# Technology Readiness of the Cryogenic Sapphire Oscillator

Christophe Fluhr, Benoît Dubois
FEMTO-Engineering
15B avenue des Montboucons,
25030 Besançon Cedex – France

Julien Paris
My Cryo Firm SARL,
104 Avenue de la Résistance,
93100 Montreuil, France

Guillaume Le Tetu, Valérie Soumann
Enrico Rubiola, Vincent Giordano
FEMTO-ST Institute Time & Frequency Dpt.
26 Rue de l'Épitaphe
25000 Besançon
giordano@femto-st.fr

***Summary* —The cryogenic sapphire oscillator (CSO) delivers a reference signal exhibiting the lowest frequency fluctuations. For the best units, the Allan deviation (ADEV) is $\sigma_y(\tau) < 10^{-15}$ for integration time between 1 and $10^4$ s, with a drift $< 10^{-14}$ in one day. The oscillator is based on a sapphire monocrystal resonating at 10 GHz in a whispering-gallery mode, cooled at 6 K for highest Q-factor and zero thermal coefficient. We report on the progress accomplished implementing eleven CSOs in about 10 years starting with the first sample delivered to the ESA station in Argentina. Short- term stability is improved by a factor of 3-10, depending on τ, and the refrigerators electric power is reduced to 3 kW. Frequency stability and overall performances are reproducible, with unattended operation between scheduled maintenance every two years. The CSO is suitable to scientific applications requiring extreme frequency stability with reliable long-term operation. For example, flywheel for primary frequency standards, ground segment of GNSS, astrometry, VLBI, and radio astronomy stations. The CSO technology developed at the FEMTO-ST Institute is now mature for deployment in real very demanding applications**

***Keywords — Time and frequency metrology. ultra-stable oscillators, frequency stability***

## I. INTRODUCTION

Short term fractional frequency stability in the $10^{-15}$ range has been demonstrated more than 20 years ago with the use of high Q-factor microwave dielectric sapphire resonator cooled near the liquid helium temperature [1,2]. In the early 2000s, Cryogenic Sapphire Oscillator (CSO) breakthrough performances and early uses in the field of Time and Frequency Metrology have been demonstrated with prototypes still operating within a liquid-He bath [3-7]. In 2010, at FEMTO-ST Institute, we demonstrated for the first time the possibility to use a cryocooler while maintaining a state-of-the-art frequency stability [8]. Since, we undertaken large engineering efforts to rationalize the CSO design and its development, reduce its electrical consumption and improve its immunity to environmental perturbations [9-12]. Our most advanced CSO, codenamed ULISS-2G, is now available as a stand-alone 3 kW instrument integrated in a 19" rack. In this paper, by comparing the performances of 11 CSOs we have built since 2012, we demonstrate the reliability and the reproductivity of our technology.

## II. FEMTO-ST CSO DESIGN

Figure 1 shows the CSO as delivered by FEMTO-Engineering [13]. Details on the technological choices we made relating to the various subsets of the instrument will be given at the conference.

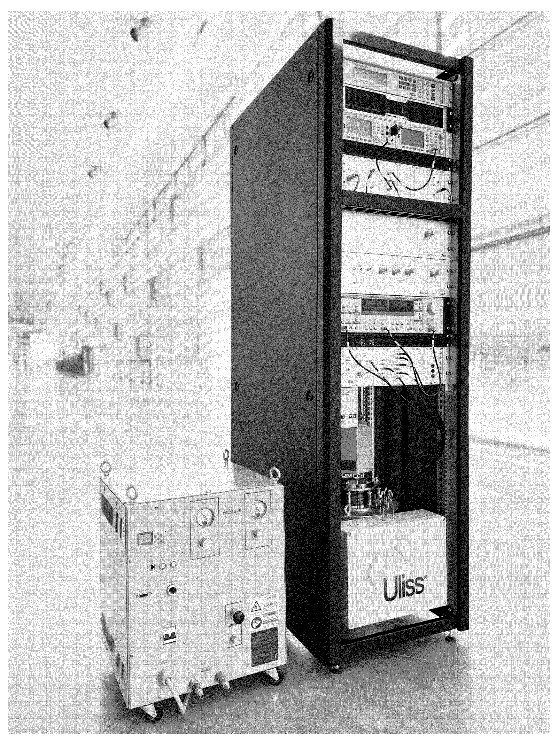


*Fig. 1: View of the CSO. The cryostat is integrated at the bottom of a 19" rack supporting also the frequency synthesis and the control electronics. In the left: the 3kW water-cooled He compressor (Air-cooled version is also available).*

The high Q sapphire resonator is maintained near 6 K in a cryostat cooled with an autonomous Pulse-Tube (PT) cryocooler. The CSO is a Pound-Galani oscillator: the resonator is used in transmission mode in a regular oscillator loop, and in reflection mode as the discriminator of the classical Pound servo. The sustaining stage and the control electronics are at room temperature. The CSO output signal at the resonator frequency drives a frequency synthesizer, which delivers several output frequencies: 10 GHz, 100 MHz and 10 MHz in the typical implementation. Eventually the synthesizer outputs can be disciplined at long term on an external 100 MHz signal for example from a Hydrogen Maser. A monitoring system checks on all the CSO key parameters.

## III. Typical Performances

Figure 2 shows the Allan deviation (ADEV) of the 7 CSOs delivered to metrological Institutes around the world since 2018. These results have been obtained by the three-cornered-hat (TCH) method with two of the Oscillator-IMP platform CSOs as reference [14]. The lattes are placed in a dedicated metrological room stabilized in temperature (22 ± 0.5 °C) and humidity (50% ± 10%), whereas the CSO under test was implemented in the laboratory workshop equipped only with the standard air-conditioning system.

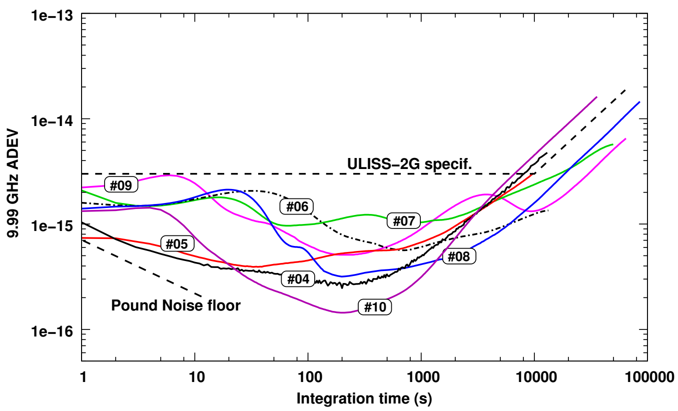


*Fig 2. Fractional frequency stability of the ULISS-2G CSOs as measured by comparing the CSO under test with two other reference CSOs through the three-cornered-hat -method. #04 is the first ULISS-2G prototype. #10 was just running for the first time. Its drift will decrease with time.*

The most important result is that the fractional frequency instability of all the CSOs is below $3\text{x}10^{-15}$ for 1 s $<\tau<$ 10,000 s. The typical long-term drift is below $1\text{x}10^{-14}$/day. The discrepancies of the actual ADEV from the expected asymptotical power law are understood and will be explained at the conference.

## IV. Conclusion

Our most advanced CSO technology provides a fractional frequency stability better than $3 \times 10^{-15}$ for 1 s$< \tau <$ 10,000 s and below $1\times10^{-14}$ over 1 day, with a limited electric consumption, i.e. 3 kW single phase. These performances have been obtained in a standard laboratory environment. Implemented in a metrological room with an efficient temperature control and a limited human presence, such ultra-stable oscillators are able to achieve a fractional frequency stability close to $1 \times 10^{-16}$ near $\tau$ = 100 s. This CSO technology is today sufficiently mature to be offered as a commercial product able to run continuously for year. A simple maintenance operation: a filter change in the He circuit, which can be performed by the user, is only required every two years.

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