CRYO-COOLED SAPPHIRE OSCILLATOR WITH ULTRA-HIGH STABILITY*

G. John Dick, Rabi T. Wang and Robert L. Tjoelker

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

Abstract

We present test results and design details for the first short-term frequency standard to achieve ultra-high stability without the use of liquid helium. With refrigeration provided by a commercial cryocooler, the Compensated Sapphire Oscillator (10K CSO) makes available the superior short-term stability and phase noise performance of cryogenic oscillators without periodic interruptions for cryogen replacement. Technical features of the 10K CSO include use of a 2-stage cryocooler with vibration isolation by helium gas at atmospheric pressure, and a new sapphire/ruby resonator design giving compensated operation at 8-10K with $Q = 1 - 2 \times 10^9$. Stability of the first unit shows an Allan Deviation of $\sigma_y \leq 2.5 \times 10^{-15}$ for measuring times of 200 seconds $\leq \tau \leq$ 600 seconds. We also present results showing the capability of the 10K CSO to eliminate local oscillator degradation for atomic frequency standards. Configured as L.O. for the LITS-7 trapped mercury ion frequency standard, the CSO/LITS combination demonstrated a limiting performance of $3.0 \times 10^{-14}/\tau^{1/2}$, the lowest value measured to date for a passive atomic frequency standard, and virtually identical to the value calculated from photon statistics.

1 Background

Cryogenic oscillators operating below about 10K offer the highest possible short term stability of any frequency sources[1, 2, 3]. However, their use has so far been restricted to research environments due to the limited operating periods associated with liquid-helium cooling.

We have developed a cryogenic sapphire oscillator for ultra-high short term stability and low phase noise in support of the Cassini Ka-band Radio Science experiment[1]. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} (1 second $\leq \tau \leq$ 100 seconds) and a phase noise of -73dBc/Hz @ 1Hz measured at 34 GHz. Installation of these oscillators in stations of NASA's Deep Space Network (DSN) is planned in the years '00 - '02.

Continuous long-term operation is crucial to the applicability of short-term frequency standards since they are typically are used to "clean up" the short-term variations of a longer term atomic standard, the combined output being then distributed to various users. Furthermore, the cryogenic oscillators can provide local oscillator (L.O.) performance as required by a new generation of passive atomic standards. These include the Cesium Fountain and Trapped Ion standards which are under development at many laboratories around the world, and whose potential is presently thwarted by the lack of available L.O. performance[4, 5, 6]. Continuous operation of the L.O. is crucial to the utility of these atomic standards.

Our development was enabled in part by a new generation of 2-stage Giffard–McMahon (GM) cryocoolers which allow operation at temperatures down to 4.2K[7]. Previously, such temperatures could only be achieved by the use of an additional Joule–Thompson expansion stage, with increased complication and cost, and with reduced reliability due to the likelihood of clogging the small expansion leak.

Any cryocooler generates vibrations which, if coupled to a high–Q electromagnetic resonator, would degrade its frequency stability. However, a technology has been developed that allows isolation of cryocooler vibrations from an experiment while providing adequate cooling. In the face of very stringent vibration requirements, the experimental Mössbauer community has successfully adopted a methodology that transfers heat to cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas[8].

*This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

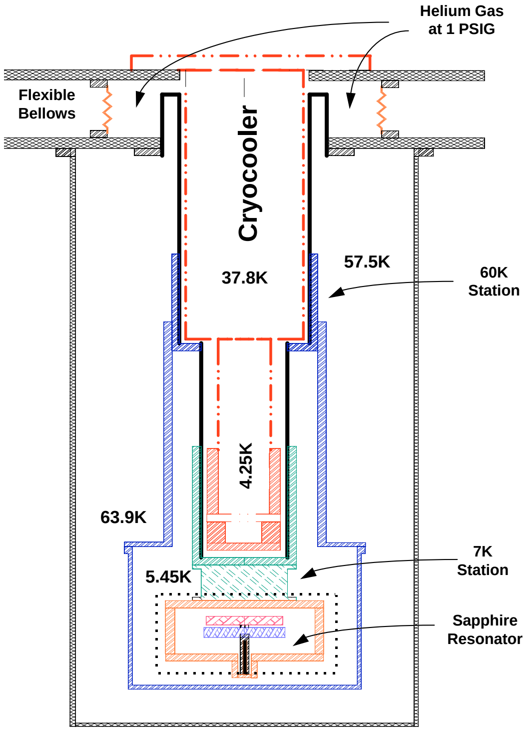

Figure 1: Cryogenic and vibration isolation systems showing measured temperatures. A small dewar fits closely around the cryocooler with the space between them filled with helium gas at atmospheric pressure.

Cryogenic standards have used both superconducting and sapphire resonators to achieve the $Q > 10^9$ required for 10^{-15} frequency stability. Superconducting resonator Q's degrade to unacceptable values above about 2K. However, Q's of a billion have been previously measured in whispering gallery sapphire resonators at temperatures up to 10K[9, 10]. If a sapphire resonator's turn-over temperature could be raised from the typical as-supplied values of 5K–6K to a reproducible 8K–10K, a practical cryo-cooled standard with 10^{-15} stability could be built.

The actual value of the turnover for any given resonator depends on the concentration of incidental (≈ 1 PPM) paramagnetic impurities as well as the properties of the electromagnetic mode that is being excited. If impurity levels could be accurately controlled it might be possible to construct resonators that would be compensated in the relatively narrow temperature band between that which can be achieved with available cryocooler cooling and the temperature at which the Q begins to degrade. However, a fairly large increase in impurity content is required because of a weak (fifth root) dependence of turn-over temperature on concentration. And, this must be accomplished without degrading the resonator Q.

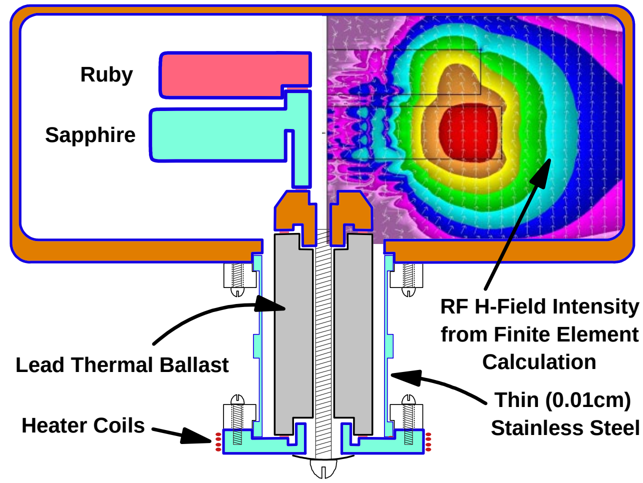

Figure 2: Compensated sapphire resonator showing details of electromagnetic and thermal design. The thin-walled stainless steel tube thermally isolates the resonator elements while providing good rf confinement. Electromagnetic field intensity varies approximately 1 order of magnitude per color band as calculated by the CYRES-2 finite–element computer program.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at cryogenic temperatures. A resonator with a mechanical compensation scheme demonstrated a stability of better than 1×10^{-13} at a temperature above 77K[11], and combined sapphire–rutile resonators have also been investigated[12]. However, the Q values of a million or so that are so far achievable with these schemes are far below those needed.

2 Design Aspects

Cryogenic aspects of design are shown in Fig. 1 and have been presented previously[1]. The cryocooler is mounted as rigidly as possible to the floor and the cryostat assembly is independently supported from the floor using conventional vibration isolation components.

Cryogenic systems providing vibration–isolation by means of helium gas conduction are available commercially based on small 7K 2-stage G-M cryocoolers. However the available performance for these units is limited to temperatures above 13K–15K, using a patented thermal design. Based on our calculations of thermal conduction by turbulent gas flow we conclude that a simple design with a gap of a few millimeters between concentric cylinders shows higher thermal conductivity

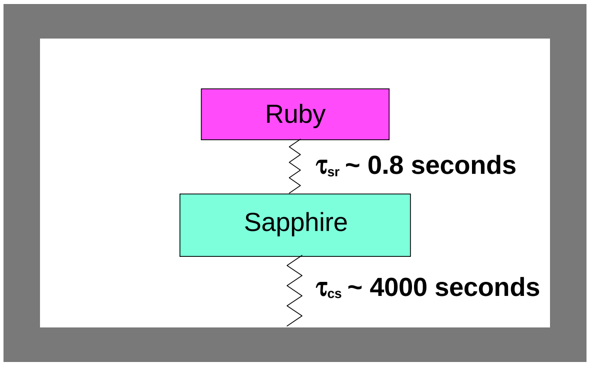

Figure 3: Block diagram of thermal design for the externally compensated resonator showing approximate time constants. Even if compensation is "perfect," variations in the external (shielding can) temperature give rise to a frequency variation due to temperature differences between ruby and sapphire elements. This effect is reduced to the extent that the can–sapphire time constant τ_{cs} is larger than the sapphire-ruby thermal time constant τ_{sr}.

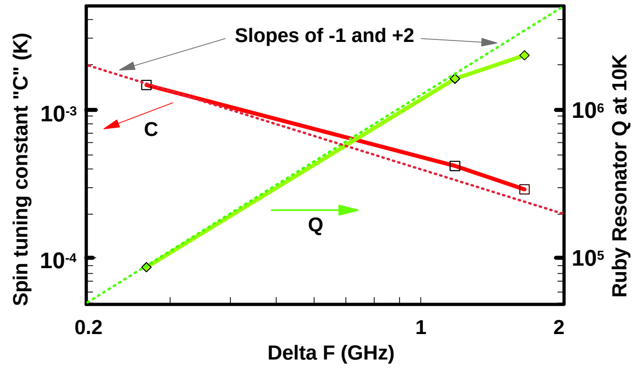

Figure 4: Measured reactive and resistive components for the permittivity of 0.03% ruby. *Delta F* is the frequency deviation from the 11.44 GHz zero field splitting for chromium impurities in ruby. Together, these two curves allow the spin-limited Q to be calculated for any ruby–sapphire compensated resonator.

for any given geometrical constraint than the patented designs[13].

Fast temperature variations at the $\approx$ 2.5 Hz cycle time are found to be reduced to about 2 mK, primarily by the large thermal mass of the helium gas at atmospheric pressure. Slow thermal variations are controlled by 3 stages of thermal regulation at the cryocooler head, the resonator can and the sapphire/ruby subassembly.

The resonator design shown in Fig. 2 compensates the frequency variation of a whispering–gallery sapphire resonator by means of a proximate and thermally attached ruby element. The high chromium concentration in the ruby gives a large compensation effect that can be reduced by adjusting its position. The ruby was constructed so as to allow assembly gaps of either 2mm or 4mm between ruby and sapphire elements.

A $WGE_{14,1,1}$ mode was chosen to minimize the size of the copper shielding container while still allowing a shield–limited Q of greater than 10^{10}. With significant axial H–fields, the WGE mode also facilitates coupling to the ruby element which is displaced axially from the sapphire. An operating frequency of 10.4GHz was chosen to give effective spin–tuning without excessive losses. Finite element calculations were used to calculate energy in the ruby element and its diameter was adjusted to give the desired $\approx$ 0.12% energy content[14].

Although a thin ruby element could still have provided the required compensation, gravitational sag would have resulted in excessive (10^{-7}/g) acceleration sensitivity. The thickness of the ruby was chosen so that its sag approximately matches that of the sapphire element. A good match should result in a low 10^{-9}/g sensitivity.

The thermal design of the resonator has been previously discussed[1] and is presented in Fig. 3.

Compensation design involves balancing the Debye expansion ($\propto T^4$) by a $1/T$ spin–dependent term. The sign of the spin term is appropriate for compensation for frequencies below the 11.44GHz zero-field splitting. Microwave coupling to the spins depends on the geometry of the resonator and the electromagnetic mode–the WGE mode excited in the sapphire does not couple to the spins. This gives us a relatively constant baseline resonator behavior (without turnover) as shown in Fig. 5, thus avoiding the variability of spin-tuning from sample to sample in even the best sapphire. A rotation of the magnetic field orientation from the vertical in the ruby is observable in Fig. 2 and provides effective coupling to the ruby spins.

Finally, ruby spin–tuning values are required to calculate the ruby electromagnetic energy requirement given above and the spin–loss values will place a limit on Q, and on the loss of Q with increasing turn–over temperature[15]. Our measurements of the characteristics of a 0.03% ruby sample are shown in Fig. 4 and have been confirmed with measurements of 5 more samples. For our operation 1GHz below the zero–field splitting we calculate a spin–loss limiting Q of about 3×10^9.

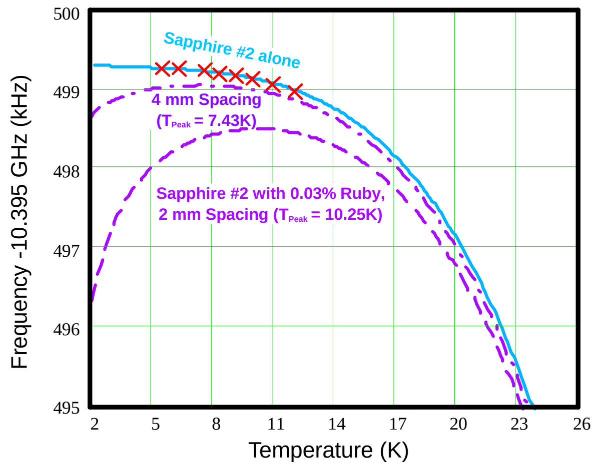

Figure 5: Predicted temperature dependence for the compensated resonator. A relief in the ruby element (see Fig. 2) allows assembly with either 2mm or 4mm spacing. Also shown is the measured (uncompensated) dependence of the sapphire element alone.

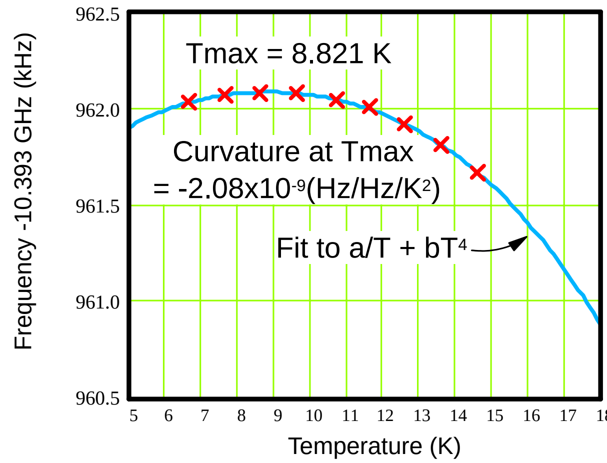

Figure 6: Measured temperature dependence of the compensated resonator with a 4mm spacing between sapphire and ruby elements. This resonator shows a turn–over temperature of 8.821K compared to the predicted value of 7.43K shown in Fig. 2.

In order to accurately calculate the electromagnetic coupling to the ruby, mode frequencies for the WGE mode in the sapphire element and for the lowest WGE and WGH modes of the ruby were first measured. These values were compared to finite element calculations for the isolated elements, and small adjustments ($\approx 0.1\%$) were made to the effective dielectric constants used in the calculation to bring the frequencies into agreement with measured values. This allowed an accurate calculation of mode characteristics, even though resonant coupling is significant.

Fig. 5 shows the calculated thermal characteristics of our first compensated resonator for "as cut" sapphire and ruby elements. We expected the ruby parts would need to be remachined in order to get the required coupling energy, but this was not required.

3 Experimental

Fig. 6 shows the first reported frequency turnover for a resonator with adjustable compensation and ultra-high Q. The turnover temperature at 8.821K for the first assembly is close to the calculated value of 7.25K. The Q of the first sapphire was about 300 million at 8K–10K with or without the ruby compensating element. The mode excited is $WGE_{14,1,1}$ at 10.395 GHz.

Frequency stability tests were performed with and without the ruby compensation element. Even without compensation, the thermal ballast removes short-term variations, showing a random–walk type stability of approximately $3 \times 10^{-15} \times \tau^{1/2}$, observed for measuring times above about 30 seconds. Based on our thermal analysis, we expect the short–term behavior to improve as $1/\tau$ for measuring times longer than 0.8 seconds, the ruby–sapphire thermal response time. This would give a stability of less than 1×10^{-15} for measuring times $\tau \geq 10$ seconds.

Compensated stability tests with the first resonator assembly showed a flicker floor of about 7×10^{-15}. We have not yet determined if the floor was due to the somewhat low resonator Q or to an observed frequency pulling with RF amplitude of more than 1×10^{-11}/dB.

Sapphire and ruby elements for a total of 6 resonators were purchased and the (unloaded) Q's for the remaining 5 sapphires were found to be significantly higher than that of the first one. These other elements all showed (inferred unloaded) Q's between 1 and 2 billion. The ruby elements were also all tested and mode frequencies, Q's and temperature turnovers (e.g. $\approx$ 32K for the $WGH_{12,1,1}$ mode at 10.26GHz) were verified.

Fig. 7 shows frequency stability measurements for the first resonator after it was sent back to the supplier for an "after–polish anneal" which had been skipped on the first two samples in order to meet our delivery schedule. The resonator as assembled the second time shows an unloaded Q of about 1×10^9 with almost exactly critical coupling. Additionally, probably due to the better coupling, the resonator showed a sharply reduced RF amplitude pulling of $\approx 10^{-12}$/dB. The turnover temperature increased slightly to 8.54K.

The short–term part of the stability shown in Fig. 7 is limited by maser performance with no additional fluctuations attributable to the CSO. The flicker floor is below 2.4×10^{-15}.

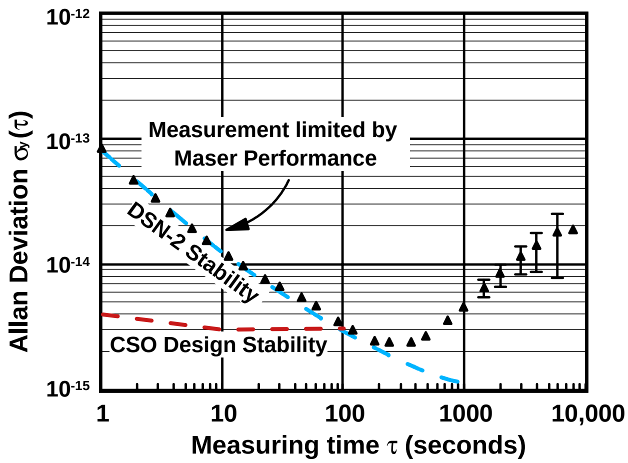

Figure 7: Measured frequency stability for the 10K CSO against a DSN-2 hydrogen maser tuned for best short-term stability. Even this "hot" H-maser reference dominates the observed short term variation. The long-term turn-up is due to the CSO and is likely caused by sensitivity of the rf electronics to room temperature variations.

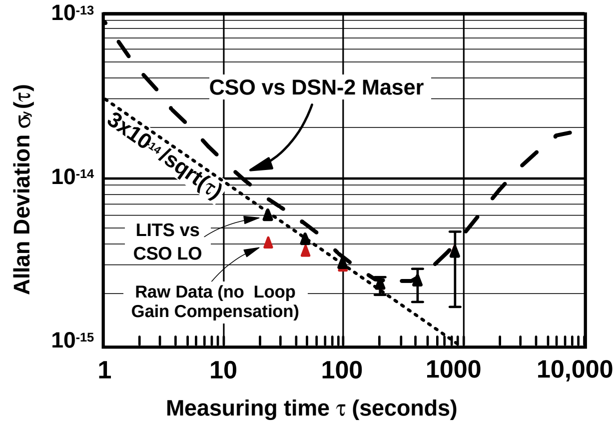

Figure 8: Comparison of the CSO to the LITS trapped–ion frequency standard tuned for high S/N. The short-term variation of $3 \times 10^{-14}/\tau^{1/2}$ is the same as that calculated from the LITS S/N and cycle time, and is the lowest value reported to date. There is no evidence of any degradation of LITS performance by the 10K CSO L.O.

Phase noise measurements against both DSN and SAO H-masers show maser noise in each case for frequencies below about 70Hz, where cryostat vibrations can be seen.

The low 10^{-13}/day drift of the CSO allowed easy application as an L.O. for the JPL Linear Ion Trap Standard (LITS)[4, 5]. Frequency pulling of $\delta\nu/\nu = 10^{-11}$ was possible by addition of an external DC voltage to the Pound frequency lock circuitry of the CSO. The LITS was tuned for high S/N and low $1/\tau^{1/2}$ fluctuations, yielding a calculated deviation for statistical (light count) variations of $3.0 \times 10^{-14}/\tau^{1/2}$.

Fig. 8 shows the Allan Deviation of the frequency corrections required by the CSO when configured as L.O. for the LITS. At short times the data can be seen to show almost exactly the $3.0\times10^{-14}/\tau^{1/2}$ predicted variation, and for longer times the higher stability of the LITS uncovers the long-term frequency wander of the CSO. For measuring times below 100 seconds the data have been compensated for reduced gain of the feedback loop. The uncompensated data is shown for reference. The required compensation was calculated by a computer simulation of the "1–2–1" feedback scheme which is typically used in pulse-mode passive atomic frequency standards.

The significance of this demonstration is two–fold. First, use of the CSO as L.O. allows us for the first time to see the LITS stability essentially undegraded by L.O. effects[16]. Secondly, the coefficient of the $1/\tau^{1/2}$ slope is the lowest measured to date for a passive microwave atomic frequency standard, demonstrating again that the LITS technology exceptional stability for measuring times of thousands of seconds to weeks and months.

Fig. 9 shows a comparison of the CSO–LITS standard with a SAO hydrogen maser. The measured stability is limited at all measuring times by hydrogen maser frequency fluctuations.

4 Conclusions

The 10K Compensated Sapphire Oscillator has been demonstrated as the first continuously operable frequency standard with ultra–high short term stability. Phase noise tests are being addressed with construction of a second unit which should be operational within a few months. Stability is clearly superior to the hydrogen maser at short measuring times, and we expect to meet the requirement of 3–4$\times10^{-15}$ stability for 1 second $\leq \tau \leq$ 100 seconds for the CASSINI Ka–band Experiment. Phase noise measurements are expected soon with the completion of a second unit.

Freed of the limitations of quartz or hydrogen maser L.O.'s the new generation of passive atomic standards such as the LITS and Cesium Fountain can now be operated continuously while realizing their inherent capabilities. A local oscillator with the capability of the 10K CSO can enable these standards to achieve stabilities of better than $1 \times 10^{-14}/\tau^{1/2}$.

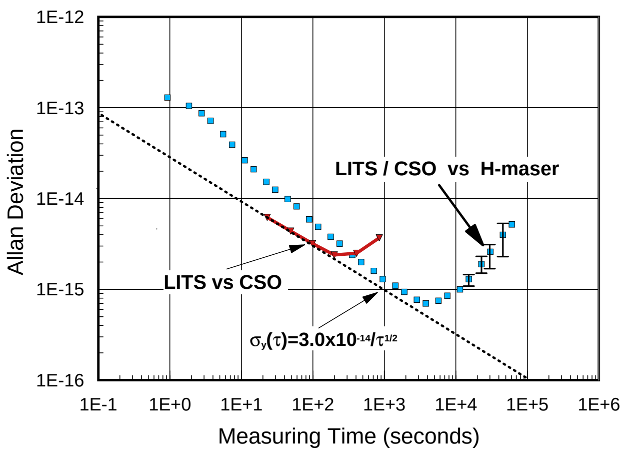

Figure 9: Comparison of the combined LITS / CSO to a SAO H-maser with excellent long-term stability. This represents the first demonstration of performance equal or better than a hydrogen maser for all measuring times.

References

[1] J. Dick and R. T. Wang, "Cryocooled sapphire oscillator for the CASSINI Ka-band Experiment", *Proc. 1997 International IEEE Frequency Control Symposium*, pp. 1009–1014, 1997.

[2] R. T. Wang and G. J. Dick, "Improved Performance of the Superconducting Cavity Maser At Short Measuring Times", *Proceedings of the 44th Annual Frequency Control Symposium*, pp. 89–93, 1990.

[3] A. N. Luiten, A. G. Mann, N. J. McDonald and D. G. Blair, "Latest Results of the U. W. A. Cryogenic Sapphire Oscillator," *Proc. 1995 International Frequency Control Symposium*, pp. 433–437, 1995.

[4] R. L. Tjoelker, C. Bricker, W. Diener, R. L. Hamell, A. Kirk, P. Kuhnle, L. Maleki, J. D. Prestage, D. Santiago, D. Seidel, D. A. Stowers, R. L. Sydnor, and T. Tucker, "A Mercury Ion Frequency Standard Engineering Prototype for the NASA Deep Space Network," *Proc. 1996 International Frequency Control Symposium*, pp. 1073–1081, 1996.

[5] R. L. Tjoelker, J. D. Prestage, L. Maleki, "Record Frequency Stability with Mercury in a Linear Ion Trap," *Proc. 5th Symp. on Freq. Standards and Metrology*, Woods Hole MA, Oct 15–19 1995.

[6] G. Santarelli, S. Ghezali, Ph. Laurent, S. N. Lea, M. Bahoura, K. Szymaniec, E. Simon and A. Clairon, "Recent Results of the LPTF Cesium Fountain Primary Frequency Standard," *Proc. 1995 IEEE International Frequency Control Symposium*, pp. 60–65, 1995.

[7] Balzers KelCool 4.2GM Cryocooler from Leybold Vacuum Inc., Cryogenics Div., 8 Sagamore Park Road, Hudson, NH 03051-4914.

[8] P. Boolchand, G.H. Lemon, W. J. Bresser, R. N. Enzweller and R. Harris, "A general purpose cold finger using a vibration-free mounted He closed-cycle cryostat", *Rev. Sci. Instrum.*, 66, No. 4, pp. 3015-3057, April 1995.

[9] A. G. Mann, A. N. Luiten, D. G. Blair, and M. J. Buckingham, "Ultra-stable Cryogenic Sapphire Dielectric Microwave Resonators", *Proceedings of the 46th Annual Frequency Control Symposium*, pp. 167-171, 1992.

[10] HEMEX sapphire from Crystal Systems, 27 Congress street, Salem, MA 01970 USA.

[11] D. G. Santiago, G. J. Dick and R. T. Wang, "Frequency Stability of 1×10^{-13} in a Compensated Sapphire Oscillator Operating Above 77K," *Proc. 1996 International IEEE Frequency Control Symposium*, pp. 772–775, 1996.

[12] M. E. Tobar, J. Krupka, J. G. Hartnett, E. N. Ivanov and R. A. Woode, "Sapphire–Rutile Frequency Temperature Compensated Whispering Gallery Microwave Resonators," *Proc. 1997 IEEE Intl. Frequency Control Symposium*, pp. 1000–1008, 1997.

[13] G. D. Raithby and K. G. T. Hollands, "Natural Convection", *chapter in Handbook of Heat Transfer Fundamentals*, second edition, W. M. Rohsenow, J. P. Hartnett and E. N. Ganic, editors, McGraw–Hill, 1985.

[14] R. A. Osegueda, J. H. Pierluissi, L. M. Gill, A. Revilla, G. J. Villalva, G. J. Dick, D.G. Santiago and R. T. Wang, "Two Dimensional Finite Element Determination of Modes and Frequencies for an Anisotropic Cylindrical Dielectric Resonator" *Proc. 10th Ann. Rev. of Progress in Appl. Computational Electromagnetics (ACES)* 1994.

[15] P. H. Ceperly and J. G. Castle, Jr., "UHF Losses in Sapphire and Ruby at Low Temperatures", *IEEE Trans. Nuclear Science*, NS-19, pp. 222-225, 1972.

[16] G. J. Dick, "Local Oscillator Induced Instabilities in Trapped Ion Frequency Standards", *Proc. 19th Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp. 133–147, Redondo Beach, CA, 1987.