A Cryogenic Sapphire Oscillator with 10^{-16} mid-term ADEV

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***Summary* —We report in this letter the outstanding frequency stability performances of an autonomous cryogenic sapphire oscillator presenting a flicker frequency noise floor below 2×10^{-16} near 1, 000s of integration time and a long-term Allan Deviation (ADEV) limited by a random walk process of $\sim 1 \times 10^{-18}\sqrt{\tau}$. The frequency stability qualification at this level called for the implementation of sophisticated instrumentation associated with ultra-stable frequency references and ad hoq averaging and correlation methods.**

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

I. INTRODUCTION

Tests of fundamental physic [1-3], radioastronomy [4] or fundamental and applied metrology [5] make an extensive use of ultra-stable frequency sources, for which there is a constant demand for improved frequency stability performance for measurement time ranging from 1 to 10^6 s. Atomic frequency standards are of course preferred when accuracy and long-term frequency stability are required. But even in this case, an ultra-stable signal source based on a high Q-factor macroscopic resonator is needed to reach the ultimate frequency stability of the atomic clock [6,7].

The Cryogenic Sapphire Oscillator (CSO) is an autonomous microwave oscillator able to meet the requirements for many very demanding applications. Today, the CSO is available as a stand-alone instrument consuming only 3 kW single phase [8]. For these instruments the conservative ADEV specification is: $\sigma_y(\tau) \leq 3\times10^{-15}$ for $1 \text{ s} \leq \tau \leq 10{,}000$ s and better than 1×10^{-14} over one day. In this letter, we report on the frequency stability characterization of a newly implemented CSO between 1 s to about 3 days. Its ADEV is below 2×10^{-16} between 100 to 10^4 s.

II. CSO DESIGN

The design of this new CSO, code-named U10, is described in detail in [9,10]. It incorporated a 3 kW pulse-tube cryocooler to cool near the liquid helium temperature a 54-mm-diameter and 30-mm-height resonator machined in a high purity sapphire monocrystal. This resonator operates on the quasi- transverse magnetic whispering-gallery mode $WGH_{15,0,0}$ at $\nu_0 = 9.99$ GHz. The sapphire resonator frequency shows a turnover temperature $T_0 = 6.2$ K for which the resonator sensitivity to temperature variations nulls at first order. The appearance of this turning point results from the presence in Al_2O_3 of a small amount of paramagnetic impurities as Cr^{3+} or Mo^{3+} and is specific to each resonator. 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 placed at room temperature. The CSO output signal at the resonator frequency ν_0 drives the frequency synthesizer, which eventually delivers several out- put 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 coming from a Hydrogen Maser for example.

III. MEASUREMENT METHOD AND RESULTS

The metrological aspect is very challenging when we have to optimize and qualify a new type of ultra-stable source. If a better reference is not available, two almost identical units have to be implemented and compared. As it is impossible to ensure that each signal source contributes equally to the observed frequency fluctuations, the measured result gives only an overestimated ADEV. If an improvement is made to one unit, its impact on the measurement result can be hidden by fluctuations of the other source. A more efficient way to get the intrinsic frequency stability of the oscillator to be qualified, is to apply the three-cornered-hat (TCH) method or other equivalent Covariance method15. The price to be paid is the need of two other signal sources with comparable performances. However, the TCH or Covariance methods fall when correlations exist between two of the signal sources that are compared, giving nonrealistic variances. One of the major issues comes from mid- or long-term environment fluctuations that could induce such correlations.

The accurate qualification of U10 between 1 s to about 3 days has been made possible by the availability of a multichannel real-time phasemeter designed by one of the authors [11]. This instrument, i.e., the *Time Processor*, is based on the Tracking Direct Digital Synthesizer (TDDS) technology. In short, a dedicated DDS is phase-locked to each input signal and the phase information of the input with respect to the local oscillator is extracted from the phase-control word. The data are normalized to phase time, so that channels at different frequencies can be compared directly. The newly implemented version of the *Time Processor* is able to compare together up to 16 independent signal sources or beat-notes at different frequency. Each input is characterized by an acquisition and lock range of 5 − 400 MHz, and a cut-off frequency $f_H = 5$ Hz. The one channel resolution in term of Allan Deviation (ADEV) is $\sigma_y(\tau) = 1.7 \times 10^{-14}/\tau$ ($2.1 \times 10^{-14}/\tau$) for a 100 (10) MHz input carrier. This limitation is set by the intrinsic phase noise of the DDSs. To perform our measurements, we dispose of the OSCILLATOR-IMP platform RF and microwave ultra-stable references: a set of 3 Hydrogen Masers (HM), as well as a set of 3 high-performance CSOs, placed in two independent temperature stabilized room at 22±0.5 ◦C [12].

At short term, the reference CSOs are far better than the Hydrogen Masers. They reach an ADEV better than 1×10^{-15} for $\tau = 1$ s, while it is typically 7×10^{-14} for the HMs. Thanks to correlation and averaging that are inherent to 2 sample covariance, the influence of the reference sources frequency fluctuations on the measured ADEV is reduced by $m^{1/4}$, m being the number of measurements at a given integration time τ. The two CSOs are used for the evaluation of the short-term, since their frequency noise is much lower than masers and, thanks to the number of averages, their contribution is below 1×10^{-16}. Such level of resolution could not be reached by using the two HMs, since it would require an unrealistic acquisition time.

For $\tau \geq 700$ s, the CSOs frequency fluctuations are partially correlated due to an inherent temperature control pumping in the CSO room. The covariance method applied in this integration time range gives for U10 a negative and unrealistic ADEV. Such a level of correlation does not exist between the HMs frequency fluctuations, because i) the HM thermal sensitivity is about 10 times lower than those of CSOs, ii) the heat generated by the instruments is lower in the HM room, iii) the situation in the building is more favorable for room HM making the ambient temperature regulation easier to tune.

Figure 1 represents the U10 ADEV, obtained by combining the calculations made with two different sets of data. Until $\tau = 700$ s, the U10 ADEV is determined from the comparison with 2 CSOs, and for the longer integration times, the comparison with 2 HMs is used.

The instability of U10 is less than 2×10^{-16} for $100 \text{ s} \leq \tau \leq 10{,}000$ s, making the CSO the best commercially available oscillator based on a macroscopic resonator. At longer integration time, the U10 ADEV appears limited by a random walk process such as $\sigma_y(\tau) \sim 1.1\times10^{-18}\, \tau^{1/2}$.

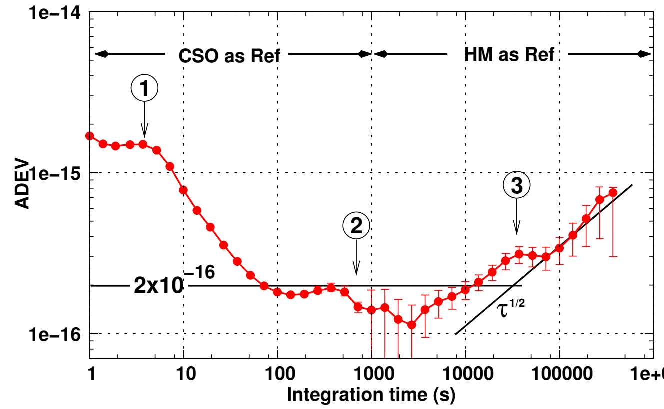

Fig 1. U10 ADEV mean estimates. Error bars : 68% confidence intervals.

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