Voltage-Controlled Sapphire Oscillator: Design, Development, and Preliminary Performance

R. T. Wang,[1] G. J. Dick,[2] and R. L. Tjoelker[1]

We present the design for a new short-term frequency standard, the voltage-controlled sapphire oscillator, as a practical and lower-cost alternative to a cryogenic sapphire oscillator operating at liquid helium temperatures. Performance goals are a frequency stability of 1×10^{-14} (1 second $\leq \tau \leq$ 100 seconds), more than 2 years of continuous operation, and practical operability. Key elements include the sapphire resonator, low-power and long-life cryocooler, frequency compensation method, and cryo-Pound design. We report the design verification, experimental results, and test results of the cryocooler environmental sensitivity, as well as a preliminary stability measurement.

I. Introduction

The voltage-controlled sapphire oscillator (VCSO) is a technology designed as a practical high-performance upgrade for applications presently limited by ultra-stable quartz oscillators. Its main features are cryogenic sapphire oscillator (CSO) capability with short-term stability of 1×10^{-14} or better (1 second $< \tau <$ 1000 seconds) in a small transportable package, and the capability of 2 years or more of continuous maintenance-free operation. Specific design factors and early progress were reported in [1,2]. This VCSO is an analog of the quartz voltage-controlled crystal oscillator (VCXO) but with much higher performance, and it is incorporated in a much reduced physical package as compared with previous cryogenic sapphire oscillator units. The VCSO is expected to provide 10 times better frequency stability and 20-dB close-in phase noise reduction at 32 GHz (Ka-band) as compared with the best available quartz oscillators. Small size and modest cryogenic requirements also make the VCSO technology an attractive candidate to meet future space oscillator requirements.

Previous JPL-designed and -built cryocooled oscillators—the 10-K Compensated Sapphire Oscillator (CSO) [3] and the 40-K CSO [4]—provide state of the art short-term performance: 10^{-14} to 10^{-15} stability together with ultra-low close-in phase noise. However, they have operability limitations due to their size, maintenance, and power requirements. Quartz oscillators are small, long-lived, and can be used in remote sites to clean up ultra-stable signals, but they substantially limit Deep Space Network

[1] Tracking Systems and Applications Section.

[2] Communications Architectures and Research Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

(DSN) phase noise performance at Ka-band and higher frequencies. While a truly miniature cryogenic sapphire oscillator is not yet within reach, an initial version that could reside in a 5-unit-high rack-mount chassis is. One promising cryocooler currently being evaluated at JPL for possible use in a DSN antenna array is the Sunpower Stirling cycle cryocooler [5]. The cryocooler goals of the DSN array and a VCSO are similar, both requiring low cost, long operational life, and the lowest possible base temperature. The Sunpower cryocooler uses 150 W and provides 2 W of cooling power at 40 K. The cooler has a lifetime of 50,000 hours (>5 years). The form factor of the cryocooler fits in a 25-cm-long, 7.5-cm-diameter cylinder. The VCSO would be very attractive as a modular upgrade in high-performance VCXO applications such as clean-up loops (CULs), low-noise flywheel oscillators, and local oscillators (LOs) for high-performance passive frequency standards. This is a much broader market than previous versions of the CSO have been able to reach, and several immediate NASA applications are the JPL Frequency Standard Test Laboratory (FSTL) and the DSN Frequency and Timing Subsystem (FTS).

The VCSO compensation methodology traces to the previously developed 40-K CSO [4], which established the low-drift and low gravity sensitivity (g-sensitivity) for a “self assembling” compensated silver/sapphire resonator design that demonstrated a quality factor (Q) of $Q = 1 \times 10^8$ at its temperature turnover of about 37 K. Using a whispering gallery transverse electric $(\mathrm{WGE})_{12,1,1}$ mode instead of the previous $\mathrm{WGE}_{10,1,1}$ increases the diameter slightly but makes possible reuse of the previous silver spacer design, and it also moves the radio frequency (RF) fields away from the central region. The resonator enclosure volume is reduced from that of the 40-K CSO by about 10 cc, with an inner diameter (ID) for the shielding can of 3.55 cm and a height of 1.58 cm. This development extends present technology to a higher-frequency resonator (32 GHz instead of the present 16 GHz) for reduced size, g-sensitivity, and size of the electronic packaging. The VCSO includes a new cryostat design and resonator interface to the selected cryocooler.

The most significant technical differences between the VCSO and previous CSO designs are due to the very small cryocooler. Available Stirling coolers are small enough to allow a very attractive and small physical package, but their use also significantly impacts other aspects of the system. In particular, the smaller cryocooler introduces larger mechanical vibrations than the large coolers that were previously used. However, a much higher mechanical frequency of operation (60 Hz versus 1.5 Hz) allows the effects of these vibrations to be ameliorated by the combination of an electronically driven mechanical balancer and an RF clean-up loop incorporating an inexpensive quartz oscillator. These two systems together effectively eliminate the vibrations without impacting VCSO performance.

II. System Design

In the design of an ultra-high-stability oscillator, many interrelated parameters must be addressed. The key individual elements are resonator Q, temperature, vibration, cryocooler, frequency compensation, resonator g-sensitivity, resonator mode configuration, resonator frequency, overall size, continuous operation period, electronics, and cost. Key interrelated parameters are as follows:

(1) Operational temperature and Q. Sapphire Q is a function of temperature: $Q(77\mathrm{K}) \sim 10^7$, $Q(4\mathrm{K}) \sim 10^9$. It is possible to reach frequency stability of a few parts in 10^{-15} with lower temperature operation. While a 4-K system can reach stability below 10^{-15}, a standard at 10^{-14} is achievable at much higher temperatures and would still be an order of magnitude better than the best quartz oscillators.

(2) Temperature and the cryocooler. The selected operational temperature depends on the designed turnover temperature of the sapphire resonator, and the achievable base temperature and cooling power of the cryocooler. Practical single-stage Stirling coolers can reach a base temperature of 33 K [5], which provides margins for dewar heat load design and any possible cooling power degradation over long-term operation. The Sunpower cryocooler also was chosen for simple long-life operation and low cost.

(3) Acceleration sensitivity and the cryocooler. Due to the 60-Hz vibration of the Stirling cooler, vibration effects need to be minimized through an active balancer and electronic crossover design. Detailed results were previously reported in [2]. A mechanical finite-element calculation program was used to design a configuration with 100 times lower g-sensitivity with a center support geometry (see Fig. 1).

(4) RF frequency and resonator mode. The resonator frequency is calculated based on the sapphire resonator physical size and the desired mode electromagnetic configuration (see Fig. 2). Finite-element calculation is used to determine the sapphire gap tuning rate, mode frequency, resonator size, coupling port position, and copper-can size. Sapphire whispering-gallery modes provide higher Q, limited only by the inherent sapphire performance. When used in Ka-band spacecraft tracking, a carefully selected output frequency at 32 GHz directly provides low signal phase noise to users without additional frequency multiplication. The higher operating frequency at 32 GHz for $WGE_{12,1,1}$ results in a smaller resonator with a smaller copper can but does increase the complexity of the silver spacer design. For initial tests, to obtain an efficient match from a coaxial cable to the sapphire resonator, we use a Teflon-filled WR-19 coaxial/waveguide adapter together with an impedance-matched alumina-filled tapered waveguide adapter. Subsequent tests revealed it is possible to use a Teflon-filled direct waveguide without an alumina taper for critical coupling.

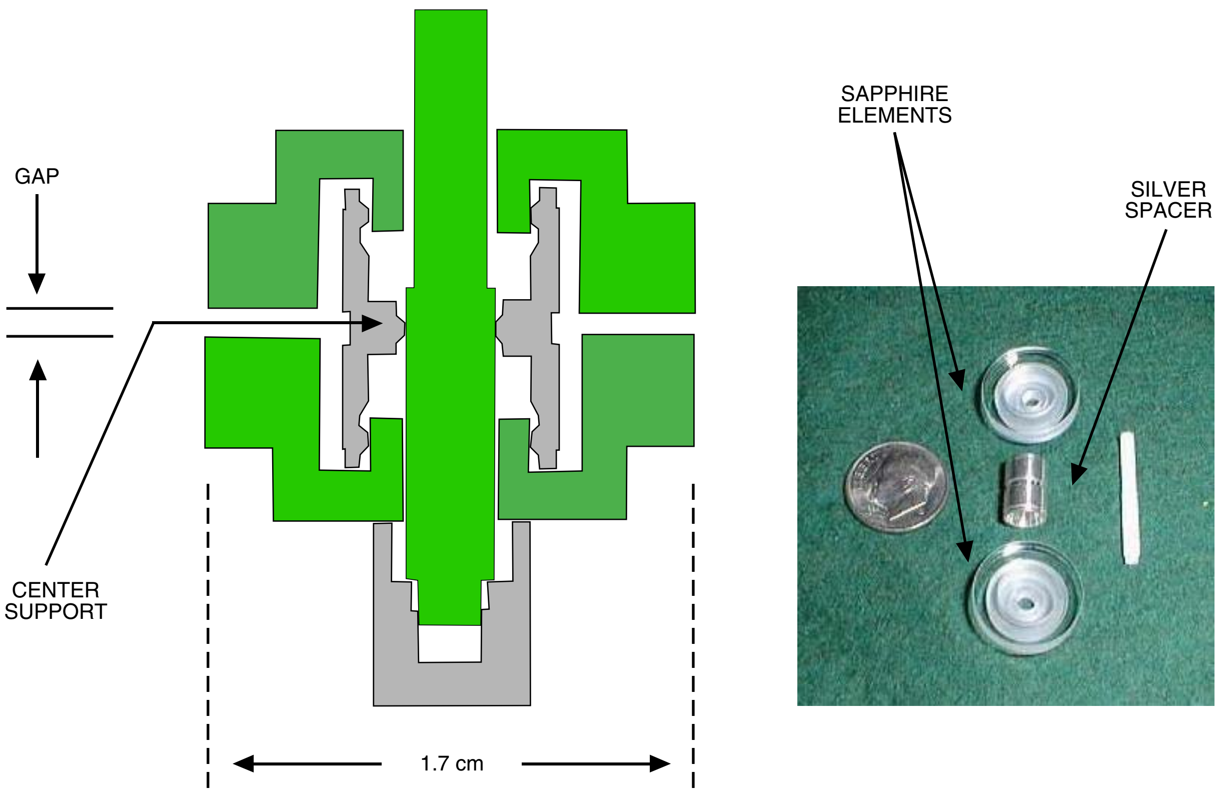

Fig. 1. Cylindrical cross section of self-assembling resonator design and component parts. Sapphire is in green and the silver parts in gray. Thermal expansion in the silver spacer adjusts the gap spacing to compensate the thermal dependence of sapphire's dielectric constant. The final assembled unit is supported from its geometrical center, reducing acceleration sensitivity of the resonant frequency to less than 10^{-10}/g.

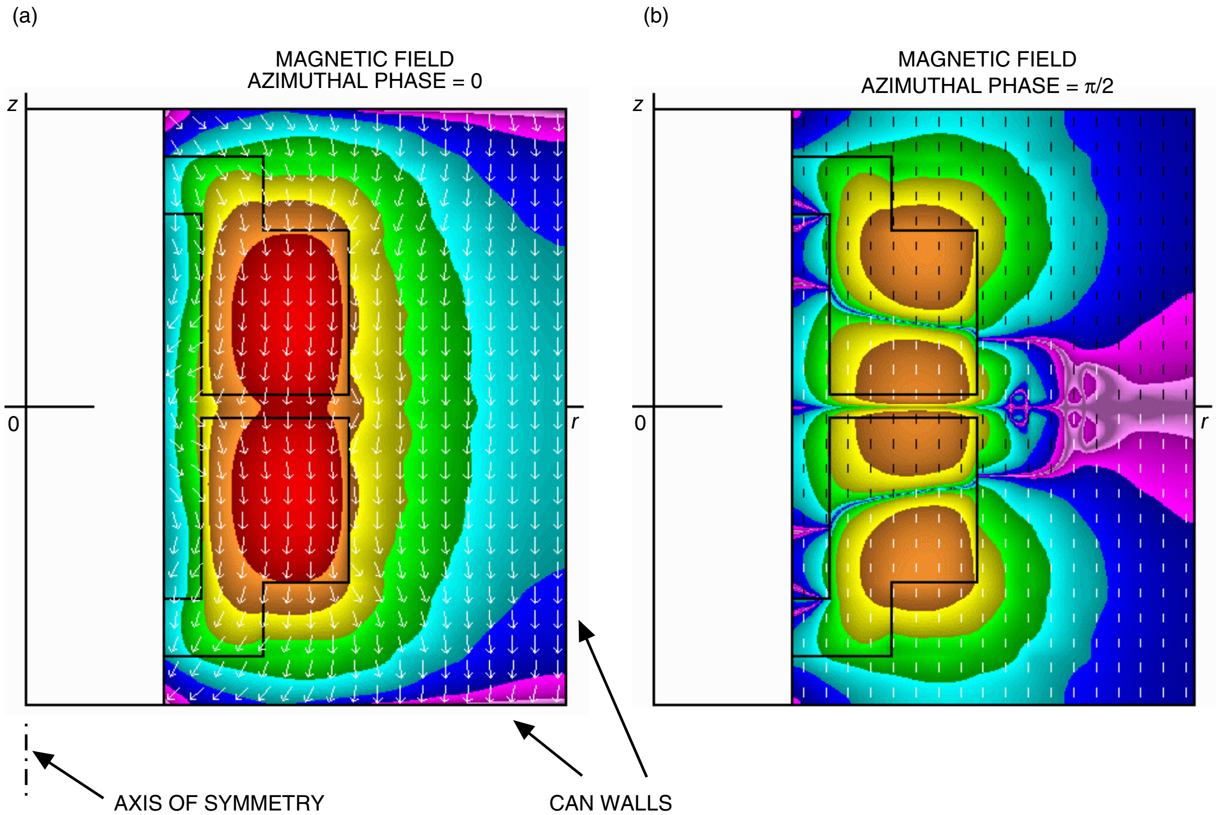

Fig. 2. Finite-element calculation of electromagnetic fields for the $WGE_{12,1,1}$ mode used to determine the container size and coupling port position: magnetic field azimuthal phase at (a) 0 deg and (b) 90 deg. Each color variation corresponds to an order of magnitude in magnetic field strength.

(5) Frequency compensation and frequency drift. Stable operation can be achieved only near a turnover temperature at which frequency sensitivity to temperature fluctuation is near zero (see Fig. 3). Without such compensation, the burden on the temperature control would increase by 1000 times. Commercially available temperature controllers lower the overall cost of the system. Frequency drift has historically been a substantial limitation in thermo-mechanical CSO operation. To address this issue, an interference fit design and selection of a low-creep material at low temperatures were folded into the sapphire resonator design. Silver was selected for its thermal properties and also for ease of machining. An electrical discharge machining (EDM) process was chosen for its lower cost, faster delivery, and possible lower chance of contamination.

III. Sapphire Resonator Design and Verification

The first set of 32-GHz sapphire resonators was assembled, tested for high Q modes, and demonstrated the turnover temperature. Figure 1 shows the cross section of the sapphire resonator assembly and a photograph of the sapphire/silver parts before assembly. Design requirements and verification are discussed in the following.

A. Electromagnetic Design

The VCSO resonator is based strongly on the previous 16-GHz design. In particular, the reuse of the silver spacer design allows use of an EDM manufacturing technique that has already been proven. Even

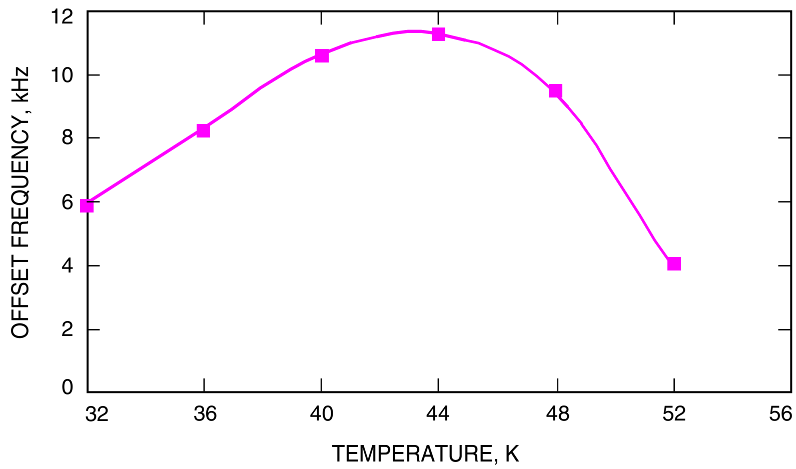

Fig. 3. Initial measured turnover temperature near 43 K for 32.05-GHz mode with a quadratic coefficient of $-1.94 \times 10^{-8}/K^2$. With 1-mK temperature control, the frequency stability can reach 2×10^{-14}. After a gap spacing adjustment, the turnover temperature was lowered to 38.910 K.

though the resonator itself is significantly smaller, the reused silver spacer design does not require that the physical tolerances between the silver and sapphire parts be made more stringent. Additionally, a higher thermo-mechanical tuning rate due to the longer length of the silver spacer relative to that of the resonator naturally gives a somewhat higher turnover temperature, a good match to the capabilities of the single-stage Stirling cooler.

Electromagnetic fields calculated for the $WGE_{12,1,1}$ mode for the sapphire resonator are shown in Fig. 2. This mode is a quasi-transverse electric mode with energy confined to the sapphire disks by the phenomenon of "total internal reflection" and with 12 full waves around its perimeter. Finite-element calculations allow optimization of the resonator parameters, such as balancing the can diameter against losses and establishing appropriate RF magnetic field values at the coupling port. The positions of the walls of the can have been adjusted to give a copper can–limited quality factor of $Q = 4 \times 10^8$ and so to allow critical coupling with a waveguide port for the expected sapphire quality factor of $Q \approx 3$ to 6×10^7. The azimuthal mode number was chosen to be $n_\phi = 12$ (instead of the previously used $n_\phi = 10$) because RF losses due to in-phase magnetic fields reduced the quality factor copper-can Q to an unacceptable value. First attempts without the cut-out region at the resonator corners resulted in a low tuning rate and consequent low value for its turnover temperature, the temperature where the net sensitivity of frequency to temperature passes through zero. The thermo-mechanical compensation process results from variation of the gap between sapphire disks for the assembled resonator as a function of temperature. This variation is primarily due to the thermal expansion coefficient of the silver spacer. This temperature dependence allows the effect of the thermal variation of sapphire's dielectric constant to be cancelled by a proper choice of tuning rate for the resonator and so to achieve a zero net variation (i.e., turnover) at the desired operational temperature.

B. Mechanical Design

Early thermo-mechanically compensated sapphire resonators suffered from excessive frequency drift, showing values as high as 10^{-8}/day [4]. For this reason, we use a design that reduces frequency drift due to mechanical creep in several ways. First, the use of a silver spacer instead of the copper previously used provides much lower cryogenic creep values [6]. Secondly, as shown in Figs. 4 and 5, a design is used for which the primary loading forces are radial and for which the crucial longitudinal dimensions can be somewhat isolated from the effects of radial creep by an appropriate design. These radial loading forces

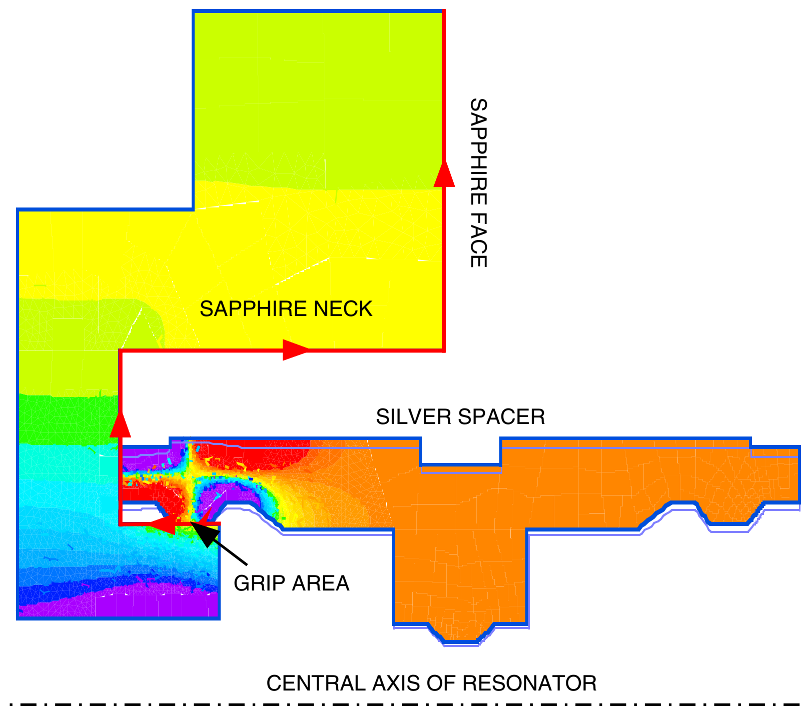

Fig. 4. Mechanical finite-element model used to minimize frequency drifts due to mechanical creep at the silver–sapphire interface (a second mirror-image part is not shown). Colors show the longitudinal motion with a zero at the yellow–green interface in the approximate center of the face, while arrows show the path for a quantitative plot shown in Fig. 5.

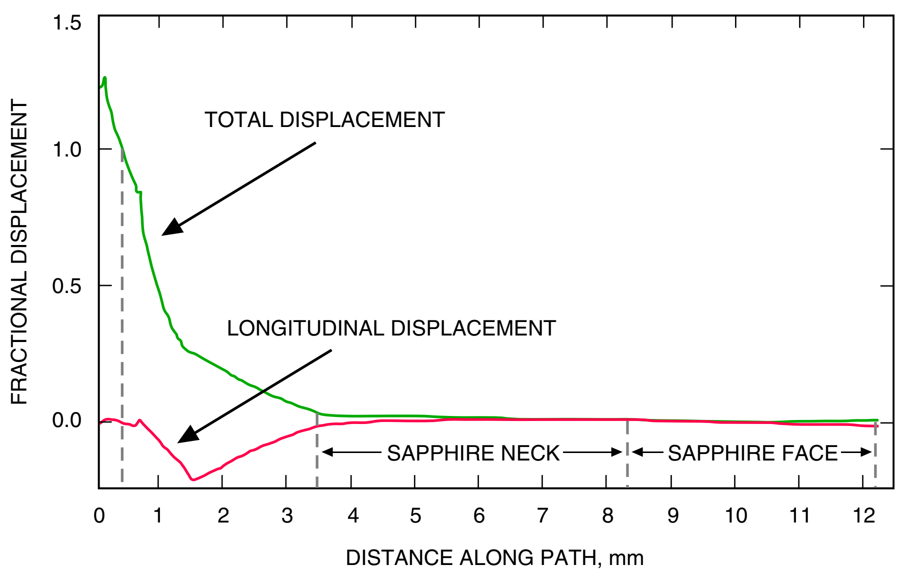

Fig. 5. Mechanical displacements evaluated along the path described by the arrows in Fig. 4, shown as the fraction of an applied radial displacement at the grip area (see Fig. 4). Careful adjustment of the sapphire dimensions in the grip region allows longitudinal displacement at the sapphire face to be reduced to less than 1 percent of the applied displacement.

result from the "self-assembling design" in which the silver spacer grips both the sapphire disks and the central sapphire support rod as the parts are cooled, resulting in small but usable clearances between the horizontal surfaces that provide support prior to cooldown.

A partial view of the resonator assembly is shown in Fig. 4 to illustrate results of the mechanical finite-element calculation. Here the spacer is given an (unphysical) radial-only thermal dependence and cooled, with the grip area constrained longitudinally. The sapphire model geometry (e.g., the height) is varied to give a zero for longitudinal motion at the center of the sapphire face. Quantitative results of this calculation are shown in Fig. 5, which shows longitudinal displacement reduced to ≈1 percent of the applied radial displacement. A similar set of calculations and optimizations is also realized for changes in the grip length of the spacer due to radial pressure at the inside center of the spacer where it grips the sapphire support rod.

C. Experimental Results

A sapphire resonator was assembled and cooled to 40 K for high Q mode scanning between 26.0 and 38.5 GHz. The desired mode frequency was verified at 32.05 GHz, a value +0.15 percent higher than calculated. After adjustment of the gap spacing, the turnover temperature was verified to be 38.910 K, lower than the calculated value of 40 to 50 K. Although lower than expected, it is still within the range of current cryocooler cooling power. The measured Q value is 10 million, which is less than the expected value of 20 million at 40 K. Q values as high as 80 million have been observed, as shown in Fig. 6. The VCSO sapphire/silver assembly design allows for frequency repeatability after the disassembly and cleaning processes. This has been demonstrated in the early stages.

IV. Cryocooler Requirements and Tests

A cryocooler is required for maintaining the sapphire resonator at a low temperature to obtain a high Q factor. At the same time, the cryocooler vibration needs to be minimized. Other cooling methods, such as liquid helium, that need regular refill are not practical for long-term operation. The overall cryocooler requirements are a base temperature near 40 K, low input power, light weight, low cost, long life, and manageable environmental sensitivity.

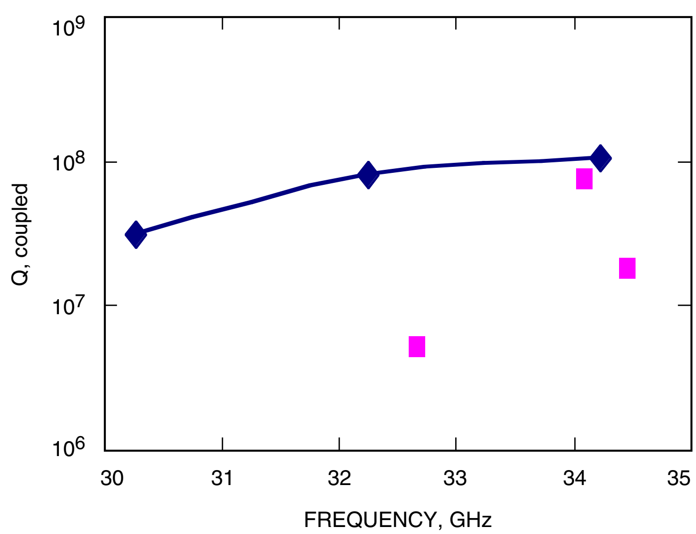

Fig. 6. Examples of high-Q modes found between 30 and 35 GHz. Line-connected data points are the possible mode sequence identified by finite-element method (FEM) calculation.

A. Functional Tests

The CryoTel cryocooler from Sunpower, Inc. has a rated lifetime of 50,000 hours and requires an input power of ≈150 W. The cooler itself and the interface to the sapphire resonator are shown in Fig. 7. The cooler is available with passive or active balancers to reduce vibration levels. The passive balancer reduces vibrations by ≈10 dB to approximately 0.3-g root-mean-square (rms), a reduction that is enhanced by addition of an electrical voice-coil mechanical driver and user-supplied electronics. We have operated the cooler continuously for 5 months and observed no failures or performance degradation. The cooler control system supports constant temperature and constant stroke operational modes. Because of the need to reduce cooler vibrations by an active feedback system, we use the constant stroke mode to reduce the burden on control of that system. Figure 8 shows measured values for ultimate temperature as a function of programmed stroke length.

B. Vibration Control

A drive electronics system to obtain active vibration cancellation has been developed. The circuit is designed to cancel the first two harmonics by manual adjustment of their phase and amplitudes. Somewhat surprisingly, the 60-Hz drive for the cooler itself (and which we use as input to our circuit) consists of a pulse-width modulation (PWM) square-wave signal at 420 Hz with inclusion of a 420-Hz notch filter. The effectiveness of the cancellation of the two vibration harmonics is shown in Fig. 9. The requirements of a 25-dB reduction at 60 Hz and of 16 dB at 120 Hz are more than met. The 55-dB reduction shown in the figure cannot be held in the long term. Overnight values more typically showed a 40-dB reduction. These values are sufficiently good that it is not clear whether an adaptive system will be required for long-term operation. Also, somewhat surprisingly, varying the cryocooler stroke gave rise to some 20-dB smaller degradation than would be expected for a constant amplitude cancellation model, indicating that the variations in cooler vibration levels and the active compensator are largely compensating each other. Disabling the passive vibration cancellation system by shorting the voice-coil terminal results in a vibration level at 60 Hz that is 10-dB larger than shown here (a value of approximately 1-g rms).

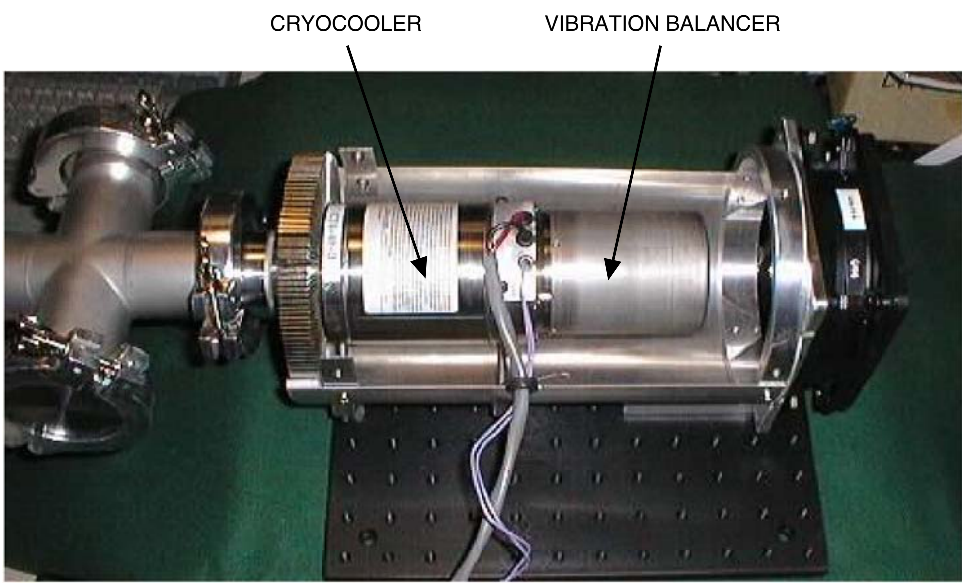

Fig. 7. The CryoTel cryocooler as tested without the control electronics and control computer. The cooler and vibration-cancelling driver are shown without a cylindrical air duct cover that channels air from the blower at the right through a heat exchanger at its left end. The cooler's cold finger extends into the vacuum fittings at the left and will be replaced with somewhat larger fittings to accommodate the resonator and heat shield; a vertical, downward-hanging configuration is planned.

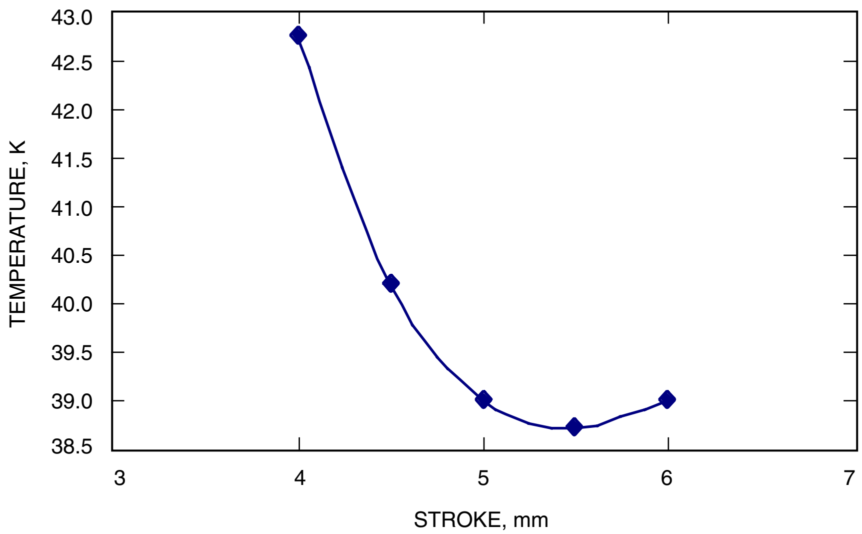

Fig. 8. Base temperature versus stroke length as measured for the cooler configuration in a horizontal position.

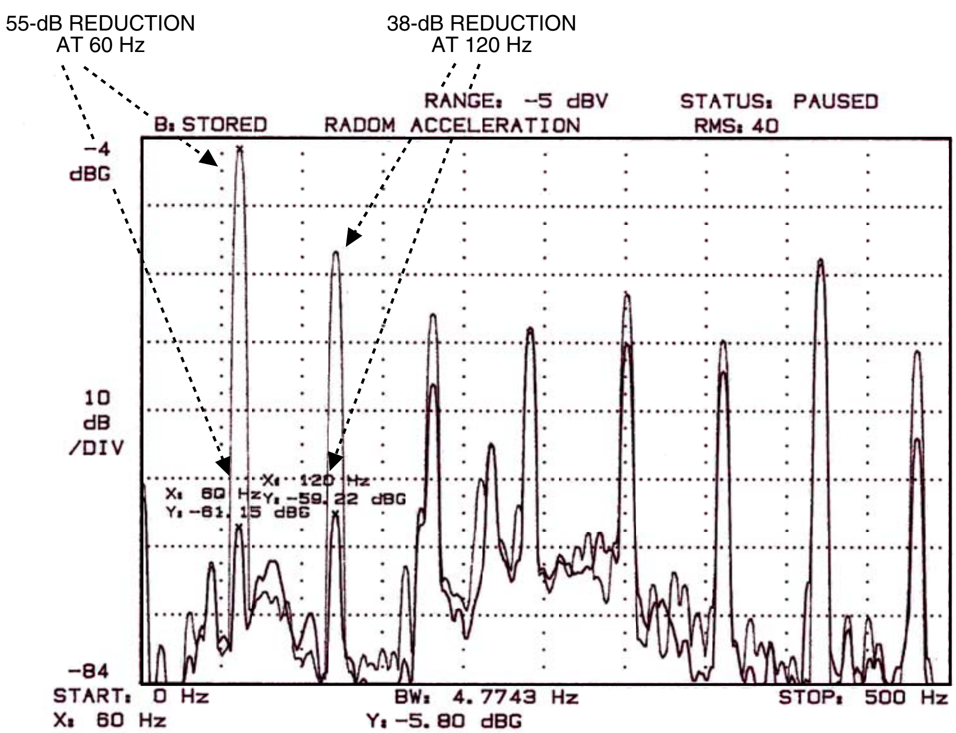

Fig. 9. Scanned image from a plotter showing an acceleration spectrum for the CryoTel cooler measured with and without active vibration cancellation. The first two vibration harmonics and their reduction values are indicated in the figure. A further 25-dB reduction by an RF clean-up loop (see Fig. 11) is required to achieve the overall 60-dB bright-line reduction goal.

C. Environmental Sensitivity

Tests were performed in an FSTL environmental chamber. Three different parameters were varied: temperature, pressure, and humidity. Temperature ranged from 15 to 35 deg C in 10 deg C steps for every 12 hours; pressure was ±30.48 cm of water for every 4 hours; and humidity ranged from 20 to 60 percent at 25 deg C for every 12-hour step. The data show no measurable correlation to pressure or humidity changes. Figure 10 shows base temperature variation related to external temperature changes. The upper curve shows the base temperature, and the lower curve shows the room temperature variation. This test was performed with a simulated radiation shield to measure the operational temperature when the sapphire resonator is incorporated. The measured external temperature sensitivity was 0.19 deg C per deg C, which implies that for every 5 deg C of ambient temperature change the base temperature will change by 1 deg C. Therefore, external temperature regulation is needed for long-term stable operation.

V. Electronics and Cryo-Pound Design

A major challenge for this new technology is to reduce or eliminate the bright-line phase noise spectra that result from vibrations in the Sunpower/Stirling cryocooler at harmonics of the 60-Hz vibration frequency. Although acceleration sensitivity for the new resonator is expected to be $\leq 0.5 \times 10^{-10}$/g, a value half that measured for the previous, larger resonator, the effects of cryocooler vibrations must still be reduced by 60 dB to be unobservable in the phase noise. An appropriate clean-up oscillator with advanced crossover design, together with active cancellation of cryocooler vibrations, can give the required reduction with 25 dB of margin. This should still allow a short-term stability of 1×10^{-14} for a measuring time of 1 second [2].

A. Electronic Crossover Design

Cyclical mechanical vibrations at 50 to 60 Hz, characteristic of small Stirling or pulse tube coolers, can be filtered by means of a clean-up oscillator without degrading ultra-high short-term stability performance. In particular, Figs. 11 and 12 show the phase noise and frequency stability performances for

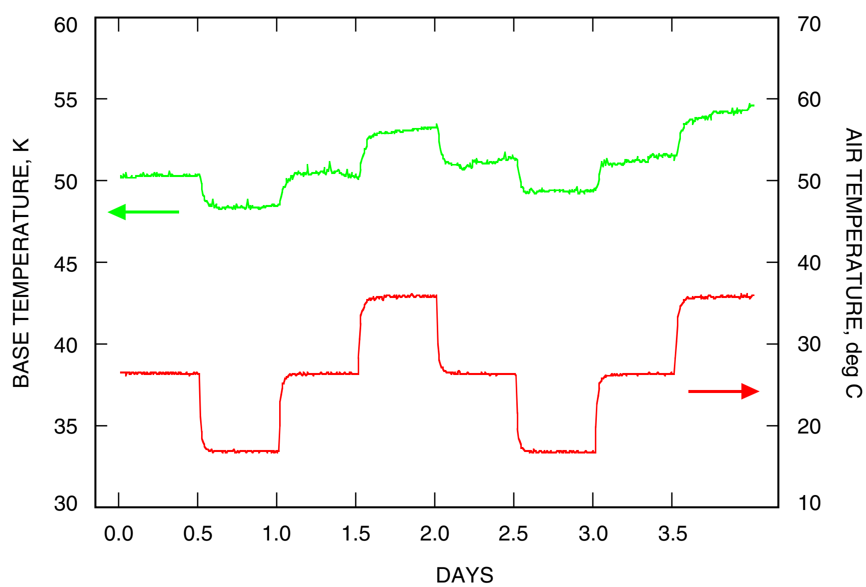

Fig. 10. Cryocooler temperature sensitivity. The lower curve shows air temperature versus time. With a step of 10 deg C for every 12 hours, the upper curve shows a correlated base temperature change with a sensitivity of 0.2. Due to outgassing in the dewar, the base temperature had a drift rate of 0.3 deg C per day. A simple gettering system is expected to remove this drift.

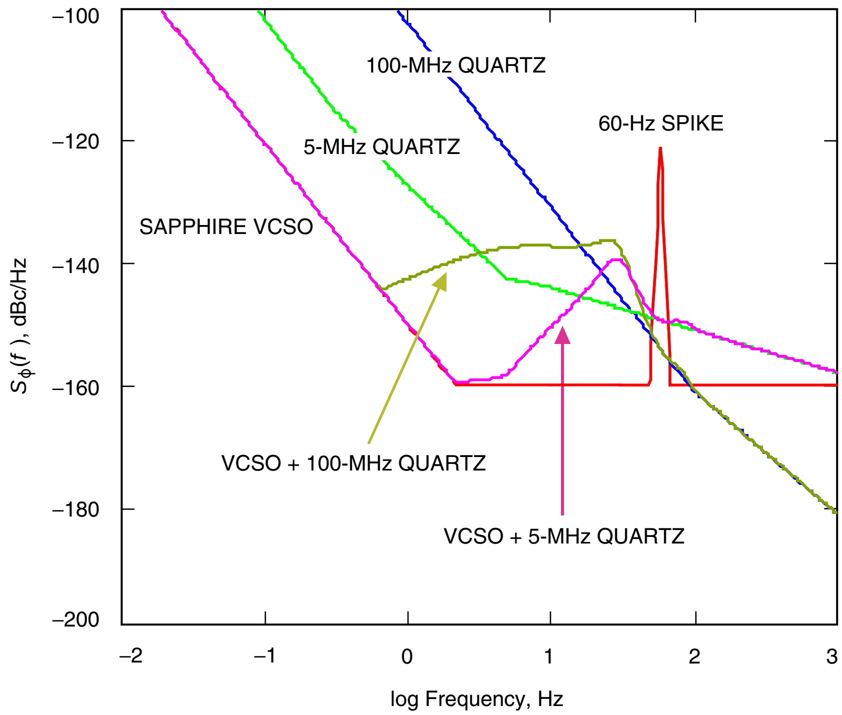

Fig. 11. A clean-up oscillator can help to reduce vibration-induced phase-noise spurs to negligible levels. Shown here are phase-noise plots for 5-MHz and 100-MHz candidate clean-up oscillators, example VCSO phase noise with a single 60-Hz vibration harmonic, and combined (crossed-over) phase noise for the VCSO together with each candidate clean-up oscillator. For comparison, the phase noise for all oscillators is scaled to 5 MHz. The crossover design here has a unity gain frequency of 25 Hz and includes notch filters for the first three vibration harmonics. Operating together with an active vibration-cancellation system described in Fig. 9, the combined system is expected to reduce vibration harmonics by more than 60 dB.

several clean-up oscillators and for a crossover design that provides highly tuned rejection at the fundamental of the cryocooler vibration frequency and its first two harmonics. The choice of unity gain or crossover frequency for the crossover circuit balances the need for the clean-up oscillator to be effective at high frequencies (favoring a low crossover frequency), while effectively ignoring its higher noise at lower frequencies (favoring a higher crossover frequency)—higher noise that would otherwise degrade the frequency stability of the combined system. With an optimal crossover frequency of only 25 Hz as determined by this trade-off, rejection of the vibration harmonics is largely up to the notch filters. We find that these filters require a $Q \approx 5$ to 10 to minimize their impact on lower frequencies and on the phase margin of the loop. However, such filters will have a substantial sensitivity to component variation with temperature, and so a software method was developed to evaluate non-ideal "balanced tee" notch filter performance. Based on these calculations, we have determined that the required 40-dB reduction for the harmonics can be held for a 1 deg C variation of the crossover electronics interior.

A cryo-Pound design promising improvements to medium- and long-term stability using a new cryogenic Pound circuit methodology is discussed in [7]. The following gives a brief description of the principal and demonstrated results.

In a cryogenic oscillator system, temperature variations in the microwave components between the cryogenic resonator and the room-temperature phase modulator may give rise to false Pound signals. Specifically for the oscillator described in [8], voltage standing wave ratio (VSWR)-induced standing

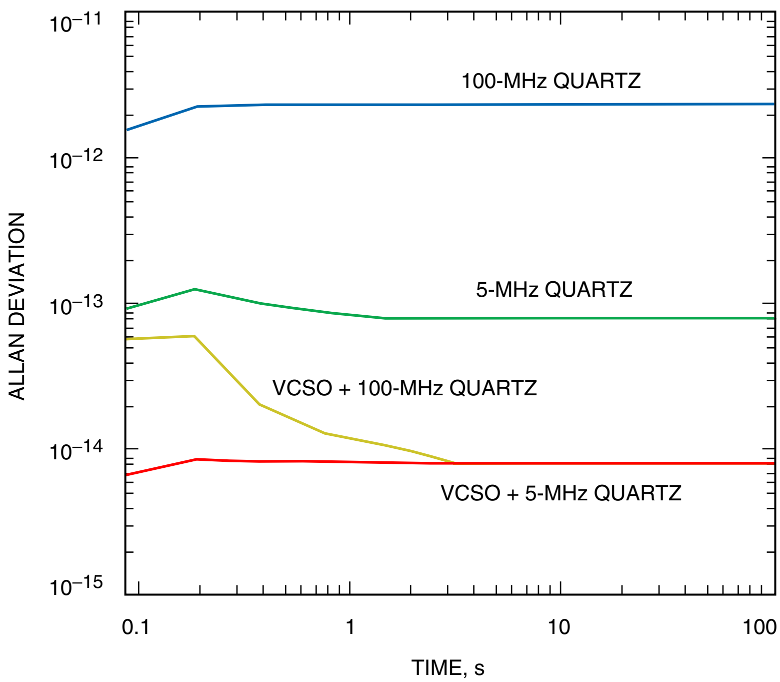

Fig. 12. Calculated Allan deviation for the phase-noise models described in Fig. 11. The crossed-over 5-MHz clean-up case is indistinguishable from the VCSO itself. Most significant is the ability to achieve the target 1 x 10^{-14} stability at 1 s with an inexpensive and small low-noise 100-MHz quartz clean-up oscillator, as is shown here.

waves in the RF transmission line entering the cryostat were estimated to give rise to a relative frequency variation of 1×10^{-13} in the presence of temperature variations of 10 K. The false Pound signals were due to an induced linear variation of the amplitudes across the phase modulation (PM) spectrum.

Our goal is to eliminate the sensitivity of the oscillator to the above-described temperature fluctuations in the microwave components kept at room temperature. This is achieved by integrating all the RF components in the Pound scheme into the highly stabilized thermal environment that the sapphire resonator is placed in. Specifically, both the phase modulation of the RF carrier and the detection of the amplitude modulation (AM) component are included in the cryogenic part of the oscillator. The critical component in this all-cryogenic Pound circuit is the tunnel diode, which is used both as phase modulator and AM detector (see Fig. 13). This diode was chosen because it functions at low temperatures and has low noise. We find experimentally that the new Pound circuit has a sensitivity of 0.1 mV/Hz, which corresponds to a calculated stability of $4 \times 10^{-16}/\sqrt{\tau}$.

In our first experimental investigations of the all-cryogenic Pound circuit, we achieved a stability of 1×10^{-13} at 1 second. Although we are still some way from the predicted possible performance, the basic principle has been illustrated. Finally, the demonstration was performed at 16 GHz, and the all-cryogenic Pound circuit is expected to work at 32 GHz, which can be incorporated into the VCSO in the future.

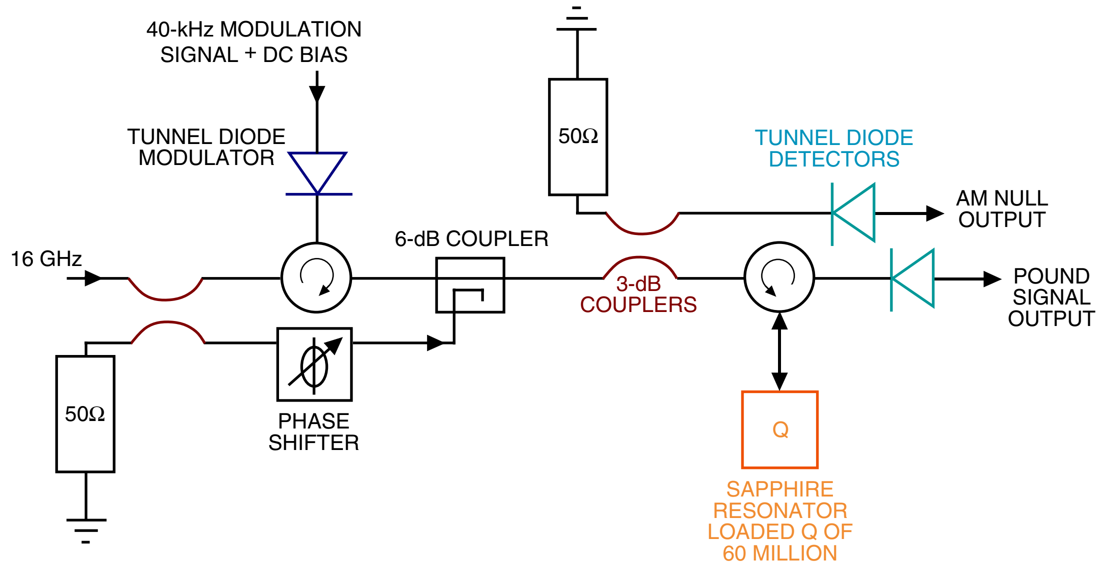

Fig. 13. The new cryogenic Pound circuit. The tunnel diode modulator is DC biased, and the phase shifter is adjusted so that the upper diode detector gives minimal output while at the same time having high power in the modulation side bands. The power in the side bands is monitored through a weakly coupled port inserted immediately to the right of the left circulator (not shown). The carrier signal (here 16 GHz) enters the cryogenic environment, gets phase modulated, and is reflected from the resonator. In general this reflection contains an AM component that is detected in a tunnel diode, thus providing the Pound signal.

VI. Integration and Initial Tests

Due to funding considerations, an initial measurement was hastily performed. To accomplish this a year ahead of schedule required that several shortcuts, such as the following, be adopted:

(1) Q value. The Q value is at 10 million (less than the expected value of 20 million). Q values as high as 80 million were observed in some modes.

(2) Coupling. The coupling of the resonator is not yet "near critical." With minor modifications, we would expect to approach critical coupling, which will increase the signal-to-noise ratio.

(3) Electronics. We reused the old 40-K CSO electronics by doubling its 16-GHz frequency output. Noise characterizations of the frequency doublers and amplifiers were not performed due to lack of resources and time. Also, the 16-GHz loop was not optimized for this operation.

(4) Detector. A 32-GHz tunnel diode detector was used "as is" without characterization of its noise level and without checking the best performance input level.

(5) Cryocooler. We reused the 40-K CSO pulse tube cooler instead of the intended Sunpower cryocooler and attached the resonator directly to the cold stage for a simplified setup.

With the above multiple compromises, the initial stability measurement shows 3.7×10^{-13} at a 1-second measurement time, and Fig. 14 shows the measured frequency stability from 1 s to 100 s. Frequency stability is expected to reach 1×10^{-14} at a 1-second measurement time with the original proposed setup.

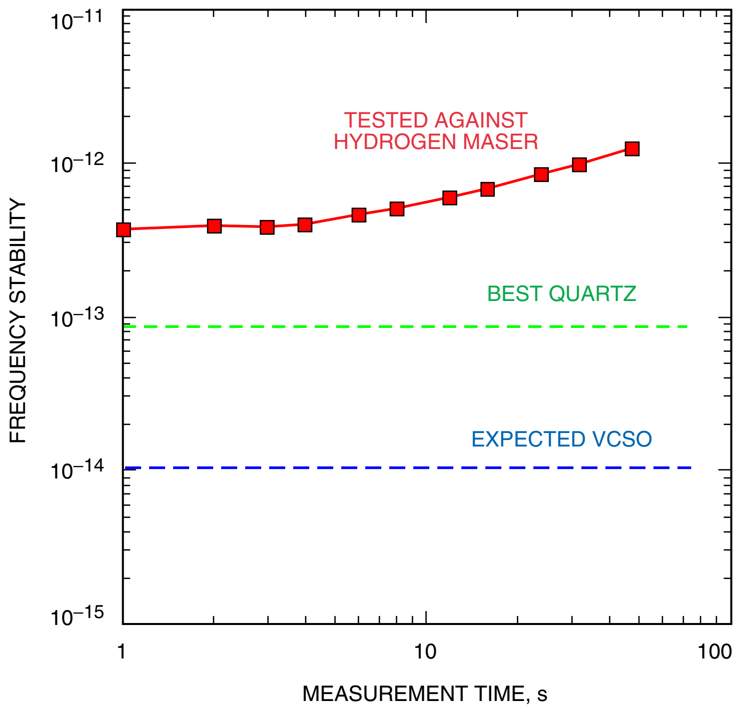

Fig. 14. Preliminary stability measurement of 3.7 x 10^{-13} at a 1-s measurement time. Shortcuts were made to accelerate this demonstration; they involved reusing previous electronics and not characterizing critical components used in the stability demonstration. A 1 x 10^{-14} performance is expected with proper setup and characterization.

VII. Conclusion

We reported on the overall design, development, and verification of a practical voltage-controlled sapphire oscillator. The first 32-GHz sapphire resonator was assembled and tested at cryogenic temperatures. Various high-Q modes were identified and compared to finite-element calculations. The desired mode shows a frequency of 32.05 GHz and a turnover temperature of 38.910 K. Measured Q values were as high as 80 million. Several turnover temperatures were found between 40 and 60 K.

The Sunpower cryocooler was tested for temperature, pressure, and humidity sensitivity. The base temperature had a sensitivity of 0.19 deg C/deg C of room temperature. No sensitivity to pressure or humidity was measured.

Future work will focus on demonstrating improved stability, integrating the Stirling cryocooler and sapphire resonator, designing and attaching vibration-reduction electronics, and installing a cryogenic Pound loop. The final goal is to demonstrate a short-term frequency stability of 1×10^{-14} with a low drift of $\sim 10^{-14}$ per day in a compact, low-cost system for long-term operation.

Acknowledgment

The authors thank William Diener for technical assistance in setting up stability measurements with an FSTL hydrogen maser and 10-K CSO.

References

[1] R. T. Wang, G. J. Dick, and R. L. Tjoelker, "Progress Report of A New Sapphire Oscillator," *Proceedings of the 2006 IEEE International Frequency Control Symposium*, Miami, Florida, pp. 691–694, 2006.

[2] G. J. Dick, R. T. Wang, R. L. Tjoelker, and R. Basu, "Design and Progress Report for Compact Cryocooled Sapphire Oscillator 'VCSO'," *Proceedings of the 2005 IEEE International Frequency Control Symposium*, Vancouver, Canada, pp. 363–367, 2005.

[3] G. J. Dick and R. T. Wang, "Stability and Phase Noise Tests of Two Cryo-Cooled Sapphire Oscillators," 13th EFTF and 1999 IEEE Frequency Control Symposium, Besancon, France, pp. 548–551, April 1999.

[4] R. T. Wang and G. J. Dick, "High Stability 40 Kelvin Cryo-Cooled Sapphire Oscillator," *Proceedings of the 2003 IEEE International Frequency Control Symposium*, Tampa, Florida, pp. 371–375, 2003.

[5] CryoTel cryocooler by Sunpower Inc.
`http://www.sunpower.com/lib/sitefiles/pdf/cryo_CT.pdf`

[6] R. Shelby and J. Fontanella, "The Low Temperature Electrical Properties of Some Anisotropic Crystals," *J. Phys. Chem. Solids*, vol. 41, pp. 69–74, 1980.

[7] R. Basu, G. J. Dick, and R. T. Wang, "Novel Design of an All-Cryogenic RF Pound Circuit," *Proceedings of the 2005 IEEE International Frequency Control Symposium*, Vancouver, British Columbia, Canada, pp. 562–568, 2005.

[8] G. J. Dick and R. T. Wang, "Stability and Phase Noise Tests of Two Cryo-Cooled Sapphire Oscillators," *IEEE Trans. UFFC*, vol. 47, no. 5, pp. 1098–1101, 2000.