ACES Status at Completion of the Engineering Models Phase

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ABSTRACT

Atomic Clock Ensemble in Space (ACES) is a pioneering mission that will use high performance atomic clocks to test fundamental laws of physics. Operated in the microgravity environment of the International Space Station, the ACES clocks, PHARAO and SHM, will generate a frequency reference reaching instability and inaccuracy at the $1{\cdot}10^{-16}$ level. A high-performance link in the microwave domain (MWL) will distribute on ground the ACES signal allowing for comparisons of distant clocks to a frequency resolution of $1{\cdot}10^{-17}$.
ACES will connect ground clocks based on different atoms and atomic transitions in a worldwide network that will probe fundamental laws of physics to high accuracy. Space-to-ground and ground-to-ground comparisons of atomic frequency standards will be used to test Einstein's theory of general relativity including a precision measurement of the gravitational red-shift, a search for time variations of fundamental constants, and tests of special relativity. Applications in geodesy, GNSS remote sensing, optical time transfer, and ranging (via the ELT optical link) will also be supported.
ACES has presently reached an advanced status of development, with engineering models of key instruments and subsystems completed and tested. The ACES Payload Critical Design Review and the Ground Segment Preliminary Design Review were recently completed. The ACES engineering model workbench has been integrated and characterized in a test campaign recently conducted at CNES facilities in Toulouse. The first prototype of the ACES MWL ground terminal is being assembled ready for delivery. The ACES ground segment architecture has been defined. Based on an extension of the standard Columbus USOC (User Support and Operations Center) located in CADMOS – Toulouse, the ACES USOC will remotely control the network of MWL ground terminals, and it will provide the necessary interface with the Columbus Control Center and the ACES user community.
The current development status of the ACES mission elements will be presented and discussed. An overview of future planning will be given.

INTRODUCTION

ACES is a distributed system designed to disseminate a high stability and accuracy clock signal [1,2]. It consists of a space payload generating the ACES atomic frequency reference and a network of ground terminals connected to high-performance atomic clocks on ground.
Transported on the International Space Station (ISS) by the Japanese transfer vehicle HTV in the 2013-2014 timeframe, the ACES payload will be installed at the external payload facility of the Columbus module, using the space station robotic arm.
The ACES payload (Fig. 1) accommodates two atomic clocks: PHARAO (acronym of "Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbit"), a primary frequency standard based on samples of laser cooled cesium atoms and SHM (acronym of "Space Hydrogen Maser"), an active hydrogen maser for space applications. The performances of the two clocks are combined to generate an on-board timescale with the short-term stability of SHM and the long-term stability and accuracy of the PHARAO clock. The on-board comparison of PHARAO and SHM and the distribution of the ACES 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). A GNSS receiver installed on the ACES

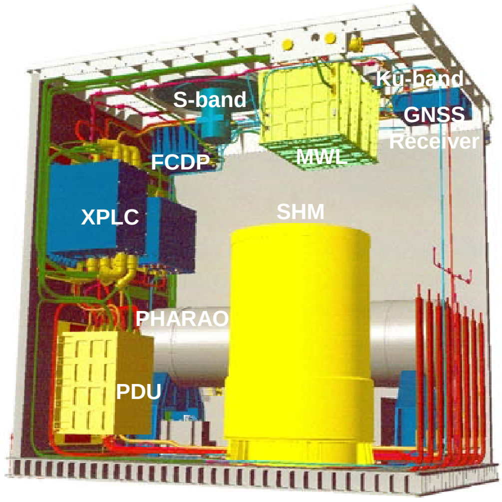

Figure 1: The ACES payload. The two MWL antennas point towards the Earth. Volume: $1 m^3$, mass: 227 kg, power: 450 W.

payload and connected to the on-board time scale will provide orbit determination of the ACES clocks. One of the main objectives of the ACES mission consists in maintaining a stable and accurate on-board timescale that will be used to perform space-to-ground as well as ground-to-ground comparisons of atomic frequency standards. The ACES clock signal will be distributed to ground via a time and frequency transfer link in the microwave domain (MWL). MWL ground terminals connected to the atomic clocks operated by the research institutes participating to the ACES mission will allow space-to-ground comparisons, enabling fundamental physics tests and applications in different areas of research.

The planned mission duration is 18 months. During the first two weeks, the functionality of the clocks and of MWL will be tested. Then, a period of 6 months will be devoted to the characterization and performance evaluation of the clocks. During this phase, a clock signal with frequency inaccuracy in the 10^{-15} range will be available to ground users. Under microgravity conditions, it will be possible to tune the linewidth of the atomic resonance of PHARAO by two orders of magnitude, down to sub-Hz values (from 11 Hz to 110 mHz). After the clocks are optimized, performances in the 10^{-16} range both for frequency instability and inaccuracy are expected. In the second part of the mission (12 months, possibly extended up to 30 months), the on-board clocks will be compared to a number of atomic clocks on ground operating both in the microwave and optical domain.

ACES will perform worldwide comparisons of advanced clocks operating on different atoms or molecules reaching a frequency resolution in the 10^{-17} regime. These measurements will test general relativity and seek for new interactions beyond the Standard Model.

ACES SCIENTIFIC OBJECTIVES

ACES will conduct the first experiments with cold atoms in a freely falling laboratory, it will perform fundamental physics tests to high resolution, and develop applications in different areas of research.

A new generation of microwave clocks for space

A new generation of space clocks reaching frequency instability and inaccuracy of few parts in 10^{16} will be validated by ACES. PHARAO will combine laser cooling techniques and microgravity conditions to significantly increase the interaction time and consequently reduce the linewidth of the clock transition. Improved stability and better control of systematic effects will be demonstrated in the space environment. PHARAO will have a fractional frequency instability of $1\cdot10^{-13}\cdot\tau^{-1/2}$, where τ is the integration time expressed in seconds, and an inaccuracy of few parts in 10^{16}. The reliability offered by active H-masers will be made available for space applications by SHM. SHM will demonstrate a fractional frequency instability of $1.5\cdot10^{-15}$ after 10000 seconds of integration time. Two servo-loops will lock together the clock signals of PHARAO and SHM generating an on-board time scale combining the short-term stability of the H-maser with the long-term stability and accuracy of the cesium clock (Figure 2).

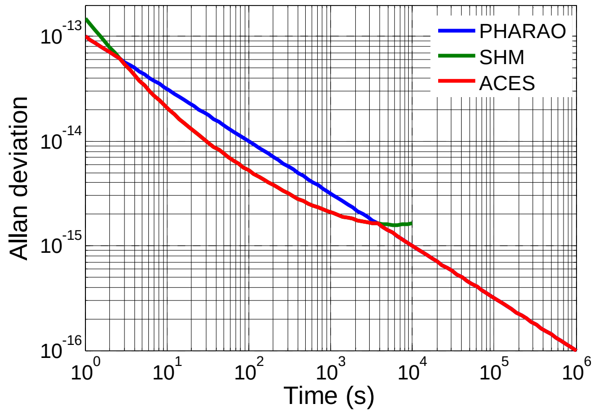

Figure 2: Fractional frequency instability specified for the PHARAO, SHM, and ACES clock signals in space.

Time and frequency transfer

The ACES clock signal will be distributed via a dedicated Microwave Link (MWL). Frequency transfer with time deviation better than 0.4 ps at 300 s, 8 ps at 1 day, and 25 ps at 10 days of integration time will be demonstrated. These performances, surpassing existing techniques (TWSTFT and GPS) by one to two orders of magnitude, will enable common view and non-common view comparisons of ground clocks with 10^{-17} frequency resolution after a few days of integration time. Thanks to the recent development of optical frequency combs [3,4], which significantly simplify the link between optical and microwave frequencies, ACES will be able to take full advantage of the progress of optical clocks [5,6,7], today reaching instability and inaccuracy levels below $1 \cdot 10^{-17}$.

ACES will also deliver a global atomic time scale with 10^{-16} accuracy, it will allow clock synchronization at an uncertainty level of a few hundreds of ps, and contribute to international atomic time scales (TAI, UTC…).

Fundamental physics tests with ACES

According to Einstein's theory of general relativity, identical clocks placed in different gravitational fields experience a frequency shift that, in the frame of the PPN approximation, depends on the difference between the Newtonian potentials at the clocks positions. The comparison between the ACES on-board clocks and ground-based atomic clocks will measure the frequency variation due to the gravitational red-shift with a 35-fold improvement on previous experiments [8], testing Einstein's prediction at the 2 ppm uncertainty level.

Time variations of fundamental constants can be measured by comparing clocks based on different transitions or different atomic species [9]. Indeed, any transition energy can be expressed in terms of the fine structure constant α and the two dimensionless constants m_q/Λ_{QCD} and m_e/Λ_{QCD}, depending on the quark mass m_q, the electron mass m_e, and the QCD mass scale Λ_{QCD} [10,11]. 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 time variations of fundamental constants reaching an uncertainty of $1 \cdot 10^{-17}$/year in case of a 1-year mission duration, down to $3 \cdot 10^{-18}$/year 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 on-board GPS satellites to ground hydrogen masers [12]. In such experiments, LLI violations would appear as variations of the speed of light c with the 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.

Applications

ACES will also demonstrate a new technique, called "relativistic geodesy", to map the Earth gravitational potential. This technique uses a precision measurement of the Einstein's gravitational red-shift between two clocks to determine the corresponding difference in the local gravitational potentials. The possibility of performing comparisons of ground clocks at the 10^{-17} frequency uncertainty level will allow ACES to resolve geopotential differences at 10 cm.

A dedicated GNSS receiver on-board the ACES payload will ensure orbit determination, important for comparing clocks and performing fundamental physics tests. In addition, the GNSS subsystem will be connected to the ACES clock signal, opening the possibility to use the GNSS network for clock comparisons or remote sensing applications (GNSS radio-occultation and reflectometry).

In addition, the ACES payload will accommodate an additional time and frequency link in the optical domain. ELT, acronym of “European Laser Timing”, is an optical link that will allow clocks comparisons, time transfer and ranging experiments. The combination of ELT and MWL will provide a bench to test two different systems, also opening the door to studies of atmospheric propagation delays (optical vs microwave). A breadboard level demonstration of the ELT hardware has been recently completed [13].

ACES STATUS

All ACES instruments and subsystems are in an advanced state of development with engineering models delivered or in final assembly. The ACES Payload Critical Design Review (CDR) and the Ground Segment Preliminary Design Review (PDR) have been successfully concluded.

The ACES Engineering Model (EM) workbench has been integrated and a dedicated test campaign has been recently completed at the CNES facilities in Toulouse (Fig. 3). ACES system level tests have concluded the engineering models phase and released the manufacturing of the flight models. ACES is scheduled for launch on the ISS in the 2013-2014 timeframe.

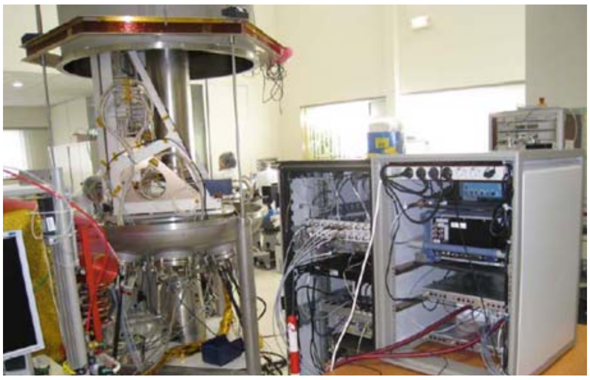

Figure 3: ACES EM system level tests at the CNES facilities in Toulouse. On the left, the vacuum chamber with the ACES EM workbench before being closed; the PHARAO tube is also visible. On the right, the RF support equipment and part of the measurement instrumentation.

The PHARAO clock

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 a major difference: PHARAO will be operated under microgravity conditions. Atoms, launched in free flight along the PHARAO tube, cross a resonant cavity where they interact twice with a microwave field tuned on the transition between the two hyperfine levels of the cesium ground state (9.192631770 GHz). In a microgravity environment, the velocity of the atoms along the ballistic trajectories is constant and can be continuously changed over almost two orders of magnitude (5-500 cm/s), allowing the detection of atomic signals with sub-Hz linewidth.

The cesium clock PHARAO is composed of four main subsystems: the cesium tube, the optical bench, the microwave source, and the computer control. The engineering model of the PHARAO clock has been completed and it is presently under test (Fig. 4).

On ground, because of gravity, PHARAO can only be operated like a fountain clock, with the atoms launched vertically along the tube. Cesium atoms have been loaded in the optical molasses, cooled down to few μK, interrogated on the clock transition by the resonant microwave field, and detected by laser-induced fluorescence emission. Microwave resonance signals (Ramsey fringes) with a signal-to-noise ratio of ~700 have been recorded demonstrating the correct interfacing of PHARAO subsystems and the correct operation of the clock. For a typical launch velocity of about 3.5 m/s, the duration of the free flight between the two Ramsey interaction regions is about 100 ms, corresponding to a width of the central fringe of about 5 Hz. When operated in microgravity, the longer interaction times will allow PHARAO to measure linewidths 10 to 50 times narrower.

The tuning and optimization of the instrument has recently been performed with the atomic cloud launched vertically against gravity at a speed of 3.56 m/s. In these conditions, an Allan deviation of $3.5\cdot10^{-13}\cdot\tau^{-1/2}$, where τ is the integration time expressed in seconds, has been measured. Frequency instabilities of $1\cdot10^{-15}$ have been reached in less than 2 days of integration time. Test results are in good agreement with theoretical predictions and with the instrument specifications. PHARAO performance on ground is mainly set by the phase noise of the local oscillator which is

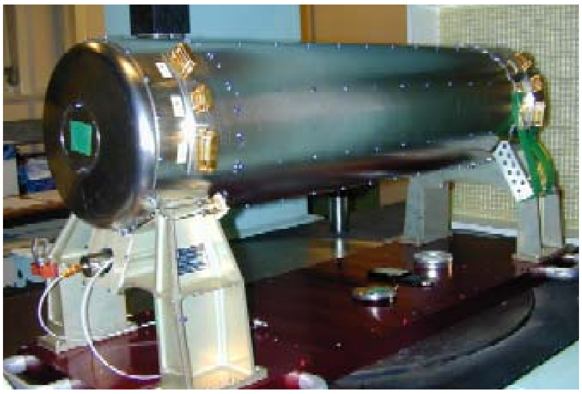

Figure 4: The engineering model of the PHARAO tube. Fully assembled, the tube has a volume of 990×336×444 mm^3 and a mass of 44 kg.

sampled by the atoms in the microwave cavity (Dick effect). In space, this effect will be reduced by one order of magnitude because of the longer interrogation time and the narrower resonance width. PHARAO accuracy evaluation is under completion. Several maps of magnetic field seen by the atoms have been measured by operating the clock on the $m_f=1 \rightarrow m_f=1$ transition and detecting the Zeeman shift of the resonance with respect to the clock transition. A measurement of the collisional shift is presently on-going. PHARAO on-ground is expected to be characterized to the $1\cdot10^{-15}$ accuracy level.

The SHM clock

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. H_2 molecules are dissociated in a plasma discharge and the resulting beam of H atoms is state-selected and sent to a storage bulb. The bulb is surrounded by a microwave cavity that, tuned on the atomic resonance, induces the maser action.

Developed by SpectraTime under ESA contract, SHM provides ACES with a stable fly-wheel oscillator. The main challenge of SHM is represented by the low mass and volume figures (42 kg, 390×390×590 mm^3) required by the space clock with respect to ground H-masers. For this purpose, the number of thermal shields of the clock has been reduced and a dedicated Automatic Cavity Tuning (ACT) system has been implemented to maintain the microwave cavity tuned to the resonance 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 will allow SHM to reach fractional frequency instabilities down to $1.5\cdot10^{-15}$ at 10^4 s of integration time.

SHM EM0, a ground model of SHM, representative in terms of software, interfaces and functions, was delivered for the ACES EM system-level tests. The manufacturing of the SHM EM1 is progressing. The maser cavity and the surrounding magnetic shields have been assembled on a dedicated test bench (Fig. 5). Active oscillation on the

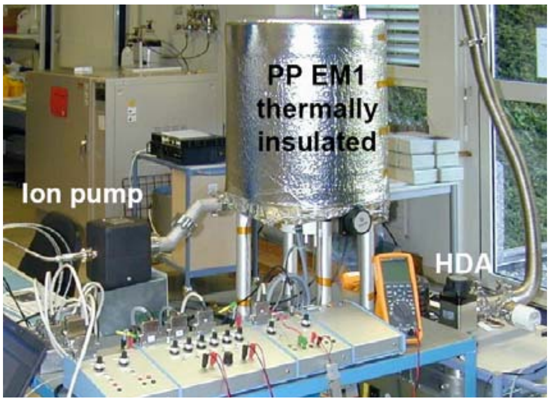

Figure 5: Physics package of SHM EM1 installed on a bench for test purposes. The cavity assembly, the ion pump and the hydrogen distribution assembly are well visible.

hydrogen clock transition has been detected and a power level of -101 dBm has been measured. Preliminary tests show a cavity quality factor of about 44000 and an atomic quality factor of $1 \cdot 10^9$. The H-maser electronics, including receiver and ACT system are presently under test. More details on SHM development and tests can be found in [14].

FCDP

The Frequency Comparison and Distribution Package (FCDP) is the central node of the ACES payload. Developed by ASTRIUM and TIMETECH under ESA contract, FCDP is the on-board hardware that compares the signals delivered by the two space clocks, it measures and optimizes the performances of the ACES frequency reference, and finally distributes it to MWL electronics.

The engineering model of FCDP has been completed and tested. The noise introduced by FCDP on the clock signal distributed at the MWL output has an Allan deviation that decreases as the inverse of the integration time, entering the 10^{-18} regime already after 10^4 s of integration time. The noise floor of the FCDP phase comparator has also been characterized. Its Allan deviation decreases as the inverse of the integration time, dropping below $1 \cdot 10^{-17}$ after 10^4 s.

Ground tests of the ACES clock signal

At completion of the ACES engineering model phase, the ACES EM workbench has been integrated at CNES premises in Toulouse with the objective of testing interfaces, functions, and performance. The ACES EM workbench includes: PHARAO EM, FCDP EM, SHM ground model (EM0), an XPLC test crate, and a PDU (Power Distribution Unit) simulator. Both PHARAO EM and FCDP EM were mounted in the CNES vacuum chamber and operated under vacuum.

As first test step, the ACES clocks were individually powered. A continuous monitoring of the PHARAO and SHM EM0 performance (both Allan deviation and phase noise) allowed to verify that the two clocks do not interfere with each other. Phase noise was monitored with respect to a cryogenic sapphire oscillator. Then, FCDP was also powered and operated to deliver the ACES clock signal at the MWL output. This sequence completed the so called mutual compatibility tests between the ACES clocks and FCDP.

As second step, the short-term servo-loop, steering the local oscillator of PHARAO on the clock signal of SHM EM0, was closed. After optimization of the servo-loop parameters, the performance of PHARAO and SHM EM0 were measured in different operational modes exercising the system both during standard operational conditions and during calibration measurements.

As last step, the long-term servo-loop was also closed and he ACES clock signal, now reproducing SHM EM0 for short-to-medium integration times and PHARAO on the long-term, was generated. The performance of the ACES clock signal was measured against the mobile fountain clock FOM operated by LNE-SYRTE. A long duration measurement was conducted both to characterize the Allan deviation of the ACES signal and to perform a frequency measurement with respect to FOM. Figure 6 shows the stability of the ACES clock signal (red) measured with respect to FOM. For integration times shorter than the long-term servo-loop time constant (~1000 s), the ACES clock signal closely follows SHM EM0, therefore the Allan deviation measurement is limited by the FOM performance. For longer integration times, the long-term servo loop forces ACES on the PHARAO clock signal providing it with the long-term stability and accuracy of the PHARAO clock. Further details on the ACES EM system-level test can be found in [15].

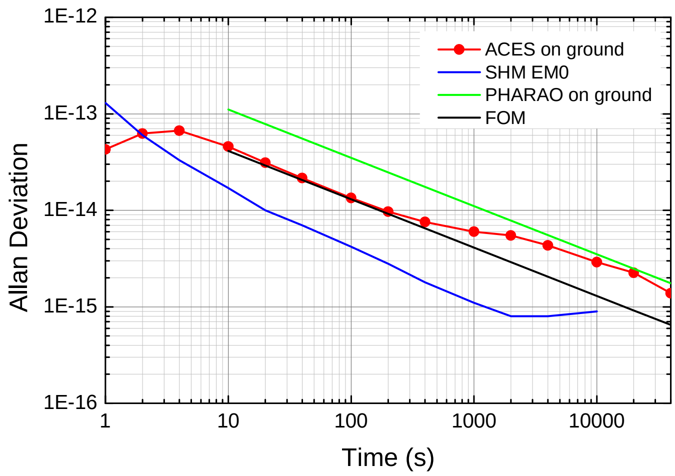

Figure 6: Performance of the ACES clock signal measured on ground with respect to FOM (red) and compared to the performance of FOM (black), SHM EM0 (blue), and PHARAO on ground (green).

MWL
The ACES clock signal distributed by FCDP is finally transmitted to ground stations by the ACES microwave link. MWL is developed by ASTRIUM, TIMETECH, TZR, and EREMS under ESA contract. The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976 [8] 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 ionosphere 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.

MWL flight segment
The engineering model of the flight segment electronic unit has been completed and tested. MWL long-term stability is ensured by the continuous calibration of the receiver channels provided by a built-in test-loop translator. For shorter durations (< 300 s), time stability is driven by the noise performance of the Ku transmitter and receiver and of the DLL (Delay-Locked Loop) boards. The 100 MHz chip rate allows to reach a time stability better than 2 ps already with code measurements. Carrier phase stability is shown in Fig. 7, where time deviations down to 80 fs at about 100 s are reported. For longer durations, time deviation remains well below the 1 ps level even in the worst conditions of signal to noise density ratio (C/N), corresponding to very low elevation angles of the ISS over a ground terminal. The thermal sensitivity of the system has been measured and used to calibrate MWL phase comparison data against temperature variations. The sensitivity to a series of key parameters such as clock input power, received signal to noise density ratios C/N, supply voltage, Doppler, Doppler rate, etc. has been measured. The susceptibility of the system to narrowband and broadband interference, as well as to multipath effects has been characterized.

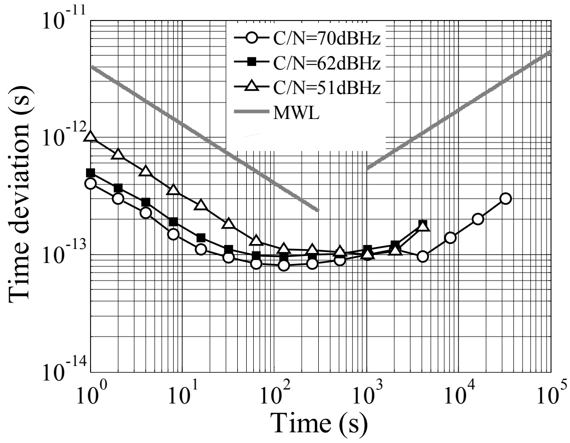

Figure 7: Stability of the ACES MWL carrier phase, expressed in time deviation, for different signal to noise density ratios (C/N). Measurements are compared to MWL system requirements.

MWL ground terminal
The MWL ground terminal electronics is similar to the MWL flight hardware, symmetry being important in a two-way system to reduce instrumental errors. The ACES MWL Ground Terminal (MWL GT) is a microwave station interfacing the local clock on ground to the ACES payload for space-to-ground clock comparisons. To reduce phase instabilities due to the tracking motion, the electronic unit of the MWL GT has been rigidly attached to the antenna unit. 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 clock and the MWL GT electronics, and interfaces directly with the ACES Users Support and Operation Center (USOC). The system is housed below a protective radome cover (Fig. 8), which also allows to stabilize the temperature of the enclosed volume by an air conditioning system, part of a separate service pallet.

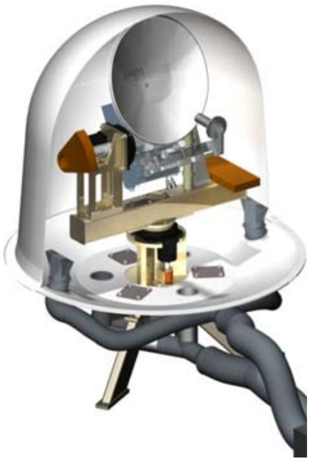

Figure 8: MWL ground terminal system design.

MWL data analysis

MWL provides time-tagged code and carrier phase measurements on the two Ku-band signals (up and down-link) and on the S-band down-link signal. Housekeeping and telemetry data, collected both at the ACES payload and on ground, provide additional calibration parameters (temperature, RF power, etc.) to be applied to MWL raw measurements. ACES scientific products are generated by analyzing MWL raw data, together with additional information, in particular ISS orbitography, parameters for the troposphere model, etc. Data analysis algorithms shall be able to deal with the intrinsic noise of the measurements, possible events of loss of signal, etc. and they shall be able provide results at the expected performance levels even in adverse conditions.

To this purpose, a complete model describing the space-to-ground comparison of clocks via MWL has been developed. The model includes relativistic corrections up to third order in v/c, still non negligible for reaching a frequency uncertainty level well below $1\cdot10^{-16}$. Algorithms to measure and control the instabilities introduced by atmospheric propagation delays (ionosphere and troposphere) are included in the code, as well as algorithms for the correct identification of phase ambiguities and cycle slips. The code has been tested on raw MWL data having the same noise behavior measured during of MWL EM tests and processed by an independent program which is introducing, according to models, atmospheric propagation delays and link-related signal attenuation. The results presented in [16,17] show a good agreement with the ACES system requirements.

ELT optical link

ELT (European Laser Timing) is an optical link presently under development for the ACES mission. The on-board hardware of ELT consists of a Corner Cube Reflector (CCR), a Single-Photon Avalanche Diode (SPAD), and an event timer board connected to the ACES time scale. Light pulses fired towards ACES by a laser ranging station will be detected by the SPAD diode and time tagged in the ACES time scale. At the same time, the CCR will re-direct the laser pulse towards the ground station providing precise ranging information.

The laser link can perform comparisons of distant clocks, both space-to-ground and ground-to-ground, to frequency uncertainty levels below $1\cdot10^{-17}$ after a few days of integration time. Due to the high-stability of the ACES clock signal, non-common view comparisons of clocks across intercontinental distances will be possible with ELT. The optical link also finds interesting applications in the distribution of the ACES time reference and in the synchronization of geodetic observatories. The system will be calibrated to deliver the ACES time scale with an accuracy better than 50 ps. Combined with MWL performance, ELT will contribute to the characterization and crossed-comparison of two different time transfer and ranging systems. Optical versus dual-frequency microwave measurements will also provide useful data for the study of atmospheric propagation delays and for the construction of mapping functions at three different wavelengths.

A study conducted at the Geodetic Observatory of Wettzell has recently confirmed the feasibility of the ELT experiment on ACES. The full detection chain proposed for ELT has been installed in a second independent detection port of the Wettzell Satellite Laser Ranging (SLR) station and tested against the Wettzell detection channel both by ranging a ground target and satellites equipped with corner cube reflectors. Detector properties such as the operation at the single photon light level regime, reliable operation under conditions of high background radiation levels, and detector jitter have been characterized. During the tests, the laser pulse width of the Wettzell SLR station was found to

be 185 ps, well in excess of the specification value of 80 ps. This has led to a jitter in the calibration and satellite return measurements based on the SPAD larger than expected (103 ps and 116 ps, respectively), but still in good agreement with the performance levels as expected from the 185 ps pulse width of the ranging laser [13].
In addition, dedicated tests of the SPAD diode developed for ELT have been recently completed at the SLR stations of Wettzell (10 Hz laser firing rate; 50 ps timing resolution of the detection channel) and Graz (2 kHz laser firing rate; 8 ps timing resolution of the detection channel). The SPAD diode was installed in the detection chains of both stations and used to perform calibration measurements. A time deviation analysis of the Wettzell and Graz measurements showed that the SPAD allows reaching a floor of 5 ps after 500 s of integration time at the Wettzell SLR station, down to about 1 ps after already 10 s of integration time at the Graz station. Such measurements are in good agreement with ELT performance requirements [18].

The ACES on-board GNSS subsystem

A GALILEO/GPS receiver will be part of the ACES payload, directly connected to the ACES clock signal. The system is designed to provide orbit determination and payload positioning for evaluating relativistic corrections in the space-to-ground clock comparison measurements. Additionally, it supports remote sensing applications from space in the field of radio-occultation and reflectometry exploring the use of the new GNSS signals.
The GNSS receiver will be accommodated on the ACES payload while the antenna will be installed externally to the ACES box. In the final configuration, the GNSS antenna will be looking along the flight direction of the ISS, with a tilt angle of about 50° with respect to the ISS velocity vector and 30° in the zenith direction. The GNSS hardware will provide ACES with a completely autonomous system for orbit determination, at the same time avoiding extravehicular activity for its installation. Even if not optimal in terms of visibility towards the GNSS constellation, the selected accommodation of the GNSS antenna fulfills ACES requirements for orbit determination [16]. In addition, this geometry turns out to be particularly favorable for supplementary GNSS science such as radio-occultation and reflectometry.
The current ACES GNSS subsystem baseline consists of a redundant set of commercial-of-the-shelf (COTS) JAVAD GNSS Triumph TRE-G3TH receiver boards and a power and data interface board. The interface board protects the GNSS receiver against latch-up events, it handles and converts the native receiver data flow into the ACES time-slotted protocol, and converts the 100 MHz ACES clock signal down to 10 MHz. The 10 MHz clock signal can be used by the receiver as clock reference signal.
A series of simulations and tests have been recently performed on the GNSS receiver [19] to assess its performances and evaluate its robustness against radiation. Signal simulation studies show that the selected GNSS receiver, based on the JAVAD Triumph technology, provides measurements with excellent quality at the expected high signal dynamics in LEO. The performed radiation tests illustrate that the JAVAD GNSS TRE-G3TH receiver boards can withstand the radiation expected during the ACES mission life time.

ACES ground segment

The ACES ground segment will be integrated within the overall ISS ground architecture providing the communication links between ground and space through the Columbus Control Center (Col-CC) and the NASA ground segment.
The main components of the ACES ground segment are the ACES Users Support and Operations Center and the network of MWL ground terminals connected to the ground clocks participating to the ACES mission. The ground terminals are remotely controlled by the ACES USOC, responsible for defining the planning of the space-to-ground clock comparison sessions along the ISS orbit. Link authorization is regulated by the ACES USOC via Code Division Multiple Access (CDMA) to the MWL flight segment hardware.
The ACES USOC provides all functions related to online monitoring and control of both the ACES payload and the MWL ground terminals network, it defines ACES utilization plan, schedules ACES operations, collects the ACES raw data, generates the ACES data products, and archives them. The USOC also manages external interfaces through which access to the ACES data and data products is provided to the users' community. A detailed description of the ACES ground segment and its functionalities is provided in [20].

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