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ULISS: A Mobile Cryogenic Ultra-Stable Oscillator

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Abstract—We recently demonstrated a Cryogenic Sapphire Oscillator (CSO) presenting a short term frequency stability better than 3×10^{-15} for $1 \text{ s} \leq \tau \leq 1,000 \text{ s}$ and achieving 4.5×10^{-15} for one day integration [1], [2]. This CSO was designed and built in the frame of a research contract funded by the European Space Agency (ESA). It incorporates a pulse-tube cooler instead of a bath cryostat – thus eliminating the need for regular supplies and manual transferring of liquid helium. The advent of reliable and cryocooled CSO opens the possibility to implement such an ultra-stable reference not only in metrological laboratories with liquid helium facilities but also in remote sites like base stations for space navigation, VBLI antenna sites, ...

In a new project: ULISS (Ultra-Low Instability Signal Source), funded by Regional and European Institutions, we are developing a new cryocooled oscillator specially designed to be transportable. The ULISS oscillator will be compared and tested in various laboratories, observatories and industrial companies throughout Europe.

In this paper we present the status of the ULISS project and the last frequency stability and phase noise characterisations of the current CSO working for more than one year in our lab.

I. INTRODUCTION

The ever-increasing need for better time synchronization in number of High-Tech and scientific applications calls for the development of new frequency references of improved stability. The figure 1 shows the relative frequency stability as a function of the integration time τ for various clocks and reference oscillators as well as the needs newly expressed by various users:

The blue area in the figure 1 represents the typical performance of microwave oscillators incorporating a dielectric sapphire resonator cooled in a liquid helium bath. The Cryogenic Sapphire Oscillator (CSO) can exhibit the highest short-term frequency stability ($< 1 \times 10^{-15}$ for $10 \text{ s} < \tau < 100 \text{ s}$). CSO is the only available technology able to meet the requirements expressed by various users (red lines in Fig.1). Few liquid helium cryogenic sapphire oscillators have been built in a small number of worldwide research laboratories [3], [4], [5], [6]. Some of these instruments have been used as local oscillator for atomic fountain clocks [7] and for fundamental physical experiments [8]. Nevertheless they are still experimental prototypes that are difficult to implement outside a well-equipped laboratory. Moreover the liquid helium cryostat has to be refilled periodically adding a heavy maintenance constraint. Yet, various applications could benefit of the performances offered by the cryogenic sapphire

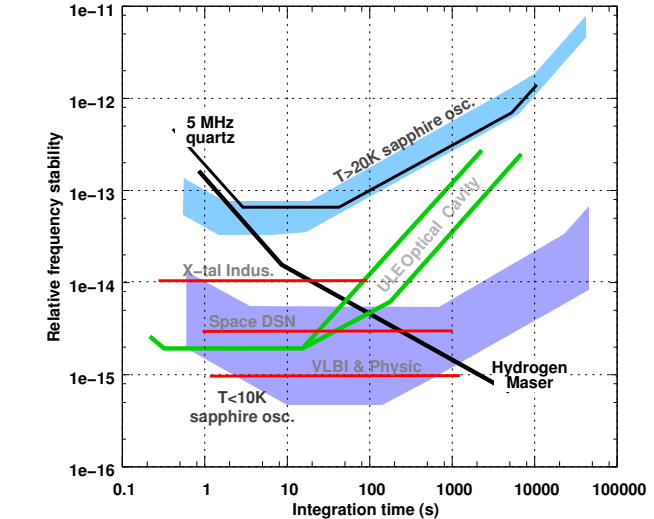


Figure 1. Relative frequency stability of some clocks and oscillators.

oscillator:

- **Space:** The interplanetary navigation is based on microwave signal exchanges between the space vehicle and a ground station equipped with a high stability timing reference. Ranging and Dopplertracking resolutions are limited by the clock instabilities. To be able to meet the stability requirements for the future space missions, the European Space Agency (ESA) sponsored the construction of a cryocooled-CSO. This project (ELISA project [9]) coordinated by the Femto-ST Institute was finalised in April 2010. The cryocooled-CSO achieves better than 3×10^{-15} frequency stability over 1 s to 1,000 s while insuring at least one year autonomy.

- **Metrology: primary frequency standards.** In an atomic clock, a local oscillator (LO) is frequency locked on the resonance frequency of an atomic transition. The best current atomic clocks using cold atoms operate sequentially. Indeed time is needed to cool the atoms before sensing the atomic transition. During this period of time no information is available for the frequency of the LO which is then free-running. Consequently the overall clock frequency stability is degraded by the short-term instability of the LO. Better than 1×10^{-14} over 1–100 s is required.

- **Metrology: frequency stability certification.** National Metrological Institutes have in charge to maintain the

standards and to establish certifications for industrial products and laboratory instruments. The frequency stability is one of the major characteristics of the signal source that could impact on the security and performances of number of systems. It is then a metrological quantity that has to be measured with the best resolution available. A standard presenting frequency stability better than 1×10^{-14} over 1–1,000 s will notably increase the current calibration capability making it compatible with all current industrial requirements.

- **Very Long Baseline Interferometry:** VLBI allows data from widely separated radio telescopes to be combined to get exceptional astronomical measurement resolution providing each radio telescope is equipped with an ultra-stable clock.

- **Industry of high performance clocks and oscillators:** To estimate, without ambiguity the frequency performances of state-of-the-art oscillators and clocks requires an ultra-stable reference. Some industrial companies making high performance quartz oscillators are interested by a versatile frequency reference of less than 1×10^{-14} frequency instability.

- **Fundamental Physics.** Special Relativity is one basic pillar of modern physics. Each basic theory has to be tested as its best, because it is so fundamentally important. The best tests of Special Relativity are based on ultra-stable oscillators for which we are locking for a frequency variation as a function of the speed and orientation of the laboratory. The frequency fluctuations of the oscillator limit the measurement resolution.

For all these applications, the autonomy and reliability of the frequency reference are major requirements. In all cases, liquid helium bath has to be rejected.

II. THE ULISS PROJECT

Our work on the field of cryogenic oscillators was initiated 15 years ago, in the former Laboratoire de Physique et de Métrologie des Oscillateurs (LPMO) which becomes part of the Time and Frequency Department of the Femto-ST Institute at its creation in 2004. The project ELISA funded by ESA represents the outcome of all these efforts: the objective set by ESA was plenty fulfilled and we demonstrated for the first time the possibility to use a cryocooler while maintaining a state-of-the-art frequency stability.

We think that today the cryocooled-CSO technology is mature enough to be proposed as a reliable frequency reference for various applications. The ULISS (Ultra-Low Instability Signal Source) project answers our wish to see the CSO-technology used by other. This project is funded by the Fonds Européen de Développement Régional (FEDER), the Région de Franche-Comté and OSEO. It has been officially launched the 1st of March 2011 and contains two main parts:

- We are building a new CSO specially designed to be transportable by road. The new oscillator will be transferred (by road) successively to several potential users' sites. It will be tested in the real experimental conditions and critical result analysis will be carried out with the user. Hence

the potentiality to improve their experiments as well as the reliability and autonomy of the CSO will be clearly demonstrated. These international tests will also give the opportunity to establish precisely the requirements specific to each potential user.

- A business unit: ULISS[®] has been created and is currently managed by the Université de Franche-Comté with the objective to commercially propose the CSO technology. The first purpose of this entity is the implementation of the first prototype, i.e. ELISA, in the ESA ground station situated in Malargüe (Argentina).



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III. CSO PERFORMANCES

The CSO architecture is depicted in the figure 2. The heart of the instrument is a Whispering Gallery Mode Sapphire resonator stabilized at its thermal inversion point, i.e 6.1K. Such a low temperature is achieved in a closed-cycle Pulse-Tube Cryocooler specillary designed to ensure a high thermal stability ($\pm 1\text{mK}$) and a low level of mechanical vibration: axial displacement less than $2 \mu\text{m}$ at the PT cycle frequency ($\approx 1\text{Hz}$). The CSO is designed to oscillate at $9.99 \text{ GHz} \pm 5 \text{ MHz}$. The difference with the 10 GHz round frequency is compensated by a low noise DDS. VHF and RF signals are synthesized from the stabilized 10 GHz [10]. The system is complemented with a Phase-Comparator (PCO) enabling to lock the synthesized outputs to an incoming 100 MHz signal.

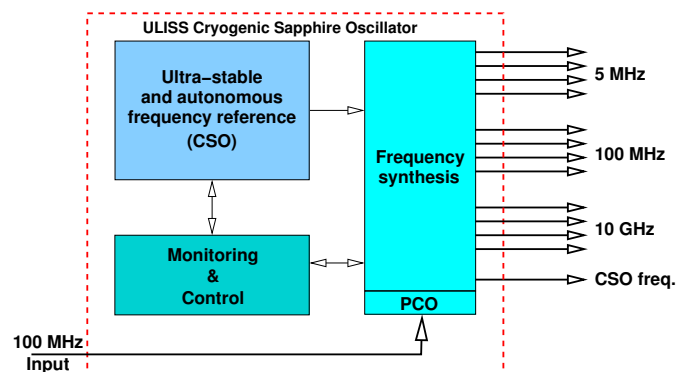


Figure 2. ULISS CSO architecture

The typical frequency stability performance of the CSO is shown in the figure 3. It is compared with the ADEV of other frequency references as active and passive Hydrogen Maser. The CSO bridges the gap between (unstable) high spectral purity oscillators and H maser. Here, we show fully conservative results. In all our measurements we do not remove drift, drift rate etc and we show the total noise of two

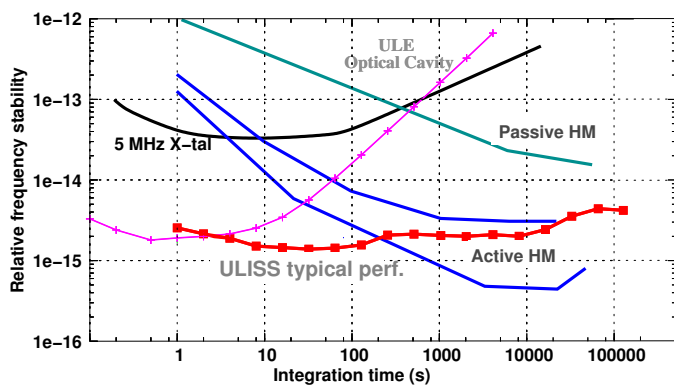


Figure 3. ULISS typical stability compared to some other clocks and oscillators.

oscillators, instead of taking away 3 dB under the assumption of two equal units.

IV. AN EXAMPLE OF APPLICATION

As a Metrology laboratory associated with the Laboratoire National d'Essai et de Métrologie (LNE), a first evident application for us is the characterization of ultra-stable oscillators. Short term frequency stability of Quartz X-tal oscillator progresses only very slowly for more than 10 years and seems limited to $0.5 - 1 \times 10^{-13}$. In the X-tal oscillator, the location of the main source of noise is still not known and could be the quartz resonator frequency fluctuations and/or the sustaining amplifier phase noise. Even if some effort have been deployed to improve the resolution of measurement set-ups [11], [12], the limiting cause has still not be revealed. The ambiguity of the results remains due to the fact that the current instruments do not allow for the characterisation of individual oscillator or resonator.

The CSO overcomes this issue, and offers an unprecedented resolution in the short term frequency stability measurement. Owing to the Uliss high stability, the frequency-stability measurement of most oscillators becomes straightforward as demonstrated by the experiment schematized in figure 4:

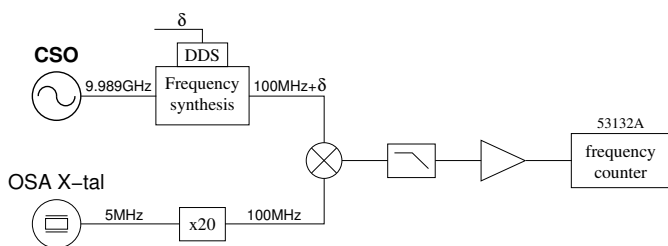


Figure 4. Simple measurement set-up used to evaluate the ADEV of a state-of-the-art X-tal oscillator.

An ultra-stable quartz X-tal oscillator from Oscilloquartz (modele 8607-B) [13] is simply compared to the CSO. The measurement is made at 100 MHz to ensure a sufficient resolution at short integration times. The beatnote frequency

is adjusted by acting on the DDS command to optimize the counter operation. The raw result of this comparison is shown in figure 5. 1s gate time samples have been recorded during 4,800 s, and ADEV computed without any post-treatment.

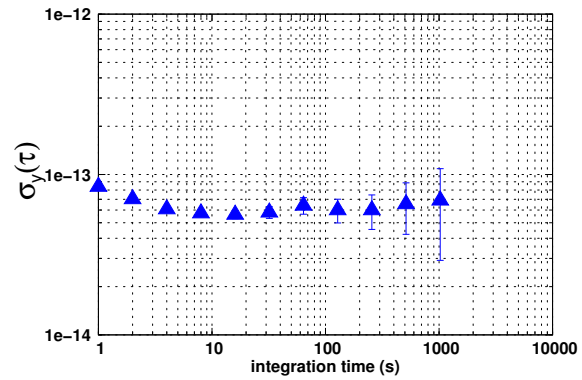


Figure 5. Relative frequency stability of a new Oscilloquartz 5 MHz X-tal oscillator as measured with the CSO.

As revealed by the CSO, the short-term frequency stability of this X-tal oscillator constitutes a world record. The measured ADEV is limited by a flicker floor of 5×10^{-14} and still remains better than 8×10^{-14} at $\tau = 1,000$ s.

V. ACKNOWLEDGEMENTS

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