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A SPACE-BASED SUPERCONDUCTING MICROWAVE OSCILLATOR CLOCK

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ABSTRACT

Superconducting Cavity Stabilized Oscillators, SCSO, have produced the most stable clocks to date, achieving an Allen variance of 3×10^{-16} for integration times between 10^2 and 10^3 seconds. Cavity frequency variations are mainly caused by acceleration effects due to gravity and vibrations, temperature variations, and fluctuations in the energy stored in the cavity. We describe the status of a project aimed at building an improved cavity system suitable for use on the International Space Station, ISS. Primary experimental applications include the measurement, in conjunction with other types of clocks, of the dependence of fundamental constants on the gravitational potential, gravitational redshift measurements, and the measurement of the anisotropy of the velocity of light. A major secondary application is as a flywheel for the atomic clocks co-located on the ISS.

INTRODUCTION

With the advent of laser-cooled atoms, the prospects for substantially more stable atomic clocks have dramatically improved. It now appears that laser-cooled cesium and rubidium frequency standards with stabilities of better that 10^{-16} are feasible in space, and single atom clocks with stabilities of 10^{-18} are discussed. When coupled with SCSO's, these developments open up additional possibilities for experiments in fundamental physics. On large length scales and under extreme conditions Einstein's theory of General Relativity (GR) encapsulates many of the fundamental physical laws used for predicting the intertwined behavior of matter and space. One of the most fundamental aspects of this theory is the behavior of clocks. So far, these have been used to test the theory in three different ways. A hydrogen maser was used (Vessot *et al.*, 1980) to measure the gravitational red shift to about a part in 10^4 using a rocket flight to an altitude of 10,000 km. The Shapiro (1964) time delay for electromagnetic signals passing close to the sun has been measured to a part in 10^3. Finally, the assumption of Local Position Invariance (LPI) in the Einstein Equivalence Principle has been tested (Turneaure *et al.*, 1983) to a part in 10^2. Beyond GR, clocks have been used to test some of the foundations of special relativity by looking for effects due to a possible anisotropy of the velocity of light (Will, 1992), and to set bounds (Prestage *et al.*, 1995) on the present rate of change of the fine structure constant.

To date, only atomic clocks have been used in space-based relativity missions. Yet, for periods of up to about 1000 s, SCSOs are the most stable clocks (Stein and Turneaure, 1975). The major disadvantages in their application have been the degraded stability at longer times and the complexities of using cryogenic technology in space. In recent times the latter objection has become less compelling with the flight demonstrations of COBE and IRAS, both operating at low temperatures for about a year. Also, a recent shuttle flight has demonstrated on-orbit helium re-supply capability as the major objective of the SHOOT program (DiPirro *et al.*, 1994). The Low Temperature Multi-Platform Facility (LTMPF) planned for the ISS will allow relatively cheap access to temperatures as low as 1.5K in space for a wide range of missions with duration's up to 6 months. A variety of clocks are being developed for flight on the ISS, most of which are atomic clocks with very good stability for time periods in excess of 1,000 seconds. We are developing a SUperconducting Microwave Oscillator (SUMO) which should significantly augment the scope and capability of the space clock ensemble. SUMO is essentially the space version of the SCSO. Comparing three 8.6 GHz TM_{010} niobium cavities, Stein and Turneaure (1975) have achieved a frequency stability of 3×10^{-16}, with unloaded quality factors as high as 10^{11}. For comparison, recent work with superconductor-coated sapphire-resonators (Luiten *et al.*, 1994) and compensated sapphire oscillators (Dick *et al.*, 1998) have reached short-term frequency stabilities between 10^{-14} and 10^{-15}.

The LPI principle of GR 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 an improved LPI test 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's motion in its eccentric orbit around the Sun. The basis of the test is the observation that the frequencies of a microwave cavity and an atomic clock have different dependencies on fundamental physical constants. This test is expected to improve the 2% LPI measurement of Turneaure *et al.* (1983) by a factor of about 100. For intervals in the range 10^2 - 10^4 s SUMO will provide a high stability, low phase noise signal capable of being slaved to atomic clocks, providing them with a 'flywheel' and greatly enhancing their performance. SUMO will be an insert in the LTMPF and will require three to six months of operation in order to meet its science objectives.

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 (Hills and Hall, 1990) on the isotropy is $\Delta c/c \sim 2\times10^{-13}$. Comparing the frequencies of two orthogonaly mounted cavities at roll and orbital rates, the expected limit for the linear isotropy will be $\Delta c/c \sim 10^{-16}$. Longer-term experiments, using two or more SUMO-type oscillators and separate facilities, include precision red-shift measurements, verification of the isotropy of the velocity of light, and possibly the detection of gravitational waves.

APPARATUS

The SUMO project currently uses the original SCSO setup to develop and test system and electronics enhancements. The SCSO microwave resonator is a solid superconducting niobium TM_{010} mode cavity, operating in ultrahigh vacuum at 1.2K, at 8.6GHz. Mechanical stability is achieved by making the walls of the cavity about the same thickness as its 1.3cm radius. Figure 1 is a schematic section through the SCSO. 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 of a permanent internal vacuum with a pinch-off, and by the exterior vacuum can. Magnetic shields insure that the field at the cavity is less than 10^{-2} Gauss. The connection between the cavity and the room temperature electronics was made using a stainless steel waveguide with copper baffles in order to minimize thermal losses. In the SCSO setup, the temperature of the cavity was controlled to 1 μK short term and to about 10 μK per week. The dewar and the microwave system were tilt-controlled to reduce the effect of variations in local gravity.

The SCSO electronics system utilizes the high Q cavity resonance to stabilize a voltage-controlled oscillator. In the original design a small part of the power of a Gunn oscillator with variable frequency was used to excite the cavity. This signal was phase-modulated at 1MHz, 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 output. For the original measurements of Turneaure *et al.*, (1983) the Allan variance σ behaved as $\sigma = 10^{-14}/\tau$ for $\tau < 30$ s, reaching a noise floor of 3×10^{-16} for $30 < \tau < 1000$ sec. For $\tau > 1000$ s the fractional long-term drift of the SCSO was about 2×10^{-13}/day. Figure 2 shows a block diagram of the frequency-locked loop presently in use for the development of the SUMO electronics. The design is similar to the original SCSO electronics, but upgraded to take account of operating experience. Additional improvements will include the use of modern microwave technology and a power-stabilizing servo. The present signal source is a varactor-tuned dielectric resonator oscillator selected for very low close-in phase noise.

Vibrations and variations in local gravity can change the frequency by changing the dimensions of the cavity. For the TM_{010} mode cavity the frequency is dependent to first order only on the average diameter of the resonator. In the SCSO measurements, earth tides were easily observable at the 10^{-14} frequency variation level, in agreement with model calculations. The sensitivity of the cavity frequency to variations in acceleration can be reduced significantly by supporting the cavity from its center, therefore compensating any change in the length of the top half with an opposite change in the bottom half. Figure 3 shows a finite element model of the SUMO cavity, including the mid-cavity supporting structure. The results of the finite-element analysis for three different support systems for the cavity are shown in Figure 4. The variation of the cavity radius, in nm, is plotted versus the vertical cavity axis from top to bottom, for top-flange support, bottom-flange support, and best center-flange implementation support. 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 at least two orders of magnitude. 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.

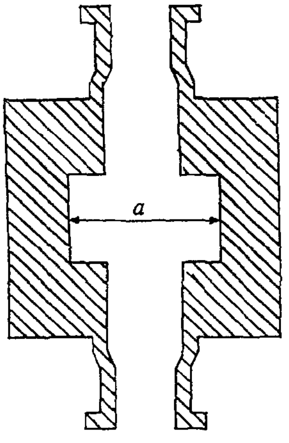

Fig. 1. Cross section of SCSO with a=1.3 cm. TM_{010} mode ν=8.6 GHz.

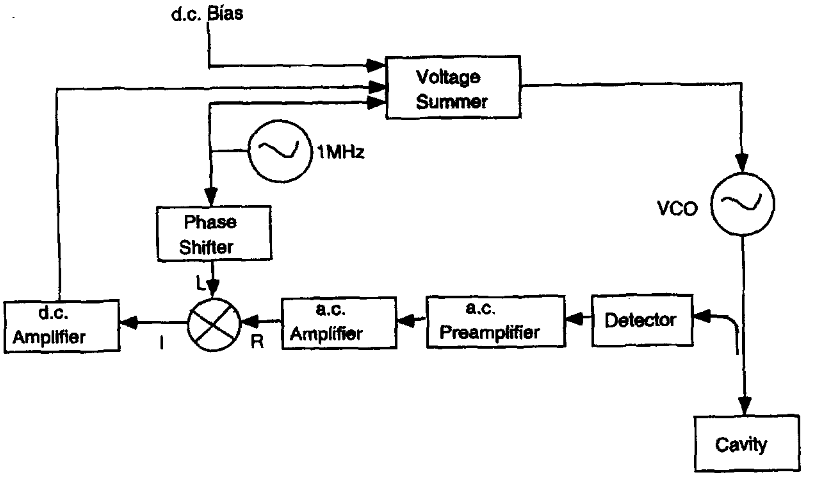

Fig. 2. Block diagram of the frequency-locked loop

Fluctuations in the microwave energy stored in the cavity change the radiation pressure on the cavity walls and modify the non-linear part of the superconducting surface reactance. Fortunately, these are quite small effects that can be minimized with a modest level of power control. An alternative approach is to operate with lower power. Utilization of a cryogenic low noise tunnel diode detector with an effective noise temperature in the 100's of K (rather than in the 1000's of K as previously) would allow us to lower the stored power to $\sim 6\times10^{-9}$ J. In the absence of any active power control, where the fluctuations are typically of order 1%, we would expect a limiting frequency stability, $\delta f/f$, of 10^{-17}. Thus for the present set of experiments, we may be able to avoid using a power control circuit. Temperature variations affect the frequency stability via thermal expansion and the temperature dependence of the skin depth. At 1.2 K these effects are approximately equal and the total temperature coefficient is around 2×10^{-10}/K.

Paramagnetic salt thermometers (Lipa *et al.*, 1994) have been used in space to detect temperature changes of less than 1nK, and to control drift rates to below 10^{-12} K/s. We plan to use a simplified version of this system to achieve temperature control to about 5 nK, reducing the temperature-induced frequency fluctuations to the 10^{-18} level. Figure 5 shows a schematic view of the 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. In another mode, one cavity could be slaved to an atomic clock. With the above improvements we expect to be able to reduce the noise floor well into the 10^{-17} range frequency stability level. Comprehensive analyses of the electronics and cavity support requirements are in progress.

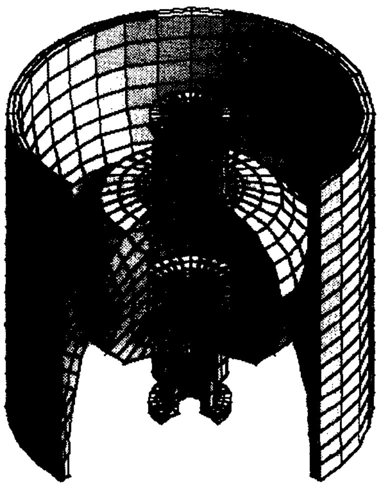

Fig. 3. Finite element model for center-supported cavity

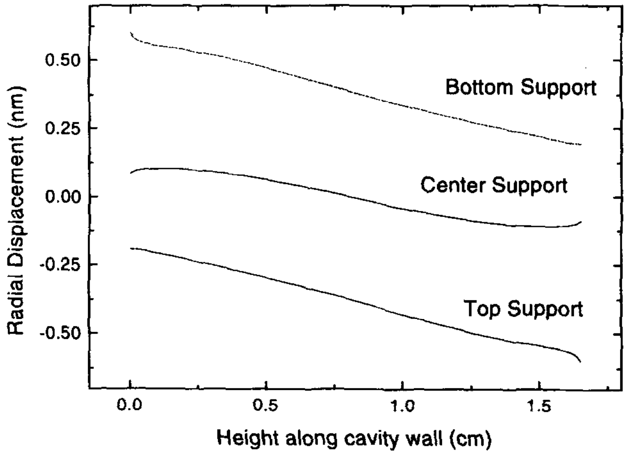

Fig. 4. Finite element analysis results for three cavity-support methods: top, bottom, and best center flange implementation

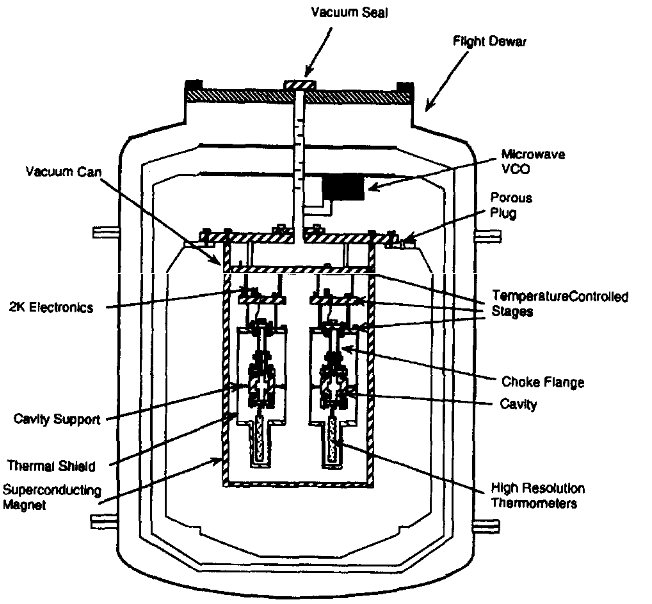

Fig. 5. Flight instrument configuration

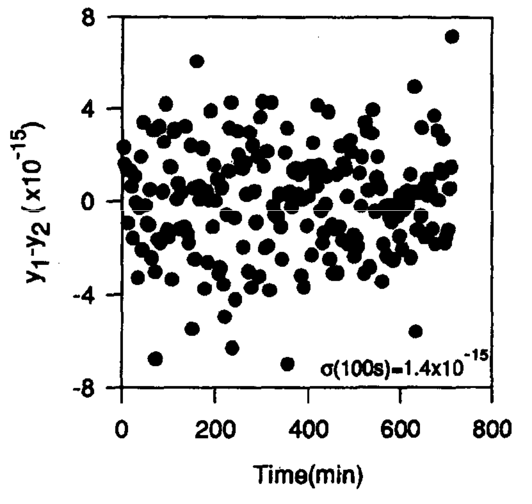

Fig. 6. Preliminary SUMO frequency stability

STATUS

The quality factors of the original cavities have been re-measured to be about 5×10^{10} after long term storage in vacuum. While the original data is lost, this appears to be a deterioration of at most a factor of two over 20 years. Figure 6 shows the variance of the frequency for adjacent 100 s averaging intervals over a 12 hour run for a pair of cavities and using a new electronics system. The corresponding Allan variance is 1.4×10^{-15} at 100 s. To date, no vibration or tilt isolation has been implemented, and the temperature has been controlled to only about 5 μK, at an operating temperature of 1.5 K. The limitation on the frequency stability for this experimental setup is consistent with the observed temperature fluctuations in the thermal control servos. We are currently developing the detailed plans for center-supported cavities and new thermal control systems using the paramagnetic salt thermometers.

CONCLUSIONS

The analysis of the limitations of superconducting cavity oscillators indicates that improvements to the 10^{-17} range are quite possible. The original clock technology demonstrated a frequency stability of 3×10^{-16} for time intervals between 10 and 1000 seconds. Preliminary measurements have already achieved levels in the 10^{-15} range at 1.5 K, competitive with modern atomic clocks. A design suitable for use in space is under development. On the Space Station, SUMO can be used in conjunction with atomic clocks to perform a test of the LPI assumption of GR, the equivalence principle via the gravitational redshift, and as a low phase-noise flywheel for other clocks.

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