RESULTS OF THE ACES ENGEERING MODEL SYSTEM TEST

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ABSTRACT

Atomic Clock Ensemble in Space (ACES) is a European Space Agency (ESA) project to be deployed externally to the Columbus Laboratory on the International Space Station (ISS). Two high performance atomic clocks on-board ACES generate a frequency reference with stability and accuracy at the $1x10^{-16}$ level. The performance of the ACES clock signal results from the combination of the good short-term stability of an active hydrogen maser (SHM) and the long-term stability and accuracy of a primary standard based on samples of laser cooled Cs atoms (PHARAO). The two clocks are controlled by two servo loops, the first stabilizing the PHARAO local oscillator on SHM clock signal, the second correcting the long-term instabilities of SHM using the error signal generated by the PHARAO Cs resonator. This frequency reference, distributed to the ground by a link in the microwave domain is used to perform comparisons of distant clocks and to test Einstein's theory of general relativity. ACES main instrument and subsystems have now reached a high technology readiness level, demonstrated by the completion and the successful test of their engineering models. In particular, a dedicated test campaign has recently verified the performance of the ACES system, where PHARAO and SHM, locked together via the ACES servo loops, are operated as a unique oscillator to generate the ACES frequency reference. The test campaign conducted at CNES premises in Toulouse between July and November 2009 has concluded the engineering models phase, releasing the manufacturing of the ACES flight models. The setup of the ACES system test campaign, the specific tests performed, and the achieved results will be presented and discussed.

INTRODUCTION

ACES payload is composed of different instruments and subsystems developed by ASTRIUM (D) under ESA contract. The two on-board clocks instruments are: the cold atoms clock **PHARAO,** funded and developed by CNES, which provides a stable and accurate frequency based on Caesium atoms [1]. Thanks to its accuracy in the 10^{-16} level, PHARAO will measure the gravitational red-shift by comparison with accurate clocks on ground with an uncertainty of 2,5 ppm using the ACES MicroWave Link (MWL) [2]. The Space H-Maser **SHM** is developed by Spectratime under the responsibility of Astrium. SHM is the ACES fly-wheel oscillator, important for the in flight characterization of the PHARAO accuracy. In addition, its medium-term stability is important to perform special relativity tests and to compare ground clocks in non-common view.

The two clocks operate together in the ACES system to achieve its final performance. PHARAO USO (Ultra Stable Oscillator) is phase locked onto SHM by the short term servo loop (STSL), with a time constant of a few seconds. The ACES STSL is operated by the Frequency Comparison and Distribution Package (**FCDP**). At the same time the Long Term Servo Loop (LTSL) steers SHM frequency using the error signal generated by Cesium atoms in the PHARAO resonator with a time constant that is a few thousands seconds in the ACES in-flight conditions. On ground, due to the reduced performance of PHARAO, typical time constant is around one day. LTSL is managed by the ACES Application Software resident in the ACES computer (XPLC).
The high level description of the loops is described in Fig. 1.

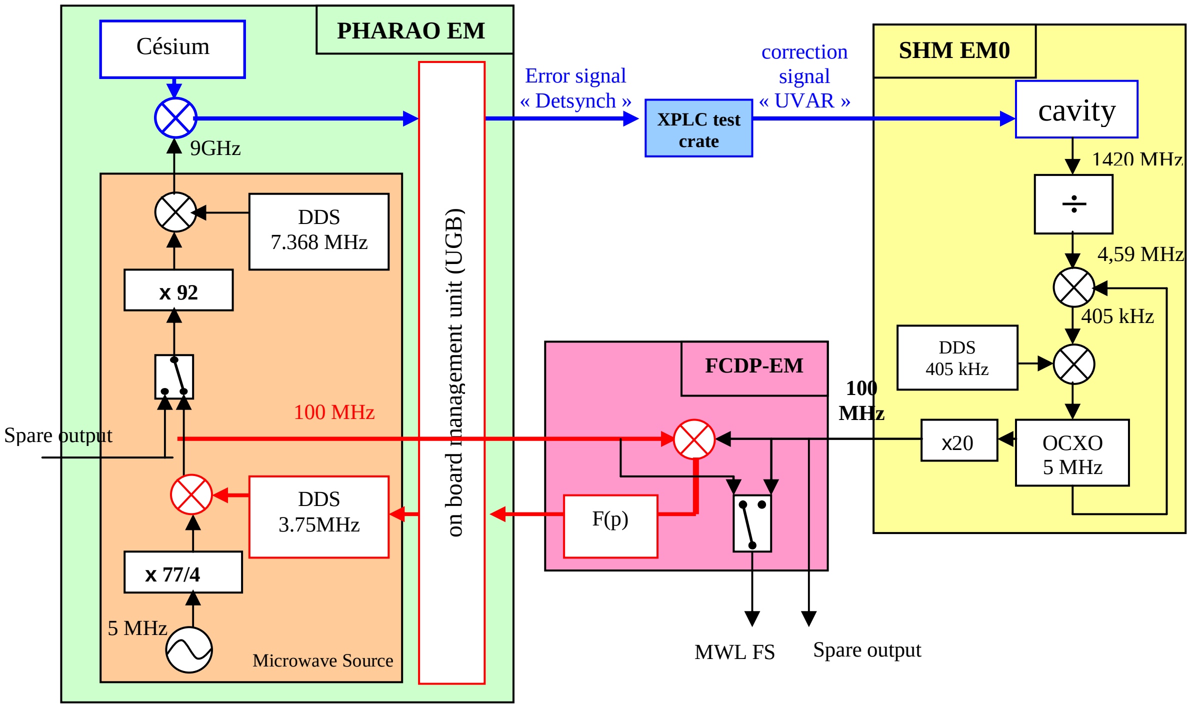


Fig. 1. Simple sketch of ACES EM instruments used for the tests to show the functioning of the loops. The STSL is drawn in red. The LTSL is drawn in blue

The payload is completed by the following elements: The Power Distribution Unit (**PDU**) which is in charge to deliver power to all the subunits, the **XPLC** who manages all the internal and external communication, the Microwave link (**MWL**), the European Laser Timing (**ELT**) optical link and a **GNSS** subsystem providing orbit determination of the ACES clocks.
Before completion of the ACES EM phase, a test campaign at system level has been conducted to verify interfaces, functions, and performances of the ACES EM workbench assembling together: PHARAO EM, SHM ground model (EM0), FCDP EM, and the XPLC test-crate where the ACES ASW (Application Software) V1 was running to control the complete system. The ACES EM workbench was powered by a test equipment simulating the ACES PDU.
The campaign was an important test step where, for the first time the engineering models of the ACES instruments and subsystems came together for interface, functional and performance verification. Tests were performed under the ACES nominal operating conditions with both the STSL and LTSL closed.
The objectives of ACES System tests can be summarized as follows:

- Assemble for the first time the sub-systems of ACES in order to:
    - Validate the ASW interfaces and protocols to the subunits
    - Verify the functionality at system level
    - Verify the performances at system level
- Prepare and validate a procedure for the FM tests
- Validate the Loop Optimization Tool software [5]

SET-UP OF THE ACES TESTS

The ACES payload involves high performance microwave clocks, consequently, it is not easy to find frequency references good enough to validate its performances even on ground where the PHARAO performance are degraded with respect to its nominal operation in space. To perform such validation the rationale is to use a set of reference clocks to characterize the stability of the ACES clock signal for different integration times:

- For short integration times the Cryogenic Sapphire Oscillator (CSO) from the University of Western Australia (UWA) whose Allan Deviation is better than SHM-EM0 until 100 seconds was used. The use of CSO is then well suited to characterize the STSL. Moreover, the CSO has very low phase noise and therefore it can be used as reference to measure the phase noise of ACES. As the CSO output signal is at 12 GHz a dedicated microwave support has been used to down convert it to generate 100 MHz and 9 GHz reference signals.
- For long integration times, the mobile fountain (FOM) from SYRTE was used to validate long term stability and accuracy of ACES. FOM is then well suited to characterize the LTSL.
- During the test campaign it turned out, that due to the excellent performance of the SHM EM0 at medium term no better reference was available at CNES Toulouse. Therefore the medium term behaviour of ACES could not be fully characterized.

Using the test outputs on the ACES subsystems it was possible to measure directly the ACES signals routing them to dedicated measuring equipments. This allowed to validate the information included in the ACES Telemetry against direct measurements that will not be available in flight. Different direct measurements have been performed: stability measurements, phase noise measurements and phase transient measurements.

The measurement of the signal stability, expressed by an Allan Deviation (ADEV) plot, is provided by a dedicated RF EGSE (PCO part). The PCO is a phase comparator which can measure the phase of 5 inputs by comparison with one reference. The frequency reference used for the PCO was CSO locked on SHM EM0 with a time constant of about 100 seconds. The post processing of the phase comparison data gives us the stability of SHM and PHARAO (after passing through the FCDP) with respect to this reference.

Two different systems have been used to perform phase noise measurements. The first one was the test bench available in CNES and extensively used during the unit level test of PHARAO, the second one was the phase meter included in the Astrium RF EGSE used to characterize FCDP EM phase noise during the unit level tests. This measurement is important because the final stability of PHARAO, and so of ACES, depends on the phase noise of the 9 GHz coming from the Microwave Source (SH) of PHARAO [3] or from SHM via the spare output (this signal is used in the backup mode in case of failure of the PHARAO USO).

The functioning of PHARAO is cyclic: with a typical period of about 1 s, atoms are laser-cooled, launched, probed on the Cs clock transition in the Ramsey cavity, and finally detected. If the phase of the USO is perturbed synchronously to the PHARAO cycle, this perturbation will systematically affect the atoms interrogation in the Ramsey cavity, and the accuracy of PHARAO can be degraded. For this purpose, phase transient measurements are used to detect any disturbance synchronous to the PHARAO cycle, after integration of the different subsystem together with PHARAO in the ACES EM workbench.

During ground tests ACES is commanded by a PaCTS system (Payload Control Test System). The PaCTS has been designed to test the payloads to be operated on the International Space Station and it has been extensively used in many other missions before. It has a standard interface with the database (TC and TM) defined by the specific ASW, therefore the ACES database could be tested during the EM verification.

To have a consistent archiving system of all data coming from different EGSEs and ACES a dedicated archive system has been implemented as part of the ACES EGSE.

PERFORMANCES OF THE ACES CLOCKS

Stability

Due to gravity effects the PHARAO stability differs on ground and in flight: in flight the stability will be better as the free-fall conditions allow to launch the atoms with very low velocity whereas on ground the gravity imposes to launch the atoms with a minimum velocity limiting the interaction time in the Ramsey cavity. Consequently the stability of PHARAO-EM on ground is only $3{,}4.10^{-13}.\tau^{-1/2}$ while full performance of $9.10^{-14}.\tau^{-1/2}$ would be reached in space.

SHM-EM0 has been characterized in CNES before starting the ACES EM tests using the CSO, FOM, and an H-Maser. The stability of SHM-EM0 at one second is around 9.10^{-14} with a very low drift of 6.10^{-16} per day.
The ADEV of PHARAO and SHM are given in Fig. 2.

The ADEV plot of the two clocks permits to see the crossing between the stability of the USO and SHM giving the time constant that is needed to optimize the Short Term Servo Loop in order to have the best performance.
Similarly, the crossing between the stability of SHM and PHARAO can be seen. It gives the time constant needed to optimize the Long Term Servo Loop, steering the SHM EM0 frequency on the stable and accurate signal of PHARAO.
These measurements are then used as reference inputs for the Loop Optimization Tool. This is a dedicated MATLAB code, developed by Timetech and Astrium, to reproduce ACES clocks´ behaviour. Choosing different loop filter parameters for the two ACES loops it is possible to simulate the performance of the final ACES signal. The objective is to have a very reliable simulation tool in order to optimize parameters, and load them on ACES by TC, rather than perform such procedure on the real clocks during the mission.

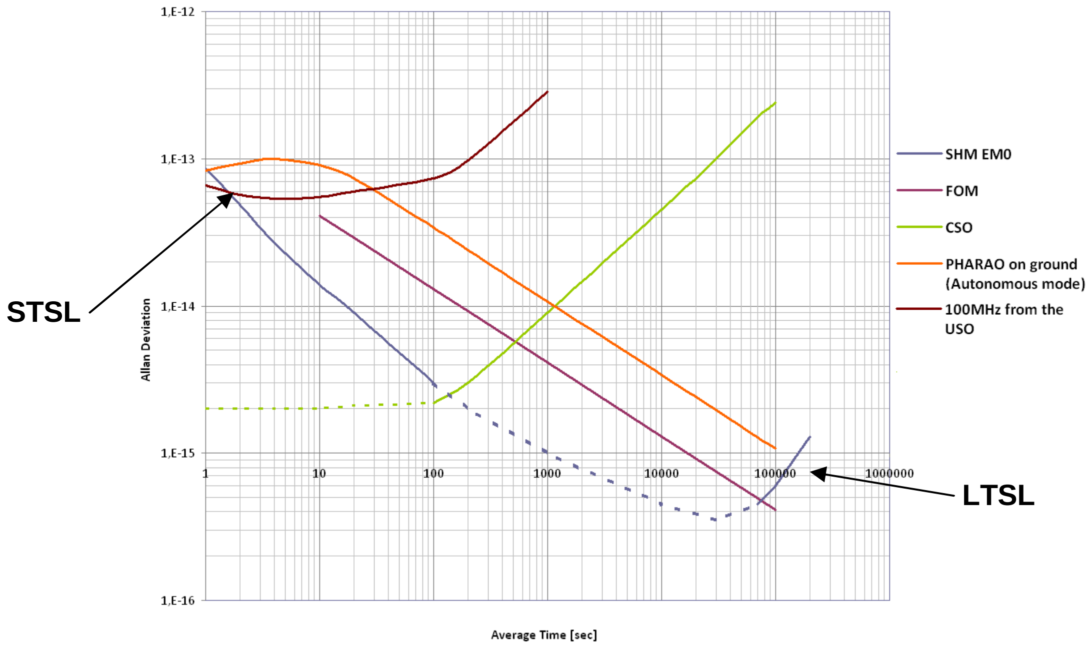


Fig. 2. ADEV of PHARAO-EM in Autonomous mode and SHM-EM0, superimposed on the ADEV of the CSO and FOM. The doted lines are due to the fact that we had no better clock available to test this part of stability

Accuracy

The measurement of the accuracy of PHARAO is described in [4]. Its accuracy is a few 10^{-15}. The LTSL should transfer the frequency of PHARAO to SHM. To verify this point, the error signal of “Detsynch” (see Fig. 1) should average to zero. Secondly FOM can be used to verify that the frequency of ACES is the same than PHARAO.

Phase noise and Phase transient

The phase noise of PHARAO and SHM and the phase transient of PHARAO are given in Fig. 3. In the phase transient measurement a synchronous phase perturbation around 500ms is present in the reference measurement. This perturbation is a well known feature, which is due to a PHARAO microcommand which occurs before the atoms cross the Ramsey cavity.

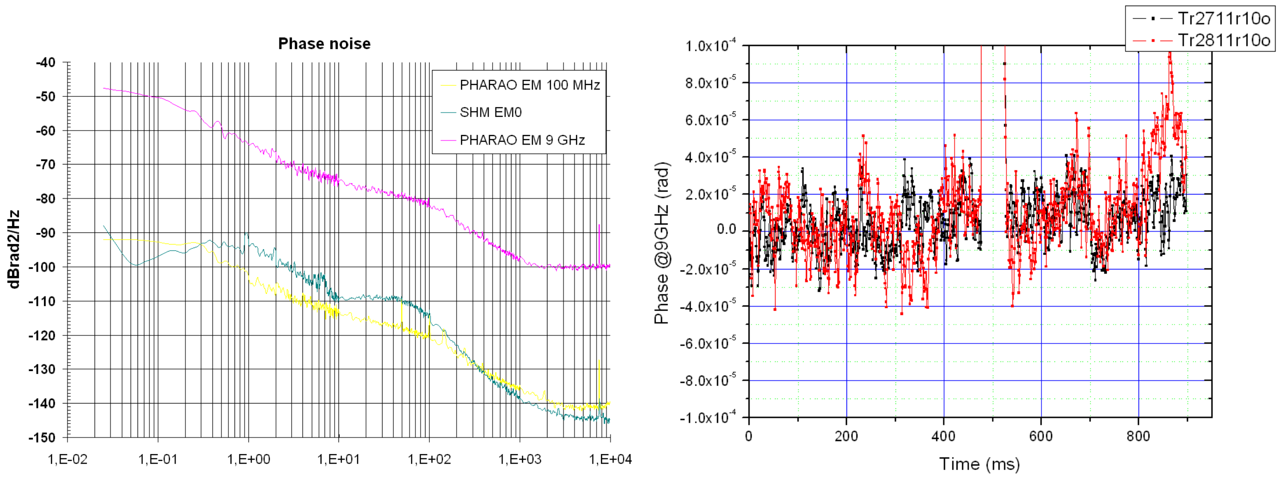
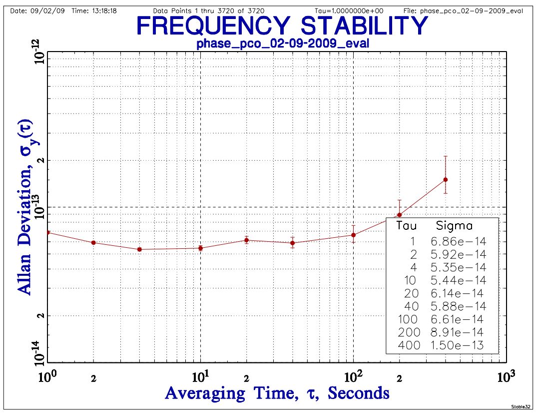


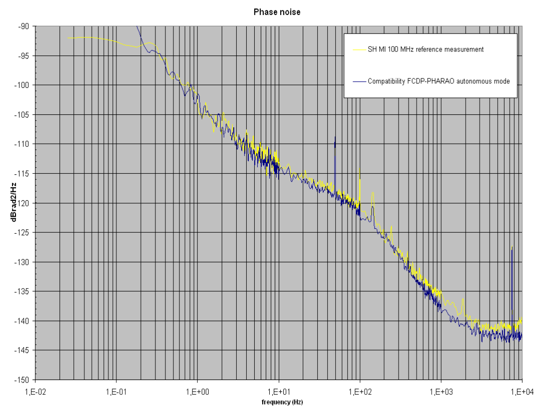
Fig. 3. Phase noise of the 100 MHz and 9 GHz delivered by the Microwave Source of PHARAO EM and by SHM (left). Phase transient measurement of PHARAO at 9 GHz for two runs of measurement (right, in red and black)

AUTOCOMPATIBILITY TESTS

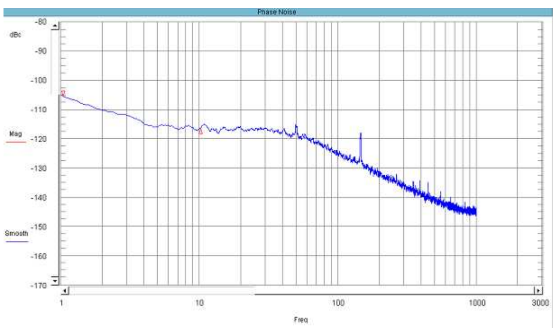
The objectives are to verify the compatibility between all the subsystems involved in the tests while they are working together. ACES TM managed by the ASW and RF measurements performed with test equipments are compared with the one collected during the unit level tests to see if any disturbance due to a crosstalk between the instruments appears. During the tests, different instruments modes of PHARAO and FCDP are exercised. As an example, we plot in Fig. 4 some measurements done during the tests.



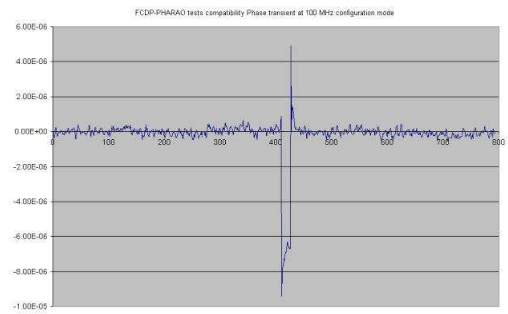
ADEV of PHARAO in Configuration mode with the PCO (we see the stability of the USO)



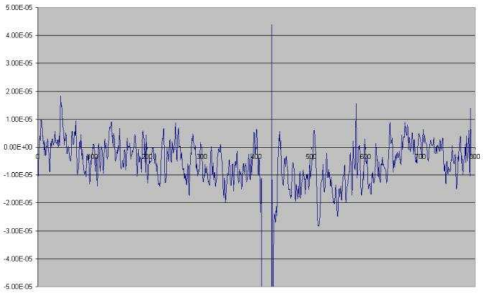
Phase noise at 100 MHz of PHARAO in Configuration mode with CNES test bench



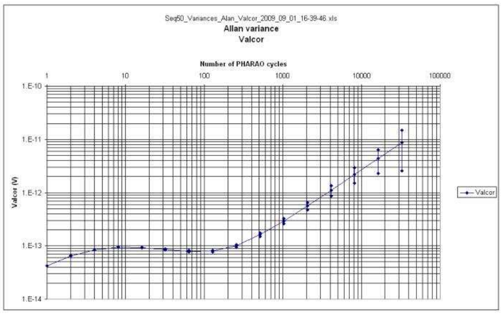
Phase noise at 100 MHz of PHARAO in Configuration mode with Astrium test bench



Phase transient of PHARAO at 100 MHz in Configuration mode with CNES test bench



Phase transient of PHARAO at 9 GHz in Configuration mode with CNES test bench



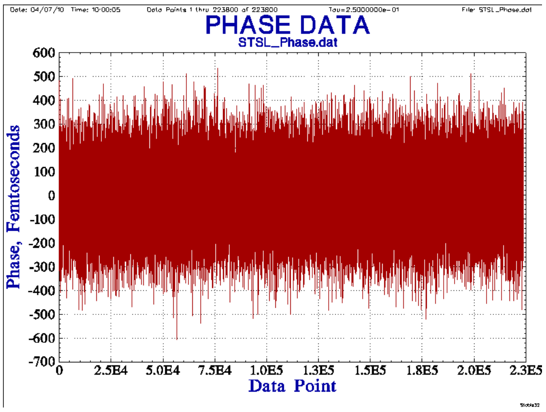
ADEV of PHARAO in Autonomous mode from the frequency correction data applied to the PHARAO local oscillator (Valcor)

Fig. 4. Example of measurements performed during the Autocompatibility tests when PHARAO is in Configuration mode and in Autonomous mode. In Configuration mode, the PHARAO local oscillator is free running; in Autonomous mode, a servo loop steers the PHARAO local oscillator using the error signal generated by Cesium atoms in the PHARAO clock. The known phase transient caused by the PHARAO microcommand are clearly visible in the phase transient diagrams.

No perturbation has been found in the measurements with respect to unit level tests in the exercised operational modes and no TM parameter collected by the ASW showed an unexpected behaviour. The test was successfully completed.

SHORT TERM SERVO LOOP TESTS

The first step was to verify that the STSL can be closed correctly. The frequency delivered by the Microwave Source of PHARAO is compared to the one from SHM EM0 in the FCDP: when the measured frequency difference is lower than a specific threshold (0.1 Hz) FCDP goes automatically in phase comparison mode and closes the phase locked loop. Phase comparison measurements are collected through the FCDP scientific telemetry (refer to Fig. 5a). Through the FCDP telemetry, it is possible to directly check how the loop is behaving looking at the frequency correction when the loop has been commanded to be closed. (refer to Fig. 5b). The frequency correction (FCW) is routed directly to the PHARAO USO via the serial line protocol that manages the communication between the subsystems (red arrow in Fig. 1).



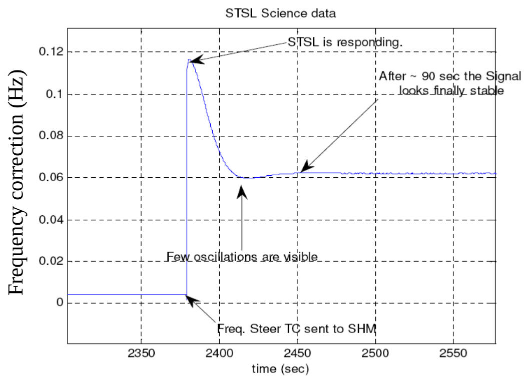


Fig. 5a

Fig. 5b

Fig. 5. Fig. 5a shows the Phase Deviation Values (PDV) computed by FCDP with the STSL closed and stable. The average of the signal is around zero with a noise better than 10^{-16}. Fig. 5b shows the frequency correction (FCW) computed by FCDP during the closure of the loop

The second step was to optimize the loop by using different parameters for the loop filter and validate at the same time the Servo Loops Optimization Tool. The optimization process consists in minimizing the Allan Deviation of the USO and at the same time verifying that the phase noise is not degraded by the loop.

First results were compared to the simulation model and a difference was found. After offline data analysis was found that the cause was a wrong parameter in FCDP that induced an additional delay in the loop. Once the correct parameter was uploaded in FCDP, the STSL could be optimized and the loop reacted as predicted by the Simulation Model (Fig. 6).

This comparison demonstrates the sensitivity of the simulation tool and proves its usefulness for clock optimization during later testing and inflight operation.

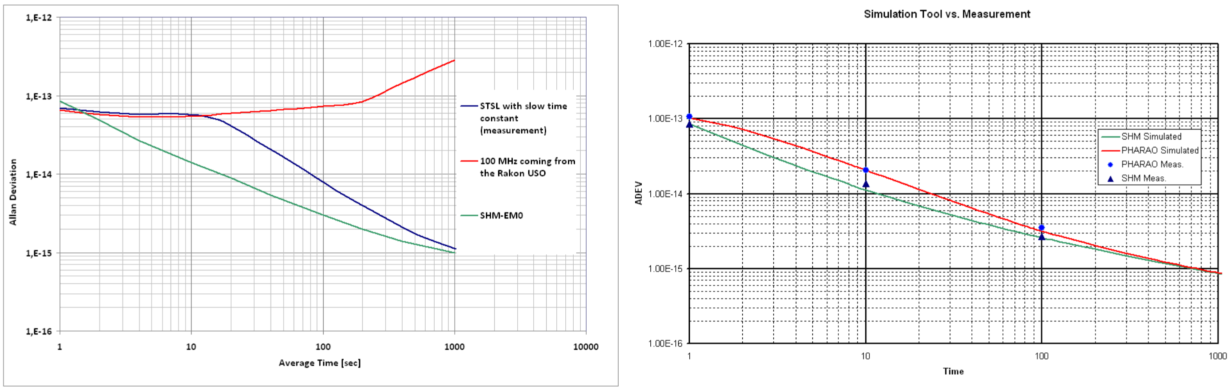


Fig. 6. Left: Firsts locking of the STSL with a slow time constant. Right: The direct measurements (dotted curves) of PHARAO and SHM EM0 outputs compared with simulated response from the Simulation Tool after optimization of the loop

LONG TERM SERVO LOOP TESTS

The main objective of this test is to verify the functionality of the LTSL and its performances after optimization of the parameters of the loop with the simulation tool. These measurements will also allow to validate the simulation tool for the LTSL. In addition, it shall also verify that the accuracy of PHARAO is correctly transferred to the ACES clock signal after closure of the ACES servo.

As shown in Fig. 7, the crossing between SHM EM0 and PHARAO for LTSL occurs at around one day. This time constant is too long to test the functionality of the loop as it leads to several days of continuous acquisition. Moreover, as mentioned before, PHARAO will have better performances in flight than on ground for both accuracy and stability. SHM FM will also be less stable than SHM-EM0. Consequently the crossing point between PHARAO and SHM in flight stabilities will be at around 3000 s.

Therefore different sets of parameters for the LTSL transfer function have been implemented, giving the opportunity to test extensively the optimization tool against real data: a fast time constant, which corresponds to shorter measurements, has been used to test the functionality (verify that was possible to close the loop) and then a time constant of 10^4 seconds was chosen to test the LTSL for performance evaluations, even if that meant to degrade SHM EM0. The performance test on LTSL lasted six days of acquisition leaving the ACES system controlled by the ASW.

Fig. 7. ADEV of PHARAO on ground and in flight, and ADEV of SHM-EM0 and SHM-FM. These differences lead to a different optimized time constant of the loop (red circles)

First results were compared to the simulation tool and a discrepancy was found. Indeed, the time constant of the loop was not the one predicted by the simulation (ten times slower). A more careful analysis of the data showed that the this discrepancy was indeed due to errors in the Simulation Model.

Figure 8 shows long duration measurements with the ACES servo loops closed. The plots show the very good agreement between simulated curves and actual measurements after corrections done in the Simulation Tool.

The last measurement consists on comparing ACES with FOM. First of all, there is a good agreement between the frequency of PHARAO alone and the frequency of ACES. Secondly FOM was also used to verify the stability of ACES: in Fig. 8 (on the right) the red curve is the comparison of ACES and FOM, and the orange curve is the simulation of ACES. There is a good agreement between the measurement and the simulation because the red curve is the quadratic sum of the stability of ACES and the stability of FOM.

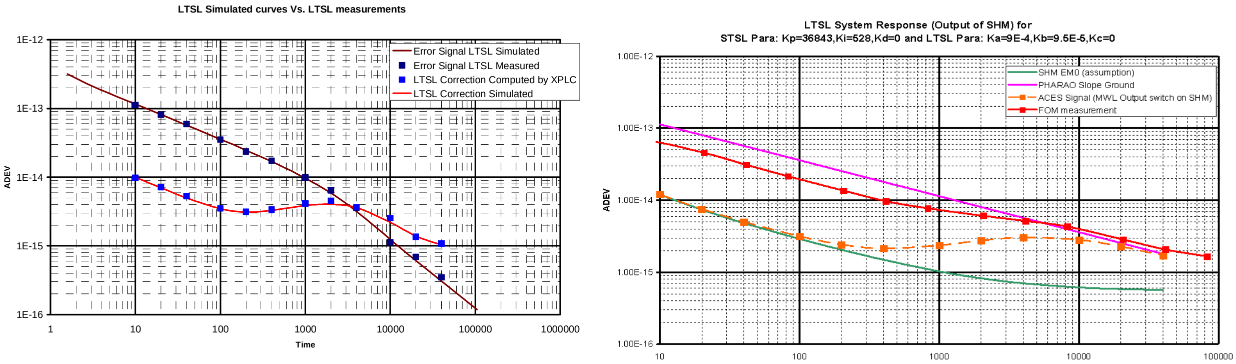


Fig. 8. Performances of the ACES signals during LTSL long performance tests compared with the simulated values. On the left, the plot the error signal and the signal correction of the LTSL is shown. The error signal decreases to zero with a 1/T slope reaching a noise lower than a few 10^{-16} after 40000s of integration time. On the right, we compare the measurement done with FOM with the simulation of the ACES signal.

CONCLUSION

The ACES System Tests have been successfully concluded. The compatibility between subsystems at system level has been verified and the ASW interface to these subsystems has been validated. The ACES database (TC and TM) has been checked against PaCTS which mimics the communication between ISS and the payload. The correct operation of the STSL and of the LTSL has been extensively tested and verified against ground requirements. The Optimization Tool has been "optimized" using real measurements and it is now a reliable tool to simulate the ACES clock behaviour.

During the five months of testing several hurdles had to be taken and were removed, giving the opportunity to the team familiarize with the complex setup of the ACES system test and refine the test procedures that will also be used on the ACES FM. ACES-EM was able to deliver a stable and accurate signal with the best performances out of SHM-EM0 and PHARAO-EM.

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