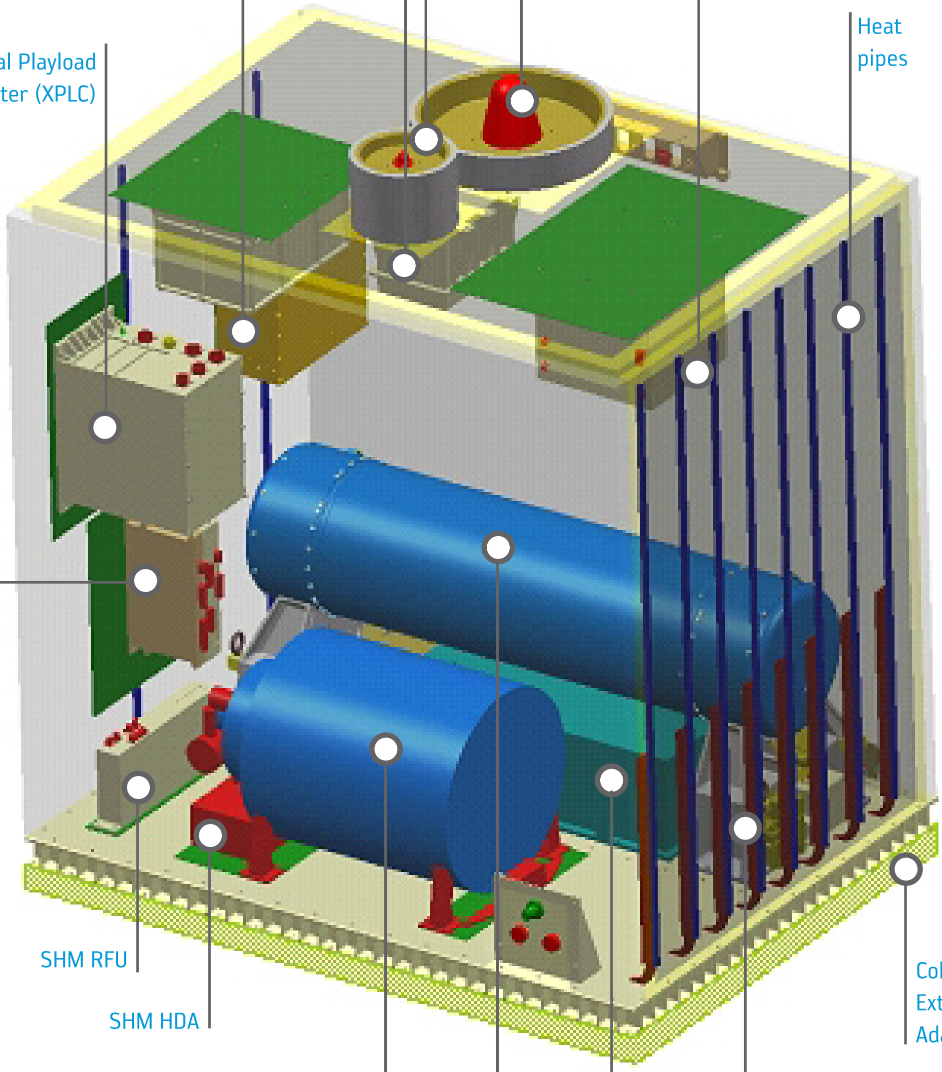
→ ATOMIC CLOCK ENSEMBLE IN SPACE (ACES)

Operation of ultra-stable clocks on the ISS

ACES will bring a new generation of atomic clocks in the microgravity environment of the ISS. The ACES payload will distribute a stable and accurate time base that will be used for space-to-ground as well as ground-to-ground clock comparisons. The direct comparison of ultra-precise atomic clocks is crucial for the exploitation of ACES potential in different areas of research: fundamental physics (General Relativity and String Theory tests), and time and frequency metrology, but also geodesy and gravimetry precise orbit determination, Earth monitoring, Very Long Baseline Interfrometry, global positioning and navigation.



esa	PROJECT:	International Space Station	
TITLE: Atomic Clock Ensemble in Space (ACES)		DOCUMENT N°: ESA-HSO-COU-020	REV. 2.0

ERASMUS Centre - Directorate of Human Spaceflight and Operations

Operations and Utilisation

ACES is a complex payload, involving both state-of-the-art instruments and subsystems. The heart of the payload is represented by an atomic clock based on laser cooled Caesium atoms. The performances of the Caesium frequency standard PHARAO are combined with the characteristics of a Space Hydrogen Maser. The ACES clock signal merges together the good short and medium term frequency stability of SHM with the long term stability and accuracy of a primary frequency standard based on Caesium cold atoms. The on-board clock-to- clock comparison (PHARAO-SHM) and the distribution of the clock signal are ensured by the so called Frequency Comparison and Distribution Package (FCDP), while all data handling processes are controlled by the eXternal PayLoad Computer (XPLC). One of the main objectives of the ACES mission consists in maintaining a stable and accurate onboard timescale that can be used for space-to-ground as well as ground-to-ground comparisons of frequency standards. Stable and accurate time and frequency transfer is achieved by using a specially developed state-of-the-art microwave link (MWL), which is necessary not only to characterise the ACES clocks ensemble, but also to perform general relativity tests of high scientific relevance.

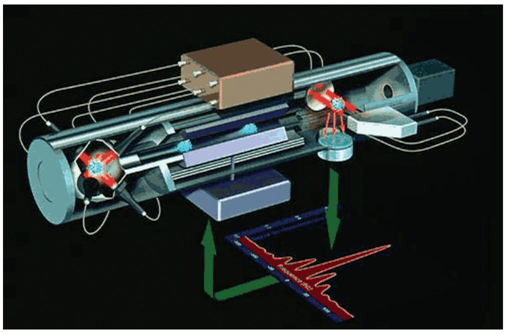
PHARAO

Projet d'Horloge Atomique Par Refroidissement d'Atomes En Orbite - a laser cooled atomic clock, developed by CNES, France.

PHARAO is a microgravity Caesium clock based on laser cooled atoms. It is developed by SYRTE, LKB, and funded by CNES. Its operation is very similar to ground based atomic fountains. Atoms launched in free flight cross two microwave cavities tuned to the hyperfine transition between the two energy levels of the Caesium ground state. The interrogation method, based on two separate oscillating fields (Ramsey scheme), allows for the detection of an atomic line whose typical width is inversely proportional to the transit time between the two microwave cavities. The resonant microwave field at 9.192631770 GHz (SI definition of the second) is synthesized starting from an ultrastable quartz oscillator and stabilized on the clock line using the error signal generated by the Caesium resonator. In this way, the intrinsic qualities of the Caesium hyperfine transition in terms of accuracy and frequency stability are transferred to the microwave oscillator.

In a microgravity environment, the velocity of atoms along the tube axis is constant and can be selected over almost two orders of magnitude (5 - 500 cm/s). Therefore, very long interaction times (up to few seconds) are possible, while keeping reasonable the size of the instrument.

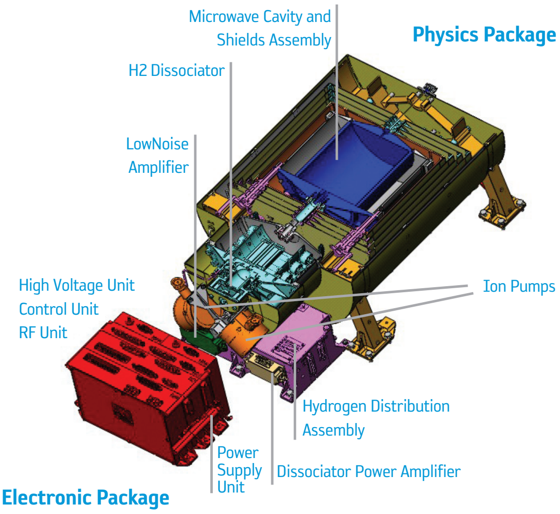
PHARAO will provide a 100 MHz clock signal with fractional frequency instability and accuracy at the 10-16 level.



SHM

The Space Hydrogen Maser is developed by Spectratime, Switzerland.

Hydrogen maser performances do not depend on the microgravity environment. However, because of their simplicity and predicted reliability, H-masers are expected to be key instruments in future satellite positioning systems and other science missions such as, ultra-high resolution space-space VLBI ("Very Long Baseline Interferometry") experiments. H-masers are based on the hyperfine transition of atomic hydrogen at 1.420405751 GHz. H2 molecules are dissociated by a plasma discharge and the resulting beam of H atoms is state selected and sent to a storage bulb. The bulb is made of a sapphire which loads a microwave cavity that, tuned on the resonance frequency, supports the maser action.



The ACES mission will be a test-bed for the space qualification of the active hydrogen maser. The onboard frequency comparison between SHM and PHARAO will be a key element for the evaluation of the accuracy and the short/medium-term stability of the Caesium clock. Further, it will allow to identify the optimal operating conditions for PHARAO and to select a good compromise between frequency accuracy and stability.

FCDP AND THE ACES CLOCK SIGNAL

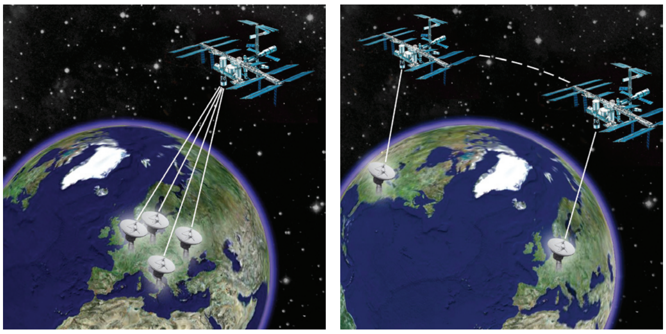
The Frequency Comparison and Distribution Package (FCDP), developed by EADS under ESA responsibility is the node of the atomic clock ensemble. PHARAO and SHM 100 MHz clock signals are delivered to FCDP and compared in both frequency and phase. The direct comparison of the two clocks has two purposes: to drive the short term servo loop for phase locking PHARAO local oscillator onto SHM and to evaluate the onboard clock stability. Finally, FCDP distributes the ACES clock signal to MWL.

THE ACES MICROWAVE LINK MWL

The MWL is a key element of the ACES mission. Developed by EADS under ESA responsibility, it ensures stable frequency transfer for direct comparison of atomic clocks on very long distances. MWL will allow both space-to-ground as well as ground-to-ground clock comparisons. Direct comparisons of ground clocks at a high level of stability will be possible using both the common view and the non-common view technique.

ACES scientific objectives

MISSION OBJECTIVES ACES PERFORMANCE	
Test of a new generation of space clocks	
Cold atoms in a micro-gravity environment	Study of cold atom physics in microgravity.
Test of the space cold	PHARAO performances: frequency stability better than 3 x 10-16 clock PHARAO at one day and accuracy at the 10-16 atom level. The short-term frequency stability will be evaluated by direct comparison to SHM. The long term stability and the systematic frequency shifts will be measured by comparison to ultra-stable ground clocks.
Test of the Space Hydrogen Maser SHM	SHM performances: frequency stability better than 2.1 x 10-15 at 1,000 s and 1.5 x 10-15 at 10,000 s. The medium term frequency instability will be evaluated by direct comparison to ultra-stable ground clocks. The long-term stability will be determined by the on-board comparison to PHARAO.
Precise frequency transfer	
Test of the MWL performance	Time transfer stability will be better than 0.3 ps over one ISS pass, 6 ps over 1 day, and 23 ps over 10 days.
Time and frequency comparisons between ground clocks	Common view comparisons will reach an uncertainty level below 1 ps per ISS pass. Non common view comparison will be possible at an uncertainty level of: 2 ps for τ = 1,000 s 5 ps for τ = 10,000 s 20 ps for τ = 1 day
Absolute synchronisation of ground clocks	Absolute synchronisation of ground clock time scales with an uncertainty of 100 ps.
Contribution to atomic time scales	Comparison of primary frequency standards with accuracy at the 10-16 level.
Fundamental physics tests	
Measurement of the gravitational red shift level	The uncertainty on the gravitational red-shift measurement will be below 50 x 10-6 for an integration time corresponding to one ISS pass (~ 300 s). With PHARAO full accuracy, uncertainty will reach the 2x 10-6.
Search for a drift of the fine structure constant with different atoms	Time variations of the fine structure constant α can be measured at the level of precision α-1 x dα / dt < 1 x 10-16 year-1. The measurement requires comparisons of ground clocks operating.
Search for Lorentz transformation ground of SME	Measurements can reach a precision level of δc / c ≈ 10-10 in the search for anisotropies of the speed of light. These measurements rely on the time stability of SHM, PHARAO, MWL, and clocks over one ISS pass.



Common view (left) and non common view comparisons (right).

SCIENTIFIC BACKGROUND

In 1967, the second - as one of the base units in the International System of Units SI - was defined as the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the Caesium-133 atom.

The extremely high accuracy possible for the second using the measurement of atomic frequencies gives the second a privileged role among all the other units, and justifies it's use in the definition of many secondary SI units.

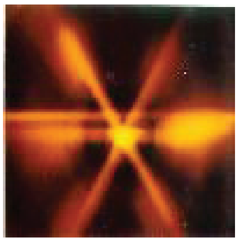
THE ATOMIC FOUNTAIN CLOCK

Atomic clocks based on Cs atoms are commonly called primary frequency standards because they are used for the operative definition of the SI Second . At present the most stable and accurate clocks are represented by atomic fountains based on laser cooled atoms. The working principle is shown in the figure. Atoms produced by a Caesium oven are used to load an optical molasses. Due to the interaction of the atom laser field, the kinetic energy of atoms is dissipated and temperatures in the µK region can be reached. The cold atom sample is launched upwards and during it's ballistic flight interacts twice with a field produced by a microwave resonator, once on the way up, once on the way down. The microwave field, almost resonant with the transition between the two hyperfine levels of the ground state excites the atoms. The relative population of the hyperfine levels is finally measured downstream by collecting the fluorescence light induced by the interaction with a probe laser beam. When the microwave field is resonant with the 9192631770 Hz transition, the population of atoms excited in the upper hyperfine level is a maximum. This signal is used to actively control the synthesizer driving the microwave field in the cavity. In a microgravity environment interaction times can be much larger than on Earth, and therefore much narrower lines can be detected on the clock transition.

Operations and Utilisation

LASER COOLING

Laser cooling is a technique that uses light to cool atoms to a very low temperature. The simplest form of laser cooling is referred to as optical molasses, since the dissipative optical force resembles the viscous drag on a body moving through molasses.



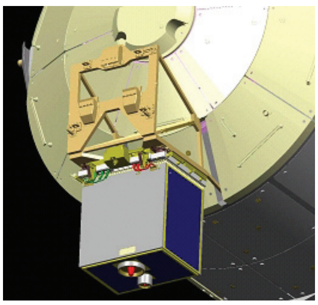
This technique works by tuning the frequency of light slightly below an electronic transition in the atom. Because the light is detuned to the "red" (i.e. at lower frequency) of the transition, the atoms will absorb more photons if they move towards the light source, due to the Doppler effect. Thus if one applies light from two opposite directions, the atoms will always scatter more photons from the laser beam pointing opposite to their direction of motion. In each scattering event the atom loses a momentum equal to the momentum of the photon. If the atom, which is now in the excited state, emits a photon spontaneously, it will be impacted by the same amount of momentum but in a random direction. The result of the absorption and remission process is to reduce the speed of the atom, provided its initial speed is larger than the recoil velocity from scattering a single photon. If the absorption and emission are repeated many times, the mean velocity, and therefore the kinetic energy of the atom will be reduced. Since the temperature of an ensemble of atoms is a measure of the average internal kinetic energy, this is equivalent to cooling the atoms.

ACCOMMODATION & TRANSPORT

ACES is scheduled for a late-2013 launch to the station aboard a Japanese HTV unmanned cargo carrier. The Station's robotic arm will transfer ACES to the nadir (Earth-pointing) position on the Columbus External Payload Facility.

OPERATIONAL CONCEPT

The stable and accurate time delivered by ACES will be used to perform space-to-ground as well as ground-to-ground clock comparisons. This information, together



The ACES payload accommodated on the Columbus External Payload Facility. MWL antennas pointing towards the Earth are visible.

with payload telemetry, ISS ancillary data and precise orbit determination data will be collected by the facility responsible centre, elaborated and made available for fundamental physics studies and other applications, e.g. time and frequency metrology, geodesy.

The ACES mission consists of three operational phases: commissioning and in-orbit validation, payload characterisation, and utilisation.

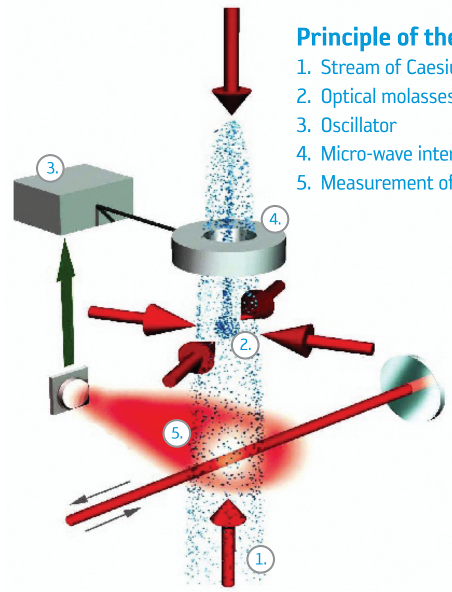
The first phase lasts several weeks and is concluded by the successful validation of payload.
During the second phase which will last 6 months PHARAO performances will be evaluated. The Caesium clock will be characterised through the on-board comparison with SHM (short term) and space-to-ground clock comparison (long term).
In the utilisation phase, PHARAO parameters will be set at their optimal values and the links will be synchronised in order to have an ACES time base with the best performance both on the short, medium and long-term. During this phase the ACES time scale will be compared with the ground clocks.

UTILISATION SCENARIO

Unique to ACES is the possibility for a worldwide participation to the data exploitation programme through a global array of ground users interested in comparing their ground-based atomic clocks with the ACES clock signal and in analysing the scientific data. This is organised by the ACES International Working Group.

SCHEDULE

The validation and utilisation phase is scheduled for 18 months. The first 6 months will be dedicated to characterizing and evaluating the clocks and the Time & Frequency (T&F) link, followed by its utilisation phase, including a demonstration of T&F distribution involving users around the world. ACES operation can be extended to 30 months.
ACES is scheduled to be launched in 2013.



Principle of the atomic fountain

1. Stream of Caesium atoms
2. Optical molasses
3. Oscillator
4. Micro-wave interactions
5. Measurement of fluorescence

Illustrations: ESA/D. Ducros