PHASE-LOCK LOOPS IN VIBRATION ENVIRONMENTS[1]

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Abstract

A popular scheme for achieving low phase noise across a large range of offset frequencies is to employ an oscillator at an output frequency with low far-from-carrier noise that is phase-locked to a reference that has low close-to-carrier noise. We investigate the effects of vibration on phase-locked loop (PLL) when two oscillators with different vibration sensitivity are phase-locked. For experimental verification, a 2.5-GHz surface-transverse wave (STW) oscillator integrated with and phase-locked to a reference 10-MHz quartz-crystal oscillator is chosen. The vibration sensitivity of a STW oscillator used for the experiment is slightly lower than the vibration sensitivity of the 10-MHz reference. The PLL is optimized for at-rest operation and then evaluated in the presence of different levels of random vibration.

I. INTRODUCTION

At microwave frequencies, the success of electronic systems often depends critically on the ability to reduce the phase (or time) noise of the reference oscillator clocking such systems. Space and military systems require increasingly complex low-noise timing that must operate in harsh environments. In terms of system precision, there are noteworthy advantages to operation directly at microwave frequencies while having high vibration tolerance **[1-5]**. However, the level of vibration-induced phase-modulated (PM) noise becomes excessively large at X-band and higher frequency ranges, often seriously affecting, even prohibiting, use of microwave systems that employ phase-locked loops (PLLs) **[1,5]**.

A popular synthesis scheme for achieving low PM noise across a large range of offset frequencies is to employ an oscillator at an output frequency with low far-from-carrier noise that is phase-locked to a reference, such as an oven-controlled crystal oscillator (OCXO), that has low close-to-carrier noise **[6-12]**. On the one hand, such high-frequency output oscillators with low far-from-carrier noise are dielectric resonator oscillators (DRO), bulk acoustic wave (BAW) oscillators, yttrium, iron and garnet (YIG) oscillators, surface-acoustic wave (SAW) oscillators, and surface-transverse wave (STW) oscillators. On the other hand, low close-to-carrier noise is significantly better using high-Q, lightly driven quartz oscillators operating at below 100 MHz, often at 5 or 10 MHz.

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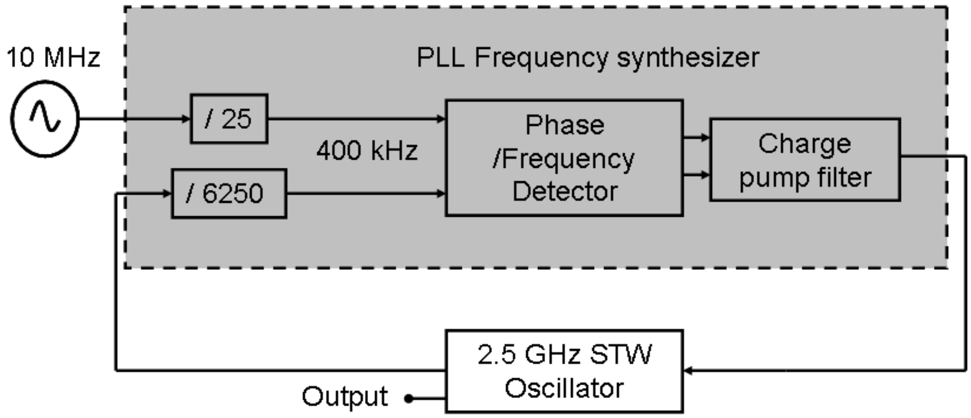
This paper is intended to study the effect of vibration on PLL when two oscillators with different vibration sensitivity are phase-locked.

II. MOTIVATION FOR PHASE-LOCKED OSCILLATORS

A low-noise, miniature microwave (2.5 GHz) oscillator using a STW resonator was designed and built by a third party **[13]**, with the intent of lowering vibration sensitivity for use as the low-jitter clock source for high-performance analog-to-digital converters. To meet the low-jitter objective, the oscillator was designed for a low thermal phase noise floor. Small size was achieved by choosing a STW resonator as the stabilization element along with a silicon-germanium (SiGe) sustaining amplifier. SiGe enables the sustaining amplifier to provide a high linearity, thus excellent 1/f noise performance of silicon at gigahertz frequencies. A low noise floor was achieved through the combination of high oscillator loop power and low noise figure, which were simultaneously attained through a two-stage SiGe sustaining amplifier design. Low wideband noise (less than −175 dBc/Hz) has been achieved in a very small circuit board area of 11 mm × 13 mm. This is adequate for low phase noise far from the carrier; however, other applications also need low phase noise close to the carrier. The STW oscillator's moderate close-in phase noise of −90 dBc/Hz at 1 kHz offset is not low enough for use in several other applications. To further reduce the close-to-carrier phase noise, the STW oscillator was configured with an electronic frequency control (EFC) and phase-locked to a 10-MHz commercial quartz-crystal oscillator having lower close-to-carrier phase noise when multiplied by a factor of 250 to 2.5 GHz. Figure 1(a) shows a diagram of the oscillators configured in a PLL, and the phase-locked oscillators module is depicted in Figure 1(b).

A PLL is an electronic feedback system that is used to control a slave oscillator, in this case the 2.5-GHz oscillator, locking its phase to that of a master or reference oscillator, in this case the 10-MHz quartz oscillator. The slave oscillator's phase is controlled only within the bandwidth (BW) of the PLL. The selection of PLL BW is used to tailor the overall composite phase noise of the synthesized output. We define crossover frequency (f_{cross}) to be the offset frequency where the normalized PM noise of both oscillators is equal. The optimum PLL BW under no vibration is usually chosen to be at f_{cross}, which provides the lowest PM noise of each oscillator when phase-locked together. A PLL is implemented so that the close-to-carrier phase of STW oscillator follows the lower close-to-carrier noise of the quartz oscillator. Figure 2 shows a plot of the phase noise of the 2.5-GHz oscillator that is phase-locked to the 10-MHz quartz oscillator with the scheme in Figure 1(a). Noise introduced from the synthesis electronics moves the optimal PLL bandwidth from the ideal f_{cross} at 10 kHz to about 250 Hz. The high level of frequency synthesizer noise is due to the fact the STW oscillator is not exactly at 2.5 GHz and cannot be tuned to a multiple of the 10-MHz master oscillator. This requires frequency division of both oscillators down to a common intermediate frequency of 400 kHz for the phase comparison. The high division ratio exacerbates the already high noise of the divider in the PLL integrated circuit. One can see the reduction in the phase noise in the 2.5-GHz oscillator for $f < 250$ Hz down to ~6 Hz. For $1 \text{ Hz} < f < 6$ Hz, the 2.5-GHz oscillator roughly follows the quartz oscillator phase noise. This result is expected based on simulation studies using the components and their respective noise levels.



(a)

(b)

Figure 1. (a) Block diagram of the synthesis scheme for locking the 2.5-GHz STW oscillator to the 10-MHz quartz oscillator. The PM noise floor of PLL frequency synthesizer inside the loop BW is approximately -87.0 dBc/Hz when the input frequency of the phase/frequency detector = 400 kHz, and the output frequency of the oscillator = 2.5 GHz. (b) Picture of phase-locked oscillators module.

III. EFFECT OF VIBRATION ON FREE-RUNNING STW AND QUARTZ-CRYSTAL OSCILLATORS

In this section, we investigate the effects of vibration on the PM noise of each oscillator used in the PLL. Because the vibration sensitivity is usually different, the PLL response should also be different, depending on the type and level of vibration that is present.

Figure 3 shows the single-channel measurement system used to measure the PM noise and vibration sensitivity of the oscillators. The locked oscillators combine to produce a single signal; hence, it is one device under test (DUT). However, the STW and quartz oscillators will first be measured separately. This DUT is placed on a shaker table driven by a programmable signal generator that drives a variable-gain, high-power amplifier providing either a random-noise or a sine-wave single-axis vibration to the DUT. For PM noise measurements, the output of the DUT is mixed with a source of very low PM noise to generate a beat frequency between 1 MHz and 30 MHz. This signal is then fed into a direct digital phase noise measurement system (DPNMS) that analyzes the beat signal against a low-noise 10 MHz reference quartz oscillator **[14]**.

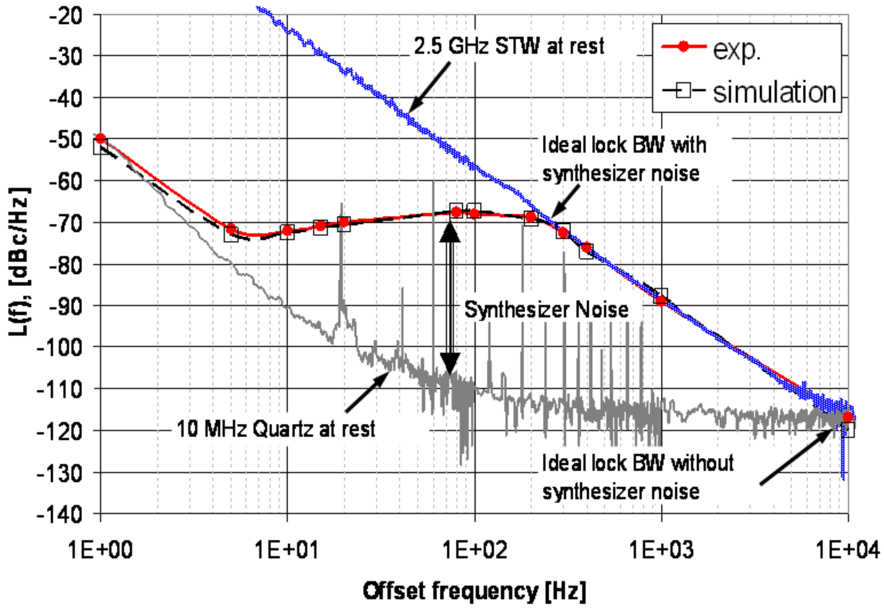


Figure 2. Measured and simulated PM noise of the combined 2.5-GHz and 10-MHz quartz (scaled to 2.5-GHz) oscillators at rest with the scheme shown in Figure 1(a). The frequency synthesizer noise is included. L(f) ─ single-sideband PM noise.

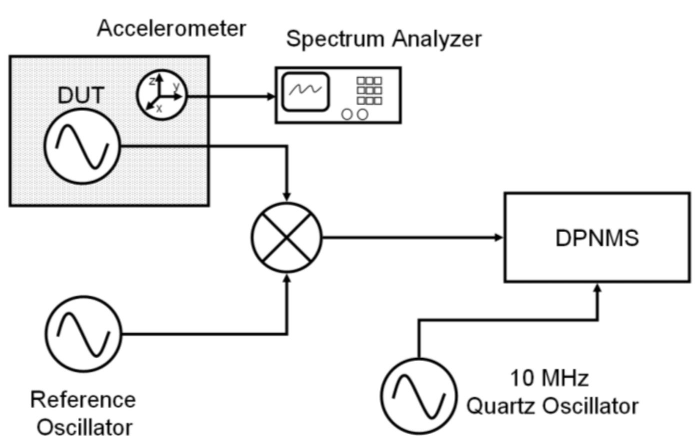
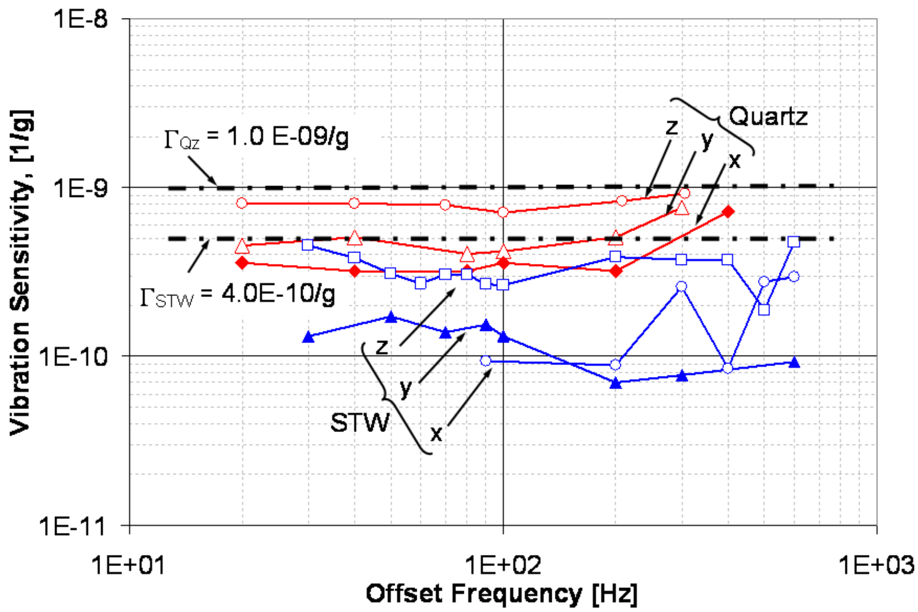


Figure 3. Setup for measuring PM noise and vibration sensitivity of oscillators. DPNMS ─ Direct digital phase noise measurement system.

Figure 4 plots the phase noise of two oscillators. This non-vibrated environment has the 2.5-GHz STW and 10-MHz quartz oscillators at rest in a quiet lab setting. Also shown in Figure 4 are phase noise plots of the oscillators when subjected to random-noise vibration in the range of 20 Hz to 600 Hz with an rms level of 5 mg^2/Hz along the x, y, and z axes. Note that the STW oscillator under vibration has virtually no change in its phase noise, while the quartz oscillator noise increases significantly at offsets of 20 Hz to

600 Hz, directly correlated with the vibration spectrum **[15]**. This is because vibration sensitivity **[1]** is greater for the vibration-sensitive quartz resonator than for the vibration-tolerant STW resonator **[16]**.



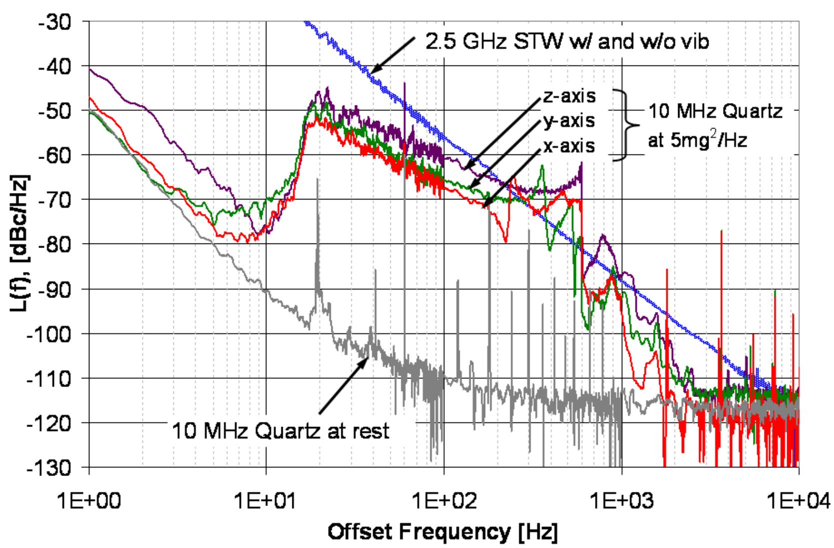


Figure 4. PM noise of the 2.5-GHz STW oscillator is shown in the topmost straight, smooth plot. The 10-MHz quartz oscillator is shown in the bottommost plot. Also shown are the PM noise plots when both oscillators are subject to 20 Hz to 600 Hz random vibration, rms level of 5 mg^2/Hz. Note the dramatic increase in noise in the quartz oscillator, while no change occurs in the STW oscillator.

For each oscillator, the vibration sensitivities along the x, y, or z axes are computed and plotted vs. f_v, the vibration frequency in Figure 5. The square root of sum of vibration sensitivities squared in all three axes gives the total sensitivity **[16]** and is represented by dotted and dashed lines in Figure 5. For the reference 10-MHz quartz oscillator, $\Gamma_{Qz} \sim 1.0 \times 10^{-09}$/g, while for the output 2.5 GHz STW oscillator, $\Gamma_{STW} \sim 4.0 \times 10^{-10}$/g.

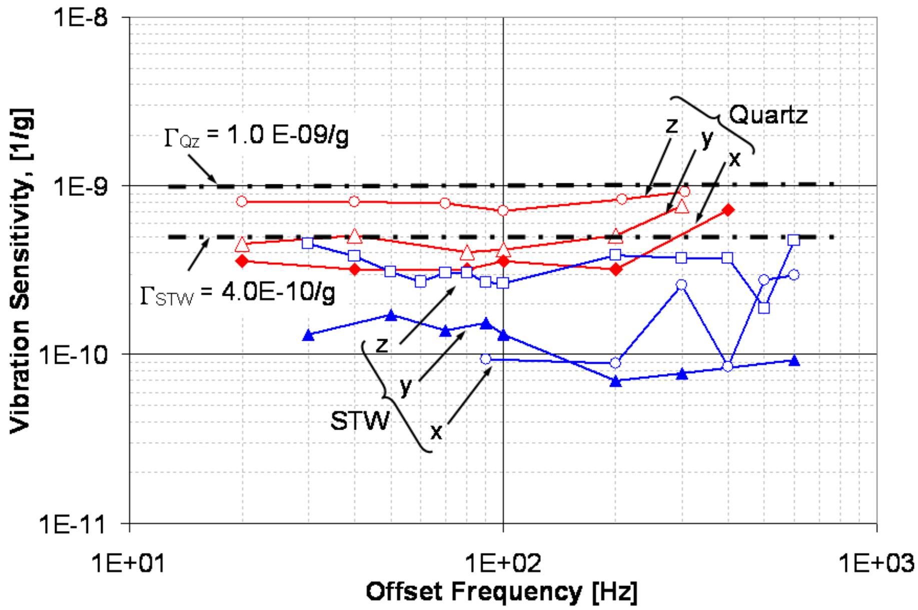


Figure 5. Vibration sensitivity of the 10 MHz quartz and 2.5 GHz STW oscillators along the x, y, and z axes.

We note in Figure 5 that the vibration sensitivity is different for different axes. This complicates the matter for the discussion at hand; however, for what follows, we can treat one axis only, chosen as the z-axis, which has the highest sensitivity. We can keep in mind that the x- and y-axes will have a similar line of discussion.

IV. IDEAL PHASE-LOCKED LOOP BANDWIDTH VS. VIBRATION LEVEL

A phase-locked loop is built to control the phase of the 2.5-GHz oscillator, by the phase of a reference, in this case the 10-MHz quartz oscillator. If the frequency-synthesis scheme of Figure 1 were noise-free, f_{cross} would be chosen as ~10 kHz, as revealed by f_{cross} of at-rest phase noises shown in Figure 2. For the sake of the following discussion, we will assume that a 10-kHz PLL bandwidth is used for these oscillators. Figure 6 shows that f_{cross} shifts to a much lower offset frequency, ~500 Hz, as a function of common field-environment vibration levels of 0.5 mg^2/Hz on the z-axis. Moreover, f_{cross} shifts to ~200 Hz under a larger vibration level of 7 mg^2/Hz.

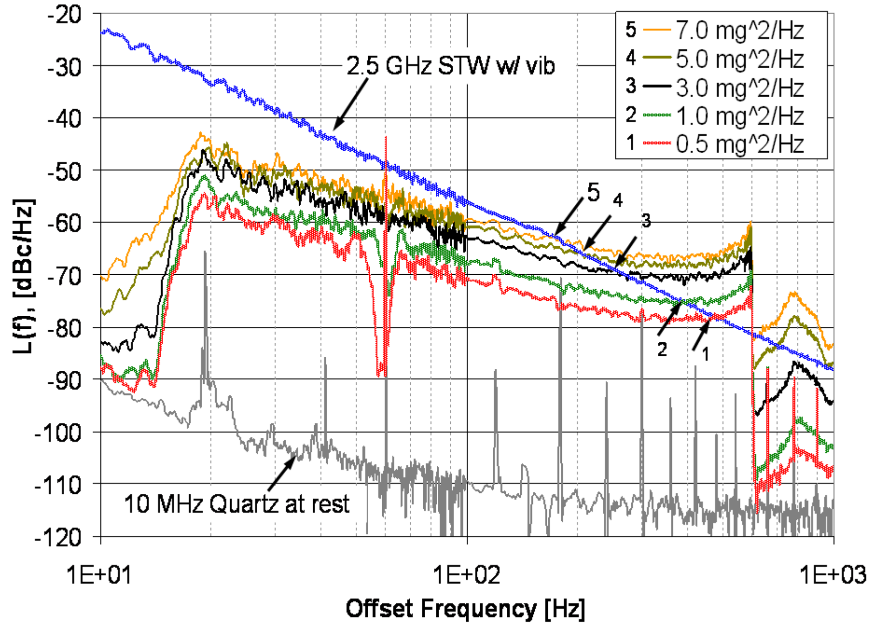


Figure 6. PM noise of free-running oscillators under vibration along the z-axis. Vibration sensitivity of each oscillator causes the optimum PLL BW at f_{cross} shown by arrows to depend on vibration level. A random vibration is applied between 20 Hz $\leq f_v \leq$ 10 kHz.

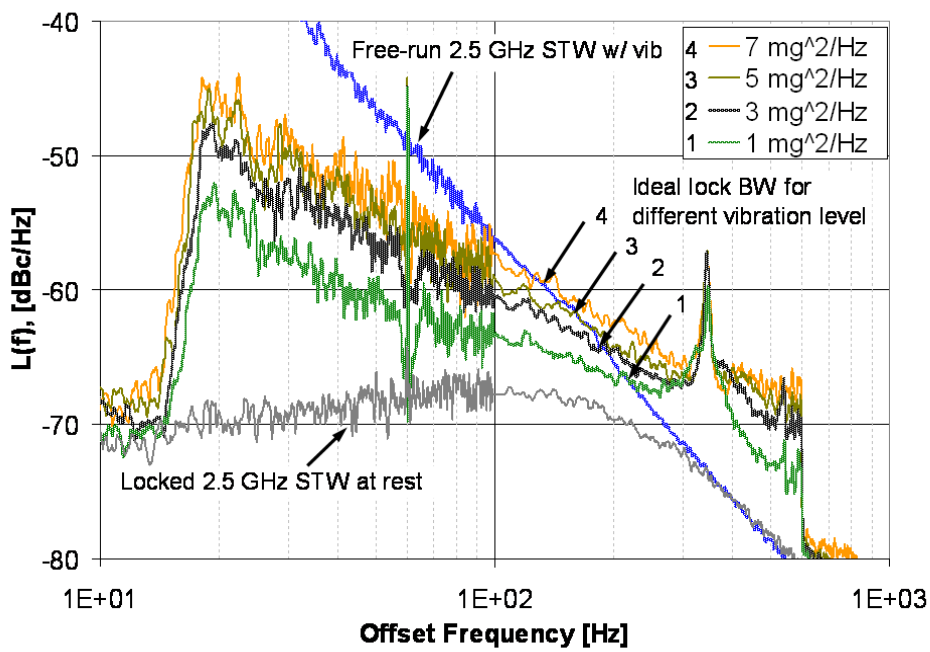


Figure 7. Overall vibration sensitivity of the combined oscillators in the PLL can be reduced by shifting the ideal lock point shown by arrows.

In Figure 7, the bottom curve is the measured overall phase noise of the locked oscillators at rest, as shown in Figure 1 for $10 < f < 1000$ Hz. By mere coincidence, the range of optimum PLL BWs with nominal vibration is in the neighborhood of the 250 Hz PLL BW used here because of the 6250/25 synthesis-divider noise. f_{cross} spans 220 Hz at 1 mg^2/Hz random vibration to 130 Hz at 7 mg^2/Hz random vibration, as shown in Figure 7. Given these measurements, it is theoretically possible to electronically adjust the PLL BW inversely as the vibration level measured on an accelerometer. We could obtain an optimized PLL for varying vibration along any given axis.

V. CONCLUSION

We study the effect of vibration on phase-locked oscillators with different vibration sensitivities. We experimentally verified one case where the vibration sensitivity of a slave oscillator (2.5-GHz STW resonator) is lower than that of a master oscillator (10-MHz quartz reference). The combined PM noise+ from the phase-locked STW oscillator and quartz oscillator at rest is optimized for lowest overall phase noise. In a vibration environment, the 2.5-GHz STW has a $\Gamma_{STW} \sim 4.0 \times 10^{-10}$/g and low far-from-carrier phase noise while locked to the 10-MHz quartz oscillator with $\Gamma_{Qz} \sim 1.0 \times 10^{-09}$/g and low close-to-carrier-noise used as a reference. We have measured the PM noise and vibration sensitivity of each oscillator and find that their differing vibration resistance results in a shift in the ideal synthesizer PLL BW in the presence of different levels of vibration. To obtain an optimized PLL, we plan to dynamically adjust the PLL BW in future experiments. The achievable level of improvement remains to be determined for combined oscillators.

VI. ACKNOWLEDGMENTS

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