Cold atoms in space

Nearly unperturbed environment: long interaction time

**Parabolic flights:** 1991, 1997,…2018

**Cold atom clocks:** Laurent et al. 1997

**Atom interferometers:**


EP test: $^{87}\text{Rb}$-$^{39}\text{K}$ Nature Comm., 2016

**Drop tower:**

BEC: Van Zoest et al. Science 2010

Matter wave interferometer, 2015

**Sounding rocket:** BEC in 2017

CAL on ISS: Rb BEC in 2018

Frequency combs

**Satellite:**

Rb clock in Chinese

Tiangong 2: 2017. But linewidth 1.8 Hz is not narrower than in Earth-based fountains

Liu et al., Nat Comm’ 2018
The space clock mission ACES
To be launched to ISS in 2021, by Space X Dragon capsule

- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access
ACES ON COLUMBUS EXTERNAL PLATFORM on ISS

Current launch date: 2021
Mission duration: 18 months to 3 years
A Prediction of General Relativity

The gravitational clock shift

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

Gravity-probe A:
- Space H maser on a sounding rocket: 10 000 kms, 2 hour flight
- Ground maser
- Orbit determination by radio station tracking

Also seen in lab with optical clocks!
C. W. Chou et al., Science 329, 1630, 2010

Eccentric Galileo satellites
P. Delva et al. PRL 2018
Redshift at 2.5 E-5
Factor 5 better
Also S. Hermann et al., PRL 2018

Gravitational Redshift + Time dilation tested at $1.4 \times 10^{-4}$
PHARAO cold atom clock

- Cooling zone
- Selection
- Ramsey Interrogation
- State detection

Cesium reservoir

Microwave cavity

3 Magnetic shields and solenoids

Ion pump

Accuracy goal: $10^{-16}$ in space
Flight model tests completed in Toulouse
Expected accuracy and stability: $10^{-16}$ in space
Delivery to ESA: July 2014
Test of Einstein effect at 2 ppm
PHARAO Team in Toulouse
PHARAO Cesium Tube on the Shaker
PHARAO Laser Source

Mass: 21 Kg, Vol: 17 liters, Power: 35 W
Flight model assembly: January 2014

Extende cavity lasers
Autolock on cesium saturated absorption lines
PHARAO Flight Model Performance Tests

Cryo-oscillator

Mobile Fountain FOM

100MHz

+ CNES H-MASER frequency stability

Ground Commands

Frequency comparison accuracy

- Orbital simulations in vacuum
- Temperature and Magnetism
$$\sigma_y(\tau) = 3.3 \times 10^{-13} \tau^{-1/2}$$

With ultra-stable Quartz
Limited by gravity!

Will enable $1.05 \times 10^{-13} \tau^{-1/2}$
in space with narrower line
Crucial for the redshift test

Frequency comparison PHARAO- FOM = $7 \times 10^{-16} \pm 15 \times 10^{-16}$ stat.

Accuracy evaluation: currently $1.8 \times 10^{-15}$ on the ground

Main contributors:
- distributed cavity phase shift
- Cold Collisions

Will be evaluated in space by tuning the launch velocity over one order of magnitude

See work by P. Laurent and Kurt Gibble

Should enable $10^{-16}$ in space
Mass: 227 kg, Power: 450 W

Challenges: thermo-mechanical stability, three year operation
Famous ACES Visitors at ADS Friedrichshafen

Claude Cohen-Tannoudji  Ted Hänsch
Ultra-stable frequency comparisons on a worldwide basis:
Ground Clock comparisons @ $10^{-17}$ over one week
Contribution to TAI

See talk by Wolfgang Schäfer

Common view

Error < 0.3ps over 300 s
To be checked by fiber-link

non common view

Error < 3ps over 3000 s
Frequency comparisons at $10^{-17}$ over 4-5 days
Global clock network for search for time or space variations of fundamental constants by long distance clock comparisons at $10^{-17}$ /year
Need for operating microwave and optical clock over extended periods

15 years of TAI calibration

The ACES data will have a similar structure and will require continuous operation of microwave and optical clocks over several 20 day long sequences

Slide courtesy of B. Fang
Current Network of Ground Institutes

+ 1 transportable MWL GT for other European institutes

+ 1 transportable MWL GT for calibration/troubleshooting purposes
METAS, INRIM,...

Delivery of first MWL GT unit to PTB: end of 2015
Relativistic Geodesy

The clock frequency depends on the Earth gravitational potential $10^{-16}$ per meter.

Best ground clocks have accuracy of $1.4 \times 10^{-18}$ and will improve!

Competitive with satellite + levelling techniques at ~ 20 cm level

Possibility to measure the **potential difference** between the two clock locations at $10^{-17}$ level ie 10 cm and $10^{-18}$ ie 1 cm with fiber link.

Atomic clock performance enabling geodesy below the centimetre level

W. F. McGrew$^{1,2}$, X. Zhang$^{1,3}$, R. J. Fasano$^{1,2}$, S. A. Schäffer$^{1,4}$, K. Beloy$^{1}$, D. Nicolodi$^{1,2}$, R. C. Brown$^{1,8}$, N. Hinkley$^{1,2,9}$, G. Milani$^{1,5,6}$, M. Schioppo$^{1,10}$, T. H. Yoon$^{1,7}$ & A. D. Ludlow$^{1,2*}$

NIST, Nature December 2018
Mission Management Plan: prior access to data for one year
Paper authorship

Actual trend:

LIGO-VIRGO model: members of the collaboration apply to the Ligo Science Collaboration with a research program. Once accepted by LSC (more than 2/3 of votes) they are automatically authors of all the collaboration papers.

Planck Model
A core team. Scientific projects developed by subgroups but also authored by all members of the collaboration.

ACES model to be discussed
ACES Science

- Theory
- Data analysis

- Fiber links
- GPS, Two-Way

- Ground Clocks
- Microwave
- Optical

- MWL

- PHARAO
- SHM
- GNSS

- ELT

- Laser ranging stations
- ELT
- Data analysis
• Each member of IWG is responsible for the team that He is representing within IWG
• For each experiment He proposes a list of people who are involved in the experiment
• This list is discussed in IWG and agreed (or not) by IWG (2/3 of votes)
• Each member of IWG signs all papers where ACES is involved
• As described in ACES Mission Science Management Plan, papers involving ACES are submitted first to an Editorial Board composed of ACES IWG members for approval.
Participants