PROGRESS ON 10 KELVIN CRYO-COOLED SAPPHIRE OSCILLATOR

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Abstract
We present recent progress on the 10 Kelvin Cryocooled Sapphire Oscillator (10K CSO). Included are incorporation of a new pulse tube cryocooler, cryocooler vibration comparisons between G-M and pulse-tube types, phase noise, and frequency stability tests. For the advantage of a single stage pulse tube cryocooler, we also present results for a 40K Compensated Sapphire Oscillator (40K CSO).

Introduction
Cryogenic sapphire oscillators have been pursued for many years with the goal of developing an ultra-stable frequency standard. A list of previous publications presented a number of compensated sapphire oscillators range from thermo-mechanical at 77 Kelvin to paramagnetic tuning at 1.6 Kelvin. [1-11]. Other oscillators with compensation by thermal expansion have so far showed a relatively low quality factor of $2 \times 10^6$, and large frequency drift of $\delta f/f = 10^{-9}$/day, precluding long-term frequency locking to an external source. A limitation of previous designs is the frequent refill of cryogens causing higher operational cost. With the 10K CSO and 40K CSO's, we are operating cryogenic oscillator without the use of cryogens. Recent advances in pulse-tube cryocoolers have the potential to substantially enhance long-term CSO operation. Compared to a few weeks of operation with liquid helium cooling, the cryocooler allows one to three years of uninterrupted operation. In addition to the JPL CSO's, other groups are also incorporating cryocoolers to extend cryogenic oscillator run time. [12-13]

10K CSO: The 10K CSO was built to support the Cassini Ka-band Radio Science experiment and is designed to operate continuously for periods of a year or more[2]. Currently three units are operational: one in NASA’s deep space network (DSN) and two at the JPL test laboratory. Short term stability has been routinely verified at $2 \times 10^{-15}$ at one second measuring time, and $2 \times 10^{-15}$ at 1000 seconds, with drift of approximately $1 \times 10^{-14}$ per day. The first generation of the 10K CSO incorporated a Gifford-McMahon type of cryocooler which has a life time of one year before maintenance. By replacing this with a pulse tube cooler, the anticipated minimal continuous operation period has been extended to three years.

The 10K CSO is based on an externally compensated resonator that uses paramagnetic chromium impurities in a thermally attached ruby element to provide a controllable compensation mechanism. This allows the operational temperature to be adjusted so as to lie in the relatively narrow temperature band between that which can be realistically achieved with available cryocooler cooling (7-8K) and the point at which the Q is degraded (10K). Sapphire resonators have been tested which show quality factors of $Q \approx 10^9$ at temperatures up to 10K. However, stable operation can only be achieved near a preferred “turnover temperature” which is typically too low (1.5K-6K) to reach with by cryocooler, and which varies from resonator to resonator depending on the concentration of incidental (~1 PPM) paramagnetic impurities. The range of measured turnover temperature is 7.2 to 8.8K compares well to a calculated value of 7.3K. The mode excited is WGE$_{14,1,1}$ at 10.395 GHz. Figure 1 shows the cross section of the cryostat including cold-head and sapphire resonator.

40K CSO: 40K CSO design goals are a frequency stability of $1 \times 10^{-14}$ or better (1 second $\leq \tau \leq 100$ seconds), a year or more continuous operation, and a compact rack-mount configuration. 40K CSO [1] development builds on JPL capabilities demonstrated in the successful development of the 10K CSO[2] and 77K CSO [3], short term frequency
standards which achieve stability in the $10^{-14}$s and $10^{-15}$s without the use of liquid helium. The 40K CSO is designed to provide most of the capability of the 10K CSO in a small, low power package. Mated with JPL’s LITS trapped ion standards [4], a 40K CSO would offer inexpensive long-term operation and replacement of hydrogen masers in NASA’s Deep Space Network (DSN). It also offers the L.O. performance required by the new generation of laser-cooled frequency standards. Potentially operable with a cryocooler drawing only 100-300 W, a 40K CSO can provide needed performance with much lower cost and power than were previously available for both ground and flight capabilities. This compares to 5kW required by the 10K CSO cryocooler.

Design Summary

10K CSO:

Design details for the 10K CSO were reported previously [2]. To briefly summarize, the following figures show the core ideas of 10K CSO design and its performance. Figure 2 shows the finite element calculation results of EM field distribution which allows us to use the whispering gallery modes with a copper wall configuration. Figure 3 shows stability tests of the 10K CSO vs Hydrogen-maser and vs a second 10K CSO. Frequency stability between two 10K CSO’s shows a $1\times10^{-14}$ at 1S and $2\times10^{-15}$ at 300-1000S. Although the 10K CSO shows $\times10$ better short-term stability than H-maser, high demand users at DSN require both the best stability of 10K CSO and the $1\times10^{-15}$ stability of H-Maser at 1000 S. Therefore a phase lock loop was built to lock the CSO long term frequency to H-Maser. In the following section, we will show the results of phase lock loop and the preliminary results of a new digital frequency lock loop.

40K CSO:

Acceleration sensitivity and cryocooler: Due to the low vibrational level of new pulse tube coldhead [14], the sapphire resonator can be mounted directly on the coldhead. This configuration simplifies the design compared to the 10K CSO and provides a longer operation period. A mechanical FEM program was used to design a configuration with 100x lower g-sensitivity with a center support geometry that gives better results than is achieved with end support.

Temperature and cryocooler: Operational temperature will depend on the turnover temperature of sapphire resonator, the base temperature of cryo-cooler, and its cooling power. Single stage pulse tube coolers can reach a base temperature of 33 K. A single stage coldhead was chosen for reliability and lower cost, compared to a two stage cooler, while the pulse-tube technology itself provides improved service periods and vibration levels.

RF frequency and resonator mode: Resonator frequency is calculated from sapphire size and mode configurations. FEM calculation can be used to determine these parameters, see figure 2. Sapphire whispering gallery modes provide higher Q, limited only by sapphire’s inherent performance. Output frequency at 16 GHz will provide low phase noise signal to users without additional frequency multiplier. Higher frequency operation with a WGE(10,1,1) operating mode results in a small resonator with a smaller copper can but it does increased the complexity of the silver spacer design. Stable operation can only be achieved near a preferred “turnover temperature” at which frequency sensitivity to temperature fluctuation is zero. Without frequency compensation, the burden on the temperature control increases by 1000x. Temperature controllers are
commercial equipment, which lowers the overall cost of the system. With a silver spacer, 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 together with 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. We have demonstrated the design success of the interference fit. The sapphire resonator shows a Q of $1.4 \times 10^9$ at 16 GHz with a turnover temperature of 36.6 K. A new pulse tube coldhead was incorporated in this test and it shows a low vibration level and a base temperature of 33K.

Selection of compensation material depends not only on the expansion coefficient but also on the creep rate. The creep rate can be directly related to frequency drift because spacer size changes directly the gap space between sapphire parts. Silver was selected for its low creep rate at cryogenic temperature which is nearly two orders of magnitude lower than copper at 40 K.[15,16]

Allan Deviation of 40K CSO verses 10K CSO shows a good short term stability of $3 \times 10^{-14}$ at 1 S. After 3 weeks of operation the drift rate is $2.2 \times 10^{-11}$ per day, reduced from its initial value by almost 10x. The present value is 100x lower than was shown by the 77K CSO.

**Test Results**

We are reporting progress on the measured vibration level of two stage pulse tube cryocooler, history of turnover temperature and resonator frequency, phase noise measurements, cryocooler experience, results of phase lock loop, and preliminary results of a digital frequency lock loop. Results of measured sapphire Q, cryocooler vibration data, and interference fits design were presented in a previous publication [1].

- **Vibration level:**
  
  Vibration sensitivity for 10K CSO is $< 1 \times 10^{-9}/g$ and for 40K CSO is $1 \times 10^{-10}/g$. Figure 4 shows the measured vibration level of a two stage G-M coldhead and Figure 5 shows the pulse tube coldhead. The G-M coldhead has a vibration level of 337 micro-g at 2.4 Hz. Pulse tube coldhead has 337 micro-g at 1.4 Hz. Within 20 Hz, G-M peak at 1.2 m-g at 12Hz and pulse tube peaks at 573 micro-g at 2.8 Hz. Pulse tube coldhead ease the overall vibration isolation requirement yet it’s still not quiet enough for direct mounting of resonator.

- **Turnover temperature and Resonator Frequency repeatability:**

  The turnover temperature was recorded from Jan. 2001 to June 2004 for 10K CSO with an average of 7.180 Kelvin and a standard deviation of 0.044 Kelvin. This variation comes from relaxation of lead post, and the indium spacer between sapphire and ruby. Observation shows variation at least $\geq$2 smaller after three cycling to room temperature. In the same period, the resonator frequency (~10.4GHz) shows a standard deviation of 631 Hz.

![Figure 4: Vibration measurement of a two stage G-M coldhead in the vertical direction. Coldhead cycling frequency is 2.4 Hz.](image)

![Figure 5: Vibration measurement of a two stage pulse tube coldhead in the vertical direction.](image)

- **Phase noise:**

  Phase noise of 10K CSO was measured against a low noise quartz clean up loop. Data were taken at 100 MHz: -106 dBc@1Hz, -123 dBc @10Hz, -129 dBc @100Hz, -131 dBc@1000Hz, and -131 dBc @10KHz. We believe these are the phase noise of quartz oscillator and the true phase noise of 10K pulse tube CSO can only be verified with two pulse tube CSO.

- **Cryocooler experience:**
The use of cryocooler extended the cryogenic oscillator run time from a helium fill system of 2-3 weeks to one to two years. Two types of cryocooler tested in the last six years. For comparison of two stage cooler, G-M and pulse tube were 5 KW system and both are water cooled. G-M coldhead require services every 12-16 months. Although good for laboratory use, it’s still not cost effective enough for overseas installation and operation. The pulse tube cooler was tested for 6460 hours with no sign of temperature degradation. A new 10K CSO with pulse tube coldhead will be installed in a Goldstone DSN station for long term observation and to support the Cassini Radio science experiment from 2004 to 2008.

A single stage pulse tube cooler was custom made for 40K CSO by Cryomech. Base temperature increased by 4 Kelvin after 16 months operation. Cycling to room temperature did not resolve this problem. Due to its custom made status, the factory agrees to investigate the possible cause.

♦ Phase Lock Loop and Frequency Lock Loop:

In DSN operation, the Hydrogen maser is the primary frequency standard for its stability of 1x10^{-15} at 1000s. To get the best stability of the combined 10K CSO and Hydrogen Maser, a locking loop is desired; either phase lock or frequency lock. Figure 6 shows the test of 10K CSO lock to a Hydrogen Maser and compare to the same Maser using a phase lock loop and figure 7 is using a digital frequency lock loop (DFLL). Frequency lock loop is yet to be optimized. FLL is also been experimented by Saalaoui [17] to lock Cesium clock to Hydrogen Maser. The advantages of our DFLL are; (a) no loss of signal when Maser signal is disrupted, (b) easy porting to another long term frequency standard like Mercury Ion Clock or Cesium fountain, (c) use of off-the-shelf components, no custom made requirements. Detail design will be published elsewhere.

Conclusions/Acknowledgment

We have presented the progress on the 10K and 40K CSO’s. Two of the 10K units have G-M coldhead with an average run time of 16 months. The third 10K CSO with a pulse tube coldhead shows no degradation of base temperature after 6460 hours of operation. The two-stage pulse tube coldhead is expected to last two to four years before service while compressor service is needed after 20,000 hours. The 40K CSO shows an increase of base temperature of 4K after 2 years of continuous operation. Demonstrated stability measured between the 40K CSO and the 10K CSO is 3x10^{-14} at 1s with a floor of 2.6x10^{-14}. A new frequency lock loop is under development to allow locking of 10K CSO and Hydrogen maser. The desired final output frequency stability will be 1x10^{-14} at 1s and 1x10^{-15} at 1000s. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

References


14. PT60 Pulse Tube Cryocooler, from Cryomech Inc. 113 Falso Drive, Syracuse, new York 13211.

