Mission Concept and Scientific Objectives

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1 INTRODUCTION

Atomic Clocks Ensemble in Space (ACES) is an ESA mission in fundamental physics based on the operation of high stability and accuracy atomic clocks in the microgravity environment of the International Space Station (ISS). The time scale generated by the ACES clocks on-board the ISS is delivered on Earth through a high-performance two-way time and frequency transfer link (Figure 1). The clock signal is used to perform space-to-ground as well as ground-to-ground comparisons of atomic frequency standards.

Figure 1: The ACES mission. Ultra-stable atomic clocks on-board the International Space Station are compared to a network of ground clocks through a high performance two-way time transfer system.

ACES scientific objectives cover both fundamental physics and applications. In fundamental physics, a new type of atomic clock using laser cooled atoms will be operated in microgravity with $10^{-16}$ relative frequency stability and accuracy. Tests of Special and General Relativity with improved precision will be performed as well as a search for temporal variations of fundamental constants. In the application domain, frequency comparisons between distant clocks both space-
to-ground and ground-to-ground will be performed worldwide with unprecedented resolution. ACES will demonstrate a new type of “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. Finally, ACES will contribute to the improvement of the global navigation satellite systems (GNSS) and to future evolutions of these systems. It will demonstrate new methods for monitoring of the oceans surface based on scatterometric measurements of the GNSS signal and it will contribute to the monitoring of the Earth atmosphere through radio-occultation experiments.

The progress of scientific research since the selection of ACES in 1997 and the mission launch date, presently scheduled in 2014, have led the ACES Science Team to revisit the initial ACES mission objectives in the frame of the recent scientific context and its possible evolution at the time of the mission. This report presents an analysis of the ACES mission in light of the recent advances in the fields of fundamental physics and time and frequency metrology.

After a short introduction presenting the programmatic evolution of the ACES project (Section 2), the mission concept and the payload architecture are discussed (Section 3). This information provides the background necessary to present and review the ACES scientific objectives (Section 4). Finally, the present status of the various mission elements is described in Section 5.
2 HISTORICAL BACKGROUND

A group of several proposals [RD1,RD2], dealing with the joint international project “Atomic Clock Ensemble in Space” (ACES), was submitted in response to the ESA Announcement of Opportunity, issued in December 1996, for externally mounted payloads [RD3] within the ISS utilization program.

The proposals were evaluated by an external peer review panel in terms of scientific and technical merit, as well as of their relevance for microgravity research. Considered as one of the most exciting microgravity experiments ever conceived, ACES was accredited with the highest scientific merit [RD4,RD5].

In November 2000, the payload could no longer be accommodated within the allocated resources budget and it was necessary to de-scope some of its elements. In April 2001, the ACES Steering Committee members accepted as baseline a payload configuration composed of [RD6]:

- The primary frequency standard PHARAO, acronym of “Projet d’Horloge Atomique par Refroidissement d’Atomes en Orbit”, developed in France and provided by CNES
- The Space Hydrogen Maser SHM, developed in Switzerland and provided by the Neuchâtel Observatory (ON)
- The on-board Frequency Comparison and Distribution Package (FCDP)
- The time and frequency transfer link in the microwave domain MWL
- The Command and Data Handling Unit (CDHU) and the Power Distribution Unit (PDU) as support equipment.

Before starting the C/D phase, the accommodation of the payload was re-oriented from the NASA developed Express Pallets System to the External Payload Facilities of the Columbus module (CEPF). Analysis showed that the Express Pallets Adapter (ExPA) was not compatible with the CEPF interface. As a consequence, it was necessary to develop a dedicated Columbus External Payload Adapter (CEPA).

The delays recently incurred in the development of ACES clocks resulted in a launch readiness date not compatible anymore with a Shuttle flight because of the intention manifested by NASA to phase out the Shuttle fleet in 2010. Following these contingencies, during the Mission Preliminary Design Review (September 2006), it was decided to redesign the ACES launch and on-orbit accommodation scenario, based on the utilization of the JAXA transfer vehicle HTV.

According to the present schedule, the ACES payload will be ready for launch in 2014.
3 THE ACES MISSION

3.1 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). Scheduled for launch in the 2014 time frame, ACES will be accommodated on-board the ISS, on the External Payload Facility of the Columbus module (Figure 2).

The station is orbiting at a mean elevation of 400 km with 90 min of rotation period and an inclination angle of 51.6°. ACES is composed of a flight payload and ground terminals mainly located in advanced time and frequency laboratories. The payload occupies a volume of about 1 m$^3$ and involves both state-of-the-art instruments and subsystems (Figure 3). The heart of the payload is represented by a primary 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"), provided by CNES (France), are combined to the characteristics of a Space Hydrogen Maser (SHM), developed by Neuchâtel Observatory (Switzerland). The ACES clock signal will therefore merge together the good medium-term frequency stability of the hydrogen maser 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 ensured 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 frequency transfer is achieved by using a MicroWave Link (MWL). MWL will compare the ACES clocks with ground clocks and enable fundamental physics tests as well as applications in different areas of research.

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 linewidth of the atomic resonance will be varied by two orders of magnitude (from 11 Hz to 110 mHz). Performances in the $10^{-16}$ range both for frequency stability and accuracy are expected. In the second part of the mission, the o-board clocks will be compared to a number of ground based clocks operating both in the microwave and optical domain. The recent development of optical frequency combs [3,4], subject of the 2005 Nobel Prize in physics to T. Hänsch and J. Hall, significantly simplifies the link between the optical and microwave domains. 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 currently accepted four fundamental interactions.
Figure 2: The ACES payload installed at the External Payloads Facility of the Columbus module. The two microwave antennas pointing to Earth are visible.

Figure 3: The ACES payload. Instruments and subsystems fit into a thermally regulated payload with a volume of about 1 m$^3$, a total mass of 227 kg, and a power consumption of 450 W.
3.2 ACES Instruments and Subsystems

3.2.1 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 the major difference of zero-g operation. Atoms slowly launched in free flight cross two microwave fields tuned to the transition between the two hyperfine levels of the cesium ground state (Figure 4). The interrogation method, based on two separate oscillating fields (Ramsey scheme), allows the detection of an atomic line whose 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 quartz oscillator and stabilized to 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). Differently from atomic fountain clocks presently operated on ground, very long interaction times (up to few seconds) will be possible, while keeping reasonable the size of the instrument.

Figure 4: Principle of the cesium frequency standard PHARAO. Cesium atoms are cooled to 1 \( \mu \text{K} \), loaded in an optical molasses (left side of the drawing) and launched along the vacuum tube. During their ballistic flight, the atomic sample crosses two Ramsey interrogation regions where atoms are probed on the clock transition by a microwave field. Two resonant laser beams orthogonal to the atomic trajectories (right end of the tube) detect the population of the two hyperfine levels. Finally, the error signal derived from the atomic line is used to tune the microwave field in resonance with the clock transition.
PHARAO will provide a clock signal with fractional frequency instability below $1 \cdot 10^{-13} \cdot \tau^{-1/2}$, where $\tau$ represents the integration time in seconds (Figure 5), and inaccuracy in the $1 \cdot 10^{-16}$ regime. The error signal generated by the cesium resonator will be sent to XPLC, processed, and used to correct SHM for long-term frequency drifts. PHARAO will also provide all the frequency correction parameters necessary to evaluate the clock accuracy. According to ACES mission objectives, PHARAO performances will be verified through preliminary tests on ground and a full in-flight validation.

![Figure 5: Expected instability of PHARAO, SHM, and of the ACES clock signal expressed in Allan deviation ($\sigma_y$) and time deviation ($\sigma_x$). The ACES clock signal will combine the short and medium term frequency stability of SHM with the long term stability and accuracy of a primary frequency standard based on laser cooled cesium atoms.](image-url)
3.2.2 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 that, tuned on the resonance frequency, induces the maser action (Figure 6).

```
   σ_y^{SHM}(τ = 1 s) = 1.5 \cdot 10^{-13}
   σ_y^{SHM}(τ = 10 s) = 2.1 \cdot 10^{-14}
   σ_y^{SHM}(τ = 100 s) = 5.1 \cdot 10^{-15}
   σ_y^{SHM}(τ = 1000 s) = 2.1 \cdot 10^{-15}
   σ_y^{SHM}(τ = 10000 s) = 1.5 \cdot 10^{-15}
```

Figure 6: Schematics of the ACES Space Hydrogen Maser.

The ACES mission will be a test-bed for the space qualification of the active hydrogen maser SHM developed by the Neuchâtel Observatory. The on-board 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 (see Figure 5):
The demonstration of these performances, both with ground based tests and an on-flight calibration procedure, is one of ACES primary mission objectives.

3.2.3 FCDP

The Frequency Comparison and Distribution Package (FCDP) is the central node of the ACES payload. Developed by ASTRIUM and TimeTech under ESA responsibility, FCDP is the on-board hardware that compares the signals delivered by the two space clocks, measures and optimizes the performances of the ACES clock signal, and finally distributes it to the microwave link (Figure 7).

![Figure 7: Block diagram showing FCDP main functions.](image)

The 100 MHz clock signals generated by PHARAO and SHM are sent to the inputs of FCDP and, selected by a series of high isolation RF switches, are addressed to the TEST, the MWL, and the SPARE outputs. TEST outputs are used for on-ground tests to verify FCDP performances. When active, the SPARE output sends the SHM 100 MHz clock signal to the microwave frequency synthesis chain of the PHARAO clock, bypassing the PHARAO local oscillator (a 5 MHz ultra-stable quartz). The MWL output is directly connected to the microwave link electronics which finally transfers the ACES clock signal to Earth.

Using the dual mixer time difference method, FCDP performs an on-board comparison of the cesium clock PHARAO and the space hydrogen maser SHM. The measurement of the relative phase is used to determine the combined Allan deviation of the two clocks and, at the same time, to drive a phase locked loop that stabilizes the phase of the PHARAO local oscillator on the SHM 100 MHz clock signal (short-term servo loop). The servo loop, with a typical time constant of a few seconds, provides the overall ACES clock signal with the outstanding stability of SHM on short and medium integration times (Figure 5). Both the phase comparison and the servo control are implemented in compact Field Programmable Gate Arrays (FPGA’s).

In parallel, a dual balanced mixer circuit measures the relative phase of PHARAO and SHM when the phase locked loop is closed. This signal is sampled and stored in a RAM, before being
processed according to the FFT algorithm which, hard coded in a second FPGA, measures the power spectral density of the two on-board clocks.

FCDP contribution to the noise of the delivered clock signal and to the comparison of the two on-board clocks is required to be 10 times smaller than the noise of the least noisy of the ACES clocks, both in terms of phase noise power spectral density and in terms of Allan variance for integration times between 1 s and 10 days. These performances have been carefully tested and verified on the engineering model of FCDP.

3.2.4 MWL

The ACES clock signal distributed by FCDP is finally transmitted to ground stations by MWL. MWL is developed by ASTRIUM, Kayser-Threde, and TimeTech under ESA responsibility. The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976 [5].

The system operates continuously with a carrier frequency in the Ku band (about 15 GHz). 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 phase measurement removes the phase ambiguity between successive comparison sessions separated by large dead times. The system is designed for

![Signal link design of the ACES MWL.](image-url)
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 continuous 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. Depending on the latitude, the ISS has typically 5 useful passes on a given ground terminal. As measurements rely on phase comparisons, white phase noise is assumed to limit the performances of MWL for integration times $\tau$ between 10 s and 300 s. MWL performances for short integration times shall fulfill the following requirement:

$$\sigma^\text{MWL} (10 \text{ s} \leq \tau \leq 300 \text{ s}) \leq 4.1 \cdot 10^{-12} \cdot \tau^{-1/2},$$

corresponding to a time deviation of 0.24 ps at 300 s of integration time.

Clock-to-clock comparisons in the $10^{-17}$ regime can be possible only if the link has an excellent long-term stability (up to 10 days of integration time). Assuming that MWL exhibits a white frequency noise behavior for durations longer than 1000 s,

$$\sigma^\text{MWL} (\tau > 1000 \text{ s}) \leq 1.7 \cdot 10^{-14} \cdot \tau^{1/2},$$

corresponding to 5.1 ps at 1 day and 16.2 ps at 10 days of integration time.

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 and of course relativistic effects.

### 3.2.5 XPLC

Developed by ASTRIUM under ESA responsibility, XPLC is the on-board computer that ensures control, monitoring, telemetry, and telecommand management for all ACES instruments and equipment.

Besides the standard function of an on-board computer, XPLC plays a major role in ACES operations since it is directly involved in the servo loop signals generation and distribution. XPLC computes the frequency correction signal used to steer SHM on the discrimination signal generated by the PHARAO cesium resonator. This frequency locked loop, commonly called long-term servo loop, provides the ACES clock signal with the long-term stability and accuracy of PHARAO (see Figure 5). At the same time, XPLC transmits the data elaborated by the FCDP short-term servo loop to phase lock PHARAO local oscillator on SHM (see also Section 3.2.3). These data are sent to PHARAO at 4 Hz rate using a specific link.

All telecommands are dated when leaving XPLC. Similarly, the computer defines a time tag for all telemetry data when entering XPLC.
3.2.6 PDU

The Power Distribution Unit is developed by ASTRIUM under ESA responsibility. The device distributes the power supply to the instruments and the subsystem of the ACES payload. All power lines are independent so that any failure propagation is avoided.
4 ACES SCIENTIFIC OBJECTIVES

The scientific objectives of the ACES mission are described in [RD7]. They cover three important areas of research:

- High performance atomic clocks for space applications;
- High performance time and frequency transfer;
- Precision tests of fundamental laws of physics.

The ACES Science Team has recently revisited the mission objectives projecting them in the context of the scientific progress expected at the time of the mission.

In this Section, we show that the recent advances in the field of atomic clocks and precision measurements have increased the interest of the ACES mission objectives. In particular, the progress of optical clocks on the one hand and the outstanding performances of the ACES microwave link on the other hand will significantly enrich the scientific return of ACES. New applications in global positioning and navigation, geodesy, and Earth observation will be also discussed.

For convenience, we will adopt the scheme presented in RD7, following the enunciation given there both for primary (#PO) and secondary (#SO) ACES mission objectives.

4.1 Primary Mission Objectives

4.1.1 TEST OF A NEW GENERATION OF SPACE CLOCKS

#PO1.- It is a primary objective of the ACES mission to explore and demonstrate the high performance of a new generation of atomic clocks in the space environment and to demonstrate the ability to achieve high stability on time and frequency transfer.

ACES will be a test bench for the validation of a cold atom primary frequency standard, PHARAO, realizing in space the SI second. ACES will also validate an active hydrogen maser for space applications, SHM. The ACES clock signal will be transferred to ground via the high performance time and frequency transfer link MWL.

#PO1.1- Cold Atom Physics in Microgravity

The ACES mission will study the cooling and the manipulation of atoms with laser light in a microgravity environment.

The study of cold atom physics in microgravity will be an essential step both to optimize the performances of the ACES clock signal and to test techniques which will be crucial for the development of a second generation of atomic quantum sensors for space. ACES will pioneer these studies.

The space clock PHARAO is a primary standard based on samples of laser cooled cesium atoms which will demonstrate for the first time the potential of cold atoms in microgravity for the precision measurement of time and frequency. As explained above, the atomic sample, cooled
down to a temperature of 1 µK, is launched along the PHARAO vacuum tube. Because of the low thermal velocities, it will evolve freely for durations between 5 and 10 s (at least one order of magnitude longer than what is achievable on Earth). This corresponds to a significant increase of the interaction time between atoms and microwave field and therefore to the detection of very narrow lines on the clock transition. Colder samples also correspond to a higher number of detected atoms, equivalent to a higher signal-to-noise ratio and a lower quantum projection noise. Optimization of the cooling cycle will be crucial both to improve the clock stability and to study systematic frequency shifts affecting the clock accuracy (residual Doppler effect for instance). Differently from atomic fountains on Earth, the possibility to vary the atomic velocity over two orders of magnitude while keeping the external environment unchanged is specific to the PHARAO instrument.

These studies will be important for the design of new atomic quantum sensors for space applications. Ultra-cold temperatures and long interaction times possible under microgravity condition will produce instruments with outstanding performances for the measurement of time and frequency, accelerations, rotations, and faint forces. The expertise and know-how developed within the ACES mission will be made available for the second generation of atomic quantum sensors for space, already proposed by the scientific community within the ELIPS2 program: atomic clocks in the optical domain (ESA AO-2004-100), atom interferometry sensors for space applications (ESA AO-2004-64 and ESA AO-2004-82), and a facility for studying Bose-Einstein condensates in microgravity (ESA AO-2004-133). Europe has presently a leading role in the field of cold atom sensors for space, thanks to the close collaboration between scientists, ESA, and National Space Agencies on the ACES program.

#PO1.2- PHARAO Stability and Accuracy

The ACES mission will demonstrate that PHARAO stability, expressed in Allan deviation ($\sigma_y(\tau)$), is better than $1 \times 10^{-13} \tau^{-1/2}$ for an integration time $\tau$ up to 10 days (see Figure 5) and that its accuracy is better than $3 \times 10^{-16}$ with the goal of reaching an accuracy of $1 \times 10^{-16}$.

For many applications in fundamental physics, navigation, or geodesy, the clock performances in space are essential. The instruments on-board GPS and GALILEO satellites represent the state-of-the-art technology in terms of clocks for space applications. Compact rubidium and cesium clocks, specially developed for navigation satellites, show a fractional frequency instability at 1 s of $7 \times 10^{-15}$ and $5 \times 10^{-12}$ respectively, with a stability floor around $10^{-14}$. The ACES clock signal, combining the performances of PHARAO and SHM, will be 10 to 100 times more stable and accurate.

The accuracy evaluation of PHARAO requires the measurement of all frequency shifts with an uncertainty lower than $10^{-16}$. This goal will be achieved by using both SHM (to the $10^{15}$ level) and ultra-stable ground-based clocks via the microwave link (down to the $10^{-16}$ range). The characterization of PHARAO in microgravity will highlight major effects limiting the clock accuracy. The low and constant velocity of atoms in space and the associated long interaction times are extremely favorable factors for improving the clock accuracy. Collisions between cold atoms will be a particular point of interest as they directly affect the ultimate accuracy of cold cesium space clocks.
The PHARAO clock stability will be measured in two steps. The short and medium-term frequency stability will be evaluated by comparing PHARAO to SHM on-board the ISS. When the integration time is between 10 and 1000 s, SHM frequency stability is better than PHARAO one and the on-board comparison of the two clocks allows to fully characterize PHARAO. For integration times longer than 1000 s, PHARAO will be compared to ultra-stable ground atomic clocks located in several time and frequency laboratories around the world.

In the last decade, the accuracy and the stability of atomic frequency standards improved significantly. Cold atom fountain clocks using cryogenic oscillators have demonstrated performances comparable to ACES [6]. At the same time, frequency standards based on atoms or ions with transitions in the optical domain have already reached fractional frequency stability and accuracy of $\sim 7 \cdot 10^{-17}$ and keep promising even more ambitious targets (10$^{-18}$ range) [7]. Thus, it is clear that in the 2014-2015 time frame PHARAO will not be the most stable and accurate atomic clock. Such remarkable advances of ground clocks, that at first sight could reduce the interest in ACES, on the contrary provide an even stronger justification to the scientific case proposed by this mission. For the first time, ACES will be able to perform worldwide comparisons of ground clocks at the 10$^{-17}$ stability level (or better), taking full advantage of the outstanding performances of frequency standards in the optical domain. This will significantly improve tests on the time variation of fundamental constants. ACES will also allow relativistic geodesy at the 10 cm level, a scientific objective that was not part of the 1997 proposal, but emerged in the last two years within the ACES Science Team. Moreover, in 2014-2015 the PHARAO clock will still be the best primary frequency standard available, with a stability and accuracy of 1$\cdot 10^{-16}$. With these performances, ACES will give a remarkable contribution to the improvement of international atomic time scales.

Microwave clocks have reached nowadays a high degree of maturity. As already demonstrated by the tests performed on the engineering models both of PHARAO and SHM, such instruments are now ready for space. On the contrary, optical clocks have a much lower technology readiness level. Clocks in the optical domain presently operate in a laboratory environment, using advanced opto-electronics that still needs substantial efforts before being suitable for space applications. Space qualification of optical clock technology is a long-term program on which the Agency is presently investing resources to start prototyping activities. Atomic standards in the optical domain represent the future of time and frequency metrology in space, but, considering present technological and programmatic constraints, it is difficult to imagine such instruments ready for space applications before 2020. Furthermore, these optical clocks will certainly benefit from the know-how and expertise developed for ACES.

#PO1.3- Space Hydrogen Maser Short Term Stability

The ACES mission will demonstrate that SHM frequency stability, expressed in Allan deviation ($\sigma_y(\tau)$) is better than (see Figure 5):

\[
\begin{align*}
\sigma_y^{\text{SHM}}(\tau = 1 \text{ s}) &= 1.5 \cdot 10^{-13} \\
\sigma_y^{\text{SHM}}(\tau = 10 \text{ s}) &= 2.1 \cdot 10^{-14} \\
\sigma_y^{\text{SHM}}(\tau = 100 \text{ s}) &= 5.1 \cdot 10^{-15}
\end{align*}
\]
Active hydrogen masers are instruments widely used for metrological applications because of their reliability and their very good short and medium-term performances. A 200 kg maser has been launched to space in 1976 in the GPA experiment which still provides the best measurement to date of the Einstein’s gravitational red-shift [5].

ACES will validate in space a 38 kg and 40 W active hydrogen maser, demonstrating a frequency stability of $5.1 \cdot 10^{-15}$ at 100 s, down to $1.5 \cdot 10^{-15}$ at 10000 s of integration time. These performances will be measured by the on-board comparison to PHARAO for integration times $\tau > 3000$ s. In this region, PHARAO stability is much better than SHM one, allowing a complete characterization of the maser and of its long-term drift. Below 200 s, the on-board comparison of SHM and PHARAO will only give an upper limit for the maser stability. For time durations between 200 s and 2000 s, SHM will be compared to high stability clocks on ground via MWL. As SHM performances do not depend on gravity, the accurate evaluation of the clock on ground will provide a reference measurement during the on-orbit characterization of the instrument.

SHM plays a key role in the ACES mission as reference clock for the on-board characterization of PHARAO. The evaluation of PHARAO accuracy is performed through differential measurement to a stable reference. During the characterization phase, the PHARAO clock is alternatively operated on two different cycles in which a key parameter affecting one of the systematic frequency shifts is changed in a controlled way. The frequency measurement needs to be averaged on a number of PHARAO cycles and therefore requires a reference with very good short and medium-term frequency stability. This reference signal will be provided by SHM. Finally, the high reliability of the hydrogen maser is of key importance to establish the on-board time scale. SHM will act as a flywheel ensuring the phase continuity of the clock signal distributed by ACES.

ACES will represent a real breakthrough in terms of technological development of active hydrogen masers for space applications. SHM will exceed the performances of passive masers developed for GALILEO by at least one order of magnitude.

#PO1.4- Space-Ground Time and Frequency Transfer

The ACES mission will demonstrate the capability to perform phase/frequency comparison between space and ground clocks with a resolution at the level of 0.3 ps over one ISS pass (300 s), 7 ps over 1 day, and 23 ps over 10 days.

The ACES microwave link MWL represents a major step in time transfer methods. Designed to distribute the ACES clock signal, MWL is able to perform space-to-ground comparisons at the $10^{-17}$ fractional frequency instability level. Differently from GPS based techniques, MWL is a two-way system in which both the ground terminal and the space segment emit and receive microwave signals. This enables the cancellation of tropospheric fluctuations, ionospheric delays, and several other sources of technical noise.
Frequency comparisons between space and ground clocks depend on the time stability of the link during the pass duration of the ISS. Figure 9 reports the number of ISS passes over a ground station at a given latitude as a function of the visibility time. The analysis, performed over 30 days, shows that the typical duration of an ISS pass over a given ground station is between 300 and 400 s with about 5 useful ISS passes per day. MWL time fluctuations will be lower than 0.3 ps at 300 s, 7 ps at 1 day, and 23 ps at 10 days of integration time (see Figure 10). These performances exceed standard time and frequency transfer systems (TWSTFT, GPS CP, GPS P3) by at least a factor 50 [8,9].

![Figure 9: Number of ISS passes over a ground station at a given latitude as a function of the visibility time. The insert reports ISS passes over Paris (48° of latitude). The analysis has been performed over 30 days. The typical duration of an ISS pass over a given ground station is between 300 and 400 s.](image)

The two-way link used for the GPA experiment [5] demonstrated in 1976 a space-to-ground comparison of two hydrogen masers at the level of $8 \times 10^{-15}$ for an integration time of 1000 s. Two-way clock comparisons via satellite (TWSTFT) are regularly performed by metrological institutes using telecommunication satellites which however are not optimized for time transfer.

MWL design and implementation [RD8,RD9] draws on these resources and achievements, but with major improvements. The engineering model of the flight segment electronics unit has presently started its performance test campaign and the first results already confirm a performance level well compatible to requirements.
In the optical domain, the T2L2 (Time Transfer by Laser Link) instrument has performances comparable to the ACES MWL. T2L2, developed by the Observatoire de la Côte d’Azur (OCA) and CNES, was part of the 1997 ACES initial proposal, but was de-scoped in 2000. T2L2 will fly on Jason-2 to perform common view comparisons of distant clocks [10]. However, due to the modest stability of its local oscillator compared to SHM and PHARAO, T2L2 will not be able to perform competitive non-common view comparisons of clocks on intercontinental distances and, as all optical links, it will be able to operate only in conditions of clear sky.

ACES will allow comparisons of distant clocks in all weather conditions, thus gathering over the mission duration a considerable amount of data. Such comparisons will reach a stability level that will be hardly exceeded in the next 15 years. MWL performances have already attracted the interest of many metrology laboratories and research institutes (see Annex II) which will surely not miss the opportunity of using this system for clock comparisons on a worldwide basis. Beyond its key role in the ACES mission, MWL will also find important applications in future GNSS systems, in the comparison of atomic clocks on ground, and in geodesy. These applications are discussed in detail below.

4.1.2 TIME AND FREQUENCY COMPARISONS BETWEEN GROUND CLOCKS

#PO2.- *It is a primary objective of the ACES mission to demonstrate the capability to compare ground clocks at high accuracy level on a world-wide basis.*

ACES will perform comparisons of distant clocks both in common view and non common view with an unprecedented time stability level.
**PO2.1- Common View Ground Clock Frequency Comparison**

The ACES mission will demonstrate the capability to compare ground clocks in common view with a resolution better than 1 ps.

Due to the low orbit of the ISS and the limited duration of each pass, the common view technique will be suitable for comparing ground clocks over continental distances, for instance within Europe. In a common view comparison, the common mode noise of the on-board clock cancels out and only the link instability remains. With the ACES MWL, the standard deviation of the average time error between the on-board clock and a given ground clock is expected to be lower than 0.3 ps on the ISS pass duration (~300 s). Based on these performances, the time instability in a common view comparison of distant ground clocks will amount to $\sqrt{2} \cdot 0.3$ ps, equivalent to a frequency resolution of $1.4 \cdot 10^{-15}$ at 300 s of integration time. If the time delay between two channels of the MWL remains stable at this level, the resolution of the frequency comparison expressed in Allan standard deviation improves linearly with the time interval between measurements. In this case, as shown by the red curve in Figure 11, MWL will be able to perform common view comparisons of distant clocks below the $1 \cdot 10^{-17}$ level after one day of integration time, almost two orders of magnitude below the current GPS CP technique. During the mission duration, three to five common view comparisons per day will be performed between any pairs of clocks on the same continent (see Figure 12).

In 2006, GPS CP and TWSTFT have been used to compare ground clocks at the $5 \cdot 10^{-16}$ level after 30 hours of averaging time [9]. Expected (blue line) and measured (thick line in blue) performances of a time and frequency link based on the GPS CP technique are shown in Figure 11. The performances demonstrated by these links are still far from ACES and, to our knowledge, no upgrade of the GPS (or GALILEO) network is planned in a near future. Therefore, it is not at all obvious that GPS will reach the $1 \cdot 10^{-17}$ level in a reasonable averaging time to match the anticipated stability of optical clocks in 2014-2015.

Very recently, time transfer by optical fibers over 100-200 km has demonstrated $10^{-17}$ frequency resolution. This technique might be extended to ~1000 km using a sufficient numbers of repeaters and fiber noise cancellation systems, implying a substantial technical effort. It is clear however that such links will keep a regional character while ACES will be able to ensure worldwide coverage thanks to the low orbit and favorable inclination of the ISS. On the other hand, the local comparison between ACES MWL and fiber based systems will determine the ultimate operational performance of both links, an extremely important issue considering that the $10^{-17}$-$10^{-18}$ stability range is at the frontier of current research. Finally, coherent optical time transfer methods, recently developed by SYRTE-PTB-LPL in Europe and NIST-JILA in the USA, can readily be applied to satellite-satellite communication systems to achieve time and frequency transfer at the $10^{-18}$ level and prepare links of second generation for future space missions.
**Figure 11:** ACES expected performances in the common view (red line) and non common view (green line) frequency comparison of ground clocks. The thick line in blue shows the measured Allan deviation of the GPS CP as reported in [9]. The black line reports the Allan deviation as a function of the estimated duration of continuous operation for different clocks, as expected at the time of the ACES mission. The area below the black curve is not accessible because of the expected clock performances and technology. This curve has some arbitrary character, but reflects the fact that the most advanced laboratory prototypes are complex instruments with reduced continuous operation (half a day for instance) while clocks with more modest performance such as GPS clocks have continuous operation over several years. The expected performances of the ACES MWL in space will be between the red and the green curves, i.e a factor 20 to 50 below GPS CP.

**Figure 12:** Duration of common view events of the ISS between Paris and Firenze, Paris and Toulouse, Paris and Braunschweig. The analysis has been performed on a total duration of 30 days.
#PO2.2- Non-Common View Ground Clock Frequency Comparison

The ACES mission will demonstrate the capability to compare ground clocks in non common view with a resolution better than $10^{-13} \cdot \Delta t^{1/2}$ for $\Delta t > 1000$ s. That is, 3 ps and 10 ps for space-ground comparisons separated by 1000 s and 10000 s respectively.

This science objective takes full benefit of the excellent on-board time scale realized by the combination of SHM and PHARAO (see Figure 5). Indeed, in the non common view method, the on-board time scale error over the time interval between the two frequency comparisons (relativistic corrections included) must be added to the link noise budget. As an example, in case of two comparisons separated by half the orbital period (2700 s), the on-board timescale error, which amounts to less than 2 ps, shall be quadratically added to the 1.2 ps link error, which occurs twice. This leads to the green curve in Figure 11 showing ACES performance for the non common view comparison of distant clocks. Intercontinental comparisons of remote clocks via ACES can reach a frequency resolution of $10^{-17}$ at about one week of integration time. In practice, the mission analysis has shown that, depending on the site latitude, one or two comparisons per day occur with a time interval of less than 3000 seconds and several comparisons per day with longer time intervals (Figure 13). Therefore, multiple frequency comparisons between a variety of advanced ground clocks will be possible among the institutes which have manifested their interest to participate to the ACES mission. This has important consequences for the fundamental physics tests described below.

![Figure 13](image1.png)

**Figure 13:** Non common view comparisons between Paris and Perth occurring in 30 days. The dead time between the two space-to-ground comparisons corresponds to ~2000 s when Paris is acquired before Perth and ~3600 s when Perth is acquired before Paris. Non common view comparisons below 2000 s are not possible when the 2 ground terminals do not belong to the same hemisphere. Non common view comparisons above 3600 s are possible considering passes belonging to different orbits.
Time transfer systems based on GPS and GALILEO satellites or on TWSTFT could potentially compete with these performances. Despite of the fact that GPS is a one way system, because of the multiple satellite tracking and the large number of geodetic receivers measuring the GPS signal carrier phase, largely redundant data for the comparison of distant clocks exists. Numerical models then establish a global solution for the time evolution of the GPS satellite clock frequency, orbits, relativistic corrections, and ground clocks. Today, this method provides a frequency resolution of $5 \cdot 10^{-16}$ at one day, but an improvement by a factor 20 to 50 is still required to match the performances of the ACES MWL. Alternatively, averaging over much longer durations raises the problem of continuous operation of the ground optical clocks, which are still laboratory prototypes (limit indicated by the black curve in Figure 11). However, even at a level of $10^{-16}$ after 5 to 10 days of integration time, the global operational character of the GPS system can be an excellent complement to the existing ACES MWL.

A GALILEO/GPS receiver will be part of the ACES payload and directly connected to the ACES clock signal. The receiver will secure orbit determination and positioning at the required accuracy level. At the same time, it will make available the stable and accurate frequency reference delivered by ACES to a wider community interested in clock applications in different areas of research. The potential applications of ACES in combination with a GNSS receiver, were already proposed in the project “GALILEO on-board the International Space Station” (AO-2004-143) submitted to ESA in answer to the Announcement of Opportunity issued in 2004. They will be discussed in detail in Section 4.3.2.

4.1.3 FUNDAMENTAL PHYSICS EXPERIMENTS

#PO3. - It is a primary objective of the ACES mission to perform fundamental physics tests with large improvements in measurement precision.

These tests concern General Relativity (as the gravitational red-shift measurements and the search for possible time variations of fundamental physical constants) as well as Special Relativity (as the search for a possible anisotropy of the speed of light).

#PO3.1- Gravitational Red-shift

The ACES mission will measure the gravitational frequency red shift with a relative uncertainty of $3 \cdot 10^{-6}$ (improvement by a factor 25 over Gravitational Probe A).

As a direct consequence of Einstein’s Equivalence Principle (EEP), a source of radiation in a gravitational potential $U_s$ appears to an observer in a different gravitational potential $U_0$ shifted in frequency by an amount $\Delta f/f = -\Delta U/c^2$, where $\Delta U = U_s - U_0$ is the difference of the gravitational potential between the source and the observer positions.

The most accurate measurement of the gravitational red-shift was performed in 1976 by the GPA experiment [5]. GPA made a direct comparison of two hydrogen masers, one on ground, the other in a spacecraft launched nearly vertically upwards to an elevation of 20000 km. GPA measured both the relativistic second order Doppler effect and the gravitational red-shift to an uncertainty of $70 \cdot 10^{-6}$. 
ACES will perform a precision measurement of the gravitational red-shift using a different approach. Instead of modulating the red shift by changing the altitude of the satellite as done in the GPA experiment, ACES will use the high accuracy of the PHARAO clock ($10^{-16}$) and of ground clocks ($10^{-16}$ or better) to make an absolute measurement of the frequency difference. Knowing precisely the orbital parameters of the space and the ground clocks (position and velocity), the measured frequency difference between PHARAO and the ground clocks can be directly compared to theory. ACES will perform a red-shift measurement at 2 ppm, corresponding to an improvement of a factor of 35 over GPA. As the ISS orbit slowly changes as a function of time, the gravitational red-shift will also be modulated, but only by about 10% of its magnitude.

The red-shift is proportional to $g_0R_0/c^2(1−R_0/R)$, where $g_0$ is the gravity acceleration on the ground, $R_0$ is the Earth radius and $R$ the orbital radius. On the ISS orbit, $R−R_0=450$ km, $1−R_0/R = 7\%$, and the Einstein’s effect amounts to $0.45\cdot10^{10}$. Considering that a 1 m difference in elevation corresponds to a frequency change of $10^{-16}$, the precision level reached by ACES in the measurement of the gravitational red-shift ($2\cdot10^{-6}$) could be challenged either by a less performing clock on a higher orbit or much better clocks operating on smaller potential differences.

In the first case, space clocks on-board GPS or GALILEO satellites orbit at much higher altitudes (~20000 km), but because of their limited performances cannot be used for an accurate measurement of the gravitational red-shift. To our knowledge, there is no planned space mission that could compete with ACES on the red shift measurement.

In the second case, the situation is different. Clocks with 100 times better accuracy than PHARAO could perform a measurement competitive with ACES on a difference in altitude of only ~3-4 km (Chamonix-Aiguille du Midi for instance, or Mauna Kea base and summit, both sites having well equipped laboratories). It is not excluded that such clocks might exist in 2014-2015, but a very significant technological effort to bring these laboratory-type equipments into operational devices in the field would have to be made. Similarly, a balloon experiment based on clocks with $10^{-17}$ accuracy over 40 km elevation difference would have a sensitivity equivalent to ACES. However, the precise measurement of the Einstein’s gravitational red-shift requires the knowledge of the altitude and the Earth potential at the clock position with an accuracy which increases as the height difference decreases.

This question is directly related to a new application of ultra-stable clocks, which will be explored with ACES, the “Relativistic Geodesy” (see Section 4.3.1). This new application of ACES was identified within the ACES topical team on “Geodesy and Clocks”. The method builds upon the recent progress of optical clocks and the performances of the ACES MWL. In relativistic geodesy, the gravitational potential difference between two points where two ultra-stable and accurate clocks are located is measured by comparing the frequencies emitted by the two clocks.

The Earth gravitational potential on the geoid is known to about 10 cm, corresponding to a relative frequency shift of $10^{-17}$. Global Earth potential models can estimate gravitational potential differences between distant points with 10 cm accuracy, but the reconstruction of the geoid becomes more and more difficult when the distance between the two locations increases,
particularly over intercontinental distances. The knowledge of the potential and of its variability will set a limit on the relativity test itself. From recent geodesy models, we know that local potential variations on the order of a few centimetres can occur, induced for instance by sea tides. Thus, a red-shift test competitive with respect to the ACES measurement, would require the knowledge of the potential difference, for example between Chamonix and Aiguille du Midi, with a precision of 1 cm, at present well beyond the state-of-the-art. Specific gravity acceleration measurements on a grid around the experiment location to reconstruct the local potential would be needed and important efforts in addition to the development of robust mobile clocks with $10^{-18}$ accuracy would be required. Therefore, this is very unlikely to occur before ACES flight.

#PO3.2- Drift of the Fine Structure Constant

The ACES mission will measure the possible drift of fine structure constant $\alpha$ at the level of $\alpha^{-1} \cdot (d\alpha/dt) \sim 10^{-16}/\text{year}$.

Already in 1937, Dirac suggested that it was worth checking if the fundamental constants of physics were indeed constant. In General Relativity as in other metric theories of gravitation, a time change of non-gravitational constants is forbidden. This is a direct consequence of the Einstein's Equivalence Principle. However, several modern theories predict the existence of new interactions which violate General Relativity. Damour and Polyakov [11], as well as other authors, predict time variation of fundamental constants and in particular of the fine structure constant which characterizes the strength of the electromagnetic interaction.

Atomic transition (hyperfine and electronic) can be expressed in terms of the fine structure constant $\alpha$, the electron to proton mass ratio $m_e/m_p$, and the magnetic moment of the proton $g_p$. As suggested in [12,13], this dependence can be pushed a step further. Grand unification theories imply that a time variation of $\alpha$ is accompanied by a variation of the strong interaction strength and the fundamental masses. Within this framework, comparisons of atomic frequencies can be used to test the time stability of the three dimensionless constants $\alpha$, $m_q/\Lambda_{\text{QCD}}$, and $m_e/\Lambda_{\text{QCD}}$, where $m_q = (m_u + m_d)/2$ is the quark mass, and $\Lambda_{\text{QCD}}$ is the QCD mass scale [12,13,14].

High accuracy atomic clocks offer the possibility to perform advanced tests of possible time variations of fundamental constants [12,13,14,15,16,17,18] and ACES will bring a major contribution to this research by its capacity of global frequency comparisons. Four well chosen atomic transitions are enough to constraint three independent frequency ratios and establish limits on the time variations of the three fundamental constants $\alpha$, $m_q/\Lambda_{\text{QCD}}$, and $m_e/\Lambda_{\text{QCD}}$. With more than four atomic clocks, redundant data allows identifying any non-vanishing variation of fundamental constants unambiguously and with a clear signature.

The measurement involves the comparison of atomic or molecular frequency standards based on different elements as a function of time. Any change of the frequency difference between two clocks might be attributed to a change of fundamental constants or to imperfections in long-term behavior of the clocks. Atomic physics predicts the relative rate of change of various clocks if one or several fundamental constants vary with time. Therefore, to perform a convincing test, it is mandatory to involve a large number of clocks and to make cross correlations between the
measurements. ACES will provide the means for performing comparisons between different atomic clocks, based on hyperfine transitions (e.g. Cs, Rb, Hg\(^+\), Yb\(^+\) microwave clocks) or on electronic transitions (e.g. H, Ca, Mg, Sr, Yb, Ag, Hg\(^+\), Yb\(^+\), Sr\(^+\), In\(^+\), Al\(^+\), Ca\(^+\) optical clocks). At present, a number of laboratories have ultra-stable clocks operating with different atoms or ions: cesium (LNE-SYRTE, NIST, NRLM, ON, PTB, NPL, INRIM, Yale University, USNO ...), rubidium (LNE-SYRTE, Penn State University, PTB, NPL), mercury ion (NIST, JPL), ytterbium ion (PTB, CSIRO), aluminum ion (NIST), calcium ion (University of Innsbruck, and University of Marseille). Neutral atom clocks using optical lattices at the “magic wavelength” develop very fast, most notably at Tokyo University, JILA, NIST, LNE-SYRTE, and PTB. In 2007, they have reached accuracies comparable to the cesium fountain clocks with excellent prospects for gaining still one or two orders of magnitude.

The precision of this test relies both on the accuracy level of the contributing ground clocks and on the frequency stability of the ACES clock signal and the ACES MWL. This scientific objective, established in 1997 at the 10\(^{-16}\)/year accuracy level, was considered at that time as very ambitious in a relatively unexplored domain. Today, limits on time variations of fundamental constants set by clock comparisons reach a level of 3–5\(^{-16}\)/year. Thanks to the on-board time scale, to the performances of MWL, and to the progress of optical clocks on ground, the ACES mission will reach an accuracy level of 1\(^{-17}\)/year after one year of measurements. A resolution of 3\(^{-17}\)/year could be reached over three years (the sensitivity is inversely proportional to the time between consecutive measurements). By combining the results of several complementary clock comparisons, it will be possible to deduce limits not only on the time variations of \(\alpha\), but also on the strong and weak interaction constants.

To measure the interest of the ACES global comparison, we can develop the following argument. It is possible that a major national laboratory, such as NIST, PTB, or LNE-SYRTE, develops 3 optical clocks based on elements with different atomic numbers and performs local frequency comparisons over several years at the level of 10\(^{-18}\) to set a very stringent limit on \(\alpha\) variations. It is difficult to predict how many years will be required before this can become possible. Today, only one group in the world at NIST (USA) has reached a relative frequency stability of 4\(^{-17}\) and accuracy of 7\(^{-17}\) with two trapped ion clocks operating simultaneously for a few hours. Concerning neutral optical clocks, their development is very recent and no frequency stability significantly below 10\(^{-15}\) has been measured yet. Then, three possible scenarios could emerge:

- The above-mentioned group does detect unambiguously a variation of fundamental constants before the ACES mission. This is a major discovery because it breaks down our current understanding of the world. Then ACES, by its global comparison capacity, should spectacularly confirm this first result identifying any non-vanishing variation of fundamental constants with a clear signature and the stakes in fundamental physics will be major.
- Such a discovery is made thanks to the ACES mission because of the much larger number of clocks involved in the comparison. This would be a great success for the ACES.
- No drift of constants is detected at the level of 10\(^{-18}\)/year. Physicists will search with ever-increasing sensitivity, new clocks, and new time and frequency transfer
links (Cosmic Vision proposals). In the mean time, very stringent limits will have been set on the variability of fundamental constants and on several theoretical predictions from String theory.

#PO3.3- Anisotropy of the Speed of Light

The ACES mission will test the validity of special relativity by detecting the possible anisotropy of light velocity at the level of $\delta c / c < 10^{-10}$.

The foundations of Special Relativity lie on the hypothesis of Local Lorentz Invariance. According to this principle, the outcome of any local test experiment in free fall is independent of the velocity of the apparatus. A number of alternative theories that allow for violations of Special Relativity have been recently developed (see [19] for a review). Such theories postulate some "universal rest frame" $\Sigma$ in which the basic postulates of Special Relativity are valid and where the slow clock transport and Einstein synchronization procedures for distant clocks [20] are equivalent. In Special Relativity, this is also valid in any inertial frame $S$ moving in $\Sigma$ at constant velocity. However, the existence of a privileged reference frame implies, for example, that the speed of a light signal transmitted one-way between two distant points, as measured by clocks that were synchronized using slow clock transport, is a constant not depending on the direction of signal transmission in the "universal rest frame" $\Sigma$, but not in $S$.

In general, the Robertson-Mansouri-Sexl approach is used to classify relativity tests [19]. A more recent approach proposed by Kostelecky et al introduces a theoretical frame for possible extensions of the standard model which violate Lorentz invariance [21,22,23]. For experiments measuring one-way signal transmission times, a simple test theory based on the parameter $\delta c/c$ is often used. In this interpretation, distant clocks are synchronized in $S$ using slow clock transport. Then $c$ is the round trip speed of light (independent of the chosen synchronization convention) and $\delta c$ the deviation from $c$ of the speed of light in $S$, measured by the transport-synchronized clocks, for a signal propagating one-way along a particular direction. Thus, experiments look for a variation $\delta c$ as a function of the direction of the signal transmission in $S$.

In special relativity $\delta c/c=0$ which, of course, reflects the fact that the two synchronization conventions are equivalent.

A number of experiments searching for a non-zero value of $\delta c/c$ have been carried out either by direct measurements of the variation of one-way transmission times of light signals between distant clocks [24] or by indirect measurements searching for the variation of the first order Doppler shift [5,25,26,27]. A violation of special relativity is, in this model, linked to a particular spatial direction (velocity of $S$ in $\Sigma$) and the experiments search for the modulation of the effect as the direction of signal transmission is changed. Consequently, experiments that rely on the rotation of the Earth for a change of the direction are only sensitive to the component of $\delta c/c$ in the equatorial plane.

ACES is expected to improve previous limits on $\delta c/c$ by one order of magnitude with respect to existing measurements based on laser spectroscopy of fast ions and almost two orders of magnitude with respect to tests based on GPS satellites. The space clocks will be continuously compared to ground clocks during the ISS pass. The time transfer link will exchange microwave signals in both directions between the clocks. All emission and reception times are measured in
the local clock time scale, both in space and on ground. The difference of the measured
reception and emission times provides the one-way travel time of the signal plus some unknown
constant offset $\Delta_s$, related to the fact that the clocks are not synchronized by slow clock
transport. Then, the difference of the up and down travel times, sensitive to a non zero value of
$\delta c/c$ along a preferred direction, is given by

$$T_{up} - T_{down} = \Delta_s + \Delta_m + 2 \frac{\delta c}{c} T \cos \theta,$$

where $T$ is half the return travel time, $\theta$ is the angle between the link and the preferred direction,
$\Delta_m$ includes known small corrections due to path asymmetries, atmospheric delays, etc…, and $\Delta_s$
is the unknown constant due to de-synchronization.

The sensitivity of the experiment is determined by the instabilities over one passage of both the
clocks and MWL. With an overall time instability over one ISS pass below 1 ps, the expected
sensitivity to $\delta c/c$ is $6 \times 10^{-11}$ which is equivalent to a test on the parameter $\alpha$ of the Robertson-
Mansouri-Sexl theory (not to be confused with the fine structure constant!) at the $2 \times 10^{-8}$
accuracy level.

This scientific objective, very actual today, could be weakened in the future by the progress
expected in experiments based on laser spectroscopy or synchrotron emission of fast ions.
However, even if the scientific research on ground progresses significantly in the next 6 years,
the very fundamental nature of this test justifies experiments based on different methods (fast
ions or ACES) and the measurement performed by ACES will still remain an important outcome
of the mission.

### 4.2 Secondary Mission Objectives

**#SO1. - SHM Long Term Stability**

*It is a secondary objective of the ACES mission to characterise the long-term (above $10^4$
seconds) stability of the Space Hydrogen Maser.*

This objective is of technological nature. The characterization of SHM long-term stability is
based on long duration phase comparison data. This information will enrich the knowledge of
the behaviour of ultra-stable atomic clocks in actual space environment, such as impact of
temperature variations during orbital motion and capacity to correct for them, aging induced by
radiation, breakdowns, etc. Let us just recall that the first two passive hydrogen masers of the
European GALILEO project will be launched only in 2007. The ACES mission will go beyond,
establishing the performance of an *active* hydrogen maser in space with a frequency stability
more than one order of magnitude better than the GALILEO passive masers.

**#SO2. - Ground Clocks Synchronization**

*It is a secondary objective of the ACES mission to demonstrate the feasibility of synchronising
ground clocks with a time uncertainty at the level of 100 ps.*

Almost all ACES scientific objectives rely on frequency comparisons between clocks.
Nevertheless, the ACES time and frequency link will also allow the absolute synchronization of
ground clock time scales with an uncertainty of 100 ps (calibration of MWL atmospheric propagation and instrumental delays). Current time synchronization errors between national laboratories are at the level of one to a few nanoseconds.

The direct comparison of ground-based primary frequency standard at the $10^{-16}$ level will give an important contribution to existing atomic time scales and will be useful to check the calibration of other time and frequency links (GPS, Two Way Satellite Time and Frequency Transfer, T2L2, GALILEO), currently used in the construction of international atomic time scales.

**#SO3.- Contribution to International Atomic Time Scales**

*It is a secondary objective of the ACES mission to provide the capability to improve the long-term stability and the accuracy of international atomic time scales.*

One of the scientific goals of ACES is to demonstrate the high performances of the primary frequency standard PHARAO in space. The direct comparisons of PHARAO and the ground clocks contributing to the EAL (Échelle Atomique Libre) will offer the opportunity to improve the accuracy of TAI (Temps Atomique International). As a matter of fact, the larger the number of primary standards contributing to TAI, the better is the long-term stability and the accuracy of TAI. TAI is computed by BIPM and is generated from the data of about 300 cesium clocks. As all primary cesium standards using cold atoms, PHARAO will contribute to the steering of the TAI with a weight that will depend on its uncertainty budget. With an accuracy of $10^{-16}$, PHARAO will have a significant role during the mission duration. Furthermore, ACES will contribute to TAI by its capability to compare worldwide primary standards at the $10^{-17}$ level. This frequency resolution is well below the current uncertainty of these clocks and comparison methods (Figure 11).

The progress of optical clocks naturally raises the interesting question of a possible redefinition of the second using an atomic transition in the optical domain rather than in the microwave domain. The ACES Science Team believes that this redefinition is unlikely to occur before the ACES launch. To consider such redefinition of the SI second, substantial work remains to be done to bring optical clocks to a sufficient number and a sufficient reliability to construct an operational system. ACES will act as a catalyst in this domain as global and regular comparisons between these clocks will be possible. ACES will thus complement the existing although less performing time transfer links using GPS or TWSTFT.

**#SO4.- Ultra Stable ACES Time Scale**

*It is a secondary objective of the ACES Mission to demonstrate the capability to transmit an ultra-stable space time scale to ground users with a time accuracy at the level of 100 ps.*

This application is closely related to #SO2. Ground users will be able to synchronize their local timescale to the stable and accurate clock signal delivered by ACES with a time accuracy of 100 ps, more than one order of magnitude beyond current techniques. Even though ACES is not designed to be an operational system to deliver permanently timing signals (as GPS), during the mission duration it will distribute a global time scale useful to validate existing GNSS systems (GPS, GLONASS, and GALILEO). ACES will enable tests of new technologies and algorithms for future positioning and navigation satellites networks. In a longer term perspective, the ACES
mission can be seen as a precursor of a future ultra-precise space-time reference system in space based on few satellites in high Earth orbit equipped with optical clocks, advanced inter-satellite and satellite-to-ground links. This is a strategic issue for future European navigation and positioning systems beyond the first generation of GALILEO.

4.3 **ACES Technology and Applications**

ACES will also have important applications in geodesy, global positioning and navigation, and major Earth Science themes.

4.3.1 **RELATIVISTIC GEODESY WITH ACES**

ACES will demonstrate for the first time a new kind of geodesy based on the accurate measurement of the Einstein’s gravitational red-shift. In relativistic geodesy, the difference of the gravitational potential between two (several) positions, where two (several) ultra-stable and accurate clocks are located, can be measured by performing clock-to-clock comparisons.

As shown in Figure 11, the ACES mission will enable clock comparisons on intercontinental distances at the $10^{-17}$ level after one week of integration time. In the 2014-2015 timeframe, the availability of optical clocks with accuracy at the $10^{-17}$ level and the performances of ACES will allow the direct measurement of differences in the gravitational potential at the 10 cm level. Such precision is not accessible with GPS methods because of the prohibitive measurement duration. Finally, this new technique will nicely complement the results of geodetic missions such as CHAMP, GRACE and GOCE. Depending on the speed of development of optical clocks on the ground, this science objective of ACES can become a major achievement for the mission.

In the longer term, with clocks at the $10^{-18}$ stability and accuracy level, the variability of the local potential will be accessible, opening fascinating perspectives for ACES in the coming decade. This also points towards a serious limit for clock synchronization and time transfer on ground. In fact, to take full benefit of these future clocks, it will be necessary to operate them in spacecrafts orbiting around the Earth at relatively high altitudes where spatial and temporal variations of the Earth gravitational potential are smoothed out. This represents a clear challenge for future space missions at the 2020-2025 horizon. In this respect, ACES appears again as a precursor for these missions.

4.3.2 **ACES AND THE GNSS NETWORK**

The technology development pioneered by ACES will make available better clocks and high performance time and frequency transfer links for the validation of GNSS systems (GALILEO, GPS, GLONASS…). A GALILEO/GPS receiver will be part of the ACES payload and directly connected to the ACES clock signal. The receiver will firstly secure orbit determination and payload positioning at the required accuracy level. Secondly, it will make available the stable and accurate frequency reference delivered by ACES to a wider community interested in clock applications in different areas of research including:
• Precise orbit determination of the ISS
• Continuous monitoring of the GNSS clocks and time transfer via the GNSS network
• Utilization of the ACES clock signal for remote sensing via radio-occultation and scatterometry experiments

Such applications have been proposed and extensively discussed in the project “GALILEO on-board the International Space Station” (AO-2004-143), submitted to ESA in answer to the Announcement of Opportunity issued in 2004.

4.3.2.1 Precise Orbit Determination

The GALILEO/GPS receiver installed on-board the ACES payload will provide the data needed to reconstruct the ISS orbit and, in turn, position and velocity of the ACES clocks. This information is crucial to correct the ACES frequency reference for relativistic effects and reach the expected stability levels. Considering the performances of dual frequency receivers, the required accuracy on position and velocity of the ACES payload will be easily met. A dual-frequency receiver with an antenna placed on an extension boom deployed from the ACES payload should allow orbit determination at the 10 cm level using GPS satellites only, with the possibility of improving these performances by a factor 1.5 to 2 if GALILEO and/or GLONASS satellites are used too.

Ultimate performances will depend on the antenna position and its field of view. Based on kinematic and reduced-dynamic algorithms, a dual-frequency receiver connected to an antenna with sufficient field of view towards the GNSS constellation is potentially able to retrieve the ISS orbit with an accuracy up to 1-3 cm in the International Terrestrial Reference Frame (ITRF) as well as in the International Celestial Reference Frame (ICRF) and to determine the ISS velocity and total acceleration. One could in addition imagine using the ACES platform for a technology demonstration in which several low cost GNSS receivers could be directly compared in flight conditions.

4.3.2.2 GNSS Time and Frequency Transfer

The dual frequency receiver connected to the ACES clock signal provides the GNSS network with a primary frequency standard of outstanding accuracy and stability, important for monitoring and characterizing the behavior of the clocks on-board navigation satellites. This information would be directly available to the wide community of GNSS users. The GNSS receiver driven by the ACES high-precision clocks can be included into the processing of the global network of GNSS receivers located in time laboratories distributed around the world, making the ACES time scale directly accessible. The GALILEO constellation will likely be in orbit by the time of the ACES launch. From this point of view, ACES will give a significant contribution to the evaluation of the European global positioning and navigation system.
The GNSS receiver connected to ACES will be also used to disseminate the ACES timing signal. The ultimate time stability of the system will depend on the antenna position and on its field of view towards the GNSS satellites constellation. In the ideal case of a zenith pointing antenna with a good field of view, it is possible to perform time transfer at an uncertainty level of 30 to 100 ps. These performances correspond to a fractional frequency instability of \(3 \times 10^{-16}\) per day and \(1 \times 10^{-16}\) over three days (see also Figure 11).

In the longer term, ACES will likely introduce new concepts for global positioning systems based on a reduced set of ultra-stable space clocks in orbit associated to simple transponding satellites.

### 4.3.2.3 GNSS Radio Occultation Experiments

Radio occultation experiments are based on the precise dual-frequency phase measurements (L-band) performed by a GPS receiver in a low Earth orbit while tracking a setting or rising GPS satellite. These measurements, combined to the satellite position and velocity, allow to derive the small phase path increase due to the propagation of navigation signals in the Earth atmosphere (excess phase). The analysis of a radio occultation event can therefore provide important information on the vertical profiles of the atmospheric pressure, temperature, water vapor, and electron density. This information is regarded as potential major data source for numerous applications in atmospheric/ionospheric research.

GPS occultation data from the COSMIC, CHAMP, and GRACE missions are used to improve global weather forecasts since 2006. However, the currently available GPS occultation measurements suffer from tracking problems in the low troposphere regions and show severe limitations reducing the reliability of the stratosphere parameters.

Radio occultation experiments would significantly benefit from the stable and accurate clock signal of ACES. Connected to the GNSS receiver, the ACES frequency reference is crucial for reducing signal tracking uncertainties and improving the knowledge of atmospheric parameters, especially in the troposphere and stratosphere. The additional signals provided by the GALILEO satellites constellation can be used to develop innovative algorithms to track occultation signals and further improve the measurement accuracy.

Another important aspect is represented by the ISS orbit. Its inclination, almost identical to that of the GNSS satellites, is able to ensure a large number of globally distributed occultation events. Compared to missions like COSMIC, CHAMP, METOP or GRACE, the low inclination of the ISS orbit increases the relative percentage of occultations at low latitudes, regions of particular interest for the formation of extreme atmospheric phenomena such as hurricanes. A dual frequency GNSS receiver, tracking in addition GLONASS and GALILEO satellites, would significantly increase the number of globally available measurements of atmospheric and ionospheric parameters.
4.3.2.4 Altimetry and Reflectometry Experiments

Traditional radar altimetry, performed for example by Jason-1 or Envisat, can provide only one nadir height measurement per time. On the contrary, bistatic GNSS reflectometry is based on the simultaneous tracking of about a dozen navigation signals reflected from oceans or ice surfaces by a single GNSS receiver. Cross-correlations of the reflected signals with the directly received signals, along with other geometrical and atmospheric modeling information, are used to perform an in-situ measurement of the ocean height at the reflection point. Detailed analysis of correlation signals provides information on ice surface properties (roughness) and ice coverage, it can be used to detect waves of significant height, and to measure wind speed and direction above the sea surfaces. The reflected signals also contain information on the propagated atmosphere and ionosphere (e.g. integrated electron content along the ray paths) which could be extracted based on the application of advanced data analysis techniques.

GNSS reflection measurements are currently regarded as potential data source for various applications in geosciences and atmospheric research. In addition, they provide sufficiently high temporal and spatial resolution to investigate very short-lived features, such as tsunamis or mesoscale eddies which play an important role in the transport of momentum, heat, salt, nutrients, and chemicals within the oceans.

The wide coverage of the ISS orbit is particularly suited to perform reflectometry experiments. In this case, the GNSS receiver requires the installation of a nadir-pointing antenna that can be easily accommodated on an extension boom deployed from the ACES payload. The experiment will demonstrate new concepts for Earth observation and monitoring and validate early warning systems with worldwide coverage that could be used in future space missions.

4.4 ACES and Atomic Quantum Sensors for Space Applications

Atomic clocks and inertial quantum sensors represent a key technology for accurate frequency measurements and for ultra-precise monitoring of accelerations and rotations. These instruments evolved out a new kind of optics based on matter waves rather than on light waves. The young and rapidly progressing domain of cold and ultra-cold atoms has recently generated Nobel Prize awarded discoveries such as laser cooling in 1997 and Bose-Einstein condensation in 2001.

Today, atomic clocks represent the sole instruments for time and frequency measurements at highest accuracy. Inertial sensors using atom interferometers display a similar potential for challenging other state-of-the-art instruments when long-term stability and accuracy are required.

Atomic quantum sensors rely on the same basic principles: cold atom physics, atom optics, and matter-wave interferometry. These techniques developed during the last decade from proof-of-principle experiments to instruments of highest sensitivity. Several benchmark experiments based on laboratory models have demonstrated sensitivities competitive with other state-of-the-art sensors. Few groups worldwide already started to work on transportable systems. The mobile atomic fountain clock FOM developed by LNE-SYRTE has already demonstrated its performances; a robust and transportable gravity gradient sensor has been developed in Stanford
and a gravity gradiometer at JPL; a transportable six-axis inertial sensor is under evaluation at LNE-SYRTE and a transportable rotation sensor is under development at the Institut für Quantenoptik of Hannover.

Space is the natural environment for atomic quantum sensors. In fact, these instruments particularly benefit from weightlessness and microgravity. In space, the interaction times between atoms and probing field can be increased by several orders of magnitude, improving even further the already excellent performances of these devices. The strong interest of space agencies in the field of matter-wave optics is well documented by the long list of projects and studies already proposed both to ESA and NASA.

In the US, the Quantum Sciences and Technology Group at JPL (Jet Propulsion Laboratory) is promoting research on ultra-stable laser systems, laser cooling, atom interferometry, and coherent matter-wave optics to foster the development of a new generation of atomic clocks and inertial sensors suitable for space applications. This activity is well reflected by the projects that in the past have been proposed to NASA:

- **Primary Atomic Reference Clock in Space (PARCS, D. Sullivan, NIST).**
  PARCS is a cesium clock based on laser cooled atoms which will be compared to ground clocks using GPS satellites. PARCS was supposed to fly concurrently with a Superconducting Microwave Oscillator (SUMO). The comparison of the two clocks provides precise test of Einstein’s theory of General Relativity.

- **Rubidium Atomic Clock Experiment (RACE, K. Gibble, Pennsylvania State University).**
  RACE is an atomic clock based on a beam of laser cooled rubidium atoms. The instrument takes advantage of the technology developed for PARCS. Expected to be more stable and accurate than cesium clocks, the direct comparison of RACE and SUMO will be used to test fundamental laws of physics.

- **Quantum Interferometric Test of the Equivalence Principle (QUITE, M. Kasevich, Yale).**
  Two samples of rubidium and cesium atoms are simultaneously cooled and trapped. During the free fall of the samples in space, atom waves are split and recombined in an interferometer, providing accurate tests of the Einstein’s Equivalence Principle with target accuracy of $10^{-15}$.

- **Condensate Laboratory Aboard the Space Station (CLASS, W. Phillips, NIST).**
  The project proposes the realization of a facility to study Bose-Einstein condensates in microgravity. Ultracold and coherent atomic sources are expected to bring major improvements to atomic quantum sensors.

Following the directives of a new space program fostering space and planetary exploration, the financial support to the NASA activities in the fundamental physics domain has been recently cut. However, the development of atomic quantum sensors for space applications is still ongoing as documented by the prototyping activities in progress at JPL and other laboratories across the US.

In Europe, the interest of the scientific community on atomic quantum sensors is demonstrated by the numerous study activities initiated by ESA.
The HYPER project (HYPER-precision cold atom interferometry in space), proposed to ESA in January 2000 in response to the call for the second and third Flexi-missions (F2/F3), highlighted the potential of cold atom interferometry in space both for inertial sensing and fundamental physics studies. HYPER was not selected for flight however it was recommended to continue studies and to initiate technology development in areas relevant for atom interferometry. This recommendation has been implemented by ESA triggering a series of studies focused on the development of the key subsystems of an atomic quantum sensor.

In the context of ESA “Cosmic Vision 2015-2025” program, atomic clocks, matter-wave interferometry, and Bose-Einstein condensation played an important role in suggesting future studies in fundamental physics.

During the last ESA Announcement of Opportunity (ESA AO-2004) the interest of the scientific community on space application of atomic quantum sensors has been clearly demonstrated by the submission of different proposals:

- **Space Optical Clocks** (AO-2004-100, S. Schiller, University of Düsseldorf).
  Optical clocks based on ensembles of ultracold atoms stored in the periodic potentials generated by standing wave fields will lead to the next leap in accuracy and stability for clock technology. The project wants to demonstrate the operation and characterize the performances of an optical clocks ensemble in a space environment, with an expected accuracy at least ten times better than ACES. The clocks will be used to perform accurate tests of General Relativity. The project is financed by the HME Directorate in the frame of the ELIPS2 program.

- **Space Atom Interferometer** (AO-2004-64 / 82, G. Tino, University of Firenze).
  The project intends to exploit the potential of matter-wave sensors in microgravity for the measurement of acceleration, rotations, and faint forces. The atom interferometer will be used to perform fundamental physics tests and to develop applications in different areas of research (navigation, geodesy ...). These activities are financed by the HME Directorate in the frame of the ELIPS2 program.

  The project is intends to study the properties of Bose-Einstein condensates in a microgravity environment. In space, the long interaction times and the slow adiabatic expansions will play a crucial role for realizing samples of coherent atoms at very low temperature, ideal for atom interferometry experiment. This project is funded at national level by DLR.

The scientific community, in response to the ESA call recently issued within the Cosmic Vision program, will submit a number of proposals based on the utilization of atomic quantum sensors for precision tests in space. The advantages of operating atomic quantum sensors in a microgravity environment are clear. In addition, free flight on pure gravitational orbits and in a vibration-free environment provides the best operating conditions to reach the quantum limits of these instruments. Atomic quantum sensors will ensure the highest levels of precision for fundamental physics tests in space.
The applications of atomic quantum sensors are truly interdisciplinary, covering diverse and important topics such as tests of fundamental physics, the realization of SI-units and metrology, global time-keeping, deep-space navigation, prospecting for resources, global navigation and positioning systems, environment monitoring, major Earth-science themes. From this point of view, ACES represents a stepping-stone of a long-term program based on the utilization of atomic quantum sensors for fundamental physics and applications. ACES will perform the first experiments on laser cooled atoms in microgravity, it will foster the necessary technology development, and for the first time it will validate in space a series of tools and instruments extremely important for future space missions: from complex laser benches to ultra-high vacuum systems, from high performance space clocks to links for stable time and frequency dissemination. The technology and expertise that ACES has materialized will be crucial for the development of the second generation of atomic quantum sensors: atomic clocks in the optical domain, atom interferometry sensors for space applications, and a facility for studying Bose-Einstein condensates in microgravity. These projects will develop in complete synergy, taking full advantage of the ACES heritage.
5 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 (M-PDR) has been successfully concluded consolidating the overall mission concept, demonstrating the feasibility of instruments and subsystems, and confirming the design of the flight hardware.

5.1 PHARAO Status

The cesium clock PHARAO is composed of four main subsystems: the cesium tube, the optical bench, the microwave source, and the computer control. Contracted to different manufacturers, the engineering models (EM) of PHARAO subsystems have been completed, successfully tested, and delivered.

The EM PHARAO clock, fully assembled at CNES premises in Toulouse, is presently under test (Figure 14). Design and recent results are described in [28].

![Figure 14: (Left) The PHARAO cesium tube without the two external magnetic shields. Fully assembled, the tube has a volume of 990×336×444 mm³ and a mass of 44 kg. (Right) PHARAO laser source. The optical bench has a volume of 530×350×150 mm³ and a mass of 20.054 kg. Ten polarization maintaining optical fibers (in yellow) provide the cesium tube with the laser beams necessary for cooling and detecting cesium atoms.

Cesium atoms have been loaded in the optical molasses, cooled down to 1 µK, and detected. Samples of $10^7$ cold atoms, launched along the PHARAO tube, have been probed on the clock transition by using the PHARAO microwave frequency source. Microwave resonance signals (Ramsey fringes) 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 and a signal-to-noise ratio of about 700 (Figure 15). When operated in microgravity, the longer interaction times will allow PHARAO to detect signals with a 10 to 50 times narrower linewidth. The central fringe has a
contrast of about 90%. Because of the deceleration induced by gravity, the two Rabi pulses characterizing the Ramsey interrogation scheme are not perfectly $\pi/2$ and the interference fringes suffer a slight loss of contrast in perfect agreement with simulation.

Figure 16 shows preliminary measurements of the PHARAO fractional frequency instability. An Allan deviation of $2.5 \cdot 10^{-13} \cdot \tau^{-1/2}$ has been measured for integration times between 1 s and $10^4$ s, using the PHARAO microwave source driven by an external cryogenic oscillator. This situation closely approaches the stability expected in flight conditions, $1 \cdot 10^{-13} \cdot \tau^{-1/2}$, obtained with longer interaction time. The result is in perfect agreement with expectations based on atom number and cycle duration. When the microwave source is driven by its internal ultra-stable quartz oscillator, the measured stability is $4 \cdot 10^{-13} \cdot \tau^{-1/2}$. This value is set by the phase noise of the quartz oscillator which is sampled by the atoms in the microwave cavity (Dick effect). Again, this measurement is in full agreement with numerical simulations. In space this effect will be reduced by a factor of ten as the resonance width will be much narrower.

Functional and performance tests on the PHARAO clock are presently ongoing. In the coming months, the clock stability and accuracy will be fully evaluated. PHARAO engineering model will be delivered to ESA for integration in the ACES payload by the end of 2007.

![Comparaison simulation/expérience de franges de Ramsey](image)

**Figure 15:** PHARAO Ramsey fringes on the clock transition. The measurements have been performed by locking the PHARAO microwave source to a cryogenic sapphire oscillator. The fringes have been recorded by detecting samples of about $10^7$ cesium atoms launched at 3.42 m/s and with a temperature of 1 $\mu$K. The central fringe has a signal to noise ratio of ~700 and a linewidth of 5 Hz.
Figure 16: PHARAO fractional frequency instability as compared to a hydrogen maser. For this measurement, the PHARAO microwave source is driven by an external cryogenic oscillator to approach the operating conditions in space. The stability is $2.5 \times 10^{-13} \cdot \tau^{-1/2}$ in accordance with expectation from atom number and cycle duration. Blue and red data points correspond to $N_{\text{det}}$ and $N_{\text{det}}/2$ detected atoms respectively.

5.2 SHM Status

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

Figure 17: (Left) The engineering model of SHM physics package fully assembled. (Right) RF electronics unit assembled in the thermally stabilized box.

The engineering model of SHM PP (Figure 17), manufactured and assembled, has successfully completed a series of functional and performance tests in combination with the laboratory
electronics developed at the Neuchâtel Observatory (ON). The fractional frequency instability of the combined system has been characterized, showing compliance to SHM specifications (Figure 18). At the same time, accurate measurements have verified that the thermal control system of the maser cavity is able to ensure temperature stability within 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 the 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 laboratory design of the maser electronics has been translated by OERLIKON into a development model (DM) which has been extensively tested on the SHM proto-engineering model (maser physics package developed for RADIOASTRON). The Allan deviation has been measured both under stable thermal conditions and for a temperature variation of 10 mK at the maser cavity (Figure 19). Even under such extreme conditions\(^1\), the ACT is able to efficiently tune the resonance frequency of the maser cavity and compensate for temperature changes without any significant degradation of the fractional frequency instability.

The engineering model of SHM EP is presently under development. Once delivered, SHM will be fully assembled and end-to-end tests will evaluate the clock performances.

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\(^1\) As mentioned before, SHM thermal control system is able to stabilize the temperature of the maser cavity within 1 mK.
Figure 19: Physics package of SHM proto-engineering model driven by the DM electronics developed by OERLIKON: Allan deviation of the clock measured under stable temperature conditions with the ACT off (green) and on (blue) and after two temperature steps of 10 mK, the ACT being in closed loop (light blue). The bandwidth of the measurement system is 3 Hz. Data are compared to SHM specifications translated to a 3 Hz bandwidth and including the contribution of the reference maser (red) and to the measurement results obtained with ON electronics (black).

5.3 FCDP Status

The engineering model (EM) of the ACES FCDP has been completed and verified against its functional, performance, and electromagnetic compatibility (EMC) requirements.

Ultra-low phase noise electronics is extremely important to distribute and characterize the signal derived from high performance atomic clocks. The direct comparison of primary frequency standards at a stability level of few parts in $10^{16}$ has already been demonstrated [6]. This technology is now available in a compact system with outstanding performances, ready to be used for space applications (Figure 20).

Performance tests have clearly demonstrated the capability of FCDP to perform clock-to-clock comparisons and to distribute the ACES clock signal to MWL with an induced noise well below the level required for ACES. The Allan deviation of the noise contribution introduced by FCDP on the distributed clock signal enters the $10^{-18}$ regime already after $10^4$ s of averaging time. Figure 21 shows the frequency stability of the clock-to-clock comparison measurements.
performed by FCDP. The Allan deviation curve reported there drops below $1 \cdot 10^{-17}$ for integration times longer than $10^4$ s.

**Figure 21:** Allan deviation of the noise introduced by FCDP in the comparison of the two on-board clocks.

In addition, a specific test has been conducted at CNES premises in Toulouse to validate the performances of the FCDP short-term servo loop. The microwave source of PHARAO has been phase locked via FCDP to the clock signal provided by a cryogenic sapphire oscillator (CSO) and alternatively a hydrogen maser. Measurements have been performed at 100 MHz and at 9.192 GHz, using both the FCDP phase comparator and laboratory instruments (Figure 22).

The excellent frequency stability of the cryogenic oscillator is crucial for correctly identifying the noise contribution of FCDP. Figure 22 shows an Allan deviation plot of the PHARAO microwave source phase locked to the cryogenic sapphire oscillator and measured against the cryogenic sapphire oscillator itself (red). Measurements are also compared to numerical simulations (black), to the Allan deviation of the free-running maser (blue), and to the expected performances of the PHARAO clock (violet). The same measurement has also been performed by using a hydrogen maser as reference oscillator and with loop parameters very close to what expected for ACES. For integration times $\tau$ longer than the servo loop time constant, the Allan deviation of the noise contribution introduced by the short-term servo loop decreases rapidly, closely following the simulated behaviour.

FCDP engineering model will be formally delivered after the completion of the integrated tests at ACES level which will directly involve the PHARAO and SHM clocks.
Figure 22: (Left) Test set-up used to measure the noise contribution of FCDP when the short-term servo loop is closed: PHARAO microwave source is phase locked on a cryogenic sapphire oscillator and alternatively to a hydrogen maser via FCDP. (Right) Allan deviation plot of PHARAO microwave source phase locked to the cryogenic sapphire oscillator measured against the cryogenic sapphire oscillator itself (red). Measurements are compared to the simulated behavior (black), to the Allan deviation of the free-running maser (blue), and to the expected performances of the PHARAO clock (violet).

5.4 MWL Status

The engineering model of the ACES microwave link is under completion. The EM performance test campaign has been recently started, providing the first results.

The time stability of the MWL code and carrier phase represents the key parameter for performing comparisons of distant clocks. The required long-term stability of the code and carrier phase measurement is reached by calibrating the receiver channels against thermal drifts with a built-in test-loop translator. The stability of the system on the ISS pass duration (~300 s) is fully dependent on the noise performance and on the reproducibility of each DLL receiver channel after proper calibration of the internal delay. Ultimate phase stability for integration times below 300s depends on the carrier phase.

Preliminary measurements of the code and carrier phase stability have been performed on the EM boards. The test setup is shown in Figure 23. The PN modulated signal, directly derived from the reference clock, is distributed to the transmitter, up-converted in 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 board to the local clock. The results, expressed in time deviation, are directly compared to MWL requirements.
The 100 MHz chip rate allows to reach a time stability below 2 ps already with code measurements (Figure 24). When carrier measurements are performed, time deviations below 0.2 ps can be observed even in the worst conditions of signal to noise density ratios. These performances demonstrate the feasibility of MWL design and keep open the possibility for improving the already good performances of the ACES time and frequency transfer link. The long-term stability of the system is presently under characterization.

Figure 23: Test setup for measuring the phase stability of carrier and code.
**Figure 24:** Stability of the code phase, expressed in time deviation, for different signal to noise density ratios (C/N0).

**Figure 25:** Stability of the carrier phase, expressed in time deviation, for different signal to noise density ratios (C/N0). Measurements are compared to MWL system requirements.
5.5 **Mission Status**

In view of the announced retirement of the Space Shuttle in 2010, the new baseline scenario for transportation and on orbit accommodation of the ACES payload has been redesigned on the basis of the Japanese H2B Transfer Vehicle (HTV) developed by JAXA. A Preliminary Design Review has been held in February 2007 to confirm the design feasibility of launching ACES on the external cargo carrier of the HTV. This review supported by JAXA and CNES, has confirmed that no showstoppers exist to transport ACES with the HTV.

The ACES mission has successfully passed two important mission reviews in the last years. A Mission System Requirement Review (M-SRR) was held in November 2005 to verify the coherence of the overall system specification for the ACES flight and ground segments. The Mission Preliminary Design Review (M-PDR) was successfully concluded in March 2007. This review confirmed that the ACES mission, whilst very challenging, is feasible within the indicated schedule which foresees the completion of ACES development in 2013.

The ACES launch to ISS is now planned in 2014 with the Japanese H2B Transfer Vehicle (HTV).
6 SUMMARY AND OUTLOOK

The operation of high stability and accuracy atomic clocks in space, the pioneering studies on samples of laser cooled atoms, the demonstration of a new time and frequency transfer link for the comparison of distant clocks, the fundamental physics tests that ACES will perform in space will represent major achievements. In each of these domains, ACES will bring advances of one to two orders of magnitude. Moreover, the mission may lead to a major discovery: a violation of General Relativity or the observation of variations of fundamental constants would break the current understanding of the physical world in which we live. Applications in global time scales, relativistic geodesy, major Earth science themes, and GNSS global navigation systems will demonstrate new techniques in strategic areas of research.

This analysis of the mission objectives shows how the progress of optical clocks on the ground is enriching the scientific potential of ACES. The robustness of the mission and of its science case resides in ACES being a unique facility in which the space clocks (PHARAO and SHM), the on-board frequency comparison and distribution system (FCDP), and the time and frequency transfer link (MWL) are generic elements allowing time and frequency metrology in space at a level never reached before and difficult to surpass in the coming 15 years.

ACES will make a first demonstration of the use of ultra-cold atoms in space for precise time measurements at the $10^{-16}$ level. The mission will be a precursor for a second generation of atomic quantum sensors such as optical clocks, accelerometers, rotation sensors, and gradiometers based on matter-wave interferometry. Cold atoms are opening fascinating perspectives for space and ACES will be the pioneer mission exploring this completely new domain and fostering the necessary technological development.

One can certainly imagine other mission scenarios with a dedicated satellite to further improve some aspects of the ACES mission. Let us mention for instance solar orbit relativity missions (SORT, ASTROD, LATOR) or missions in Earth orbit with optical clocks and advanced links such as OPTIS. Some of these proposals will be submitted to the ESA call for the Cosmic Vision program. However, considering the development time that would be required, such a scenario cannot be considered as a credible alternative to ACES. In fact, even in the most favorable conditions (programmatic and technical), a minimum of 8 years between the ACES flight and a more ambitious mission with optical clocks can be estimated. Thus, in the 2014-2015 time frame, ACES will be the best tool to test General Relativity in space and perform exciting fundamental physics research with the network of the most advanced clocks available on ground. Building upon the ACES developments and results, new explorations in fundamental physics based on a second generation of atomic quantum sensors will then become feasible.

This program is supported by a wide scientific community, which has recently reaffirmed its interest in ACES and in the utilization of quantum sensors based on cold atoms for fundamental research and advanced applications in space. The table in Annex II provides a list of universities, research laboratories, and metrology institutes which have already manifested their intention to participate to the ACES mission, making available their ground clocks and contributing to the data analysis.
7 ACKNOWLEDGEMENTS

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8 ANNEX I

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# Annex II

List of worldwide universities and research institutes that have manifested their intention to participate to the ACES mission, making available their ground clocks and contributing to the data analysis.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Clock</th>
<th>Institute</th>
<th>Contact Person</th>
<th>Country</th>
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