Atomic Clock Ensemble in Space

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Abstract. Atomic Clock Ensemble in Space (ACES) is a mission using high-performance clocks and links to test fundamental laws of physics in space. 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 $1 \times 10^{-16}$ level. A link in the microwave domain (MWL) and an optical link (ELT) will make the ACES clock signal available to ground laboratories equipped with atomic clocks. 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 Lorentz Invariance tests. Applications in geodesy, optical time transfer, and ranging will also be supported.

ACES has now reached an advanced technology maturity, with engineering models completed and successfully tested and flight hardware under development. This paper presents the ACES mission concept and the status of its main instruments.

1. Introduction

Time intervals and frequencies are physical quantities that can be measured with outstanding accuracy. As a consequence, applications of atomic clocks are numerous and very diverse. Most precision measurements, fundamental constants and SI units can be traced back to frequencies including distances, electrical units, and perhaps in the future the mass unit. With the redefinition of the meter 25 years ago and the choice of a conventional value for the speed of light in vacuum, distance measurements have been simply translated into time interval measurements.

The most visible application of atomic clocks is the satellite Global Positioning System (GPS). GPS receivers are vastly used in geodesy and Earth monitoring as well as for the comparison of distant clocks and for the generation of international atomic time scales. Precise clocks are also used for the datation of millisecond binary pulsars, which emit almost-periodic electromagnetic signals associated with the rotation of the binary star system. Finally clocks are used to perform precision tests of fundamental physical laws and to challenge our knowledge of the Universe.

Atomic Clock Ensemble in Space (ACES) is a fundamental physics mission of the European Space Agency based on a new generation of clocks to be operated in the microgravity environment of the International Space Station. ACES is a distributed system designed to disseminate a high stability and accuracy clock signal [1, 2]. It consists of a payload generating...
Figure 1. Left: The external payload facility of the Columbus module. Right: Detail of the ACES payload; the ACES payload has a volume of $1.340 \times 1.117 \times 1.320$ m$^3$, a mass of 240 kg, for a total power consumption of 450 W.

an atomic frequency reference in space and a network of ground terminals connected to high-performance atomic clocks on ground. Transported on the International Space Station (ISS) by the Japanese H-II Transfer Vehicle HTV, the ACES payload will be installed at the external payload facility of the Columbus module (see Fig. 1). The ACES payload 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 H-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 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. Two high-performance links will be used for the comparison of distant clocks, a link in the microwave domain (MWL, acronym of “MicroWave Link”) and an optical link (ELT, acronym of “European Laser Timing”). The comparison of distant clocks performed by ACES will be the primary data product of the mission. These measurements will be used to test fundamental law of physics and to develop applications in different areas of research.

ACES will be ready for launch in 2014, for a 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, performance 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.

2. ACES Science Objectives
ACES will conduct 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.

2.1. High-performance Microwave Clocks for Space
A new generation of space clocks reaching frequency instability and inaccuracy of a 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 reach a fractional frequency instability of $1 \cdot 10^{-13}/\sqrt{\tau}$, where $\tau$ is the integration time expressed in seconds, and an inaccuracy of a 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 $1.5 \cdot 10^{-15}$ after 10000 s 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 (Fig. 2).

![Figure 2](image-url)  
**Figure 2.** Left: Specified Allan deviation of PHARAO, SHM, and of the ACES clock signal. Right: Specified time deviation of MWL and ELT, compared with the time stability of the ACES clock signal.

2.2. ACES Time and Frequency Transfer Systems
The ACES clock signal will be distributed to a network of ground terminals via a dedicated MicroWave Link (MWL, see Sec. 3.5). Frequency comparisons 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 (see Fig. 2). These performances, surpassing existing techniques (Two-Way Satellite Time and
Frequency Transfer 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 development of optical frequency combs \[3, 4\], the reference signal generated by optical clocks on ground can be easily downconverted in the microwave domain and compared with ACES. In this way, ACES will 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 the 100 ps uncertainty level, and it will contribute to international atomic time scales (TAI, UTC).

ELT, acronym of “European Laser Timing”, will provide ACES with an alternative time and frequency transfer system reaching a time stability of 6 ps after 100 s of integration time, down to 4 ps between 300 s and 10000 s and with a long-term stability of 7 ps (see Fig. 2). The system can be calibrated to deliver the ACES time scale with an accuracy better than 50 ps, finding important applications in the distribution of the ACES time reference and in the synchronization of geodetic observatories.

The ACES clocks and links will allow to establish a global network for the comparison and the synchronization of distant clocks on ground.

Time and frequency transfer experiments at the $10^{-16}$ level require the modeling of relativistic effects in the space-to-ground propagation of electromagnetic signals up to $1/c^3$ terms \[8\], beyond the $1/c^2$ expansion needed for existing links. Future experiments aiming at the $10^{-18}$ level require an expansion up to $1/c^4$ \[9\].

### 2.3. 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 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 70-fold improvement on the GP-A experiment \[10\], testing Einstein’s prediction at the 2 ppm uncertainty level. In \[11\] a claim was made that atom interferometry experiments combined with a local measurement of the gravitational acceleration realizes a test of the Einstein’s gravitational redshift to $7 \cdot 10^{-9}$. However, as shown in \[12\], this claim is incorrect so that the GPA-experiment still remains the most precise test to date.

Time variations of fundamental constants can be measured by comparing clocks based on different transitions or different atomic species \[13\]. Indeed, the energy of an atomic transition can be expressed in terms of the fine structure constant $\alpha$ and the two dimensionless constants $m_q/\Lambda_{QCD}$ and $m_e/\Lambda_{QCD}$, which depend on the quark mass $m_q$, the electron mass $m_e$, and the QCD mass scale $\Lambda_{QCD}$ \[14, 15\]. 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 the three fundamental constants reaching an uncertainty as low as $1 \cdot 10^{-17}$/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 \[16\]. 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.
2.4. Applications
ACES will also demonstrate a new geodesy technique 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 to 10 cm on the geoid height.

A dedicated GNSS receiver on-board the ACES payload will ensure orbit determination, important for comparing clocks and for 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 (radio-occultation and reflectometry experiments).

The simultaneous operation of the optical (ELT) and microwave (MWL) links will provide a test bench for the characterization of the two ACES links. Optical versus dual-frequency microwave measurements will also provide useful data for the study of atmospheric propagation delays and for the construction of atmosphere mapping functions at three different wavelengths. In addition, the ACES links will provide absolute range measurements both in the microwave and in the optical domain.

3. ACES Status
All ACES instruments and subsystems have now reached a high degree of technology maturity, as demonstrated by the tests performed on the engineering models and by the ongoing activities on the flight hardware. The system tests on the ACES Engineering Model (EM) workbench conducted at CNES facilities in Toulouse (see Fig. 3) have represented a major achievement in the ACES development cycle. Their successful completion has indeed closed the EM phase with the performance verification of the ACES clock signal and it has confirmed the adequacy of the ACES design, releasing the manufacturing for the flight hardware.

![Figure 3](https://example.com/figure3.jpg)

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 vertically installed in the chamber. On the right, the RF support equipment and part of the measurement instrumentation.
3.1. The PHARAO Clock

PHARAO is a cesium clock based on laser cooled atoms developed by LNE-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, from the SI definition of the second). 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 to 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 tested. 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 a 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. 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. Once 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 on ground has been performed with the atomic clouds launched vertically against gravity at a speed of 3.56 m/s. In these conditions, an Allan deviation of 3.5 \cdot 10^{-13}/\sqrt{\tau} has been measured, where \tau is the integration time expressed in seconds. Frequency instabilities of 1 \cdot 10^{-15} have been reached in less than 2 days of integration time. PHARAO performance on ground is mainly set by the phase noise of the local oscillator which is 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 has been completed. Several maps of the magnetic field experienced by the atoms along their ballistic trajectories in the PHARAO tube have been measured by operating the clock on the m_f = 1 \rightarrow m_f = 1 transition and detecting the Zeeman shift of the atomic resonance with respect to the clock transition. The contribution of the second order Zeeman effect to the clock accuracy budget is at the level of 6.6 \cdot 10^{-16} for a bias field along the PHARAO tube of 35 nT. The cold collisions shift has been evaluated to an accuracy of 9.5 \cdot 10^{-16}. Second order Zeeman effect and collisional shift are indeed the two major contributors to the clock accuracy, presently evaluated to 1.3 \cdot 10^{-15}. PHARAO accuracy evaluation has been verified by measuring the PHARAO frequency output with respect to the LNE-SYRTE mobile fountain clock FOM (Fontaine Mobile). The result is in agreement with a zero frequency difference within 1 part in 10^{15}.

PHARAO flight model is under manufacturing in SODERN. Figure 4 shows the flight model of the PHARAO tube, recently completed and successfully tested against vibrations.

3.2. 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-
Figure 4. Flight model of the PHARAO tube. Fully assembled (including thermal shields, \( \mu \)-metal shields, fiber-coupled collimators, and harness), the tube has a volume of \( 990 \times 336 \times 444 \text{ mm}^3 \) and a mass of 44 kg.

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, \( 390 \times 390 \times 590 \text{ mm}^3 \)) 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 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 instabilities down to \( 1.5 \cdot 10^{-15} \) at \( 10^4 \) s of integration time. Figure 5 shows the H-maser physics package in the different assembly phases. Active oscillation on the hydrogen clock transition at

Figure 5. Physics package of the SHM engineering model during the different assembly phases.

a power level of -101 dBm has been measured. The cavity quality factor is about 44000 and the atomic quality factor is \( 1 \cdot 10^9 \). The H-maser electronics, including the receiver and the ACT system, have been completed and tested showing an Allan deviation in agreement with SHM performance requirements. SHM EM is presently under test. The test campaign will close the EM phase and release the manufacturing of the SHM flight model.
3.3. 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 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.

3.4. 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 chamber and operated under vacuum (see Fig. 3).

As first test step, the ACES clocks were individually powered. The continuous monitoring of the PHARAO and SHM EM0 performance (both Allan deviation and phase noise) has demonstrated that the two clocks do not interfere with each other. Phase noise measurements performed against a cryogenic sapphire oscillator have shown no degradation with respect to stand-alone characterization of the ACES clocks. Then, FCDP was also powered 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 the 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 FOM, the mobile fountain clock of 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 Cs clock.

3.5. The Microwave Link

The ACES microwave link 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 [10] and the PRARE (Precise Range and Range-Rate Equipment) geodesy instrument. Its purpose is to compare the 100 MHz signal generated by the ground clock to the signal received from the space clock via the microwave transfer link. 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.

3.5.1. MWL Flight Segment  The engineering model of the flight segment electronic unit has been completed and tested (see Fig. 7). 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 0.2 ps already with code measurements. However, ultimate performance is reached with the carrier phase measurements, which can ensure a time stability as low as 70 fs at about 100 s of integration time (see Fig. 7). For longer durations, the time stability remains well below the 1 ps level even in the worst conditions of signal-to-noise density ratio, 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, 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.

3.5.2. 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 (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

Figure 6. Performance of the ACES clock signal measured on ground with respect to FOM (red) and compared to the performance of FOM (blue), SHM EM0 (green), and PHARAO on ground (black).
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, which also allows to stabilize the temperature of the enclosed volume by an air conditioning system, part of a separate service pallet (see Fig. 8). The total weight is 650 kg: 270 kg for the radome pallet and 380 kg for the service pallet and the air-conditioning
system. About 10 kW are needed to power the MWL GT electronics and its temperature control system, the steering unit, and the air conditioning below the radome cupola. The thermal design will allow to operate the MWL ground terminals for an external temperature ranging between \(-30^\circ\text{C}\) and \(+45^\circ\text{C}\).

MWL will be validated in an end-to-end test campaign in which the FS and GT electronic units are connected by cables through a signal simulator. The signal simulator will mimic frequency and amplitude variations of the MWL signal (Ku and S-band) according to the orbit dynamics. The link delays will also be measured preparing for the calibration campaign which will take place on the flight hardware and on the ground terminals after on-site installation.

### 3.6. The ELT Optical Link
ELT is an optical link using laser pulses exchanged between the space segment and Satellite Laser Ranging (SLR) stations on the ground to compare distant clocks. The on-board hardware consists of a Corner Cube Reflector (CCR), a Single-Photon Avalanche Diode (SPAD), and an event timer board connected to the ACES time scale. Laser pulses fired towards ACES by a SLR station are detected by the SPAD diode. The fire and the detection events are tagged in the local clock time scales both in space and on ground. At the same time, the ELT CCR re-directs the laser pulse towards the ground station where it is detected and stamped in the time scale maintained at the SLR station. The measurement of the start and return time on ground and of the detection time in space allows to calculate the desynchronization between space and ground clocks, additionally providing precise ranging information.

A study conducted at the Geodetic Observatory of Wettzell has confirmed the feasibility of the ELT experiment. The full detection chain proposed for ELT has been installed in a second independent detection port of the station and tested against the Wettzell 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, and detector jitter have been characterized. The results have been found in good agreement with the expected performance levels [17].

In addition, the SPAD diode has been tested at the SLR stations of Wettzell and Graz. A time deviation of 5 ps after 500 s of integration time has been measured with the SPAD diode integrated in the Wettzell detection channel. This measurement was limited by the timing resolution of the Wettzell time tagging system. Time deviations down to about 1 ps after 10 s of integration time have been measured at the Graz station thanks to the higher firing rate and the better timing resolution available there [17, 18].

The SPAD diode is presently being characterized in terms of optical to electrical delay. Recent measurements have shown that the absolute delay between the time of arrival of the single photon onto the detector input aperture and the time when the electrical output signal exceeds the pre-defined level can be calibrated to a precision of about 10 ps [19].

### 3.7. The On-board GNSS System
A GPS/GALILEO 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 in the field of radio-occultation and reflectometry, also exploring the use of the new GNSS signals [20]. 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. 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 [21, 22]. 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/data interface board. The interface board protects the GNSS receiver against latch-up events, it formats the native receiver data flow into the ACES time-slotted protocol, and converts the 100 MHz ACES clock signal down to 10 MHz generating a reference that can be used for the receiver operation. A series of simulations and tests have been recently performed on the GNSS receiver to assess its performance 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 low Earth orbit. The performed radiation tests illustrate that the JAVAD GNSS TRE-G3TH receiver boards can withstand the radiation expected during the ACES mission life time.

3.8. The ACES Ground Segment

The ACES ground segment will be integrated in CADMOS-Toulouse 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 the 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 [23].

Acknowledgments

The authors express their warm thanks for their valuable contribution to the ACES science team, to the ACES project team at ESA, ASTRIUM, and TIMETECH, to the PHARAO team at LNE-SYRTE and CNES, to the SHM team at SpectraTime. This paper has been written on behalf of the many scientists and engineers contributing to the mission development.

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