The ACES/PHARO Mission in Flight

Christophe Salomon

2025 Balzan Prize for Atoms and Ultra-Precise Measurement of Time

Balzan GPC Adviser: Massimo Inguscio
Project Director: Christophe Salomon
Co-Directors: Peter Wolf, Philippe Laurent, and Sébastien Bize
Affiliated Institution: CNRS Laboratoire Temps Espace (LTE)
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Christophe Salomon is Emeritus Research Director at the Centre national de la recherche scientifique (CNRS). Christophe.salomon@gmail.com

The Balzan research project will be devoted to the investigation of performances of a cold atom primary caesium clock in space and ultra-precise measurements of time differences between space and ground clocks with a variety of applications in fundamental physics and metrology.

Introduction

After two decades of developments, the European ACES/PHARAO space mission was launched on April 21 2025 by a SpaceX rocket towards the International Space Station (ISS). Since April 28, the Atomic Clock Ensemble in Space (ACES) hardware has been installed on the European Columbus module on an external platform pointing towards the Earth. ACES is run by the European Space Agency. The French Space agency, Centre national d'études spatiales (CNES), hosts the ACES control centre in Toulouse and the mission data repository which is accessed by the ACES Science team. The main ACES data analysis centre is located at the Laboratoire Temps Espace (LTE), Paris Observatory, and is under the responsibility of Peter Wolf; the PHARAO space clock data is analysed under the responsibility of Philippe Laurent, also from LTE, and in coordination with CNES members.

The flight instruments on the ISS involve: (i) a cold atom caesium clock (PHARAO) developed by the Laboratoire Temps Espace at Paris Observatory, the Laboratoire Kastler Brossel at the École Normale Supérieure (Paris), and CNES; (ii) a Space Hydrogen Maser (SHM), developed in Switzerland; (iii) two space-to-ground time comparison instruments, developed in Germany, one working in the microwave domain (MWL), and one operating with short laser pulses operating in the optical domain (ELT); and (iv) a GNSS receiver for precise orbitography and an onboard computer.

Scientific Objectives

The mission objectives include the demonstration of a cold caesium primary frequency standard in micro-gravity with increased coherence time and with $2\ 10^{-16}$ relative accuracy, a 2ppm test of Einstein's gravitational redshift (one order of magnitude gain over present tests), and a search for time variations of fundamental constants and for light dark matter. With its advanced time transfer systems offering one to two orders of magnitude gain over GPS-based distant clock comparisons, ACES will also create a global comparison network of ultra-precise clocks, involving both microwave and optical frequency standards. This is particularly important in the context of the future redefinition of the second of the

International System of Units, which will be based on optical clocks which now surpass microwave clocks by a factor 100.

The ACES mission involves an international collaboration of scientists from the main metrology institutes worldwide: LTE at Paris Observatory (FR), PTB (DE), Wetzell Observatory (DE), NPL (UK), NIST (USA), JPL(USA), NICT (JP), RIKEN(JP), INRIM (IT), and METAS (CH).

In particular, the National Metrology Institutes (NMI's) participating in the ACES mission with a Microwave link terminal antenna and electronic unit connected to UTC are located in seven different countries, five in Europe, one in Japan and two in the USA. With their advanced microwave and optical clocks, they will all contribute to the scientific objectives of the mission by comparing their timing signals to that emitted by those ACES space clocks.

Mission Commissioning Phase

Since its installation on the Columbus module on April 28, the ACES mission has entered into a commissioning phase. The various instruments in space and on the ground are operated from the ACES control centre, CADMOS in Toulouse. The space instruments are currently being tested and characterized. The PHARAO space clock works very well. With very slow atoms, the PHARAO instrument has already produced two-second-long coherence time on the 9.192 GHz caesium hyperfine transition and achieved a relative frequency stability at 1 s of $1.8\ 10^{-13}$. On the other hand, a major surprise has been that the Space Hydrogen Maser did not produce any maser signal despite several attempts to initiate it. The cause of this malfunction is currently under investigation, but the SHM ion pump signal shows an anomalous behaviour, indicating a probable vacuum problem inside the hydrogen bulb. Because SHM was expected to be the onboard comparison local oscillator for assessing PHARAO accuracy in space, the Science team has to revisit the ACES mission measurement campaign strategy and schedule. Assessing PHARAO accuracy will now be done solely via space to ground phase/frequency comparisons using the microwave link.

This link is a two-way link operating in Ku band (up and down) and an S-band downlink is used for measuring the ionospheric and tropospheric delays. According to the data analysis team at Paris Observatory, the MWL time transfer system begins to produce meaningful data for scientific analysis, even if excess noise due to multipath effect on nearby surfaces on the ISS is causing a degradation of performances. Mitigation strategies are currently tested by the Science team. The ACES commissioning phase will end this year and will be followed by a scientific exploitation phase, the Science phase, which will last two and a half years.

The Balzan Research Project

This research project aims at involving young international scientists in the ACES/PHARAO data analysis. The ACES launch has attracted a great deal of interest from the international scientific community and the media. The end of the commissioning phase is an ideal period to start recruiting three young, talented international postdoctoral researchers to support the data analysis team. Over the coming four years, 2026-2029, we envision a two-year-long stay per postdoc, recruited less than four years after the PhD and based at LTE, Paris Observatory, which hosts about seventy researchers working on precision time measurements, clocks, and matter-wave interferometry. Research topics will include the characterization of the accuracy of the PHARAO caesium standard in micro-gravity, testing the Einstein gravitational shift, the search for dark matter, and comparisons of distant ground optical and microwave clocks.

Several directions will be investigated:

(1) Postdoc 1 will be under the responsibility of Peter Wolf, the data analysis responsible scientist at LTE. Within the LTE team, PD1 will be pushing the space to ground time comparison system

to its limits, in the few picosecond per day range. This will enable frequency comparisons between PHARAO and ground clocks at the 10^{-17} level. This requires working on several compensation of systematic timing errors such as conversion from amplitude changes to phase noise changes (AM/PM conversion), and compensation of ionospheric and tropospheric delays. The MWL time transfer will be validated in two modes, common views in Europe where the space clock noise cancels as well as non-common views between Europe and Japan and USA. In the common view mode, we will set up a comparison campaign between European laboratories connected by optical fibers, NPL-LTE-PTB. This will establish the accuracy of the ACES time transfer system on which most scientific objectives rely. The post-doc will set up and manage time-transfer experiments between different laboratories, the associated data analysis at ACES level, also including the data from other time transfer equipment (fibres, GNSS, two-way time transfer). He/she will extract and publish the scientifically meaningful results.

(1) Postdoc 2 will be under the responsibility of Philippe Laurent and Sebastien Bize. They will contribute to a detailed study of systematic frequency shifts in the PHARAO primary frequency standard in flight. This will be done by repeated space/ground time comparisons in various PHARAO operating conditions. As a unique primary caesium clock, PHARAO benefits from the microgravity environment with the possibility to change the atomic velocity over one order of magnitude. Unlike atomic fountains on the ground, this large velocity range offers new clock configurations for the analysis of systematic effects in a primary frequency standard. The second important characteristic of the clock is the frequency stability, described by the Allan standard deviation, which represents the resolution of the frequency measurements. A trade-off will then be found between the stability and the accuracy of the frequency measurements. Once the frequency shifts are characterized and compensated, this data will enable a test of the Einstein effect, the clock gravitational shift. This test relies on the frequency accuracy of the PHARAO clock in space as well as that of the primary caesium standards operated by the various national metrology institutes on the ground. The science goal is to reach a test at 2 ppm level, a factor of 10 improvement over existing tests. A second objective is to keep a high frequency stability on the mid-term (one ISS orbital period, 92 minutes) to be able to perform intercontinental clock comparisons and to realize the network of ultra-precise ground clocks at the 10^{-17} frequency accuracy level and below.

(2) Postdoc 3 will be under the responsibility of Sebastien Bize. He will contribute to the realization of intercontinental clock comparison campaigns using optical and microwave clocks on the ground, the PHARAO/ACES clock as a relay in space, and the MWL. Optical clocks using laser cooled and trapped atoms using Strontium or Ytterbium atoms reach today a relative accuracy better than 10^{-17}. Trapped ion optical clocks based on Yb^+, Al^+ , or Sr^+ ions also reach similar accuracies. In the context of a future redefinition of the unit of time by the Conference Générale des Poids et Mesures (CGPM) in 2030 or 2034, it is particularly important to compare these distant candidate clocks at a level below 10^{-17}, in order to gain confidence in the realization of the SI second over different continents.

These postdocs will be supported by funds to travel to the various National Metrology Institutes contributing to the ACES scientific objectives and to present their results at various international conferences or Balzan events. They will be recruited after open calls indicated on the web page of the LTE and specifically referencing the Balzan prize.

We also plan to support short term visits (1-3 months) of members of the ACES international collaboration in any of the participating institutes for accelerating the process of data analysis and publication writing. This short visit program would be open not only to post-docs but also to middle career researchers.

Finally, for the PhD students and post-docs involved in the ACES mission, a visit of the ACES control centre in CNES Toulouse will be organized.

Conclusion

Quantum technologies on Earth and in space are in a fast development phase as illustrated by the 2025 UNESCO international Year of Quantum Science and Technologies. The subject of cold atoms and fundamental physics in space is expanding strongly today, with, for instance, the NASA's Cold Atom Lab project on the ISS, the European CARIOCA project for atomic interferometry in space, the LISA project for the detection of low-frequency gravitational waves, and the microscope 2 project for testing the Equivalence Principle. Training young scientists in this field will be very useful for those who wish to devote a scientific or industrial career to it.