ATOMIC CLOCK ENSEMBLE IN SPACE

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Atomic Clock Ensemble in Space (ACES) is an ESA mission designed to test the Einstein's Equivalence Principle with high-performance atomic clocks in space and on the ground. Installed onboard the International Space Station, the ACES payload will generate a clock signal with fractional frequency instability and inaccuracy of $1 - 3 \cdot 10^{-16}$. Two links operating on microwave (MWL) and optical (ELT) frequencies will allow comparing the ACES clocks with the best atomic clocks on the ground in a global network. Space-to-ground and ground-to-ground comparisons will provide tests of Einstein's theory of general relativity, at the same time developing applications in geodesy and time & frequency metrology.
The ACES flight model is close to completion. The cold atom clock PHARAO has been tested and delivered for integration in the ACES payload. The ELT link has been completed. MWL and the active hydrogen maser SHM are presently under test. System level tests have already started and will continue all along 2017.
This paper will present the recent progress of the ACES mission and discuss future perspectives for testing fundamental physics with clocks in space.

1 ACES Mission Elements

Proposed to the European Space Agency in 1997, the *Atomic Clock Ensemble in Space* (ACES) mission relies on PHARAO, a clock based on laser-cooled caesium atoms, to generate a high stability and accuracy time reference in space [1,2,3]. The free fall conditions are crucial for PHARAO to reach or even surpass the performance of the best atomic fountain clocks on ground, while keeping a very compact volume, small mass and power consumption. Installed onboard the International Space Station (ISS), at the external payload facility of the Columbus module, the ACES payload distributes its time scale to ground clocks by using two independent time & frequency transfer links, a link operating in the microwave domain (MWL) and the ELT (European Laser Timing) optical link. On the ground, a network of MWL ground terminal and satellite laser ranging stations provides the physical interface between the ACES clock ensemble and atomic clocks on ground.

The ACES payload is shown in Fig. 1. It has a volume of about 1 m^3, for a mass of 230 kg and a power consumption of 450 W.

The main onboard instruments are the cesium clock PHARAO and the active hydrogen maser SHM. The PHARAO clock reaches a fractional frequency stability of $1.1 \cdot 10^{13}/\sqrt{\tau}$, where τ is the integration time expressed in seconds, and an accuracy of a few parts in 10^{16}. SHM is the ACES flywheel oscillator, also providing the frequency reference needed for the onboard characterization of the PHARAO clock stability and accuracy. PHARAO and SHM 100 MHz

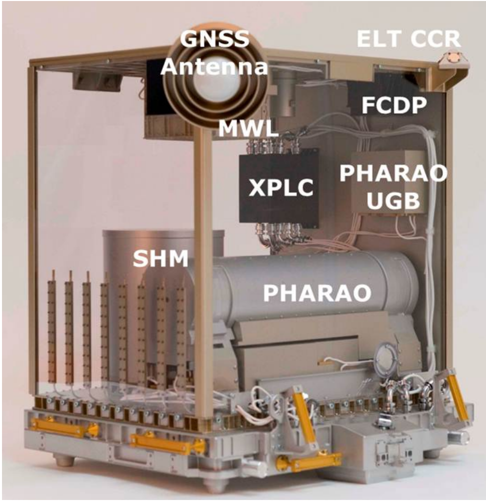

Figure 1 – The ACES payload has a volume of 1 m^3, for a mass of 230 kg and a power consumption of 450 W.

signals are compared in the phase comparator FCDP, which also distributes the ACES frequency reference to the MWL electronics. FCDP performs a phase comparison measurement between the 100 MHz clock signals generated by PHARAO and SHM and uses this information to close a phase-locked loop, which steers the PHARAO local oscillator (USO) on SHM with a typical time constant of a few seconds (short-term servo-loop). At the same time, the frequency difference (Detsynch) between the PHARAO USO and the frequency reference provided by the Cs clock transition is measured in the PHARAO resonator, sent to the ACES onboard computer (XPLC), and used to operate a frequency-locked loop steering SHM on PHARAO with a time constant of a few hundreds of seconds (long-term servo-loop). The two servo-loops lock PHARAO and SHM together generating the ACES clock signal, which now exhibits the short to medium-term stability of SHM and the long-term stability and accuracy of PHARAO.

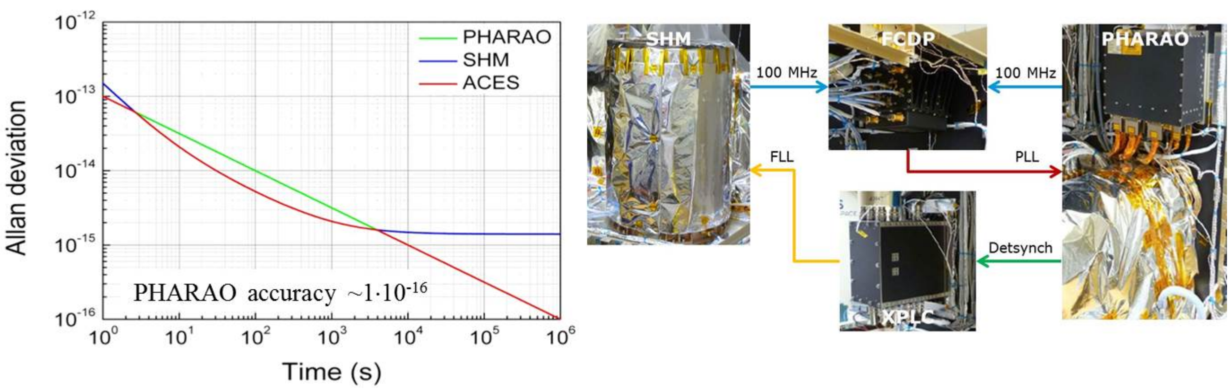

Figure 2 – The clock signal generated onboard ACES.

MWL is the ACES metrology link: coherently with the ACES clock signal, it generates the ACES time scale and compares it with the time scales locally generated by atomic clocks on the ground; furthermore, it stamps the arrival of the electrical pulses generated by the ELT detector in the onboard time. Finally, a GNSS receiver, tracking GPS, GALILEO and GLONASS signals, provides precise orbit data of the ACES clocks. The onboard receiver is driven by the ACES clock signal thus providing one additional link for comparing remote clocks in space and on the ground via the GNSS network. Figure 3 shows the ACES network of MWL ground terminals. Six fixed units will be deployed around the world, at the best institutes for time & frequency metrology: two in the US, JPL (Pasadena) and NIST (Boulder), three in Europe, at SYRTE

(Paris, FR), PTB (Braunschweig, DE), and NPL (Teddington, UK), and one in Japan, at NICT (Tokyo). One transportable MWL station will be located in Europe and shared by other institutes, including the Wettzell geodetic observatory (Wettzell, DE), METAS (Bern, CH), and INRIM (Torino, IT); a second transportable station will be dedicated to the calibration of MWL fixed terminals for time transfer experiments and for comparisons with the laser link ELT. As shown in Fig. 3, space-to-ground comparisons will occur over three continents, at the same time enabling ground-to-ground comparisons over worldwide distances by using ACES as a relay satellite.

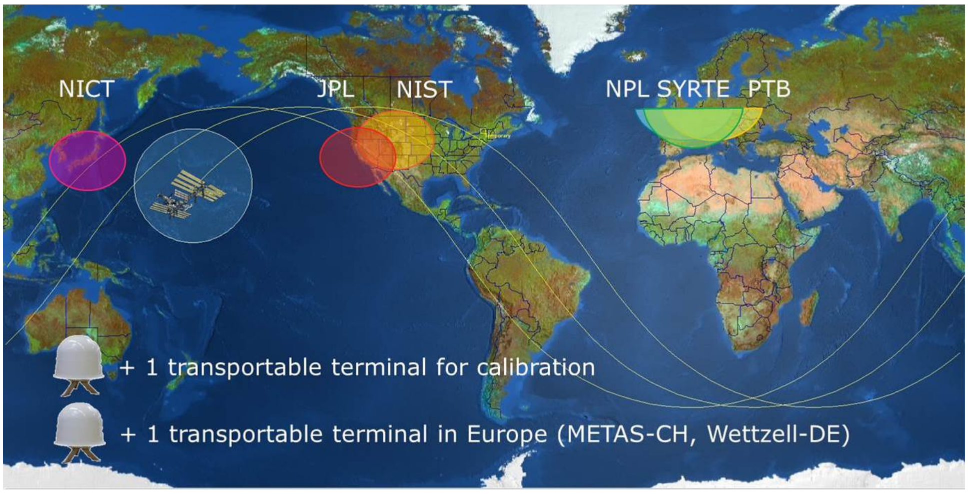

Figure 3 – The ACES network of MWL ground terminals and typical ground tracks of the ISS orbit.

Combined with the growing network of regional links using compensated optical fibers, which have already demonstrated frequency comparison capability at $1 \cdot 10^{-19}$ resolution, clock comparisons at the level of $1 \cdot 10^{-17}$ or better will soon be available with ACES on a global scale. Such performance represents one to two orders of magnitude improvement over the currently used TWSTFT and GPS time transfer systems. Several institutes, such as PTB, SYRTE, and NPL, are already interconnected by a fiber link and additional links will be operational by the time of the ACES mission. Furthermore, the fiber links between NIST and JILA (Boulder, US) as well as between NICT, NMIJ (Tsukuba, JP), and RIKEN (Tokyo, JP) will connect additional institutes sensibly enlarging the ensemble of ground clocks contributing to ACES.

The ground clocks connected to the ACES network are based on different atoms and ions, with transitions both in the microwave and in the optical domain. Microwave fountain clocks are today mature instruments, with fractional frequency stability and accuracy of a few parts in 10^{-16}, able to run on a very high duty cycle ($> 95\%$) [5,4]. They will be compared over the whole mission duration with the ACES clocks. Following the advances in optical frequency measurements using frequency combs, clocks based on the optical transitions of atoms and ions have made spectacular progress in the last years. Several optical clocks have demonstrated a stability of $3 \cdot 10^{-16}$ at 1 s, down to $2 \cdot 10^{-18}$ after 20000 s, and an accuracy in the 10^{-18} range [6,7,8,9,10,11]. These clocks are not yet as reliable as microwave fountain clocks, but with ACES they will be compared over intercontinental distances at 10^{-17} frequency resolution during dedicated measurement campaigns.

ACES, ready for launch in the fall of 2018, will be transported on orbit by Space X and automatically mated at the Clolumbus External Payload Facility (CEPF) by the ISS robotic arm. The ISS has a nearly circular orbit around the Earth with a mean elevation of 400 km, an orbital period of 5400 s, and an inclination of 51.6°. The first 6 months of operations will be devoted to the characterization and performance evaluation of the ACES clocks and links. In microgravity, it will be possible to optimize the interaction time of cesium atoms in the PHARAO clock and tune the linewidth of the atomic resonance by two orders of magnitude. After the clocks optimization, performance in the 10^{16} range both in frequency stability and accuracy are expected. In parallel, the ACES metrology links will be calibrated and characterized. During the second part of the mission (12 months, possibly extended to 30 months), the ACES clocks will be routinely compared to ground clocks operating both in the microwave and in the optical domain.

2 Scientific Objectives

2.1 Testing General Relativity with ACES

According to Einstein's theory of general relativity, identical clocks placed in different gravitational fields experience a frequency shift that depends on the difference between the Newtonian potentials at the clock positions. The comparison between the ACES clocks and ground-based atomic clocks will measure the frequency variation due to the gravitational redshift with a 70-fold improvement on the GP-A experiment [12], testing Einstein's prediction at the 2 ppm uncertainty level.

Time variations of fundamental constants can be measured by comparing clocks based on different atomic species and transitions [13,14]. Indeed, the energy of an atomic transition can be expressed in terms of the fine structure constant α and the two dimensionless constants $m_{\mathrm{q}}/\Lambda_{\mathrm{QCD}}$ and $m_{\mathrm{e}}/\Lambda_{\mathrm{QCD}}$, depending on the quark mass m_{q}, the electron mass m_{e}, and the QCD mass scale Λ_{QCD} [15,16]. ACES will perform crossed comparisons of ground clocks both in the microwave and in the optical domain with a frequency resolution of $1 \cdot 10^{-17}$ in a few days of integration time. These comparisons will impose strong and unambiguous constraints on the time variations of the three fundamental constants reaching an uncertainty of $1 \cdot 10^{-17}$/yr after one year, down to $3 \cdot 10^{-18}$/yr after three years.

The foundations of special relativity lie on the hypothesis of Local Lorentz Invariance (LLI). According to this principle, the outcome of any local test experiment is independent of the velocity of the freely falling apparatus. In 1997, LLI tests based on the measurement of the round-trip speed of light have been performed by comparing clocks onboard GPS satellites to ground hydrogen masers [17]. In such experiments, LLI violations would appear as variations of the speed of light c with the line-of-sight direction and the relative velocity of the clocks. ACES will perform a similar experiment by measuring relative variations of the speed of light at the 10^{-10} uncertainty level.

The possibility of constraining Lorentz-violating Standard Model extension (SME) coefficients of the proton and neutron as well as dark matter models with ACES are presently under study.

2.2 Applications

ACES will also demonstrate a new technique to map the Earth gravitational potential. It relies on a precision measurement of the Einstein's gravitational redshift between two clocks to determine the corresponding difference in the local gravitational potentials. The possibility of performing comparisons of ground clocks to the 10^{-17} frequency uncertainty level will allow ACES to resolve geopotential differences down to 10 cm on the geoid height.

A dedicated GNSS receiver onboard the ACES payload will ensure orbit determination of the space clocks. The receiver will be connected to the ACES clock signal, opening the possibility of using the GNSS network for clock comparisons.

The simultaneous operation of MWL and ELT will allow to cross calibrate the two links. Optical versus dual-frequency microwave measurements will provide useful data for the study of atmospheric propagation delays and for the construction of atmosphere mapping functions in S-band, Ku-band, and at optical frequencies. The ACES links will also deliver absolute ranging measurements, both in the microwave and in the optical domain.

3 ACES Status

3.1 PHARAO

PHARAO is a primary frequency standard based on laser cooled cesium atoms developed by LNE-SYRTE, LKB, and CNES. Its concept is very similar to ground-based atomic fountains. Atoms, launched in free flight along the PHARAO tube, cross a resonant cavity composed of two spatially separated interrogation zones where they interact with a microwave field tuned on the transition between the two hyperfine levels of the cesium ground state (9.192631770 GHz, from the SI definition of the second). In microgravity, the velocity of the atoms is constant and it can be continuously changed over almost two orders of magnitude (5 to 500 cm/s), allowing the detection of atomic signals down to sub-Hz linewidth.

All PHARAO subsystems have passed their qualification tests: random vibrations, thermal cycles, etc. During ground tests, PHARAO is operated under vacuum with the cesium tube aligned vertically and the atoms launched upwards at a velocity of 3.56 m/s. The space environment is emulated by changing the temperature at the clock baseplate and the magnetic field via large external Helmholtz coils. The clock performance tests at CNES lasted 4 months and ended in Summer 2014. The capture, cooling, launch, and detection of cold atoms have been optimized. The frequency stability and the major systematic frequency shifts of the clock have been measured. $5 \cdot 10^8$ atoms can be collected in the PHARAO optical molasses for a laser power of 12 mW/beam and a loading time of 1.5 s. The PHARAO Ramsey fringes are in full agreement with numerical simulations. The central fringe has a linewidth of 5.6 Hz corresponding to an interaction time of 90 ms. In micro-gravity, the linewidth can be reduced to 0.12 Hz at a launch velocity of 50 mm/s.

The PHARAO frequency stability has been measured as a function of the integration time τ by comparing the clock to the SYRTE mobile fountain FOM [18]. PHARAO Allan deviation is $3.15 \cdot 10^{-13}/\sqrt{\tau}$, with FOM contributing $1.3 \cdot 10^{-13}/\sqrt{\tau}$. The clock model predicts a frequency stability of $1.1 \cdot 10^{-13}/\sqrt{\tau}$ in microgravity. PHARAO and FOM frequencies agree to better than $2 \cdot 10^{-15}$. All major systematic frequency shifts have been measured and the frequency accuracy of the PHARAO clock has been thoroughly characterized down to the $1 \cdot 10^{-15}$ level. When operated under microgravity conditions, the PHARAO clock is expected to have an accuracy of $1 - 3 \cdot 10^{-16}$.

PHARAO is now at ADS in Friedrichshafen, integrated on the ACES baseplate.

3.2 SHM

SHM is an active H-maser operating on the hyperfine transition of atomic hydrogen at 1.420405751 GHz. Developed by SpectraTime, SHM provides ACES with a stable fly-wheel oscillator. SHM is designed to fit into a volume of $390 \times 390 \times 590$ mm^3 and a mass of 42 kg, while delivering the typical frequency stability performance of a ground maser. To this purpose, the number of thermal shields has been reduced and a dedicated Automatic Cavity Tuning (ACT) system has been implemented to steer the resonance frequency of the maser cavity against thermal drifts. SHM ACT injects two tones, symmetrically placed around the H-maser signal. The two tones are coherently detected and the unbalance between their power levels is used to close a feedback loop acting on the cavity varactor and stabilizing the resonance frequency of the microwave cavity against temperature variations. This method allows SHM to reach fractional frequency stabilities down to $1.5 \cdot 10^{-15}$ at 10^4 s of integration time.

The SHM sensitivity to temperature and magnetic field variations has been measured. The thermal sensitivity can be counteracted by a fast servo on the ACES baseplate temperature ($<$ 600 s time constant) and by the natural filtering of temperature fluctuations due to the thermal inertia of the instrument. In addition, SHM frequency variations can be calibrated as a function of temperature. SHM sensitivity to magnetic fields has been measured to about $8 \cdot 10^{-14}$/G. At this level, the magnetic field variations along the ISS orbit (± 0.4 G) are expected to introduce a degradation to the H-maser stability of $1 - 2 \cdot 10^{-14}$. These frequency fluctuations will be corrected by the ACES servo-loops. In addition, magnetic field perturbations are suppressed to high degree when taking the frequency difference between alternating PHARAO cycles over 100 s time intervals, as needed for the PHARAO accuracy evaluation. Tests will be performed to better characterize the H-maser sensitivity to external B-fields. In addition, dedicated electronics have recently been implemented in SHM to be able to degauss the mu-metal shields of the clock while on orbit.

The SHM flight model is being completed. Its delivery for integration in the ACES baseplate is expected by the end of 2017.

3.3 ACES Integrated System Tests

The flight model of the PHARAO clock, the SHM engineering model, the flight model of FCDP and XPLC have recently been integrated in the ACES payload to verify that the clocks can be operated close to each other without interfering and to validate the main functions of ACES, including the short and long-term servo-loops. The ACES performance was measured with respect to an ensemble of ground clocks operated at ADS premises in Friedrichshafen, namely an active H-maser stabilizing a cryogenic sapphire oscillator. In addition, the H-maser was permanently compared to UTC(OP) via a GPS link to constantly monitor the PHARAO frequency and to evaluate its systematic shifts. The long-term stability of the ACES clock signal was measured against the H-maser; on the other hand, the cryogenic oscillator was used to evaluate the short-term stability and the phase noise power spectral density (PSD) of the clocks.

After the standard power-on of the payload, SHM was first initialized and tuned. The Allan deviation and the phase noise PSD were measured. SHM Allan deviation is shown in Fig. 4. The measured stability is in good agreement with the SHM performance in stand-alone configuration.

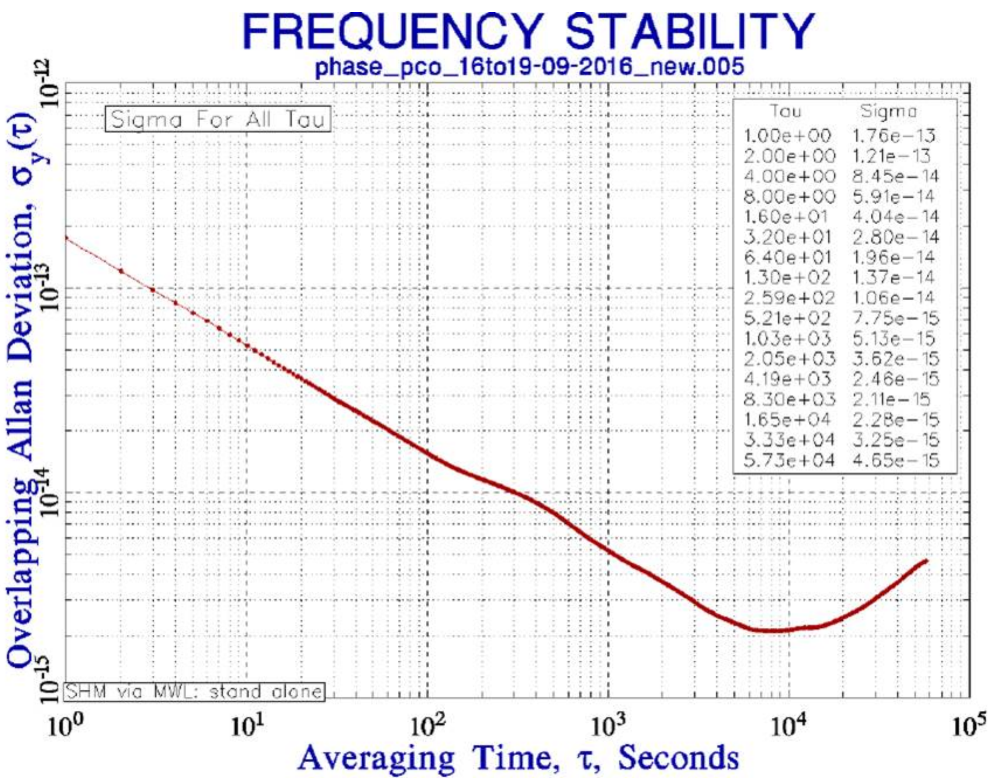

Figure 4 – Allan deviation of the SHM clock integrated in the ACES payload.

As second step, the PHARAO clock was also powered on. PHARAO was first operated in autonomous mode. In this configuration, PHARAO measures the frequency difference (Detsynch) between its local oscillator (USO) and the Cs clock transition, sends this information to the PHARAO onboard computer (UGB) that in turn closes a loop to steer the PHARAO USO on the Cs resonance. The clock stability is reported in Fig. 5, showing a good agreement with the PHARAO stability as measured during clock stand-alone tests at CNES.

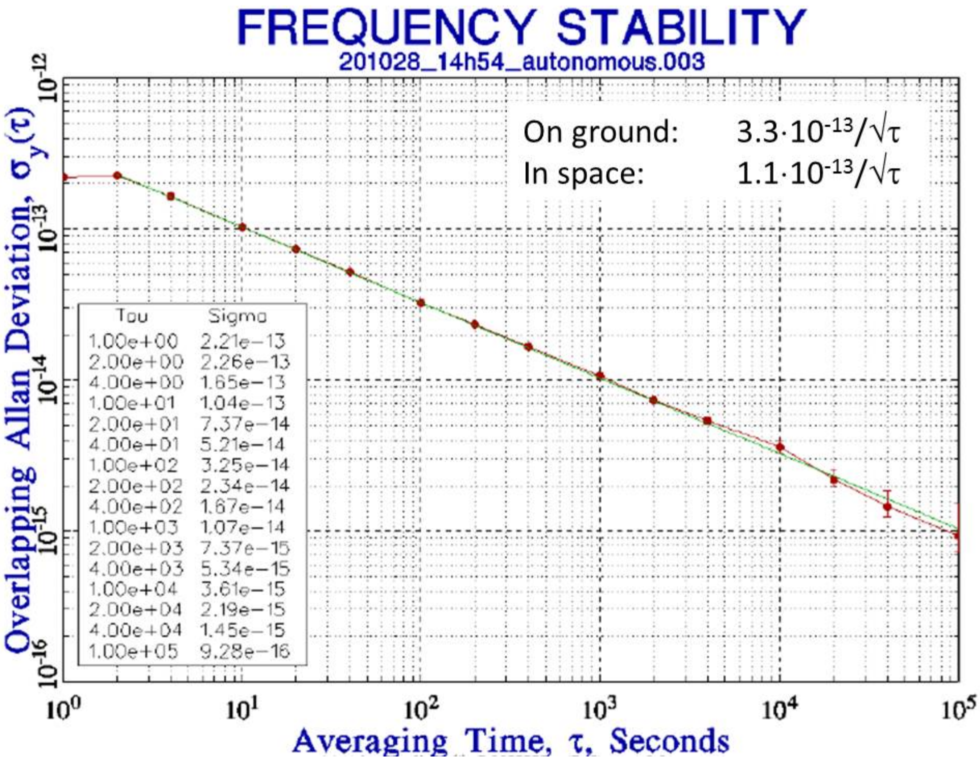

Figure 5 – Stability of the PHARAO clock when operated in autonomous mode on the ACES payload.

Finally, also FCDP was powered on and the ACES signal was distributed at the MWL output. Unfortunately, due to an error in the FCDP firmware, it was not possible to fully test the performance of the short-term servo-loop. The loop could be closed, but it was not possible to change the gain and its time constant to optimize it. On the contrary, it was possible to characterize the long-term servo-loop and evaluate the major frequency shifts affecting the PHARAO clock. This test was performed by operating ACES in its Backup mode. In this configuration, the PHARAO USO is bypassed and the clock is driven by the SHM 100 MHz signal. The long-term servo was closed with the PHARAO clock operated on two different cycles, alternating high-density and low-density clouds of laser-cooled Cs atoms. PHARAO was configured to hold the last Detsynch value when in the high-density cycle to avoid frequency jumps at the SHM output. Figure 6 shows the evolution of the long-term servo-loop error signal (Detsynch) and its Allan deviation. The loop has a time constant of about 500 s. The $1/\tau$ slope observed in the Allan deviation plot for integration times longer than 500 s shows that the loop is correctly operating. For shorter integration times, the Allan deviation shows the performance of the PHARAO clock, now $\sim 1 \cdot 10^{-12}$ at 1 s, dominated by the Dick effect due to the worse phase noise PSD of SHM compared to the PHARAO USO.

Finally, the main systematic frequency shifts at the PHARAO clock were evaluated down to the $1 \cdot 10^{-15}$ level while ACES was operated in Backup mode: the second-order Zeeman effect, the blackbody radiation shift, the cold collisions shift, and the first-order Doppler effect. As final confirmation of the accuracy of the ACES clock signal, an absolute frequency measurement with respect to the Cs fountain clocks operated at LNE-SYRTE in Paris was performed via the

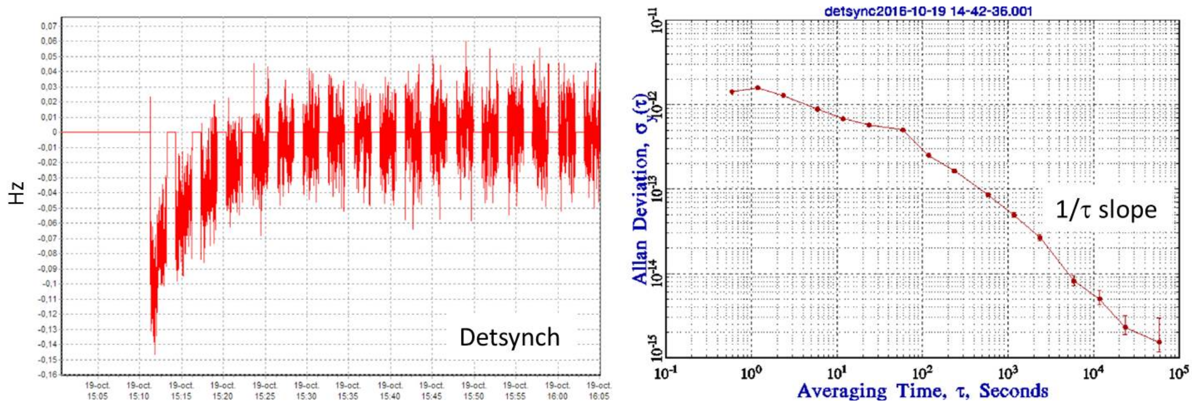

Figure 6 – ACES operated in Backup mode: (left) evolution of the error signal Detsynch when closing the long-term servo-loop; (right) Allan deviation of Detsynch.

GPS link. Figure 7 shows the Allan deviation of the remote comparison between the ground H-maser operated ADS and UTC realization in LNE-SYRTE (UTC(OP)). The comparison reaches a fractional frequency uncertainty of a few parte in 10^{15} after about 10 days of integration time. After estimating the frequency shift due to the gravitational time dilation, the absolute frequency measurement confirmed the evaluation of the PHARAO frequency shift performed in Friedrichshafen to $2 \cdot 10^{-15}$.

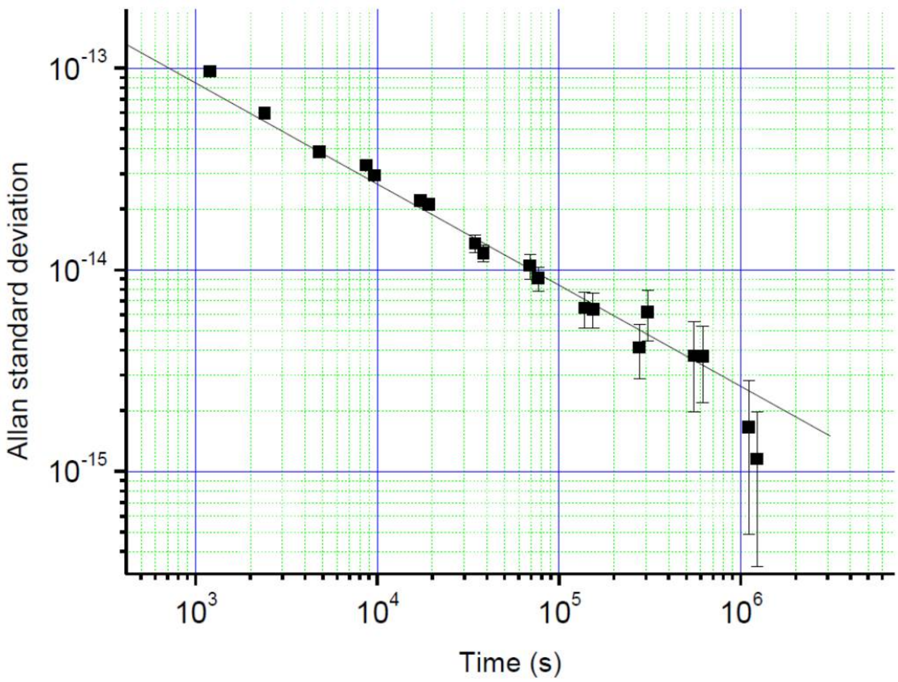

Figure 7 – Allan deviation of the remote comparison between the ground H-maser operated at ADS and UTC realization in LNE-SYRTE (UTC(OP)). The comparison reaches a fractional frequency uncertainty of a few parts in $10^{1}5$ after about 10 days of integration time.

3.4 MWL

The ACES microwave link is developed by ADS, TIMETECH, TZR, and EREMS. The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976 [12] and the PRARE geodesy instrument. The system operates continuously with a carrier frequency in the Ku-band. The high carrier frequencies of the up and down links

(13.5 GHz and 14.7 GHz respectively) allow for a noticeable reduction of the ionospheric delay. A third frequency in the S-band (2.2 GHz) is used to determine the Total Electron Content (TEC) and correct for the ionospheric time delay. A PN-code modulation (100 Mchip/s) on the carrier removes the phase ambiguity between successive comparison sessions separated by large dead times. The system is designed for multiple access capability, allowing up to 4 simultaneous ground users distinguished by the different PN-codes and Doppler shifts.

The engineering model of the flight segment electronic unit has been tested in end-to-end configuration with the ground terminal electronics in the presence of signal dynamics (attenuation and Doppler frequency variations as predicted along the ISS orbit). On the short-term (< 300 s), the time stability is driven by the noise performance of the Ku-band transmitter and receiver and the DLL (Delay-Locked Loop) boards. The 100 MHz chip rate allows to reach a time stability at the 5 ps level already with code measurements. However, the ultimate performance is achieved with the carrier phase measurements, whose time stability is at the level 200 fs at about 100 s of integration time in the presence of signal dynamics. The thermal sensitivity of the system has been calibrated. The sensitivity to a series of key parameters such as clock input power, received signal-to-noise density ratios, supply voltage, Doppler, and Doppler rate has also been measured.

MWL ground terminal (GT) electronics are similar to the MWL flight hardware, symmetry being important in a two-way system to reduce instrumental errors. The electronics unit of the MWL GT has been rigidly attached to the antenna unit to reduce phase instabilities due to the tracking motion. The Ku-band signal is delivered to the antenna feeder via a waveguide; a high stability RF cable is used for the S-band. The antenna is a 60 cm offset reflector with a dual-band feed system automatically pointed in azimuth and elevation by a steering mechanism. A computer controls the steering unit based on ISS orbit prediction files, collects telemetry and science data both from the local clocks and the MWL GT electronics, and it interfaces directly with the ACES Users Support and Operation Center (USOC). The system is housed below a protective radome cover, which also allows to stabilize the temperature of the enclosed volume by an air conditioning system, part of a separate service pallet. The thermal design allows to operate the MWL GT for an external temperature between $-30°$C and $+45°$C.

The MWL flight model is under assembly and board level tests have already started. The delivery of MWL flight segment electronics for integration in the ACES payload is expected by end 2017. The first MWL ground terminal has been deployed in PTB. The network is expected to be completed in the second half of 2018.

3.5 ELT

ELT, acronym for European Laser Timing, is an optical link based on picosecond laser pulses exchanged between Satellite Laser Ranging (SLR) stations on ground and the ACES payload. The onboard hardware consists of a corner cube reflector, a Single-Photon Avalanche Diode (SPAD), and an event timer board connected to the ACES time scale. Laser pulses fired towards the ISS are detected by the SPAD diode and stamped in the ACES scale. At the same time, the ELT reflector re-directs the laser pulses towards the ground station. The measurement of the start and return times on ground and of the detection time in space is then used to determine the desynchronization between space and ground clocks as well as the range.

Developed by the Technical University of Prague and CSRC, the SPAD diode has been tested in conjunction with a laboratory time tagging board providing sub-picosecond resolution. The time deviation of the combined system has a floor slightly below 200 fs. Peak-to-peak time fluctuations amount to a few picoseconds over several days of measurement. The detector is extremely robust against stray light and temperature variations. The temperature sensitivity has been measured between $-60°$C and $+70°$C showing a mean slope as low as 0.48 ps/K.

The flight model of the detector has been tested and delivered. The corner cube reflector is already integrated on the ACES payload.

Acknowledgments

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