Direct Stability Measurement of Cryogenic Sapphire Oscillators with Tracking DDSs and Two-Sample Covariance

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***Abstract*—We demonstrate the first stability measurement of 10 GHz cryogenic sapphire oscillators (CSOs) at the 100 MHz output by direct comparison of three units. Thanks to the low background noise of the Tracking DDS, and to the use of two-sample covariances, it is no longer necessary to beat the oscillators down to the HF region. The stability of our oscillators is of 2×10^{-15} at 1 s, limited by the CSO internal synthesizer, while the flicker floor of one unit is of 3×10^{-16}.**

Keywords—Cryogenic oscillator, Allan covariance, Frequency stability, Noise, DDS, Frequency synthesis.

I. INTRODUCTION

Cryogenic Sapphire Oscillators (CSOs) provide microwave signals with excel in short-term stability for measurement time τ from 100 ms to one day. The stability is of parts in 10^{-16} up to 10^{-15} at the microwave output [1]. Additional outputs are available, at 10-100 MHz via dedicated frequency synthesis, which introduces a small degradation at $\tau < 10$ s. Thus, at small τ the stability exceeds that of masers and other atomic standards. Reliability is another relevant feature, which makes the CSO a good flywheel for time scales, and Earth segment of satellite systems and solar system exploration.

The stability measurement of such CSOs is possible only by comparing three similar units. The task is challenging because the short-term instability it significantly lower than the background noise of commercial instruments. For this reason, until now the measurement was possible only by beating the microwave outputs, with no synthesizer [2]. Owing to machining tolerances, each oscillator is different, and the beat notes fall in the 10 MHz region. This provides a leverage factor of the order of 60 dB, which relaxes the specifications for the instrumentation. Of course, this method does not enable the characterization of the complete machine, including the synthesizer. Now we remove the limitation of the beat note method, and we demonstrate the direct ADEV measurement of each CSO at the 100 MHz output.

II. METHOD

We use a dedicated instrument [3], which consists of 6 tracking DDSs, each exhibiting $2 \times 10^{-14}/\tau$ background noise. The tracking DDS is a digital PLL where the DDS is locked to the input by acting on the phase control word, instead of the clock frequency. The output of the instrument is a stream of phase-time data for the 6 channels, sampled at the rate of 10 samples per second and associated to time tags.

The output of each CSO is split into two channels. There result two data streams per CSO, with statistically independent background noise. Data are collected by an external computer, and processed with a two-sample covariance algorithm [4].

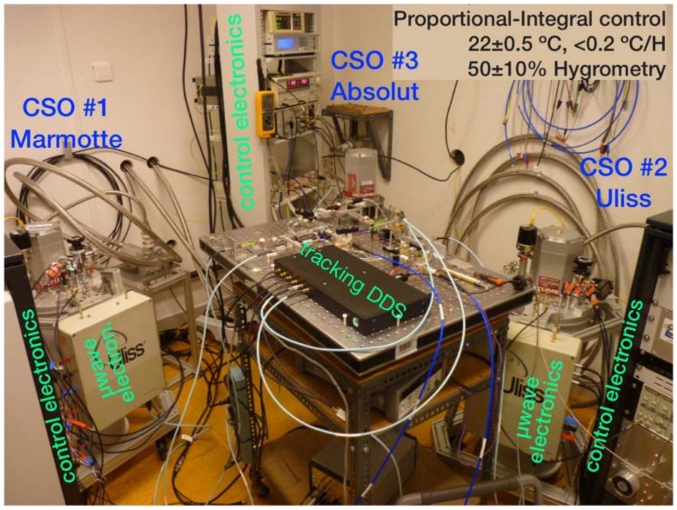

Figure 1 Photo of the experimental setup.

This algorithm is equivalent to the traditional three-cornered hat method, to the extent that the results converge to the Allan variance of the individual oscillators. However, this algorithm is superior to the three-cornered hat in that the contribution of the instrument background converges to zero for large averaging size. This type of measurement relies on the hypothesis that the tree oscillators are statistical independent. The most common correlated phenomena are microwave leakage and fluctuations of the environment. The microwave leakage is in principle absent in our experiment because the resonator bandwidth is of the order of 10 Hz, a few orders of magnitude smaller than the frequency difference between the oscillators. The fluctuations of the environment are strongly reduced by a sophisticated HVAC installation, where a proportional integral control guarantees a temperature of 22 ± 0.5 °C with a maximum drift of 0.2 °C/H, and humidity of $50\% \pm 10\%$. The He pumps are located in a nearby room, and operators are not present during the measurements. We observed that spurs are reduced by setting the synthesizers at three different frequencies slightly off the nominal value of 100 MHz. The experimental setup is shown on Figure 1.

III. RESULTS

Processing a few days of data, we calculate the ADEV of the three CSOs for τ from 1 s to 10^4 s. The results are shown on Table I. The background noise is of 4×10^{-16} at $\tau = 1$ s, decreasing. The value at $\tau = 1$ s is limited by the phase noise of the frequency divider in the frequency synthesis. Taking the average on two decades as a conservative estimate of the flicker floor, the best CSO features a flicker floor of 3×10^{-16}.

TABLE 1 CSO'S ALLAN DEVIATION $\sigma_y(\tau)$

τ, s	Marmotte	Absolut	Uliss
1	3.8×10^{-15}	2.1×10^{-15}	1.5×10^{-15}
10	8.5×10^{-16}	5.5×10^{-16}	7.3×10^{-16}
10^2	3×10^{-16}	3.2×10^{-16}	4.8×10^{-16}
10^3	2.8×10^{-16}	6×10^{-16}	4.6×10^{-16}
10^4	3.8×10^{-16}	7×10^{-16}	3.8×10^{-16}

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