Status of the ACES Mission

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Abstract— **The Atomic Clock Ensemble in Space (ACES) is an European Space Agency project to be deployed externally to the Columbus Laboratory on the International Space Station. ACES, consisting of an cold-atom Cesium clock PHARAO and an active space hydrogen maser SHM, will provide frequency stability and accuracy at the 10^{-16} level which can be disseminated to the ground via a dedicated Microwave Link. ACES is planned to be launched in 2013. Here we report on the current status of the ACES project, the most recent results in the ACES development and the status of preparation for the system test campaign with the ACES Engineering Model subsystems in summer 2009.**

I. ACES Mission Overview

The Atomic Clock Ensemble in Space (ACES) [1,2] is a mission in fundamental physics based on the performances of a new generation of atomic clocks operated in the microgravity environment of the International Space Station (ISS). The station is orbiting at a mean elevation of 400 km with 90 min. of orbital period and an inclination angle of 51,6°. Transported on orbit by the Japanese transfer vehicle HTV, ACES will be installed at the external payload facility of the Columbus module using the Space Station robotic arm.

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 the Space Hydrogen Maser (SHM), an active hydrogen maser for space applications. The performances of the two clocks are combined together to generate an on-board timescale with the short-term stability of SHM and the long-term stability and accuracy of the cesium clock PHARAO. The on-board comparison of PHARAO and SHM and the onboard 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 payload and connected to the on-board time scale will provide precise 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 which 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 transferred to ground by a time and frequency transfer link in the microwave domain (MWL). MWL provides the capability to compare the ACES frequency reference to ground clocks distributed worldwide, 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 the PHARAO clock by two orders of magnitude, down to sub-Hertz 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 (duration of 12 with possible extension up to 30 months), the on-board clocks will be compared to a number of atomic clocks operating both in the microwave and optical domain. ACES will perform worldwide comparisons of advanced clocks operating on different atoms or molecules with 10^{-17} frequency resolution. These measurements will test the

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current laws of physics and seek for new interactions beyond the Standard Model.

II. ACES Scientific Objectives

The worldwide access and the microgravity conditions offered by the space environment make ACES a unique facility. 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. The primary scientific objectives of ACES can be grouped in the following domains.

A. Test of new generation of space clocks

A new generation of 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 reach a fractional frequency instability of $1\cdot10^{-13}\cdot\tau^{-1/2}$, where τ is the integration time expressed in seconds from 1 second up 10 days, 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 only 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 (Fig. 1).

B. Stable and accurate time and frequency transfer via a dedicated Microwave Link

The accurate and stable ACES clock signal will be distributed by a dedicated Microwave Link (MWL). Frequency transfer with time deviation better than 0.3 picoseconds at 300 seconds, 7 picoseconds at 1 day, and 23 picoseconds 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 few days of integration time. From this point of view, ACES will take full advantage of the recent progress of optical clocks [3,4], today reaching instability and inaccuracy levels of few parts in 10^{17}.

In addition, ACES will deliver a global atomic time scale with 10^{-16} accuracy, it will allow clock synchronization at an uncertainty level of 100 picoseconds, and contribute to international atomic time scales (TAI, UTC…).

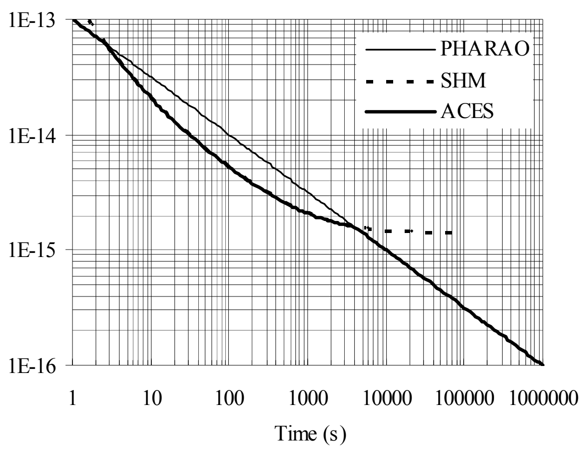

Fig. 1. Expected fractional frequency instability of PHARAO, SHM and of the ACES clock.

C. Conduction of Fundamental Physics Tests

The ACES performances will be used to conduct a suit of fundamental physics experiments to test Einstein's theory of general relativity with improved accuracy. With the progress recently achieved by clocks in the optical domain, accuracy levels even higher than originally foreseen will be reached.

According to Einstein's theory, identical clocks placed at different positions in stationary gravitational fields experience a frequency shift that, in the frame of the PPN approximation, depends directly on the Newtonian potential at the clock position. 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 [6], 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 [4, 5]. 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} [7, 8]. ACES will perform cross comparisons of ground clocks both in the microwave and in the optical domain with a resolution of $1\cdot10^{-17}$ over few days of integration time. These comparisons will impose strong and unambiguous constraints on time variations of fundamental constants reaching an uncertainty of $1\cdot10^{-17}$/year in case of a 1-year mission duration and $3\cdot10^{-18}$/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 [9]. 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 light velocity at the 10^{-10} uncertainty level.

D. Other Applications

A dedicated GNSS system on-board the ACES payload will ensure orbit determination of the ACES clocks to the performance level required for fulfilling the primary mission objectives. The GNSS system together with the ACES clock signal opens the field for other applications, namely clock comparisons via the GNSS network, GNSS radio occultation measurements and coherent reflectometry measurements.

ACES will demonstrate a new "relativistic geodesy" which, based on a precision measurement of the Einstein's gravitational red-shift, will resolve differences in the Earth gravitational potential at the 10 centimeter level. ACES will contribute to the improvement of the global navigation satellite systems (GNSS) and to their future evolution. Better clocks and high-performance time and frequency transfer techniques will be available for space applications. New concepts for global positioning systems based on a reduced set of ultra-stable space clocks in orbit associated with simple transponding satellites could be studied. Finally, ACES could be used to perform GNSS reflectometry measurements and to contribute to the analysis of the Earth atmosphere through radio-occultation experiments.

The implementation of the European Laser Timing unit (ELT) as part of the ACES payload is currently under study and a breadboard level demonstration is under way [10]. ELT would provide the capability for space to ground comparison of clock signals reaching 4 picoseconds at 300 seconds and with a longterm stability better than 7 picoseconds. Space to ground time transfer with accuracy at the 50 picoseconds will also be possible. ELT will also allow laser ranging at the centimeter level per single shot and a comparison of the different ranging techniques would become possible, namely one-way optical ranging vs. two-way optical ranging and microwave ranging. Based on ELT measurements the analysis of propagation delays in the atmosphere will become possible. The ELT performance requirements will be reviewed after completion of the currently ongoing breadboard demonstration tests at the geodetic observatory Wettzell.

III. ACES STATUS

The ACES Mission is presently in phase C/D. All instruments and subsystems are in an advanced state of development with engineering models delivered or in final assembly. The ACES Payload Critical Design Review is planned for summer 2009.

The ground segment baseline design and the overall operation concept has been reviewed and the ground segment Preliminary Design Review is planned in summer 2009.

A. PHARAO

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 two times with a microwave field tuned on the transition between the two hyperfine levels of the cesium ground state. The interrogation method, based on two spatially separated oscillating fields (Ramsey scheme), allows the detection of an atomic line whose width is inversely proportional to the transit time between the two interaction regions. 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 centimeter/seconds) allowing the detection of atomic signals with sub-Hertz linewidth.

The cesium clock PHARAO is composed of four main subsystems: the cesium tube, the optical bench, the microwave source, and the control computer.

The engineering model of the PHARAO clock has been completed and is presently under test at CNES premises in Toulouse. Design and recent results are presented in [11].

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 light-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 launch velocity of 3.42 m/s, the duration of the free flight between the two Ramsey interaction regions is about 100 ms, corresponding to a typical 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. Fig. 2 shows preliminary measurements of the clock performances. A fractional frequency instability of $2.3\cdot 10^{-13}\cdot \tau^{-1/2}$ can be measured for integration times τ between 1 and 10^4 seconds when the PHARAO microwave source is driven by an external cryogenic oscillator. This situation closely approaches the specified stability of $1\cdot 10^{-13}\cdot \tau^{-1/2}$, reachable in a microgravity

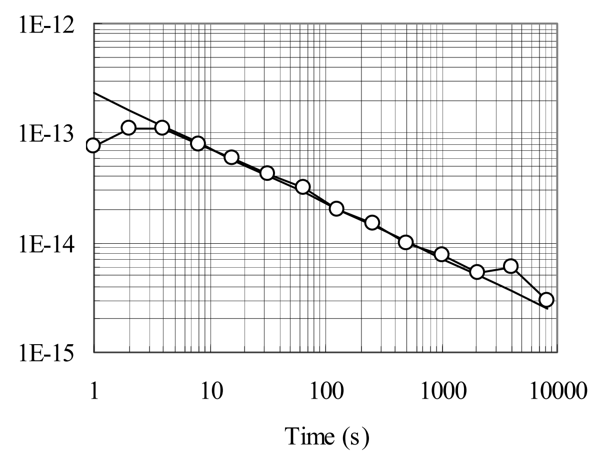

Fig. 2. PHARAO fractional frequency instability as compared to a hydrogen maser. For this measurement, the PHARAO microwave source is driven by an external cryogenic oscillator to approach the operating conditions in space. The stability of $2.3\cdot 10^{-13}\cdot \tau^{-1/2}$ is in good agreement with theoretical predictions.

environment with longer interaction times. The result is in agreement with theoretical predictions based on atom number and cycle duration. When the microwave source is driven by its internal ultra-stable quartz oscillator, the measured stability is $4\cdot10^{-13}\cdot\tau^{-1/2}$. This value is set by the phase noise of the quartz 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 much narrower resonance width.

At the moment the functional and performance tests on the PHARAO clock are ongoing [12] and the PHARAO Engineering model will be delivered for the ACES EM system level test in July 2009.

B. SHM

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 in a storage bulb. The bulb is surrounded by a sapphire-loaded microwave cavity which, tuned on the atomic resonance, induces the maser action.

The SHM is developed at Spectratime (CH) under ESA contract. The SHM EM0 has already been delivered with performances and interfaces representative to the flight model (e.g. onboard software). SHM EM0 will be used for the ACES Engineering Model system level tests starting in summer 2009. The manufacturing of the SHM EM1 representing the SHM FM in form, fit and function has commenced.

C. FCDP

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

Ultra-low phase noise electronics is extremely important to distribute and characterize the signal of high-performance atomic clocks. This technology is now available in a compact system, ready to be used for space applications.

The engineering model of the ACES FCDP has been completed (Fig. 3) and tested. The noise introduced by FCDP on the distributed clock signal rapidly averages down entering the 10^{-18} regime already after 10^4 seconds of integration time. Fig. 4 shows the Allan deviation of the noise floor of FCDP phase comparator. The curve decreases as the inverse of the integration time, dropping below $1\cdot10^{-17}$ for $\tau>10^4$ seconds.

In addition, a specific test has been conducted at CNES premises in Toulouse to validate the performances of the phase-locked loop which stabilizes the local oscillator of PHARAO on the clock signal generated by SHM. The microwave source of PHARAO has been phase-locked via FCDP to the clock signal provided by a cryogenic sapphire oscillator (CSO). The excellent short-term stability of the CSO is crucial for correctly identifying the noise contribution of FCDP when the servo-loop is closed. Fig. 5 shows the Allan deviation plot of the PHARAO microwave source phase-locked to the cryogenic sapphire oscillator and measured against the CSO itself (circles). Measurements are also compared to numerical simulations (squares), to the Allan deviation of the free-running microwave source of PHARAO (triangles), and to the expected performances of the PHARAO clock (solid line). For integration times τ longer than the servo-loop time constant, the Allan deviation of the noise contribution introduced by the short-term servo-

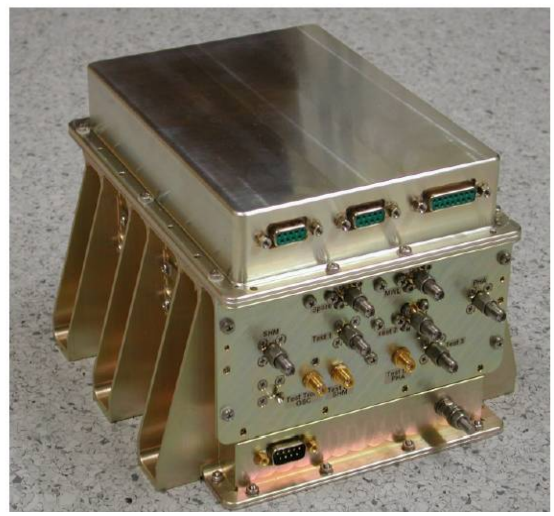

Fig. 3. ACES FCDP engineering model

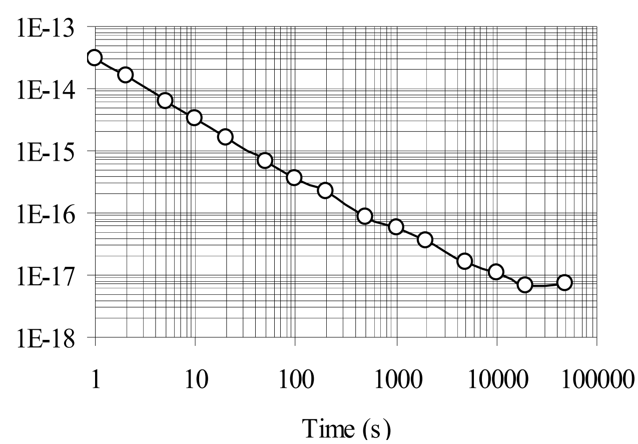

Fig. 4. Allan deviation of the noise introduced by FCDP in the comparsison of the two on-board clcoks.

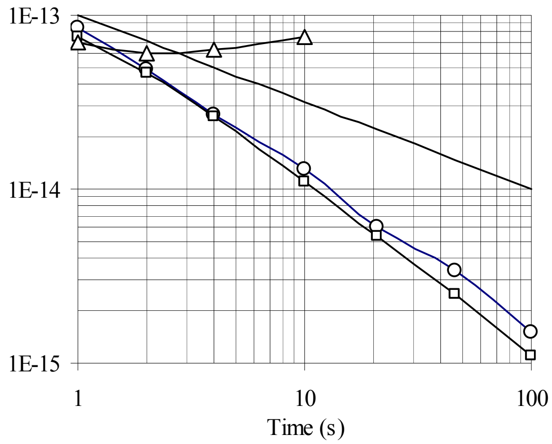

Fig 5. Allan deviation of the PHARAO microwave source phase-locked to the cryogenic sapphire oscillator and measured against the cryogenic sapphire oscillator itself (circles). Measurements are compared to the simulated behavior (squares), to the Allan deviation of the free-running microwave source of PHARAO (triangles), and to the expected performances of the PHARAO clock (solid line).

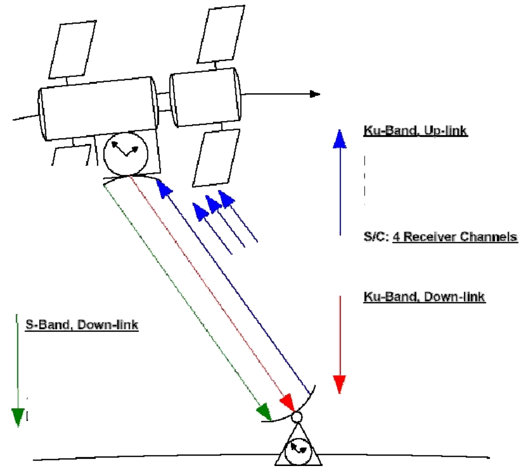

Fig. 6. The MWL system consists of the MWL flight segment and the MWL ground terminal providing two-way communication in the Ku-band and additional downlink comminucation in S-band. The flight segment supports communication sessions with up to four ground terminals simultaneously.

loop rapidly decreases, closely following the simulated behaviour. The measurement has been repeated by using different parameters for the servo-loop transfer function. Finally, the microwave source of PHARAO has been stabilized on the clock signal generated by a H-maser using loop parameters very close to what expected for ACES.

The FCDP engineering model will be formally delivered after the ACES system level tests together with the PHARAO and SHM clocks.

D. MWL

The ACES clock signal distributed by FCDP is finally transmitted to ground stations by the ACES microwave link. MWL is developed by ASTRIUM, Kayser-Threde, Timetech and TZR under ESA management. The proposed MWL concept is an upgraded version of the Vessot two-way technique used for the GP-A experiment in 1976 [6] and is illustrated in Fig. 6. It is composed of the MWL flight segment as part of the ACES payload and a ground terminal located at Time and Frequency institutes.

The system operates continuously with a carrier frequency in the Ku-band (about 15 GHz). The high carrier frequency of the up- and down-links allows for a noticeable reduction of the ionospheric delay. A third frequency in the S-band is used to determine the ionosphere Total Electron Content (TEC). A PN-code modulation of the carrier removes the phase ambiguity between successive comparison sessions separated by large dead times. The system is designed for multiple access capabilities, allowing up to 4 simultaneous ground users distinguished by the different PN-codes and Doppler shifts.

The first set of tests on the engineering model of the MWL flight segment electronic unit has been completed. Tests at MWL system level involving both flight segment and ground terminal are planned to commence in October 2009 and additional environmental tests are planned in 2010.

Code and carrier phase stability determine the performance levels achievable in the comparisons of distant clocks. 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 seconds, corresponding to the ISS pass duration), time stability is driven by the noise performance of the Ku transmitter and receiver and the reproducibility of each DLL channel after proper calibration of internal delays.

Measurements of the code and carrier phase stability have been performed on the engineering model of the flight segment electronic unit. The PN modulated signal, directly derived from the reference clock, is distributed to the transmitter, up-converted to the Ku-band, and fed to the Ku-band receiver via an internal test-loop. After down conversion the signal is finally locked by the DLL to the local clock. The 100 MHz chip rate allows to reach a time stability below 2 picoseconds already with code measurements. However, the full performance level is provided by the carrier phase measurements. As shown in Fig. 7, time deviations below 0.2 picoseconds can be observed on the carrier phase even in the worst conditions of signal to noise density ratios.

The test campaign also verified that the MWL electronics performs according to specification under variation of the thermal environment, the space clock signal amplitude, the RF signal amplitude, the Doppler shift and the input DC power voltage.

IV. 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 Columbus Control Center and NASA ground segment. The main ACES Ground

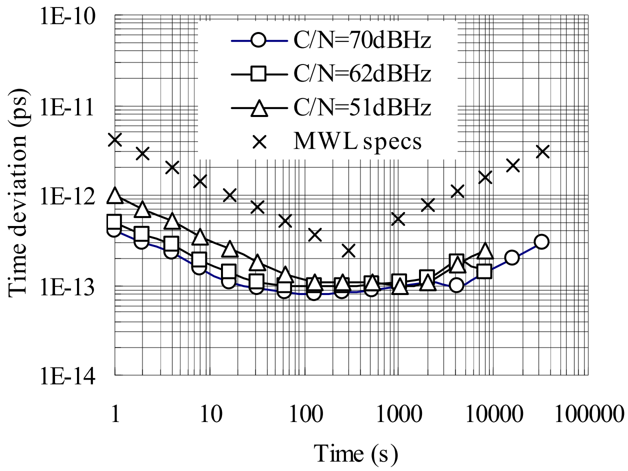

Fig. 7. Stability of the carrier phase, expressed in time deviation, for different signal to noise density ratios (C/N0). Measurements are compared to MWL system requirements

Segment components are the ACES Users Support and Operations Center (ACES-USOC) and a network of MWL Ground Terminals distributed worldwide and connected to the ACES-USOC. The ACES-USOC provides all functions related to online monitoring and control of the ACES payload and the MWL Ground Terminal network, the ACES operational utilization, the ACES operations planning and the provision of the ACES scientific data to the ACES user community. A detailed description of the ACES Ground Segment and its functionalities is provided in [13].

V. Planning up to Launch

With the engineering models of the payload elements now available, a sequence of software interface tests between the ACES onboard computer (i.e. the XPLC) and the various ACES subsystems is conducted. The XPLC-SHM interface test was successfully completed in February 2009 and the XPLC-FCDP in April 2009. The interface tests between XPLC to PHARAO and MWL flight segment are planned in the coming period up to end June 2009.

The ACES System level test campaign will take place in CNES-Toulouse from July to September 2009. This test will bring together all EM hardware and will comprise both functional and performance testing.

The first MWL ground terminal will become available in Autumn 2009 and the MWL end-to-end test between the MWL flight segment and MWL ground terminal is planned to begin in mid October 2009.

The instrument flight models will be delivered late 2011/early 2012. After integration and testing, the ACES payload will be ready for launch in 2013.

Acknowledgment

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