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New-generation of cryogenic sapphire microwave oscillators for space, metrology, and scientific applications

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This article reports on the characterization of cryogenic sapphire oscillators (CSOs), and on the first test of a CSO in a real field installation, where ultimate frequency stability and continuous operation are critical issues, with no survey. Thanks to low-vibration liquid-He cryocooler design, Internet monitoring, and a significant effort of engineering, these oscillators could bridge the gap from an experiment to a fully reliable machine. The cryocooler needs scheduled maintenance every 2 years, which is usual for these devices. The direct comparison of two CSOs demonstrates a frequency stability of 5×10^{-16} for $30\ \text{s} \leq \tau \leq 300$ s integration time, and 4.5×10^{-15} at 1 day (1×10^{-14} typical). Two prototypes are fully operational, codenamed ELISA and ULISS. ELISA has been permanently installed the new deep space antenna station of the European Space Agency in Malargüe, Argentina, in May 2012. ULISS is a transportable version of ELISA, modified to fit in a small van (8.5 m^2 footprint). Installation requires a few hours manpower and 1 day of operation to attain full stability. ULISS, intended for off-site experiments and as a technology demonstrator, and has successfully completed two long-distance travels.

I. INTRODUCTION

Some applications require a reliable microwave oscillator exhibiting the highest short-term stability. This is the case of like the ground stations for space exploration and probe navigation, geodesy, Very Long Baseline Interferometry (VLBI), and also physical experiments and primary clocks. The target stability can be of parts in 10^{-15} at $1 < \tau < 10^3$ s measurement time, yet ever increasing.

After the invention of the Boitier à Vieilliseement Amélioré (BVA),[1] high end oven-controlled quartz oscillators (OCXOs) now provide a stability of about 10^{-13} at $\tau = 1$ s, attaining 5×10^{-14} if one can afford selecting the best resonator out of a production. Such custom units were called ultra-stable oscillators (USOs), and later the same term was eventually used referring to other types of oscillators. Unfortunately, no improvement has been made after the record stability of 5×10^{-14} at 1 s measured at the Jet Propulsion Laboratory (JPL) on a prototype from the Laboratoire de Chronométrie d'Electronique et de Piézoélectricité (LCEP),[2] and the research has still not provided a new path. Resonators implemented with alternate piezoelectric materials,[3] such as Langasite and Langatate, never achieved the short-term stability of the quartz.

Atomic clocks are available as commercial products which deliver reliable and stable frequency out of the box.[4,5] While the Cs standard features the highest absolute accuracy, such accuracy is available only after long measurement time. By contrast, the hydrogen maser (HM) is generally preferred when high short-term stability is desired (1×10^{-15} at 10^4 s), though it drifts in the long run. All commercial atomic clocks, and also virtually all small-size laboratory prototypes, rely on an OCXO frequency locked to the atomic transition with a time constant generally in the range of 1–100 s. Broadly speaking, the clock stability is the OCXO stability at $\tau \approx 1$–100 s, and at longer time rolls off following the $\sqrt{1/\tau}$ law (white frequency noise) determined by the detection ~~of~~ the atomic resonance. Ion and atom-lattice clocks, however promising, are at the stage of laboratory experiments chiefly aiming at long-term stability. The conclusion is that the atomic clock is still unsuitable to provide stability of 10^{-15} at 1–10^3 s.

In the region of $\tau = 0.1 \ldots 1$ s, the highest stability is achieved with a laser stabilized to a complex version of the Fabry-Perot (FP) cavity.[6] The cavity spacer is implemented with low-expansion vitro-ceramic materials, such as the Corning ultra-low expansion (ULE), whose thermal expansion has a turning point at a comfortable value close to the room temperature. These oscillators have been originally designed to

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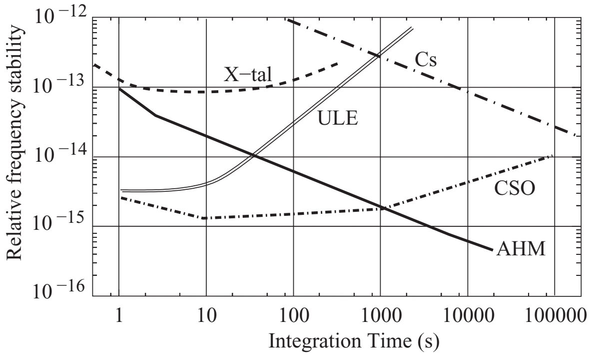

FIG. 1. Comparison of some commercially available frequency standards with respect to the integration time. X-tal: 5 MHz quartz oscillator,[20] Cs: cesium beam frequency standard,[4] ULE: 1.5 μm laser stabilized on a ULE cavity,[8] AHM; active hydrogen maser,[5] and CSO: cryogenic sapphire oscillator[21]

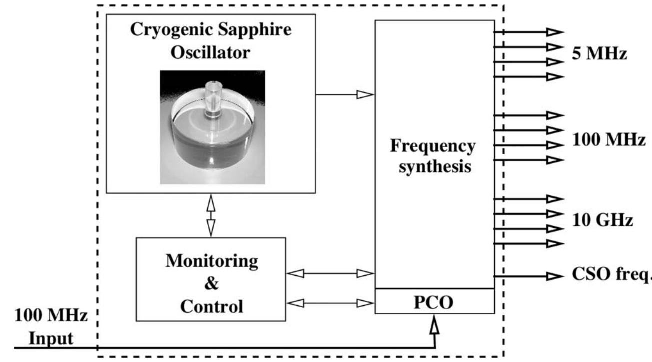

FIG. 2. The cryogenic sapphire oscillator architecture.

serve as the flywheel the new-generation optical frequency standards. Commercial versions are available as the temperature stabilized FP etalon in its vacuum environment,[7] or as the complete cavity-stabilized laser.[8] The FP-stabilized laser suffers from a large drift (typically 10^{-12}/day for the ULE spacer), and requires a femtosecond (FS) laser as the interface that delivers the microwave output. In turn, the FS laser is expensive and cumbersome, it can hardly work longer than weeks without loosing internal frequency locking, and suffers from the low signal-to-noise ratio per mode inherent in the wide bandwidth.

Fig. 1 gives the typical performances of commercially available clocks and oscillators.

The microwave CSO provides outstanding short-term stability, up to parts in 10^{-16} at $\tau \approx 10$ s integration time,[9,10] and also exhibits excellent long term stability.[11,12] At least 20 prototypes of such oscillator have been implemented for primary metrology and physical experiments,[13–16] in which the sapphire is cooled in a large liquid-He Dewar flask. The liquid He requires refilling every 3–4 weeks, and also senses the atmospheric pressure. Such oscillators have been serving quite well for scientific experiments, and also as the flywheel of primary Cs fountain clocks.[17–19] However, the liquid-He bath is incompatible with field applications requiring reliable and unsurveyed operation.

Our first prototype, codenamed ELISA, implemented under contract with the European Space Agency (ESA), exhibits a stability of 3×10^{-15} at $1 \leq \tau \leq 10^3$ s.[22–24] The design required a specific cryocooler to keep the mechanical vibrations within 1 μm at the pulse-tube frequency of $\approx$1 Hz. The bottleneck for long-run uninterrupted operation is scheduled maintenance of the cryocooler, which occurs every 2 years. ELISA exhibits the unprecedented stability of 4×10^{-15} at 1 day, with still no evidence of drift[25] after 4 days. Thanks to these properties, it bridges the gap between the relatively unstable high-spectral-purity USOs and the atomic clocks, which show comparatively poor spectral purity (Fig. 1).

ULISS (Ultra-Low Instability Signal Source) is a different implementation of ELISA, adapted for transportation with a small van (8.5 m^2 footprint, 7 m^3 load capacity). The ULISS project aims at testing the CSO technology in some European metrological sites to evaluate its potential for real applications.[26] The oscillator and the cryocooler are basically the same, while only the mechanical arrangement had to be modified to fit in the available space.

This article demonstrates that the CSO technology is now mature for real field applications, where unattended and reliable operation is of paramount importance, and at most remote monitoring is possible. We first report on the implementation of ELISA and ULISS. While the main principles and technology are already published,[22–24] here we discuss briefly the CSO system design and its main functionality. Then, we assess the stability by direct comparison of the two units. Then, we report on the installation of ELISA in the new ESA Ground Station DSA3 in Malargüe, Argentina. Finally we summarize the main experiments at the LTF and at the CNES, the first two of the ULISS travels, which of course we call *Odyssey*.

II. CSO DESIGN

The architecture of the instrument is represented in Fig. 2. The heart of the instrument is a whispering gallery mode sapphire resonator stabilized at its thermal inversion point, around 6 K. Such a low temperature is achieved in a closed-cycle pulse-tube (PT) cryocooler specially designed to ensure a high thermal stability ($\pm$1 mK) and a low level of mechanical vibrations: axial displacement less than 2 μm at the PT cycle frequency ($\approx$1 Hz). The CSO, which oscillates at 9.989 GHz, is complemented by an ultra-low noise frequency chain that generates the useful frequencies: 10 GHz, 100 MHz, and 5 MHz. The output frequencies can be tuned with a resolution better than 1×10^{-15} through the command of an internal direct digital synthesizer. Four isolated outputs for each frequency deliver 13 dBm. A phase-comparator (PCO) enables to lock the synthesized outputs to an incoming 100 MHz signal. The overall instrument is schematized in the Fig. 3.

Its total electrical consumption is 6 kW and the compressor can be air-cooled or has to be connected to a water chiller or an existing climatization system. The overall instrument can be easily placed in a small van (see Fig. 4) and has already experienced more than 1000 km by road and four successive starting-up/stopping cycles.

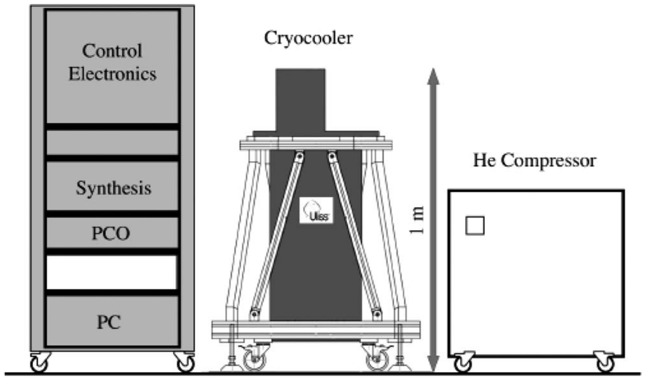

FIG. 3. Scheme of the cryogenic sapphire oscillator ULISS. The cryostat, the electronic rack, and the compressor can be easily moved and placed in a small van by a single operator.

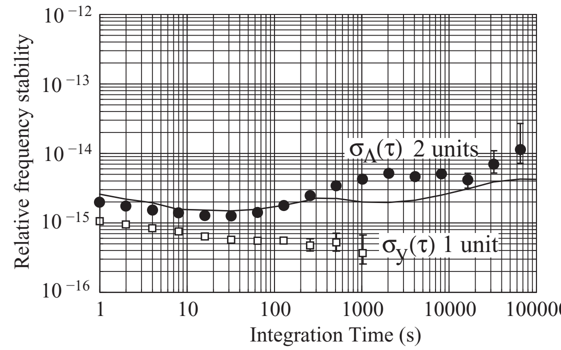

FIG. 5. ULISS CSO typical stability. The solid line indicates the ELISA frequency stability as measured in.[25]

III. CSO FREQUENCY STABILITY

The second unit completely finalized and incorporating the same electronics than the first one has been run for the first time in November 2011 and directly compared with ELISA. The two CSO signals were mixed and the resulting 750 kHz beatnote directly counted with a Agilent Λ-counter (Agilent 53132A) using a gate time $\tau = 1$ s. Data were collected during more than 3 days. The relative frequency deviation $\sigma_\Lambda(\tau)$ was computed for the different integration times τ by grouping the 1-s data. The result is given in Fig. 5 (bold circles). No data post-processing has been done: neither abnormal point suppression nor drift removing.

The obtained short-term relative frequency stability, i.e., for $\tau \leq 300$ s is identical to the one already observed when comparing ELISA and a liquid helium cooled CSO[25] (solid line in Fig. 5). For longer integration times, we observed a hump around 2000 s and a frequency drift of 1×10^{-14}/day, which can be attributed to a residual CSO sensitivity to environmental perturbations. It should be mentioned that these measurements have been realized during infrastructure works in the building: implementation of an air conditioning system in our laboratory which is not still effective. This result is thus conservative. In spite of these bad meteorological conditions, these performances demonstrate the reproducibility of our CSO technology.

The last curve in Fig. 5 (open squares) is the relative frequency deviation calculated from a quiet selected time period of about 10 000 s extracted from the entire data set. The selected data have been recorded during the night when the environmental perturbations are minimized. The calculated standard deviation corresponds to a flicker noise floor, i.e., its value does not depends on τ. This flicker floor comes from the USO internal noise sources. As the two CSOs operate at a different frequency, we assume that these noise sources are

FIG. 4. ULISS in the van.

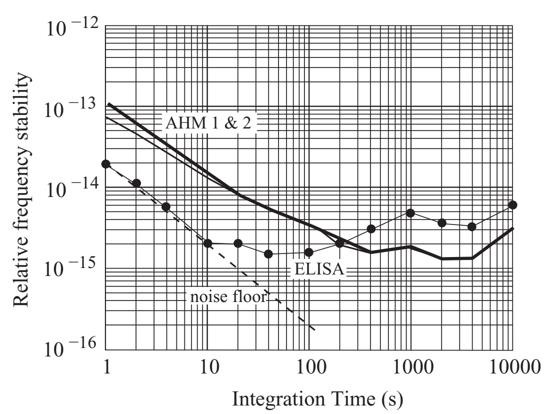

FIG. 6. Individual frequency stability of the three frequency standards of DSA3: HM1, HM2, and ELISA. The dashed line indicates the noise floor of the PCO limiting the measurement to $2 \times 10^{-14}/\tau$.

decorrelated. In that case if the two CSOs are assumed to be identical, it is completely justified to divide the result by $\sqrt{2}$ to obtain the frequency stability of one sole unit. Moreover, the Λ-counter has a specific statistical procedure giving a result, $\sigma_\Lambda(\tau)$, which slightly differs from the true Allan deviation $\sigma_y(\tau)$.[27] Reference 28 gives the correspondence between $\sigma_\Lambda(\tau)$ and the true Allan deviation $\sigma_y(\tau)$. For white frequency of flicker frequency noise: $\sigma_\Lambda(\tau) \approx 1.3 \times \sigma_y(\tau)$. The open squares in the Fig. 5 represent $\sigma_y(\tau)$ evaluated taking into account these two corrections. The flicker floor of one unit is thus

$$\sigma_y(\tau) = 4 \times 10^{-16} \quad \text{for } 10\,\text{s} \le \tau \le 1000\,\text{s}. \qquad (1)$$

Although the following procedure has reasonable assumptions and is often used to present USO characterizations, it represents in our opinion an optimistic evaluation. By remaining aware of this uncertainty, the flicker floor given in Eq. (1), can be considered as the best stability achievable by a well adjusted CSO in stable environmental conditions. The upper curve is the typical frequency stability achievable with our CSO in standard laboratory conditions.

IV. INSTALLATION OF ELISA IN DSA3

Initially ELISA was build as a demonstrator to evaluate the possibility to get a high-frequency stability, i.e., better than 1×10^{-14} at short term, without using liquid helium. As ELISA demonstrated very good performances surpassing the initial specifications, it was decided to implement it in the new Deep Space Antenna Ground Station DSA3 in Malargue (Ar) still under construction. Thus all the instrument was conveyed by air to Buenos Aeres, then by truck to Malargue. Eventually, about 30 km on an unpaved track enable to reach the ESA station.

The frequency and time system of the station consists in two active hydrogen masers and all the means to deliver the useful frequencies and to synchronize the antenna equipments. ELISA was integrated in this F&T system as a complementary ultra-stable source for demonstration purpose. Only few days were necessary to restart ELISA and we conducted preliminary validation tests by comparing ELISA with the two HM. In this remote site we had not access to all the necessary instrumentation, and thus it was not possible to conduct a true 3-cornered-hat-method. Only two synchronous phase difference measurements were possible, the last phase difference was obtain by subtracting the two former data. In this case the phase comparator noise, which is not rejected, limits the stability evaluation at $2 \times 10^{-14}/\tau$. The instrumental noise floor is clearly visible on the results (see Fig. 6).

This measurement has been done after the installation of the complete F&T system. The two hydrogen masers and the CSO were running continuously during about 1 week, but have been greatly perturbed by the work in the station (infrastructure work and cabling). Moreover, the new installed air-conditioning system was not at all tuned. The temperature into the masers and CSO rooms is varying periodically over 1 h of 2 Kpp, which explains the stability degradation observed around 1000 s for the three frequency standards. This situation should be greatly improved when whole instrumentation will be installed and the station will run in operational conditions. The frequency stability of ELISA evaluated here, confirms the previous measurements. At short term the CSO frequency stability is better than 3×10^{-15}.

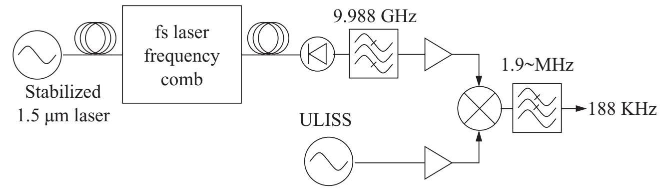

FIG. 7. Set-up used at LTF to compare the stabilized laser to ULISS.

V. SUMMARY OF THE ULISS'S ODYSSEY

A. Test of an all-optical microwave signal generation

The LTF of Neuchâtel is currently developing an all-optical generation of ultra-stable microwave signals. The optical frequency reference consists in a compact and low-cost planar-waveguide external cavity laser stabilized to a high finesse Fabry-Perot ultra-low expansion optical cavity.[29] The frequency stability of this optical reference is eventually transferred to microwave through optical-to-microwave frequency division with a femtosecond laser frequency comb. Optimizing such a complex instrument is not an easy task as the short-term relative frequency stability is expected to be in the range of 10^{-15}. The comparison with ULISS was the opportunity to evaluate the first prototype without the need to build a second equivalent system. The set-up used to make this comparison is given in Fig. 7.

The pulse train of the stabilized femtosecond laser has been sent to a large bandwidth photodiode. The 40th harmonic of the Er:fiber femtosecond laser repetition rate of 250 MHz was filtered and amplified, and eventually mixed with the 9.988 GHz ultra-stable signal generated by ULISS. The resulting beatnote at 188 kHz was counted to evaluate the frequency stability. The measurement result is shown in Fig. 8.

B. Test of state-of-the-art quartz oscillator

The stay of ULISS in Neuchâtel also allowed the short-term stability evaluation of quartz oscillator industrial

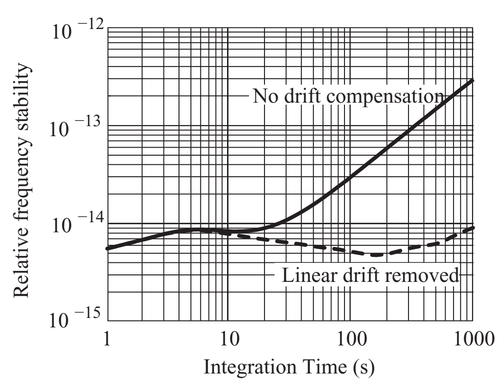

FIG. 8. Preliminary stability of the LTF stabilized laser preliminary as measured by comparison with ULISS.

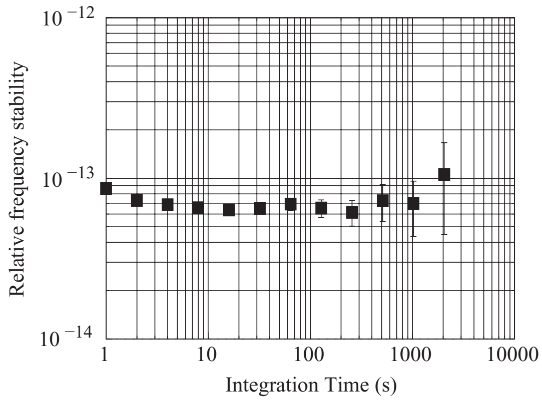

FIG. 9. Frequency stability of a 5 MHz quartz crystal oscillator prototype as measured by comparison with ULISS.

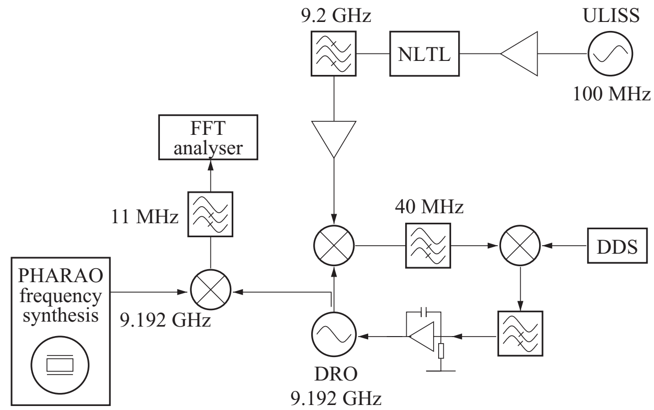

FIG. 11. Generation of a 9.192 GHz ultra-stable signal from the ULISS 100 MHz output.

prototypes developed by Oscilloquartz. To ensure a sufficient resolution of the measurement instrumentation, the quartz signal frequency has been multiplied by 20 and compared to the 100 MHz coming from the ULISS synthesizer. The results is given in Fig. 9 showing an exceptional flicker floor of 5–6$\times$ 10^{-14} extending up to almost 1000 s.

This is the first time that such a frequency performance has been observed without ambiguity for a quartz crystal USO. It demonstrates the potentiality of ULISS to be used to qualify high-performances industrial products.

C. Test of an ultra-low noise microwave frequency synthesis

CNES is in charge of developing and integrating the PHARAO clock, which is the main French contribution to the Atomic Clock Ensemble in Space (ACES), an ESA project. The PHARAO project aims at operating a cold-atoms cesium clock in microgravity in the International Space Station (ISS). The performances of this cold-atoms clock will be combined with those of an active hydrogen maser (HM) to generate an onboard timescale using the excellent short-term stability of the HM and the long-term stability and accuracy of the cesium clock PHARAO. This assembly constitutes the core of the ACES instrument. Today, the CNES is completing the qualification of the PHARAO instrument.

ULISS was thus used to qualify the flying model of the PHARAO microwave source designed by Thales. The 9.192 GHz signal that will probe the cold cesium atoms is generated from a synthesis chain referenced to a state-of-the-art quartz oscillator. Apart from the 9.192 GHz signal, the PHARAO synthesis chain delivers a high stability 100 MHz signal to compare PHARAO to the HM. A stringent phase noise specification has been imposed on these two outputs. The use of ULISS as a frequency reference greatly simplified this performance validation of the PHARAO microwave source. Figure 10 shows the 100 MHz phase-noise measured using the ULISS 100 MHz as reference.

Figure 11 shows the scheme used to generate a 9.192 GHz signal from ULISS.

A nonlinear transmission line (NLTL) generates the harmonics of the incoming 100 MHz. The 92th harmonic is filtered and compared to the signal of a 9.192 GHz dielectric resonator oscillator (DRO). A direct digital synthesizer compensates for the frequency difference and is used to phase lock the DRO to the 92th harmonic of ULISS 100 MHz. The lock loop bandwidth is 300 kHz. The comparison with the PHARAO 9.192 GHz is shown in Fig. 12

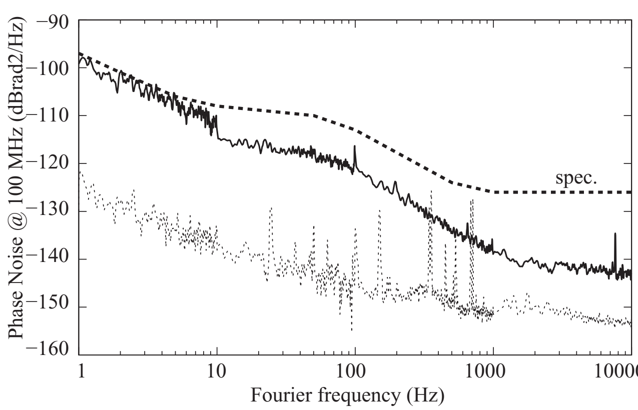

FIG. 10. Phase noise of the PHARAO synthesis 100 MHz output (bold line). Phase noise of the ULISS 100 MHz output (thin line) and PHARAO specifications (dotted line).

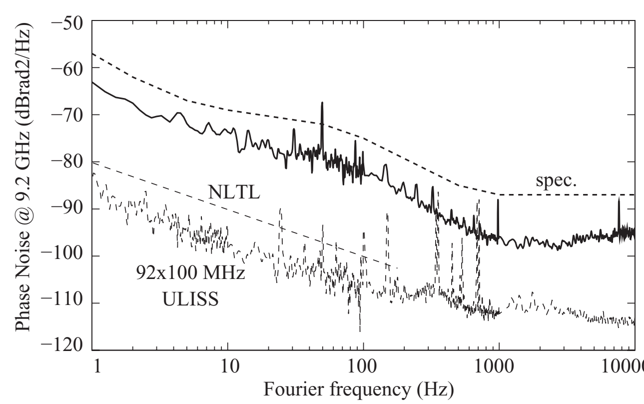

FIG. 12. Phase noise of the 9.192 GHz interrogation signal of the PHARAO clock (bold line) and PHARAO specifications (bold dotted line). Expected phase noise floor: multiplied ULISS 100 MHz and NLTL contributions (thin dotted lines).

We did not measure the phase noise of the 9.192 GHz reference signal generated from the ULISS 100 MHz output. However, we indicate in Fig. 12, the contribution of the multiplied ULISS 100 MHz and what the expected contribution of the NLTL multiplication chain. Indeed we already tested this scheme to evaluate the short-term frequency stability of a 12 GHz whispering gallery mode maser oscillator.[30] The measured relative frequency stability was limited at short term by a noise floor of $\sigma_y(\tau) \approx 10^{-14}/\tau$. Converted into phase noise such a stability limitation corresponds to a flicker phase noise $S_\varphi(f) = \frac{h_1}{f}$ with $h_1 = -81$ dBrad^2/Hz, which is still far below the PHARAO specifications. The measured phase noise is in accordance with the expectations. ULISS has already been requested by CNES for the next steps of the PHARAO qualification.

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