Cold Atom Clocks in Microgravity: The ACES Mission

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Abstract
Atomic Clock Ensemble in Space (ACES) is a mission in fundamental physics which will operate a new generation of atomic clocks in the microgravity environment of the International Space Station. Designed to be installed at the external payload facility of the Columbus module, ACES will accommodate the cold-atom clock PHARAO and the active hydrogen maser SHM. The on-board time scale will reach fractional frequency instability and inaccuracy of few parts in $10^{16}$. The ACES clock signal will be distributed on Earth by a link in the microwave domain and used for the comparison of atomic frequency standards, both space-to-ground and ground-to-ground. Based on these comparisons, ACES will perform accurate tests of Einstein’s theory of general relativity and develop applications in time and frequency metrology, global positioning and navigation, geodesy, and gravimetry. After a general overview of the mission concept and its scientific objectives, the present status of the ACES mission is discussed.

1. Mission overview

Atomic Clock Ensemble in Space (ACES)\(^1\)\(^2\) is a mission in fundamental physics based on the performances of a new generation of atomic clocks operated in the microgravity environment of the International Space Station (ISS). The station is orbiting at a mean elevation of 400 km with 90 min. of rotation period and an inclination angle of 51.6°. Transported on orbit by the Japanese transfer vehicle HTV, ACES will be installed at the external payload facility of the Columbus module (Fig. 1) using the Space Station robotic arm.

The ACES payload accommodates two atomic clocks: PHARAO (acronym of “Projet d’Horloge Atomique par Refroidissement d’Atomes en Orbit”), a primary frequency standard based on samples of laser cooled cesium atoms, and SHM, an active hydrogen maser for space applications. The performances of the two clocks are combined together to generate an on-board timescale with the short-term stability of SHM and the long-term stability and accuracy of the cesium clock PHARAO. The on-board comparison of PHARAO and SHM and the distribution of the ACES clock signal are ensured by the Frequency Comparison and Distribution Package (FCDP), while all data handling processes are controlled by the eXternal PayLoad Computer (XPLC). A GNSS receiver installed on the ACES payload and connected to the on-board time scale will provide precise orbit determination of the ACES clocks. One of the main objectives of the ACES mission consists in maintaining a stable and accurate on-board timescale which will be used to perform space-to-ground as well as ground-to-ground comparisons of atomic frequency standards. The ACES clock signal will be transferred on ground by a time and frequency transfer link in the microwave domain (MWL). MWL compares the ACES frequency reference to ground clocks worldwide distributed, enabling fundamental physics tests and applications in different areas of research.

The planned mission duration is 18 months. During the first two months, the functionality of the clocks and of MWL will be tested. Then, a period of 4 months will be devoted to the performance evaluation of the clocks. During this phase, a clock signal with frequency inaccuracy in the $10^{-15}$ range will be available to ground users. The microgravity environment will allow to tune the linewidth of the atomic resonance of the PHARAO clock by two orders of magnitude, down to sub-Hertz values (from 11 Hz to 110 mHz). After the clocks optimization, performances in the $10^{-16}$ range both for frequency instability and inaccuracy are expected. In the second part of the mission (12 to 30 months),
the on-board clocks will be compared to a number of atomic clocks operating both in the microwave and optical domain. The recent development of optical frequency combs\cite{3,4}, awarded with the 2005 Nobel Prize in Physics, significantly simplifies the link between optical and microwave frequencies. In this context, ACES will perform worldwide comparisons of advanced clocks operating on different atoms or molecules with $10^{-17}$ frequency resolution. These measurements will search for new physics and new interactions beyond the Standard Model.

2. ACES scientific objectives

The worldwide access and the microgravity conditions offered by the space environment make of ACES a unique facility. ACES will conduct the first experiments with cold atoms in a freely falling laboratory, it will perform fundamental physics tests to high resolution, and develop applications in different areas of research.

A new generation of clocks reaching frequency instability and inaccuracy of few parts in $10^{16}$ will be validated by ACES. PHARAO will combine laser cooling techniques and microgravity conditions to significantly increase the interaction time and consequently reduce the linewidth of the clock transition. Improved stability and better control of systematic effects will be demonstrated in the space environment. PHARAO will reach a fractional frequency instability of $1 \cdot 10^{-13} \tau^{-1/2}$, where $\tau$ is the integration time expressed in seconds, and an inaccuracy of few parts in $10^{16}$. The reliability offered by active H-masers will be made available for space applications by SHM. SHM will demonstrate a fractional frequency instability of $1.5 \cdot 10^{-15}$ after only 10000 s of integration time. Two servo-loops will lock together the clock signals of PHARAO and SHM generating an on-board time scale combining the short-term stability of the H-maser with the long-term stability and accuracy of the cesium clock (Fig. 2).

This clock signal will be distributed by MWL. Frequency transfer with time deviation better than 0.3 ps at 300 s, 7 ps at 1 day, and 23 ps at 10 days of integration time will be demonstrated. These performances, surpassing existing techniques (TWSTFT and GPS) by one to two orders of magnitude, will enable common view and (TWSTFT and GPS) by one to two orders of performances, surpassing existing techniques integration time will be demonstrated. These

![Fig. 2 Expected fractional frequency instability of PHARAO, SHM, and of the ACES clock signal.](image)

In addition, ACES will deliver a global atomic time scale with $10^{-16}$ accuracy, it will allow clock synchronization at an uncertainty level of 100 ps, and contribute to international atomic time scales (TAI, UTC…).

These performances will be used to test Einstein’s theory of general relativity to high accuracy. With the progress recently achieved by clocks in the optical domain, accuracy levels even higher than originally foreseen will be reached.

According to Einstein’s theory, identical clocks placed at different positions in stationary gravitational fields experience a frequency shift that, in the frame of the PPN approximation, depends directly on the Newtonian potential at the clock position. The comparison between the ACES on-board clocks and ground-based atomic clocks will measure the frequency variation due to the gravitational red-shift with a 35-fold improvement on previous experiments\cite{5}, testing Einstein’s prediction at the 2 ppm uncertainty level.

Time variations of fundamental constants can be measured by comparing clocks based on different transitions or different atomic species\cite{6}. Any transition energy can be expressed in terms of the fine structure constant $\alpha$ and the two dimensionless constants $m_\mu/\Lambda_{QCD}$ and $m_e/\Lambda_{QCD}$, depending on the quark mass $m_\mu$, the electron mass $m_e$ and the QCD mass scale $\Lambda_{QCD}\cite{7,9}$. ACES will perform crossed comparisons of ground clocks both in the microwave and in the optical domain with a resolution of $1 \cdot 10^{-17}$ in few days of integration time. These comparisons will impose strong and unambiguous constraints on time variations of fundamental constants reaching an uncertainty of $1 \cdot 10^{-17}$/year in case of a 1-year mission duration and $3 \cdot 10^{-18}$/year after three years.

The foundations of special relativity lie on the hypothesis of Local Lorentz Invariance (LLI). According to this principle, the outcome of any local
test experiment is independent of the velocity of the freely falling apparatus. In 1997, LLI tests based on the measurement of the round-trip speed of light have been performed by comparing clocks on-board GPS satellites to ground hydrogen masers. In such experiments, LLI violations would appear as variations of the speed of light c with the direction and the relative velocity of the clocks. ACES will perform a similar experiment by measuring relative variations of the light velocity at the $10^{-10}$ uncertainty level.

Other applications of the ACES clock signal are currently under investigation. ACES will demonstrate a new “relativistic geodesy” which, based on a precision measurement of the Einstein’s gravitational red-shift, will resolve differences in the Earth gravitational potential at the 10 cm level. ACES will contribute to the improvement of the global navigation satellite systems (GNSS) and to their future evolution. Better clocks and high-performance time and frequency transfer techniques will be available for space applications. New concepts for global positioning systems based on a reduced set of ultra-stable space clocks in orbit associated with simple transponding satellites could be studied. Finally, ACES could be used to demonstrate new methods for monitoring the oceans surface based on scatterometry measurements of the GNSS signal and to contribute to the analysis of the Earth atmosphere through radio-occultation experiments.

3. ACES status

The ACES Mission is presently in C/D phase. All instruments and subsystems are in an advanced status of development with engineering models delivered or in final assembly.

The ACES Mission Preliminary Design Review has been successfully concluded consolidating the overall mission concept, demonstrating the feasibility of instruments and subsystems, and confirming the design of the flight hardware.

3.1 PHARAO

PHARAO is a cesium clock based on laser cooled atoms developed by SYRTE, LKB, and CNES. Its concept is very similar to ground based atomic fountains, but with a major difference: PHARAO will be operated under microgravity conditions. Atoms, launched in free flight along the PHARAO tube, cross a resonant cavity where they interact two times with a microwave field tuned on the transition between the two hyperfine levels of the cesium ground state. The interrogation method, based on two spatially separated oscillating fields (Ramsey scheme), allows the detection of an atomic line whose width is inversely proportional to the transit time between the two interaction regions. In a microgravity environment, the velocity of the atoms along the ballistic trajectories is constant and can be continuously changed over almost two orders of magnitude (5-500 cm/s) allowing the detection of atomic signals with sub-Hertz linewidth.

The cesium clock PHARAO is composed of four main subsystems: the cesium tube, the optical bench, the microwave source, and the computer control.

The engineering model of the PHARAO clock has been completed and is presently under test at CNES premises in Toulouse. Design and recent results are presented in 11). Cesium atoms have been loaded in the optical molasses, cooled down to few μK, interrogated on the clock transition by the resonant microwave field, and detected by light-induced fluorescence emission. Microwave resonance signals (Ramsey fringes) with a signal-to-noise ratio of ~700 have been recorded demonstrating the correct interfacing of PHARAO subsystems and the correct operation of the clock. For a launch velocity of 3.42 m/s, the duration of the free flight between the two Ramsey interaction regions is about 100 ms, corresponding to a typical width of the central fringe of about 5 Hz. When operated in microgravity, the longer interaction times will allow PHARAO to measure linewidths 10 to 50 times narrower. Fig. 4 shows preliminary measurements of the clock performances. A fractional frequency instability of $2.3 \times 10^{-13} \tau^{-1/2}$ can be measured for integration times $\tau$ between 1 s and $10^3$ s when the PHARAO microwave source is driven by an external cryogenic oscillator. This situation closely approaches the specified stability of $1 \times 10^{-13} \tau^{-1/2}$ reachable in a microgravity environment. The result is in agreement with theoretical predictions based on atom number and cycle duration. When the microwave source is driven by its internal ultra-stable quartz oscillator,
the measured stability is \(4 \times 10^{-13} \cdot \tau^{-1/2}\). This value is set by the phase noise of the quartz oscillator which is sampled by the atoms in the microwave cavity (Dick effect). In space, this effect will be reduced by one order of magnitude because of the much narrower resonance width.

Functional and performance tests on the PHARAO clock are presently ongoing. In the coming months, the clock stability and accuracy will be evaluated.

3.2 SHM

Because of their simplicity and reliability, hydrogen masers are used in a large variety of applications. Passive and active masers are expected to be key instruments in future space missions, satellite positioning systems, and high-resolution VLBI (Very Long Baseline Interferometry) experiments.

The clock operates on the hyperfine transition of atomic hydrogen at 1.420405751 GHz. H₂ molecules are dissociated in a plasma discharge and the resulting beam of H atoms is state selected and sent in a storage bulb. The bulb is surrounded by a sapphire-loaded microwave cavity which, tuned on the atomic resonance, induces the maser action.

SHM is composed of an electronic package (EP) and a physics package (PP). The heart of the physics package is represented by the microwave cavity. The main elements of the electronics package are the RF unit, the power supply unit, and the SHM controller.

The engineering model of SHM PP (Fig. 5) has successfully completed a series of functional and performance tests in combination with the maser electronics developed at the Observatoire de Neuchâtel (ON). The fractional frequency instability of the combined system has been measured, demonstrating performances in agreement with the specified values (Fig. 6). At the same time, accurate measurements have verified that the thermal control system of the maser cavity is able to ensure the expected temperature stability of 1 mK. These preliminary tests have been crucial both to verify SHM physics package and to validate the design of the maser electronics: mainly the RF receiver locking SHM local oscillator to the atomic signal and the automatic cavity tuning (ACT) system which corrects the resonance frequency of the maser cavity against temperature drifts.

The engineering model of SHM EP is presently under completion.

3.3 FCDP

The Frequency Comparison and Distribution Package (FCDP) is the central node of the ACES payload. Developed by ASTRIUM and Timetech under ESA management, FCDP is the on-board
hardware which compares the signals delivered by the two space clocks, measures and optimizes the performances of the ACES frequency reference, and finally distributes it to the microwave link.

Ultra-low phase noise electronics is extremely important to distribute and characterize the signal of high-performance atomic clocks. This technology is now available in a compact system, ready to be used for space applications.

The engineering model of the ACES FCDP has been completed (Fig. 7) and tested. The noise introduced by FCDP on the distributed clock signal rapidly averages down entering the $10^{-18}$ regime already after $10^4$ s of integration time. Fig. 8 shows the Allan deviation of the noise floor of FCDP phase comparator. The curve decreases as the inverse of the integration time, dropping below $1 \cdot 10^{-17}$ for $\tau > 10^4$ s.

In addition, a specific test has been conducted at CNES premises in Toulouse to validate the performances of the phase-locked loop which stabilizes the local oscillator of PHARAO on the clock signal generated by SHM. The microwave source of PHARAO has been phase-locked via FCDP to the clock signal provided by a cryogenic sapphire oscillator (CSO). The excellent short-term stability of the CSO is crucial for correctly identifying the noise contribution of FCDP when the servo-loop is closed. Fig. 9 shows the Allan deviation plot of the PHARAO microwave source phase-locked to the cryogenic sapphire oscillator and measured against the CSO itself (circles). Measurements are compared to the simulated behavior (squares), to the Allan deviation of the free-running microwave source of PHARAO (triangles), and to the expected performances of the PHARAO clock (solid line). Parameters for the servo-loop transfer function. Finally, the microwave source of PHARAO has been stabilized on the clock signal generated by a H-maser using loop parameters very close to what expected for ACES.

FCDP engineering model will be formally delivered after testing it together with the PHARAO and SHM clocks.

3.4 MWL

The ACES clock signal distributed by FCDP is finally transmitted to ground stations by the ACES microwave link. MWL is developed by ASTRIUM, Kayser-Threde, and Timetech under ESA management. The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976.

The system operates continuously with a carrier
The high carrier frequency of the up- and down-links allows for a noticeable reduction of the ionospheric delay. A third frequency in the S-band is used to determine the ionosphere Total Electron Content (TEC). A PN-code modulation of the carrier removes the phase ambiguity between successive comparison sessions separated by large dead times. The system is designed for multiple access capabilities, allowing up to 4 simultaneous ground users distinguished by the different PN-codes and Doppler shifts.

The engineering model of the MWL flight segment electronic unit has been completed and is presently under test. Code and carrier phase stability determine the performance levels achievable in the comparisons of distant clocks. MWL long-term stability is ensured by the continuous calibration of the receiver channels provided by a built-in test-loop translator. For shorter durations (~300 s, corresponding to the ISS pass duration), time stability is driven by the noise performance of the Ku transmitter and receiver boards and the reproducibility of each DLL channel after proper calibration of internal delays.

Preliminary measurements of the code and carrier phase stability have been performed on the engineering model of the flight segment electronic unit. The PN modulated signal, directly derived from the reference clock, is distributed to the transmitter, up-converted to the Ku-band, and fed to the Ku-band receiver via an internal test-loop. After down conversion the signal is finally locked by the DLL to the local clock. The 100 MHz chip rate allows to reach a time stability below 2 ps already with code measurements. However, the full performance level is provided by the carrier phase measurements. As shown in Fig. 10, time deviations below 0.2 ps can be observed on the carrier phase even in the worst conditions of signal to noise density ratio (C/N). The long-term stability of the system is presently under characterization.

### 3.5 ACES ground segment

The architecture of the ACES ground segment has been designed. The ACES USOC (Users Support and Operations Center) will operate the payload via the Columbus control center, it will remotely control the MWL ground terminals, receive telemetry and scientific data, and finally analyze and distribute them to the scientific community.

The physical interfaces towards the Columbus control center, the MWL ground terminals, the ground clocks, and the ACES service providers (precise orbit determination, data analysis, technical and scientific support…) have been identified.

On the basis of the scientific and engineering tasks needed, a mission operations concept has been defined. It includes the planning, the execution, the evaluation, the exploitation, and the support needed during the complete life-cycle of ACES.

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