Autonomous cryogenic sapphire oscillators employing low vibration pulse-tube cryocoolers at NMIJ

Takeshi Ikegami1, Ken-ichi Watabe1, Shinya Yanagimachi1, Akifumi Takamizawa1 and John G. Hartnett2

1 Radio-Frequency Standards Group, National Metrology Institute of Japan (NMIJ), AIST, Tsukuba, Ibaraki, Japan
2 Institute of Photonics and Advanced Sensing (IPAS), and, the School of Physical Sciences, University of Adelaide, Adelaide, Australia

E-mail: t.ikegami@aist.go.jp

Abstract. Two liquid-helium-cooled cryogenic sapphire-resonator oscillators (CSOs), have been modified to operate using cryo-refrigerators and low-vibration cryostats. The Allan deviation of the first CSO was evaluated to be better than 2×10^{-15} for averaging times of 1 s to 30 000 s, which is better than that of the original liquid helium cooled CSO. The Allan deviation of the second CSO is better than 4×10^{-15} from 1 s to 6 000 s averaging time.

1. Introduction

Cryogenic sapphire oscillators (CSOs) are still the most frequency-stable oscillator operating in the microwave frequency region [1]. Their frequency stability, expressed as Allan standard deviation, reaches a few times 10^{-16} over averaging times of 1 s to 1 000 s. This short-term stability cannot be obtained in any commercial device, for example, in BVA OCXOs or hydrogen masers.

Recently, the cesium atomic-fountain primary frequency standards, when limited by a quantum projection noise, have a short-term frequency stability approaching a few times 10^{-14}. In order to avoid the influence of the Dick effect (the degradation of frequency stability due to dead time), a more stable local oscillator than obtainable in commercially available devices is required. Thus CSOs have been successfully implemented as local oscillators for such frequency standards [2], [3].

On the other hand, the development of optical atomic clocks is rapid and their frequency stability and uncertainty approaches 10^{-18}. In near future, the redefinition of the unit of time, the “second,” is expected [4]. One purpose of optical clocks is the improvement of the international timescale, TAI (International Atomic Time). The uncertainty of TAI has been determined by a balance of the frequency stabilities between primary frequency standards (currently Cs atomic fountains), time comparison methods (GPS or two-way satellite time transfer), and local oscillators (LOs, currently, hydrogen masers), to the current value of about 3×10^{-16}. Because primary frequency standards (current Cs atomic fountains, and optical clocks in future) do not operate continuously over years, better LOs to replace the current hydrogen masers will be necessary. The LO should be stable enough to keep good time and phase, even when a primary standard stops operating and hence it cannot calibrate the LO during those periods. If stable LOs are successfully developed that can operate continuously without phase jumps over many years, they can be calibrated with the best optical clocks and can be
used as LOs for timekeeping. Using an optical comb technology, a microwave signal, which is phase-coherent to the optical frequency of an optical clock, can be easily produced by frequency division. Such a microwave signal is easily compared to the microwave output of a CSO, and the CSO can be conditioned by an optical clock intermittently. Thus the CSO acts as a flywheel between conditioning cycles. Therefore, a CSO may also be considered as a candidate LO for timekeeping, which can possibly replace the current hydrogen masers in an era of optical clocks. Therefore, either a LO in the microwave or optical regimes will form a new LO after the re-definition of the second. The choice should be made on the better frequency stability, regardless of it being at optical or microwave frequencies. From a practical viewpoint, a LO in the microwave region might be convenient to produce electrical signals such as 10 MHz, which are most used commonly.

However, it has been difficult to use liquid-helium-cooled CSOs for any purpose that requires long-term continuous operation, due to the high maintenance cost of regular liquid helium refills and the phase jumps which occur on the output signal during refilling of the liquid cryogen, about every 3 weeks. In order to overcome these problems, a low vibration cryostat has been implemented using a pulse-tube-cryocooler [5], [6]. Cryogenic sapphire oscillators have been converted to use this technology (hereafter, designated ‘cryoCSO’) and as a result their frequency stability has been measured to be better than that of liquid-helium-cooled versions [6], [7]. At NMIJ, two liquid-helium-cooled CSOs, which had been operated since 2005, were converted using pulse-tube cryo-refrigerators and low vibration cryostats and their resulting performance evaluated.

2. NMIJ Cryogenic Sapphire Oscillators using liquid helium
We operated 2 cryogenic sapphire oscillators since 2005. The characteristics of our liquid-helium cooled CSOs is briefly reviewed below [8].

![Sapphire crystal and silver-plated copper cavity](image)

**Figure 1.** (colour online) (a) Sapphire crystal and silver-plated copper cavity, (b) the distribution of the electric field intensity inside a crystal (WGH_{12,0,0} mode), (c) schematics of cryogenic sapphire oscillator.

Three high quality (HEMEX grade) sapphire crystals from Crystal Systems were cut and polished cylindrically with a height of 30 mm and a diameter of 50 mm (Fig.1(a)), and are used as electromagnetic resonators. The Whispering-Gallery (WG) mode (Fig.1(b)) is used, which has a high loaded quality factor of about 10^9 at a crystal temperature below 10 K. We used the WGH_{15,0,0} mode, which has the highest quality factor. All crystals have a turning point at a temperature greater than the
liquid helium temperature of 4.2 K, where the temperature dependence of the resonance frequency of the crystal is nulled to first order. The turning points are 6.1 K at 10.812 GHz (designated crystal1 hereafter, with a loaded quality factor $Q_L = 5 \times 10^8$ at this temperature), 7.0 K at 10.810 GHz (crystal2, $Q_L = 7 \times 10^8$), and 7.6 K at 10.811 GHz (crystal3, $Q_L = 4 \times 10^8$). Each crystal is mounted inside a silver-plated copper cavity with 2 SMA connectorized coaxial probes for input and output as may be seen in Fig. 1(a). These are made of flexible coaxial cable where the inner conductor is bared for a straight probe (sensitive to the E-field) or looped and soldered onto the coaxial shielding for a loop probe (sensitive to the H-field).

As shown in Fig.1(c), the cavity is set inside a vacuum can, and sealed off for thermal isolation. This inner vacuum can was installed inside a second larger vacuum can. This outer vacuum can was then inserted into a liquid helium cryostat and cooled to 4.2K. The crystal was controlled to its turning point temperature with a precision of better than 1 mK. The resonator is used both as a high Q-factor filter and as a frequency discriminating element in an oscillator. The output signal is amplified, phase-corrected, and fed back to the input of the cavity to achieve oscillation. The oscillation frequency is controlled by the resonance frequency of the crystal so as to minimize the reflected power from the resonator using a Pound stabilization method. The reflected signal is detected, with a tunnel-diode microwave power detector located in the cryogenic environment, demodulated with a lock-in amplifier, and fed back to the phase corrector. Also, the oscillating signal power is stabilized using a second cryogenic microwave power detector. Initially we built two CSOs using crystal1 and crystal2 between 2003 and 2005, and evaluated their frequency stability. Their Allan deviation was measured to be less than $2 \times 10^{-15}$ at the averaging time of 1 s to 1 000 s [8].

### 3. Modification of the liquid-helium-cooled CSOs using cryo-refrigeration

The first and second CSOs, which used liquid helium as a cryogen, were modified with pulse-tube cryocoolers and low-vibration cryostats. The changes were implemented in 2013 and 2015, respectively. Formerly, we had tried to cool the sapphire crystal by directly attaching its copper cavity to the second stage of a pulse-tube cryocooler, but that did not result in the needed performance [9].

![Figure 2](image.png)

**Figure 2.** (colour online) (a)Structure of low-vibration cryostat, (b) vacuum can connected to a cold finger.

Fig. 2(a) is a schematic of the low-vibration cryostat and Fig. 2(b) is a photograph of the vacuum can attached to the cold finger of the new cryoCSO. We used a Cryomech PT407RM pulse-tube cryocooler. In this low-vibration cryostat, helium gas is liquefied around the second stage condenser of the cryocooler and stored in the liquid helium container below the second stage as shown in Fig. 2(a). Hereafter, this second stage is called the ‘condenser’. Once a few liters of liquid helium have
accumulated, the gas inlet is closed. After that the vaporized helium gas in the chamber is constantly re-liquefied by the condenser in a closed system. No additional external supply of helium gas is needed. Below the liquid-helium container, a copper ‘cold plate’ is attached, called the ‘cold finger’ hereafter. The inner vacuum can containing the silver-plated copper cavity is attached to the cold finger, via a copper shaft (called ‘copper post’), which thermally connects the cold finger to the cavity. The liquid helium container and cold finger are mechanically separated from the cold stages of the cryocooler by a bellow supported by springs, and the vibrations of the cold stage are significantly attenuated. At the center of the copper post, a temperature sensor and a heater are attached. The heater controls the temperature of the copper post using a Lakeshore 340 temperature controller.

3.1. First cryoCSO (cryoCSO1)

For the first cryoCSO, we reused the inner vacuum can from our second liquid-helium cooled CSO (CSO2), whose heat capacity is very large and its structure is not optimized for the cryostat. The crystal2 was used for the cryoCSO1. The loaded Q-factor and coupling on the primary reflection port were re-measured to be $Q_L = 5 \times 10^8$ and $\beta_1^* = 0.51$, respectively. The incident power on the resonator and modulation index were set to 100 μW and 0.2 rad, respectively.

However, the temperature of the condenser did not reach 4.2K and the liquefaction of helium gas did not occur (maybe due to too large a heat flow to the vacuum can). Fortuitously, the resonator turning point temperature is 7 K and that was achievable and good frequency stability was obtained. The operation of the cryostat using a similar helium heat exchange gas was proposed by G.J. Dick (JPL) [10]. However our intention was to operate at about 50 kPa (meaning below atmospheric pressure) so a partial vacuum develops in the chamber, providing some additional decoupling from room temperature. Another difference from Dick’s idea is we use rigid springs to support the bellows against this partial vacuum. But in this implementation the pressure in the helium container remained around 1 atm.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** (colour online) (a) temperature stability of cryoCSO1, (b) Allan deviation of cryoCSO1.

As shown in Fig. 3(a), the temperature stability of the cold finger and the condenser were almost the same. The temperature stability at the copper post was not as good as one might have expected had the liquefaction occurred.

The frequency stability of cryoCSO1 was evaluated using our first liquid helium-cooled CSO (CSO1) kept as a short-term frequency stability reference, because it had been previously evaluated. The Allan deviation of the frequency stability for the single CSO1 is shown as a gray dotted line in Fig. 3(b) [8]. For the longer term frequency stability evaluation ($\tau > 1000$ s), a hydrogen maser (HM) was used as a reference, whose specified Allan deviation is shown as a black dotted line in Fig. 3(b). The Allan deviation of the beat signal between cryoCSO1 and CSO1 for the short averaging times of 1 s to 100 s is shown as filled pink circles in Fig. 3(b). The Allan deviation of the beat signal is almost equal
to \sqrt{2} times of that of CSO1, which means that the frequency stability of cryoCSO1 is approximately that of CSO1 at averaging times between 1 s and 100 s. The Allan deviation of the beat signal between cryoCSO1 and the HM is shown as blue filled diamonds in Fig. 3(b). That result is dominated by that of the HM except the last 2 points at averaging times of 10 000 s and 30 000 s. From this we estimated the Allan deviation of the single cryoCSO1 as a solid red line in Fig. 3(c).

An Agilent 53132A frequency counter was used in an auto mode to measure the beat signal. For the averaging time from 1 s to 100 s, the gate time was set to each averaging time (for example, 10 s gate time for 10 s averaging time). For an averaging time greater than 100 s, the gate time was fixed to 100 s and the beat frequency was averaged to calculate the beat frequency for longer averaging time (for example, we averaged 3 of the 100 s gate time data to obtain the 300 s averaging time data).

As shown in Fig. 3(b), our short-term frequency stability was a factor of three times that of the best data of Hartnett et al. [7], but at longer averaging times our result was slightly better, possibly due to better environmental conditions.

3.2. Second cryoCSO (cryoCSO2)
In the second CSO, an inner vacuum can was custom-designed for use with the cryocooler and it successfully liquefied the helium gas. Crystal3 was implemented in cryoCSO2, which had not been used in either CSO1 or CSO2, before. The loaded Q-factor and coupling of this resonator were measured to be $Q_L = 4 \times 10^8$ and $\beta_1^* = 0.52$, respectively. The power on the resonator and the modulation index were set to about 100 $\mu$W and 0.6 rad, respectively.

The temperature stability was much better in cryoCSO2 than in cryoCSO1 and was close to the resolution of the temperature controller ($\leq 100 \mu$K), as shown in the Fig. 4(a). The absolute value of the temperature of the cold finger is not accurate because an uncalibrated sensor was used. However, the temperature fluctuations are reasonably accurate. Because helium gas is liquefied around the second stage of the condenser and liquid helium is contained above the cold finger, the temperature of the cold finger is fixed at the boiling temperature of helium at the final pressure developed in that chamber. In this cryoCSO a pressure of about 50 kPa (i.e. below atmospheric pressure) was obtained, which also means that the temperature of the boiling liquid is about 3.5 K, a lot less than 4.2 K.

![Figure 4](image_url)

**Figure 4.** (colour online) (a) Temperature stability of cryoCSO2, (b) Allan deviation of cryoCSO2.

The Allan deviation of frequency fluctuations for cryoCSO2 was determined by a comparison with cryoCSO1 for the short-term stability, and against a hydrogen maser for the longer term. The Allan deviation of the beat signal between cryoCSO2 and cryoCSO1 is shown as filled pink circles in Fig 4(b). The stability of the beat between cryoCSO2 and the HM is shown as blue filled diamonds. The stability for the single cryoCSO2 is estimated as a solid red line in the figure. The frequency stability of the cryoCSO2 is worse than that of the cryoCSO1 by a factor of 2 in the short term. The reason for
this at averaging time less than 1 000 s is most probably due to reduced unloaded Q-factor at the operational temperature equal to about half that for cryoCSO1. There remains a residual frequency drift (for averaging times > 1 000 s) because the data were taken very soon after the cryocooler of cryoCSO2 was switched on. The long-term stability improves as the drift rate exponentially decays over time [7].

4. Summary
We have now modified 2 conventional liquid-helium cooled CSOs by introducing low-vibration pulse-tube cryocoolers and low-vibration cryostats. The first cryoCSO is now used with our Cs atomic fountain frequency standard, NMIJ-F2, which has achieved a nearly quantum-projection-noise-limited frequency stability of 8×10^{-14} at 1 second [3]. The cryostat design achieves heat exchange between the cryocoolers cold stage and the cold finger by use of helium gas. In the first implemented cryoCSO, helium liquefaction did not occur. However, the frequency stability was better than 2×10^{-15} between 1 s and 30 000 s and better than 1×10^{-15} between 3 s and 4 000 s.

We now have 2 units of cryocooler CSOs. Thus we plan to improve the short-term stability at 1 s into 10^{-16} regime. We plan to optimize all control parameters and reduce technical noise sources where possible as well as operate the cryoCSOs continuously, without phase jumps, over many years. Finally, we plan to operate the cryoCSOs as practical local oscillators, which will be able to keep time, with a short-term performance better than our hydrogen masers.

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