Lowest Flicker-Frequency Floor Measured on BVA Oscillators

Alexander Kuna, Jan Čermák, Ludvík Šojdr, Patrice Salzenstein, and Frederic Lefebvre

***Abstract*—In this paper we will present the results of the time-domain measurement of short-term frequency stability on 7 ultra-stable 5-MHz Boîtier à Vieillissement Amélioré (BVA, improved aging case) oscillators. The measurements took place in the Institute of Photonics and Electronics (IPE) in July 2008 and was a continuation of the stability measurements of BVA oscillators reported in our previous work.**

I. Introduction

The state-of-the-art quartz oscillators based on the BVA technique are extremely stable frequency sources in the short-term [1], [2]. Their limiting noise has a character of flicker frequency modulation with a noise floor of less than 4×10^{-14} in terms of Allan deviation, $\sigma_y(\tau)$, of average fractional frequency [3], [4]. Thus, at averaging intervals of a few seconds, the BVA quartz oscillators achieve better stability than the best active hydrogen masers.

To measure the short-term frequency stability of these precision oscillators, a highly sensitive measurement system is needed with background stability less than 10^{-14} at 1 s. Unfortunately, the commercially available instruments do not provide such performance and therefore a dedicated laboratory system has to be built to satisfy this requirement.

At the Time and Frequency Department of the Institute of Photonics and Electronics, Czech Academy of Sciences, Prague, Czech Republic, we have developed such a system based on the classical dual-mixer time-difference multiplication (DMTDM) technique [5]–[10], which we have optimized to achieve the minimum background noise at an averaging interval of 1 s. The first experimental version appeared in 2003, and since then much improvement has been made [11], [12].

The capability of our system has recently been verified in repeated measurements on the best ever produced BVA quartz oscillators [1]. The measurements have been carried out within the #847 EURAMET Project in collaboration with Franche Comté Electronique Mécanique Thermique et Optique-Sciences et Technologies, Besançon, France, and with the producer of the oscillators—Oscilloquartz SA (OSA), Neuchâtel, Switzerland. The 2 partners provided the 5-MHz 8607 OSA oscillators which we measured along with our two 8600 OSA BVA units.

Manuscript received May 18, 2009; accepted August 31, 2009. The work has been sponsored by the Czech Office for Standards, Metrology and Testing (No. III/13/08 Project).

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Digital Object Identifier 10.1109/TUFFC.2010.1446

II. Measurement Basics

The measured quantity is the variations in the phase-time difference between 2 quasi-synchronous sine-wave signals at nearly equal frequency. The measurement sensitivity is enhanced using DMTDM.

The method is based on dual mixing the 2 compared signals at frequency ν with a signal at frequency $\nu \pm \nu_{\mathrm{B}}$ from a common oscillator to provide 2 beat-note signals at ν_{B}. The multiplication factor is thus $M = \nu/\nu_{\mathrm{B}}$.

A time-interval counter then periodically measures the time interval, x_{k}, between 2 adjacent zero-crossings of the compared beat-note signals. The measurement result is the frequency stability estimated from the sequence $\{x_{\mathrm{k}}\}$ in terms of Allan deviation $\sigma_{\mathrm{y}}(\tau)$ as a function of the averaging time interval τ [3], [4].

Because these ultra-stable oscillators have comparable short-term stability, none of them can be taken as a reference as is common in metrology. Thus, what we actually obtain from the comparison is the pair stability rather than individual stability

$$\sigma_{\mathrm{AB}}^2(\tau) = \sigma_{\mathrm{A}}^2(\tau) + \sigma_{\mathrm{B}}^2(\tau). \tag{1}$$

To decompose the pair stabilities into individual stabilities we need to measure at least 3 oscillators and then employ the 3-cornered-hat method under the assumption of uncorrelated signals.

III. Phase-Time Comparator

A dedicated laboratory phase-time comparator, IPE3, based on the DMTDM technique has been used in our comparisons. The common signal of the comparator is provided from a 5-MHz MTI260–504A quartz oscillator (Milliren Technologies, Inc., Newburyport, MA). Its output frequency is offset by 5 Hz and the output level is low-noise amplified to +11 dBm.

The comparator makes use of a Stanford Research SR620 time interval counter (Stanford Research Systems, Inc., Sunnyvale, CA). The measured data are collected by PC and further processed using the Stable32 software

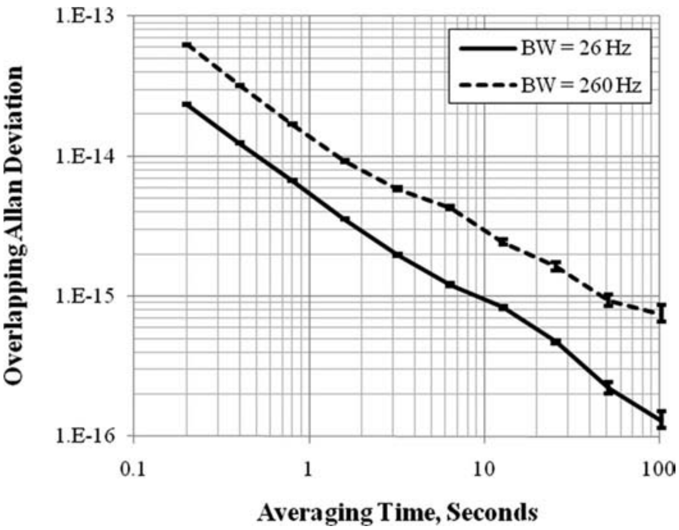

Fig. 1. Background stability of IPE3 system.

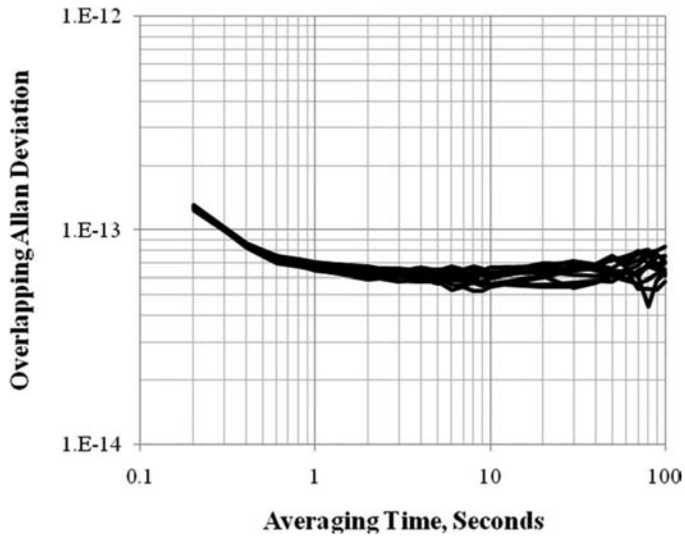

Fig. 2. Frequency stability of the E-F oscillator pair.

(version 1.54, Hamilton Technical Services, Beaufort, SC). The equivalent noise bandwidth of the IPE3 system is 26 Hz and it can be optionally switched to 260 Hz.

Fig. 1 shows the results of the system background stability tests in both bandwidths by using two +4 dBm signal powers split from one BVA reference oscillator. Given the extremely high sensitivity of the measurement, we have experienced great difficulties in reducing the electromagnetic interference and other environmental effects that occur irregularly and make the interference process non-stationary in the short-term sense.

To our knowledge, the background stability of 5.6×10^{-15} at 1 s in 26 Hz bandwidth is the best ever achieved in a time-domain measurement at 5 MHz. Thus, our DMTDM is a unique system that allows measurement of the best BVA oscillators. It may also be considered as a benchmark for the future systems that will employ immediate analog-to-digital conversion of the measured signal.

IV. Compared Oscillators

During the last measurement campaign in July 2008, we had at our disposal the 7 BVA oscillators listed in Table I. Before the measurement, all of the oscillators were mounted into extra cases, each with an arrangement for fine tuning with a relative frequency resolution of 1×10^{-12}. These extra cases also ensured additional shielding for the oscillators. The fine tuning allowed us to maintain the compared signals in quasi-synchronism to within 1 ns, which is needed to reject the noise originating from the DMTDM common oscillator [13].

Each measurement session lasted at least 4000 s, which, given the basic sampling interval of 200 ms, provided robust enough statistics for stability analysis. We have performed approximately 100 of these measurement sessions in different periods of the day and week with all possible combinations of oscillator pairs.

TABLE I. Compared Oscillators.

Oscillator	Type	Serial number	Possessed by[1]
A	8600	291	IPE
B	8600	315	IPE
D	8607	199	FEMTO-ST
E	8607	543	OSA
F	8607	567	OSA
G	8607	691	OSA
H	8607	692	OSA

Each oscillator showed a flicker frequency modulation floor of less than 1×10^{-13}.

[1]IPE = Institute of Photonics and Electronics; FEMTO-ST = Franche Comté Electronique Mécanique Thermique et Optique-Sciences et Technologies; OSA = Oscilloquartz S.A., Neuchâtel, Switzerland.

To prevent disturbances from the power line, the phase-time comparators and all of the oscillators were battery powered during all measurements. In addition, the time interval counter and the computer that collected the data were powered through an isolation transformer.

V. Measurement Results

Seven oscillators provide 21 possible oscillator pairs, from which we focused mainly on the 3 best units: E, F, and H. The oscillator pair stabilities $\sigma_{\mathrm{EF}}(\tau)_i$ and $\sigma_{\mathrm{EH}}(\tau)_i$ in the 26-Hz bandwidth are shown in Fig. 2 and Fig. 3. Fig. 4 shows $\sigma_{\mathrm{FH}}(\tau)_i$ in both bandwidths. Here the confidence intervals are hidden for sake of clarity. The corresponding numbers of performed comparisons are 11, 14, and 16 + 5, respectively.

The Stable32 analysis program was used for calculation of frequency stability of each oscillator pair. The outliers and frequency drift were removed from the measured data before all calculations. By employing the over-determined 3-cornered-hat method, we have obtained the results de-

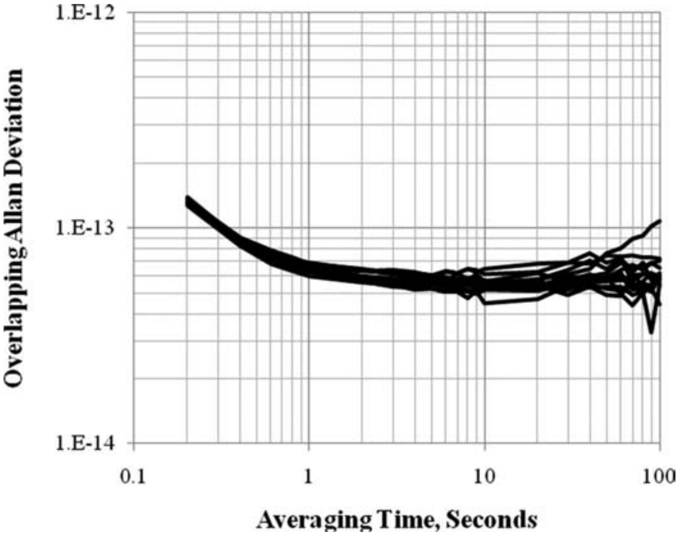

Fig. 3. Frequency stability of the E-H oscillator pair.

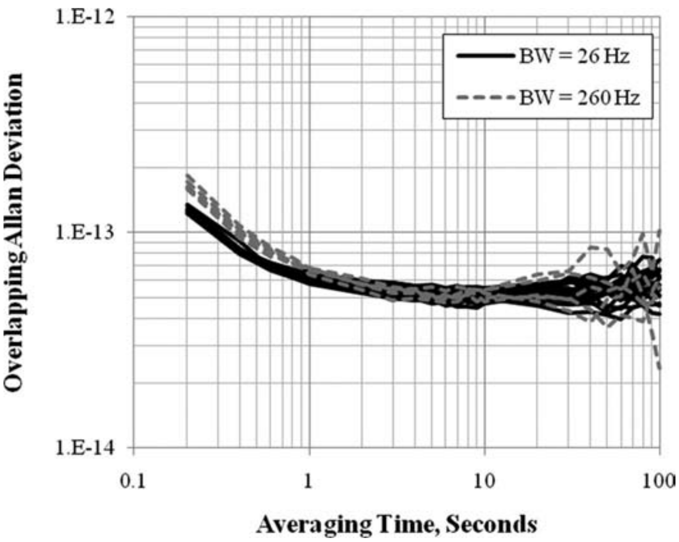

Fig. 4. Frequency stability of the F-H oscillator pair.

picted in Fig. 5. The corresponding flicker-frequency floors are 3.2×10^{-14}, 4.0×10^{-14}, and 4.5×10^{-14}, respectively, in terms of Allan deviation for averaging interval of 5 s.

VI. Conclusions

In measuring these ultra-stable oscillators, it is useful to introduce a model of the inherent stability, which is the one obtained with a near-ideal measurement system in a non-interfering and stable environment (i.e., with no external electromagnetic interference, stable temperature, no vibrations, etc.). Given the low background noise of our DMTDM system and stable environmental conditions in the laboratory, we can assume that our measurement approximates this case. It follows that the stability shown in Fig. 5 represents the oscillator noise limits and its performance potential in a given bandwidth. The user, therefore, must consider this result in terms of the oscillator's best capability. Consequently, if he wants to make full use of this capability he must operate the oscillator in near-ideal conditions concerning both the application and the environment. The FFM floor of 3.2×10^{-14} in terms of Allan deviation for an averaging interval of few seconds obtained for the H (SN 692) unit is, to our knowledge, the best value ever reported for a BVA oscillator.

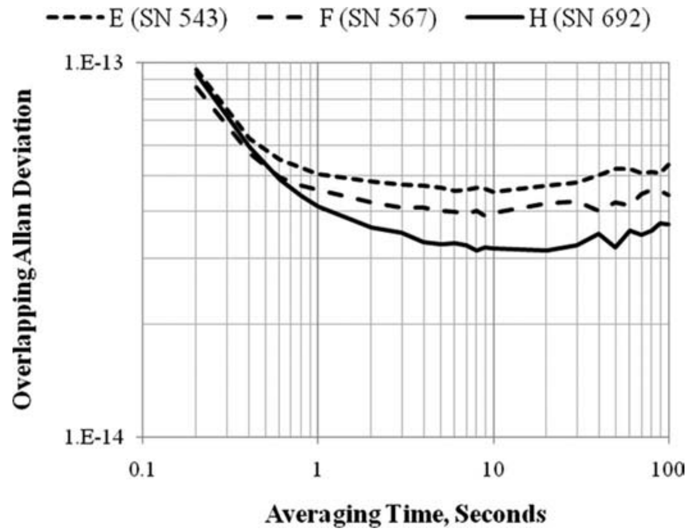

Fig. 5. Frequency stability of the reference oscillators of Oscilloquartz S.A., Neuchâtel, Switzerland.

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