A High Performance Frequency Standard and Distribution System for Cassini Ka-Band Experiment

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Abstract —**This paper provides an overview and update of a specialized frequency reference system for the NASA Deep Space Network (DSN) to support Ka-band radio science experiments with the Cassini spacecraft, currently orbiting Saturn. Three major components, a Hydrogen Maser, Stabilized Fiber-Optic Distribution Assembly (SFODA), and 10 Kelvin Cryocooled Sapphire Oscillator (10K CSO) and frequency-lock-loop, are integrated to achieve the very high performance, ground based frequency reference at a remote antenna site located 16 km from the hydrogen maser. Typical measured Allan Deviation is 1.6x10^{-14} at 1 second and 1.7x10^{-15} at 1000 seconds averaging intervals.**

Recently two 10K CSOs have been compared in situ while operating at the remote DSN site DSS-25. The CSO references were used operationally to downconvert the Ka band downlink received from the Cassini spacecraft in a series of occultation measurements performed over a 78 day period from March to June 2005.

I. INTRODUCTION

The Cassini-Huygens project is a joint NASA/ESA mission to Saturn, launched in 1997, and placed into orbit around Saturn in July 2004. Since orbit insertion and the successful Huygens landing on the moon Titan, the Cassini Spacecraft has begun a 3 year mission of continued moon flybys and observations. During this time many Radio Science gravity and occultation experiments are planned by observing perturbations of the Spacecraft downlink as measured at the DSN tracking sites. To maximize science return requires that the ground based DSN frequency references have very low phase noise and be very stable during the observation intervals.

The integration and test data of the hydrogen maser and the SFODA [1] and initial data obtained by the CSO has been previously published [2]. This frequency distribution SFODA system was developed to enable sensitive two way Doppler gravity wave searches during the spacecraft cruise phase and the CSO plays a more central role in the current occultation experiments. These Radio Science experiments, conducted at S, X, and Ka band, require the highest possible frequency reference stability over observation times ranging from 0.01 seconds to 1.5 days. The DSN frequency and timing subsystem (FTS) generates and distributes coherent signals to multiple antennas up to 30 km away. The SFODA, currently implemented on a 16 km link between the Goldstone Signal Processing Center and the antenna DSS-25 measures and compensates for distribution related phase perturbations. The 10K CSO provides short term stability cleanup and low phase noise at the antenna.

II. BACKGROUND

The DSN has motivated fiber optic distribution developments at JPL since the 1980s. With the recent trend towards antenna array architecture development and the availability of new atomic and cryogenic sapphire frequency standards [3-5], new requirements continue to push the need for improved distribution capability.

Challenges to build a high performance frequency standard and distribution system are in three major areas: high performance frequency standards, long distance distribution without degradation, and performance verification. Here we discuss the three integrated subsystems: thee Hydrogen Maser, SFODA, and 10K CSO and a frequency lock loop [2].

A. Frequency Standards: Hydrogen-Maser and 10K CSO

The Hydrogen Masers operating in the DSN were built by the Smithsonian Astrophysical Observatory between 1975 and 1990. They have been modified by JPL to improve receiver performance and to provide standard DSN interfaces. An example of measured pair stability performance is shown in Fig. 1. Typical performance is 1×10^{-13} at 1S and 1×10^{-15} at 1000S with drift rate at ~ 2×10^{-15} per day. Recently, for the Cassini Radio Science mission the online maser receiver at each of the three DSN sites has been further upgraded to use the best available Oscilloquartz VCXO's. (Typical stability 8x 10^{-14} at 1 second, and phase noise of -130 dBc @ 1 Hz from the carrier at 5 MHz.)

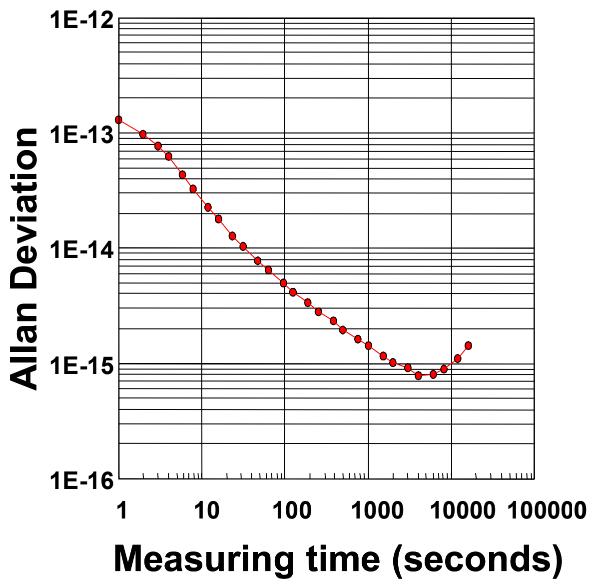

Figure 1. Measured Hydrogen Maser frequency stability shows 1E-13 at 1S and 1E-15 at 1000S.

The 10K CSO is used as a clean up oscillator for the distribution of the maser signal at DSS-25. It is based on an externally compensated resonator that uses paramagnetic chromium impurities in a thermally attached ruby element to provide a controllable compensation mechanism [2-4]. Besides JPL, other cryogenic sapphire oscillator also being pursued with different compensation methods [6-8]. 10K CSO design allows the operational temperature to be adjusted so as to lie in the relatively narrow temperature band between what can be realistically achieved with available cryocoolers (~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, the most stable operation can only be achieved near a "turnover temperature" typically too low (1.5K-6K) to reach with a cryocooler. This turnover point also varies from resonator to resonator depending on the concentration of incidental (~1 PPM) paramagnetic impurities. The measured range of turnover temperatures (7.2 to 8.8K) to date compares well to a calculated value of 7.3K. The excited $WGE_{14,1,1}$ mode is at 10.395 GHz. The design goal was that the 10K CSO did not require liquid helium and could operate continuously for more than a year.

Design details for the 10K CSO have been previously reported [2-3]. To briefly summarize, the following figures show the core elements of the resonator and mounting scheme design and performance. Figure 2 shows the cross section of the cryostat including cold-head and sapphire resonator. Figure 3 shows the finite element calculation results of EM field distribution which allows use of whispering gallery modes and a copper wall configuration. For short averaging intervals the 10K CSO provides a 10-fold improvement over the H-maser. To preserve the maser stability for averaging times long than a few hundred seconds a phase lock loop was developed to lock the CSO in the long term to the H-Maser [2]. The 10K CSO presently operates with either a Gifford-Mcmahon or Pulse tube Cryocooler. While much longer operating intervals are possible than with systems that rely on liquid helium, sustaining costs of the 10K system are still high and only cost effective in very unique and specialized applications.

At JPL we are pursuing an even more pragmatic cryogenic sapphire oscillator project development known as the Voltage Controlled Sapphire Oscillator (VCSO) [9]. The short term stability goal is 1×10^{-14} at 1S measuring time but with a much smaller and simpler cryocooler than in the 10K CSO. The VCSO is expected to have numerous applications in high performance frequency and timing systems and can serve as a portable standard to verify 10K CSO performance in the field. In addition a cryo-Pound design [10] shows promise for improved long term stability.

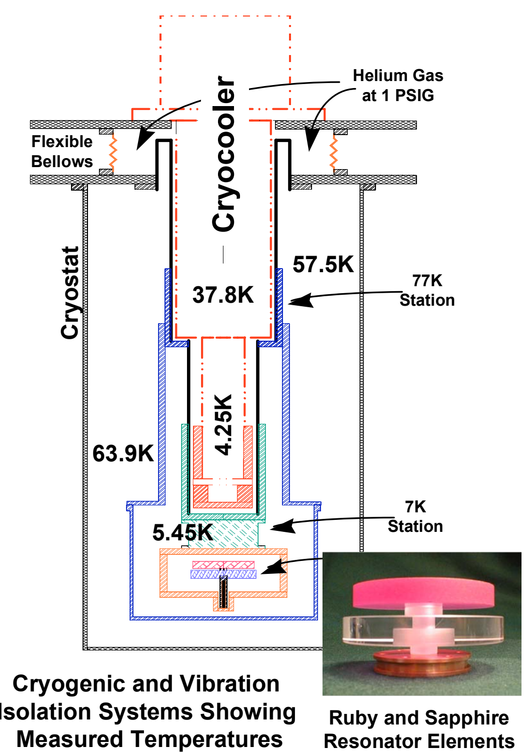

Figure 2. Cross section of 10 K CSO showing cryo-cooler integration with ruby/sapphire combination.

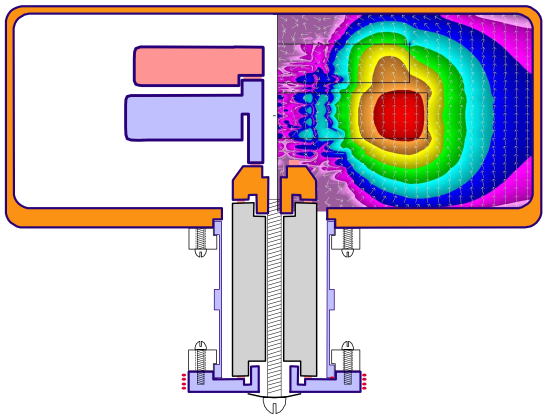

Figure 3. 10K Cross section of 10 K CSO showing sapphire/ruby combination. A Finite Element Method was used to calculate RF field distribution of the whispering gallery mode [3].

B. Distrubution System: SFODA

The DSN 34 meter antenna (DSS-25), selected to support the Cassini radio science mission, is 16 km from the central frequency standards in the signal processing center (SPC). The existing fiber optic cable from the SPC to DSS-25 is buried at a depth of approximately 1.5 meters. As seen in Figure 6, at this depth the fiber is sufficiently insulated from short term and daily thermal perturbations. Unfortunately, small regions of the fiber are exposed along the 16 km path and the thermal coefficient of the distribution optical fiber is approximately 7 ppm/°C.

The SFODA design to actively stabilize the reference frequency distribution system is based on optical closed loop feedback [11]. A reference frequency signal at 1 GHz is transmitted over the fiber link and active feedback is accomplished with a 4 km long temperature compensating fiber optic reel (Figure 4) to compensate for thermally induced phase variations over the 16 km fiber cable link. A block diagram of the SFODA is shown in Fig. 5. The optical transmitter is a commercial, single-mode distributed feedback laser diode with an integral optical isolator. The companion optical receiver with a phase lock loop and distribution amplifiers are located at the remote antenna. The distribution can deliver 100 MHz or 1 GHz. When additional cleanup is needed the 10K CSO can be inserted to supply critical users.

The major components at the SPC are the power supply, master controller, a bipolar power supply to both heat and cool the compensating reel, and the compensating reel. The electronics package in the master controller is mounted on a thermally controlled plate. The signal input to the master controller is 100 MHz from the on-line frequency standard. This signal is split and multiplied to 1 GHz for transmission over the fiber link. The X10 multiplier is a phase-locked cavity oscillator with low phase noise. The second output of the splitter is used as a reference to a phase detector which produces the phase error signal. The reference signal modulates the 1310 nm laser diode with the 1 GHz carrier. The optical output utilizes an optical isolator and an optical circulator, allowing two way transmission on a single channel fiber. The single mode channel fiber is standard SMF 28.

The 10K CSO and SFODA receiver are both located in a special environmentally controlled facility near the base of the antenna DSS-25. The facility temperature is controlled to ±50 millidegrees C. The SFODA short term stability is approximately 1.5 x 10^{-14} at one second. This was more than sufficient for the gravity wave experiment (GWE) performed when the Cassini spacecraft was in transit to Saturn. Now that Cassini is in orbit the 10K CSO is used as a clean up oscillator to provide the very low noise reference for the Ka band down-conversion of the signal received from the spacecraft.

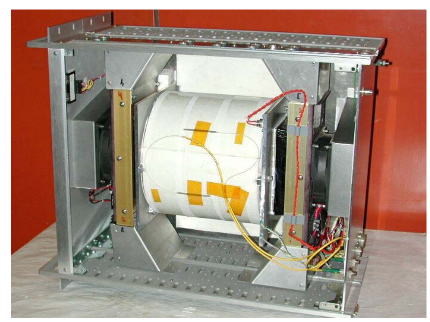

Figure 4. SFODA detail subsystem: 4km compensation reel and Masetr controller

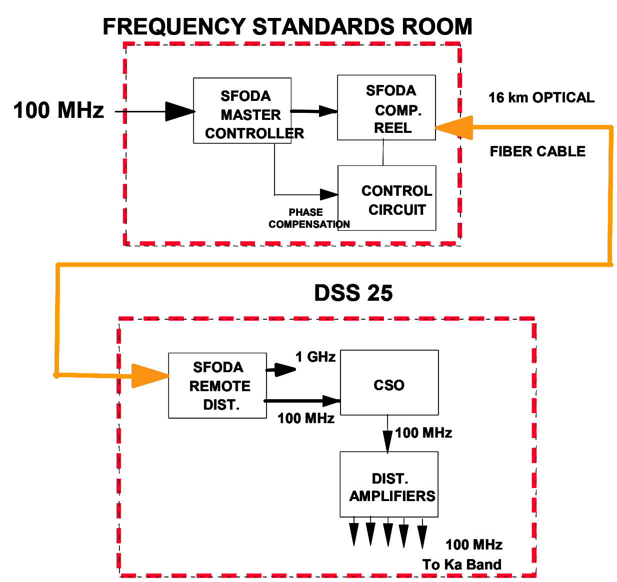

Figure 5. SFODA block diagram showing a 100MHz input, a 16km optical fiber, and clean up with the 10K CSO.

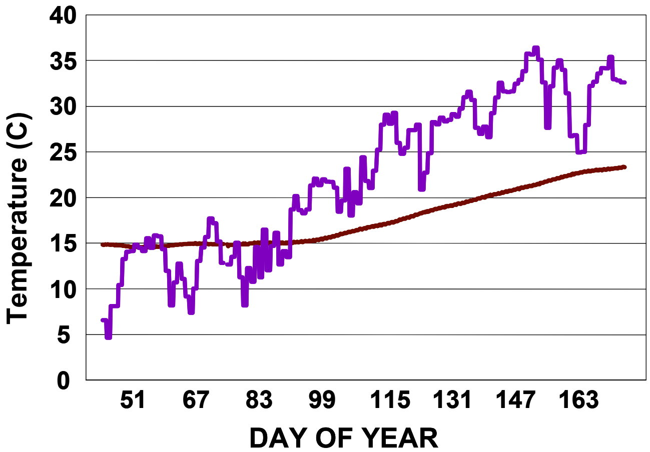

Figure 6. Purple line shows the measured surface temperature at Goldstone, California for a six month period Total temperature veriation of the fiber is about 9 deg C (brown line) comparing to a a 23 deg C of surface temperature change..

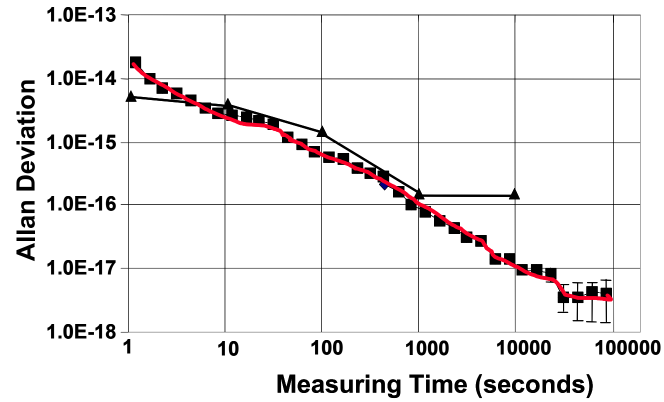

Figure 7. Noise floor of the SFODA system. Maser signal was transmitted round-trip for a total 32km in order to perform stability measurement. A noise floor of 1×10^{-14} at 1S is demonstrated in the field.

C. In-Situ Performance Verification:

Frequency stability and phase noise performance verification typically requires two sources of comparable performance. Ideally daily performance verification can be routinely performed and the measurement system is at least a factor of 10 better than the instrument being tested. A new Frequency Standard Stability Analyzer (FSSA) has been developed at JPL to fulfill this demand. FSSA consists of a PC, event timer card, and zero-crossers. Measurements can be performed simultaneously in 8 channels. The noise floor of this system is better than 8×10^{-15} at 1S for a 100MHz reference signal [12]. This capability will be available in the DSN starting in September 2005.

The following measurements of system performance in terms of frequency stability at the output of each junction were performed using older, single channel measurement capabilities. The measurement noise floor for these older systems is ~ 1×10^{-14} at 1 second averaging interval.

The stability performance of a typical Hydrogen Maser has already been shown in Fig. 1. Verification of stability of 1×10^{-13} at 1S and 1×10^{-15} at 1000S is routinely performed. The performance at the SFODA output 16 km from the maser has been verified by using a second SFODA system to send the signal back to central location. Fig. 7 shows the round trip of 32km test with a noise floor for both systems in series of 1.4×10^{-14} at 1S.

Introducing remote 10K CSO clean up

Two 10K CSO were installed at Goldstone DSN station, first in April 2001 and second in September 2004. 10K CSO performance between two CSOs located at DSS-25 is shown in Fig. 8. Short term stability has been routinely verified at 2×10^{-14} at one second measuring time, and ~2×10^{-15} at 1000 seconds, with drift of approximately 1×10^{-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 of the cold head has been extended to three years.

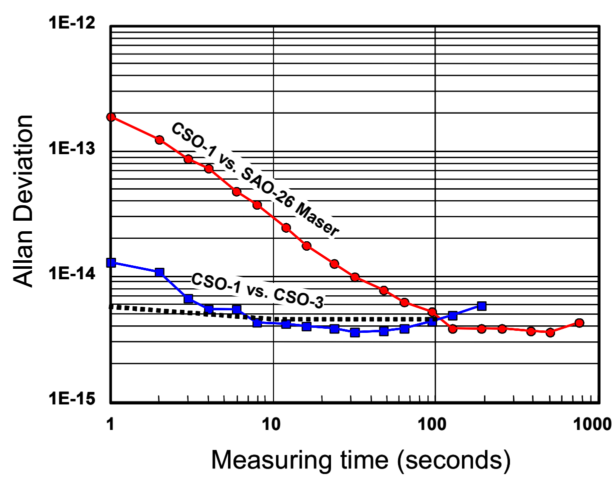

Figure 8. Blue curve shows frequency stability of two 10K CSO measured in-situ. Measured frequency stability shows 2×10^{-14} at 1S and ~2×10^{-15} at 1000S for two free running CSO. In comprison, red cuve shows 10K CSO vs. H-Maser with 10K CSO free running.

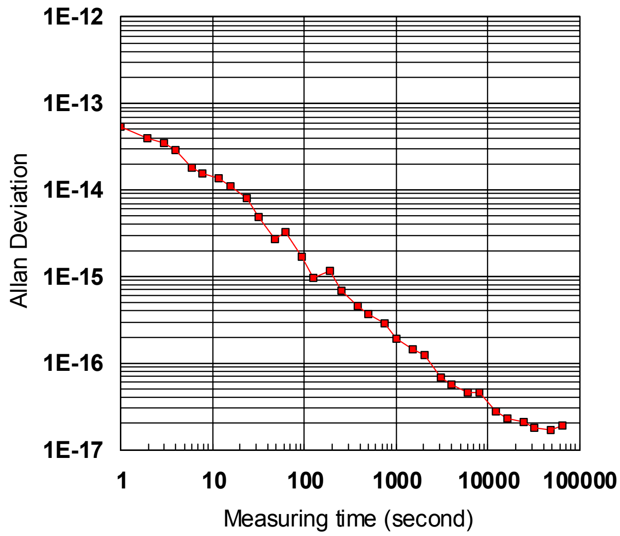

Figure 9. Demonstrated performance showing 10K CSO frequency locked to a H-Maser and compare to the same Maser. The 4×10^{-14} at 1S stability is the noise floor of the current measurement system. Therefore the FSSA will help to remove any ambiguity.

Fig. 9 shows the noise floor measurement of the frequency lock loop when 10K CSO is locked to Maser signal. This frequency lock loop allows the 10K CSO frequency output to stayed locked to the Maser within one micro-Hz at 100 MHz at 100S gate time.

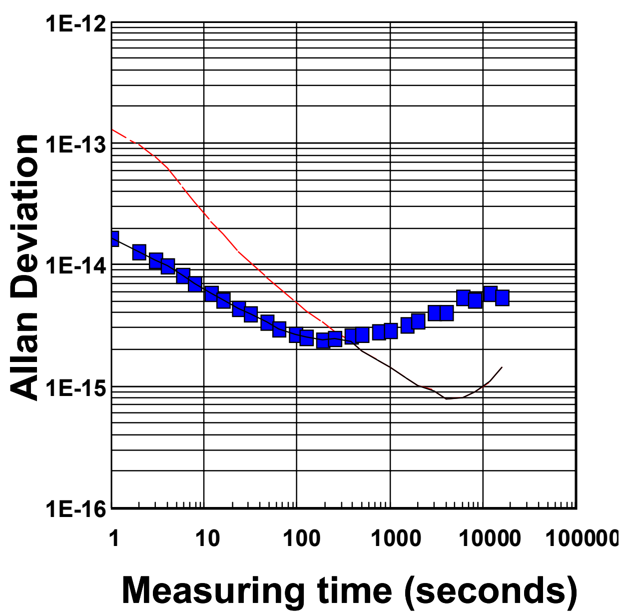

Figure 10. Two possible output configuration: One with H-Maser and SFODA showing H-Maser stability (red line) or H-Maser/SFODA/10K CSO combination demonstrated performance of 10K CSO short term stability and H-maser long term stability (blue data and black line).

Fig. 10 shows the two possible output configurations: direct Maser signal or 10K CSO clean-up. With 10K CSO as a clean-up element, the short term stability is demonstrated at 1×10^{-14} at 1S and Maser stability can be preserved in the long term.

CONCLUSION

We have demonstrated an integrated Hydrogen-Maser, SFODA, and 10K CSO system in the NASA DSN to provide a ultra-high stability reference for Cassini Ka-band experiments. Measured stability at the remote DSN site (DSS-25) is 1x 10^{-14} at 1S and 2x 10^{-15} at 1000S. This is the best in-situ stability ever demonstrated at a DSN station and provides a state of the art operational reference for down-conversion of the Ka band signal received from the Cassini Spacecraft. Radio science gravity and occultation experiments are planned to be ongoing through 2008.

ACKNOWLEDGMENT

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REFERENCES

[1] M. D. Calhoun, G. J. Dick, R. T. Wang, " A Frequency Transfer and Cleanup System for Ultra-High Stability at Both Long and Short Times for the Cassini Ka-Band Experiement", ", Proceedings 30nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, Reston, VA 1-3, Dec. 1998, pp. 405-412, 1998.

[2] R. T. Wang , G. Dick, and William A. Diener, " Progress on 10 KelvinN Cyro-Cooled Sapphire Oscillator", Proceedings of the 2004 IEEE International Frequency Control Symposium, pp. 752-756, 2004.

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

[4] R. T. Wang and G. J. Dick, "High Stability 40 Kelvin Cryocooled sapphire oscillator," Proc. 2003 International IEEE Frequency Control Symposium, 371-375, 2003.

[5] J. D. Prestage, R. L. Tjoelker, and L. Maleki "Higher Pole Linear Traps For Atomic Clock Applications", Proceedings, 13th EFTF and 1999 IEEE Frequency Control Symposium, Besancon, France, April 1999, pp. 121-124, 1999.

[6] Y. Kersale, V. Giordano, F. Lardet Vieudrin, I Lajoie, M. Chaubet, "Thermal Stabilization of Microwave Sapphire Resonator References", Proceedings, 13th EFTF and 1999 IEEE Frequency Control Symposium, Besancon, France, April 1999, pp. 585-588, 1999.

[7] M. E. Tobar, J. Krupka, J. G. Hartnett, R. G. Geyer, and E. N. Ivanov, "Measurement of Low-Loss Crystalline Materials for High–Q Temperature Stable Resonator Application", Proceedings, 13th EFTF and 1999 IEEE Frequency Control Symposium, Besancon, France, April 1999, pp. 573-580, 1999.

[8] M. E. Tobar , E. N. Ivanov, C. R. Locke, and J. G. Harnett, “Temperature Compensation of the Difference Frequency Between Modes of Orthogonal Polarization In Anisotropic Dielectric Resonators”, Proceedings of the 2002 IEEE International Frequency Control Symposium , pp. 553-558, 2002.

[9] G. J. Dick, Rabi T. Wang, Robert Tjoelker, “Design and Progress Report for Compact Cryocooled Sapphire Oscillator "VCSO"”, Proc. 2005 Joint IEEE FCS/ PTTI.

[10] R. Basu, G. J. Dick, Rabi T. Wang,” Novel Design of an All-Cryogenic RF Pound Circuit “,Proc. 2005 Joint IEEE FCS/ PTTI.

[11] M. Calhoun, J.C. Law and P.F. Kuhnle, “ Environmental Effects on Optical Fibers Used for Reference Frequency Distribution”, Proceedings of the Institute of Environmental Sciences Applications Meeting, Las Vegas, NV, May 1993.

[12] C. A. Greenhall, A. Kirk, and G. L. Stevens, “A multichannel dual-mixer stability analyzer: progress report”, 33rd PTTI Systems and Applications Meeting, pp. 377–383, Nov. 2001