RELATIVITY EXPERIMENTS WITH AN IMPROVED SUPERCONDUCTING CAVITY OSCILLATOR

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ABSTRACT

Superconducting Cavity Stabilized Oscillators (SCSO) have produced the most stable clocks to date for integration times between 10^2 and 10^3 seconds, achieving a frequency stability in the 10^{-16} range. We discuss a number of ground and space based relativity experiments using SCSO clocks. For space we propose an SCSO system of two to three cavities on the Space Station, allowing improved measurements of the Local Position Invariance and of the anisotropy of the velocity of light This experiment will be designed to also compare the SCSO with atomic clocks on the Space Station and to serve as a flywheel for these clocks. The principal contributors to cavity frequency variations are: a) acceleration effects due to gravity and vibrations b) temperature variations, and c) variations in the energy stored in the cavity. We discuss the prospects for improvements in all these areas, aimed at producing an SCSO with stability in the 10^{-17} range for integration times of 10^2-10^4 seconds.

I. OVERVIEW

Superconducting Cavity Stabilized Oscillators (SCSO's) have achieved stabilities of a few parts in 10^{16} for periods of around 100 s, making them the most precise clocks in this interval range. Stein and Turneaure**1)** have demonstrated a frequency stability of 3×10^{-16} for solid 8.6 GHz TM_{010} niobium cavities with unloaded quality factors of up to 2×10^{11}. More recent work using superconductor coated sapphire resonators**2),3)** have reached short term frequency stabilities between 10^{-15} and 10^{-14}.

Possible applications for clocks of this type and quality are: a) various experimental checks of gravitational theories, b) measurements of the time and gravitational potential dependence of fundamental physical constants, c) verification of the isotropy of the velocity of light, and d) possible detection of gravitational waves. In addition SCSO's coupled as flywheels with atomic standards would create accurate clocks of very high stability for time ranges above 0.1 s.

We propose a number of Relativity experiments in space using SCSO clocks. The vehicle for these experiments will be a system of two to three cavities on the Space Station, which provides a very low acceleration environment. The Space Station will also carry high precision atomic clocks, allowing a number of joint measurements. Firstly, the Local Position Invariance (LPI) measurement of Turneaure et al.**4)** will be improved from 2% to about 0.1%. Secondly, comparisons with the atomic clocks for the 10^2 to the 10^4 seconds range will allow the use of the SCSO as a flywheel, thus improving the performance of the overall system. As a stand alone system, the SCSO clocks will allow an improved measurement of the anisotropy of the velocity of light, two to four orders of magnitude beyond the present level of 10^{-11}. Development units of the flight SCSO system will be available on the ground for lower accuracy measurements of some of the above applications.

Anisotropy in the velocity of light is detectable as variations of the SCSO frequency with respect to the orientation of the local frame relative to the microwave cavity and its TM_{010} fields. Gravitational waves distort the cavity and could be detected by a SCSO with frequency stability better than 10^{-18}.

A complete description of the SCSO clock and its performance has been given elsewhere.**1),5)** Section II is a description of the principal disturbances causing frequency fluctuations, the proposed improvements to the clock, and some preliminary results. Section III contains our present conclusions and expectations.

II. MAIN DISTURBANCE EFFECTS AND IMPROVEMENTS IN PROGRESS

In order to enhance the performance of the SCSO clock, both its noise floor and its long term stability need improving. Improvements in the electronic system are aimed at lowering the noise floor. Long term stability can be improved by reducing the main disturbance effects, i.e. local gravity variations, temperature fluctuations, and variations in the energy stored in the cavity. For a space experiment radiation effects are critical, therefore we present an estimate of the frequency variations caused by cosmic radiation. A number of smaller disturbance effects including quantum fluctuations, thermally induced phonons, external pressure variations, and low temperature structural changes (creep) are estimated to cause frequency instabilities below the 10^{-18} level, and are thus negligible.

A. ELECTRONIC CIRCUIT

Figure 1 is a schematic view of a proposed improved oscillator electronics, conceptually similar to the original SCSO electronics. The improvements under consideration include: a) use of improved microwave technology which was not available for the original circuit, b) a stabilizing power servo, and c) extensive use of cryogenic components.

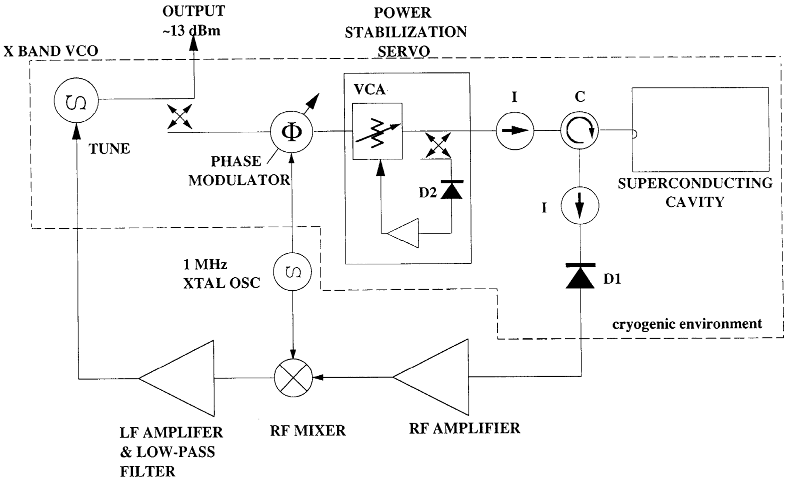

Figure 1. Schematic view of the proposed oscillator electronics.

The Gunn oscillator will be replaced with a varactor-tuned dielectric resonator oscillator (DRO) selected for very low close-in phase noise. The oscillator will be placed in the vapor cooled region of the cryostat, at around 6 K, and will be temperature controlled to 10^{-2} K. An intermediate temperature control stage at about 1.5 K, and with a thermal stability of 10^{-4} K, will provide the cryogenic environment for the phase modulator, the power stabilization servo, and the AM detector. Note that the use of cryogenic electronic components is under study, as it requires a significant amount of development, particularly when coupled with the space radiation requirements. Power stability of better than 0.1% should be easily achievable. We expect to be able to reduce the noise floor to the goal of 10^{-17} range frequency stability level. Figure 2 is a schematic representation of the proposed measurement system for the first phase of the test, with three SCSO clocks compared against each other.

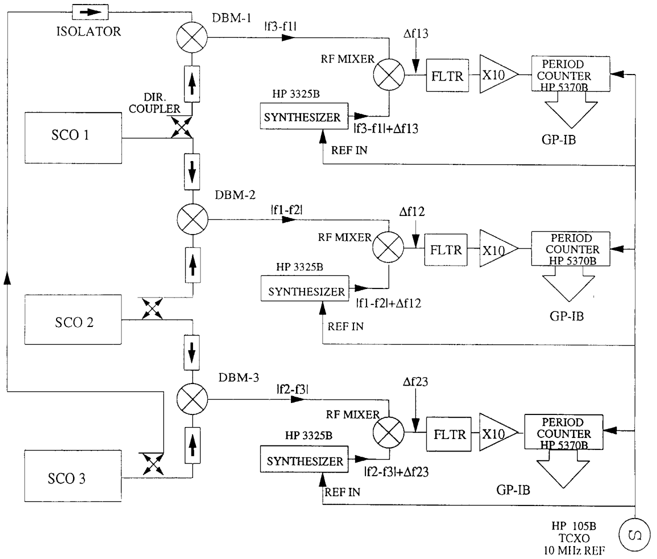

Figure 2. Measurement system for first phase of test

B. Local Acceleration and Gravity

Vibrations and variations in local gravity will change the frequency by changing the dimensions of the cavity. For the TM_{010} mode vertically mounted cavity the frequency is dependent to first order only on the average diameter of the resonator, and thus only sensitive to second order in the tilt angle. The frequency stability $\left|\delta\nu/\nu_0\right|$ is:

$$\left|\frac{\delta\nu}{\nu_0}\right| \cong \left|\frac{\delta R}{R}\right| \cong \frac{1}{3}\cdot\frac{\delta l}{l} \cong \frac{1}{3}\cdot\frac{l\rho\mathrm{C}\delta g\mathrm{n}}{Y} \Rightarrow \left|\frac{\delta\nu}{\nu_0}\right| \cong 4\times10^{-9}\cdot\frac{\delta g}{g} \tag{1}$$

where *R*, *l*, *ρ*, and *Y* are the radius, length, density and Young modulus of the cavity. Earth tides are easily observable at the 10^{-14} frequency variation level, in agreement with the model above.

The sensitivity to variations in the local field can be reduced significantly for ground based experimentation by supporting the cavity from its center, consequently compensating any change in the length of the top half with the opposite change in the length of the bottom half. Figure 3 shows the results of a preliminary finite element analysis of four different support systems for the SCSO cavity. The variation of the cavity radius, in arbitrary units, is plotted versus the vertical cavity axis, from top to bottom. Note the significantly reduced and symmetric deviation for the mid cavity support, with respect to the present top flange support system. We expect that an optimized support system will reduce the sensitivity to variations to local gravity by two to three orders of magnitude: $\left|\delta\nu/\nu_0\right| \cong 4\times10^{-11}\cdot\delta g/g$. In order to further reduce the forces exerted on the cavity, the connection to the waveguide will be made via a choke flange joint, thus leaving the center support as the only mechanical connection to the resonator.

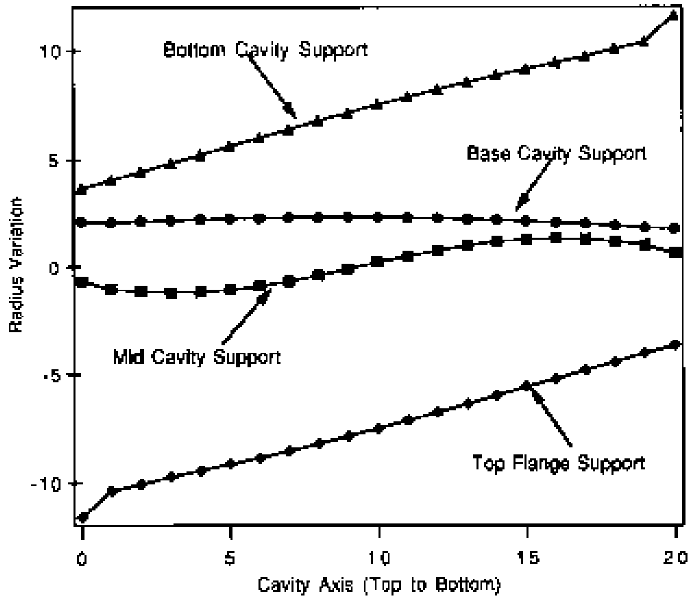

Figure 3. Finite element analysis results for various cavity support systems.

C. *TEMPERATURE FLUCTUATIONS*

Fluctuations in temperature affect the frequency stability via two main effects on the cavity: thermal expansion and the variation with temperature of the skin depth. At 1.2 K these two effects are approximately equal:

$$\left|\frac{\delta\nu}{\nu_0}\right| = B\cdot exp\left(\frac{-C\cdot g(T)}{T}\right) + D\cdot T^{E} \cong 9\times10^{-6}\cdot exp\left(\frac{-17}{T}\right) + 1\times10^{-11}\cdot T^{4} \qquad \text{(2a)}$$

$$\frac{\partial|\delta\nu/\nu_0|}{\partial T} = \frac{B\cdot C\cdot g(T)}{T^2}\cdot exp\left(-\frac{C\cdot g(T)}{T}\right) + D\cdot E\cdot T^{(E-1)} \cong 2\times 10^{-10}\cdot(\mathrm{Hz/Hz})/\mathrm{K} \qquad (2b)$$

where *B*, *C*, and *g(T)* are the coefficients describing the temperature dependence of the skin depth, while *D* and *E* are the coefficients of thermal lattice expansion. The work of Turneaure et al. was performed with short term temperature control of 1 μK, and long term stability of about 10 μK. Lipa et al.**6)** have used paramagnetic salt thermometers in a four stage thermal isolation system to demonstrate temperature stability better than 1 nK. Their system has also been flown in space as part of the Shuttle Lambda Point Experiment program. We propose to use a simplified version of this system to achieve temperature control to 10 nK or better, therefore reducing the temperature induced frequency fluctuations below the 10^{-18} level. Figure 4 is a schematic configuration of a proposed flight instrument. For clarity the figure shows the two cavities with their axes parallel, while the actual experiment places them in an orthogonal configuration, in order to facilitate the measurement of the anisotropy of the velocity of light.

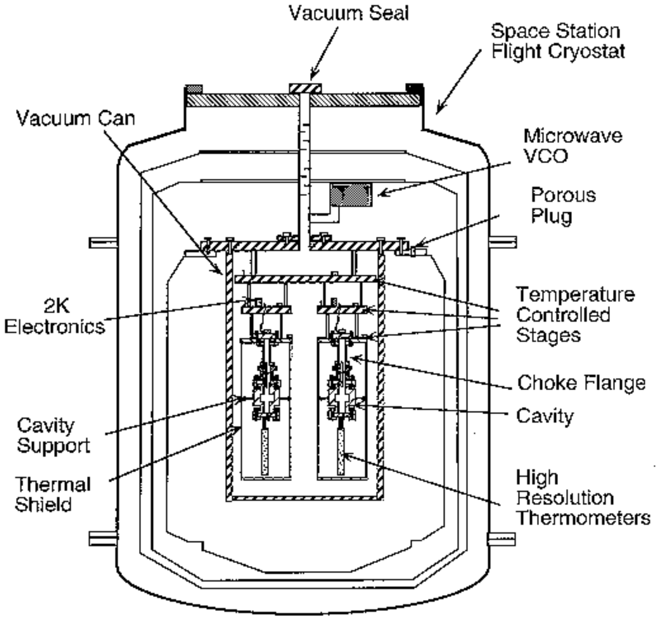

Figure 4. Flight instrument configuration.

D. FLUCTUATIONS IN THE ENERGY STORED IN THE RESONATOR

Fluctuations in the energy *U* stored in the resonator will change the electromagnetic radiation pressure on the cavity walls and modify the non-linear superconducting surface reactance. This variation can be expressed as:

$$\left|\frac{\delta \nu}{\nu_0}\right| = -\left(k_{EM} + k_x\right)\cdot U \;\Rightarrow\; \frac{\partial\left(\delta\nu/\nu_0\right)}{\partial U} \cong -1.7\times 10^{-6}\cdot\left[\mathrm{Hz/Hz/J}\right] \tag{3}$$

where the k coefficients quantify the electromagnetic radiation pressure and the surface reactance. In the Turneaure configuration the stored energy in the cavity is 6×10^{-8} J, with a short term stability better than 10^{-2}. Improved electronics will allow both better power control and sensitivity to lower stored energies, therefore reducing the frequency instabilities caused by this effect to the 10^{-18} level.

E. COSMIC RADIATION

We consider two cosmic radiation effects: temperature gradients induced by heating due to direct energy deposition, and trapped flux motion caused by local cosmic ray heating. The upper limit for energy deposited by cosmic radiation in a Space Station orbit is about 10^{-11} W/g of material or about 10^{-10} W per cubic centimeter of niobium. The thermal conductivity k of the very pure niobium used for the resonator is about 0.1 W/cm/K at 1.2 K. Using the simple thermal model of a cylinder of radius R with constant heating Q per unit volume, thermally grounded at the periphery at 1.2 K, the temperature increase ΔT at the center of the cylinder is given by: $\Delta T = Q\cdot R^2/4k$. Turning the radiation on/off will thus yield the maximum temperature difference of: ΔT=1 nK. This is well below the required stability level of 10 nK discussed in the previous section.

Cosmic rays can cause heating in the vicinity of a trapped flux line, causing it to move, and thus modifying the structure of the trapped surface field and shifting the frequency. For high energy cosmic radiation protons, which penetrate the cavity walls, the average expected energy loss in niobium is of the order of 50 MeV/cm. Using the thermal model of an instantaneous line source, the radius of the spot heated to above 5K, (about half the superconducting transition temperature for niobium, where some flux motion is possible) will be about 1 μm. The complete removal (or addition) of a flux line to the cavity surface will shift the frequency by about the ratio of the volume of a fluxon, (defined as the fluxon area multiplied by the skin depth), to the cavity volume, or $\left|\delta\nu/\nu_0\right| \cong 1\times10^{-18}$ per fluxon. However the probability of flux generation and/or annihilation in the surface of bulk niobium with low impurity levels is extremely small, making this frequency variation mechanism negligible. Motion of the fluxons by 10^{-4} of the cavity size will contribute much less to the frequency variations than flux generation and/or annihilation. Consequently we expect all trapped flux effects under cosmic radiation to be negligible.

Experiments with a 1 mCi Cobalt 60 source at 10 cm from the SCSO showed no measurable frequency shifts at the levels $\left|\delta\nu/\nu_0\right| < 1\times10^{-15}$.

III. CONCLUSIONS

SCSO clocks have demonstrated a frequency stability of 3×10^{-16} for time intervals between 10 and 1000 seconds. The main disturbance effects are due to noise in the electronics and long term drift caused by fluctuations in the temperature, the local gravity, and the electromagnetic energy stored in the resonator. Proposed improvements show the promise of achieving frequency stabilities in the 10^{-17} range. An experiment on the Space Station, using an SCSO system of cavities with this stability, can be used to perform a whole range of Relativity tests, both as an independent unit, or in conjunction with precision atomic clocks.

ACKNOWLEDGMENTS

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