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Unprecedented Long-Term Frequency Stability With a Microwave Resonator Oscillator

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***Abstract*—This article reports on the long-term frequency stability characterization of a new type of cryogenic sapphire oscillator using an autonomous pulse-tube cryocooler as its cold source. This new design enables a relative frequency stability of better than 4.5 × 10^{-15} over one day of integration. To the best of our knowledge, this represents the best long-term frequency stability ever obtained with a signal source based on a macroscopic resonator.**

I. Introduction

An oscillator consists of a resonator in closed loop with a sustaining amplifier that compensates for losses. The frequency stability is limited by the noise of the amplifier through the Leeson effect [1] and by the fluctuation of the resonator's natural frequency. The stability of the resonator's natural frequency is by far the most important parameter that limits the long-term stability. In turn, the resonator's natural frequency is affected by environmental parameters and aging. In contrast, the noise of the sustaining amplifier affects the phase noise and the short-term stability. When very-long-term stability is the most important parameter, as in timekeeping and in radionavigation systems, atomic resonances are the only viable frequency references. In this case, a flywheel oscillator is frequency locked to the atomic resonance. On the other hand, macroscopic-cavity resonators show several advantages versus the atomic resonators because of their simplicity, reliability, and power-handling capability. Higher power results in higher signal-to-noise ratio, and ultimately in low phase noise and high short-term stability. Ultimate stability in the range of 1 to 10^6 s measurement time is of paramount importance in physical experiments involving long averaging and, of course, in radioastronomy. In this paper, we demonstrate for the first time a microwave oscillator based on a macroscopic resonator with a frequency stability at long integration times that is competitive with those of classical microwave atomic clocks.

Microwave cryogenic sapphire oscillators (CSOs) exhibit the highest short-term stability, attaining parts in 10^{-16} near 10 s integration time [2]–[4]. A CSO incorporates a cryogenic whispering-gallery-mode resonator made of sapphire, which provides a Q-factor as high as 1 × 10^9 at 4.2K. In practically all functional realizations thus far, the resonator is immersed in a liquid-helium bath and maintained at its optimum temperature (generally around 6K), where its thermal sensitivity is zero to first order. Preliminary work on the use of a 2-stage Gifford-McMahon cryocooler has been described in [5]. CSOs have been used as local oscillators for atomic fountains clocks [6] and for fundamental physical experiments as local Lorentz invariance tests [7]. It is also planned to implement such oscillators in Deep Space Network ground stations to improve the tracking of space vehicles and in very long baseline interferometry (VLBI) observatories for better data correlation. For these last applications, the use of liquid helium is inconvenient and a change of technology is needed. In the frame of a European Space Agency research contract, we recently validated a new instrument nicknamed Elisa which is based on a CSO operating in a specially designed cryocooler. The detailed design and preliminary characterizations can be found in [8] and [9]. This CSO is associated with a frequency synthesis delivering round frequencies, i.e., 10 GHz, 100 MHz and 5 MHz. Elisa's relative frequency stability is better than 3 × 10^{-15} for $1 \text{ s} \leq \tau \leq 1000 \text{ s}$ and can operate continuously for two years without maintenance. As an additional benefit, this new type of CSO presents an unprecedented frequency stability at long integration times: 4 × 10^{-15} over one day without any clearly observed drift.

II. CSO Description

The resonator consists of a HEMEX grade single-crystal sapphire (Crystal Systems Inc., Salem, MA), 54.2 mm in diameter, 30 mm thick, with a 10-mm-diameter spindle allowing a stable mechnical clamping, in the center of a gold-plated copper cavity. As shown in the schematic of this assembly in Fig. 1, it is fixed on the experimental cold plate of a pulse-tube cryocooler. A special soft thermal link and a thermal ballast were designed to filter the vibrations and the 1.4 Hz temperature modulation induced by the gas flow in the cryocooler. The CSO is completed by an external sustaining circuit and two servos to stabilize the power injected into the resonator and the phase lag along the sustaining loop.

The mechanical tolerances in the resonator machining induce an uncertainty in the actual resonator frequency of ±3.5 MHz. The resonator was designed to operate on the

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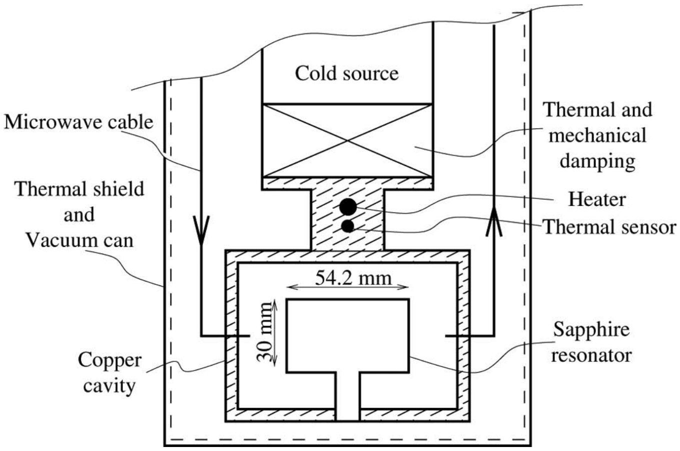

Fig. 1. Scheme of the cryogenic sapphire resonator.

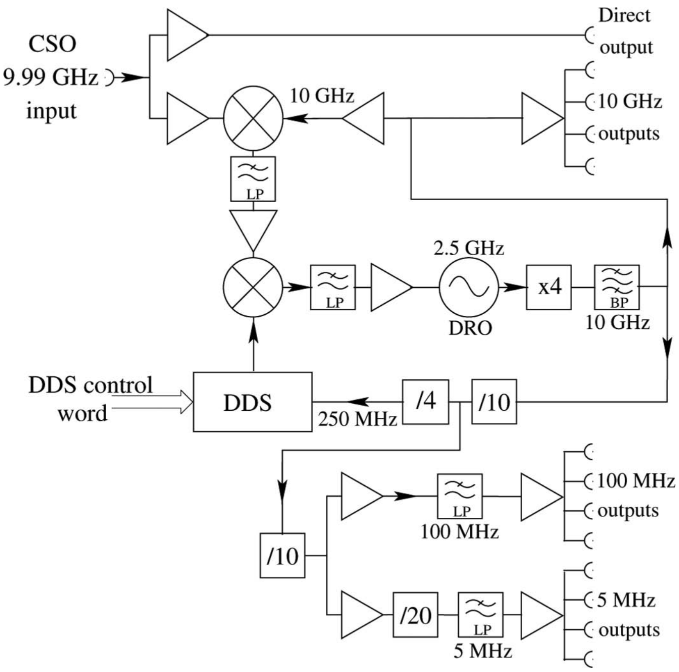

Fig. 2. Scheme of the synthesis used to generate the 10 GHz, 100 MHz, and 5 MHz signals.

$WGH_{15,0,0}$ whispering gallery mode at 9.99 GHz. The intentional 10 MHz frequency offset from the 10 GHz round frequency was chosen to permit compensation for the resonator frequency uncertainty by using a low-noise direct digital synthesizer (DDS). The actual resonator frequency measured at 6.1K is 9.989121 GHz. The anatomy of the frequency synthesis chain is shown in Fig. 2.

A 2.5-GHz dielectric resonator oscillator (DRO) chosen for its low phase noise is frequency multiplied by 4 and mixed with the CSO's signal. The resultant 11 MHz beatnote is compared with the signal coming from a DDS. The resulting error signal is used to phase lock the DRO to the CSO. Frequency dividers complete the system to generate the 100 MHz and 5 MHz frequencies from the 10 GHz signal.

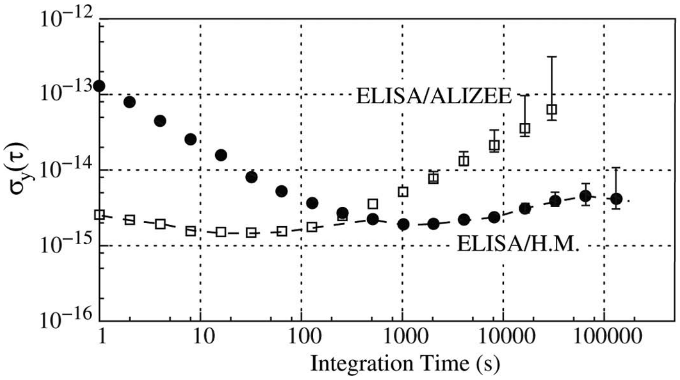

Fig. 3. Relative frequency stability as measured by beating Elisa with another CSO (squares) and the hydrogen maser (circles). The broken line represents a conservative estimate of Elisa's frequency stability from 1 s to more than 1 d.

To evaluate Elisa's frequency stability over a large integration time range, two other frequency references have been used: 1) we implemented a second CSO, Alizée, cooled in a liquid-helium Dewar flask and equipped with the same frequency synthesis. The Elisa and Alizée resonators are almost identical and were machined from the same sapphire boule. Alizée's resonator is placed in a vacuum can immersed in a 100-L liquid-helium Dewar flask. 2) A hydrogen maser which does not include an automated cavity tuning. The hydrogen maser was placed in the same room as the two CSOs. This room is not temperature controlled. The results of the two comparisons are summarized in Fig. 3.

The short-term frequency stability of the synthesized signals has been evaluated at 10 GHz by beating the Elisa's and Alizée's 10-GHz outputs. The Alizée output was intentionally frequency shifted by acting on the DDS command to get a 200-kHz beatnote. This beatnote was directly counted on an Agilent 53132A counter (Agilent Technologies, Santa Clara, CA) with a gate time $\tau = 1$ s. The relative frequency deviation was calculated for the different intregration times by grouping the 1-s data. The counter has a specific statistical procedure giving a result, $\sigma_\Lambda(\tau)$, which slightly differs from the true Allan deviation $\sigma_y(\tau)$ [10], [11]. Nevertheless, for the integration times we consider here, it gives an overestimated relative frequency deviation with respect to $\sigma_y(\tau)$. Moreover, no data post-processing has been done and we did not divide the result by $\sqrt{2}$, a practice which is generally adopted when comparating two almost equivalent oscillators. Thus, the results presented here are conservative.

The short-term frequency stability is limited by a white frequency noise process $\sigma_\Lambda(\tau) \approx 3 \times 10^{-15}\tau^{-1/2}$, which we attribute to the noise of the Pound servo used to stabilize the phase along the sustaining loop. At long-term, a random walk or a frequency drift alters the frequency stability. The implementation of Elisa was finalized in October 2009 and since then it has been continuously running apart from two short periods of time; once, for implementing an optimized rotary valve for the cryocooler and again

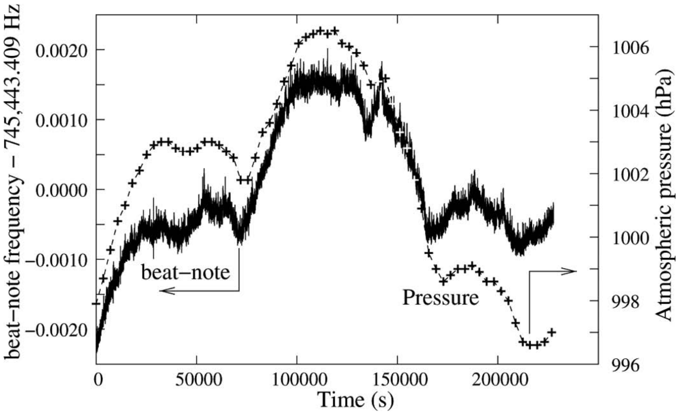

Fig. 4. Beatnote frequency (noisy curve) and atmospheric pressure (crosses) as a function of time.

after a general electrical breakdown arising in our laboratory. After each stop, Elisa was simply switched on and recovered its optimal temperature in about 8 h. Conversely, Alizée was stopped several times because of limited supplies in liquid helium. Moreover, for a long measurement campaign the Dewar flask needs to be refilled every 10 d. During this 6 mo period, several measurements were realized, demonstrating that the long-term behavior of the beatnote depends substantially on the status of Alizee and on the environmental perturbations. As an example, Fig. 4 shows the correlation between the beatnote frequency and the local atmospheric pressure. The liquid helium temperature of evaporation depends on the atmospheric pressure with a sensitivity equal to 1 mK/mbar near 4.2K. Temperature exchange by radiation between the vacuum can and the Alizée resonator takes place and perturbs the mode frequency leading to long-term instability.

The long-term stability has been evaluated at 100 MHz by using the hydrogen maser as a reference. The relative frequency stability has been computed from the phase difference data averaged over a sampling period of 1 s. The data were taken continuously for more than 5 d and the Allan deviation was computed. The result is shown in Fig. 3 (black bullets). The maser short-term instability limits the measurement for $\tau \leq 500$ s, but for longer integration times, it is obvious that Elisa is far better than Alizée. The maximum frequency instability, i.e., 4.5×10^{-15} arises near 1 d. It is likely that the hydrogen maser itself significantly contributes to this frequency instability. Indeed, its residual sensitivity has been measured to be 1.4×10^{-14}/K which is far from negligible, given that the daily variation of the temperature in the laboratory was typically a few degrees Celsius. Fig. 5 compares the previous Elisa relative frequency stability to the best ever published ultra-stable oscillator performances.

III. Conclusion

We demonstrated a cryogenic oscillator presenting the highest frequency stability over one day ever obtained with an oscillator based on a macroscopic resonator. This performance is associated with a two-year autonomy. This demonstrates that the technology of the CSO is now mature enough to envisage its implementation in applications requiring top-level performance and reliability.

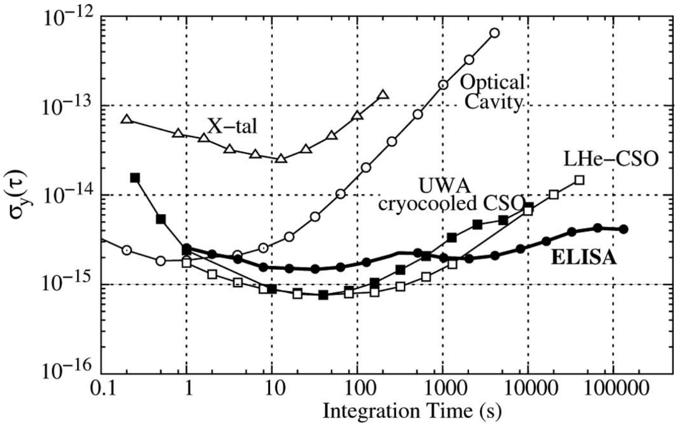

Fig. 5. ●: Estimated ELISA's relative frequency stability compared with some other frequency standards based on macroscopic resonator; △: 5-MHz quartz oscillator [12]; ○: Laser stabilized on an ultra-stable optical cavity [13]; □: UWA cryocooled CSO [14]; ■: UWA liquid-helium cooled CSO [3]. Note: To be consistent with our own procedure to evaluate the frequency stability, the published results for which the two-equivalent-oscillators hypothesis has been assumed have been multiplied by $\sqrt{2}$.

References

[1] E. Rubiola, *Phase Noise and Frequency Stability in Oscillators.* Cambridge, UK: Cambridge University Press, 2008.

[2] S. Chang, A. G. Mann, and A. N. Luiten, "Improved cryogenic sapphire oscillator with exceptionally high frequency stability," *Electron. Lett.*, vol. 36, pp. 480–481, Mar. 2, 2000.

[3] J. G. Hartnett, C. Locke, E. Ivanov, M. Tobar, and P. Stanwix, "Cryogenic sapphire oscillator with exceptionally high long-term frequency stability," *Appl. Phys. Lett.*, vol. 89, art. no. 203513, 2006.

[4] K. Watabe, J. Hartnett, C. R. Locke, G. Santarelli, S. Yanagimachi, T. Ikegami, and S. Ohshima, "Progress in the development of cryogenic sapphire resonator oscillator at NMIJ/AIST," in *Proc. 20th European Frequency and Time Forum*, Braunschweig, Germany, Mar. 27–30, 2006, pp. 92–95.

[5] G. J. Dick and R. T. Wang, "Cryo-cooled sapphire oscillator for the Cassini Ka-band," in *Proc. 1997 IEEE Frequency Control Symp.*, Orlando, FL, Mar. 17–19, 1997, pp. 1009–1014.

[6] G. Santarelli, P. Laurent, P. Lemonde, A. Clairon, A. G. Mann, S. Chang, A. N. Luiten, and C. Salomon, "Quantum projection noise in an atomic fountain: A high stability cesium frequency standard," *Phys. Rev. Lett.*, vol. 82, no. 23, pp. 4619–4622, Jun. 1999.

[7] P. Wolf, S. Bize, A. Clairon, A. N. Luiten, G. Santarelli, and M. E. Tobar, "Test of Lorentz invariance using a microwave resonator," *Phys. Rev. Lett.*, vol. 90, art. no. 060402, Feb. 14, 2003.

[8] S. Grop, P.-Y. Bourgeois, N. Bazin, Y. Kersalé, E. Rubiola, C. Langham, M. Oxborrow, D. Clapton, S. Walker, J. D. Vicente, and V. Giordano, "A crycooled 10 GHz oscillator with 10^{-15} frequency stability," *Rev. Sci. Instrum.*, vol. 81, art. no. 025102, 2010.

[9] S. Grop, P. Y. Bourgeois, R. Boudot, Y. Kersalé, E. Rubiola, and V. Giordano, "10 GHz cryocooled sapphire oscillator with extremely low phase noise," *Electron. Lett.*, vol. 46, pp. 420–422, Mar. 18, 2010.

[10] E. Rubiola, "On the measurement of frequency and of its sample variance with high-resolution counters," *Rev. Sci. Instrum.*, vol. 76, no. 5, art. no. 054703, 2005.

[11] S. Dawkins, J. McFerran, and A. Luiten, "Considerations on the measurement of the stability of oscillators with frequency counters," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 54, pp. 918–925, May 2007.

[12] P. Salzenstein, A. Kuna, L. Sojdr, and J. Chauvin, “Significant step in ultra high stability quartz crystal oscillators,” *Electron. Lett.*, vol. 46, no. 21, pp. 1433–1434, Oct. 2010.

[13] S. A. Webster, M. Oxborrow, S. Pugla, J. Millo, and P. Gill, “Thermal-noise-limited optical cavity,” *Phys. Rev. A*, vol. 77, no. 3, art. no. 033847, 2008.

[14] N. R. Nand and J. Hartnett, “Frequency stability and phase noise of an improved X-band cryocooled sapphire oscillator,” in *Proc. IEEE Int. Frequency Control Symp.*, Newport Beach, CA, Jun. 2–4, 2010, pp. 670–673.