The ACES Mission
Testing Fundamental Physics with Clocks in Space

L. Cacciapuoti
European Space Agency
Atomic Clock Ensemble in Space

ACES payload

ISS

Dragon free flier

TM/TC

Space-X

SLR stations

MWL GT network

Ground clocks

ACES USOC

ISS NASA CC

Columbus CC
The Columbus module
The ACES Payload

- **PHARAO (CNES):** Atomic clock based on laser cooled Cs atoms
- **SHM (ESA):** Active hydrogen maser
- **FCDP (ESA):** Clocks comparison and distribution
- **MWL (ESA):** T&F transfer link
- **GNSS receiver (ESA)**
- **ELT (ESA):** Optical link
- **Support subsystems (ESA)**
  - XPLC: External PL computer
  - PDU: Power distribution unit,
  - Mechanical, thermal subsystems
  - CEPA: Columbus External PL Adapter (ESA-NASA)

Volume: 1172x867x1246 mm³
Mass: 227 kg
Power: 450 W
ACES Clocks and Links Performance

PHARAO accuracy $\approx 1 \cdot 10^{-16}$

PHARAO FCDP SHM

XPLC

MWL ground terminal

ELT detector

La Thuile 21-28 March 2015

Rencontres de Moriond - Gravitation
PHARAO FM Stability

Measured on the ground:
- Stability: \(3 \cdot 10^{-13}/\tau^{1/2}\)
- PHARAO-FOM: \(2 \cdot 10^{-15}\)

Predicted performance in space:
- Stability: \(1 \cdot 10^{-13}/\tau^{1/2}\)
- Accuracy: \(1-3 \cdot 10^{-16}\)
## PHARAO Accuracy

<table>
<thead>
<tr>
<th>Systematic effects</th>
<th>GROUND (measured)</th>
<th>IN-ORBIT (extrapolation)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency shift $x 10^{-16}$</td>
<td>Uncertainty $x 10^{-16}$</td>
</tr>
<tr>
<td>$2^{nd}$ order Zeeman Shift</td>
<td>1811</td>
<td>0.5</td>
</tr>
<tr>
<td>Collisions</td>
<td>-69</td>
<td>12</td>
</tr>
<tr>
<td>Blackbody radiation shift</td>
<td>-172</td>
<td>0.4</td>
</tr>
<tr>
<td>Phase gradients</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Phase transients</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Microwave recoil</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Background gas shift</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Microwave leakage</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Quantum sideband effect</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Magnetic field gradients</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1602</td>
<td>14.4</td>
</tr>
</tbody>
</table>
SHM: An Active H-maser for Space

SHM role in ACES
- ACES flywheel oscillator
- PHARAO characterization

Technical challenges
- Low mass, volume, and power consumption
- Full performances:
  - $1.5 \cdot 10^{-13}$ @ 1 s
  - $1.5 \cdot 10^{-15}$ @ $10^4$ s

Design solution
- Full size Al cavity
- Automatic Cavity Tuning System (ACT)

Volume: 390x390x590 mm$^3$
Mass: 42 kg
• SHM EM tested under thermal vacuum in its final configuration
• Sensitivity to temperature and magnetic field perturbations measured
• EMC tests on-going; vibration tests scheduled in April
• Procurement of FM components and development of some key subsystems started
**Thermal sensitivity**

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>$\Delta T_{pp}$ (K)</th>
<th>$K_T$ (10^{-14}/K)</th>
<th>$K_T$ (10^{-14}/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5400</td>
<td>1.3</td>
<td>2.0 $\cdot$ 10^{-14}/K</td>
<td>1.9 $\cdot$ 10^{-14}/K</td>
</tr>
<tr>
<td>2000</td>
<td>1.2</td>
<td>1.0 $\cdot$ 10^{-14}/K</td>
<td>1.2 $\cdot$ 10^{-14}/K</td>
</tr>
<tr>
<td>600</td>
<td>1.5</td>
<td>---</td>
<td>2.0 $\cdot$ 10^{-15}/K</td>
</tr>
<tr>
<td>300</td>
<td>1.0</td>
<td>---</td>
<td>4.0 $\cdot$ 10^{-15}/K</td>
</tr>
</tbody>
</table>

**Magnetic sensitivity**

$K_B = 8 \cdot 10^{-14}/G$

Difference over 100 s intervals
ADEV $< 1 \cdot 10^{-16}$ after 1 day
PHARAO accuracy evaluation OK

+ calibration of slow temperature variations
• **Two-way link:**
  - Removal of the troposphere time delay (8.3-103 ns)
  - Removal of 1st order Doppler effect
  - Removal of instrumental delays and common mode effects

• **Additional down-link in the S-band:**
  - Determination of the ionosphere TEC
  - Correction of the ionosphere time delay (0.3-40 ns in S-band, 6-810 ps in Ku-band)

• **Phase PN code modulation:** Removal of $2\pi$ phase ambiguity

• **High chip rate (100 MChip/s) on the code:**
  - Higher resolution
  - Multipath suppression

• **Carrier and code phase measurements (1 per second)**

• **Data link:** 2 kBits/s on the S-band downlink to obtain clock comparison results in real time

• **Up to 4 simultaneous space-to-ground clock comparisons**
MWL End-to-end Test Configuration
MWL End-to-end Test Results

2-way carrier phase in static conditions

2-way carrier phase under signal dynamics
<table>
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<th>Delays combination</th>
<th>Uncertainty</th>
<th>Note</th>
</tr>
</thead>
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<td>Ionosphere modelling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}2}^{\text{co}} - \Delta_{\text{Tx}3}^{\text{co}}) + (\Delta_{\text{Rx}2}^{\text{co}} - \Delta_{\text{Rx}3}^{\text{co}}))</td>
<td>600 ps</td>
<td>Up to a constant offset over the mission lifetime or at least between on/off cycles</td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}2}^{\text{co}} - \Delta_{\text{Tx}3}^{\text{co}}) + (\Delta_{\text{Rx}2}^{\text{co}} - \Delta_{\text{Rx}3}^{\text{co}}))</td>
<td>400-(\sigma_x(\tau)_{\text{MWL}})</td>
<td>Stability requirement</td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}2}^{\text{co}} - \Delta_{\text{Tx}3}^{\text{co}}) + (\Delta_{\text{Rx}2}^{\text{co}} - \Delta_{\text{Rx}3}^{\text{co}}))</td>
<td>40 ns</td>
<td>Accuracy requirement</td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}2}^{\text{co}} - \Delta_{\text{Tx}3}^{\text{co}}) + (\Delta_{\text{Rx}2}^{\text{co}} - \Delta_{\text{Rx}3}^{\text{co}}))</td>
<td>1.3 ns</td>
<td>Accuracy goal</td>
</tr>
<tr>
<td>Carrier cycle ambiguity resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}1}^{\text{co}} - \Delta_{\text{Tx}1}^{\text{ca}}) + (\Delta_{\text{Rx}1}^{\text{co}} - \Delta_{\text{Rx}1}^{\text{ca}}))</td>
<td>34 ps</td>
<td>Up to a constant offset over the mission lifetime or at least between on/off cycles</td>
</tr>
<tr>
<td>(\Delta_{\text{Tx}2}^{\text{co}} - \Delta_{\text{Tx}2}^{\text{ca}}) + (\Delta_{\text{Rx}2}^{\text{co}} - \Delta_{\text{Rx}2}^{\text{ca}}))</td>
<td>34 ps</td>
<td>Up to a constant offset over the mission lifetime or at least between on/off cycles</td>
</tr>
<tr>
<td>Lambda configuration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta_{\text{Rx}1}^{\text{co}} + \Delta_{\text{Tx}2}^{\text{co}}))</td>
<td>40 ns</td>
<td>Accuracy requirement</td>
</tr>
<tr>
<td>(\Delta_{\text{Rx}1}^{\text{ca}} + \Delta_{\text{Tx}2}^{\text{ca}}))</td>
<td>40 ns</td>
<td>Accuracy requirement</td>
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<td>40 ns</td>
<td>Accuracy requirement</td>
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<td>40 ns</td>
<td>Accuracy requirement</td>
</tr>
<tr>
<td>Time transfer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\frac{1}{2}[(\Delta_{\text{Rx}1}^{\text{co}} - \Delta_{\text{Tx}2}^{\text{co}}) + (\Delta_{\text{Rx}1}^{\text{co}} - \Delta_{\text{Rx}2}^{\text{co}})])</td>
<td>100 ps</td>
<td>Accuracy requirement</td>
</tr>
<tr>
<td>(\frac{1}{2}[(\Delta_{\text{Rx}1}^{\text{ca}} - \Delta_{\text{Tx}2}^{\text{ca}}) + (\Delta_{\text{Rx}1}^{\text{ca}} - \Delta_{\text{Rx}2}^{\text{ca}})])</td>
<td>(\sigma_x(\tau)_{\text{MWL}})</td>
<td>Stability requirement</td>
</tr>
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European Laser Timing (ELT)

Detector package
500 grams
0.6 Watt
ELT EM Time stability
Entire chain Laser+Start+NPET+ELT EM

100 Hz, 8%, 3 days span +/- 1 K

<table>
<thead>
<tr>
<th>Tau</th>
<th>Sigma</th>
</tr>
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<tbody>
<tr>
<td>2.80e+01</td>
<td>2.25e+00</td>
</tr>
<tr>
<td>5.60e+01</td>
<td>1.59e+00</td>
</tr>
<tr>
<td>1.12e+02</td>
<td>1.14e+00</td>
</tr>
<tr>
<td>2.24e+02</td>
<td>7.91e-01</td>
</tr>
<tr>
<td>4.48e+02</td>
<td>5.81e-01</td>
</tr>
<tr>
<td>8.96e+02</td>
<td>4.14e-01</td>
</tr>
<tr>
<td>1.79e+03</td>
<td>2.76e-01</td>
</tr>
<tr>
<td>3.58e+03</td>
<td>1.83e-01</td>
</tr>
<tr>
<td>7.17e+03</td>
<td>1.37e-01</td>
</tr>
<tr>
<td>1.43e+04</td>
<td>1.45e-01</td>
</tr>
<tr>
<td>2.87e+04</td>
<td>1.92e-01</td>
</tr>
<tr>
<td>5.73e+04</td>
<td>1.05e-01</td>
</tr>
</tbody>
</table>

Time Deviation, EsE (EtE), picoSeconds

Averaging Time, EtE, Seconds
ELT SPAD Detector – Temperature Stability

![Image of SPAD detector setup]

![Image of temperature stability graph]

**Graph:**
- **Detection delay [ps]:** 3960 to 4030
- **Internal temperature HK [Celsius]:** -60 to 60
- **Mean slope:** 0.48 ps/K
- **Temperature stability:**
  - 0.38 ps/K
  - 0.75 ps/K

**Caption:**
- 0.75 ps/K
- 0.38 ps/K
Core Network of MWL GTs

+ 1 transportable MWL GT for calibration purposes

+ METAS (CH) + INRIM (IT) + Wettzell (DE)
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Gravitational Red-shift Measurements

Frequency shifts

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<th>Effect</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>First order Doppler effect</td>
<td>$2 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>Second order Doppler effect</td>
<td>$3 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>Gravitational red-shift</td>
<td>$5 \cdot 10^{-11}$</td>
</tr>
<tr>
<td>Sagnac effect</td>
<td>$7 \cdot 10^{-13}$</td>
</tr>
</tbody>
</table>

\[
\frac{d\tau_g}{dt} - \frac{d\tau^s}{dt} = \frac{1}{c^2} \cdot \left( U(t, \bar{x}_s^\tau) - U(t, \bar{x}_g^\tau) + \frac{v_s^2(t)}{2} - \frac{v_g^2(t)}{2} \right) + O(c^{-4})
\]
Relativistic geodesy: mapping of the Earth gravitational potential based on the precision measurement of the red-shift experienced by two clocks at two different locations

- ACES will perform intercontinental comparisons of optical clocks at the $10^{-17}$ level after 1 week of integration time, measuring the local height of the geoid at the 10 cm level.
- The global coverage offered by ACES will complement the results of the CHAMP, GRACE, and GOCE missions.
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**Fundamental physics tests**
Fundamental Constants

Frequency of hyperfine transitions:

\[ \nu_{\text{hfs}}^{(i)} \approx R_{\infty} c \times A_{\text{hfs}}^{(i)} \times g^{(i)} \left( \frac{m_e}{m_p} \right) \alpha^2 F_{\text{hfs}}^{(i)}(\alpha) \]

Frequency of electronic transitions:

\[ \nu_{\text{elec}}^{(i)} \approx R_{\infty} c \times A_{\text{elec}}^{(i)} \times F_{\text{elec}}^{(i)}(\alpha) \]

Ratios between atomic frequencies:

\[
\begin{align*}
\frac{\nu_{\text{elec}}^{(ii)}}{\nu_{\text{elec}}^{(i)}} & \propto \frac{F_{\text{elec}}^{(ii)}(\alpha)}{F_{\text{elec}}^{(i)}(\alpha)} \\
\frac{\nu_{\text{hfs}}^{(ii)}}{\nu_{\text{elec}}^{(i)}} & \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F_{\text{hfs}}^{(ii)}(\alpha)}{F_{\text{elec}}^{(i)}(\alpha)} \\
\frac{\nu_{\text{hfs}}^{(ii)}}{\nu_{\text{hfs}}^{(i)}} & \propto \frac{g^{(ii)} F_{\text{hfs}}^{(ii)}(\alpha)}{F_{\text{hfs}}^{(i)}(\alpha)}
\end{align*}
\]

Sensitivity to time variations of fundamental constants:

\[
\delta \ln \left( \frac{\nu_{\text{hfs}}^{(i)}}{R_{\infty} c} \right) \approx \frac{\delta g^{(i)}}{g^{(i)}} + \frac{\delta (m_e/m_p)}{(m_e/m_p)} + \left( 2 + \alpha \frac{\partial}{\partial \alpha} \ln F_{\text{hfs}}^{(i)}(\alpha) \right) \times \frac{\delta \alpha}{\alpha}
\]

\[
\delta \ln \left( \frac{\nu_{\text{elec}}^{(i)}}{R_{\infty} c} \right) \approx \left( \alpha \frac{\partial}{\partial \alpha} \ln F_{\text{elec}}^{(i)}(\alpha) \right) \times \frac{\delta \alpha}{\alpha}
\]
...but $g^{(i)}$ and $m_p$ are not “fundamental” constants as they depend on
- QCD mass scale $\Lambda_{\text{QCD}}$
- Quark mass $m_q = (m_u + m_d)/2$

Therefore comparisons of atomic frequency will test the time stability of the three fundamental constants

In general

$$\delta \ln \left( \frac{\nu^{(i)}}{R_\infty c} \right) \simeq K^{(i)}_\alpha \times \frac{\delta \alpha}{\alpha} + K^{(i)}_q \times \frac{\delta (m_q/\Lambda_{\text{QCD}})}{(m_q/\Lambda_{\text{QCD}})} + K^{(i)}_e \times \frac{\delta (m_e/\Lambda_{\text{QCD}})}{(m_e/\Lambda_{\text{QCD}})}$$

$K^{(i)}_\alpha \neq 0, K^{(i)}_q \neq 0, K^{(i)}_e \simeq 1$  
$K^{(i)}_\alpha \neq 0, K^{(i)}_q \simeq 0, K^{(i)}_e \simeq 0$  
$K^{(i)}_\alpha \simeq 0, K^{(i)}_q \simeq 0, K^{(i)}_e \simeq 1/2$

hyperfine transitions  
electronic transition  
vibrational transitions in molecules

V.V. Flambaum, arxiv:physics/0302015  
Fundamental Constants
## ACES and Fundamental Physics Tests

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Special Relativity Tests

**Kinematic test theories (RMS framework):** Preferred reference frame (CMB) in which light is assumed to propagate isotropically

**Dynamic test theories (SME framework):** Lorentz transformations violating terms in the Hamiltonian of the system

Measurement principle:
- Exchange of microwave signals between ACES clocks and ground clocks along the ISS orbit
- Difference of measured reception and emission times provides the one-way travel time of the signal plus some unknown constant offset (desynchronization, path asymmetries, propagation delay …)
- Difference of the up and down travel times sensitive to a non zero value of $\frac{\delta c}{c}$

$$T_1 - T_2 = \Delta_s + \Delta_l + 2 \frac{\delta c}{c} T \cos \theta$$

$$\left( T_1 - T_2 \right) - \left( T_3 - T_4 \right) + \Delta_a = 2 \frac{\delta c}{c} T \left( 1 - \cos \theta \right)$$

P. Wolf, PRA 51, 5016 (1995)
Beyond ACES: Space Optical Clocks

- Atomic clock fractional frequency instability at the quantum projection noise limit:
  \[ \sigma_y(\tau) = \frac{1}{\pi} \frac{\Delta \nu}{\nu_0} \frac{1}{\sqrt{N_{at}}} \sqrt{\frac{T_c}{\tau}} \]
  - \( \Delta \nu \sim 1 \text{Hz} \), limited by the interaction time
  - \( N_{at} \sim 10^6 \), limited by cooling and trapping techniques, collisions, etc.

- From the microwave to the optical domain
  - Frequency instability is inversely proportional to \( \nu_0 \): optical transitions show a potential increase of almost 5 orders of magnitude
    • Microwave fountain clocks: \( \sigma_y(\tau) = 10^{-14} \tau^{-1/2} \)
    • Optical clock: \( \sigma_y(\tau) = 10^{-18} \tau^{-1/2} \)
  - Accuracy: \( 10^{-18} \)

- Technical issues and solutions
  - Measurements of optical frequencies \( \rightarrow \) fs frequency-comb generator
  - Recoil and Doppler effect \( \rightarrow \) trapped ion clock or lattice clock
  - Reference oscillator noise \( \rightarrow \) better clock lasers and reference cavities

**SOC as ACES follow-on mission**

Sr lattice clock with \( 1 \cdot 10^{-17} \) fractional frequency instability and inaccuracy