Progress Report For A New Cryogenic Sapphire Oscillator

R. T. WANG, G. J. DICK, R.L. TJOELKER
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109-8099, U.S.A.
Rabi.T.Wang@JPL.NASA.GOV

Abstract — We present design progress and subsystem test results for a new short-term frequency standard, the Voltage Controlled Sapphire Oscillator (VCSO). Included are sapphire resonator and coupling design, cryocooler environmental sensitivity tests, Q measurement results, and turnover temperature results. A previous report presented history of the design related to resonator frequency and frequency compensation [1]. Performance goals are a frequency stability of 1×10^{-14} ($1 \text{ second} \le \tau \le 100 \text{ seconds}$) and two years or more continuous operation. Long-term operation and small size are facilitated by use of a small Stirling cryo-cooler (160W wall power) with an expected 5 year life.

I. INTRODUCTION

The VCSO is designed as a practical high performance replacement for ultra-stable quartz oscillators in local oscillator, cleanup, and flywheel applications in the frequency generation and distribution subsystems of NASA's Deep Space Network. Continued from the previously developed 40K CSO [2], it established the low-drift, and low g-sensitivity for a "self assembling" compensated silver/sapphire resonator design that demonstrated a quality factor of $Q = 1\cdot10^8$ at its temperature turnover of about 37 K. Also using a WGE(12,1,1) mode instead of the previous WGE(10,1,1) increases the diameter slightly, but this change makes possible re-use of the previous silver spacer design, and also moves the RF fields away from the central region. Previous resonator enclosure volume is reduced by 84% to about 10 cc..

II. DESIGN DETAILS

In the design of an ultra-high stability oscillator, the issues must be addressed in an inter-connected fashion. The key individual elements are: resonator Q, temperature, vibration, cryogen/cryocooler, frequency compensation, resonator g-sensitivity, resonator modes, resonator frequency, size/continuous operation period, electronics, and cost.

- **Operational Temperature** and **Q**: Sapphire Q is a function of temperature: $Q(77K) \sim 10^7$, $Q(4K) \sim 10^9$. It's possible to reach frequency stability in a few parts in 10^{-15} with the sacrifice of lower temperature operation. Compromise can be reached when a lower stability level and a higher operational temperature are needed.
- **Temperature** and **cryocooler**: Operational temperature dependents on the turnover temperature of the sapphire resonator, the base temperature of cryo-cooler, and its cooling power. Single stage Stirling coolers can reach a base temperature of 33 K [3]. The Sunpower cryocooler was chosen for reliability and lower cost.
- **Acceleration sensitivity** and **cryocooler**: Due to the existing 60 Hz vibrational level of this Stirling cooler, vibration effects can be minimized thru an active balancer and electronic cross over design. Detail results were previously reported [1]. A mechanical Finite-Element calculation program was used to design a configuration with 100x lower g-sensitivity with a geometry center support. (See Figure 1)
- **RF frequency** and **resonator mode**: Resonator frequency is calculated from sapphire size and mode configurations. (See Figure 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 sapphire inherent performance. Output frequency at 32 GHz will provide low signal phase noise to users without additional frequency multiplication. The higher operating frequency at 32GHz for WGE(12,1,1) results in a smaller resonator with a smaller copper can but it does increase the complexity of the silver spacer design. To obtain an efficient match from a

coaxial cable to the sapphire resonator, we use a Teflon-filled WR-19 coax/waveguide adapter together with an impedance-matched alumina-filled tapered waveguide adapter.

- **Frequency compensation** and **frequency drift**: Stable operation can only be achieved near a preferred "turnover temperature" at which frequency sensitivity to temperature fluctuation is zero. (See Figure 4) Without frequency compensation, the burden on the temperature control would increase by 1000x. Commercially available temperature controllers lower the overall cost of the system. With a silver spacer (see figure 1) a "preferred" temperature is selected. Frequency drift has historically been a substantial problem in thermo-mechanical CSO operation. To address this issue, an interference fit design and selection of a low creep material at low temperature 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.

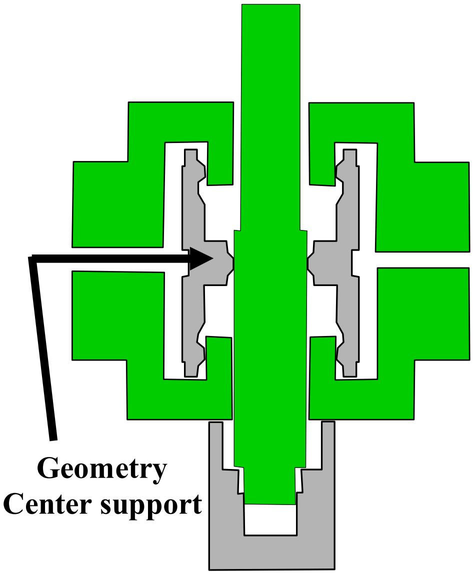

Figure 1. Cylindrical cross section of self-assembling resonator design. Sapphire is in green and silver parts in gray. Overall size is 1.7cm in diameter and 1.3 cm in height. The final assembled unit will be supported from geometry center providing better than 10^{-10} /g sensitivity.

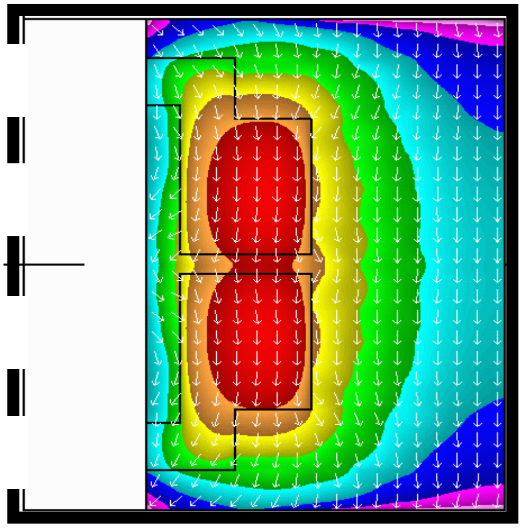

Figure 2. Finiet Element Calculation of electronmagnetic fields for the WGE(12,1,1) mode. Each color represents one order of magnetude. Copper can size and RF coupling port location are selected based on these calculation.

III. EXPERIMENTAL RESULTS

Results are presented in the following two sections: resonator verification and cryocooler environmental sensitivities.

(1) Resonator verification:

The first 32GHz resonator was assembled and tested for high Q modes and turnover temperature.

High Q modes: Scanning for modes was performed from 26.0 to 38.5 GHz. Example of high Q modes is shown in Figure 3. Q valves are higher than the designed 30 million And mode identification process is still in progress and these modes were tested during first cool down. Typical temperature coefficient shows about 10^{-7}/K with no turnover temperature. Finite element calculation shows an increase of 30% gap spacing will give rise to a 65MHz frequency increase. Therefore the indication of high mode frequency and no measurable turnover temperature between 34 and 50 K shows a larger than desired gap spacing. After adjustment of the sapphire gap spacing, turnover temperatures were found at second cool down.

Turnover temperature: At least 7 modes were found with turnover temperature. The mode frequency is rage from 26.8 to 37.7 GHz and the turnover temperature range is between 40.2K and 60 K. One example is shown in Figure 4. The preliminary verification of quadratic coefficient shows a value of $-1.9\times10^{-8}/K^2$, similar to the previous 40K CSO value of $-3.0\times10^{-8}/K^2$[2]. Detail results and analysis will be reported in the future.

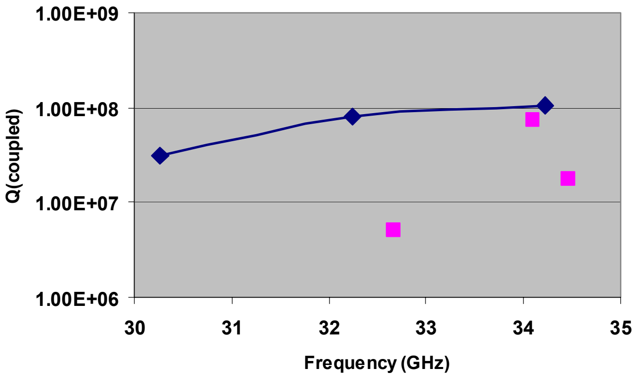

Figure 3. Examples of high Q modes found between 30 to 35 GHz. Blue data points are the possible mode sequence identified by FEM..

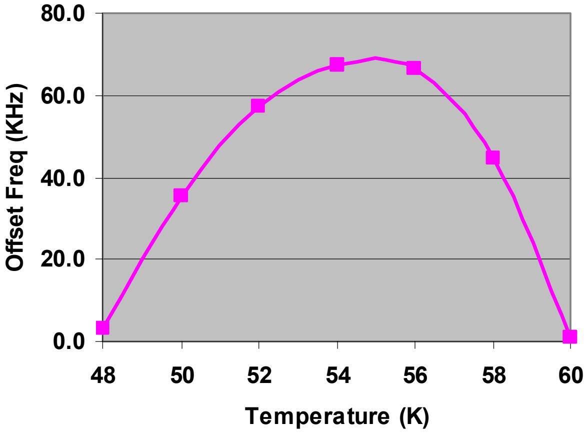

Figure 4. Example of measured turnover temperature at 54.468K. Mode frequency is 43.86 GHz with a quadratic coefficient of -3.02 x $10^{-8}/K^2$.

(2) Cryocooler Environmental Sensitivities:

The commercial cryocooler [3] was placed in an environmental chamber to test for sensitivity to temperature, pressure, and humidity. For temperature test, the parameters are from 15 to 35 Deg C with 10 Deg C step every 12 hours. Figure 4 shows the cryocooler base temperature vs. time. 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 test results show a sensitivity of 0.19 Deg C/Deg C. Therefore for every 5 Deg C change of room temperature there is one Deg C change in the base temperature. For best base temperature performance, the ambient air temperature should be regulated accordingly.

For pressure and humidity test, the parameters are +/- 12” of water for every four hours and 20% to 60% at 25 Deg C for every 12 hours steps respectively. There were no correlations to either parameter.

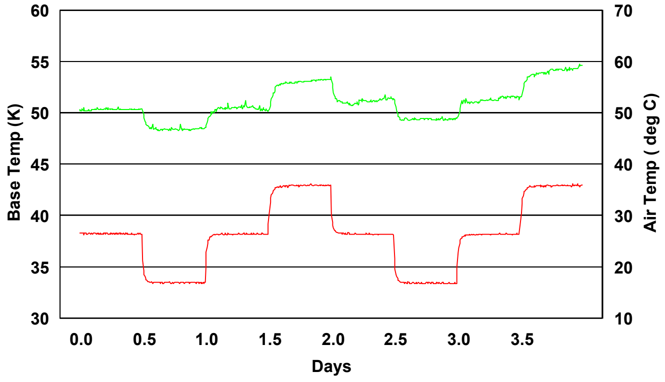

Figure 5. Cryocooler temperature sensitivity test: Base temperature is sensitive to external temperature change by a factor of 0.19. The lower curve shows air temperature vs. time. The step is 10 Deg C for every 12 hours. The upper curve shows base temperature record correlated to external temperature change. Due to outgassing in the Dewar, the base temperature has a drfit rate of 0.3 Deg C per day. A simple gettering system will remove this drfit.

IV. CONCLUSION

We report on progress on development of the VCSO. The first 32 GHz sapphire resonator was assembled and tested at cryogenic temperature. Some high Q modes were identified and compared to finite element calculations. Measured Q values were as high as 80 million. Several turnover temperatures were found between 40K and 60 K for various modes. Mode identification is still in progress.

The cryocooler was tested for temperature, pressure, and humidity sensitivity. The base temperature has 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 verifying turnover temperature at the desired mode and integrate cryocooler and sapphire resonator. The final goal is to demonstrate short term frequency stability of $1x10^{-14}$ with a low drift of 10^{-14} per day.

ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration and funded through the internal DSMS development, operation, and services office.

REFERENCES

[1] 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, pp. 363-367, 2005

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

[3] CryoTel cryocooler by Sunpower Inc. 182 Mill St. Athens, Ohio, 45701, USA.