Direct comparison of two Cryocooled Sapphire Oscillators presenting relative frequency instability at 10^{-15}

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***Abstract*— In this paper we present the direct comparison of two microwave Cryocooled Sapphire Oscillators demonstrating a relative frequency stability better than $2{\times}10^{-15}$ at short term and of the order of $1{\times}10^{-14}$ over one day integration. We also report the frequency stability evaluation of a microwave signal generated from a planar waveguide external cavity laser (PW-ECL) referenced to a Fabry-Perot cavity through optical-to-microwave frequency division with a commercial Er:fiber optical frequency comb owned by the "laboratoire temps-fréquence" (LTF) of the university of Neuchâtel, Switzerland, and the phase noise measurement of the engineering model of the Pharao clock frequency synthesis owned by the "Centre National d'Etudes Spatiales" (CNES) at Toulouse, France. These lastest results were obtained by moving one of our Cryogenic Sapphire Oscillator (CSO) from the FEMTO-ST Institute to these two metrological sites.**

I. Introduction

We recently developped a Cryogenic Sapphire Oscillator (CSO) named Elisa presenting a short term frequency stability better than $3{\times}10^{-15}$ for 1 s $\leq \tau \leq$ 1000 s and achieving $4.5{\times}10^{-15}$ for one day integration [1], [2]. This CSO was designed and built in the framework of a research contract funded by the European Space Agency (ESA). It incorporates a pulse-tube cryocooler instead of a bath cryostat, thus eliminating the need for regular supplies and manual refilling of liquid helium. The advent of reliable and cryocooled CSO open the possibility to implement such an ultra-stable reference not only in metrological laboratories with liquid helium facilities but also in remote sites like base stations for space navigation, VBLI antenna sites, ... [3], [4]
In our project ULISS (Ultra Low Instability Signal Source), funded by Regional and European Institutions, we built a new cryocooled oscillator named ULISS specially designed to be transportable. The ULISS oscillator was already used to qualify with success a high stability frequency source located at Neuchâtel, Switzerland, and the PHARAO frequency synthesis Toulouse, France. ULISS was specially moved from FEMTO-ST for the measurement compaigns.
In this paper we present the frequency stability characterization of the newly built CSO demonstrating the reproductibility of our technology and we summarize the main results obtained at the LTF and CNES.

A. Schematic architecture of the Cryocooled Sapphire Oscillator Instruments

The architecture of a Cryocooled Sapphire Oscillator Instrument is represented in the figure 1.

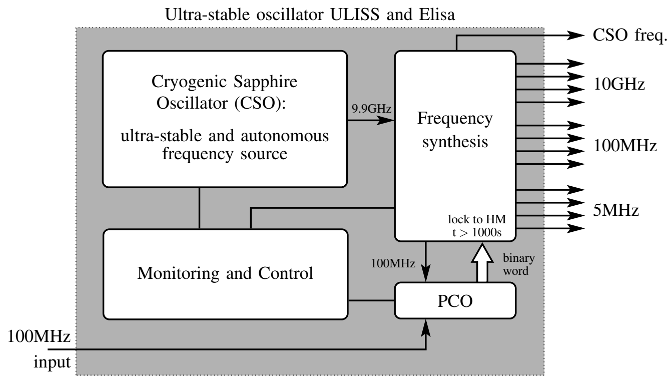

Fig. 1. Schematic architecture of a Cryocooled Sapphire Oscillator Instrument

The CSO design and its characterization were already described in the references [1], [2], [5]–[7].

II. ULISS frequency stability characterization

ULISS unit is a copy of the first unit Elisa and was finalized the 11th November 2011. The two CSO outputs were mixed to generate a beatnote at 750kHz. This beatnote was directly counted on an Agilent 53132A Λ-counter parametrized with a gate time $\tau = 1$ s [8], [9]. After approximately 4 days of acquisition, the relative frequency deviation $\sigma_\Lambda(\tau)$ was calculated for the different integration times τ by grouping the 1 s data. The first significant result was measured the 12th December 2011, the time to tune the different servo control loops. The result is given in the figure 2. No data post-processing has been done: no abnormal point suppression nor drift removing.

We measured a relative frequency stability $\sigma_\Lambda(\tau)$ better than $2{\times}10^{-15}$ for integration times 1 s $\leq \tau \leq$ 200 s. For longer integration times, we observed a hump around 2000 s, that we still have to determined the source, and a drift of $1{\times}10^{-14}$/day. The second curve of the figure 2 is the relative frequency deviation calculated from a quiet selected time period of about

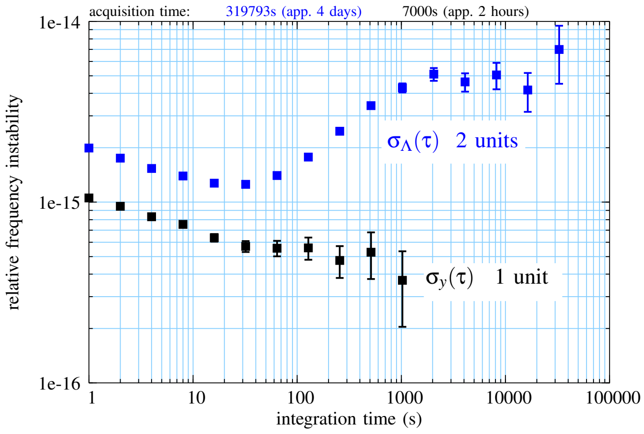

Fig. 2. Relative frequency stability of the 9.99 GHz CSO outputs

7000 s extracted from the complete set of data. The calculated standard deviation corresponds to a flicker 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 decorrelated. In that case and if the two CSOs are assumed identical, it is justified to divide the result by $\sqrt{2}$ to obtain the frequency stability of one unit. Moreover the reference [9] gives the correspondance 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 figure 2 represent $\sigma_y(\tau)$ evaluated taking into account these two corrections. The flicker floor of one unit is thus:

$$\sigma_y(\tau) = 4 \times 10^{-16} \text{ for } 30 \text{ s} \leq \tau \leq 500 \text{ s} \tag{1}$$

Although the following procedure has reasonable assumption and is often used to present USO characterization. It represents an optimistic evaluation. Remainder aware of this uncertainty, the flicker floor given in the equation 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.

III. ULISS's ODYSSEY

A. Test of an all-optical microwave signal generation

The ULISS's odyssey started the 15th February 2012 at the LTF of Neuchâtel. ULISS was operational three days later and was used as frequency reference to evaluate the frequency stability of a microwave signal generated from an optical frequency reference.

The optical frequency reference consists in a compact and low-cost planar waveguide external cavity laser (PW-ECL) stabilized on a high finesse Fabry-Perot ULE optical cavity. The frequency stability of this optical reference is transfered to microwave domain through optical-to-microwave frequency division with an femtosecond laser frequency comb. The comparison set-up is given in the figure 3.

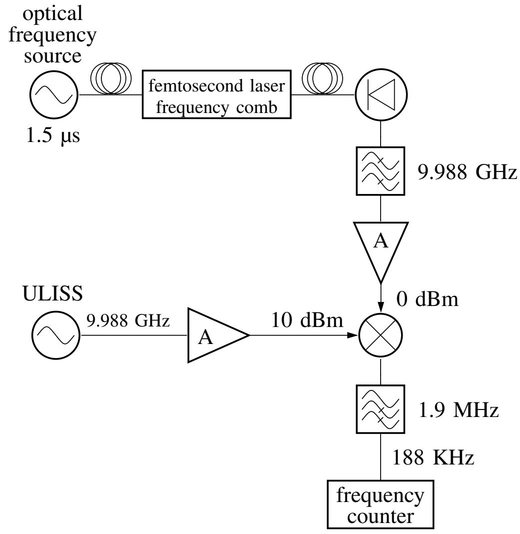

Fig. 3. Comparison set-up

The beam of the stabilized femtosecond laser was sent to a large bandwidth photodiode. The output signal of the photodiode is filtered to keep the 40th harmonic of the femtosecond laser repetition rate, amplified and mixed with the amplified 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 the figure 4.

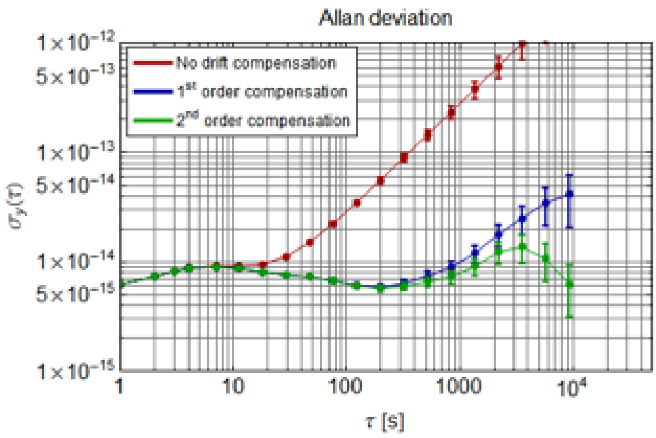

Fig. 4. Relative frequency stability of the 9.99 GHz microwave signal generated with the femtosecond laser and ultra-stable laser

ULISS allowed to evaluate the frequency stability of an all-optical microwave signal generator without the need of a second equivalent unit.

B. Test of an USO X-tal

During the measurement compaign at the LTF, a quartz oscillator prototype from the Oscilloquartz company was characterized in term of frequency stability. The set-up measurement scheme is presented on figure 6.

To ensure a sufficient resolution of the measurement instrumentation, the quartz signal frequency was multiplied by

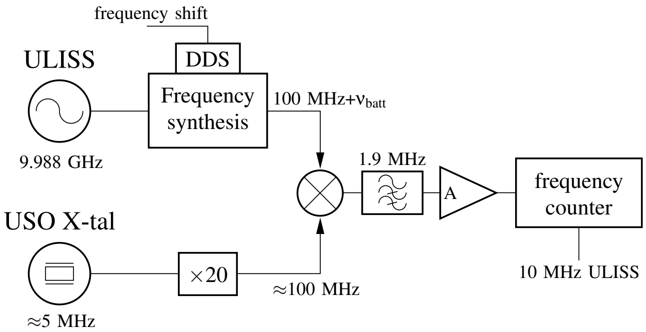

Fig. 5. Quartz oscillator frequency stability measurement set-up

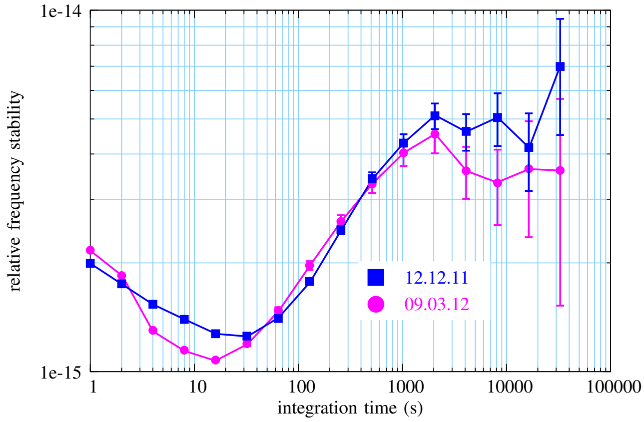

Fig. 7. Relative frequency stability of the 9.99 GHz CSO output before and after the trip to the LTF at Neuchâtel

20 and compared to the 100 MHz coming from the ULISS frequency synthesis. The best result is shown on figure 6.

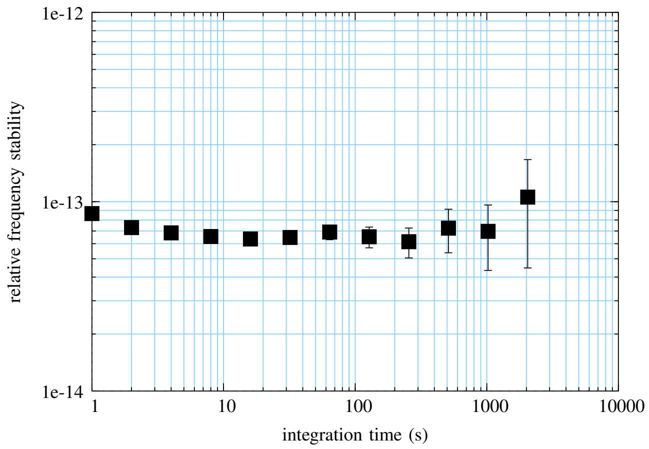

Fig. 6. Relative frequency stability of the best quartz oscillator

This is the second time that such a performance was observed unambiguously for a quartz crystal USO [10]. The frequency stability measured at the FEMTO-ST Institute in 2010 and at the LTF are identicals. It demonstrates the potentiality of ULISS to be used to qualify high-performances industrial products.

The 5th May, ULISS returned back to the FEMTO-ST Institute and was tested against Elisa to checked if any malfunctions appeared due to the trip. The 9th May, the same frequency stability as our first measurement compain was measured (figure 7).

This result is enough to prove the robustness and reliability of our ultra-stable frequency source.

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

The PHARAO project aimed to operate a cold-atoms caesium 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 (Atomic Clock Ensemble in Space) instrument.

Today, the PHARAO instrument is completing its qualification. ULISS was thus be used to qualify the flying model of the PHARAO 9.192GHz local oscillator. The signal that will probe the cold atoms is generated from a frequency synthesis referenced on a state-of-the-art quartz oscillator. Apart from the 9.192GHz signal, the PHARAO's frequency synthesis delivers a high frequency stable 100 MHz signal to compare PHARAO to the HM. Drastic phase noise specification has been imposed on these two outputs. The use of ULISS as a frequency reference greatly simplfied the validation of the PHARAO's frequency synthesis. The figure 8 represents the phase noise measurement set-up used to characterize the 9.192 GHz output signal.

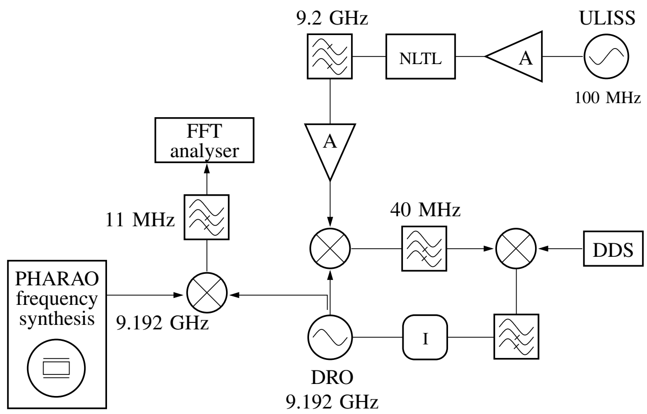

Fig. 8. Set-up of the 9.192 GHz signal generation and phase noise measurement

A nonlinear transmission line (NLTL) generates some harmonics of the incoming amplified 100 MHz generated from ULISS. After filtering, the 9.2 GHz signal is amplified and compared to the signal of a 9.192 GHz Dielectric Resonator Oscillator (DRO). A Direct Digital Synthesizer locked on ULISS output signal compensates the frequency difference and is used to phase lock the DRO. The result is shown in the figure 9 and was obtained two days after our arrival at CNES site.

The 100 MHz phase noise measurement set-up is far sim-

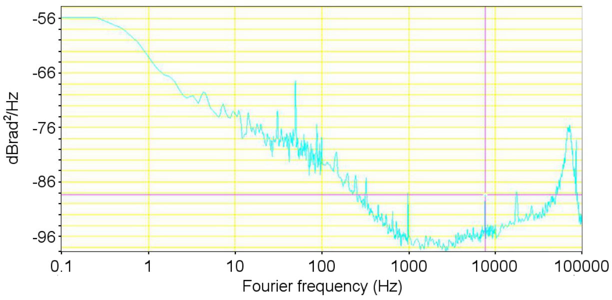

Fig. 9. Phase noise of the PHARAO frequency synthesis at 9.192GHz

pler. The 100 MHz output of ULISS is adjusted, by shifting the frequency output of the ULISS's frequency synthesis DDS, to perfectly fit to the 100 MHz output of the PHARAO's frequency synthesis, with the use of a industrial phase comparator produced by the company Timetech Gmbh. The result is shown in the figure 10.

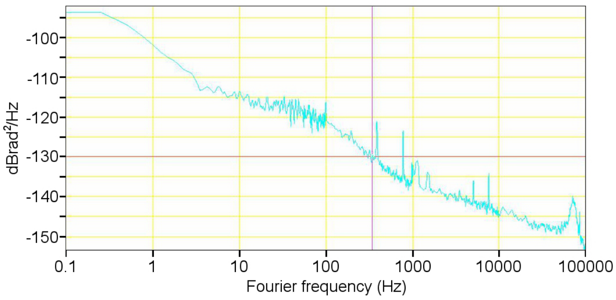

Fig. 10. Phase noise of the PHARAO frequency synthesis at 100Hz

The results fit to the phase noise measurement results made few years ago at CNES except the modulation observed at 80 KHz Fourier frequency. The modulation is justified by a malfunction of the ULISS's frequency synthesis DRO.
Despite the modulation, the results are convincing and show the utility of such kind of state-of-the-art frequency source for the characterization of low phase noise frequency source.

IV. Conclusion

The results shown on this paper demonstrate the technology maturity and reliability of our CSOs. We reached our objective to develop a transportable version of the state-of-the-art crycooled sapphire oscillator Elisa with equivalent performances and we already visited two scientific institutes which led to interesting collaboration and results.

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References

[1] S. Grop, P.-Y. Bourgeois, N. Bazin, Y. Kersalé, E. Rubiola, C. Langham, M. Oxborrow, D. Clapton, S. Walker, J. DeVicente and V. Giordano, Elisa: a cryocooled sapphire oscillator with 1.10-15 frequency stability, Revue of Scientific Instruments, 81, 2010.

[2] S. Grop, W. Schafer, P.-Y. Bourgeois, Y. Kersalé, M. Oxborrow, E. Rubiola and V. Giordano, Unprecedented High Long Term Frequency Stability with a Microwave Resonator Oscillator, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 58, 8, 1694-1697, 2011.

[3] V. Giordano, S. Grop, P.-Y. Bourgeois, Y. Kersalé, E. Rubiola, M. Mrad, C. Langham, M. Oxborrow and W. Schafer, Cryogenic sapphire microwave oscillators for space, metrology and scientific applications, General Assembly and Scientific Symposium, URSI, Istanbul, Turkey, 2011.

[4] J. G. Hartnett, N. R. Nand, Ultra-low vibration pulse-tube cryocooler stabilized cryogenic sapphire oscillator with 10-16 fractional frequency stability, IEEE Trans. on MTT, 58, 3580-3586, 2010.

[5] S. Grop, P.-Y. Bourgeois, R. Boudot, Y. Kersalé, E. Rubiola and V. Giordano, 10 GHz cryocooled sapphire oscillator with extremely low phase noise, Electronics Letters, 46, 6, 420-422, 2010.

[6] S. Grop, W. Schafer, P.-Y. Bourgeois, Y. Kersalé, M. Oxborrow, E. Rubiola and V. Giordano, Unprecedented High Long Term Frequency Stability with a Microwave Resonator Oscillator, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 58, 8, 1694-1697, 2011.

[7] S. Grop, P.-Y. Bourgeois, E. Rubiola, W. Schafer, J. DeVicente, Y. Kersalé and V. Giordano, Frequency Synthesis Chain For The ESA Deep Space Network, Electronics Letters, 47, 6, 386-388, 2011.

[8] E. Rubiola, On the measurement of frequency and of its sample variance with high-resolution counters, Revue of Scientific Instruments, 76, 5, 2005.

[9] S. T. Dawkins, J. J. McFerran and A. N. Luiten, Considerations on the measurement of the stability of oscillators with frequency counters, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, 54, 5, 918-925, 2007.

[10] S. Grop, B. Dubois, P.-Y. Bourgeois, Y. Kersalé, E. Rubiola, G. Haye and V. Giordano, ULISS: A Mobile Cryogenic U ltra- Stable Oscillator, Joint conference of the 2011 IEEE IFCS-EFTF, San Francisco, US, 2011.