1997 IEEE INTERNATIONAL FREQUENCY CONTROL SYMPOSIUM

ENVIRONMENTAL SENSITIVITIES OF CAVITY-TUNED HYDROGEN MASERS

T. E. Parker, J. E. Gray and T. K. Peppler

National Institute of Standards and Technology
Time and Frequency Division, 847.5
325 Broadway
Boulder, CO 80303 USA

Abstract

With the increasing number of cavity-tuned hydrogen masers in use around the world in time scales and as reference oscillators for primary frequency standards, it is necessary to have a complete understanding of the environmental sensitivities of the masers. Common-mode frequency fluctuations are of great concern and the degradation of maser frequency stability due to environmental fluctuations should be minimized. Measurements of environmental sensitivities (temperature, relative humidity, atmospheric pressure, line voltage and magnetic field) have demonstrated that the frequency stability of cavity-tuned hydrogen masers is not significantly degraded if the masers are contained in a reasonably controlled environment.

KEY WORDS - Environmental sensitivities, hydrogen maser, cavity tuned

Introduction

The number of hydrogen masers being used in time scales around the world has increased significantly over the last ten years [1-3]. The Bureau International des Poids et Mesures (BIPM) now uses data from 33 masers in the generation of International Atomic Time (TAI). Masers are also now commonly used as reference oscillators for primary frequency standards since they offer fractional frequency stabilities below 1×10^{-15} at time intervals on the order of hours to days. With cavity tuning this stability can be extended to tens of days. The National Institute of Standards and Technology (NIST) has five cavity-tuned masers [4] at its site in Boulder, Colorado, USA, three of which are currently in the NIST AT1 time scale [1]. The remaining two masers will very likely be in the scale by the end of 1997. One of the masers is also routinely used as the reference oscillator for the primary frequency standard NIST-7 [5], and for research on new technologies for primary frequency standards. Each maser at NIST is contained in its own environmental chamber to control temperature (~ ± 0.1 °C peak to peak) and relative humidity (~ ± 2 % peak to peak).

With the increased role of masers in time scales and as references for primary frequency standards it is important to have accurate knowledge concerning the environmental sensitivities of the masers for time intervals up to at least several days. In most laboratories the only frequency source with short-term frequency stability comparable to that of a maser is another maser. Therefore, it is necessary to know if there are any common-mode frequency fluctuations which would not be visible in a comparison between masers. Since common-mode fluctuations generally come from environmental sensitivities, these sensitivities must be known. Pressure sensitivity is of particular concern since controlling pressure is very expensive and, if not controlled, all of the masers at a given site will respond to the same fluctuations in atmospheric pressure. Furthermore, the lowest pressure sensitivity currently guaranteed by the manufacturer [4] would result in frequency fluctuations larger than 1×10^{-14} occurring simultaneously in all of the masers just due to normal barometric pressure fluctuations. These fluctuations would not be observable in comparisons among masers at the same site. Previous measurements of the pressure sensitivity of hydrogen masers without cavity tuning have shown evidence of frequency fluctuations as large as 1×10^{-13} [6]. Fortunately, we have found that the pressure sensitivity in the cavity-tuned masers is at least 10 times smaller than the manufacturer's specification.

In a more general sense, it is also desirable to know to what extent environmental fluctuations degrade the maser stability even if the frequency fluctuations are not common-mode. To accomplish these goals a program is underway at NIST to measure the environmental sensitivities of the masers, and where possible to do this in the same type of chamber they are normally operated in. The sensitivities of the maser frequencies to (a) temperature, (b) relative humidity (RH), (c) barometric pressure, (d) line voltage, and (e) vertical magnetic field (the most sensitive direction) have been measured on several masers. Previous measurements of environmental sensitivities of cavity-tuned hydrogen masers have been made [7] but not over the appropriate time interval or at the level of accuracy required for use in time scales or as references for primary frequency standards.

Environmental Sensitivities

Frequency sensitivities to temperature, relative humidity, line voltage, and magnetic field were all measured in the same type of chamber in which the masers normally operate. This was done to ensure that gradients in temperature and humidity present in the chambers used for normal operation are also present during the measurements of the sensitivities. However, pressure sensitivity had to be measured in a specially constructed chamber that has approximately the same internal dimensions as the other chambers. This chamber is capable of pressures changes up to +/- 15% of an atmosphere about the ambient barometric pressure. The frequency sensitivity for each environmental parameter was measured by changing the appropriate parameter and recording simultaneously the frequency difference between the test maser and at least two other reference masers that were held in a constant environment. In each case every effort was made to change only one parameter at a time. It is important to note that no attempt was made to understand the physical cause of any particular environmental sensitivity, but simply to characterize its value. Apparent sensitivities to pressure, humidity, and line voltage may in fact be caused partially or entirely by changes in temperature or temperature gradients inside the maser. Knowing these details is important to reducing the environmental sensitivities of the masers, but is not necessary in order to quantify the sensitivities.

Measurement of Temperature Sensitivity

Figure 1 illustrates how the temperature sensitivity measurements were carried out. The lower trace shows the temperature as measured by a sensor mounted on the outside of Maser 5 and the upper trace shows the frequency difference between Maser 5 and one of the reference masers. Data were taken at 2 hour intervals. Over the course of thirty five days the temperature was increased above normal by two degrees for a period of seven days and also decreased below normal for a seven day interval. The average frequency drift between the two masers has been removed from the data in Fig. 1. The frequency of the test maser shows a transient shift at the time of each temperature transition, which lasts for about 16 hours, followed by a steady-state shift which correlates with the steady-state temperature. These characteristics indicate the presence of both dynamic and a static temperature coefficients. The static temperature coefficient was determined by comparing the average frequency over the final six-day interval of each temperature deviation period with the average of the frequencies in the periods immediately before and after the temperature excursion. Using only the last six days of each seven day cycle eliminates the dynamic effects from the measurement. The measured frequency shift was then divided by the change in temperature to give the static temperature sensitivity, which is $-3.4\pm0.2 \times 10^{-15}/°C$ in this case. A complete measurement cycle takes thirty five days. There was a significant amount of frequency noise in the data, so the same analysis was performed with two or three different reference masers. The average of these results serves to reduce the influence of the reference maser noise.

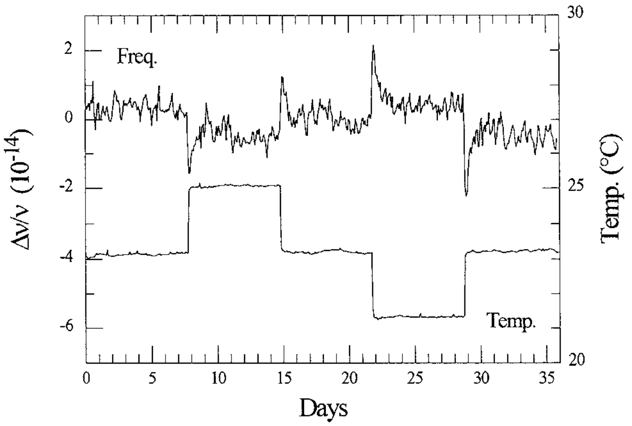

Figure 1 Influence of temperature steps on the frequency of Maser 5.

A precise value for the dynamic temperature coefficient cannot be obtained since the internal temperature of the maser was not measured. The temperature measured on the outer surface of the maser changes much more rapidly than that of the internal maser parts that actually affect the frequency. However, a transient frequency shift of approximately 2×10^{-15} occurred at each 2 °C temperature change.

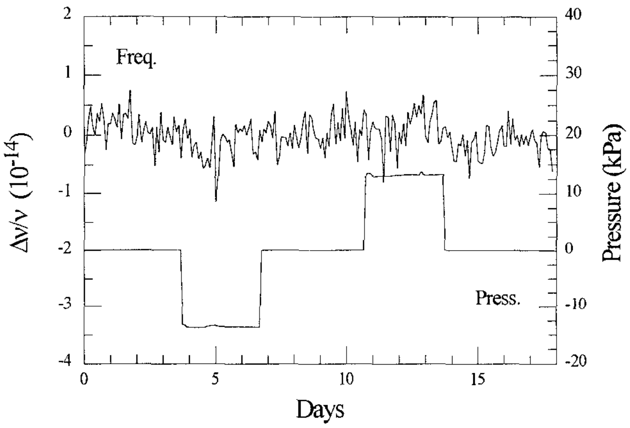

Figure 2 Influence of pressure steps on the frequency of Maser 4.

Measurement of Pressure Sensitivity

Figure 2 shows data from Maser 4 for changes in pressure about the ambient atmospheric pressure. The corresponding frequency changes are less obvious here, but a pressure sensitivity of $+0.8\pm0.2 \times 10^{-15}$ per 5 kPa of pressure change was observed (0.1 kPa = 1 millibar). It was necessary to repeat the cycle shown in Fig. 2 several times to reduce the measurement uncertainty to a reasonable level. Since no dynamic effects are present, the measurement cycle here was reduced to only sixteen days, with three day pressure steps and a four day interval between steps. The four day interval was chosen simply to keep the measurements in synchronization with the normal work week.

Summary of Results

Table 1 summarizes the results of all the tests performed to date. Table blocks with no values indicate that those parameters have not yet been measured in our laboratory. This is also true for the magnetic field sensitivities of Masers 3 and 4, where only the values measured by the manufacturer are shown. Line-voltage and magnetic field sensitivities were determined using the same measurement cycle as shown for pressure in Fig. 2. The measurement of sensitivity to relative humidity used a longer cycle as discussed below. No data is available for Masers 1 or 2 since they have been in the NIST time scale since 1994 and cannot be used for environmental testing.

Temperature: All of the measured static temperature sensitivities (S_T) are within the manufacturer's specifications. The smaller value observed on Maser 5 reflects an additional level of temperature stabilization added by the manufacturer to that maser. Masers 3 and 4 also exhibited dynamic temperature effects of about the same magnitude as that observed on Maser 5, but they were less significant and more difficult to observe because of the larger static coefficients on these masers. Since relative humidity is also controlled in these chambers, there was no change in relative humidity during the temperature tests. However, this does result in a change in absolute humidity that is coherent with the temperature changes. No attempt was made to correct for this situation since the same coherence would also be present for the smaller temperature fluctuations that exist in normal

Table 1 Summary of Environmental Sensitivities

Sensitivity	Maser 3	Maser 4	Maser 5
$S_T(10^{-15}/^\circ C)$	-9±1	-8±1	-3.4±.2*
$S_{RH}(10^{-15}/\%)$	+0.4±.1	-0.2±.1	–
$S_P(10^{-15}/5\ \mathrm{kPa})$	+0.4±1.8	+0.8±.2	–
$S_V(10^{-15}/\mathrm{volt})$	$<\|0.1\|$	–	–
$S_H(10^{-15}/100\ \mu T)$	17†	6†	47±14

* Dynamic temperature response is not included

† As measured by manufacturer at ± 100 μT (± 1 gauss)

operation.

Relative Humidity: Sensitivities to relative humidity (S_{RH}) are quite small and large steps (+/- 9%) in humidity had to be used to measure them. Small changes in temperature were sometimes observed to coincide with the humidity steps, but no corrections for temperature were made in calculating the values in Table 1. If corrections are made for the temperature changes the humidity sensitivities are slightly reduced. A humidity step length of fourteen to twenty one days was used with the humidity measurements to ensure that processes with long time constants would be observed. Test cycles much longer than this are of limited value since frequency drift or aging in masers is usually large enough to make environmental parameters irrelevant in the long term.

Pressure: The manufacturer guarantees a pressure sensitivity (S_P) of less than $15 \times 10^{-15}/5$ kPa and the observed values are smaller than this by at least a factor of ten. This effectively eliminates one potential major cause of common-mode frequency fluctuations. The large uncertainty for the pressure sensitivity of Maser 3 in Table 1 stems from the fact that this maser exhibited occasional erratic frequency transients during the course of the measurements. These transients were not reproducible like the dynamic frequency effects in Fig. 1, and did not always occur simultaneously with the pressure steps. Sometimes they would occur many hours after the pressure change, or not at all. Also, the signs of the frequency transients were not consistent with the signs of the pressure steps. It is clear however, that the transients are related to relatively sudden pressure excursions since they do not occur at all in extended periods when there are no deliberate pressure changes. No significant coherent temperature changes were observed during the pressure tests, but there were small changes (~1%) in the relative humidity that coincided with the pressure changes. Making corrections for coherent variations in temperature and/or relative humidity has little impact on the observed pressure sensitivities.

Line-voltage: Virtually no frequency sensitivity to line-voltage (S_V) changes was observed and the entry in Table 1 simply represents the measurement uncertainty. This measurement will be made more precisely on Masers 4 and 5. None of the other environmental parameters showed any coherent variations with the line-voltage variations.

Magnetic field: Sensitivity to magnetic field (S_H) was measured by placing a set of Helmholtz coils around one of the environmental chambers. The coils were oriented to create a vertical magnetic field since this is the most sensitive direction of the masers. Calibration was accomplished by measuring the field strength and uniformity as a function of electrical current with nothing inside the coils. This process needs to be repeated with the coils located around an empty environmental chamber; however, this is not expected to significantly affect the calibration since the chamber is constructed mostly of non-magnetic material. Nevertheless, until this is accomplished our results for magnetic field sensitivity should be considered as preliminary. During testing with the maser in the chamber the vertical field strength is monitored on the top surface of the maser. The field on the maser in the test chamber is typically around -73 μT (100 μT = 1 gauss) just due to the Earth's magnetic field. Changes about this value caused by current in the Helmholtz coils were found to be about twice the magnitude of those observed in the empty coils. For the purposes of calculating the magnetic field sensitivity, however, the field values for the empty coils were used. Tests were performed for field changes of +/- 10 μT and +/- 5 μT. S_H appears to be nonlinear since the magnitude of the observed frequency change is about 65% larger when the total field strength is increased as opposed to when the field is decreased by the same amount. The value listed in Table 1 is the average of the responses for the two directions.

Sensitivity to vertical magnetic field is of particular interest since the value for Maser 5 measured in our laboratory is almost an order of magnitude larger than that measured by the manufacturer on the same maser ($5 \times 10^{-15}/100$ μT) and is substantially larger than that of any of the other masers. Even a calibration error could not account for this discrepancy. However, the effectiveness of passive magnetic shielding is known to be highly nonlinear and our measurements are consistent with this. The manufacturer's measurements were made for field changes of +/- 100 μT, while our measurements were made for much smaller values (all relative to the empty Helmholtz coils). Another possible reason for the discrepancy is that the magnetic shielding may have degraded during the transportation of the masers from the manufacturing site to our facility. Unfortunately we have not yet been able to duplicate the manufacturer's test conditions in our laboratory because of the close proximity of the magnetic-field test chamber to other masers that are in the NIST time scale. The lower field variations of our tests are more meaningful for our situation since the normal field fluctuations in our laboratory are on the order of ± 1 μT or less. Except for magnetic field sensitivity, no significant nonlinearity was observed in any of the other environmental sensitivities, even though a range of values in the steps were used.

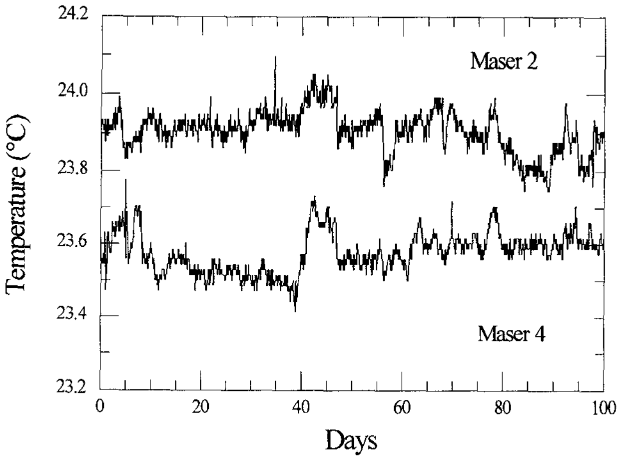

Figure 3 Temperature in two environmental chambers for a 100 day period.

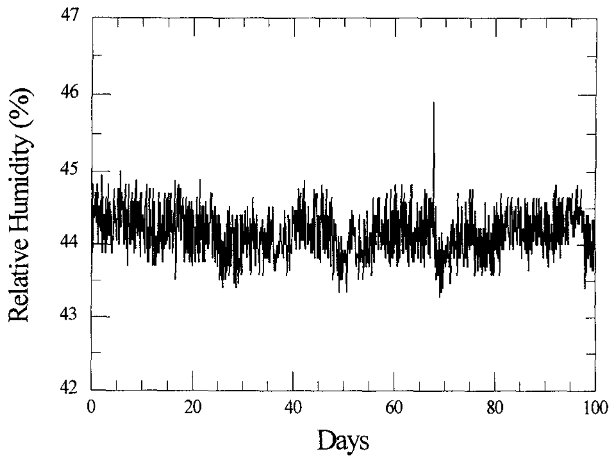

Figure 5 Relative humidity in the environmental chamber of Maser 2.

Impact of Environmental Factors on Maser Frequency Stability

In addition to the determination of the maser environmental sensitivities, the stabilities of the environmental parameters in the maser chambers and maser room are also being monitored. Temperature, relative humidity, and vertical magnetic field (the most sensitive axis of the masers) are all monitored in the chambers in which the masers normally operate. Barometric pressure and power-line voltage are monitored in the maser room. Figure 3 shows typical temperature values in the chambers of Masers 2 and 4 for a period of 100 days in early 1997. The temperatures are measured every 2 hours by sensors on the outside surface of the masers. These are the same sensors used in the temperature-sensitivity tests. Typical variations are on the order of +/- 0.1 °C, with occasional larger swings. There is only a moderate level of correlation between the temperatures in the two chambers. The rise in temperature in both chambers between the 40th and 47th day correlates with the room temperature; otherwise, most of the structure does not correlate between chambers or with the room. The correlation coefficient at a time interval of a few days is only about +0.4 between the two chambers. In contrast, the correlation coefficients between changes in frequency and changes in an environmental parameter over a time interval of a few days are respectively -0.8 and +0.5 for the data in Figs. 1 and 2.

Figure 4 is a plot of the barometric pressure in the maser room for the same 100-day period as that in Fig. 3. Figures 5 and 6 are respectively the relative humidity in the chamber for Maser 2 and the power-line voltage in the

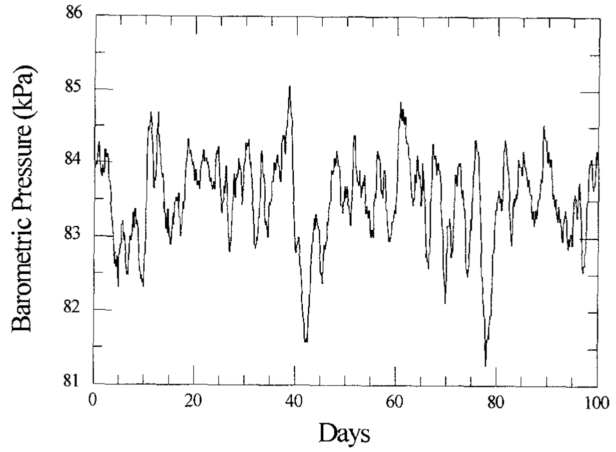

Figure 4 Barometric pressure in the maser room.

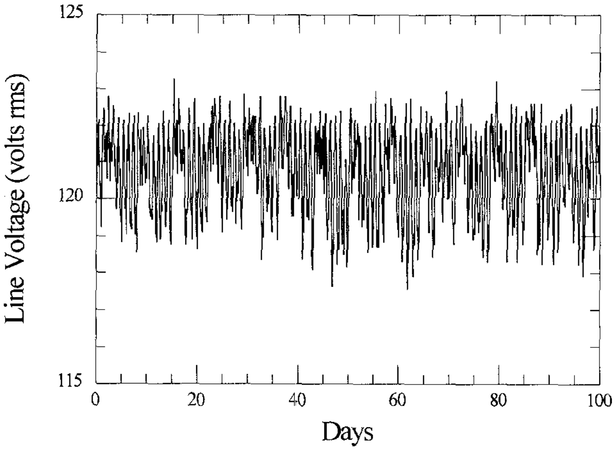

Figure 6 Line-voltage fluctuations in the maser room.

maser room for the same 100-day period. The line voltage clearly has a periodic daily variation of about 5 volts peak to peak. On weekends the amplitude of the variation is less. Figure 7 shows the vertical magnetic field in the chamber of Maser 2 for the same time interval. The obvious quantization is caused by the analog-to-digital converter. Long-term field changes as large as 1.5 μT were observed in some other chambers that were closer to objects being moved.

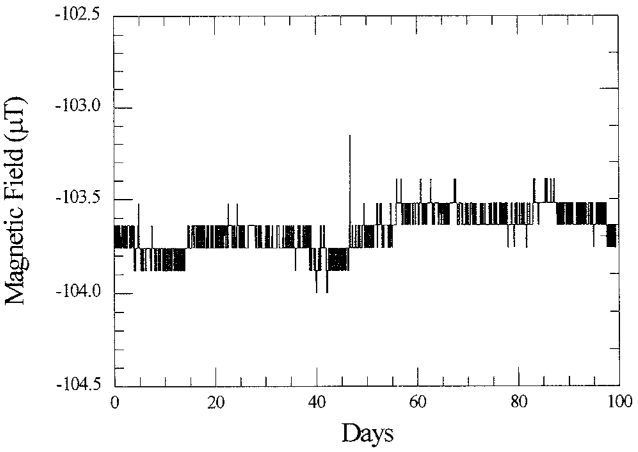

Figure 7 Vertical magnetic field in the environmental chamber of Maser 2.

A two-sample variance analysis of the observed environmental parameter fluctuations, along with the measured sensitivities, allows one to estimate the influence of the environment on the observed FM noise levels of the masers. Figure 8 shows the Allan deviation, $\sigma_y(\tau)$, of Maser 4 as determined from a 3 corner hat measurement with Masers 1 and 2. The value for $\sigma_y(\tau)$ at $\tau = 20$ days is not shown since it has a negative variance. Also shown in Fig. 8 are the estimated levels of frequency instabilities caused by the five environmental parameters being monitored. These levels of instability were quantified by first doing a two-sample variance on the environmental parameters measured either in the environmental chamber of Maser 4, or in the maser room. The effective level of frequency fluctuations induced by each of the environmental parameters was then calculated by multiplying the environmental two-sample deviations by the Maser 4 sensitivities in Table 1. Since the line-voltage sensitivity of Maser 4 has not been measured, the value for Maser 3 was used. Also a magnetic field sensitivity of 2x10^{-14}/100 μT was used. The data in Fig. 8 is for the same 100 day period shown in Figs. 3 - 7.

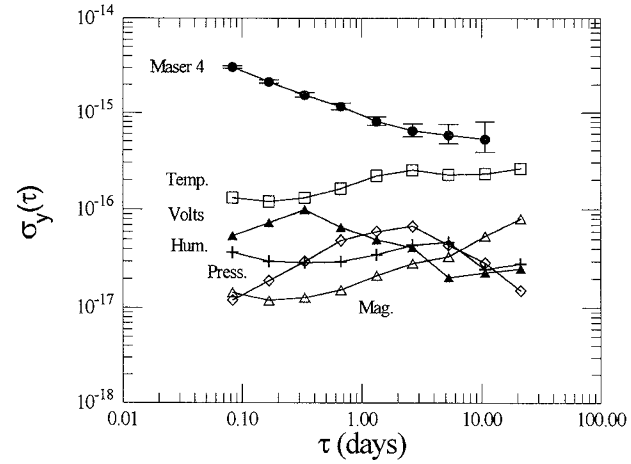

Figure 8 Allan deviation of Maser 4 •, along with environmental contributions from temperature □, line voltage ▲, relative humidity +, pressure ◊, and magnetic field Δ.

Figure 9 shows the same type of plots for Maser 2, one of our most stable masers. Since the environmental sensitivities of Maser 2 have not been measured, the largest observed sensitivity of any maser in Table 1 was used for each of the five parameters. The increasing value of $\sigma_y(\tau)$ at $\tau = 20$ days reflects the impact of frequency drift in the maser.

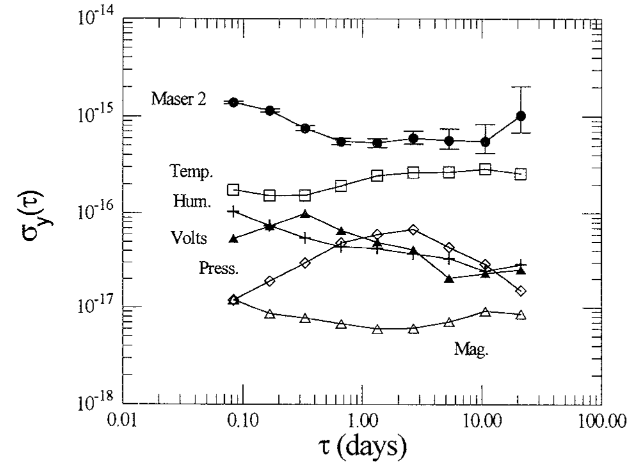

Figure 9 Allan deviation of Maser 2 •, along with environmental contributions from temperature □, line voltage ▲, relative humidity +, pressure ◊, and magnetic field Δ.

Though the maser noise reaches levels as low as 5x10^{-16}, it is clear from the data in Figs. 8 and 9 that fluctuations in environmental parameters do not play a significant role in determining the frequency stability of the masers in our laboratory. Temperature effects are the largest contributor but they are at least a factor of two below the maser noise. All of the other environmental fluctuations are below 1×10^{-16}. Even combining all of the environmental contributions in a root-sum-square process does not change the situation. An improvement to maser stability of only about 15 % would be achieved at some values of τ if all of the environmental instabilities were eliminated. It is also clear that large common-mode frequency fluctuations are not a problem since all of the environmental contributions are small. Temperature effects have the largest impact but the correlation between temperature fluctuations in different chambers is not high. Also the correlation between maser frequency and chamber temperature at time intervals of a few days is less than 0.2.

Conclusions

The flicker floors of the best masers in our laboratory are about $\sigma(\tau) = 5 \times 10^{-16}$ at τ of a few days, and our analysis indicates that none of the environmental fluctuations are large enough to be a significant contributor to this level of frequency fluctuations. However, the frequency fluctuations induced by fluctuations in temperature, barometric pressure, relative humidity, line voltage and magnetic field on maser frequency are only a factor of 2 to 10 below the measured maser noise levels, indicating that care must be exercised in controlling the environment of the masers. Of these five parameters, temperature fluctuations are the largest contributor to frequency fluctuations in the masers. There is no evidence of any significant common-mode frequency fluctuations in the masers.

Acknowledgments

The authors acknowledge the valuable assistance of Laurent Gaudron and Valentin Hanns in construction of the pressure chamber and the Helmholtz coils.

References

[1] T.E. Parker and J. Levine, "Recent Improvements in the Performance of the NIST AT1 Time Scale," in *Proc. 1996 IEEE International Frequency Control Symposium*, pp. 1131-1136, 1996.

[2] L. A. Breakiron, "Timescale Algorithms Combining Cesium Clocks and Hydrogen Masers," in *Proc. 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp. 297-305, 1991.

[3] C. Thomas, "Impact of New Clock Technologies on the Stability and Accuracy of the International Atomic Time TAI," *IEEE Trans. on Ultrason., Ferroelect., and Freq. Contr.*, vol. 44, no. 3, pp. 693-700, 1997.

[4] Sigma Tau Standards series 2000 cavity-tuned hydrogen masers. Commercial equipment has been identified since it would be impossible to duplicate the results without this information. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology.

[5] W.D. Lee, J.H. Shirley, J.P. Lowe and R.E. Drullinger, "The Accuracy Evaluation of NIST-7," *IEEE Trans. Instrum. Meas.*, vol. IM-44, no. 2, pp. 120-123, 1995.

[6] R.A. Dragonette and J.J Suter, "Barometric Pressure Induced Frequency Offsets in Hydrogen Masers," in *Proc. of the 45th Annual Symposium on Frequency Control*, pp. 586-590, 1991

[7] T.K. Tucker, "Operating and Environmental Characteristics of Sigma Tau Hydrogen Masers used in the Very Long Baseline Array (VLBA)," in *Proc. 20th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, pp. 325-336, 1988.