## Moriond Workshop, March 2003

## « Gravitational Waves and Experimental Gravity »

# Status of the ACES mission

**The ACES system**

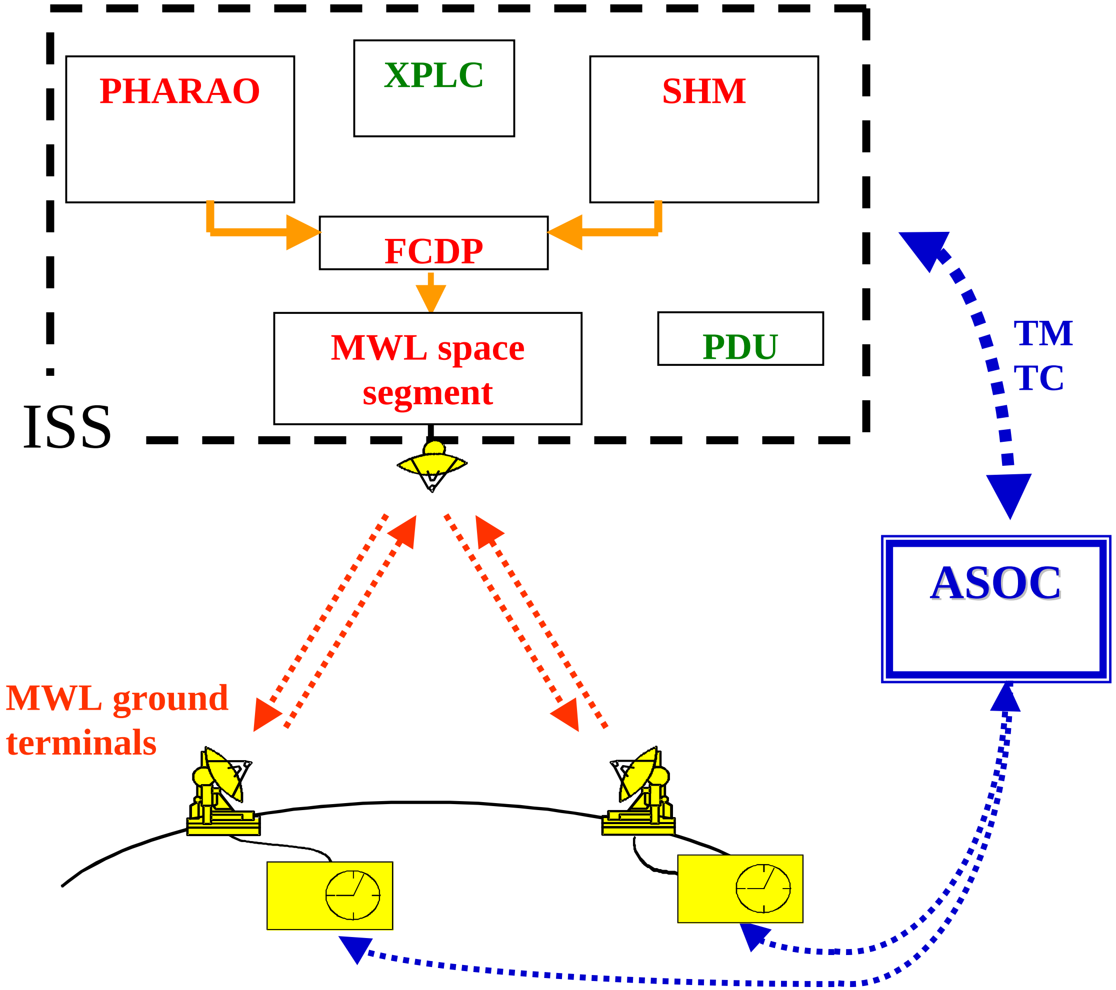
**The ACES payload :**

- **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**

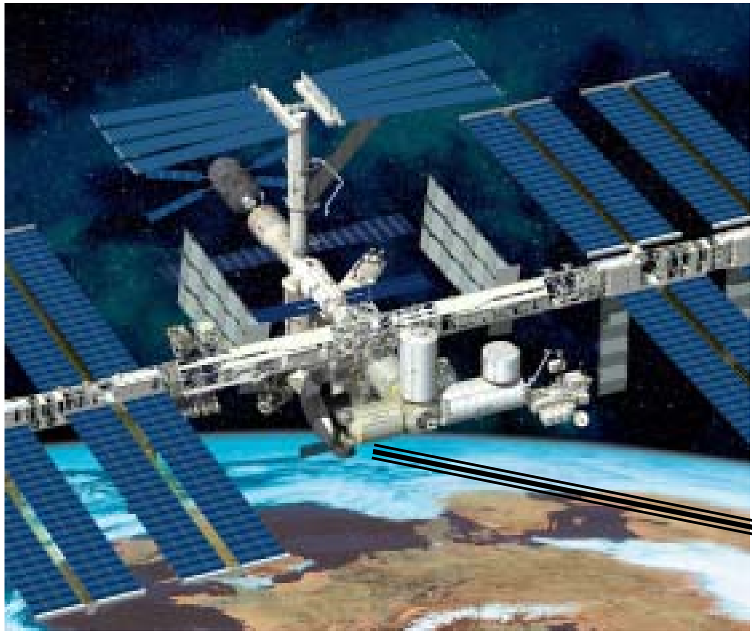
**Specific needs :**

**Precise ISS orbit determination**

**ACES payload microvibrations level**

# The ACES payload

## ACES on ISS



**Launch ULF-3 end of 2006**

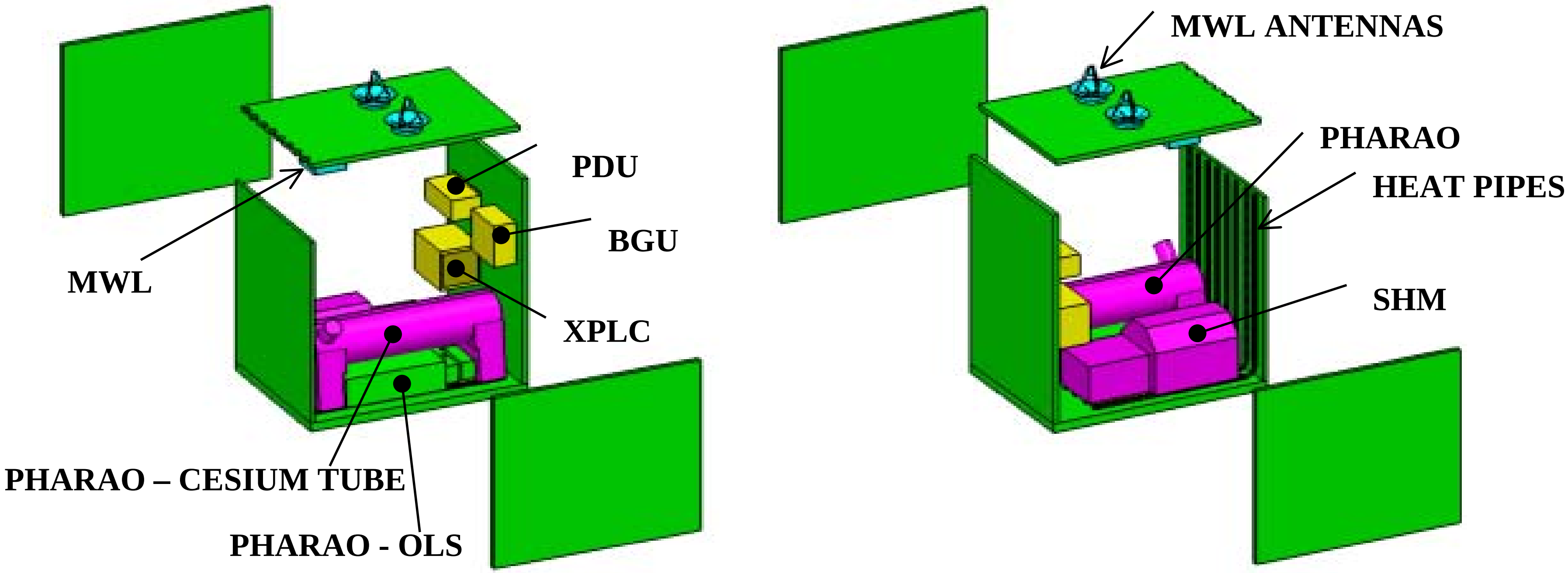
**COLUMBUS module**

**Express Pallets**

**ACES LOCATION**

# ACES PAYLOAD

**(Astrium, France and Germany)**




**Volume ≈ 1 m$^3$ Mass ≈ 225 kg Power ≈ 400 W**

# ACES SPACE CLOCKS : PHARAO & SHM

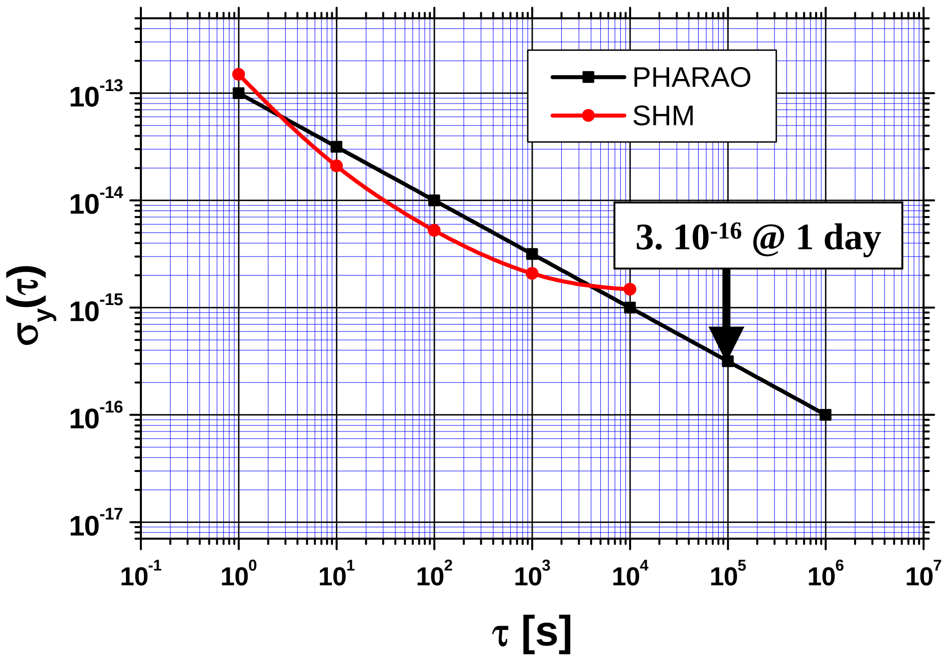
# ACES space clocks performance

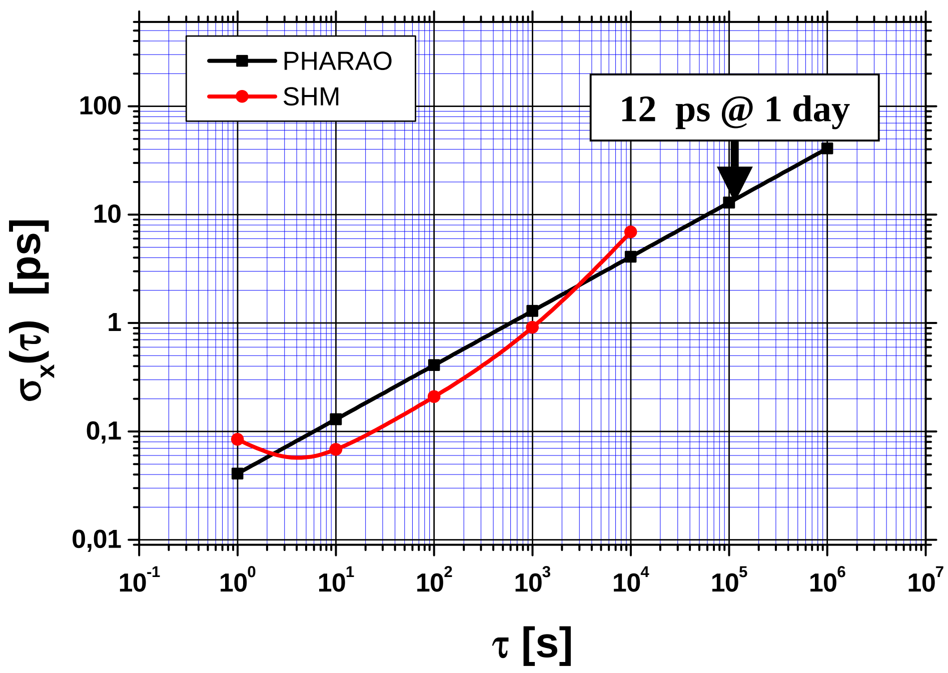
**PHARAO stability** better than $\sigma_y(\tau) = 10^{-13}.\tau^{-1/2}$ (in frequency)

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

**PHARAO accuracy** target : $10^{-16}$

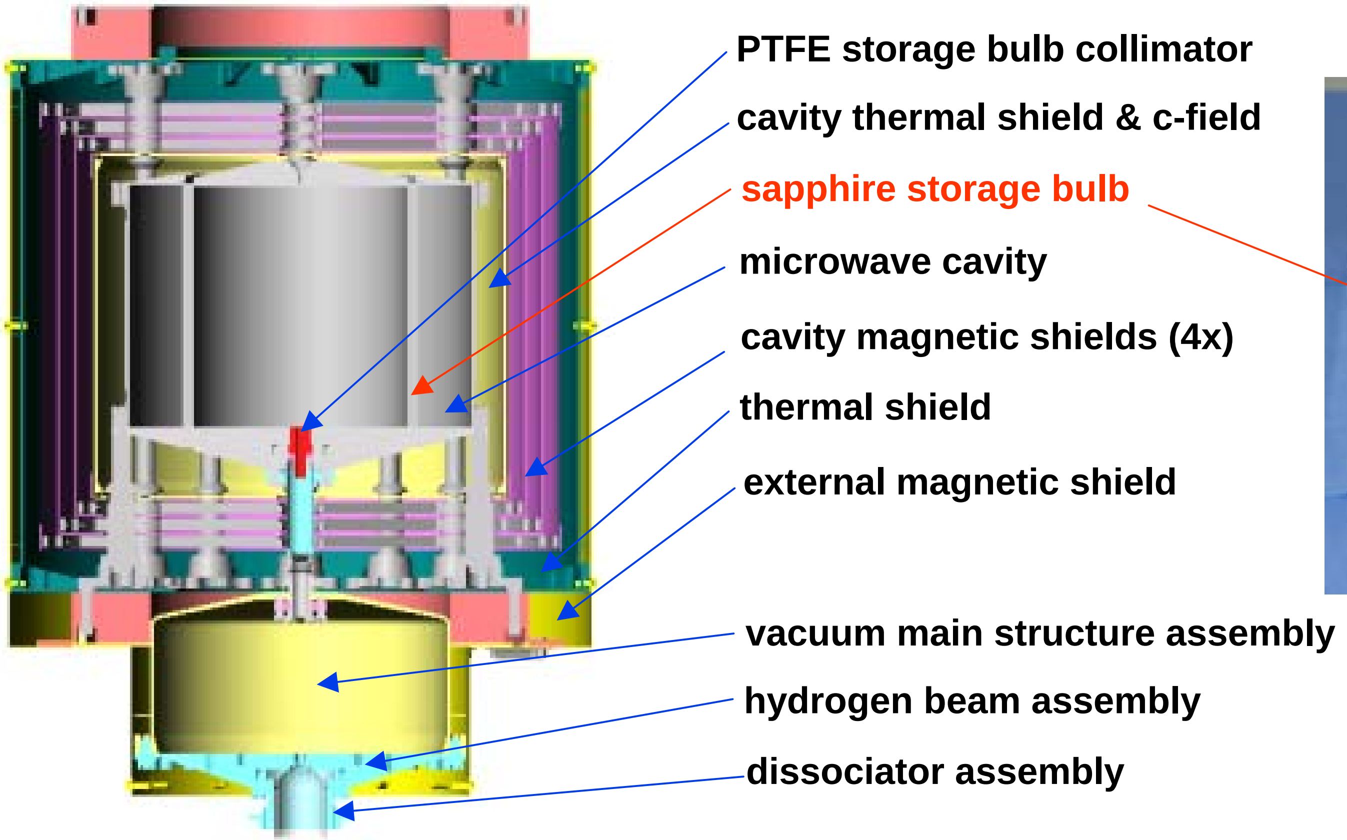
**SHM stability** better than PHARAO stability for mid-term

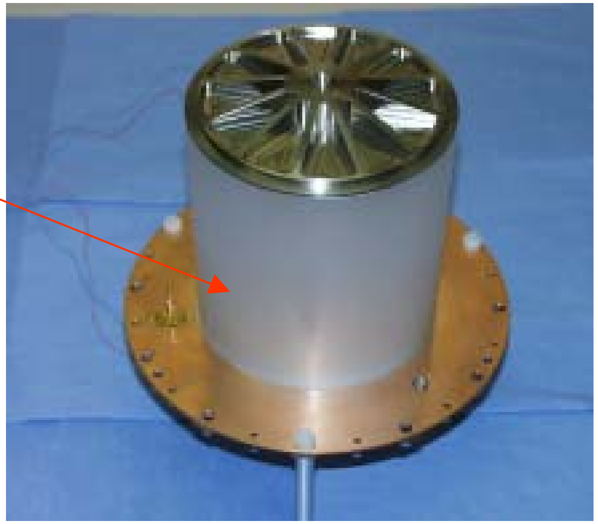


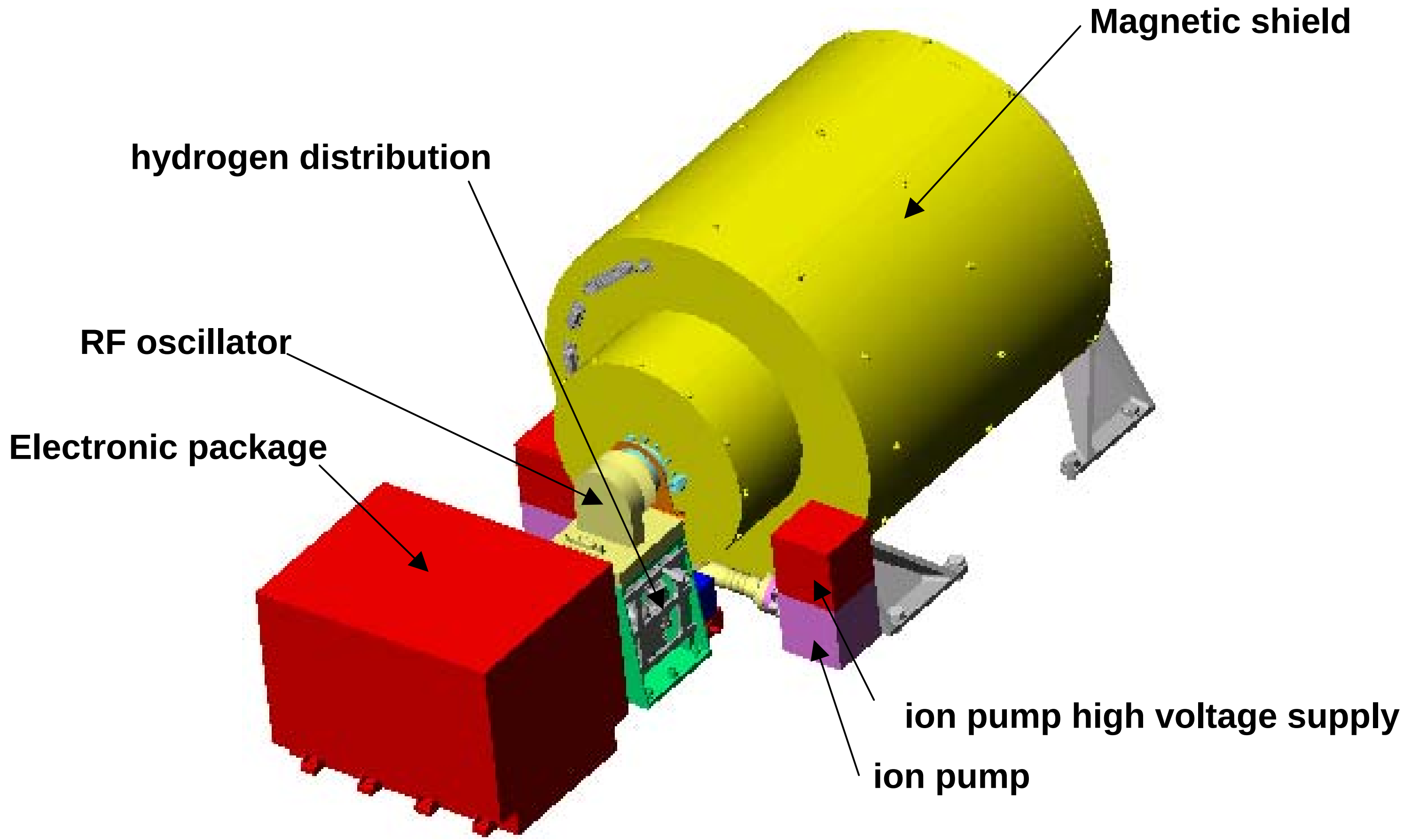
# SHM PHYSICS PACKAGE
(Neuchâtel Observatory, Switzerland)

## physics package cut view



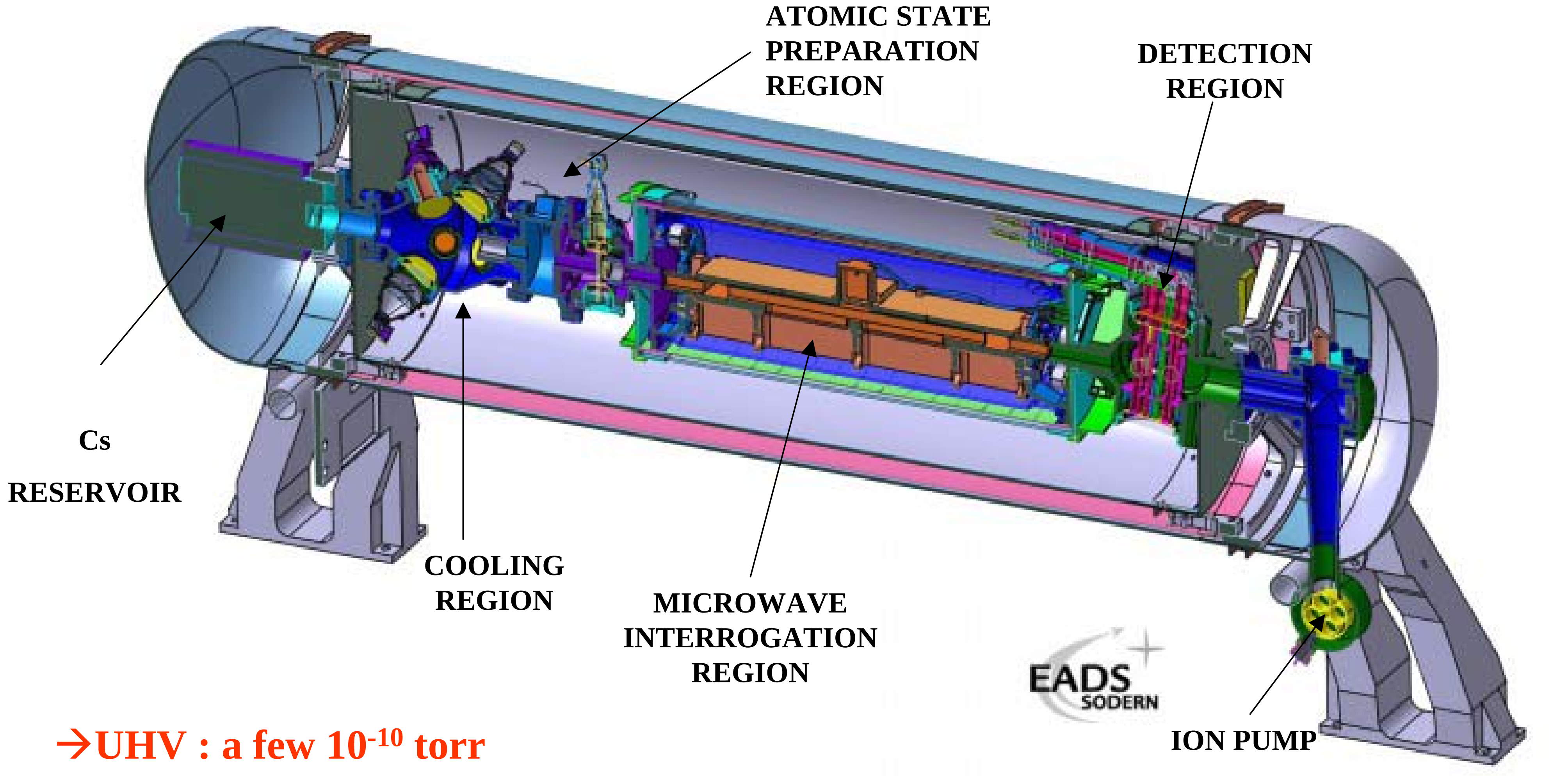
# SHM DESIGN




→ 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)



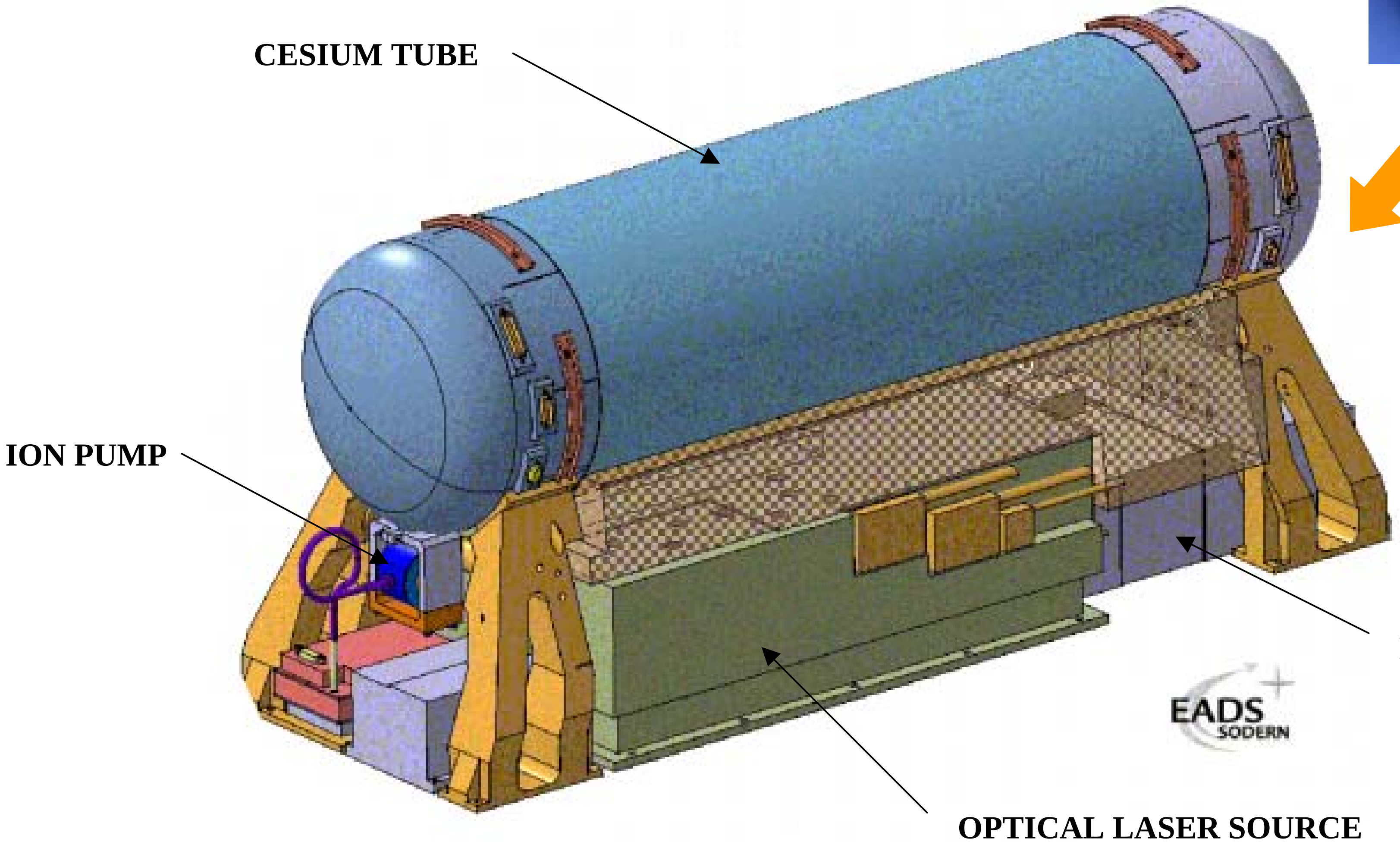

→UHV : a few $10^{-10}$ torr

→Cavity temperature control (0.1 °C), magnetic control ($< 1\ \mu G \approx 0.1$ nT)

# PHARAO DESIGN

PHARAO COMPUTER

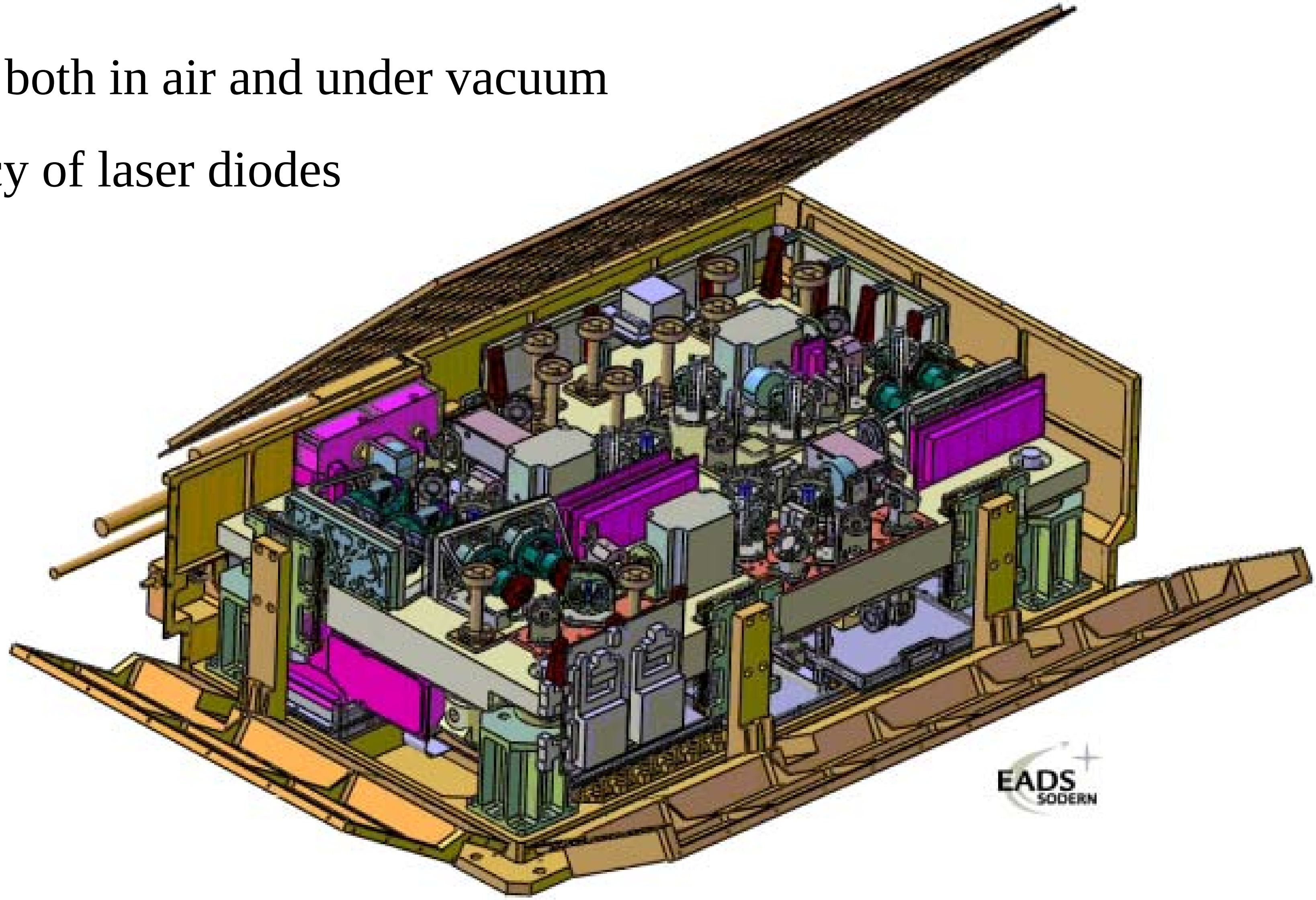
(EREMS)



# OPTICAL LASER SOURCE DESIGN
**(SODERN, France)**

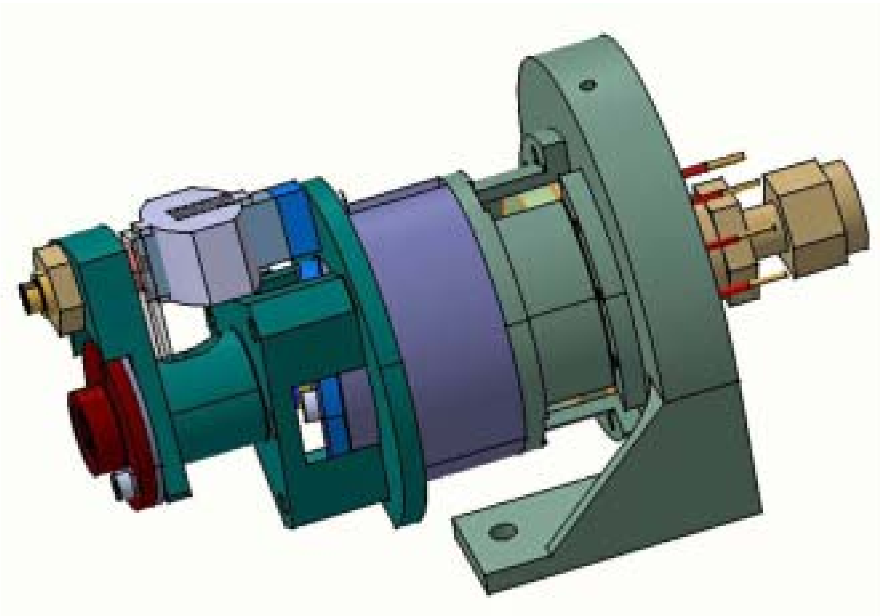
Alignment both in air and under vacuum

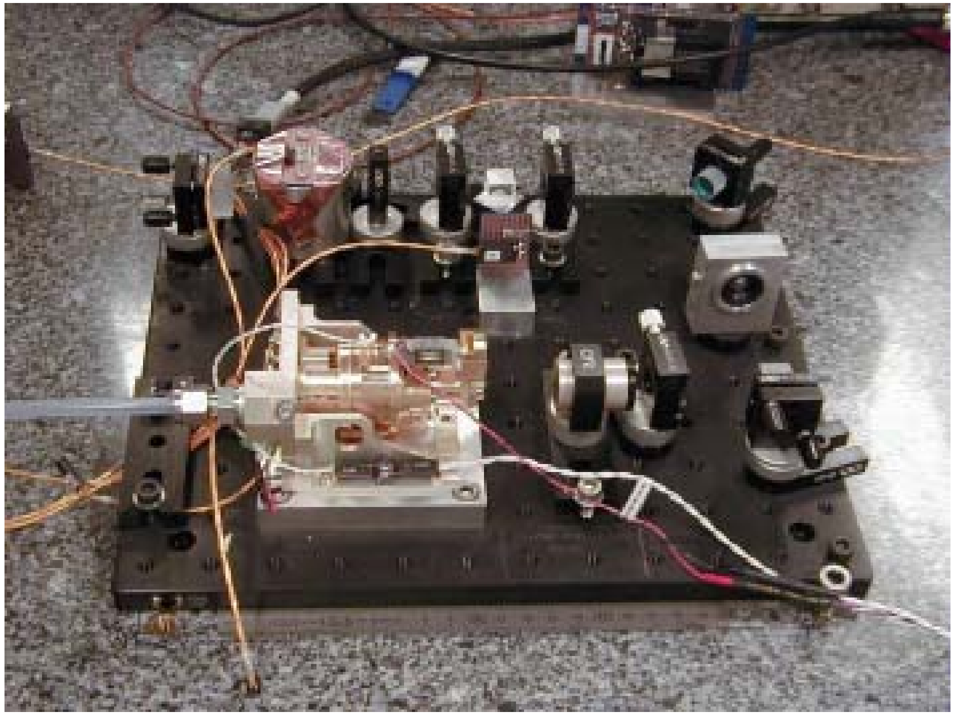
Redundancy of laser diodes



# EXTENDED CAVITY LASER DESIGN
**(SODERN, France)**

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



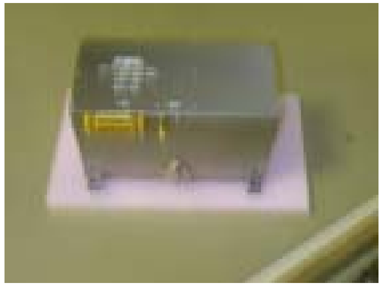


ECL breadboard test

# 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)**

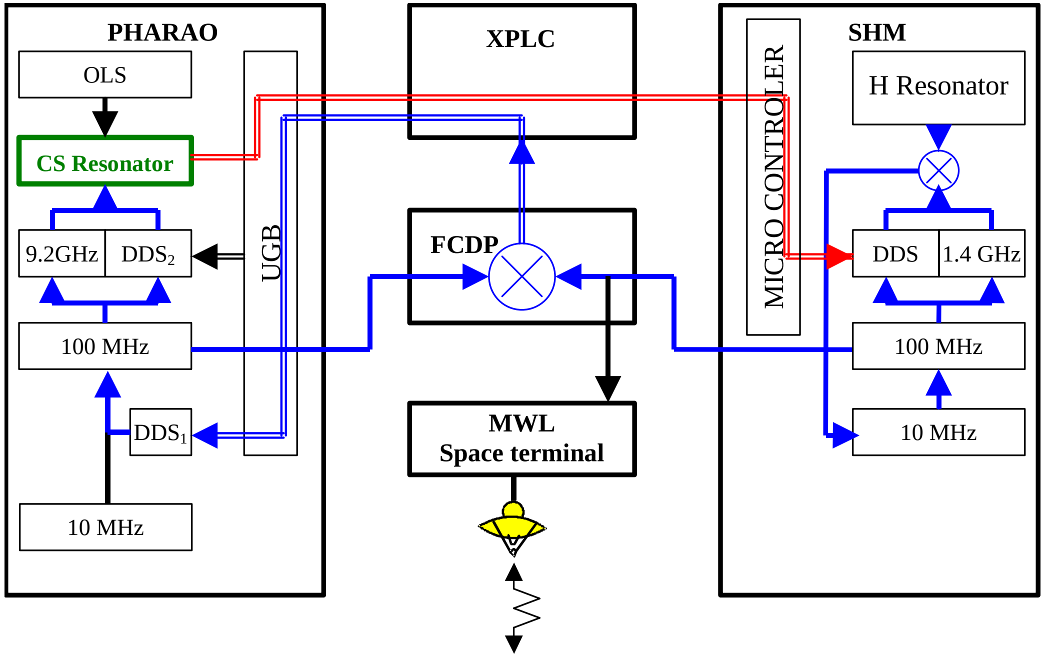
Vacuum chamber for PHARAO tests

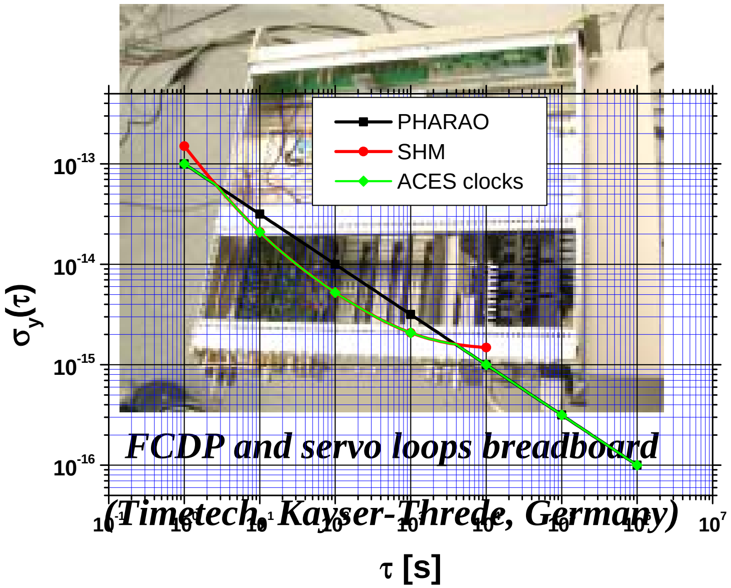
Clocks comparisons in space :

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

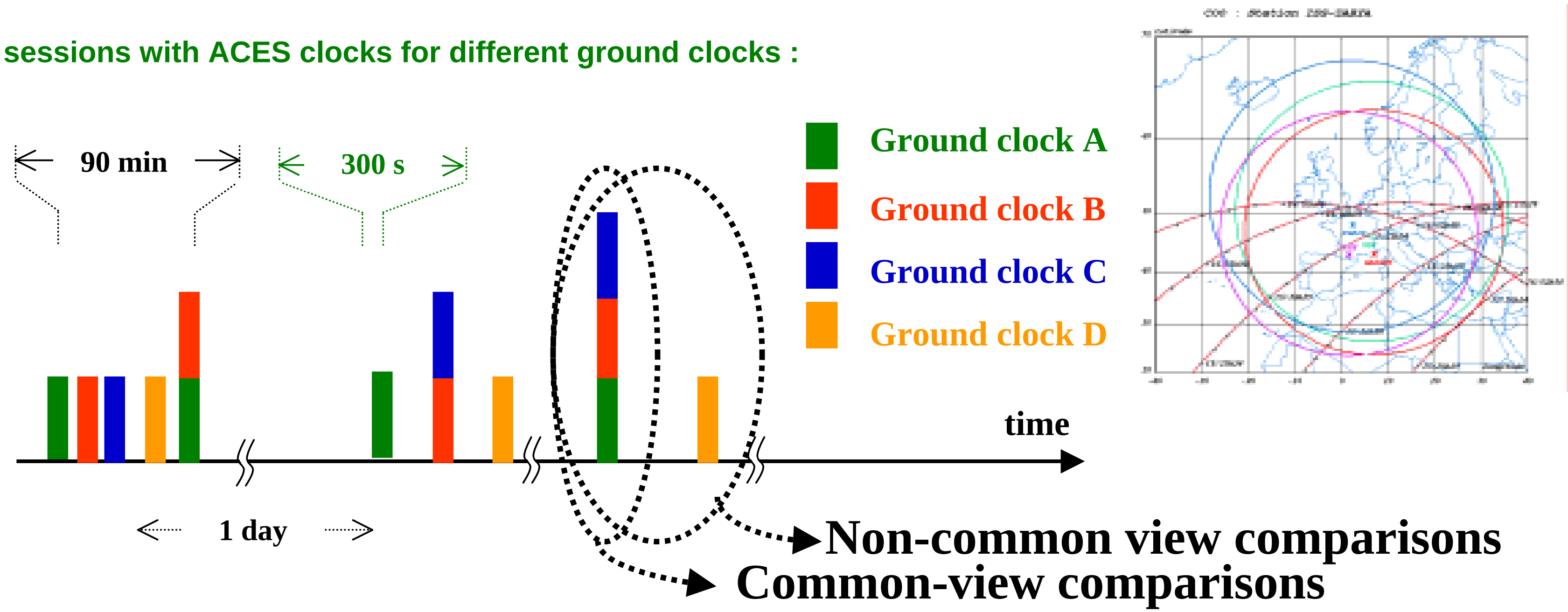
**All ACES major scientific objectives rely on space – ground comparisons :**

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

# Clocks comparisons with MWL

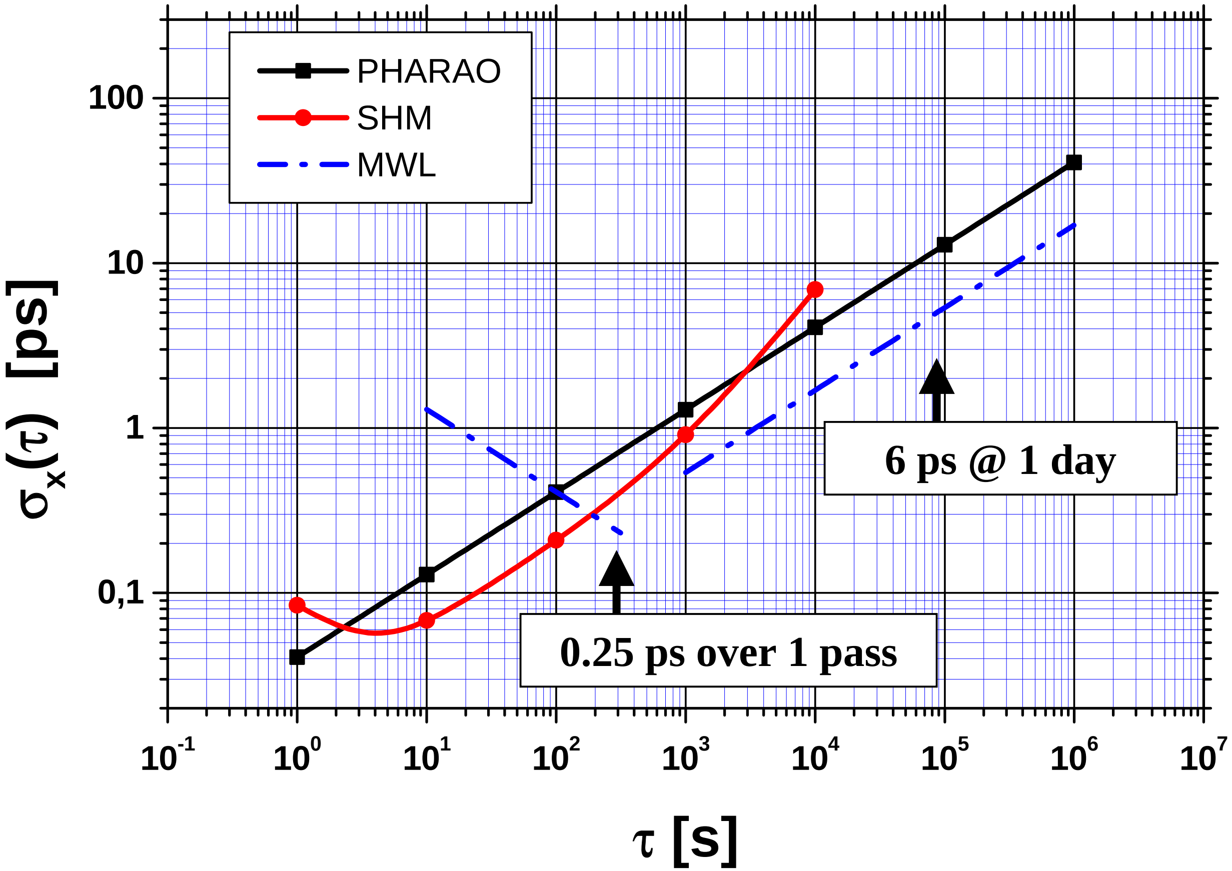
- Low orbit of ISS : 400 km
- Period : 90 min
- Mean visibility duration : 300 s

Comparison sessions with ACES clocks for different ground clocks :



# MWL PERFORMANCE

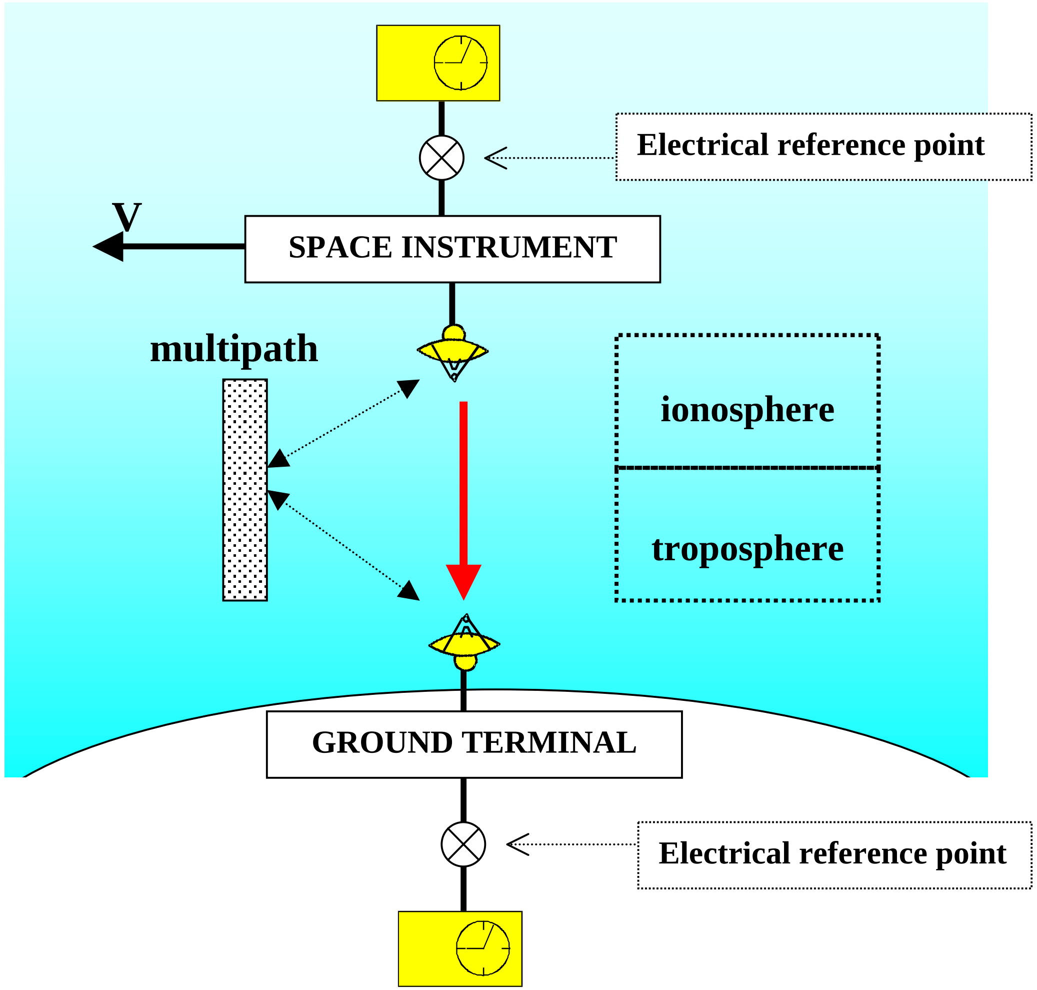
**STABILITY :**




**ACCURACY : No need (time interval comparisons only)**

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

# COMPARISON BETWEEN TWO DISTANT CLOCKS




- **TROPOSPHERIC DELAY**

**(temperature, humidity)** → **10 ns**

- **IONOSPHERIC DELAY**

**(TEC, varies as $1/f^2$ )** → **10 ns**

- **MULTI-PATH EFFECT**

**(distance, reflectivity of spurious reflectors)**

- **INSTRUMENTAL DELAYS**

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

- **RELATIVISTIC EFFECTS**

**(Position and velocities of space and ground clocks )**

| | |
|---|---|
| → 1st order Doppler effect | → $2.\ 10^{-5}$ |
| → 2nd order Doppler effect | → $3.\ 10^{-10}$ |
| → Sagnac effect | → $7.\ 10^{-13}$ |
| → Gravitational shift | → $4.\ 10^{-11}$ |

## CHARACTERISTICS OF MWL

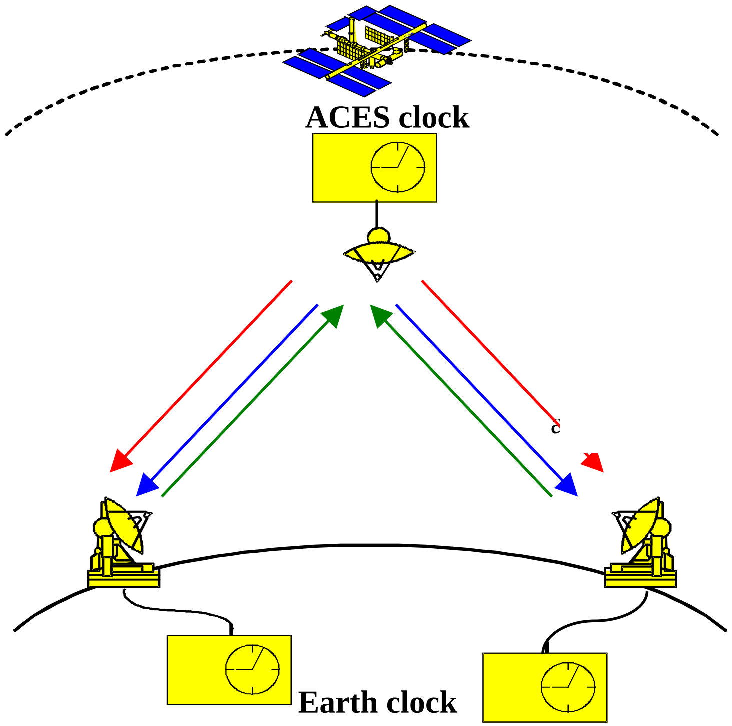
(Timetech, Kayser-Threde, Germany)

**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**

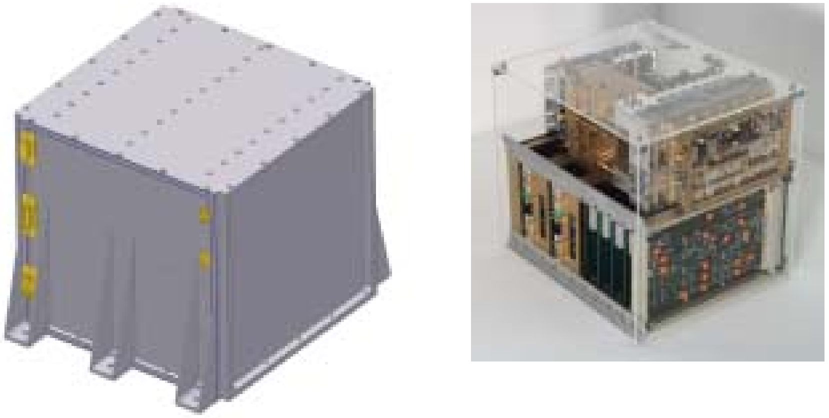
**Data link (2 kBits/s in S-band down link)**

→ **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

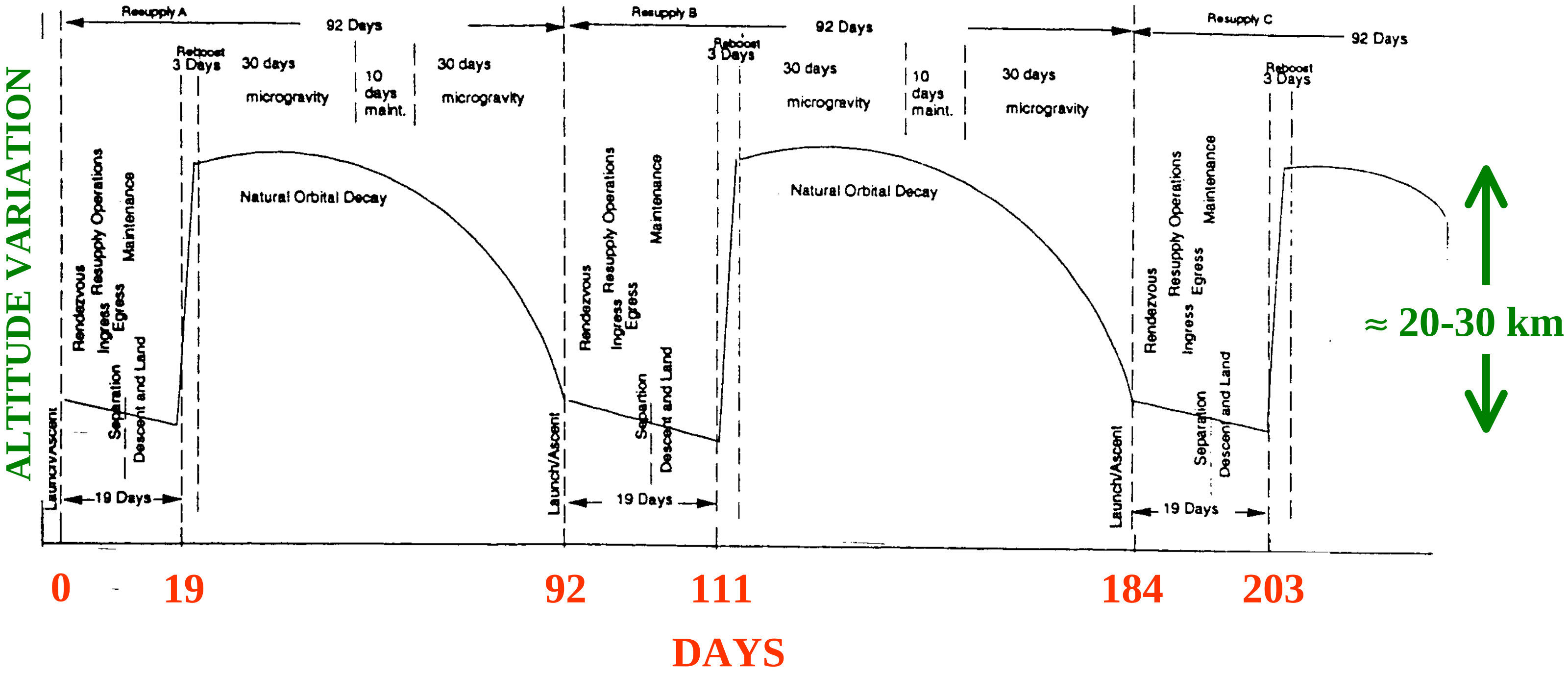
| | Relativistic effects | | Orbitography requirements | |
|---|---|---|---|---|
| | Type | Order of magnitude | Type | Precision (1σ) |
| Clocks | Gravitational potential | $-6.9\ 10^{-10}$ (Ground) | Position (altitude) | 1.7 m (1 day) |
| | | $-6.5\ 10^{-10}$ (ISS) | | 0.5 m (10 days) |
| | 2nd order 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 | $7.\ 10^{-13}$ | | |

OVER THE WHOLE CLOCK TRAJECTORY

OVER ONE COMPARISON SESSION

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

# ISS ALTITUDE VARIATIONS




→ **Determination of ACES payload orbit :**

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

**+ MWL ranging + laser ranging**

# ACES OPERATIONS

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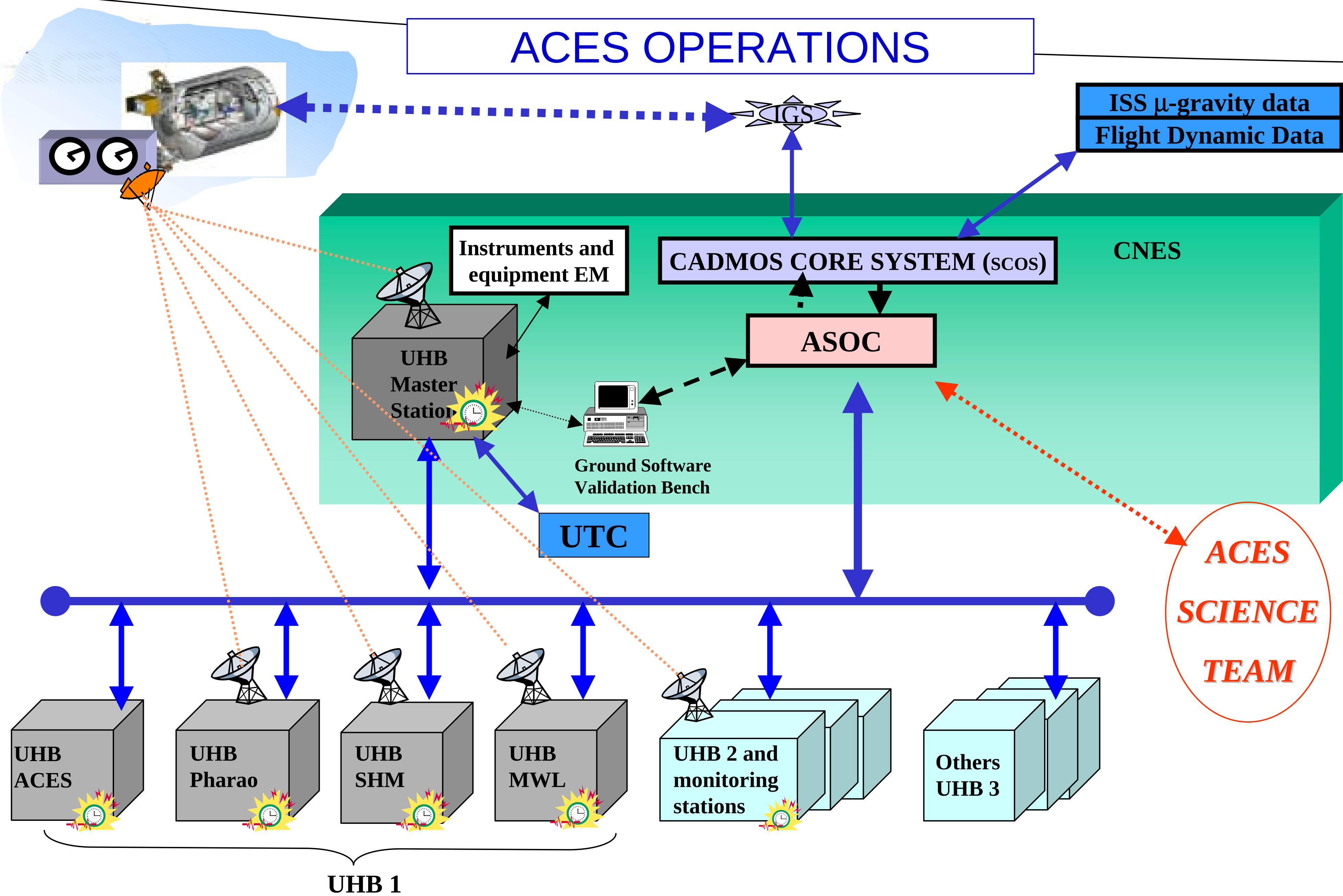

# CONCLUSIONS

→ **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 !*