Environmental Factors and Hydrogen Maser Frequency Stability

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Abstract—**It is necessary to have a complete understanding of the environmental sensitivities of cavity-tuned hydrogen masers 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 have demonstrated that the frequency stability of a cavity-tuned, active hydrogen maser is not significantly degraded if the maser is operated in a moderately controlled environment. Under these conditions, common-mode frequency fluctuations caused by the observed environmental factors also are negligible.**

I. Introduction

The number of hydrogen masers being used in time scales around the world has increased significantly over the last 10 years [1]–[3]. The Bureau International des Poids et Mesures (BIPM) now uses data from more than 25 masers in the generation of International Atomic Time (TAI). Masers also are commonly used as reference oscillators for primary frequency standards because 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 commercially available cavity-tuned, active hydrogen masers[1] at its site in Boulder, Colorado, all of which are currently used in the NIST AT1 time scale [1]. One of the masers also is routinely used as the reference oscillator for the primary frequency standard NIST-7 [4] and for research on new technologies for primary frequency standards. The masers are all operated in the low hydrogen pressure mode for higher line Q ($\sim 2 \times 10^9$), but otherwise are not optimized for either highest line Q (least sensitivity to the environment), or best short-term stability. Each maser at NIST is contained in its own environmental chamber to control temperature ($\sim \pm 0.1°\text{C}$ peak-to-peak) and relative humidity ($\sim \pm 2\%$ peak-to-peak).

To obtain optimum performance in time scales and as references for primary frequency standards, it is important to have accurate knowledge of maser environmental sensitivities for time intervals up to at least several days. In many laboratories the only frequency source with short-term frequency stability comparable to that of a maser is another maser. Therefore, it is also necessary to know if there are any common-mode frequency fluctuations that would not be visible in a comparison between masers. Because common-mode fluctuations generally come from environmental sensitivities, these parameters must be known. Consequently, NIST has conducted a series of measurements to determine these sensitivities [5], [6], and the results are reported here.

Pressure sensitivity is of particular concern because 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[1] could result in fractional frequency fluctuations larger than 1×10^{-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 1×10^{-13} [7]. 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 not only to measure the environmental sensitivities of the masers, but also to monitor the stabilities of the environmental parameters during normal operation in the time scale. The sensitivities of the maser frequencies to temperature, relative humidity, barometric pressure, power line voltage, and vertical DC magnetic field (the most sensitive axis) have been measured on several units. Our measurements indicate that these environmental factors do not significantly degrade maser frequency stability if the environment is suitably controlled. Previous measurements of environmental sensitivities of cavity-tuned hydrogen masers have been made [8], but not over the appropriate time interval or at the precision required for use in time scales or as references for primary frequency standards. Environmental sensitivities for other types of hydrogen masers have also been reported in [9].

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[1] Sigma Tau Standards Corp. series 2000 cavity-tuned hydrogen masers. Commercial equipment has been identified because 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.

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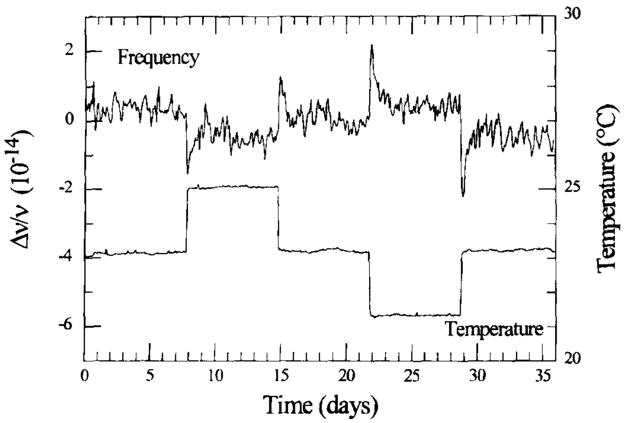

Fig. 1. Influence of temperature steps on the frequency of maser 5.

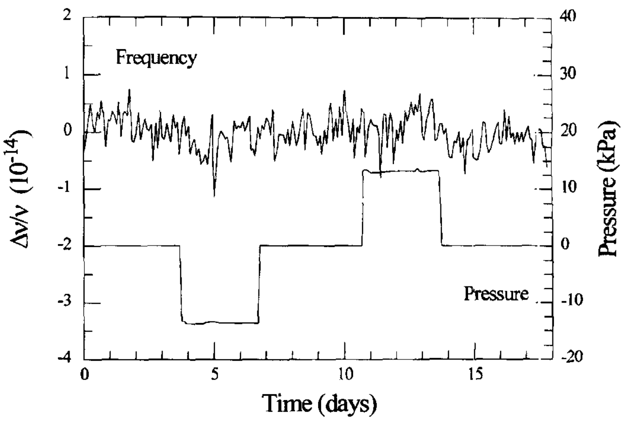

Fig. 2. Influence of pressure steps on the frequency of maser 4.

II. 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 of temperature and humidity in the chambers used for normal operation in the NIST time scale also were 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. 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. 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. To illustrate the measurement process, a detailed description will be given for the measurement of temperature and pressure sensitivities.

A. Measurement of Temperature Sensitivity

Fig. 1 illustrates how the temperature sensitivity measurements were carried out. The lower tracing shows the temperature as measured by a sensor mounted on the outside surface of maser 5; the upper tracing shows the fractional frequency difference between maser 5 and one of the reference masers. Data were taken at 2-hour intervals, and the mean fractional frequency difference and average linear frequency drift ($\sim 6 \times 10^{-16}$/day) have been removed for visual clarity. The fact that the relative frequencies are not exactly the same at the beginning and end of the test cycle simply reflects incomplete drift removal. Over the course of 35 days, the temperature was increased above normal by 2°C for a period of 7 days, and decreased 2°C below normal for a 7-day interval. The frequency of the test maser shows a transient shift on the order of 2×10^{-14} at the time of each temperature transition, which lasts for about 16 hours. This is followed by a steady-state shift that correlates with the steady-state temperature. These characteristics indicate the presence of both dynamic and static temperature effects.

The static temperature coefficient was determined by comparing the average frequency during each temperature deviation period with the average of the frequencies in the periods immediately before and after the temperature excursion. This eliminated any error caused by linear frequency drift. Using only the last 6 days of each 7-day cycle eliminates the dynamic effects from the measurement. The average of the measured frequency shifts was then divided by the average change in temperature to give the static temperature sensitivity, which is $-3.4 \pm 0.2 \times 10^{-15}$/°C in this case. By using both positive and negative temperature shifts, any errors caused by quadratic frequency drift were also eliminated. Some measurements were made over a 10°C temperature range to confirm that the static and dynamic effects are linear.

There was significant frequency noise in the data, so the same analysis was performed with two or three different reference masers. The average of these results reduces the influence of the reference-maser noise. In some cases a maser ensemble was used as the reference.

B. Measurement of Pressure Sensitivity

Fig. 2 shows data from maser 4 for changes in pressure about the ambient atmospheric pressure. The corresponding fractional frequency changes are less obvious, but a pressure sensitivity of $+0.16 \pm 0.04 \times 10^{-15}$/kPa was observed (1 kPa = 10 mbars). It was necessary to repeat the cycle shown in Fig. 2 several times to reduce the measurement uncertainty to an acceptable level. As with temperature, there was no evidence of nonlinearity. Because no dynamic effects are present, the measurement cycle was reduced to only 16 days, with 3-day pressure steps and a 4-day interval between steps. The 4-day interval was chosen simply to keep the measurements in step with the normal work week.

III. SUMMARY OF ENVIRONMENTAL SENSITIVITIES

Table I summarizes the results of all of the environmental tests. Table blocks with no values indicate that those parameters have not been measured. 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, because 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, and masers 1 and 4 have been partially characterized. No data are available for maser 2 because it has been continuously used in the time scale since 1994. The first column of Table I gives the coefficients for temperature, relative humidity, pressure, line voltage, and vertical DC 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. Except for temperature and vertical DC magnetic field, most of the sensitivities are at or below the measurement uncertainties. The last column gives the duration for which the environmental parameter was changed from its nominal value in order to determine the environmental sensitivity.

A. 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, although there is a large difference from maser to maser. The manufacturer has made a number of changes to the masers over the years, so it is difficult to identify the cause of the variations. All of the masers exhibited transient frequency shifts when the temperature steps were first applied. Because there were relatively small static frequency shifts on masers 1 and 5, the dynamic responses could be quantified and are -4×10^{-14} and -2×10^{-14}, respectively, for a +2°C step. It was 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. Because relative humidity also is controlled in these chambers, there was no change in relative humidity during the temperature tests. However, this results in a change in absolute humidity that is coherent with the temperature changes. No attempt was made to correct for this situation because the same coherence also would be present for the smaller temperature fluctuations that exist in normal operation.

B. Relative Humidity

Sensitivities to relative humidity (S_{RH}) are small, and large steps ($\pm9\%$) had to be used to measure them. (Humidity control in the chambers during normal operation is typically $\sim\pm2\%$ peak-to-peak.) 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 I. A humidity step of 14 to 21 days duration was used to ensure that processes with long-time constants would be observed. Test cycles much longer than this are of limited value because frequency drift or aging in masers is usually large enough to make environmental parameters irrelevant in the long term.

C. 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 of the more serious potential causes of common-mode frequency fluctuations. (See Section IV.) The large uncertainty of the pressure sensitivity of maser 3 in Table I 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 pressure steps. However, it is clear that the transients are related to large, relatively sudden pressure excursions, because 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 ($\sim1\%$) in the relative humidity coincided with the pressure changes. Correcting for coherent variations in relative humidity has a negligible impact on the observed pressure sensitivities.

D. Power Line Voltage

The power line voltage was varied by ±5 volts and essentially no sensitivity to line voltage (S_V) was observed. For the two masers that were measured, the sensitivity was less than the measurement uncertainty. None of the other environmental parameters showed any coherent variations with the line-voltage variations.

TABLE I

SUMMARY OF MASER ENVIRONMENTAL SENSITIVITIES.

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

[1] Dynamic temperature response of $\sim -/+4 \times 10^{-14}$ for a $+/-2^\circ$C temperature step is not included.

[2] Dynamic temperature response of $\sim -/+2 \times 10^{-14}$ for a $+/-2^\circ$C temperature step is not included.

[3] As measured by manufacturer at ± 100 μT (± 1 G).

E. Magnetic Field

Sensitivity to DC 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, because this is the most sensitive axis of the masers, as confirmed by our own measurements. (The horizontal sensitivity of maser 3 is more than a factor of 15 smaller than the vertical sensitivity.) 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 was monitored on the top surface of the maser. The field on the maser in the test chamber due to the Earth's magnetic field is typically around 73 μT (100 μT = 1 G). 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 calculating the magnetic field sensitivity, however, the fields in the empty coils were used. Vertical DC magnetic field also was monitored at the reference masers to ensure that they were not affected by the Helmholtz coils.

Tests were performed for field changes of ± 10 μT and ± 5 μT. S_H appears to be nonlinear because the magnitude of the observed frequency change is about 50% larger when the total field strength is increased than when the field is decreased by the same amount. The values listed in Table I are the average of the responses for the two directions.

Sensitivity to vertical magnetic field is of particular interest because 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 (Table I). 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 in our laboratory the high field levels of the manufacturer's tests 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.

AC magnetic fields can cause DC frequency shifts due to rectification caused by the nonlinearity of the field sensitivity. We expect this to be small, however, and it has been confirmed on maser 3 that the root-mean-square AC (60 Hz) sensitivity in all three axes is less than $\pm 2 \times 10^{-16}$ for a 10 μT rms. field. This is at least a factor of 50 smaller than the vertical DC field sensitivity.

IV. IMPACT OF ENVIRONMENTAL FACTORS ON MASER FREQUENCY STABILITY

In addition to the determination of maser environmental sensitivities, stabilities of environmental parameters in the maser chambers and maser room also are being monitored. Temperature, relative humidity, and vertical DC magnetic field 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 [5]. A two-sample (Allan) deviation analysis of the observed environmental parameter fluctuations, along with the measured sensitivities, allows one to estimate the influence of the environment on the observed frequency noise of the masers.

Table II summarizes the stability characteristics of the five environmental parameters for masers 3 and 5 over two

TABLE II
STABILITY CHARACTERISTICS OF NIST ENVIRONMENTAL CHAMBERS.

Environmental parameter	Chamber for Maser 3 TOTAL Allan deviation ($\tau = 1$ day)	Standard deviation	Chamber for Maser 5 TOTAL Allan deviation ($\tau = 1$ day)	Standard deviation
Temperature (°C)	16×10^{-3}	35×10^{-3}	8×10^{-3}	25×10^{-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

different 95-day periods. Table II gives values for the TOTAL Allan deviation at $\tau = 1$ day along with the standard deviation for the entire 95-day period. (The TOTAL Allan deviation is essentially the same as the conventional Allan deviation, but has better confidence. For details on the TOTAL Allan deviation see [10].) The same sensors used in the environmental sensitivity tests also were used to monitor the environment in the chambers. Because, as discussed earlier, the magnetic field sensors on the masers measure twice the actual external field changes, the magnetic field values in Table II are half the measured variations. The chamber in which maser 5 is now housed had no humidity control (the other four do) at the time of the test, which explains the large standard deviation for relative humidity in Table II. Air flow through this chamber is very slow, so the short-term fluctuations in humidity were small, but over the long term the changes could be large.

Generally temperature and relative humidity instabilities inside the environmental chambers originate from variations of internal gradients or instabilities in the control circuitry. Consequently there is little correlation of temperature and humidity fluctuations between different chambers [5]. Only when there is a large variation in the room temperature is a correlation seen in the internal temperatures, but this happens infrequently. Vertical DC magnetic fields also show relatively little correlation between chambers because most of the field disturbances of any consequence are localized (something containing iron gets moved) and the gradients are large over the typical distances between chambers. However, pressure and line voltage fluctuations are highly correlated among the different masers.

Fig. 3 shows the TOTAL Allan deviation, $\sigma_{y,\mathrm{TOTAL}}(\tau)$, of the maser 3 frequency (drift removed) as determined from a 3-cornered-hat measurement (solid circles). Fig. 3 also shows the estimated frequency instabilities caused by the five environmental parameters being monitored (static temperature, hollow squares; humidity, crosses; DC 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, then multiplying by maser 3 sensitivities in Table I. For example, the estimated TOTAL Allan deviation at 1 day due to the static temperature effect is obtained by multiplying 0.016 from Table II by 9×10^{-15} from Table I.

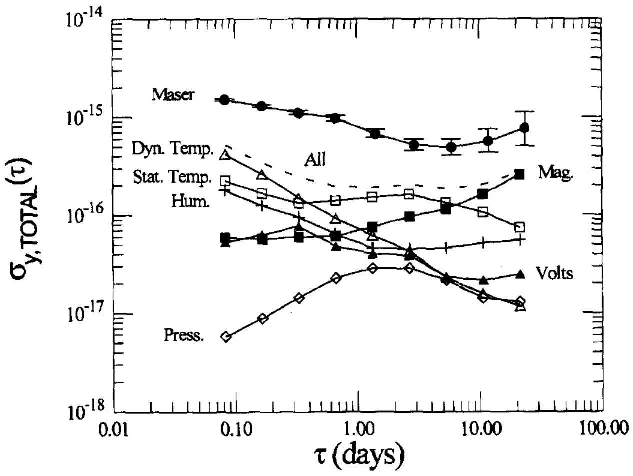

Fig. 3. Measured TOTAL Allan deviation of maser 3 (●), along with environmental contributions from static temperature (□), relative humidity (+), DC magnetic field (▪), line voltage (▲), barometric pressure (◇), and dynamic temperature effect (△). The dashed line represents a root-sum-square of all the environmental contributions.

With the dynamic temperature effect, the frequency change is proportional to the time rate of change of temperature. The estimated TOTAL Allan deviation due to this effect is obtained by performing a first difference on the temperature data to obtain a new time series representing temperature changes per unit time. The Allan deviation then is calculated from this new time series and multiplied by the dynamic response observed on the masers. For maser 3 a dynamic response of 1×10^{-14} for a 1°C step was used to calculate the data in Fig. 3. The response time of the maser frequency to a temperature step is on the order of 4 to 6 hours, and 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 because it is a complicated process and would result only in making a small effect even smaller.

The dashed line (with no symbols) in Fig. 3 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. For clarity, confidence limits are shown only for the measured maser noise. Fig. 4 shows the same type of plots

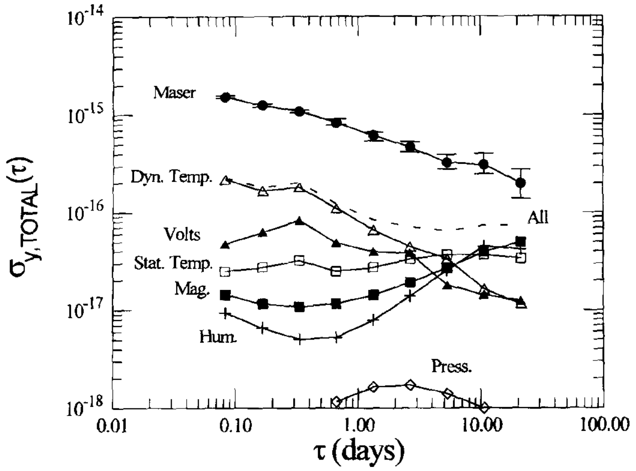

Fig. 4. Measured TOTAL Allan deviation of maser 5 (●), along with environmental contributions from static temperature (□), relative humidity (+), DC magnetic field (■), line voltage (▲), barometric pressure (◇), and dynamic temperature effect (△). The dashed line represents a root-sum-square of all the environmental contributions.

for maser 5, one of our most stable masers. The reduced value of $\sigma_{y,\mathrm{TOTAL}}(\tau)$ at $\tau = 20$ days is very likely not real, but caused by the frequency drift removal process. Results similar to that for maser 3 also have been obtained with masers 2 and 4 [5].

The data clearly show that fluctuations in environmental parameters at time intervals up to 20 days do not play a significant role in determining the frequency stability of masers in our laboratory, even though the maser noise levels are as low as 3 to 4×10^{-16}. 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 1×10^{-16}. Combining all of the environmental contributions quadratically does not change the conclusion. Eliminating the observed environmentally induced frequency fluctuations entirely would produce, at best, a 10% improvement in maser frequency stability at some values of τ.

The determination that environmentally induced frequency fluctuations are small compared to the noise levels of the masers is supported by observations that generally there are no statistically significant correlations between a maser's frequency fluctuations and variations of temperature, relative humidity, or DC magnetic field in that maser's environmental chamber. Because, as discussed earlier, there is little correlation in these three environmental parameters between the different chambers, some correlation between frequency difference and environmental factors in the same chamber would be seen when two masers are compared if the sensitivities were large enough to play a major role in the maser noise. However, such correlations are not seen. The situation is very different for barometric pressure and power line voltage fluctuations, which are common to all the masers. Here, if the sensitivities were large, all maser frequencies would exhibit the same variations and, therefore, no pressure or voltage-induced frequency difference fluctuations could be seen when the frequency of one maser is compared to another. Thus no correlations would be evident, but it would not necessarily mean low sensitivities.

The fact that environmentally induced frequency fluctuations are small compared to the maser noise also means that common-mode frequency fluctuations caused by the five investigated environmental parameters are not a significant problem. Furthermore, frequency fluctuations caused by temperature, relative humidity, and DC magnetic field variations would not produce significant common-mode frequency fluctuations anyway because these parameters are not strongly correlated between the different chambers.

In Figs. 3 and 4, the general shapes of the two curves representing all of the environmental contributions (dashed lines) are similar to that of the maser noise characteristics (solid circles), though there are differences in the details. The data clearly indicate that the five environmental instabilities investigated are not large enough to be responsible for the maser frequency noise, but the similarities in curve shape may not be totally coincidental. The manufacturer believes that the maser stability beyond about 1,000 s (excluding long-term drift due to wall shift) is dominated by cavity pulling and the cavity servo [11]. It is possible that temperature fluctuations internal to the maser caused by instabilities in convection, conduction, and 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 result in similarly shaped curves being generated. However, the maser frequency stability characteristics 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.

V. Conclusions

Our analysis indicates that none of the environmentally induced frequency variations that were investigated are large enough to be a significant contributor to maser noise at intervals up to 20 days even though the flicker floors of the best masers in our laboratory are as low as $\sigma_y(\tau) = 3$ to 4×10^{-16} at τ of a few days. However, temperature and vertical DC magnetic field sensitivities are large enough that care must be exercised to ensure that they do not degrade maser performance. Operation of a maser in a less-controlled environment such as a typical room environment would lead to a degradation in frequency stability. The observed environmental parameters cannot be a significant source of common-mode frequency fluctuations because the magnitudes of the induced frequency fluctuations are too small. Though fluctuations in temperature, relative humidity, atmospheric pressure, magnetic fields, and power line voltage have been eliminated as a source of common-mode frequency fluctuations, this does not guarantee common-mode problems do not exist. Other sources, such as ground loops, are possible, and these need to be investigated.

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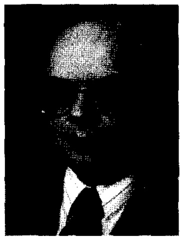

Thomas E. Parker (M'79–SM'86–F'94) was born in Natrona Heights, Pennsylvania, on September 17, 1945. He received his B.S. in physics from Allegheny College in 1967. He received his M.S. in 1969 and his Ph.D. in 1973, both in physics, from Purdue University.

In August 1973, Dr. Parker joined the professional staff of the Raytheon Research Division, Lexington, Massachusetts. Initially, his work was primarily related to the development of improved temperature-stable surface acoustic wave materials. Since 1977, Dr. Parker was responsible for the development of high performance surface acoustic wave (SAW) oscillator technology at the Research Division, including the "All Quartz Package" for SAW devices. His primary interest was frequency stability, with an emphasis on $1/f$ noise, vibration sensitivity, and long-term frequency stability. In June 1994 Dr. Parker joined the Time and Frequency Division of the National Institute of Standards and Technology in Boulder, Colorado. He is the group leader for the Atomic Frequency Standards Group, and his interests include primary frequency standards, time scales, and time transfer technology.

Dr. Parker is a Fellow of the IEEE, and a member of Sigma Xi and Sigma Pi Sigma. He has served as an elected member of the Administrative Committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society (1988–1990), and as Chair of the Frequency Control Standing Committee of the UFFC-S (1989–1997). He also has served on the Technical Program Committees of both the Ultrasonics and the Frequency Control Symposia. He was the Technical Program Committee Chair for the Frequency Control Symposium in 1990 and 1991 and the General Chair in 1997 and 1998. Dr. Parker is currently the Associate Editor for Frequency Control - Acoustics of the UFFC-S Transactions. He received the 1998 Outstanding Transactions Paper Award from the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society as a co-author of two papers which appeared in the May 1988 and November 1988 issues of the Transactions. Dr. Parker was the recipient of the Thomas L. Phillips "Excellence in Technology Award" from Raytheon in 1992. In 1994 he received the W. G. Cady Award presented by the IEEE International Frequency Control Symposium. Dr. Parker was the 1996 Distinguished Lecturer of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society.