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The measurement of time / La mesure du temps

The ACES/PHARAO space mission

La mission spatiale ACES/Pharao

Philippe Laurent[a], Didier Massonnet[b], Luigi Cacciapuoti[c],
Christophe Salomon[d,*]

[a] *SYRTE, CNRS UMR 8630, Observatoire de Paris, LNE, UPMC, 61, avenue de l'Observatoire, 75014 Paris, France*
[b] *CNES, Centre spatial de Toulouse, 18, avenue Édouard–Belin, 31401, Toulouse, France*
[c] *European Space Agency, ESTEC, Noordwijk, ZH 2200 AG, The Netherlands*
[d] *Laboratoire Kastler–Brossel, ENS–PSL Research University, CNRS, UPMC, Collège de France, 24, rue Lhomond, 75005 Paris, France*

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ABSTRACT

Proposed in 1997, the ACES/PHARAO experiment is a space mission in fundamental physics with two atomic clocks on the International Space Station, a network of ultra-stable clocks on the ground, and space-to-ground time transfer systems. The ACES flight instruments are near completion and launch in space is planned for the first half of 2017 for a mission duration of three years. A key element of the satellite payload is a cold-atom clock designed for microgravity environment, PHARAO, operating with laser-cooled cesium atoms. Here we first report on the design and tests of the PHARAO flight model, which is now completed and ready for launch. We then briefly present the status of development of the other instruments of the ACES payload, the Space Hydrogen Maser, the microwave time-transfer system (MWL), and the laser time transfer ELT.

RÉSUMÉ

Proposée en 1997, l'expérience ACES/Pharao est une mission spatiale en physique fondamentale avec deux horloges atomiques sur la Station spatiale internationale, un réseau d'horloges ultra-stables à terre et de systèmes de transfert de temps de l'espace jusqu'au sol. Les instruments de vol ACES sont proches de l'aboutissement et leur lancement dans l'espace est planifié pour la première moitié de 2017 pour une durée de mission de trois ans. Un élément-clé de la charge utile du satellite est une horloge atomique à atomes froids conçue pour la microgravité, Pharao, qui fonctionne avec des atomes de césium refroidis par laser. Nous commençons par décrire la conception et les essais du modèle de vol Pharao, qui est maintenant opérationnel et prêt pour le lancement. Nous présentons ensuite brièvement l'état de développement des autres instruments de la plateforme ACES, le maser passif à hydrogène, le système de transfert de temps par liaisons micro-ondes (MWL) et le transfert de temps par lien laser (ELT).

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[*] Corresponding author.
E-mail address: salomon@lkb.ens.fr (C. Salomon).

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1. The ACES mission

Ultracold atoms have become essential tools in modern precision measurements of space-time. Using matter-wave interferometers, local accelerations, gradients of accelerations, and rotations are measured with very high precision, see for instance [1,2]. The measurement of time using atomic clocks has also experienced spectacular progress in the recent years. Both atomic clocks and matter-wave interferometers use quantum mechanical interference between internal or external degrees of freedom to perform very sensitive phase measurements, and, as shown in [3], interferometers and clocks belong to the same class of "quantum sensors". For these sensors, the space environment is very attractive as it offers the possibility to considerably increase the coherent interaction time between electromagnetic fields and freely propagating ultracold matter-waves in well-controlled conditions.

Preliminary demonstrations of cold atom production in reduced gravity [4] and of the operation of a laser-cooled cesium clock in jet plane parabolic flights [5] were followed by atom interferometry in parabolic flights [6], Bose–Einstein condensation in free fall [7] and matter-wave interferometry with large interaction times in a ∼10-m tower [8], and in a free-fall tower [9]. All these experiments prepared the science and technology for bringing these instruments from ground-based operation into micro-gravity conditions to advance the frontier of precision measurements, tests in fundamental physics, and other applications in navigation and geodesy.

The ACES mission (Atomic Clock Ensemble in Space) was proposed to the European Space Agency (ESA) and the French Space Agency (CNES) in 1997 with the goal of operating a laser-cooled cesium primary clock in space and exploit its performance for fundamental physics tests [5,10]. The offered flight opportunity was a payload with a volume of about 1 m^3 outside the International Space Station (ISS), attached to a balcony of the European module, Columbus, which was launched in 2008 to the ISS. The ISS has a nearly circular orbit around the Earth at a mean elevation of 400 km s with an orbital period of 5400 s and an inclination of 51.6 degrees. The ACES scientific objectives have four main components, the operation of a laser-cooled cesium primary standard in space, a precision measurement of the Einstein effect, the gravitational shift of the clock frequency predicted by General Relativity, tests of Lorentz invariance, and a search for time or spatial variations of fundamental physical constants by long-distance clock comparisons.

More quantitatively, the primary ACES scientific objectives are:

- to demonstrate the performance of the cold-atom clock PHARAO in microgravity environment. The expected frequency stability of the cesium clock in space is $1{\cdot}10^{-13}\tau^{-1/2}$ for $1\ \text{s} < \tau < 10^6$ s and accuracy below $3{\cdot}10^{-16}$;
- to demonstrate the performance of an active hydrogen maser in space with a stability of 10^{-13} at 1 s, down to $1.5{\cdot}10^{-15}$ at 10 000 s;
- to perform high-resolution space-ground and ground-ground time and frequency transfer in the microwave domain. The link stability should reach around 0.3 ps after 300 s of integration time and less than 6 ps after 1 to 10 days of integration;
- to perform high-resolution space-ground time transfer using an optical link with 50-ps accuracy and 5-ps stability;
- to perform a test of the gravitational red shift with 2 ppm accuracy;
- to test Lorentz Invariance (LI) in the Robertson–Mansouri–Sexel framework and Standard Model Extension (SME) [11];
- to search for time variations of fundamental constants by global clock comparisons with a sensitivity of 10^{-17} per year.

These mission objectives were previously detailed in [12–15] and are also discussed in [37] and [30]. Here we only summarize the main aspects and present the current status of development of the ACES mission elements.

2. The ACES flight payload

Fig. 1 presents a schematic view of the flight elements. The payload contains two high-precision atomic clocks. PHARAO, a cesium primary frequency standard, operates with atoms that are cooled to 1 μK, corresponding to an *rms* velocity of 7 mm/s. Its design is optimized for operating in micro-gravity environment. SHM, an active (space) hydrogen maser, serves as a phase-preserving reference oscillator with very good short- and medium-term stability. The signals of the two clocks are combined to benefit from the SHM stability in the short term and the PHARAO clock stability on the long term, i.e. above 2000 s, to provide an optimized onboard time scale. These two clocks will be compared to ground clocks operating in the microwave or optical domain using a microwave two-way time-transfer system (MWL) operating in the Ku band as well as a laser time-transfer system ELT. Because of the low orbit of the ISS, a time-transfer session with a ground receiver/emitter will last on average 400 s and can be repeated about 4–6 times per day. Therefore, it is important to perform phase-preserving successive time-transfer sessions in order to reach a precision in time scale comparisons of a few picoseconds and frequency comparisons down to the $1{\cdot}10^{-17}$ range after a few days of averaging. Over a single ISS path, the MWL specification corresponds to a time instability of 0.3 ps, increasing to 5 ps per day and 7 ps at 10 days. The company Airbus Defence and Space (ADS) is the prime contractor for this flight payload. It is responsible for the overall integration, tests, and operation of the ACES ensemble mounted on a temperature-regulated base plate with typical stability of 1 degree Celsius. Launch will be provided by NASA using a Space X rocket in the first half of 2017. The planned mission duration is 18 months, with a potential extension to 3 years.