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ENVIRONMENTAL EFFECTS ON THE MEDIUM AND LONG TERM FREQUENCY STABILITY OF QUARTZ OSCILLATORS

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ABSTRACT

The medium and long term frequency stability of most quartz oscillators is degraded by various environmental effects, the most important of which appear to be acceleration, temperature, load change, pressure, and possibly humidity. In this paper we show preliminary data which indicate that the medium and long term frequency stability of some oscillators can be improved by controlling the pressure and humidity around the oscillator. On one 5 MHz oscillator controlled by a fifth-overtone, AT-cut resonator of the BVA style, we measured a fractional frequency stability, $\sigma_y(\tau) = 3\ (\pm 1) \times 10^{-13}$, in a bandwidth of 100 Hz for measurement times of 0.03 s to 460,000 s after removing a drift of -7.7×10^{-13}/day. Initial measurements on a different oscillator controlled by a traditional 5 MHz, fifth-overtone, AT-cut resonator indicated up to a factor of 2 improvement in the medium term stability when the pressure and humidity were controlled. These data were obtained on only one oscillator of each type and may or may not be representative. If these improvements can be obtained in other precision crystal oscillators, then crystal oscillators may become usable in some applications generally thought to require atomic standards.

INTRODUCTION

Most precision, quartz-crystal-controlled oscillators exhibit a flicker-of-frequency floor which is approximately given by the phenomenological equation $\sigma_y(\tau) = 2.8 \times 10^{-7}/Q$ for measurement times of order Q/ν. Here, $\sigma_y(\tau)$ is the fractional frequency stability, ν is the oscillation frequency, and Q is the unloaded quality factor of the resonator [1-7]. For times much longer than Q/ν, the frequency stability generally is degraded by various environmental effects. The most important effects appear to be acceleration, temperature, load change, pressure and possibly humidity. Some oscillators may also show a sensitivity to magnetic field probably caused by the electronics. The level of flicker frequency appears to be very closely tied to the inverse of the forth power of the unloaded quality factor, Q^{-4}. Gagnepain has shown that the predominant contribution to the flicker level is acoustic scattering losses [6]. In this paper we show experimentally that when the obvious environmental effects such as acceleration, temperature, pressure, humidity, and load changes are controlled, the frequency stability (of at least one crystal controlled oscillator) is constant within a factor of 2 for measurement times from 0.03 s to at least 460,000 s. This indicates that the observed flicker-of-frequency spectrum is not just a superposition of multiple noise processes over a narrow range of times, but rather represents a fundamental noise process within the oscillator and quite likely is due to the quartz resonator, which extends over 7 orders of magnitude in Fourier frequency or averaging times. If such performance can be duplicated in other oscillators, then the areas in which quartz controlled oscillators can be used may potentially be expanded.

MEASUREMENTS OF MEDIUM AND LONG TERM FREQUENCY STABILITY

We have recently begun measurements on the medium and long term frequency stability of several bulk-wave, quartz-resonator-controlled oscillators. One of the oscillators uses a traditional fifth-overtone, 5 MHz, AT-cut resonator while the other uses a fifth-overtone, 5 MHz, AT-cut resonator of the BVA design [8]. They are both precision oscillators exhibiting very good frequency stability for measurement times from 0.03 s to 100 s. For these tests the changes in acceleration, vibration, and load impedance were minimized. The initial tests were performed in a room with temperature changes of about ± 1 K and the naturally occurring changes in atmospheric pressure and humidity.

Figure 1 shows the frequency offset from the NBS time scale for the oscillator that used the traditional AT-cut resonator for averaging times of two hours. Figure 2 shows the fractional frequency stability, $\sigma_y(\tau)$, as a function of measurement time with the drift removed. These data are consistent with random-walk-frequency noise and are similar to those observed by others with AT resonators subject to temperature fluctuations [3,5]. Figure 3 shows the initial frequency stability results when this oscillator was installed inside a simple chamber which stabilized the pressure and humidity. At longer times there is about a factor of 2 improvement in the frequency stability over that obtained while it was open to the atmosphere.

Figure 4 shows the frequency offset from the NBS time scale for the 5 MHz oscillator which used the fifth-overtone, AT-cut, BVA resonator. The temperature stability was of order ± 1 K. Figure 5 shows the fractional frequency stability with the drift removed. Figure 6 shows the frequency of the BVA controlled oscillator after installing it inside a very simple enclosure which largely isolated it from changes in both the external pressure and humidity and controlled the temperature to about ± 0.1 K. The average frequency shift of several in 10^{11} from the value shown in figure 4 appears to be largely due to changes in the load impedance which occurred when the length of the cable was changed. Initially, the frequency drift rate was nearly zero but returned to near the original value after one week of operation. Figure 7 shows the fractional frequency stability, $\sigma_y(\tau)$, as a function of measurement time (exclusive of the first 8 days) with the drift removed. Degrading the temperature stability to ± 1 K degrades the frequency stability approximately 50%. We have also included the short-term-stability performance for a measurement bandwidth of 100 Hz. The 90% error bars on the medium and long term data have been calculated for flicker noise. Figure 8 shows the time residuals after removing the second difference.

These data indicate that, at least for the one BVA oscillator, the noise can be modeled as white phase noise in the short term (which is most likely due to the electronics [1]), flicker frequency in the medium term, and frequency drift in the long term. The random walk frequency noise observed in the traditional AT-cut, resonator-controlled oscillator and in the BVA-AT-cut oscillator open to the atmosphere is insignificant when the pressure and humidity are controlled (under benign laboratory conditions). The mechanism by which the atmospheric fluctuations perturb the frequency are open to speculation. Perhaps the pressure and humidity fluctuations cause small changes in the temperature and/or temperature gradients within the oven.

CONCLUSION

We have shown that the medium term frequency stability of two different 5 MHz oscillators controlled by two different types of AT-cut resonators are somewhat sensitive to changes in atmospheric pressure and possibly humidity. Stabilizing the pressure and humidity, in addition to the normal parameters in an otherwise controlled laboratory setting, improves the frequency stability for measurement times in the region of hours to days. In particular the frequency stability of the BVA controlled oscillator was spectacular, $\sigma_y(\tau) = 3\ (\pm\ 1) \times 10^{-13}$ for measurement times from 0.03 to 460,000 s (measurement bandwidth 100 Hz). Further tests on oscillators controlled by both AT- and SC-cut resonators of several different designs are necessary in order to verify that these effects are generic to unsealed precision oscillators. If this indeed proves to be true, then quartz crystal controlled oscillators engineered to minimize these effects may well be used in areas which have traditionally been dominated by atomic frequency standards.

ACKNOWLEDGEMENTS

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REFERENCES

1. F.L. Walls and A.E. Wainwright, "Measurement of the Short Term Stability of Quartz Crystal Resonators and the Implications for Crystal Oscillator Design and Applications," IEEE Transactions on Instrumentation and Measurement, IM-24, 15-20 (1975).

2. J.J. Gagnepain, J. Ubersfeld, G. Goujon and P. Handel, "Relation Between 1/f Noise and Q Factor in Quartz Resonators at Room and Low Temperatures, First Theoretical Interpretation," In Proc. of the 35th Annual Symposium on Frequency Control, 476-483 (1981).

3. J.J. Gagnepain, "Fundamental Noise Studies of Quartz Crystal Resonators, Proc. of the 30th Annual Symposium on Frequency Control, 84-92 (1976).

4. J.J. Gagnepain, M. Oliver and F.L. Walls, "Excess Noise in Quartz Crystal Resonators," in Proc. of the 37th Annual Symposium on Frequency Control, 218-225 (1983).

5. Y. Noguchi, Y. Teramachi and T. Musha, "1/f Frequency Fluctuation of a Quartz Crystal Oscillator, Proc. of the 35th Annual Symposium on Frequency Control, 484-491 (1981).

6. M. Planat and J.J. Gagnepain, "Temperature Dependence of 1/f Noise in Quartz Resonators in Relation with Acoustic Attenuation," Noise in Physical Systems and 1/f Noise, (Edited by A. D'Amico and P. Mazzetti, Elsevier Science Publishers B.V., 1986), pp. 323-326.

7. T.E. Parker, "Characteristics and Sources of Phase Noise in Stable Oscillators," Proc. of the 41st Annual Symposium on Frequency Control, 99-110 (1987).

8. R. Besson, "A New Piezoelectric Resonator Design," Proc. 30th Symposium on Frequency Control, 78-83 (1976).

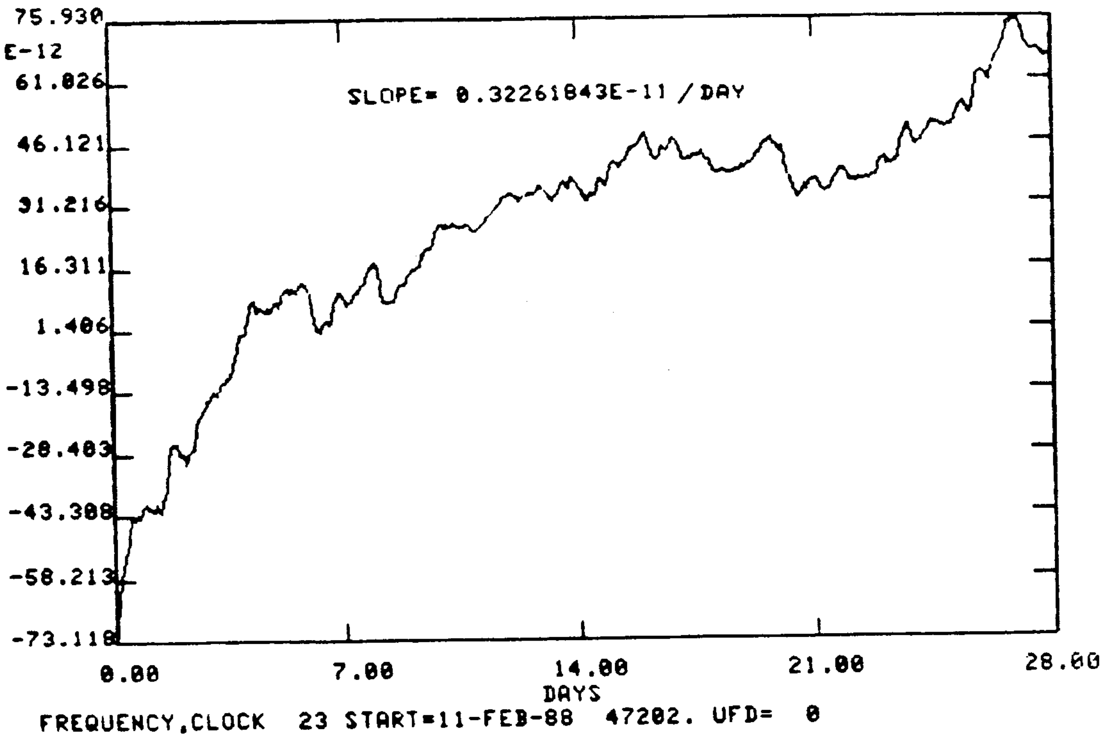

Figure 1. Frequency offset from the NBS time scale for a 5 MHz oscillator (clock 23) controlled by a fifth-overtone, AT-cut resonator of traditional design.

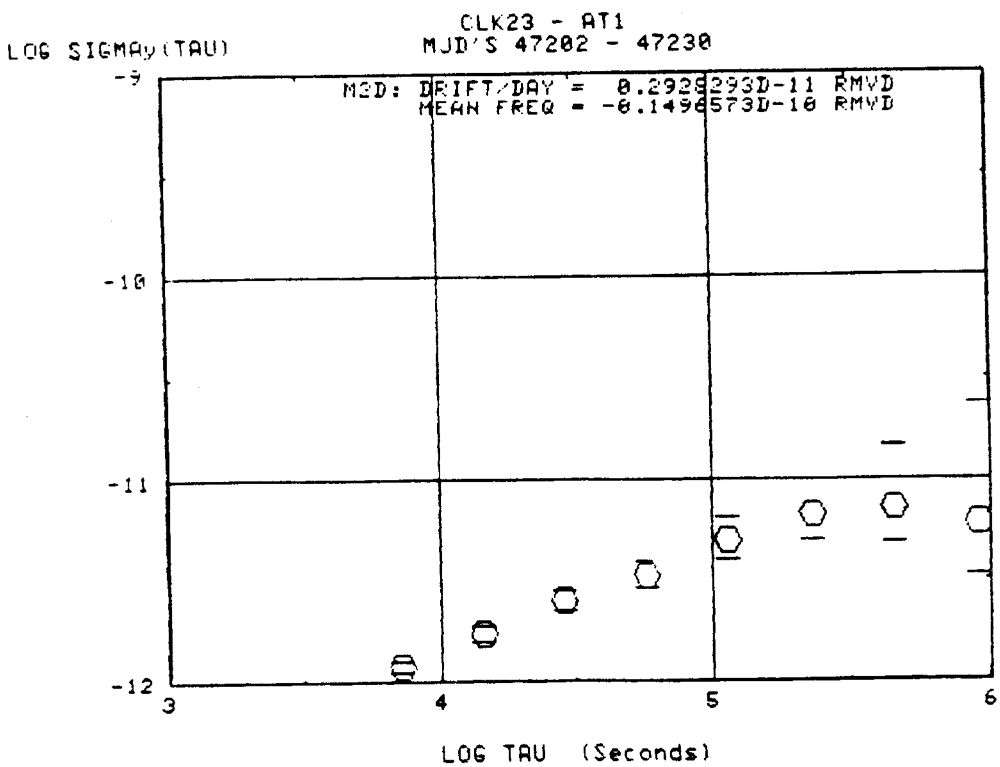

Figure 2. Fractional frequency stability, $\sigma_y(\tau)$, as a function of measurement time for clock 23 with the drift removed. The noise is nearly pure random walk frequency.

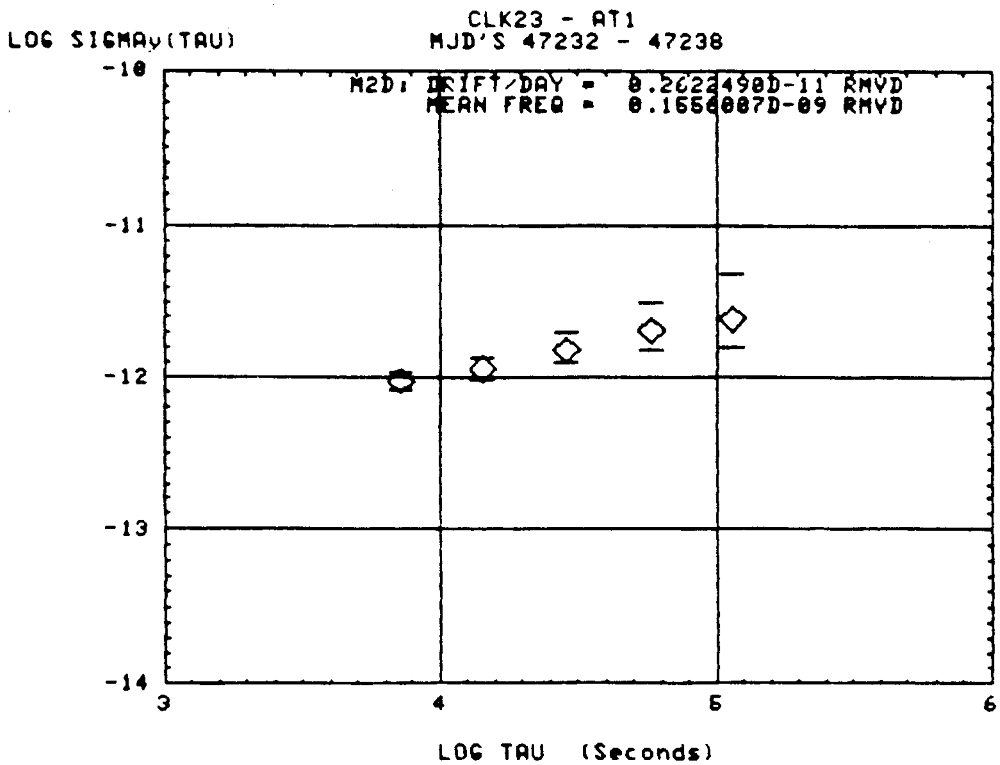

Figure 3. Fractional frequency stability, $\sigma_y(\tau)$, of clock 23 after it was installed inside a chamber to control the atmospheric pressure and humidity surrounding it.

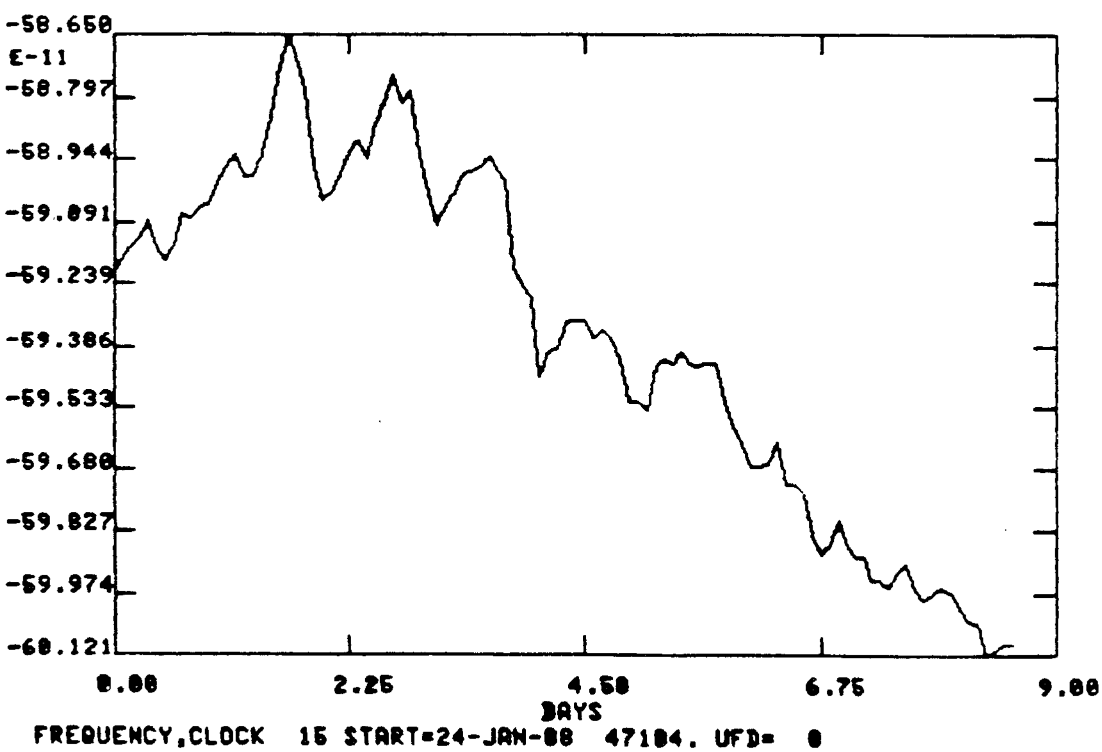

Figure 4. Frequency offset from the NBS time scale for a 5 MHz oscillator (clock 15) controlled by a fifth-overtone, AT-cut resonator of the BVA style [8].

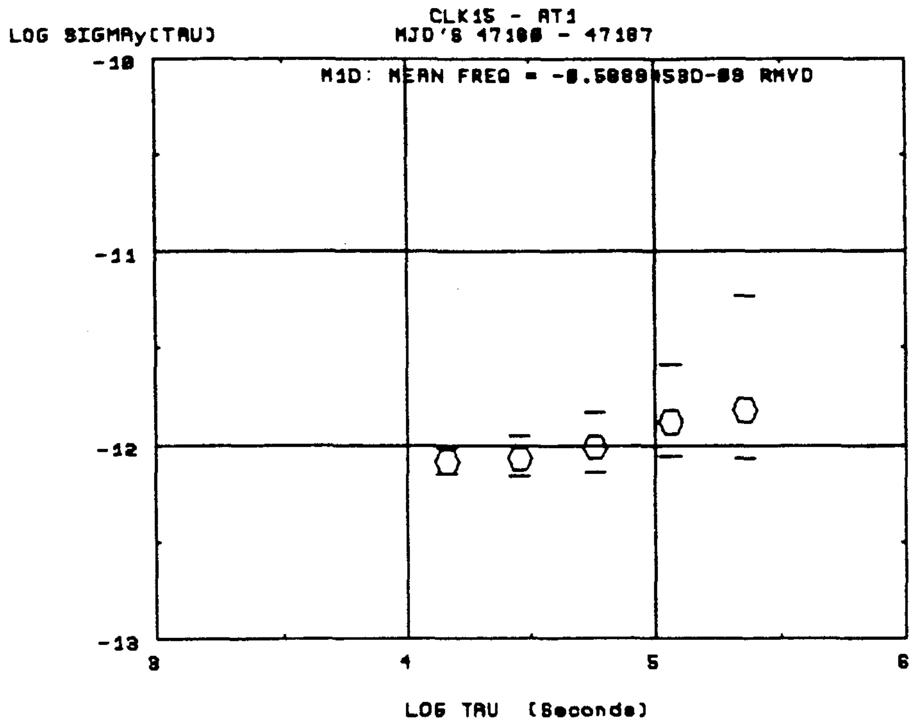

Figure 5. Fractional frequency stability, $\sigma_y(\tau)$, of clock 15 as a function of measurement time with the drift removed. The short term frequency stability is the same as that shown in figure 7.

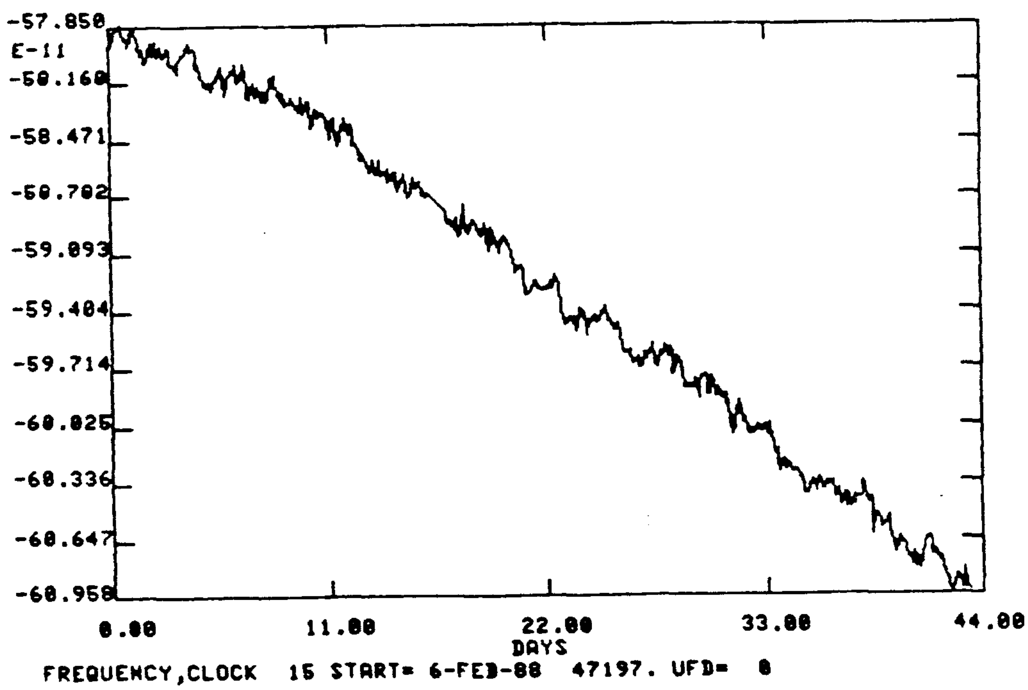

Figure 6. Frequency offset of clock 15 after installing it inside a simple chamber to control the atmospheric pressure and humidity surrounding it, and adding temperature control to approximately ± 0.1 K.

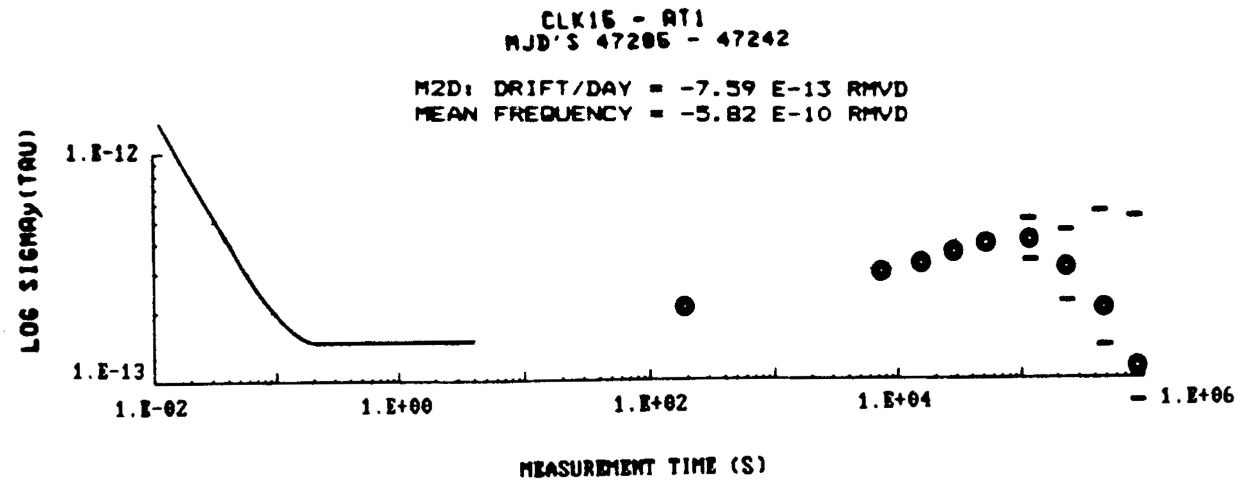

Figure 7. Fractional frequency stability, $\sigma_y(\tau)$, of clock 15 inside the chamber and additional temperature control to approximately ± 0.1 K with the drift removed. The short term frequency stability in a measurement bandwidth of 100 Hz is also indicated.

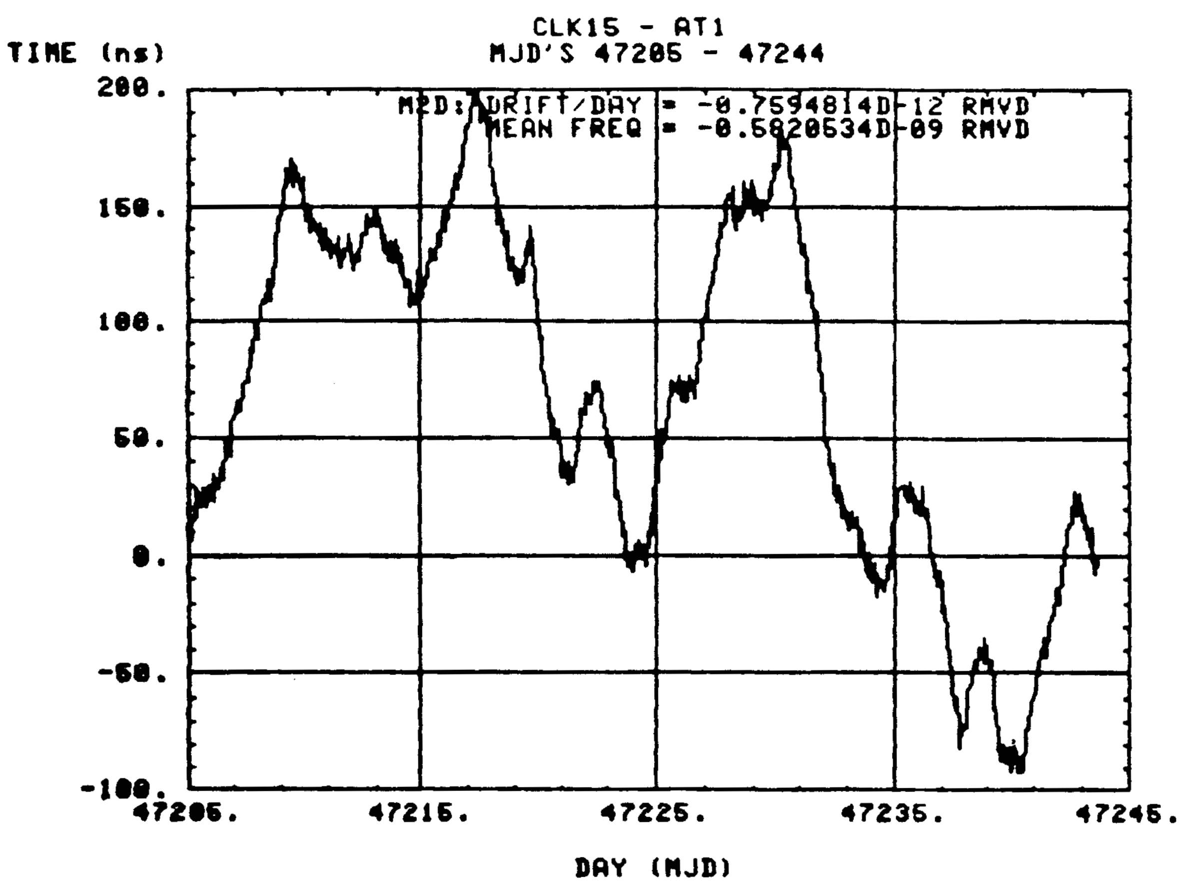

Figure 8. Time residuals of clock 15 inside the chamber after removing a 2nd difference as an approximation to the frequency drift.