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A SUPERCONDUCTING MICROWAVE OSCILLATOR CLOCK FOR USE ON THE SPACE STATION

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I. Introduction

The International Space Station provides an ideal platform for high precision frequency measurements, both as applied to scientific experiments and as regards basic time metrology. Consequently, a variety of clocks are being developed for flight on the Space Station, a majority of which are atomic clocks with very good stability for time periods in excess of 1,000 seconds. We plan to significantly augment the scope and capability of the ensemble of space clocks by adding to it a SUperconducting Microwave Oscillator, SUMO.

SUMO is a space version of the Superconducting Cavity Stabilized Oscillator, SCSO; the most precise clock developed to date for the interval range of around 100 seconds. Comparing three 8.6 GHz TM_{010} niobium cavities operating at 1.2 K, Stein and Turneaure[1)] have achieved a frequency stability of 3×10^{-16}, with unloaded quality factors of up to 10^{11}. Recent work with superconductor coated sapphire resonators[2)] and compensated sapphire oscillators[3)] have reached short-term frequency stabilities between 10^{-14} and 10^{-15}.

Sections II and III give short descriptions of the SUMO project and the SCSO technology it is based on respectively. Section IV is a description of the principal disturbances causing frequency fluctuations, the planned improvements to the SCSO and preliminary results of the development work for SUMO. Section V contains our conclusions.

II. SUMO

The Local Position Invariance principle of Einstein's theory of gravitation assumes that clocks made in different ways all keep exactly the same time, no matter where they are co-located in the universe. This might not be true if some of the laws of physics vary slightly from place to place. SUMO's primary science objective is to perform a Local Position Invariance (LPI) test of General Relativity, by comparing the microwave cavity frequency with that of an atomic clock to a part in 10^{17}, as a function of position and gravitational potential. The gravitational potential varies with the orbital motion of the Space Station, as well as with the Earth motion in its eccentric orbit around the Sun. Note that the frequencies of the microwave cavity and the atomic clocks have a different dependence on fundamental physical constants. This test is expected to improve the 2% LPI measurement of Turneaure et al.[4)]. We expect to achieve a 0.1% measurement.

For the 10^2 to the 10^4 seconds range SUMO should also provide a high stability low phase noise signal capable of being slaved to the atomic clocks, providing them with a flywheel and greatly enhancing their performance.

SUMO will be an insert in the Low Temperature Microgravity Physics Facility, LTMPF, and will require three to six months of operation in order to meet its science objectives. A superconducting niobium resonator operating at pumped liquid helium temperature, about 1.2 K, with a quality factor in excess of 10^{10} will stabilize the microwave oscillator. The microwave oscillator will generate a single frequency at approximately 9.2 GHz, between 2 to 20 MHz different from the frequency of a Cesium fountain clock, so chosen to minimize the hardware required to compare the frequencies of the two clocks. The difference signal will be sampled at about once per second and downlinked. Total size and mass for SUMO are determined by the LTMPF in which it will be housed.

Longer term experiments using two or more SUMO type oscillators include a) precision red-shift measurements, b) verification of the isotropy of the velocity of light, and c) possible detection of gravitational waves. 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 fields of the TM_{010} cavity. Presently the best limit of the isotropy of the velocity of light is $\Delta c/c \leq 10^{-11}$. Comparing the frequencies of two orthogonaly mounted cavities at roll and orbital rates, the expected limit for the linear isotropy will be $\Delta c/c \leq 10^{-16}$. Gravitational waves distort the cavity and could be detected by a SCSO with frequency stability better than one part in 10^{18}.

III. SCSO

The SUMO project uses the original SCSO hardware to develop and test system enhancements and space electronics. The SCSO microwave resonator is an 8.6 GHz superconducting niobium TM_{010} mode cavity, operating in ultrahigh vacuum at 1.2 K. Mechanical stability is achieved by making the walls of the cavity of about the same thickness as its 1.3 cm radius.

Figure 1 is a schematic representation of the cavity and its mounting scheme in a vacuum can that is immersed in pumped liquid helium. The cavity is supported from the top and connected with indium sealed vacuum flanges to the pump-out port and to the microwave waveguide. High vacuum conditions for the cavity are maintained by means

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of a permanent internal vacuum with a pinch-off and by the exterior vacuum can. The temperature of the cavity was controlled to 1 μK short term and 10 μK per week. Magnetic shields insure that the field at the cavity is less than 10 mG. Both the dewar and the electronics are tilt controlled to reduce the effect of variations in local gravity. The entire apparatus consisting of three SCSO systems is cooled in a top loading dewar.

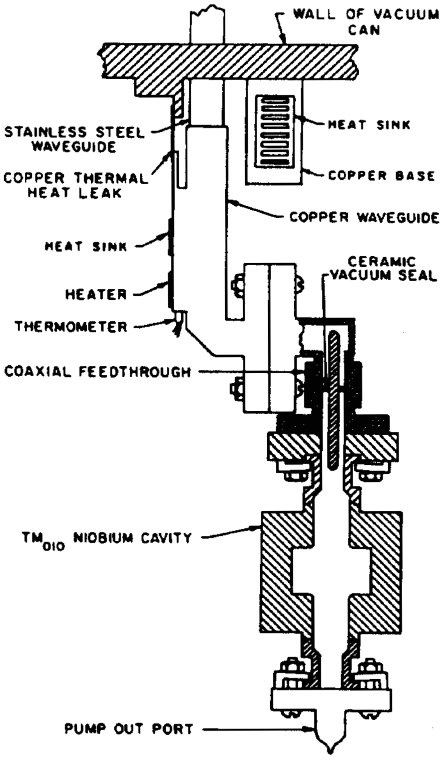

Figure 1. Schematic of SCSO resonator and mounting

Special care is taken in preparing the resonator cavity surfaces in order to achieve the highest Q values. The cavity is machined of ultra pure niobium and then undergoes a conditioning process consisting of an initial chemical cleaning, a 1900 °C ultrahigh vacuum firing, a chemical etching of a 100 μm surface layer, and a final 1900 °C ultrahigh vacuum firing. Typical values for the unloaded Q factor obtained by this method are about 10^{11}. The Q is limited by surface effects and not the temperature.[5)]

The SCSO utilizes the high Q cavity resonance to stabilize a voltage-controlled oscillator. In the original design a small portion of the power (~1 μW) of a Gunn oscillator with variable frequency was used to excite the cavity. This signal was phase modulated at 1 MHz and the AM modulated signal reflected by the cavity was then detected. The sign and amplitude of the detected AM signal represent the deviation of the Gunn oscillator frequency from the cavity frequency, and were used to servo the Gunn oscillator. The connection of the resonator to room temperature is made using stainless steel waveguide with copper baffles in order to minimize thermal losses. Figure 2 shows a block diagram of the SCSO developed at Stanford University.

The Allan and Hadamard variances for the original measurements,[1)] with a 10 Hz noise bandwidth, are plotted in Figure 3 as a function of the sampling time τ. For $\tau < 30$ s, $\sigma_y = 10^{-14}/\tau$. The noise floor of 3×10^{-16} is reached for $30 \text{ s} < \tau < 1000$ s. Figure 4 shows that for $\tau > 1000$ s, the fractional long-term drift of the SCSO is about 2×10^{-13}/day.

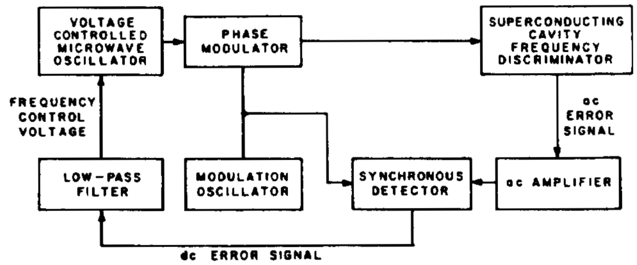

Figure 2. Block diagram of SCSO

Three SCSOs were used to measure the frequency stability of the device. Combined with two hydrogen masers this ensemble also yielded a 2% level confirmation of the independence of the hyperfine constant α from the variation the Sun's gravitational potential over 10 days.[4)]

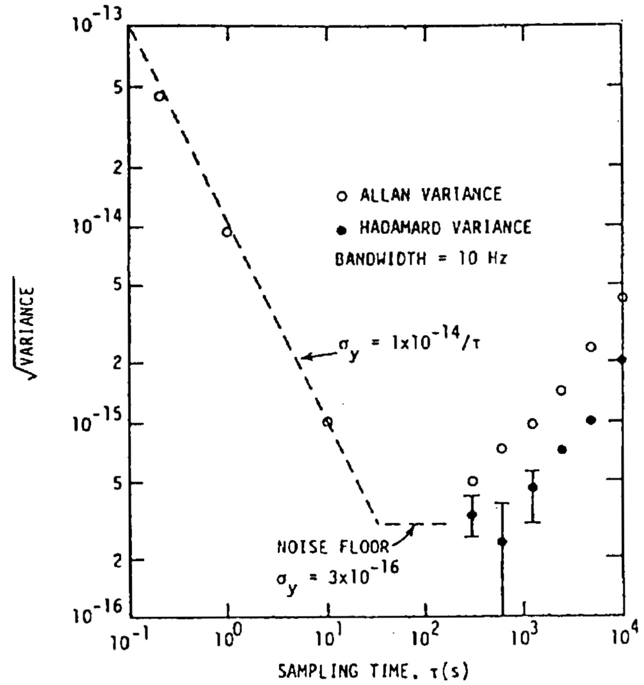

Figure 3. Allan and Hadamard variances for the SCSO

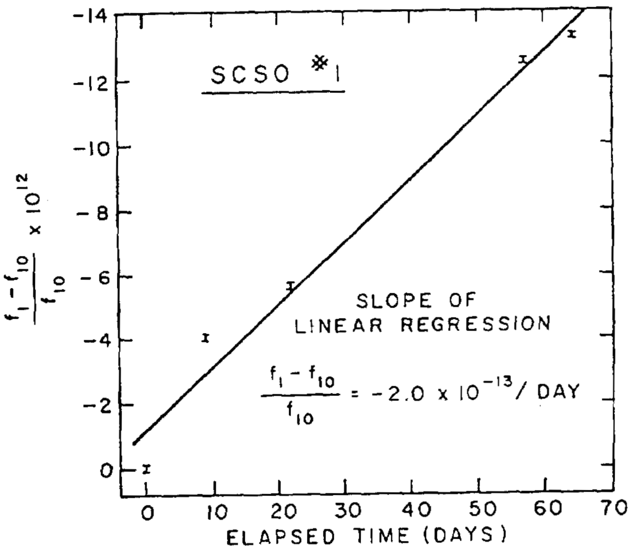

Figure 4. Long term stability of SCSO

IV. Developing SUMO from SCSO

In order to enhance the performance of the SCSO clock, both its noise floor and its long term stability need improving. Space Station utilization of SUMO requires space-compatible electronics and support equipment, as well as solutions for an environment with variations in acceleration of the order of 10^{-6} m/s^2. 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 space experiments radiation effects are an issue, and therefore we present an estimate of the frequency variations caused by cosmic radiation. A number of smaller disturbances 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 5 is a block diagram of the frequency-lock-loop presently in use for the development of SUMO electronics, a concept similar to the original SCSO electronics. The final improvements will include the use of improved microwave technology, not available for the original circuit and a stabilizing power servo. The Gunn oscillators are being replaced with varactor-tuned dielectric resonator oscillators (DRO) selected for very low close-in phase noise. Power stabilization to the level of about 0.1% will be implemented in the next version of the system. We expect to be able to reduce the noise floor to the goal of 10^{-17} range frequency stability level.

A comprehensive analysis of the electronics performance is in progress. Figure 6 shows the schematic of the system with inputs for disturbances.

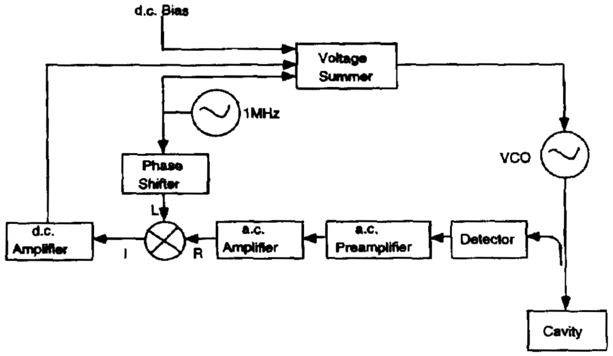

Figure 5. Block diagram of the frequency-lock-loop

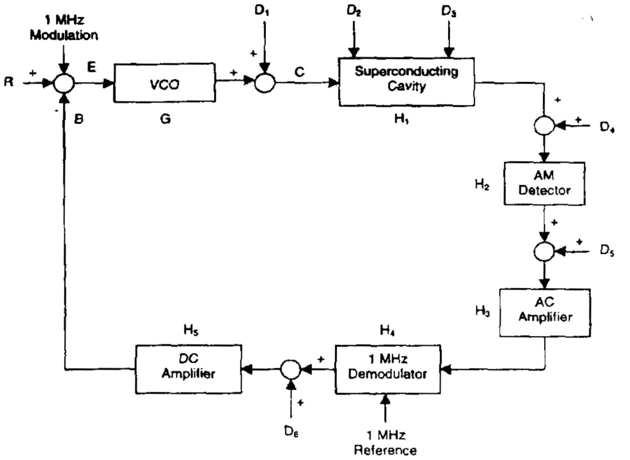

Figure 6. Schematic for analysis of the electronic circuit

Figure 7 is a schematic representation of the measurement system being developed for SUMO, with three resonators compared against each other. The 10 MHz reference oscillator is phase locked to one of the superconducting cavities in order to reduce its phase noise.

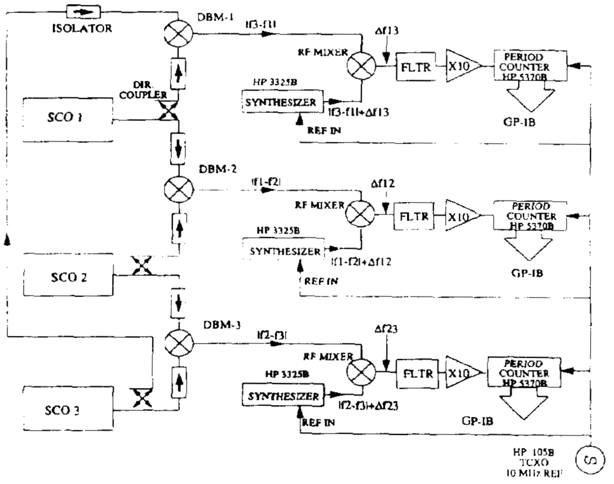

Figure 7. System for 3 cavities comparison

The quality factors of the original cavities have been re-measured, after long term storage in vacuum, to be between 2×10^{10} and 5×10^{10}. This indicates that no significant deterioration of Q has occurred for about 20 years of storage. Figure 8 gives the variation in fractional frequency $(\bar{y}_1 - \bar{y}_2)^2$ for 100 second averaged adjacent data points. The data covers a period of 12 hours, and is taken with the original cavities and a new electronics system. The Allan variance is 3.6×10^{-15} at 100 seconds. Note that no vibration and tilt isolation has been yet implemented, and that the temperature is controlled to only about 15 μK. The main disturbance to the frequency stability for this experimental setup is attributable to temperature fluctuations at the 15 μK level. This result is in excellent agreement with the calculated temperature sensitivity of the SCSO (see section IVc) and with the original results by Stein and Turneaure[1], scaled from their 1 μK temperature control stability.

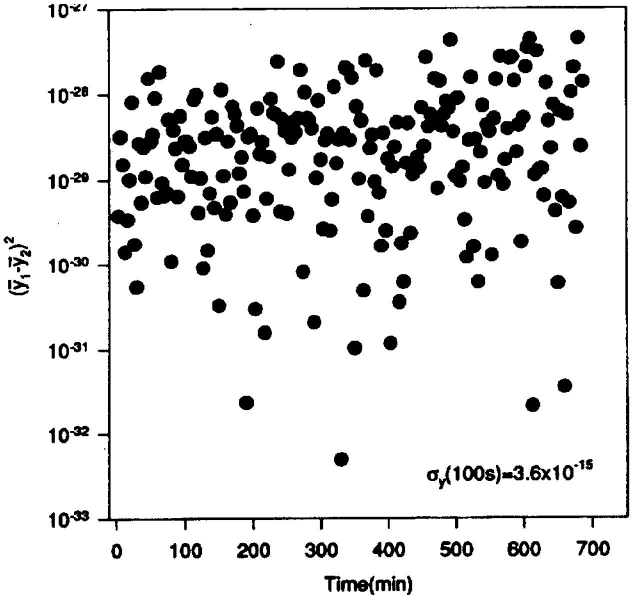

Figure 8. Frequency stability for preliminary version of SUMO electronics

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 is:

$$\left|\frac{\delta v}{v_0}\right| \cong \left|\frac{\delta R}{R}\right| \cong \frac{1}{3}\cdot\frac{\delta l}{l} \cong \frac{1}{3}\cdot\frac{l\rho(\delta g)}{Y} \Rightarrow \left|\frac{\delta v}{v_0}\right| \cong 4\times10^{-9}\cdot\frac{\delta g}{g} \quad (1a)$$

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.

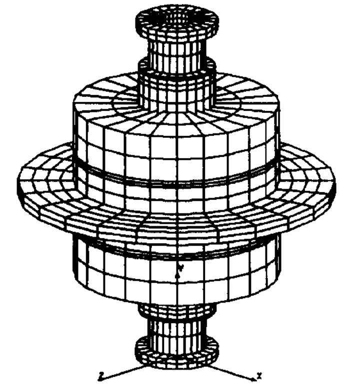

Figure 9. Finite element model for center-supported cavity

The sensitivity to variations in the local gravity 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 9 gives a picture of the finite element grid used in the structural analysis of a center-supported cavity.

Figure 10 shows the results of the structural analysis for four different support systems for the cavity; top, bottom, ideal center support, and best center flange implementation. The variation of the cavity radius, in nm, is plotted as a function of position along the vertical cavity axis, from bottom to top. Note the significantly reduced and symmetric deviation for the mid cavity supports, 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 about two orders of magnitude:

$$\left|\frac{\delta v}{v_0}\right| \cong 4\times10^{-11}\cdot\frac{\delta g}{g} \quad (1b)$$

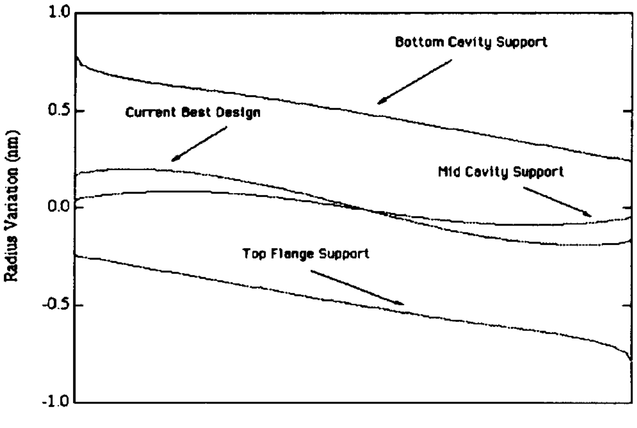

Figure 10. Finite element analysis results for four cavity-support methods: top, bottom, ideal center support, and best center flange implementation

In order to reduce further 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.

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 and given by:

$$\left|\frac{\delta\nu}{\nu_0}\right| = B\cdot\exp\left(\frac{-C\cdot g(T)}{T}\right) + D\cdot T^E \tag{2a}$$

$$\left|\frac{\delta\nu}{\nu_0}\right| \cong 9\times10^{-6}\cdot\exp\left(\frac{-17}{T}\right) + 1\times10^{-11}\cdot T^4 \tag{2b}$$

$$\frac{\partial|\delta\nu/\nu_0|}{\partial T} = \frac{B\cdot C\cdot g(T)}{T^2}\cdot\exp\left(\frac{-C\cdot g(T)}{T}\right) + D\cdot E\cdot T^{(E-1)} \tag{2c}$$

$$\frac{\partial|\delta\nu/\nu_0|}{\partial T} \cong 2\times10^{-10}\cdot(\mathrm{Hz/Hz})/\mathrm{K} \tag{2d}$$

Where *B*, *C*, and *g(T)* are the coefficients describing the temperature dependence of the skin depth, and *D* and *E* are the coefficients of thermal lattice expansion. The work of Turneaure et al.[4] 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 plan 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 11 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.

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:

$$\left|\frac{\delta\nu}{\nu_0}\right| = -(k_{EM} + k_x)\cdot U \tag{3a}$$

$$\frac{\partial(\delta\nu/\nu_0)}{\partial U} \cong -1.7\times10^{-6}\cdot(\mathrm{Hz/Hz})/J \tag{3b}$$

The *k* coefficients quantify the electromagnetic radiation pressure and the surface reactance. In the original SCSO 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.

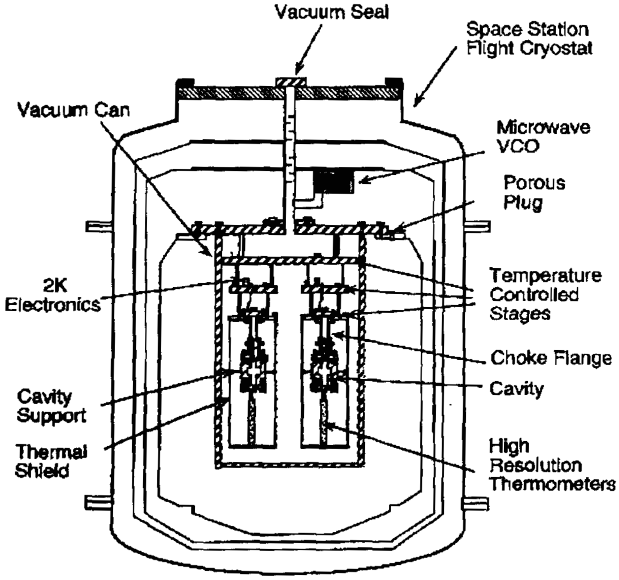

Figure 11. Flight instrument configuration.

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 $\Delta T=1$ 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 $|\delta\nu/\nu_0| \cong 1\times10^{-18}$ 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. Earlier experiments with a 1 mCi Cobalt 60 source at 10 cm from the SCSO showed no measurable frequency shifts at the levels $|\delta\nu/\nu_0| < 1\times10^{-15}$.

V. Conclusions

SUMO is being developed for use on the Space Station based on SCSO clock technology which has demonstrated a frequency stability of 3×10^{-16} for time intervals between 10 and 1000 seconds. The main disturbance effects are due to noise and bias drift 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, with preliminary results in the 10^{-15} range at 15 μK temperature control. On the Space Station, SUMO will be used in conjunction with atomic clocks, to perform a test of the equivalence principle by null gravitational redshift experiment, and as a low phase noise flywheel for these clocks.

Acknowledgments

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