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INFLUENCE OF ENVIRONMENTAL FACTORS ON HYDROGEN MASER FREQUENCY STABILITY

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ABSTRACT

It is necessary to have a complete understanding of the environmental sensitivities of hydrogen masers in order to obtain optimum frequency stability, and to avoid common-mode frequency fluctuations. Measurements of environmental sensitivities (temperature, relative humidity, atmospheric pressure, line voltage and magnetic field) made at the National Institute of Standards and Technology (NIST) have demonstrated that the frequency stability of cavity-tuned hydrogen masers is not significantly degraded if the masers are contained in a controlled environment. Under these conditions common-mode frequency fluctuations are not a problem.

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 38 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 $1x10^{-15}$ 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, four of which are currently used in the NIST AT1 time scale [1]. The remaining maser will very likely be included in the scale by the end of 1998. 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. Consequently, NIST has conducted a series of measurements to determine these sensitivities. The results of these measurements are reported here.

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] could result in fractional frequency fluctuations larger than $1x10^{-14}$ occurring simultaneously in all of the masers just due to barometric pressure fluctuations. These fluctuations may 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 fractional frequency fluctuations as large as $1x10^{-13}$ [6]. Fortunately, we have found that the pressure sensitivity in the cavity-tuned masers is more than 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 has been carried out at NIST to measure the environmental sensitivities of the masers, as well as to monitor the stabilities of the environmental parameters during normal operation. The sensitivities of the maser frequencies to (a) temperature, (b) relative humidity, (c) barometric pressure, (d) line voltage, and (e) vertical magnetic field (the most sensitive axis) have been measured on several units. Previous measurements of environmental sensitivities of cavity-tuned hydrogen masers have been made [7], but not over the appropriate time interval or at the 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 pressure changes up to ±15% about the ambient barometric pressure. Preliminary results were presented at the 1997 IEEE International Frequency Control Symposium, and details of the techniques used to measure the environmental sensitivities can be found in [8]. No attempt was made to investigate 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 this information is not needed to quantify the sensitivities.

SUMMARY OF RESULTS

Table 1 summarizes the results of all of the environmental tests. Table blocks with no values indicate that those parameters have not been measured. This table is more complete than that given in [8]. The five masers at NIST were purchased between 1990 and 1996 and are numbered in the order in which they were obtained. The most recently purchased masers have been more thoroughly characterized since the environmental testing could be done before the masers were put to use in the NIST time scale. Older masers can be tested only when they are taken out of the time scale for various reasons. Masers 3 and 5 have been completely characterized, while masers 1 and 4 have been partially characterized. No data are available for maser 2 since it has been in the NIST time scale continuously since 1994. The first column of the table lists the coefficients for temperature, relative humidity, pressure, line voltage, and magnetic field (at 10 µT and 100 µT). The next four columns list the values of the measured sensitivities for each maser expressed as fractional frequency changes (10^{-15}) per unit change of the environmental parameter. The last column gives the duration for which the environmental parameter was changed from its nominal value in order to determine the environmental sensitivity.

Temperature - S_T is the static temperature coefficient and corresponds to the fractional frequency shift per degree Celsius after all of the transient frequency shifts have disappeared. All of the values of S_T are within the manufacturer's specifications, though there is a large variation from maser to maser. The manufacturer has

TABLE 1 - Summary of environmental sensitivities

Sensitivity	Maser 1	Maser 3	Maser 4	Maser 5	Step Interval (days)
$S_T(10^{-15}/°C)$	+1.3±0.2*	-9±1	-8±1	-3.4±0.2**	3 - 7
$S_{RH}(10^{-15}/\%)$	-	+0.4±0.2	-0.2±0.2	-0.04±0.2	14 - 21
$S_P(10^{-15}/kPa)$	-	+0.08±0.4	+0.16±0.04	+0.004±0.04	3
$S_V(10^{-15}/V)$	-	-0.09±0.2	-	-0.08±0.1	3
$S_H(10^{-15}/10\ \mu T)$	-	-13±2	-	+4.7±1.4	3
$S_H(10^{-15}/100\ \mu T)$†	$\|4\|$	$\|17\|$	$\|6\|$	$\|5\|$	0.02

* Dynamic temperature response of ~ -/+4x10^{-14} for a +/-2 °C temperature step is not included

** Dynamic temperature response of ~ -/+2x10^{-14} for a +/-2 °C temperature step is not included

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

made a number of changes to the masers over the years so it is difficult to identify the exact cause for the variations. All of the masers exhibited transient frequency shifts when the temperature steps were first applied and this indicates the presence of a dynamic temperature response (see ref. 8). Because of small static coefficients, the dynamic responses on masers 1 and 5 could be quantified and are -4×10^{-14} and -2×10^{-14} respectively for a +2 °C step. It is difficult to quantify the dynamic responses on masers 3 and 4 because of the larger static temperature effects, but they appear to be about the same as that of maser 5.

Relative humidity - Sensitivities to relative humidity (S_{RH}) are small, and large steps (±9%) in relative humidity had to be used to measure them. Small changes in temperature sometimes coincided with the humidity steps, but correcting for these steps has no significant impact on the values of S_{RH} in Table 1. A humidity step of 14 to 21 days in length was used 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) less than 3×10^{-15}/kPa and the observed values are smaller than this by more than a factor of 10. (1 kPa is on the order of the average day to day barometric pressure variations.) This effectively eliminates one potential 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 measurements. These transients were not reproducible like the dynamic temperature effects 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 large, relatively sudden pressure excursions, since they do not occur at all during extended periods when the pressure changes only gradually due to normal barometric pressure variations. No significant coherent temperature changes were observed during the pressure tests, but small changes (~1%) in the relative humidity did coincide 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 - Frequency sensitivity to line voltage (S_V) is very small and is not cause for concern as a source of common-mode frequency fluctuations. 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 axis of the masers. Calibration was accomplished by measuring the field strength and uniformity inside the chamber as a function of electrical current but without a maser present. 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 approximately twice the magnitude of those observed in the empty coils due to flux concentration by the maser. 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 50% larger when the total field strength is increased as opposed to when the field is decreased by the same amount. The values listed in Table 1 are the average of the responses for the two directions.

Sensitivity to vertical magnetic field is of particular interest since the frequency shifts of masers 3 and 5 measured in our laboratory for 10 μT changes in magnetic field are almost as large as those measured by the manufacturer on the same masers for 100 μT field changes. See Table 1. No sign information was available for the manufacturer's measurements. The effectiveness of passive magnetic shielding is highly nonlinear, and this may explain the differing results. Also, the manufacturer's tests were conducted for a much shorter time interval. Another possible reason for the discrepancy is that the magnetic shielding may have degraded during transportation of the masers from the manufacturing site to our facility. Unfortunately we cannot duplicate the manufacturer's test conditions in our laboratory because of the proximity of the magnetic-field test chamber to other masers used in the NIST time scale. Therefore, the discrepancy between our measurements and the manufacturer's observations remains unexplained. However, 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 was used.

TABLE 2 - Stability characteristics of NIST environmental chambers

	Maser 3 MJD's 50755-50850		Maser 5 MJD's 50710-70805	
Environmental Parameter	TOTAL Allan Dev. (τ=1 day)	Std. Dev.	TOTAL Allan Dev. (τ=1 day)	Std. Dev.
Temperature (°C)	$16x10^{-3}$	$35x10^{-3}$	$8x10^{-3}$	$25x10^{-3}$
RH (%)	0.14	0.50	0.16	2.29
Pressure (kPa)	0.32	0.53	0.33	0.59
Power-line (V)	0.44	1.01	0.55	1.23
Magnetic field (μT)	0.05	0.30	0.03	0.15

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, while barometric pressure and power-line voltage are monitored in the maser room. The measurements are made every 2 hours. Detailed examples of the characteristics of the various environmental parameters are given in [8]. A two-sample (Allan) 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 of the masers.

Table 2 summarizes the stability characteristics of the five environmental parameters for masers 3 and 5 over two different 95 day periods. The table gives values for the Allan deviation at τ = 1 day along with the standard deviation for the entire 95 day period. The same sensors used in the environmental sensitivity tests were used to monitor the environment in the chambers. Since, as discussed earlier, the magnetic field sensors on the masers measure about twice the actual external field changes, the magnetic field values in Table 2 are half the measured variations. The chamber in which maser 5 is housed has no humidity control at this time, which explains the large standard deviation for relative humidity in Table 2. Air flow through this chamber is very slow so the short-term fluctuations in humidity are small, but over the long-term the changes can be large.

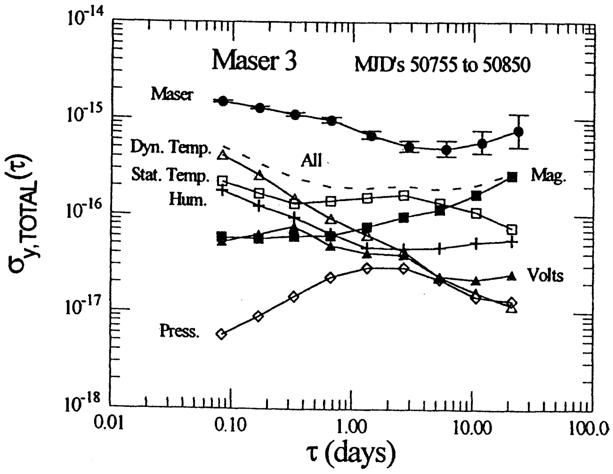

Figure 1 Allan deviation of maser 3, along with environmental contributions.

Figure 1 shows the TOTAL Allan deviation, $\sigma_{y,TOTAL}(\tau)$, of the maser 3 frequency (drift removed) as determined from a 3 corner hat measurement (solid circles). (For details on the TOTAL Allan deviation see [9].) Figure 1 also shows the estimated frequency instabilities caused by the five environmental parameters being monitored (static temperature - hollow squares, humidity - crosses, magnetic field - solid squares, line voltage - solid triangles, and barometric pressure - hollow diamonds) as well as that estimated for the dynamic temperature effect (hollow triangles). These instabilities were determined by calculating the TOTAL Allan deviation of the measured environmental data and then multiplying this by the maser 3 sensitivities in Table 1. For example, the estimated TOTAL Allan deviation at 1 day due to the static temperature effect is obtained by multiplying 0.016 from Table 2 by $9x10^{-15}$ from Table 1.

In a dynamic temperature effect the frequency change is proportional to the time rate of change of temperature. The estimated Allan deviation due to this effect is obtained by first performing a first difference on the temperature data to obtain a new time series representing temperature changes per unit time. The Allan deviation is then calculated from this new time series and multiplied by the dynamic response observed on the masers. For maser 3 a dynamic response of

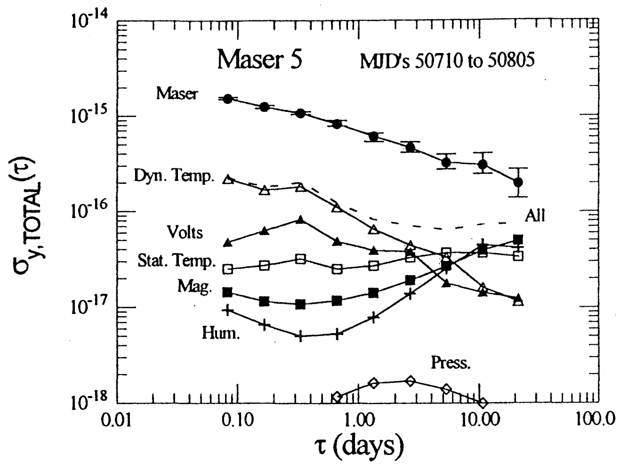

Figure 2 Allan deviation of maser 5, along with environmental contributions.

$1\mathrm{x}10^{-14}$ for a 1 °C step was used to calculate the data in Fig. 1. The response time of the maser frequency to a temperature step is on the order of 4 to 6 hours [8]. This obviously has an influence on the two-sample deviation data at intervals less than the response time. However, no attempt was made to correct for this since it is a complicated process and would only result in making a small effect even smaller.

The dashed line in Fig. 1 with no symbols is calculated from the square root of the sum of the squares for all of the environmental parameters and represents the estimated total contribution from environmental factors.

Figure 2 shows the same type of plots for maser 5, one of our most stable masers. The decreasing value of $\sigma_y(\tau)$ at $\tau = 20$ days is very likely not real, but caused by drift removal.

Figures 1 and 2 are similar to Figs. 8 and 9 in [8], but these new results are for two different, fully characterized masers, and no estimates of environmental sensitivities had to be made. Though the maser noise levels are as low as 3 to $4\mathrm{x}10^{-16}$, Figs. 1 and 2 show that fluctuations in environmental parameters do not play a significant role in determining the frequency stability of the masers in our laboratory. This is particularly true for maser 5, which generally has very low environmental sensitivities. Temperature and magnetic field fluctuations are the largest contributors, but the resulting frequency fluctuations are more than a factor of 2 below the maser noise. The other environmentally induced fractional frequency fluctuations are generally below $1\mathrm{x}10^{-16}$. Combining all of the environmental contributions in a root-sum-square process does not change the conclusion. Eliminating the observed environmentally induced frequency fluctuations entirely would produce at most a 10% improvement in maser frequency stability at some values of τ.

In Figs. 1 and 2 the general shapes of the curves representing all of the environmental contributions (dashed lines) are similar to that of the maser noise characteristics. Could this be an indication that there is an error in estimating the magnitudes of the environmental effects? This is not likely for several reasons. First of all, the environmental effects have been carefully measured. Second, there is some structure in each of the maser frequency and combined environmental curves that is not consistent. Third, no statistically significant correlations were observed between the environmental parameters and the maser frequencies. However, the similarities in shape may not be totally coincidental. The manufacturer believes that the maser stability beyond about 1000 s (excluding long-term drift due to wall shift) is dominated by cavity pulling and the cavity servo [10]. It is very possible that temperature fluctuations *internal* to the maser caused by convection, conduction, and instabilities in the thermal control circuitry, play a role in determining the maser frequency stability. In this case the static and dynamic temperature effects would be present, and similarly shaped curves would be generated. However, they would be more closely related to the internal environment of the maser than to the external environment. This possibility is consistent with the observation that maser 5, which has the lowest noise levels at 10 days, also has an extra layer of thermal control on the cavity [11].

CONCLUSIONS

The flicker floors of the best masers in our laboratory are about $\sigma_y(\tau) = 3$ to $4\mathrm{x}10^{-16}$ at τ of a few days, and our analysis indicates that none of the external environmental fluctuations are large enough to be a significant contributor to such frequency fluctuations. This also means that none of the observed environmental parameters can be a significant source of common-mode frequency fluctuations. However, some of the environmental sensitivities are large enough that care must be exercised to ensure that they are not a problem. Generally, temperature and magnetic field sensitivities require the most attention.

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