Cryogenic sapphire oscillator with exceptionally high long-term frequency stability

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***Abstract*—A cryogenic sapphire microwave resonator oscillator (CSO) has been constructed, which now consistently exhibits the best measured long-term and fractional frequency performance for such an oscillator. The single oscillator long-term square root Allan variance was measured at about $2 \times 10^{-17}\sqrt{\tau}$ with a negative drift of about 2.2×10^{-15}/day for integration times $\tau > 1000$ s, limited by diurnal cycles. The short-term fractional-frequency is highly reproducable and also state-of-the-art: 5.6×10^{-16} for an integration time $\tau \approx 20$ s. The CSO's short-term stability represents a performance improvement by a factor of 40 compared to the 1990 version of the CSO, but by a factor of 5 on the 1995 version, yet by a factor of 10 on the long term performance of the latter. Also a comparison is made with the 2000 version.**

I. Introduction

Cryogenic sapphire oscillators [1]–[4](CSOs) have achieved the best short term stabilities at microwave frequencies of any electromagnetic oscillator or clock with a fractional instability less than a part in 10^{15}. It appears that only with the development of optical clocks could this be surpassed. Such oscillators are essential for interrogating atomic frequency standards at the quantum limit of projection noise [5], otherwise aliasing effects will dominate due to the periodic sampling between successive interrogations of the atomic transition. For this reason, the University of Western Australia (UWA) designed oscillators are now operational at the National Measurement Institute (NMI) in Sydney, Laboratoire national de métrologie et d'essais - Système de Références Temps-Espace (LNE-SYRTE) in Paris, the French Space Agency (CNES), in Toulouse, at the National Metrology Institute of Japan (NMIJ), in Tsukuba, and at the National Institute of Information and Communications Technology (NICT) in Tokyo, Japan. Other applications, which have attracted attention in recent years, include generating stable optical frequencies from a CSO in the laboratory [6] and over large distances with compensated optical fiber networks [7]. Also, some best tests of fundamental physics have been undertaken, such as tests of Lorentz invariance, which compare a CSO with a H-maser, [8]–[10] and drift in the fine structure constants, which use fountain clocks with a CSO as the interrogation oscillator [11], [12] or by comparing two modes of orthogonal polarization within a CSO [13].

The increased activity in testing fundamental physics is largely due to the advances in technology, which are capable of more precise measurement, as well due to the development of theoretical frameworks that provide new interpretations [14]–[22]. The initial experiments relied on the Earth's rotation, and the degraded performance at the semi-sidereal and sidereal periods limited these measurements. The most recent (and most sensitive) experiments include two CSOs rotating in the laboratory, which allows one to analyze the signal over the most sensitive time scale (20-30 seconds) and dig out from the noise any putative signal in a much shorter period of time. This has resulted in the measurement of the isotropy of the speed of light [23] to about one part in 10^{16}. However, the experiment used earlier 1990 versions of the CSO [24], with a short-term frequency instability a factor of 40 worse than that of the CSOs reported here. That is an improvement of a factor of 5 on the 1995 version [26], yet by a factor of 10 in the long term performance. In the future upgraded versions of the CSO will be substituted into the current rotating experiment with the possibility of improving our sensitivity by up to a factor of 40. Here we outline the design and performance of the upgraded version of our CSO. [28]

II. Cryogenic Sapphire Oscillator

A. HEMEX resonator

A highly stable CSO has been built based on Crystal Systems HEMEX grade single-crystal sapphire. The sapphire crystal was mounted inside a silver-plated copper cavity with internal dimensions of Dc = 80 mm and Lc = 50 mm. See fig. 1 for further detail. The sapphire was cut with its crystal axes aligned within one degree of the cylinder axis and a very high degree of cylindrical geometry. It was optically polished on all surfaces. The crystal dimensions at room temperature are; D = 51.00 mm, L = 30.00 mm, with two support spindles of diameter 11.83 mm machined on the top and bottom along the cylinder axis. The top support spindle is 8 mm long while the bottom one is 19 mm long. The latter was use to securely support the sapphire in a clamping mechanism held from the bottom. The former was merely used as an aid to cleaning the sapphire. That is, the top spindle was used to support the sapphire while it was drying after being removed from the cleaning solution. Hence all contact with the main body of the sapphire was avoided.

The highest Q-factor modes in the liquid helium cooled sapphire resonators are Whispering Gallery (WG) modes [25] and as a result the $WGH_{16,0,0}$ mode at 11.200 GHz was chosen for the oscillator. This mode is quasi-TM like where

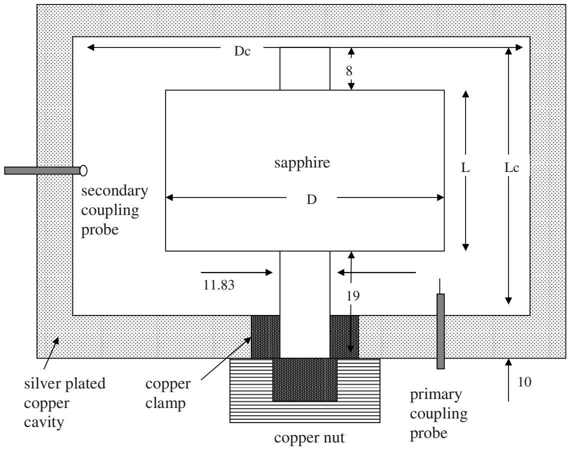

Fig. 1. Schematic on the sapphire loaded copper cavity showing the support structure and coupling probes. All dimensions are in mm.

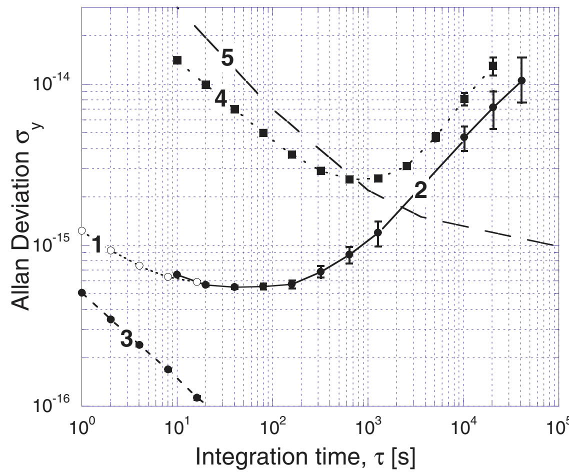

Fig. 2. Oscillator fractional frequency stability represented by the square root Allan variance as a function of integration time, τ. Curve 1 is the SRAV calculated from 15.9 hours of data (or 57317 samples) collected with a gate time of 1 s. Curve 2 is the SRAV calculated from 16.7 hours of data (or 6022 samples) collected with a gate time of 10 s. Curve 3 is the frequency counter noise floor. Curve 4 is the SRAV calculated from 9 days of data (or 76333 samples, shown in fig. 3) also collected with a 10 s gate time. Curve 5 is the Kvarz hydrogen-maser stability specification, where the line represents the upper limit.

the magnetic energy is mostly aligned perpendicular to the cylinder axis and exhibited a turning point in the frequency-temperature dependence at 7.2319 K. The sapphire resonator was coupled to two coaxial lines with a primary coupling of 1.06 and an unloaded Q-factor of 1.5×10^9 measured at the turnover point temperature.

B. Loop oscillator

A loop oscillator was implemented using a high-gain Endwave JCA812-5001 microwave amplifier as the sustaining stage. [24], [26] The microwave amplifier provides about 47 dB of gain and hence about 12 dBm of circulating power and about 0 dBm of dissipated power inside the resonator. Also frequency, temperature, power control and spurious AM index control servos were implemented. The frequency control was achieved using standard Pound techniques with a SRS830 lock-in amplifier and two GT Microwave voltage controlled phase shifters, one as a modulator of the microwave loop and the other as an error corrector. The temperature control was achieved with a Lakeshore 340 temperature controller and a CGR-2000 carbon glass sensor. The resonator temperature was controlled at the frequency-temperature turnover point with a control error of less than 100 K. This was due to the exceptional quality of the particular model of temperature controller used. The power and AM index control was implemented using UWA custom designed control circuitry.

III. Stability Measurements

To test the oscillator over long time scales ($\tau > 10^3$ s) a Kvarz hydrogen maser was used, while over time scales less than this ($\tau < 10^3$ s) another nominally identical CSO was used. The second oscillator was built for the atomic frequency standards group at NICT, in Tokyo, and allowed us to characterize the short term stability of our oscillator before it was shipped to Japan. The same quasi-TM mode, with nominally identical resonance frequency, was selected in that resonator also, which exhibited a turning point in the frequency-temperature dependence at 7.3095 K. The resonator has a primary coupling of 0.97 and an unloaded Q-factor of 1×10^9 at the turnover point temperature.

A. Short term

For short-term stability measurements, the beat frequency of 131.181 kHz between the two CSOs was measured with an Agilent 53132A frequency counter referenced to a stable 10 MHz signal from the hydrogen-maser. The resulting fractional frequency stability of the microwave signal was calculated and is shown in fig. 2 as the square root Allan variance (SRAV) σ_y a function of integration time, τ. The resulting SRAV $\sigma_y = 1.2 \times 10^{-15}/\sqrt{\tau}$ for $1\ s < \tau < 4\ s$ then falling to 5.6×10^{-16} at 20 s (a minimum) then climbing to 1.05×10^{-15} at 10^3 s. Between $1\ s < \tau < 8\ s$ the frequency counter gate time was set 1 s (curve 1) and $\tau > 8$ s a gate time of 10 s was selected (curve 2). The frequency stabilities are inferred for a single oscillator by assuming equal contributions to the overall noise from each. Therefore a factor of $\sqrt{2}$ has been applied to the short-term data. The beat signal was measured many times and for integration times $\tau < 10^3$ s the results were repeatable within statistical errors. The oscillator short term frequency stability was not limited by the noise floor of the frequency counter shown by curve 3.

B. Long term

For long-term stability measurements our CSO was compared to a synthesized 11.200 GHz signal derived from a Kvarz H-maser using a step recovery diode. A beat frequency of 386 kHz was counted with a 10 s gate time and the SRAV calculated. This is shown in curve 4 of fig. 2 and is compared to the specification of the maser manufacturer (curve 5). For $\tau > 10^3$ s we start to see the CSO instability over the maser intrinsic noise and therefore a factor of $\sqrt{2}$ need not be applied. At shorter integration times we see the maser noise only. Judging form the dependence of oscillator frequency stability on integration time, its long term performance is limited by a random walk process. Curve 2 in fig. 2 indicates a SRAV dependence $\sigma_y = 2 \times 10^{-17}\sqrt{\tau}$ for $\tau > 10^3$ s.

C. Comparison against other CSOs

These results may be compared to those of Chang et al [27]. They quote for integration times where $1\ s < \tau < 4\ s$ an oscillator SRAV $\sigma_y = 5.4 \times 10^{-16}/\sqrt{\tau}$. At 32 s, a minimum of 2.4×10^{-16} is reached and for integration times longer than 100 s, they claimed the oscillator frequency stability degrades approximately as $3 \times 10^{-17}\sqrt{\tau}$, with drift removed, which was of the order of 10^{-13}/day. However they only used about half an hour worth of data (inferred from the published error bars) and showed no repeatability of their measurements. No time series data were published [27], [30]. On the other hand our results conclusively show that short data segments do not reliably characterize the oscillator short term frequency instability. For example, we can select from our measured data "quiet" half hour segments and calculate an Allan deviation of 4×10^{-16} near 20 s of averaging time.

The fractional frequency drift of oscillator of the CSO reported here was measured to be -2.2×10^{-15} /day, which is almost two orders of magnitude lower than that reported by Chang et al [27]. Such a low drift rate, we believe, was achieved due to the optimal geometry of the shielded sapphire resonator characterized by the absence of any spurious modes in the vicinity of the operating one. This is highlighted in fig. 2 where only curve 2 has had drift removed, resulting in only a slight improvement in SRAV for $\tau > 2 \times 10^3$ s. Also the measurements were repeatable and large amounts of data were collected over many days giving consistent results. See fig. 2 caption for details. Further comparisons may be made with the long term drift of the LPMO oscillator of Bourgeois et al [4] with a published fractional frequency drift of -6×10^{-14}/day, with the JPL oscillator characterized by a drift rate of -10^{-14}/day [29] and with other UWA CSOs [1], which have negative drifts of the order of 10^{-13}/day.

D. Comparison against H-maser

In order to evaluate the long term performance we measured our CSO against the synthesized H-maser signal for long periods of time. The data sets were taken over 9 days (fig. 3), 18 days (fig. 4) and 8 days (fig. 5), in chronological order. But because of slight frequency offsets (of about 5 to 10 mHz) the data sets cannot be represented on the same plot. One known cause of these frequency offsets is the small changes in the level of circulating power associated with the adjustment of a set point of the power control system. Between the data of fig. 3 and fig. 4 the 200 liter dewar holding the sapphire resonator was refilled with liquid helium, which introduced thermal gradients that shifted the frequency slightly.

From a linear fit to the data of fig. 3 we get -2.2×10^{-15} /day fractional frequency drift and to those of fig. 5 we get

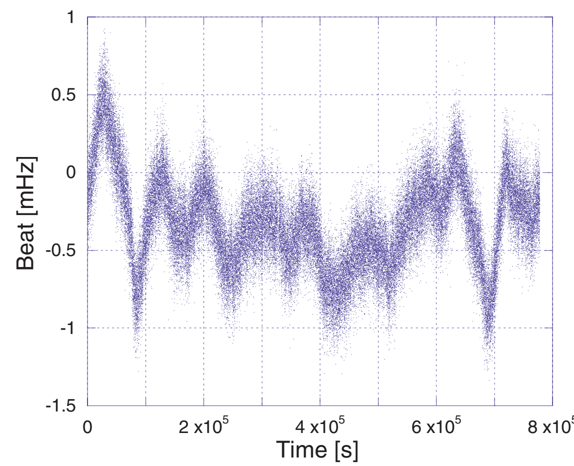

Fig. 3. Beat note minus 386 kHz between the CSO and a synthesized signal from a Kvarz H-maser, measured over 9 days using a10 s gate time.

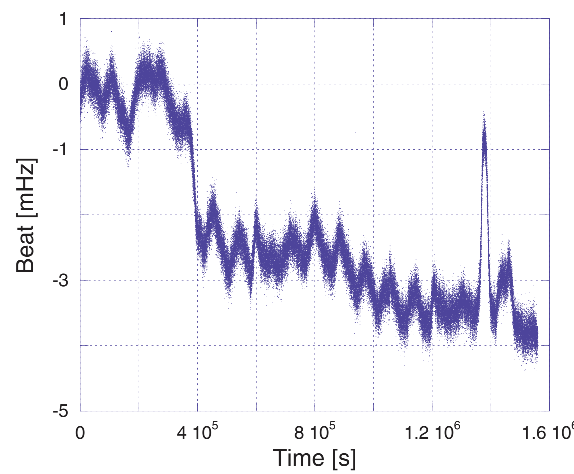

Fig. 4. The same as fig. 3 but over 18 days.

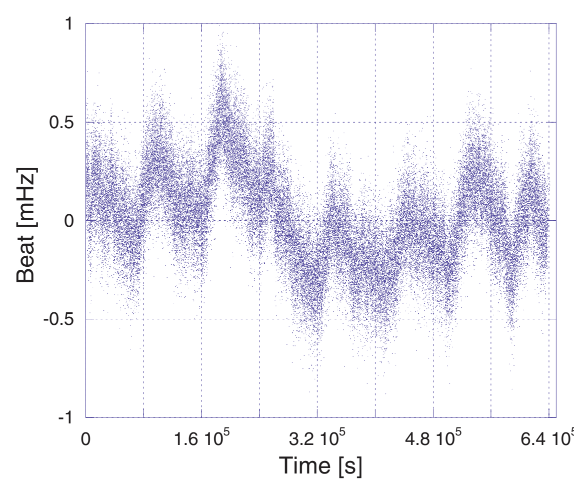

Fig. 5. The same as fig. 3 but over 8 days.

-3.3×10^{-15}/day. The data run of fig. 4 had two disturbances, which we believe biases the measurements. Firstly after 5 days one of stoppers on the helium dewar came out and the internal helium pressure dropped. Normally this is maintained at some level as the helium gas recovery lines have a finite back pressure. The phenomenon is seen at 4×10^5 s in fig. 4. Secondly some heavy objects were dropped near the experiment at about 1.4×10^6 s but the oscillator slowly recovered. If we measure the drift rate between these two points we get -7.7×10^{-15}/day.

Clearly the oscillator is dependent on external environmental effects. In all three data sets (figs 3 - 5) the diurnal oscillations are clearly seen and mostly due to daily temperature variations. Analysis of these 24 hours oscillations has shown that the peaks do not exactly occur with a 24 hour separation. This indicates that temperature is the main driver, because the diurnal temperature effects may lag or advance from day to day due to specific weather conditions, but needs further investigation. To improve the long term stability of the "sapphire clock," it needs to be placed in a temperature control environment, which we are currently building in our lab.

IV. Conclusion

We report on the measurement of the long term performance of an ultra-stable cryogenic sapphire oscillator operating at 11.200 GHz, which is the best measured to date for such an oscillator. This was achieved with the construction of two nominally identical sapphire oscillators with measured fractional frequency instabilities of 5.6×10^{-16} over 20 s of integration time. Two of these CSOs are currently being developed as an advanced Lorentz invariance experiment with a rotation period of 20 s to take advantage of their exceptional stability there.

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