ULISS Project: 2013 Progress Report

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***Abstract*—The ULISS Cryogenic Sapphire Oscillator (CSO) offers unprecedented short-term frequency performances. It was specially designed to be transportable by car in order to test this new technology in different European sites. During the last 18 months, it was used to qualify with success several high stability frequency sources. In February 2013, a new measurement campaign was lead at CNES, Toulouse (France) to qualify the flight model of the frequency synthesis of the PHARAO clock. During the same period we built a second CSO unit based on the same design and conducted new characterisations of frequency stability and environmental sensitivity. Optimisation of the system has led to an improved frequency stability reaching currently better than 1×10^{-15} at 10,000 s integration times. Eventually we developed a new low phase noise and high-resolution frequency synthesis delivering 10 GHz, 100 MHz and 9.192 GHz ultra stable signals. In this paper we draw a progress report on the ULISS project, updating performances and describing the latest experiments conducted with our CSO in different sites in Europe.**

I. Introduction

The ULISS project aimes to promotte the Cryogenic Sapphire Oscillator (CSO) technology, which today has reach enough maturity to be used outside a well equiped metrological lab [1]. The CSO offers unprecedented short term frequency stability currently reaching better than 1×10^{-15} for integration times ranging from few seconds to 3 hours. Some units have demonstrated a relative frequency stability of 5×10^{-15} over 1 day without any clear drift identified [2]. A specialy designed CSO was build to be transportable by road, and during the last year ULISS was tested in different european sites. Experience feedback allowed to make the prototype progress. In this paper we present the last results obtained by comparing directly two identical CSOs operating at 9.99 GHz.

II. FEMTO-ST CSO Technology

The CSO is based on a microwave whispering gallery mode sapphire resonator made of a 54 mm diamter and 30 mm hight high purity sapphire cylinder. This resonator was designed to present a high-Q quasi-TM mode, i.e. $WGH_{15,0,0}$ at 9.99 GHz ± 5 MHz. The difference to the 10 GHz round frequency allows the use of a low noise Direct Digital Synthesizer (DDS) to compensate for the sapphire resonator machining tolerances [3], [4]. At the liquid helium temperature, the Q-factor approches 1 billion and the temperature-frequency senstivity presents a null near 6K. We developped in the frame of an ESA project a CSO (nicknamed ELISA) incorporating a cryocooler as cold source, which can be operated during two years without any maintenance. This first prototype was eventually installed in the ESA ground station in Malargua (Argentina) in May 2012. ULISS a mobile version of the same instrument was build at the end of 2011. Before the implentation of the fisrt prototype in Argentina, the two CSOs was comparated and the results were presented in [5] demonstrating a relative frequency stabilty better than 1×10^{-15} at short term with a flicker floor of 4×10^{-16}. At long term, the Allan standard deviation was limited by the CSO residual temperature sensitivity. ADEV reaches 1×10^{-14} at one day. The figure 1 shows the interior of the CSO cryostat. We can see the two stages of the cryocooler with the copper braids used to transfert the cooling power to the resonator whithout transmitting the Pulse-Tube mechanical vibrations. The figure 2 shows the cryostat and rack containing the electronic controls and the frequency synthesis.

Fig. 1: *ULISS cryostat interior.*

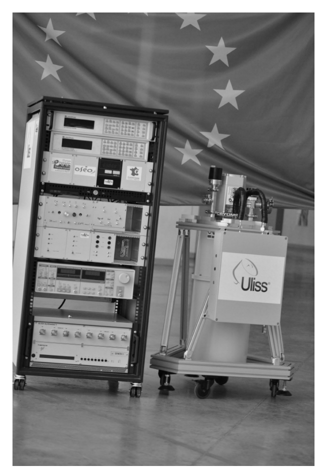

Fig. 2: *ULISS CSO with electronic controls rack.*

The sustaining loop is placed at room temperature in a thermaly stabilized aluminium box (see Fig. 2). ULISS incor-

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porates a Pound and a power servo controls to correct phase and power fluctuations along the sustaining loop.

III. ULISS'S ODYSSEY CONTINUES

The objectif of the ULISS project is to propose to european potential users to test directly in their applications an ultrastable cryocooled sapphire oscillator. During the past 18 months, Uliss visited several sites by making approximately 9000 km by the road in a van:

- LTF Neuchâtel, Switzerland, January 2012. ULISS was used to qualify an ultrastable laser source looked on an ULE cavity and to measure the frequency stability of quartz Xtal oscillator industrial prototypes.
- CNES Toulouse, France, March 2012. First validation of the PHARAO clock synthesis.
- Exhibition of the EFTF 2012, Göteborg, April 2012.
- CNES, Toulouse, France, February 2013. Second run in the validation of the PHARAO instruments.
- UTINAM Institute, Besançon, France, April, 2013. Validation of the composite clock.
- SYRTE Paris, France, june, 2013. First tests with SYRTE metrological equipments.
- Exhibition of IFCS-EFTF joint meeting 2013, Prague, July 2013.
- Wettzel VLBI station, Germany, measurements with the ring laser, August 2013.

Between these differents measurement compaigns, ULISS came back to Besançon and was continously improved/adapted to fulfil the users requirements and to solve some encountered issues. The Pound servo was optimized: one integrator was added to provide enough gain at low frequencies. Preliminary tests using digital electronic controls have been realized during the past year, but due to the lack of time have not been integrated in the systems that we describe here. After the stay in SYRTE last June, where preliminary tests have been conducted with the higest resolution, a wide effort was recently dedicated to solve some EMC issues: replacement of bad switching power supplies, improvement of the earth and ground loops...

Initally ULISS was equiped with the same frequency synthesis than ELISA developped by TimeTech [6]. This frequency synthesis has three frequency outputs: 5 MHz, 100 MHz and 10 GHz. As several users need other frequencies, we designed our own frequency synthesis to get 500 MHz, 1 GHz and 9.192 GHz outputs. The CSO frequency stability is totally transfered at the microwave outputs. For the VHF and RF outputs, we observe as expected a small degradation due to the intrinsic noise of electronic components operating these frequency bands.

IV. BUILDING OF A NEW UNIT

The building of a new CSO was finalised at the end of 2012. In its design this CSO is identical to ULISS. Nevertheless some differences exist:

- The mechanical tolerances of sapphire resonator geometry were relaxed to decrease the cost of this key component. It results a frequency difference between the two CSOs of about 7 MHz.
- As the ULISS Odyssey focus a large part of our efforts, the second CSO is not totally optimized. It suffers from some technical problems that can be solved in a next step: i.e. i) the compressor He pressure is not optimized for 50 Hz supply, ii) due to some still non well identified leaks, the residual pressure inside the cryostat is 1×10^{-6} mbar, one order of magnitude higher than those obtained in the first system , iii) we suspect a possibly bad thermal contact in the resonator set-up. It results the cryocooler is less efficient than those of ULISS. The lower temperature currently achievable is 5 K (instead of 3.8 K), not far from the resonator turnover temperature, which is 5.8 K . In these conditions, the temperature control was found difficult to get optimized.

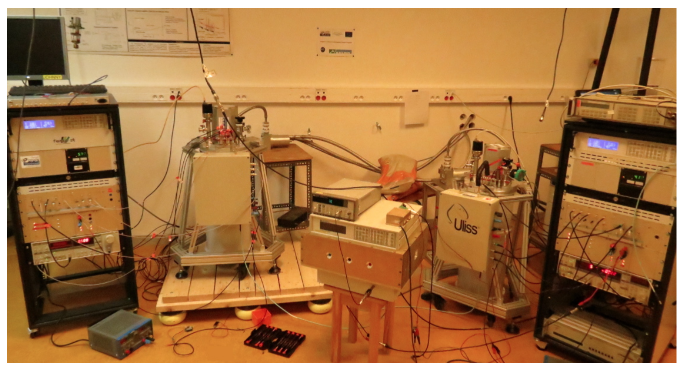

Fig. 3: The two CSOs during the last characterisation campaign (July 2013).

V. IMPROVEMENTS AND COMPARISON OF THE TWO CSOS

The ULISS travels requires a big effort of logistics and takes away our best reference for several weeks. Thus, since the first operation of the second CSO, we had only the possibility to make three short comparison campaigns in order to optimize its parameters. Nevertheless we made some progress in the electronic control loops (Pound and Power servos), improving the signal to noise ratio of the error signal detection and adding gain at low frequencies. We also modified the thermal filtering imrpoving the rejection of slow temperature variations of the Pulse-Tube.

The figure 4 shows multiple ADEV characterisations obtained by counting directly the 7 MHz beat-note during approximatly 15 hours. As usual we present the ADEV without any post-traitment. It clearly shows the reproductibity of the measurements and the exceptionnal flicker floor of 5×10^{-16}. At 1s the measurement is limited by the counter contribution due to the high value of the beat-nore frequency. The bump at 20 s is due to a residual thermostat oscillation in the newly built CSO.

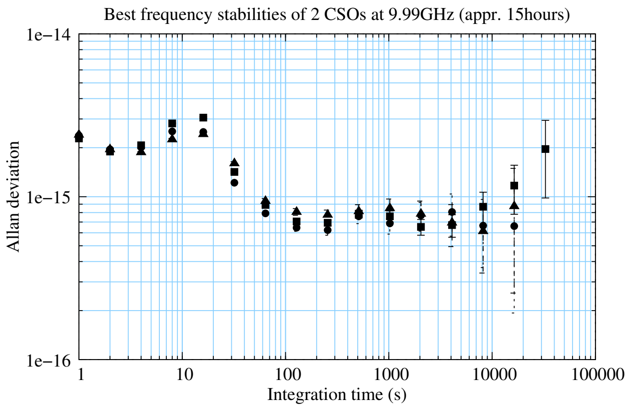

Fig. 4: 2 CSOs Short term frequency stability (July 2013).

The figure 5 shows the ADEV calculated after 5 days integration compared to the 2012 results [7]and to a state-of-the-art hydrogen Maser.

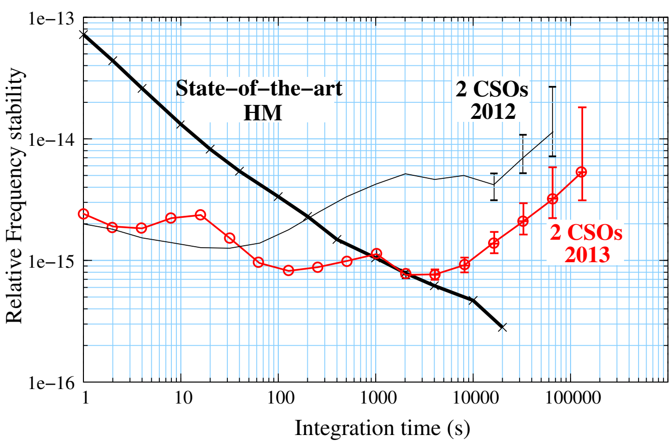

Fig. 5: CSO frequency stability.

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