THE SUPERCONDUCTING CAVITY MASER OSCILLATOR - TOWARD HIGHER STABILITY

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ABSTRACT

The all-cryogenic three-cavity superconducting maser oscillator described at PTTI 17 has undergone further testing and reconfiguration in our laboratory. These investigations have demonstrated the potentially achievable stability of this system. We shall present new test results and discuss the techniques that will be employed to reach improved stabilities in future versions of this oscillator system.

Frequency stability tests have been performed on our oscillator, comparing it to a different superconducting cavity stabilized oscillator. These new test results will be discussed. An analysis of the dominant perturbing effects will be presented insofar as they have been resolved.

New insight into the operation of the ruby maser in this prototype oscillator has led to the design of novel stabilization procedures that will allow future versions of this system to attain substantially better frequency stability. These techniques will be described and their significance for the oscillator's performance will be set forth.

INTRODUCTION

At PTTI 17 we described the prototype cryogenic oscillator system that we are using to prove the concepts under development. In this paper we shall present the results of tests conducted on this oscillator and shall discuss the implications for the design and the stability limits of future versions of cryogenic maser oscillators. A review of the oscillator system will include a description of the components, the three-cavity system and the cryogenics. The emphasis in this paper will be on the results of stability measurements, so we shall set forth the measurement system and present the results obtained to date. These results include measurements of frequency pulling effects which will be analyzed with regard to their implications for oscillator stability. Finally, techniques to limit the frequency disturbances caused by these pulling effects will be described.

REVIEW

Since the three-cavity oscillator system was described in some detail at PTTI 17, we shall recount that description only briefly here. The two major elements of the oscillator are the superconducting cavity and the ruby maser. Our cavity is formed by depositing a lead (Pb) film onto a shaped sapphire substrate. Figure 1 shows measured values of the quality factor Q for such a cavity. The best value measured was 2.3×10^{9} at a

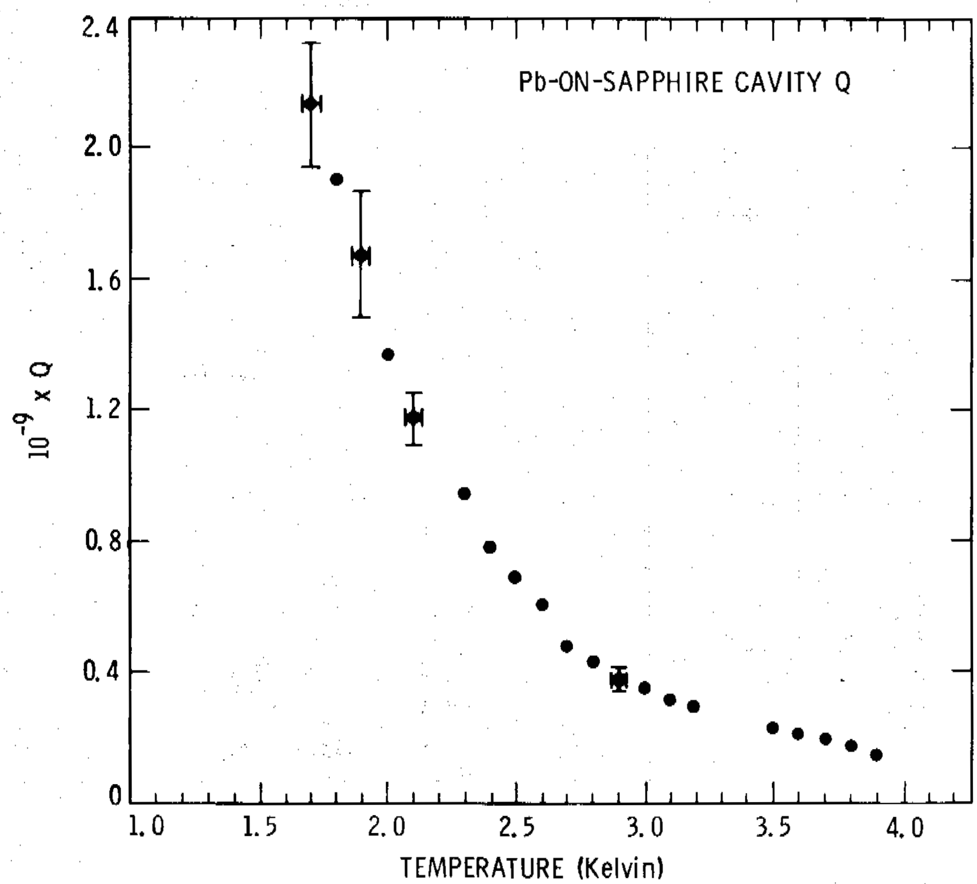

Fig. 1. Quality factor Q of a Pb-on-sapphire resonant cavity with resonant frequency of 2.69 GHz.

temperature of 1.6 Kelvin and at the cavity's resonant frequency of 2.69 GHz. The sapphire substrate reduces response of the cavity frequency to temperature, tilt and vibration disturbances. The ruby maser has been operated in oscillators utilizing low-Q cavities to characterize its noise properties. These tests indicate that the ruby maser, known previously to have a very low noise temperature, also displays the lowest level of 1/f noise obtainable at these microwave frequencies. To illustrate, an upper limit for the multiplicative phase noise predicted by these tests is -145 dBc/Hz at 10 Hertz from the carrier frequency; the best active solid state devices demonstrate only -110 dBc/Hz noise levels when measured at 10 Hertz from the carrier frequency.

The ruby maser requires that a magnetic field be applied to bias the chromium ion energy levels to the correct splitting. The superconducting film, on the other hand, would have its Q degraded if it were subjected to the 500 Gauss field of the maser. A third cavity is therefore used to situate the superconducting cavity away from the high field region, and superconducting shields are placed to further reduce the magnetic field at the high-Q cavity. Details of the design of this three-cavity system can be found in previously published papers.[1 2 3]. The three-cavity system is all cooled below 1.0 Kelvin by pumping on a pot of ^4He, the whole cooled region being in an isolation vacuum surrounded by a bath of liquid helium at atmospheric pressure.

The quality factor of the three-cavity oscillation mode is determined by the fractions of the oscillation energy in the three cavities and their cavity Q's.[2] The energy distribution is controlled by the experimenter by adjusting the cavity frequencies and the coupling strengths between the cavities. A lower three-cavity mode Q allows frequency pulling effects to be characterized more easily. Higher mode Q leads to more stable oscillator performance. We have operated the oscillator with mode Q's of 10^7, 10^8, and $5x10^8$. Results of stability measurements and frequency pulling effects obtained with these three configurations will be described below.

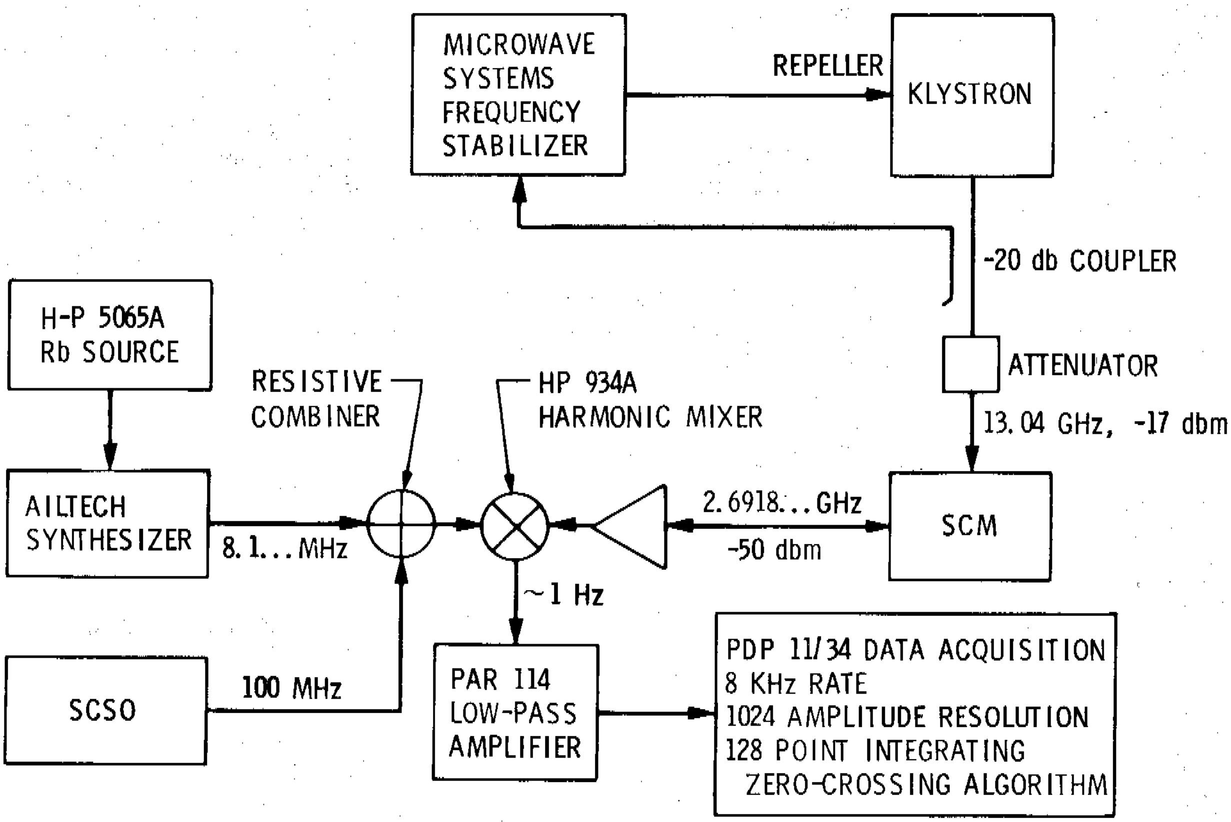

Fig. 2. Block diagram of the data gathering system used to measure Allan variance values of frequency fluctuations. Typical signal frequencies and amplitudes are indicated.

STABILITY MEASUREMENTS

The data gathering set-up used to evaluate the stability of the superconducting cavity maser oscillator (SCM), depicted in Fig. 2., is only slightly modified from the version described at PTTI 17. A high quality quartz crystal stabilized voltage controlled oscillator, with frequency synthesizer, multipliers and filters, is used in a phase locked loop to generate a 100 MHz output from the SCSO with relative stability equal to the 8.629 GHz oscillation frequency. This 100 MHz signal is fed to the harmonic mixer through a resistive combiner along with an approximately 8 MHz signal generated by the synthesizer. The 27th harmonic of the 100 MHz frequency is differenced with the 8 MHz frequency to form a 2.692 GHz frequency. This frequency mixes with the SCM signal to produce an output from the harmonic mixer of a few Hertz frequency. The data acquisition system then measures and records this lower frequency to form Allan variance values.

One change that has recently been incorporated in the data gathering technique is the incorporation of an integration of the signal near the zero crossing to improve the determination of the crossing point. This idea was suggested to us by a colleague[4]. The measurement limits depicted below for this data gathering system reflect the improvement realized with this new algorithm.

The comparison oscillator for these stability tests is a superconducting cavity stabilized oscillator (SCSO) of the Stein-Turneure type[5], which utilizes a bulk niobium high-Q cavity. Its frequency is 8.629 GHz, the loaded Q of the cavity is 2×10^{10}, and its stability performance as measured against a hydrogen maser oscillator is shown in Fig. 3. During the

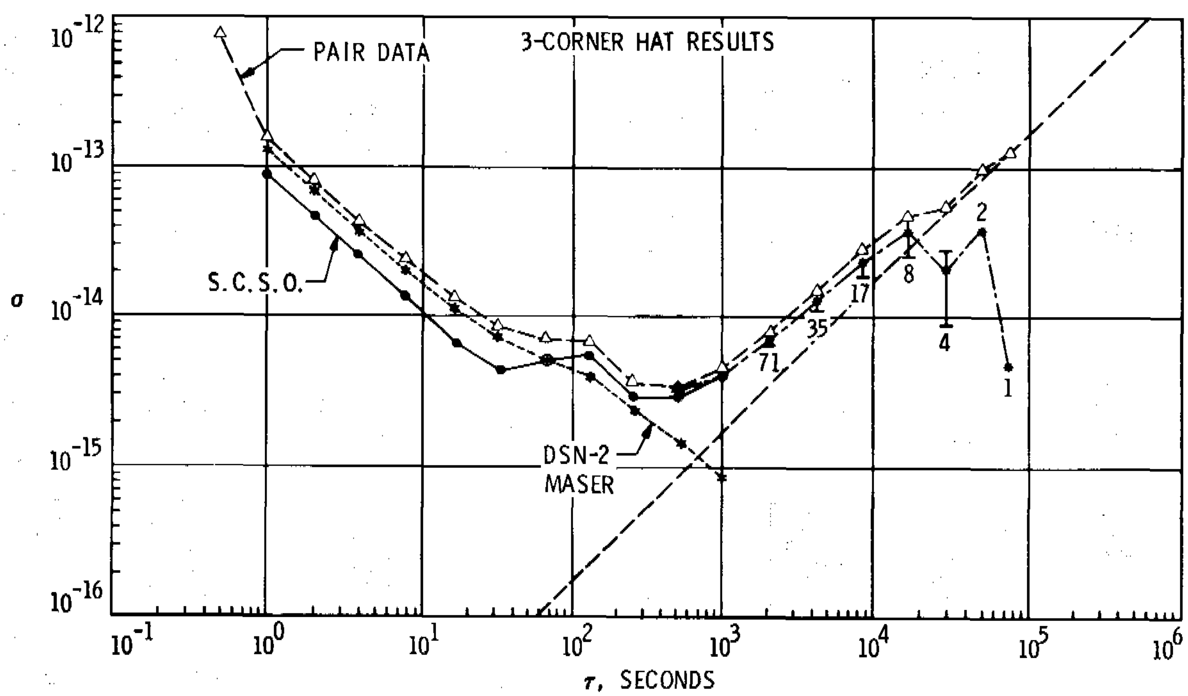

Fig. 3. Allan variance of frequency fluctuations for the superconducting cavity stabilized oscillator (SCSO), measured versus two hydrogen masers in a three-corner hat technique. The SCSO is the comparison oscillator used to characterize our superconducting cavity maser (SCM) oscillator.

measurements characterizing this SCSO, the room temperature electronics were enclosed in an insulated box with heaters and temperature sensors that allowed the ambient temperature to be controlled to 0.1°C. This temperature controlling system has not been employed in our tests. However, our stability measurements have been conducted in a basement laboratory where the temperature varies less than 1.0°C.

The cryostat in which the three-cavity oscillator operates is at least twenty years old. This old age is evidenced by repeated leaks into the isolation vacuum that occur only when the cryostat is cooled to liquid helium temperatures. Operation with such a leak requires continuous pumping of the isolation vacuum space to obtain temperatures at or below 1.0 Kelvin. The resulting heat leak limits both the lowest temperature and the temperature stability achievable. The stability data to be reported were all obtained with a leak into the isolation vacuum.

In Fig. 4 the best stability data we have obtained for our SCM oscillator

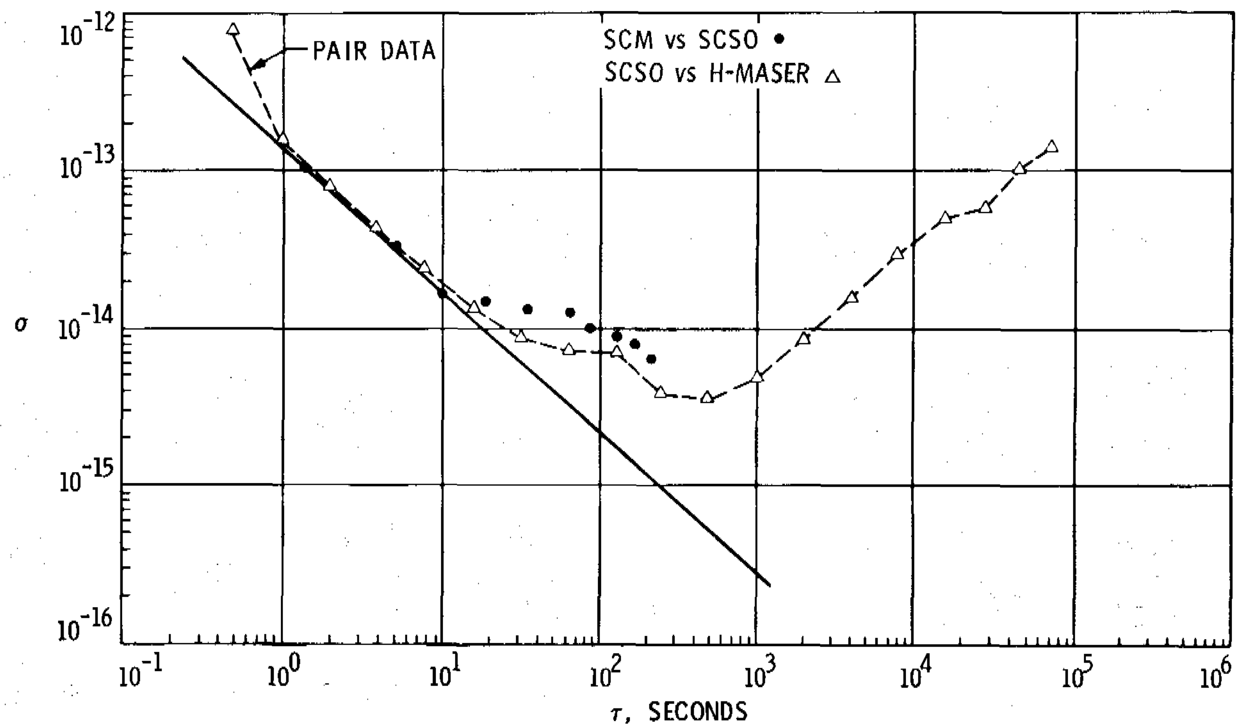

Fig. 4. Allan variance of frequency fluctuations for the superconducting cavity maser (SCM) oscillator, measured versus the SCSO. The triangles show, for comparison, the pair data for the SCSO versus the Hydrogen Maser. The solid line represents the limiting resolution of the data gathering system.

are shown as Allan variance values along with a dashed curve representing the SCSO-H-maser data. The solid straight line at short times illustrates the limiting stability measurable with the characterizing system described above. The data show that the SCM demonstrates stability at least equal to the measuring system at short times, but shows relatively poorer stability at measuring times beyond 100 seconds. Temperature drift is believed to be the cause of this degraded performance. Inability to stabilize the temperature precluded longer measuring times. The best value obtained is 6×10^{-15} at a measuring time of 256 seconds.

While these data are approaching the stability of 10^{-15} expected for this oscillator system, the need to improve the stability is obvious. We are presently setting up the oscillator system at the Frequency Standards Laboratory at Jet Propulsion Laboratory. Efforts will be made to restore the integrity of the isolation vacuum before operating the oscillator at low temperatures. At the Frequency Standards Laboratory we shall have access both to improved stability-characterizing systems and to hydrogen masers for comparison oscillators.

SOURCES OF INSTABILITY

Important as the stability measurements are to proving the merit of the SCM, equally important to the developers is determining the major sources of instability. Testing the response of the oscillator frequency to various operating parameters specifies the frequency pulling strength of each parameter. This information then guides the developers to delimit the variation of these parameters sufficiently to achieve a specified frequency stability. In this way the effort for stability improvement is guided toward the critical problem areas, and the limiting frequency stability can be estimated from the ability to restrict the variation of the parameters. Results of some of these frequency pulling measurements have been reported previously, so only a summary of the most significant results will be discussed here.

The significant parameters are temperature, magnetic field applied to the ruby, pump signal frequency and the pump signal amplitude. While the magnetic field at the ruby has a rather direct pulling mechanism on the oscillation frequency, the existence of superconducting materials to lock in a stable magnetic field makes obtaining the part in 10^{8} field stability necessary for frequency stability of 10^{-17} not unduly difficult. Similarly, the requirement for the pump signal frequency to vary less than 4 parts in 10^{9} is manageable either by locking the pump source to a quartz frequency standard, or by synthesizing the pump signal from the SCM output. The pulling effects of the temperature and of the pump signal amplitude are of somewhat more concern.

As depicted in Figure 5, the resonant frequency of the Pb-on-sapphire cavity is expected to vary with temperature because of reactance changes in the superconducting film and because of expansion of the sapphire, both of these effects causing the frequency to decrease with increasing temperature. At 1.0 K this frequency variation is expected to be -3×10^{-11} per degree, so only a modest 30 microdegree temperature stability would be required to obtain 10^{-15} frequency stability. This response to temperature, coming mainly from the reactance change of the superconducting film on the high-Q cavity, should decrease nearly exponentially with

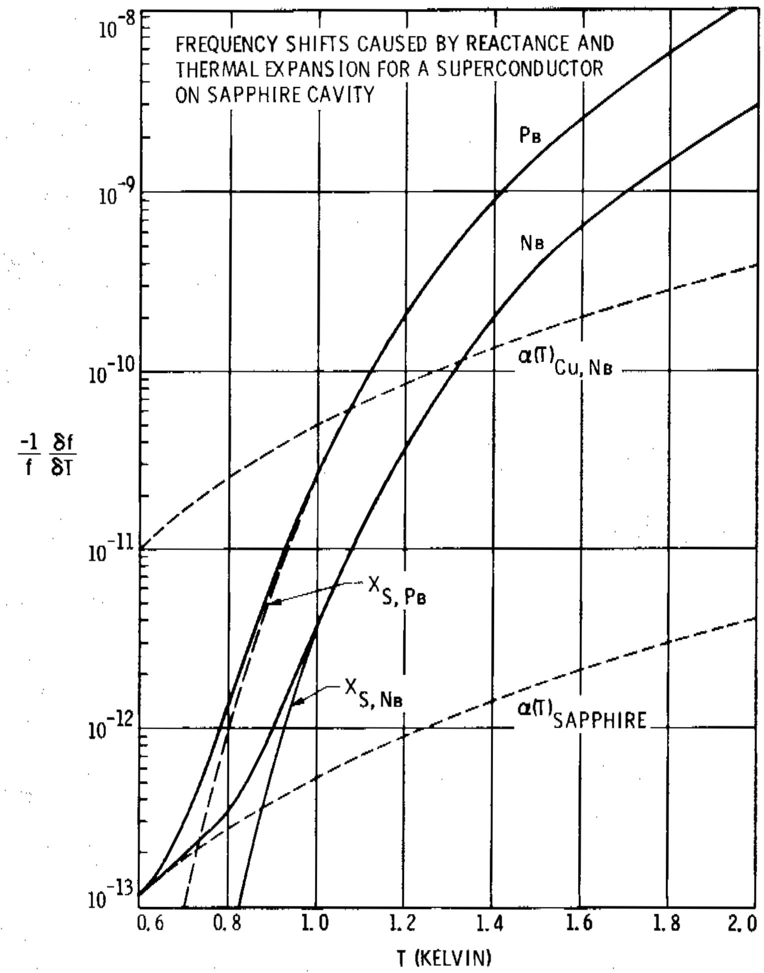

Fig. 5. Relative frequency shifts $[-1/f]\delta f/\delta T$ caused by temperature fluctuations in a superconductor on sapphire cavity, at temperatures indicated on the abscissa.

temperature, so at 0.9 K the coefficient is down to -7×10^{-12}, and obtaining 10^{-17} frequency stability requires only microdegree temperature stabilization. However, the measured frequency variation with temperature is considerably larger and is an <u>increase</u> of frequency with increase of temperature. Values of 10^{-9} and 3×10^{-10} have been measured in different configurations of the oscillator, with little dependence on temperature. The cause of this frequency pulling with temperature is still unresolved, but a suggestion[6] that impurity-induced susceptibility changes could be the source does agree with our results. With so large a coefficient, the difficulty experienced with control of the temperature has led to the dominant frequency fluctuations, as suggested previously. The occurrence of this large positive coefficient at low temperatures implies that at a higher temperature (near 1.4K) there should be a frequency maximum, giving a zero in the temperature coefficient. This temperature behavior will be examined further in our next experiments.

We have noted previously the rather large response of the oscillator frequency to the amplitude of the pump signal. This pulling is now understood to result from the influence that the pump signal has on polarization of the chromium ions in the ruby. The coefficient of 2.5×10^{-12} per decibel of pump amplitude implies the need to stabilize that amplitude to .004 decibel to obtain 10^{-15} frequency stability, a requirement that can be met by ordinary stabilization schemes. Obtaining 10^{-17} frequency stability will require some less conventional amplitude stabilization method.

DISCUSSION

The objective of 10^{-15} frequency stability in our SCM at 1000 seconds measuring times has been shown to be obtainable with rather modest requirements set on the performance of the components. One minimal requirement is to achieve good vacuum integrity for the isolation vacuum so the temperature can be reduced appropriately and can be properly stabilized. We have not yet incorporated amplitude stabilization for the pump signal but intend to add this feature soon. These two improvements should suffice to give the frequency stability set out for this prototype oscillator.

For subsequent versions of the superconducting cavity maser oscillator further improvements are necessary to reach 10^{-17} or better frequency stability. One method to improve on the temperature stability is to employ a superconducting quantum interference device (SQUID) and a Curie law susceptibility sample to measure temperature. Such a design has been shown to yield temperature resolution below a nanodegree[7], and so might be expected to give 10^{-7} degree or better temperature stabilization. Such a temperature stability would reduce frequency fluctuations caused by temperature variations into the 10^{-17} range, without any reduction of the response coefficient for temperature variations.

ACKNOWLEDGEMENTS

Since our first contribution to PTTI 15 in 1983, we feel we have progressed rapidly in bringing the prototype system into operation and attaining frequency stabilities better than 10^{-14}. Significant contributions to this progress has been the availability of equipment and the expertise at the Frequency and Timing Research Group at the Jet Propulsion Laboratory. Their generosity in the past has led us to join their group in the new Frequency Standards Laboratory now being set into operation.

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QUESTIONS AND ANSWERS

GERNOT WINKLER, UNITED STATES NAVAL OBSERVATORY: Not really a question, but a comment. I am really impressed by these numbers. My comment should not be construed as not reflecting that, but I wonder if we spent the same effort to control, for example, the power level in cesium standards to one thousandths of a dB, the magnetic field to 10E-8 and the temperature of the oven and surroundings to a micro degree, what kind of stability would we get? Now I realize that we are not operating at superconducting temperatures, so these stabilities cannot be achieved, but the point is clear. We have not spent anywhere near the same effort in squeezing out potential performance from our conventional frequency standards as you are doing in your case.

MR. STRAYER: I agree with that. As any gravity wave detector person will tell you, there are a bunch of peripheral advantages to using low temperatures.