• A cold atom Cesium clock in space
• Fundamental physics tests
• Worldwide access
The ACES experiment consists in 2 instruments plus “tools”:

1. **Pharao**: Cold atom clock  
   ⇒ Laser cooled cesium clock designed for micro-gravity

2. **Space Hydrogen Maser – SHM**  
   ⇒ Reference clock and local oscillator for Pharao

3. **Frequency Comparison and Distribution Package – FCDP**  
   ⇒ Frequency comparison and processing

4. **Micro-Wave Link – MWL**  
   ⇒ Link for time-frequency transfer to the ground
ACES General View

Earth

\[
\begin{align*}
M &= 227 \text{ kg} \\
P &= 450 \text{ W}
\end{align*}
\]
ACES ON COLUMBUS EXTERNAL
PLATFORM

Current launch date: 2010
Mission duration: 18 months
Accuracy of the atomic time

Current accuracy:
- Microwave: $6 \times 10^{-16}$
- Optical: $5 \times 10^{-17}$
Frequency stability of ACES Clocks

Allan deviation of the 2 clocks:

- Stability of SHM in time intervals of 3 to 3000 s, well adapted to:
  - ISS single pass (duration: 200-400 s)
  - Evaluation and optimization of PHARAO
- ACES: slow servo of SHM onto PHARAO

Stability at one day: $3 \times 10^{-16}$

- at 10 days: $1 \times 10^{-16}$
Fountain:
\[ v = 4 \text{ m/s}, \ T = 0.5 \text{ s} \quad \Delta \nu = 1 \text{ Hz} \]

- PHARAO:
\[ v = 0.05 \text{ m/s}, \ T = 5 \text{ s} \quad \Delta \nu = 0.1 \text{ Hz} \]
PHARAO Space Clock: first cold atoms!

Laser source

Cesium tube

Clock Ramsey resonance

Functional tests starting in CNES Toulouse
Laser Source

20.054 kg, 36W, 30 liters, Vacuum and Air operation, T=10-35 deg.

Main active components:
4 ECDL
4 DL
6 AOM
30 PZT
11 motors
6 photodiodes
8 peltier coolers
Cesium Tube

L=900 mm, M= 45 kg, P= 5 W.

Ramsey cavity
Tested in fountain
2. Ultra-stable frequency comparisons on a worldwide basis:
   - Clock comparisons $@ 10^{-16}$
   - Contribution to TAI
   - Space-ground and ground-ground comparisons

   Gain: x 10 wrt current GPS.

   Common view

   non common view
**Expected Performances of ACES T/F link**

**STABILITY:**
- Time stability better than:
  - 0.3 ps @ 300 s
  - 6 ps over 1 day integration time
- Two way system: will allow clock comparisons at $10^{-17}$ per day

Development: Timetech, Kayser-Threde, EADS-ST
3. Test General Relativity:

Einstein effect: Red shift
x 35 sensitivity improvement over GP-A

Search for a possible drift of the fine structure constant $\alpha : 10^{-16}$ / year (x 10)

Test of Lorentz invariance and SME (x10 to x 100)
A Prediction of General Relativity

\[ \frac{v_2}{v_1} = \left( 1 - \frac{U_2 - U_1}{c^2} \right) \]

Redshift: +4.59 \times 10^{-11}
With 10^{-16} clocks
ACES: 2 \times 10^{-6}
Do fundamental physical constants vary with time?

$G$, $\alpha_{\text{elm}}$, $\alpha_{\text{strong}}$, $m_e / m_p$...

**Principle**: Compare two or several clocks of different nature as a function of time

ex:

Microwave clock/Microwave clock
rubidium and cesium
Microwave/Optical clock
Optical Clock/Optical clock
$^{87}\text{Rb} - ^{133}\text{Cs}$ Comparison over 6 years

\[ \frac{d}{dt} \ln \left( \frac{v_{\text{Rb}}}{v_{\text{Cs}}} \right) = (-0.5 \pm 5.3) \times 10^{-16} / \text{year} \]

Within Prestage et al. theoretical framework:

\[ \frac{\dot{\alpha}}{\alpha} = (1.0 \pm 12) \times 10^{-16} / \text{year} \]

H. Marion et al., PRL (2003), Bize 2005, Peik 2005

$\nu_{\text{Rb}} = 6\,834\,682\,610.904\,335\,(12)\,\text{Hz}$
ACES: a link between different clocks at $10^{-16}$

- Transition or oscillator
- solid resonator: $R_y/\alpha$
- electronic transition: $R_y$
- fine structure transition: $\alpha^2 R_y$
- hyperfine transition: $g_p (m_e/m_p) \alpha^2 R_y$

With $R_y = \alpha^2 m_e c^2/2h$

Femtosecond laser system for frequency comparisons

2005 Nobel prize for physics

J. Hall
T. Hänsch
ACES Ground Stations (May 06)

Australia: UWA, CSIRO(Sydney)
Austria: Univ. Innsbruck
Brazil: Univ. Sao Carlos
Canada: NRC
China: Shangai Obs, NIM, NTSC
Germany: PTB, MPQ, Univ. Hannover, Univ. Düsseldorf, TU Muenchen, Univ. Erlangen
France: SYRTE, CNES, Obs. Besançon, OCA, LPL
Italy: IEN, Univ. Firenze
Japan: Tokyo Univ., NMIJ, CRL
Russia: Vniftri, ILS Novosibirsk
Swiss: METAS, ON
England: NPL
USA: JPL, NIST, JILA, Penn St. Univ., USNO
Taiwan: Telecom research lab
Int. Agency: BIPM

Total: 35 institutes + theory groups
> 280 researchers
Engineering models of instruments currently under tests
PHARAO-SHM-FCDP Performances tests: April 2007
Microwave link delivery: spring 2007

Flight models: 2007-2009

Launch planned for 2010

Shuttle in 2010?
Back-up (1): ATV/Progress/ HTV after Columbus launch
Back-up (2): dedicated satellite, Proteus class (minisat)
Future of clocks in space

Clocks on Earth at 10^{-17} will be limited by the knowledge of the local Earth potential and of its fluctuations.
Next step: dedicated satellites for global time dissemination

Fast advances in optical clocks: 10^{-17} - 10^{-18} is realistic
A new Relativistic Geodesy: based on red-shift
Improved positioning and navigation

Space is a quiet environment: ultra-stable lasers, optical resonators and clocks (OPTIS)

Vastly improved tests of GR in solar orbit
LATOR, SORT, Shapiro delay, differential redshift, …

Space-Space VLBI with sub-micro arc-second resolution
New matter wave sensors, BEC and atom lasers
ACES contributors


64 scientists from 10 countries

Thanks to all!