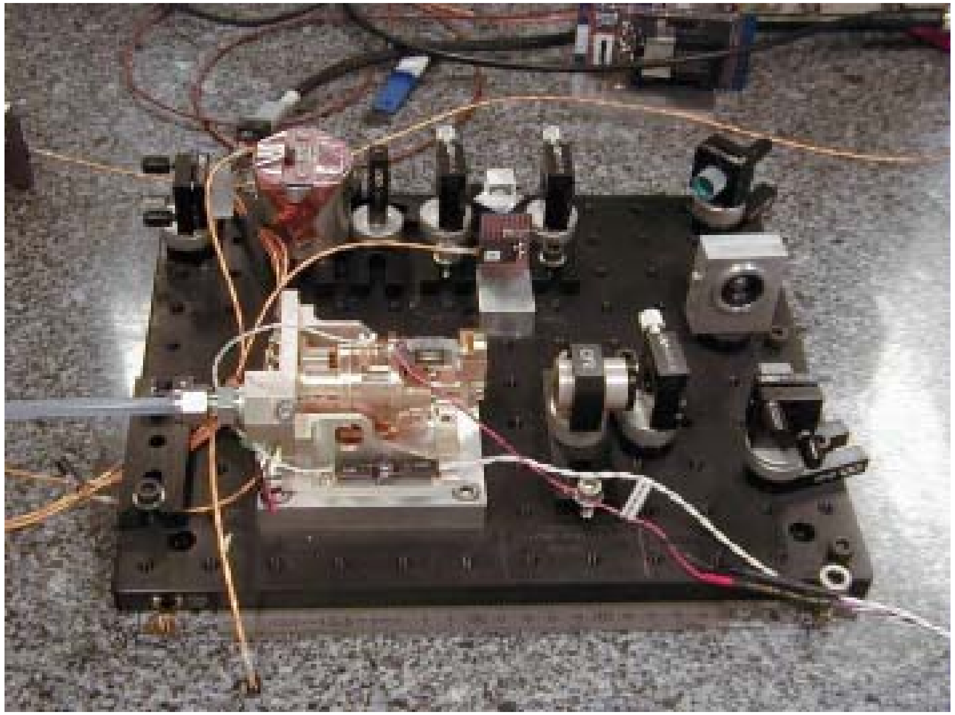
Redundancy of laser diodes



EXTENDED CAVITY LASER DESIGN
(SODERN, France)

→ High spectral purity laser diode for laser cooling and clock signal detection



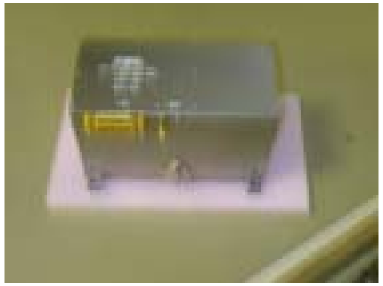


ECL breadboard test

MICROWAVE SOURCE DESIGN

(Thalès,Cemac, France)

→High spectral purity microwave interrogation signal (@ 9.192 GHz) to avoid any degradation of PHARAO frequency stability



- ***High performance quartz oscillator***

  → stability $7. 10^{-14}$ @ 1 s

- ***Microwave source detail***

PHARAO GROUND TESTING EQUIPMENT
(CNES, France)

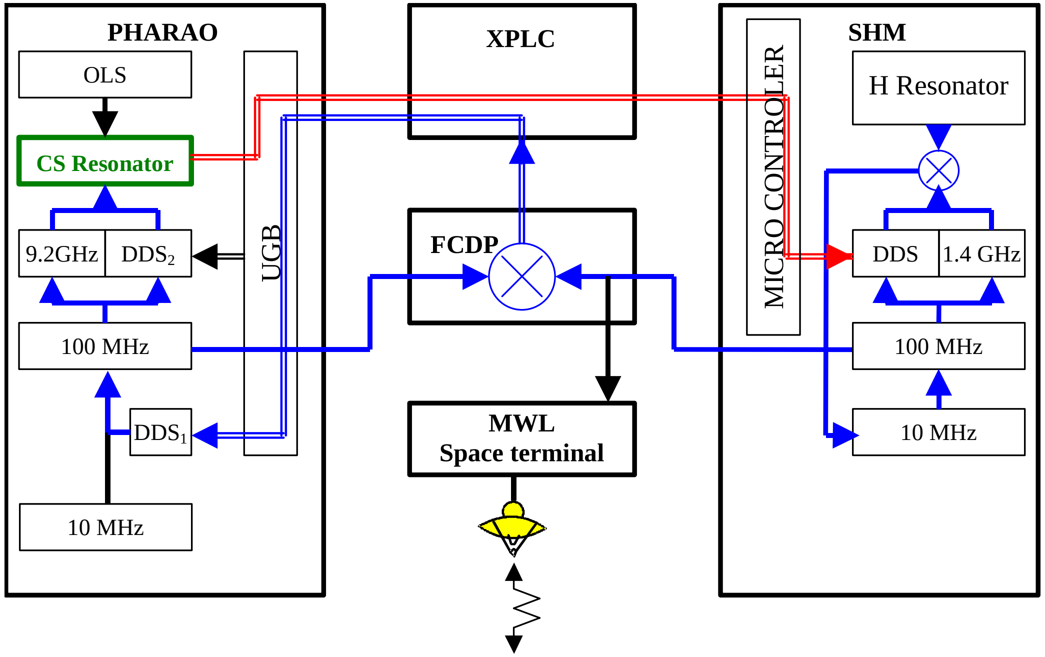
Vacuum chamber for PHARAO tests

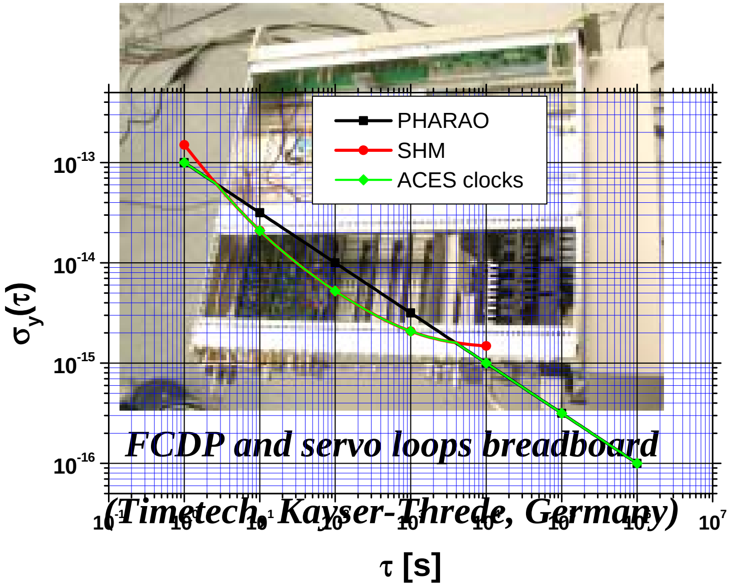
Clocks comparisons in space :

the FCDP……

…… and the SERVO LOOPS

The FCDP and the « Servo loops »





Short term servo loop : improvement of PHARAO mid-term stability

Long term servo loop : correction of SHM frequency drifts

→ The signal delivered to the ground has the stability of the best clock and PHARAO accuracy

Space –ground clocks comparisons with the microwave link MWL

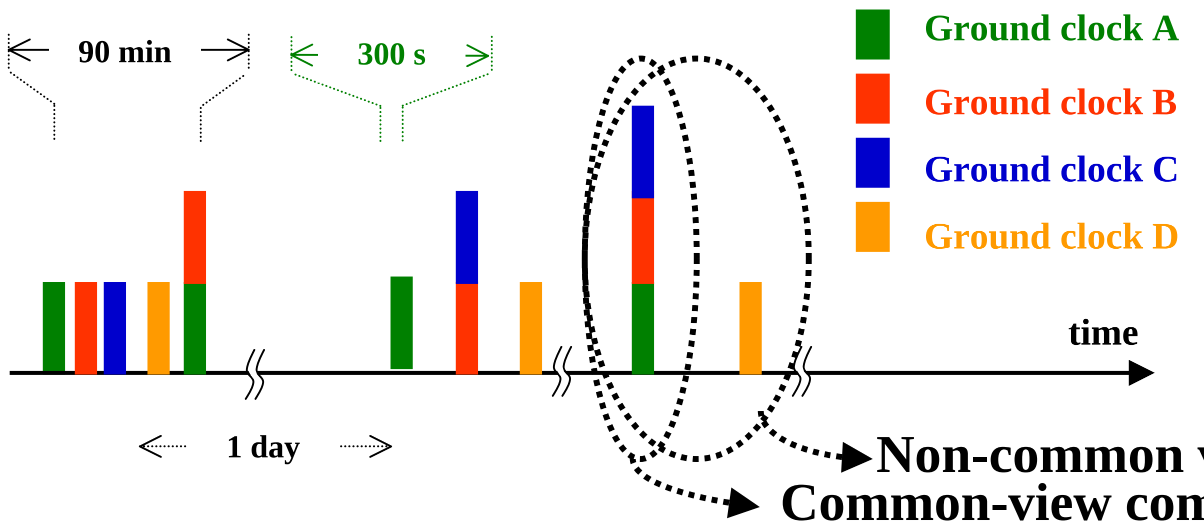
All ACES major scientific objectives rely on space – ground comparisons :

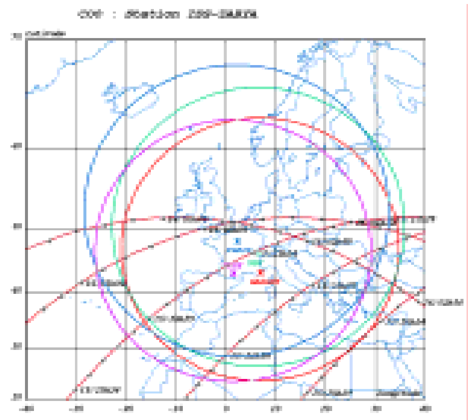
- **Short term comparisons (special relativity tests : $\delta c/c$)**
- **Long term comparisons (general relativity tests : red shift, α variation)**

Clocks comparisons with MWL

- Low orbit of ISS : 400 km
- Period : 90 min
- Mean visibility duration : 300 s

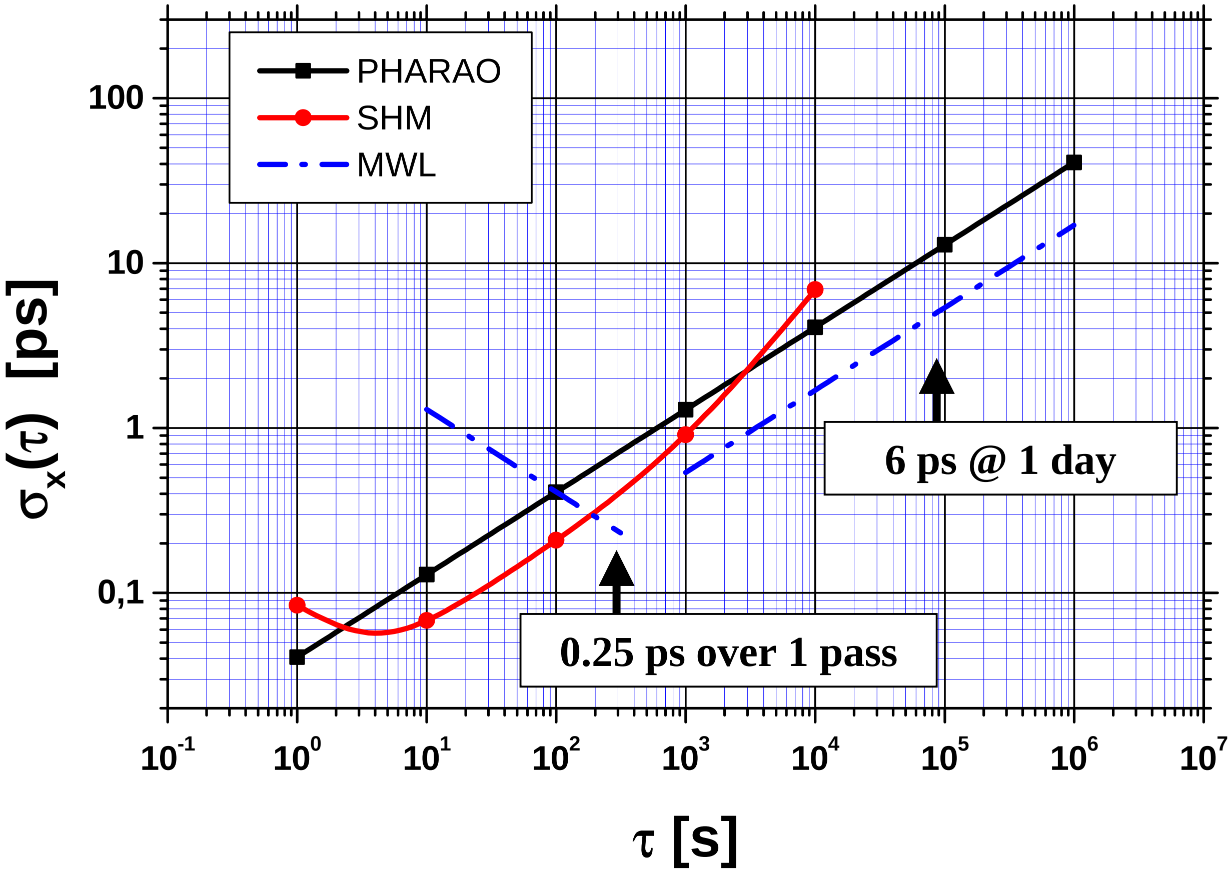
Comparison sessions with ACES clocks for different ground clocks :





MWL PERFORMANCE

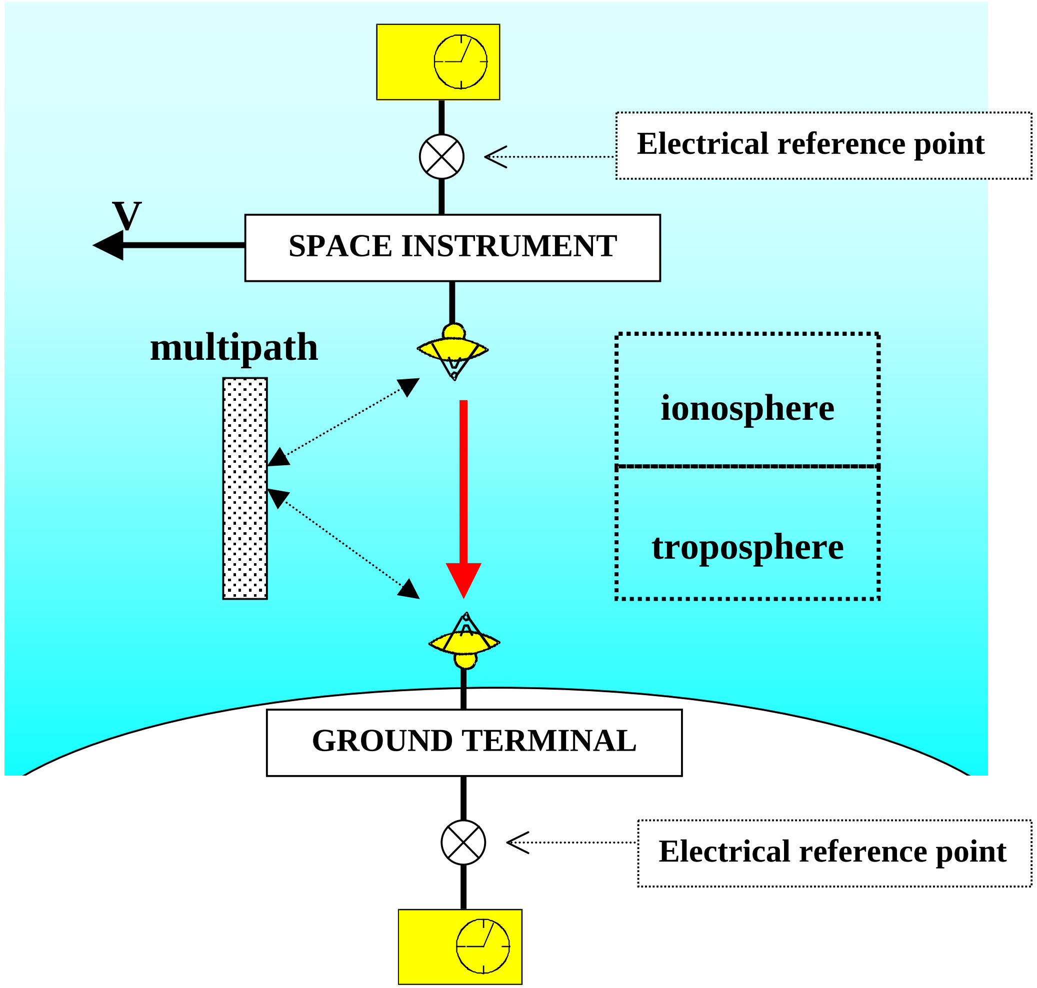
STABILITY :



ACCURACY : <u>No need</u> (time interval comparisons only)

But the MWL ground terminal delays will be calibrated with an uncertainty below 100 ps

COMPARISON BETWEEN TWO DISTANT CLOCKS



- **<u>TROPOSPHERIC DELAY</u>**

(temperature, humidity) → **10 ns**

- **<u>IONOSPHERIC DELAY</u>**

(TEC, varies as $1/f^2$) → **10 ns**

- **<u>MULTI-PATH EFFECT</u>**

(distance, reflectivity of spurious reflectors)

- **<u>INSTRUMENTAL DELAYS</u>**

(temperature, frequency and power of signals, incidence angle, ….) → **100 ps/K**

- **<u>RELATIVISTIC EFFECTS</u>**

(Position and velocities of space and ground clocks)

→ **1^{st} order Doppler effect** → **$2.\ 10^{-5}$**

→ **2^{nd} order Doppler effect**	→ **$3.\ 10^{-10}$**
→ **Sagnac effect**	→ **$7.\ 10^{-13}$**
→ **Gravitational shift**	→ **$4.\ 10^{-11}$**

CHARACTERISTICS OF MWL

(Timetech, Kayser-Threde, Germany)

Two way technique in Ku band :
Down link @ 15 GHz (0.5 W)
Up link @ 13,5 GHz (4 W)

- **→ removal of troposphere, 1st order Doppler instrumental delays, …**

Additional S band down link (@ 2.25 GHz - 0.5 W)

- **→ for TEC determination**

Phase PN code modulation :

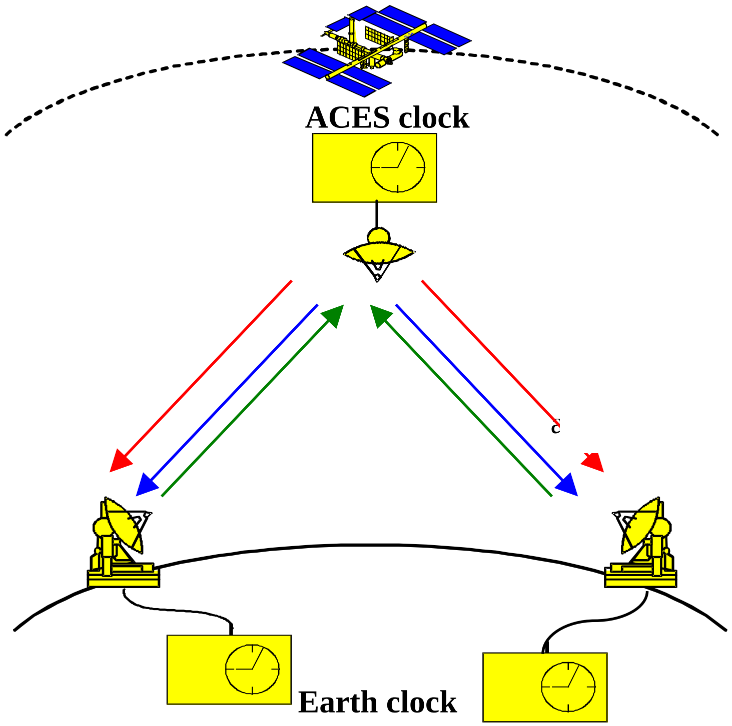
- **→ removal of 2π phase ambiguity**

Carrier phase and code phase measurements
(1 measurement / s) both in space and on the ground

Data link (2 kBits/s in S-band down link)

- **→ to obtain clock comparison results in real time**

4 simultaneous ground users capability for common view comparisons



DESIGN AND REALIZATION OF MWL
(Timetech, Kayser-Threde, Germany)


MWL space segment breadboard

Phase comparator

Main constraints :

- **Multipaths**
- **Temperature sensitivity and calibration**

Typical MWL ground terminal

ORBIT DETERMINATION

Need of ACES payload precise orbit determination

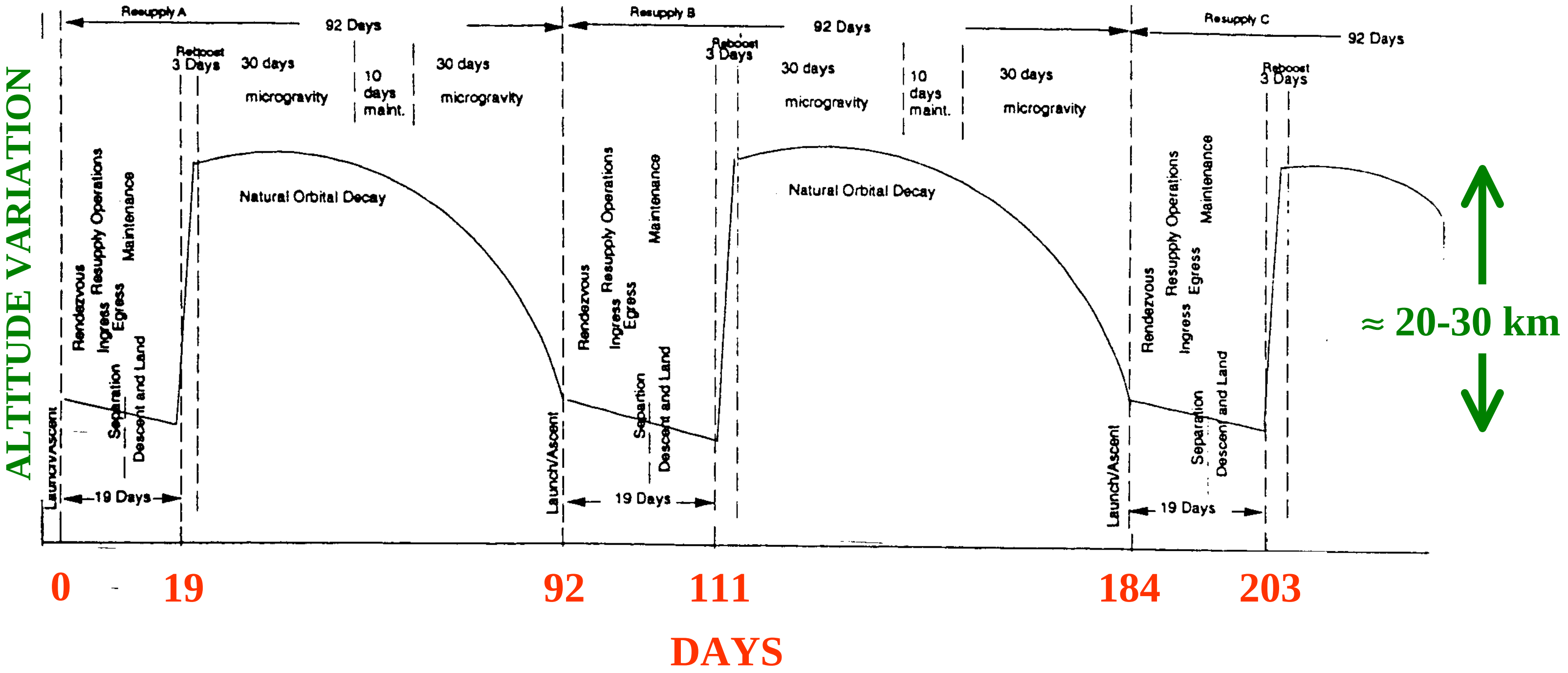
	Relativistic effects		Orbitography requirements	
	Type	Order of magnitude	Type	Precision (1σ)
Clocks	Gravitational potential	$-6.9\ 10^{-10}$ (Ground)	Position (altitude)	1.7 m (1 day)
		$-6.5\ 10^{-10}$ (ISS)		0.5 m (10 days)
	2nd order Doppler	$-1.3\ 10^{-12}$ (Ground)	Velocity	1.9 mm/s (1 day)
		$-3.3\ 10^{-10}$ (ISS)		0.6 mm/s (10 days)
Clock	Gravitational potential	$4.6\ 10^{-11}$	Position (altitude)	24 m (300 s)
Comparison	1st Order Doppler*	$2.5\ 10^{-5}$		
	2nd Order Doppler	$-3.3\ 10^{-10}$	Velocity	26 mm/s (300 s)
	Sagnac	$7.\ 10^{-13}$		

- 1st Order Doppler cancelled by two-way T/F transfer technique

OVER THE WHOLE CLOCK TRAJECTORY

OVER ONE COMPARISON SESSION

ISS ALTITUDE VARIATIONS



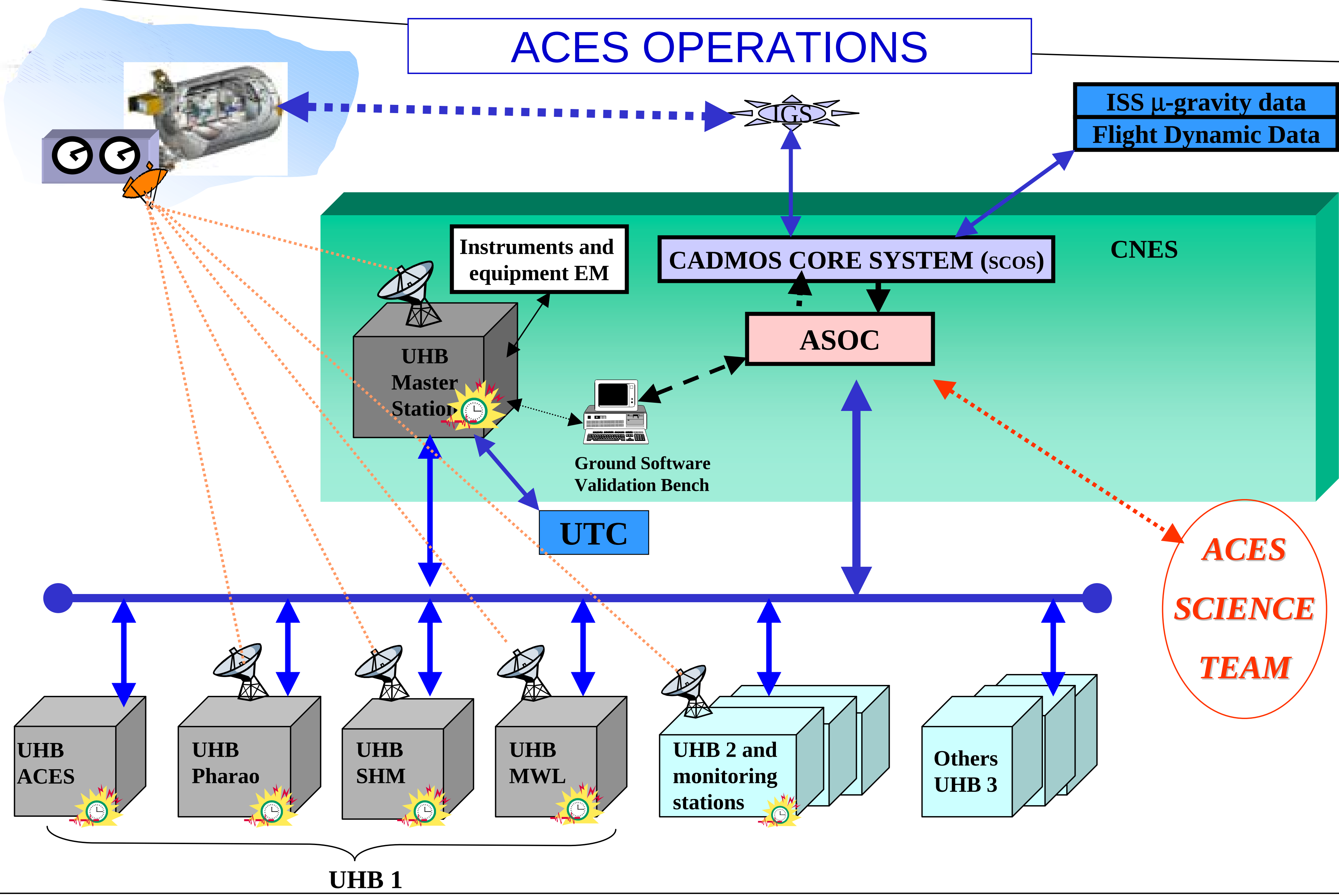
→ **Determination of ACES payload orbit :**

orbit model using ISS GPS receivers data (position, velocity, attitude)

+ MWL ranging + laser ranging

ACES OPERATIONS

ACES OPERATIONS



CONCLUSIONS

→ **SCHEDULED LAUNCH DATE : END of 2006 (mission duration > 18 months)**

→ **INSTRUMENTS ENGINEERING MODELS DELIVERED BEGINNING of 2004**

→ **DEMONSTRATION OF MWL CAPABILITY IN 2003**

→ **LARGE ACES TEAM (150 contributing people) in :**

Laboratories : BNM-SYRTE, ENS/LKB, Neuchâtel Observatory

Industrial companies : Astrium, Kayser-Threde, Timetech, Sodern, Thalès, Cemac, Erems, Contraves, …..

Space Agencies : ESA, CNES

→ ACES IS OPEN TO ANY GROUND USER

WITH OR WITHOUT AN ATOMIC CLOCK

The larger the number of ground ACES users, the greater the confidence in the results !