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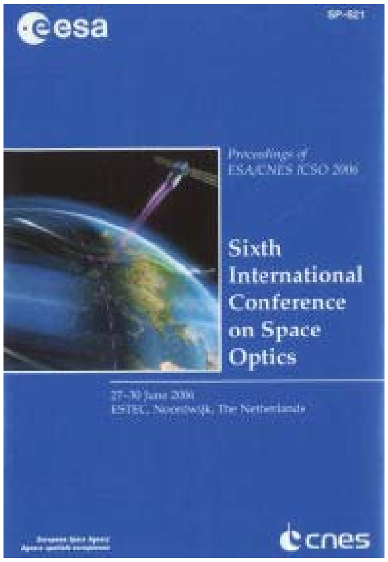

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THE ACES MISSION: SCIENTIFIC OBJECTIVES AND PRESENT STATUS

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ABSTRACT

“Atomic Clock Ensemble in Space” (ACES) is a mission in fundamental physics that will operate a new generation of atomic clocks in the microgravity environment of the International Space Station (ISS).
The ACES clock signal will combine the medium term frequency stability of a space hydrogen maser (SHM) and the long term stability and accuracy of a frequency standard based on cold cesium atoms (PHARAO). Fractional frequency stability and accuracy of few parts in 10^{16} will be achieved. The on-board time base distributed on Earth via a microwave link (MWL) will be used to test fundamental laws of physics (Einstein’s theories of Special and General Relativity, Standard Model Extension, string theories…) and to develop applications in time and frequency metrology, universal time scales, global positioning and navigation, geodesy and gravimetry.
After a general overview on the mission concept and its scientific objectives, the present status of ACES instruments and sub-systems will be discussed.

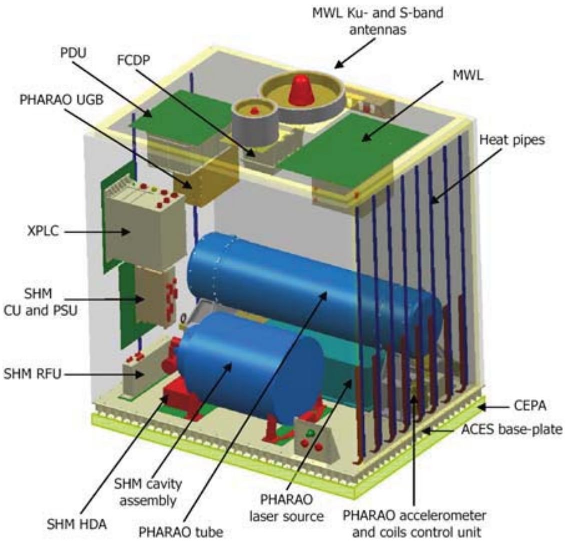

Fig. 1. The ACES payload. Instruments and subsystems fit into a thermally regulated payload with a total mass of 227 kg and a power consumption of 450 W.

1. INTRODUCTION

“Atomic Clock Ensemble in Space” (ACES) [1] is a mission in fundamental physics whose main objective is to demonstrate the performances of a new generation of atomic clocks in the microgravity environment of the International Space Station (ISS).
Scheduled for launch in 2010, ACES will be accommodated on-board the ISS, on the External Payload Facility of the Columbus module. The station is orbiting at a mean elevation of 400 km with 90 min. period and an inclination angle of 51.6°.
ACES is a complex payload, involving both state-of-the-art instruments and subsystems (see Fig. 1). The heart of the payload is represented by an atomic clock based on laser cooled cesium atoms. The performances of the cesium frequency standard PHARAO (acronym of “Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbit”, developed by CNES) are combined with the characteristics of a Space Hydrogen Maser (SHM, developed by Neuchâtel Observatory). The ACES clock signal will therefore merge together the good short and medium term frequency stability of hydrogen masers with the long term stability and accuracy of a primary frequency standard based on cold atoms. The on-board clock-to-clock comparison (PHARAO-SHM) and the distribution of the clock signal are insured by the 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 on-board timescale that can be used for space-to-ground as well as ground-to-ground comparisons of frequency standards. Stable and accurate time and

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frequency transfer is achieved by using a MicroWave Link (MWL), which is necessary not only to characterize the ACES clocks ensemble, but also to perform general relativity tests of high scientific relevance.

The planned mission duration is 18 months. During the first 6 months, the performances of SHM and PHARAO will be established. Thanks to the microgravity environment the line-width of the atomic resonance will be varied by two orders of magnitude (from 11 Hz to 110 mHz). Performances in the 10^{-16} regime both for frequency instability and inaccuracy are expected. In the second part of the mission, the onboard clocks will be compared to a number of ground based clocks operating both in the microwave and the optical domain.

2. ACES INSTRUMENTS AND SUBSYSTEMS

2.1 The cesium clock PHARAO

PHARAO is a cesium clock based on laser cooled atoms developed by SYRTE, LKB, and 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 energy levels of cesium ground state. The interrogation method, based on two separate oscillating fields (Ramsey scheme), allows 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 a 100 MHz quartz oscillator and stabilized on the clock line using the error signal generated by the cesium resonator. In this way, the intrinsic qualities of the cesium hyperfine transition, both in terms of accuracy and frequency stability, are transferred to the macroscopic oscillator.

In a microgravity environment, the velocity of atoms along the ballistic trajectories is constant and can be changed continuously 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 of $1 \cdot 10^{-13} \cdot \tau^{-1/2}$ on the integration time τ (Fig. 3) and inaccuracy at the 10^{-16} level. Further, the error signal generated by the cesium resonator will be send to XPLC, processed, and used to correct SHM for frequency drifts. PHARAO will also provide all the frequency correction parameters necessary to evaluate the clock accuracy.

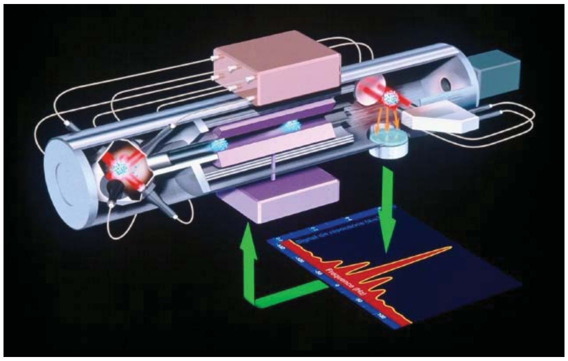

Fig. 2. The cesium frequency standard PHARAO.

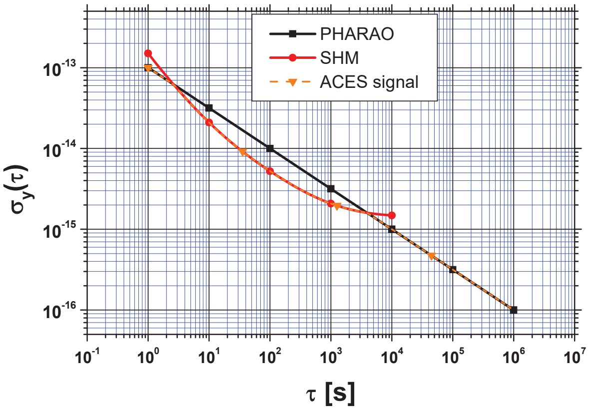

Fig. 3. Expected fractional frequency instability of PHARAO, SHM, and of the ACES clock signal. The ACES clock signal will combine the short/medium term stability of SHM with the good long term stability of PHARAO.

According to ACES mission objectives, PHARAO performances will be verified through preliminary tests on ground and a full in-flight validation. During the mission both the long term stability and the accuracy of the clock will be continuously updated.

2.2 The Space Hydrogen Maser SHM

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 space missions, satellite positioning systems, and ultra-high resolution VLBI (“Very Long Baseline Interferometry”) experiments.

H-masers are based on the hyperfine transition of atomic hydrogen at 1.420405751 GHz. H_2 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 that, tuned on the resonance frequency, induces the maser action.

The ACES mission will be a test-bed for the space qualification of the active hydrogen maser SHM developed by the Neuchâtel Observatory (ON). 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 cesium clock. Further, it will allow to identify the optimal operating conditions for PHARAO and to choose the right compromise between frequency accuracy and stability.

SHM will provide a clock signal at 100 MHz with the following fractional frequency instability (Fig. 3):

$$\sigma_y^{SHM}(\tau = 1\ \text{s}) = 1.5 \cdot 10^{-13}$$

$$\sigma_y^{SHM}(\tau = 10\ \text{s}) = 2.1 \cdot 10^{-14}$$

$$\sigma_y^{SHM}(\tau = 100\ \text{s}) = 5.1 \cdot 10^{-15}$$

$$\sigma_y^{SHM}(\tau = 1000\ \mathrm{s}) = 2.1 \cdot 10^{-15}$$

$$\sigma_y^{SHM}(\tau = 10000\ \mathrm{s}) = 1.5 \cdot 10^{-15}.$$

The demonstration of these performances, both with ground based tests and an on-flight calibration procedure, is one of ACES primary mission objectives.

2.3 The microwave link MWL

MWL is key element of the ACES mission. Developed by EADS under ESA responsibility, it ensures stable and accurate time and frequency transfer for direct comparison of atomic clocks on very long distances. MWL will allow to perform both space-to-ground as well as ground-to-ground clock comparisons. In particular, 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.

The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976 [2]. The system operates continuously with a carrier frequency in the Ku band of about 15 GHz. The high carrier frequency of the up- and down-link allows for a noticeable reduction of the ionospheric delay. A third frequency in the S band is used to determine the ionosphere TEC. A PN-code phase measurement 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.

Due to the ISS orbit, time and frequency transfer will be possible only for periods of short duration (~ 300 s). This condition defines the MWL performances on the short term. The noise introduced by the link must be minimized on the ISS single pass duration. As measurements rely on phase comparisons, white phase noise is assumed to limit the performances of MWL for integration times $10\ \mathrm{s} \le \tau \le 300\ \mathrm{s}$. Therefore, short term frequency instability has to satisfy the following requirement:

$$\sigma_x^{MWL}(10\ \mathrm{s} \le \tau \le 300\ \mathrm{s}) \le 4.1 \cdot 10^{-12} \cdot \tau^{-1/2},$$

corresponding to

$$\sigma_x^{MWL}(\tau = 300\ \mathrm{s}) \le 0.24\ \mathrm{ps}.$$

Long term frequency stability of the microwave link is necessary over an integration time from one to ten days. Assuming that MWL exhibits white frequency noise behavior for durations longer than 1000 s,

$$\sigma_x^{MWL}(\tau > 1000\ \mathrm{s}) \le 1.7 \cdot 10^{-14} \cdot \tau^{1/2},$$

corresponding to

$$\sigma_x^{MWL}(\tau = 1\,\mathrm{day}) \le 5.1\ \mathrm{ps},$$

$$\sigma_x^{MWL}(\tau = 10\ \mathrm{day}) \le 16.2\ \mathrm{ps}.$$

The direct comparison between ACES and a ground clock will be performed both on-board the ISS and on ground. Data will allow to calculate the cumulative stability of the two clocks, including the corrections for all propagation error terms.

3. ACES SCIENTIFIC OBJECTIVES

ACES will demonstrate the high performances of a new generation of atomic clocks in the microgravity environment of the ISS. Based on the direct comparison of the ACES clocks and ground based clocks, accurate tests of Einstein's theory of General Relativity and of the Standard Model Extension will be performed. The mission has four main objectives:

1. Demonstrate the high performances of a new generation of clocks for space applications: the cold cesium atoms clock PHARAO will allow to reach fractional frequency instabilities below $1 \cdot 10^{-13} \cdot \tau^{-1/2}$ with an inaccuracy at the $1 \cdot 10^{-16}$ level (refer to [3] for recent progress on ground-based atomic fountain clocks); the space hydrogen maser SHM will ensure a mid term frequency instability of $1.5 \cdot 10^{-15}$ at 10000s of integration time.
2. Demonstrate frequency transfer capability 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 (performances of present time and frequency transfer systems can be found in [4]).
3. Deliver a global atomic time scale and perform direct comparisons of ultra-stable clocks at the 10^{-16} level on a worldwide basis.
4. Perform fundamental physics tests:
   - Accurate measurement of the gravitational red-shift: The comparison between the space clock and ground-based atomic clocks will allow to measure the frequency variation due to the gravitational red-shift with a relative frequency uncertainty of $3 \cdot 10^{-6}$, improving previous measurements by a factor 25 [2,5,6].
   - Measurement of time variations of the fine structure constant: This experiment is based on the direct comparison of clocks working on different atomic species as a function of time (see also [7]); the measurement will establish strong constraints on the time variations of α allowing a direct test of the Einstein's Equivalence Principle at the level

     $$1/\alpha \cdot d\alpha/dt < 10^{-16}/\mathrm{year}.$$
   - Tests of the Standard Model Extension [8,9,10]: The measurement of the propagation delay of electromagnetic signals between the ISS and the ground stations located all around the Earth will test the validity of Special Relativity; using ultra-stable atomic clocks, it will be possible to detect relative variations of the speed of light at the level

     $$\delta c / c < 10^{-10}.$$

Other applications of the ACES clock signal are currently under investigation. ACES will improve the accuracy of the atomic time and will contribute to the definition of global time scales (TAI, UTC…). Third generation of navigation systems will benefit from the technology development related to the ACES mission: better clocks and high-performance time and frequency transfer systems will be soon available. 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. Moreover, a new kind of gravimetry and geodesy based on the accurate measurement of the Einstein's gravitational red-shift will be demonstrated.

4. PRESENT STATUS OF THE ACES MISSION

The ACES Mission is in C/D phase. All instruments and subsystems are in an advanced status of development with engineering models presently under manufacturing and test. In September 2006, ACES will undergo the Preliminary Design Review (PDR) which will consolidate the overall mission concept, the status of instruments and subsystems, and will decide on the development of the flight models.

4.1 Status of the PHARAO clock

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 models, contracted to different manufacturers, have been completed, successfully tested, and delivered. The PHARAO clock, fully assembled at CNES premises in Toulouse, is presently under test. Cesium atoms have been loaded in the optical molasses, cooled down, and detected. The sample of cold atoms, launched along the PHARAO tube, has been probed on the clock transition by using the PHARAO hyperfrequency source. Ramsey fringes have been successfully recorded, demonstrating the correct interfacing of PHARAO subsystems and the correct operation of the clock. After these preliminary functional tests, the performance verification campaign will evaluate the clock stability and accuracy.

4.2 SHM status

SHM is composed of an electronic package (EP) and a physics package (PP). The heart of the physics package is represented by a sapphire-loaded microwave cavity responsible for stimulating maser action in the hydrogen atoms contained in the storage bulb. The main elements of the EP are the RF unit, the power supply unit, and the SHM controller.

The key elements of SHM PP engineering model have been manufactured and assembled. At present, SHM PP is undergoing functional and performance tests in combination with a development model of the maser electronics manufactured at ON. The measurements performed have already demonstrated the correct operation of the automatic cavity tuning system. ON electronics correctly recover frequency drifts of the cavity resonance induced by temperature variations. First Allan deviation measurements show that the engineering model of SHM PP, in combination with the development model of maser electronics, performs correctly, meeting the specifications both on short and long integration times. The engineering model of SHM EP is presently under development and test. Once delivered SHM will be fully assembled and end-to-end tests will evaluate the clock performances.

4.3 MWL and FCDP status of the

The MWL development model has been manufactured and successfully tested. In particular, specific tests related to the operation of the delay locked loop have been successfully concluded, demonstrating the adequacy of the present design. The MWL engineering model will be complete by the end of this year, when functional and performance tests will take place.

A crucial element of the ACES payload is represented by the FCDP. This subsystem has two main functions: it will distribute the clock signal to the MWL and it will compare and phase-lock the two clocks PHARAO and SHM. The FCDP engineering model has been completed and tested. The performances of the device are very satisfactory. In the next months an integrated test involving FCDP, a ground maser, and a cryogenic sapphire oscillator will be performed at CNES premises in Toulouse to validate the servo loop that will lock PHARAO on the SHM clock signal.

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