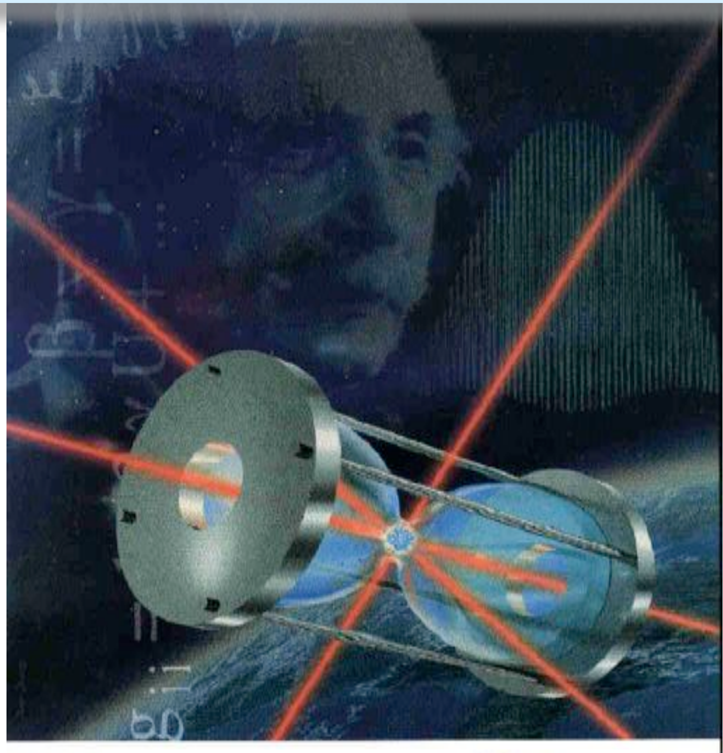
ACES: Ultra-stable Clocks in Space
Fundamental physics and Applications

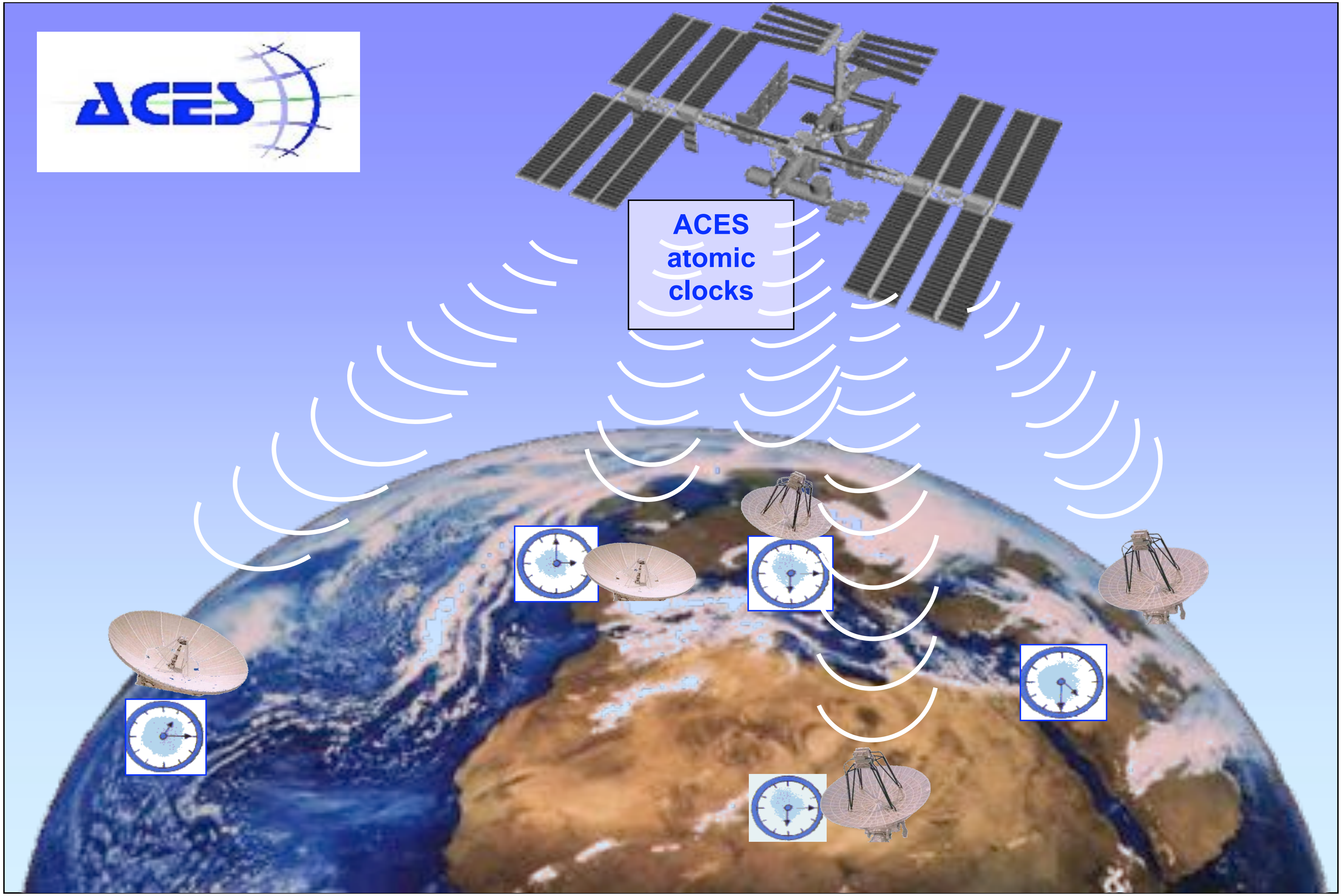
1997



IGS, May11th
2006

CENTRE NATIONAL D'ETUDES SPATIALES

C. Salomon, Ecole Normale Supérieure, Paris, France



- A cold atom Cs standard in space
- Fundamental physics tests
- Worldwide access

ACES instruments

The ACES experiment consists in 2 instruments plus “tools”:

1. **Pharao**: Cold atom clock

   ⇒ Laser cooled cesium clock designed for micro-gravity

2. **S**pace **H**ydrogen **M**aser – SHM *ON*

   ⇒ Reference clock and local oscillator for Pharao

3. **F**requency **C**omparison and **D**istribution **P**ackage – FCDP

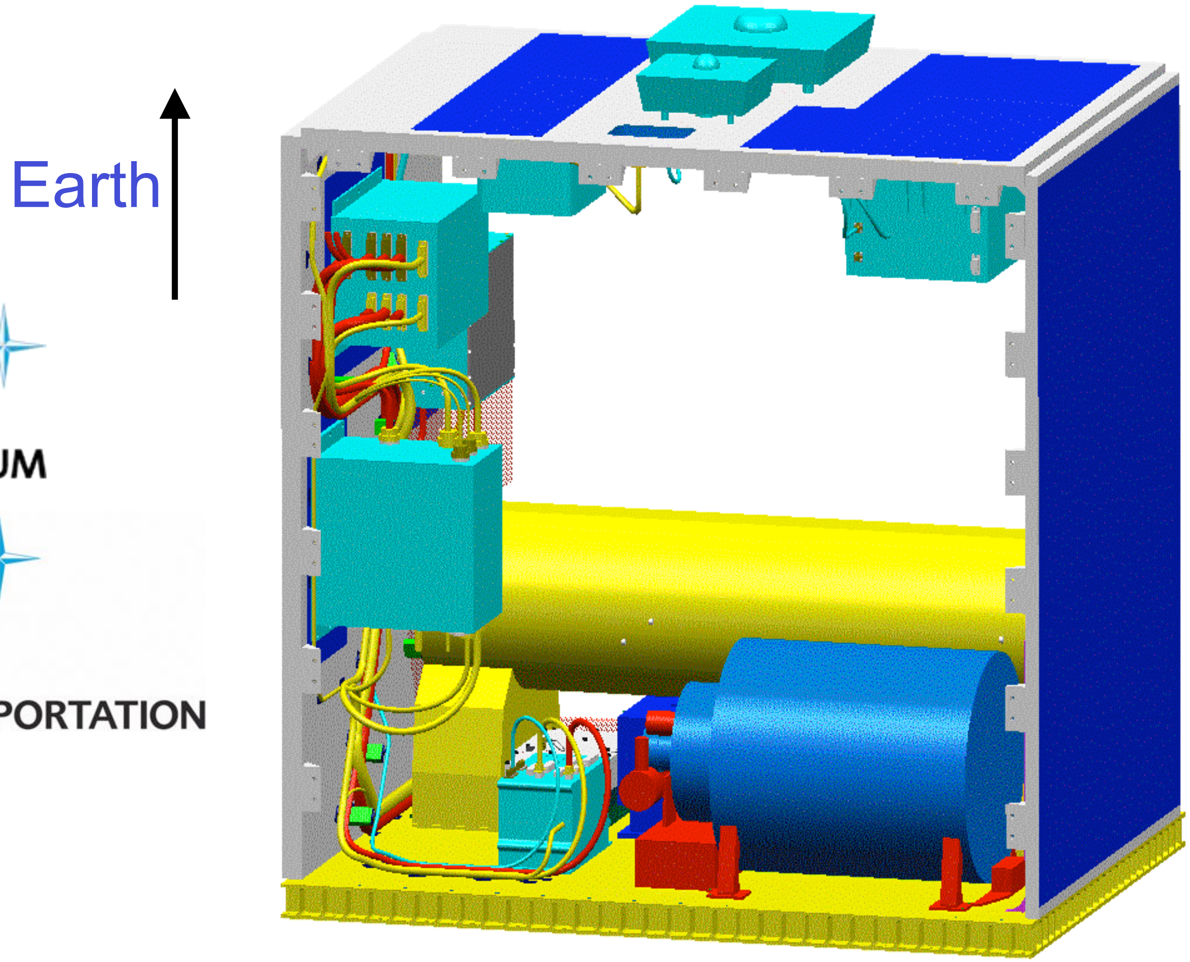
   ⇒ Frequency comparison and processing

4. **M**icro-**W**ave **L**ink – MWL

   ⇒ Link for time-frequency transfer to the ground

W. Schäfer talk

ACES General View



EADS ASTRIUM

EADS SPACE TRANSPORTATION

ACES

M = 227 kg **P = 450 W**

esa

ACES ON COLUMBUS EXTERNAL PLATFORM

ACES

Current launch date : 2010
Mission duration : 18 months

ACES OBJECTIVES (1)

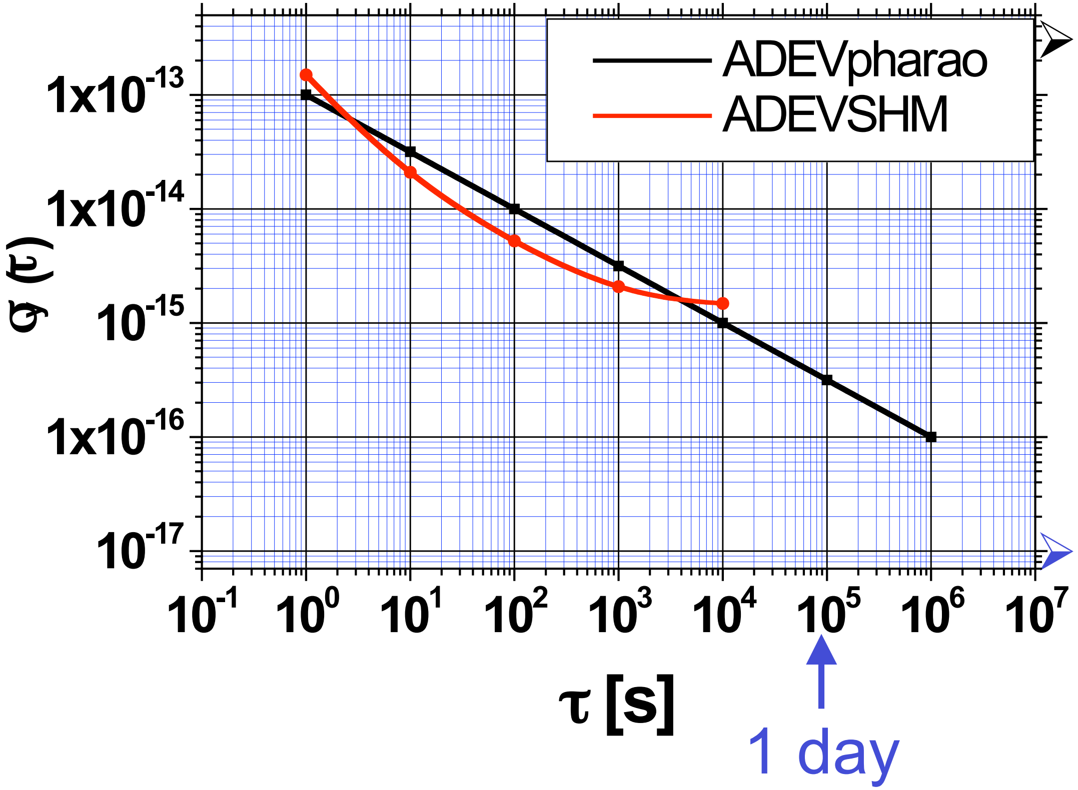
1. **Operate SHM and a cold atom clock in microgravity : PHARAO**
   - **A linewidth of 100 milliHertz**
   - **A frequency stability of :** $\sigma_y(\tau) = 7\ 10^{-14}$ **to** $1\ 10^{-13}\ \tau^{-1/2}$

     $< 3\ \ 10^{-16}$**/day**
2. **Study the ultimate stability and accuracy in space :**
   - **Accuracy :** $\sim 10^{-16}$

PHARAO performance is established through onboard comparison with SHM in FCDP and with ground clocks using MWL

Frequency stability of ACES Clocks

Allan deviation of the 2 clocks:

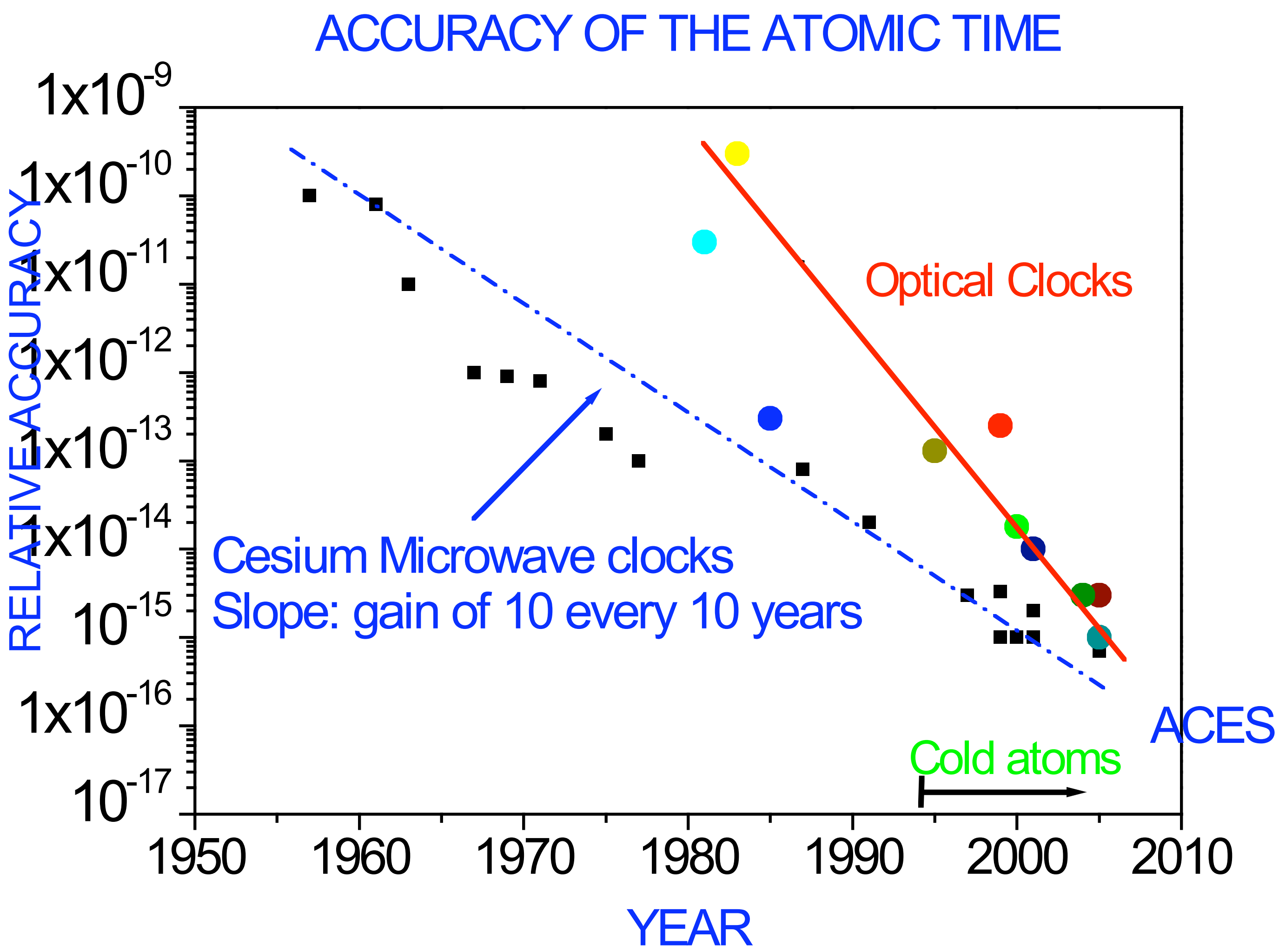


- Stability of SHM in time intervals of 3 to 3000 s, well adapted to:
  - ISS single pass (duration: 200-400 s)
  - evaluation and optimization of PHARAO
- ACES: slow servo of SHM onto PHARAO

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

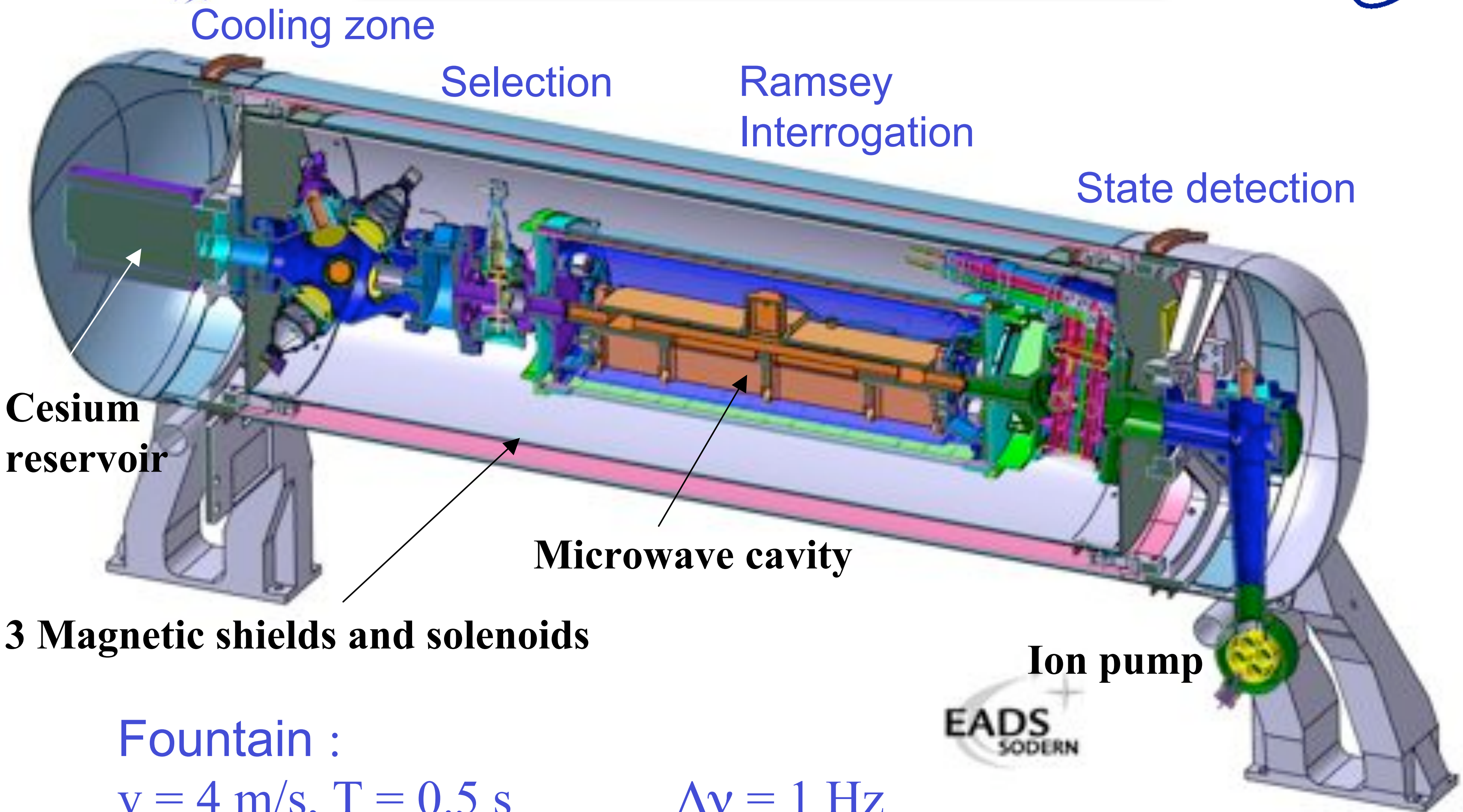
at 10 days: 1 10^{-16}

Accuracy of the atomic time



Current accuracy: $7x\ 10^{-16}$

PHARAO cold atom clock



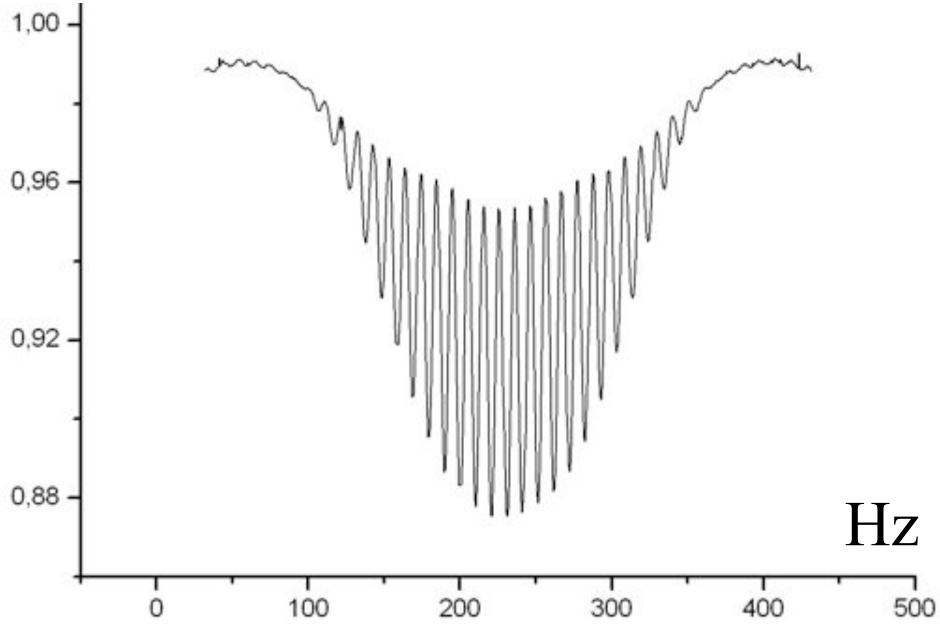
Fountain :
v = 4 m/s, T = 0.5 s   Δν = 1 Hz

- PHARAO :
  v = 0.05 m/s, T = 5 s   Δν = 0.1 Hz

PHARAO Space Clock: first cold atoms !

Cesium tube

Laser source



Clock Ramsey resonance

Functional tests starting in CNES Toulouse

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Laser Source

20.054 kg, 36W, 30 liters

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

ACES OBJECTIVES (2)

2. Ultra-stable frequency comparisons on a worldwide basis :

Clock comparisons@ 10^{-16}

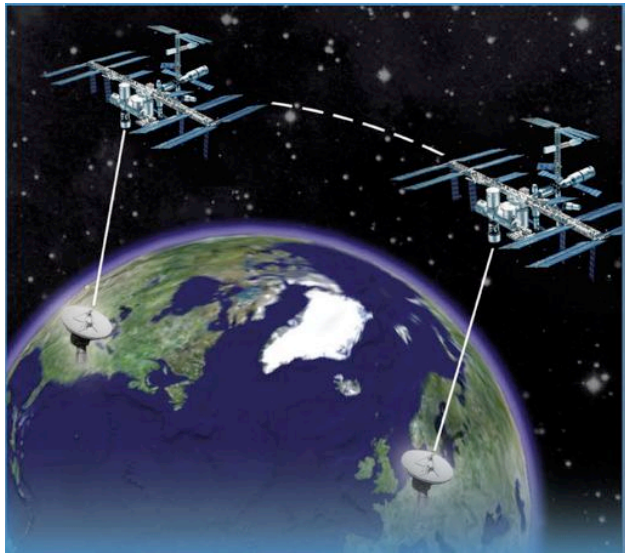
Contribution to TAI

Space-ground and ground-ground comparisons

Gain: x 10 wrt current GPS.

Common view

non common view



ACES interface with GNSS and Geodesy

- Orbitography, Svehla talk
- Interest to install dual frequency GPS receiver connected to ACES   Montenbruck talk
- Connection to IGS network
- Availability and interest of an ultra-stable reference clock in space
- MWL:Independent time transfer and comparisons with GPS/Galileo

ACES OBJECTIVES (3)

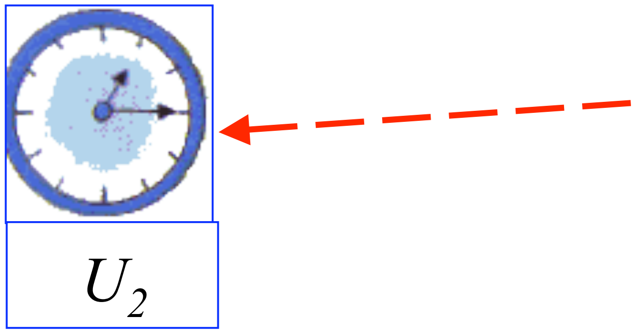
3. Test General Relativity :

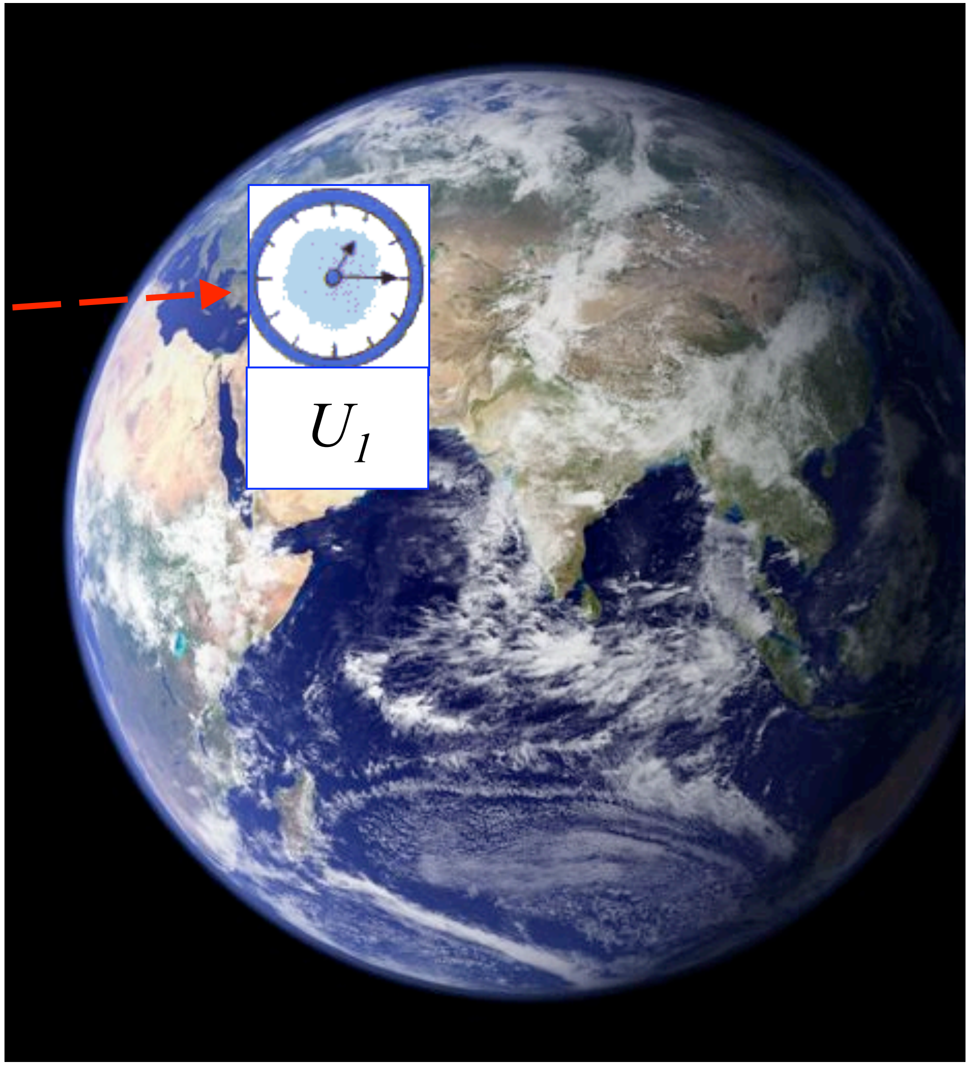
Einstein effect: Red shift : x 35 sensitivity improvement

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

Test of Lorentz invariance (x10 to x 100)

A Prediction of General Relativity

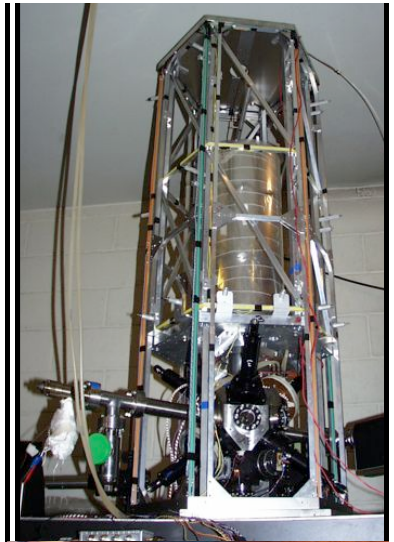




$$\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)$$

Redshift measurement:
ACES target: 2 10^{-6}

Do fundamental physical constants vary with time ?



G, α_{elm}, α_{strong}, m_e,…

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

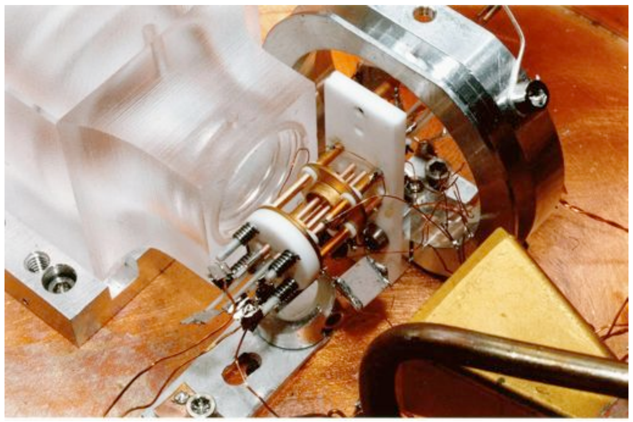
ex:

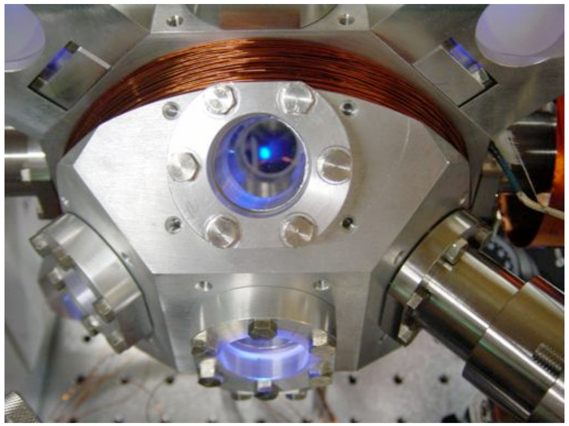
Microwave clock/Microwave clock

rubidium and cesium

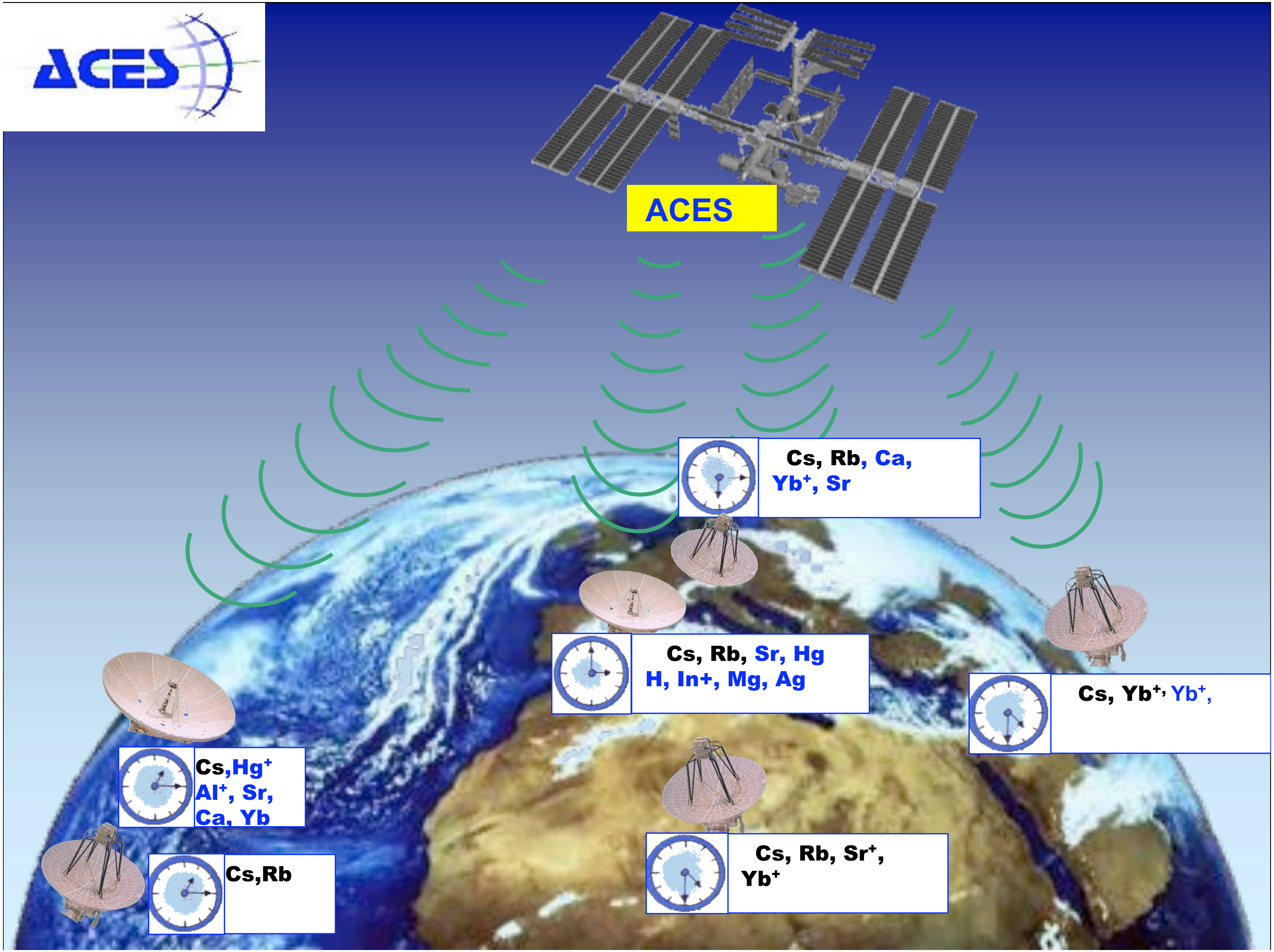
Microwave/Optical clock

Optical Clock/Optical clock





The ovens and electrodes of the NPL strontium ion end-cap trap.

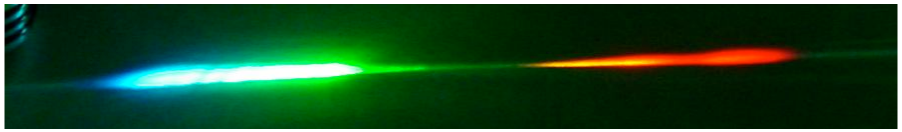

ACES
ACES
Cs, Rb, Ca,
Yb+, Sr
Cs, Rb, Sr, Hg
H, In+, Mg, Ag
Cs, Yb+, Yb+,
Cs,Hg+
Al+, Sr,
Ca, Yb
Cs,Rb
Cs, Rb, Sr+,
Yb+

ACES : a link between different clocks at 10^{-16}

- Transition or oscillator
- solid resonator: R_y/α
- 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



J. Hall
T. Hänsch

2005 Nobel prize for physics

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, Penn St. Univ., USNO
Taiwan:	Telecom research lab
Int. Agency:	BIPM

Total : 34 institutes + theory groups

> 260 researchers

Beyond ACES

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} becomes realistic
A new Relativistic Geodesy: based on red-shift

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

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

Space-Space VLBI with sub-micro arc-second resolution

New matter wave sensors

Bose Einstein Condensates in Space and Atom Lasers