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A Correlational Analysis of the Effects of Changing Environmental Conditions on the NR Atomic Hydrogen Maser

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Abstract

An extensive statistical analysis has been undertaken to determine if a correlation exists between changes in an NR atomic hydrogen maser's frequency offset and changes in environmental conditions. Data have been acquired over the past 20 months by recording the frequency offset of three NR atomic hydrogen masers along with the relative and absolute humidity, barometric pressure, and ambient temperature of the laboratory in which the masers are maintained.

Correlational analyses have been performed comparing barometric pressure, humidity, and temperature with maser frequency offset as functions of time for periods ranging from 5.5 to 17 days. Semi partial correlation coefficients as large as -0.9 have been found between barometric pressure and maser frequency offset for data covering periods as long as a week. Maser frequency offset and barometric pressure were consistently found to change simultaneously. The correlation between humidity and frequency offset is less predictable, and the resulting semi partial correlation coefficients were usually small when compared with those derived from the relationship between pressure and frequency offset. The time delay between changes in humidity and correlated changes in maser frequency offset was found to vary extensively with no predictable pattern. Analysis of temperature data indicates that, in the most current design, temperature does not significantly affect maser frequency offset in the laboratory environment.

Thus, the results of the analyses disclose a significant statistical correlation between changes in maser frequency offset and changes in barometric pressure. The statistics also reveal some correlation between humidity and frequency offset, but for reasons to be discussed, the effects of humidity should be considered secondary to the effects of changing barometric pressure.

INTRODUCTION

The NR atomic hydrogen maser has proven to be one of the most accurate time and frequency references available for use in the laboratory and in the field. The NR maser derives its stable frequency reference from electronic observation of the hyperfine transition of atomic hydrogen, which occurs at a frequency of 1.4204057518 GHz[1]. The narrow microwave resonance line characteristic of the hyperfine transition is observed using an electromagnetic resonant cavity operating in the TE_{011} mode. The resonant cavity consists of a metallic cylinder with adjustable top and bottom endplates. The movable endplates are used to adjust the cavity length for coarse tuning of the resonant frequency. The cavity resonant frequency is fine tuned by controlling the temperature of the cavity walls within 10^{-6} K.

Using superheterodyne techniques, a 5 MHz crystal oscillator is phase locked to the signal coupled from the resonant cavity. The oscillator output reflects the long-term stability (greater than 100 s) of the maser as determined by its large atomic line Q (1.33×10^9). Under optimal conditions, the NR maser typically exhibits a frequency offset of a few parts in 10^{15} over a 24-hour period.

One would expect changing environmental conditions to affect the performance of any complex electronic system adversely. The hydrogen maser is no exception. Humidity and temperature changes affect the electronic circuitry used to tune the microwave resonant cavity to the hydrogen hyperfine transition frequency. Barometric pressure changes alter the compressive forces exerted on the resonant cavity, changing its resonant frequency.

To gain a better quantitative understanding of these environmental effects, a statistical analysis of the relationship between the frequency offset of the NR hydrogen maser and the surrounding environmental conditions was undertaken. In addition to other results, two important conclusions were derived from the analysis: (1) a strong correlation exists between barometric pressure and the NR maser's frequency offset, and (2) a change in the construction of the NR maser's resonant cavity has eliminated temperature fluctuations as a critical concern in the laboratory.

EXPERIMENTAL DATA

In previous generations of NR masers, the cylindrical microwave resonant cavity was constructed entirely from aluminum. The NR maser was later improved by enclosing the resonant cavity in a cylindrical quartz sleeve. In the present design, the resonant cavity consists of a coating of conductive silver ink on the inside of a thick quartz cylinder. This arrangement gives the resonant cavity the thermal expansion coefficient of a thick quartz tube as opposed to that of the thin aluminum cylinder used in the previous design. This change reduced the thermal sensitivity of the cavity's resonant frequency from 30 KHz/°C to 3 KHz/°C.

For the past 20 months the data acquisition system described in [2] has continuously recorded the environmental conditions and the frequency offset of three NR hydrogen masers. The system calculates maser frequency offset at five-minute intervals with an accuracy of parts in 10^{15}. Ambient air temperature, relative humidity, dew point temperature, and barometric pressure are simultaneously recorded by National Institute of Standards and Technology (NIST) traceable thermometers, hygrometers, dew point sensors, and barometers with single measurement accuracies of 0.1 °C, 2%, 0.5°C, 0.01 inch Hg, respectively. The repeatability of the humidity sensors is 0.5% for the relative humidity sensor and 0.05 °C for the dew point sensor. Repeatability is a better measure of how well these instruments track humidity changes.

Figures 1A through 6A show the maser frequency offset and the offset barometric pressure over time for periods ranging from 5.5 to 17 days. The offset barometric pressure was calculated by subtracting the measured value of the barometric pressure, in inches of mercury, from 30. This offset has the effect of inverting the barometric pressure curve, making the inverse relationship between pressure and frequency offset visually clear. From the similarity of the curves in Figures 1A through 6A, a significant correlation is apparent between barometric pressure and maser frequency offset.

Figures 1B through 6B show the maser frequency offset and humidity for the time periods considered in Figures 1A through 6A. The frequency offset data in Figure 1B have been delayed by 48 hours with respect to the humidity curve. Similarly, the frequency offset has been delayed 24 hours in Figure 5B. These time delays were incorporated to demonstrate that the humidity shows a stronger similarity to the frequency offset if one allows for a time delay between changes in humidity and changes in frequency offset.

The data collected during the past 20 months have been analyzed statistically to gain a quantitative understanding of the effects seen in the graphical data. The statistics software package CSS:Statistica by Statsoft, Inc. was used to perform all statistical calculations. Semi partial correlation coefficients between the temperature and frequency offset, the pressure and frequency offset, and the humidity and frequency offset were calculated (see [**3**]). The calculations were made on blocks of data collected over periods ranging from 5.5 to 17 days. The square of the magnitude of the semi partial correlation coefficient between a dependent variable (frequency offset) and an independent variable (any one of the temperature, pressure, or humidity) gives the percentage of the total variation in the dependent variable uniquely accounted for by the independent variable with the effects of the remaining independent variables taken into account.

Temperature, humidity, and barometric pressure can be interrelated, so semi partial correlation coefficients were calculated to reduce the effects of this interrelation on the magnitude of the calculated coefficients. To allow for the potential existence of a time delay between a change in temperature or humidity and the resulting change in maser frequency offset, the semi partial correlation coefficients were calculated three times. Semi partial correlation coefficient calculations were performed using the frequency offset as it was measured and were then repeated incorporating time delays of 12 and 24 hours in the frequency offset data. For one data set containing 17 days' worth of data, a time delay of 48 hours was used.

EXPERIMENTAL RESULTS

The results of the calculations for nine sets of data are summarized in Table 1. The first data column shows the Mean Julian Date (MJD) of the first day that data were recorded for that set of coefficients. The number of days of data used in the calculations is indicated in parentheses underneath the MJD. A minimum of 100 data samples were used to calculate each of the coefficients presented in the table. Each data set consists of twenty-four equally spaced samples per day for every day considered. The next three columns are the semi partial correlation coefficients between frequency offset and temperature, pressure, and humidity, respectively.

Each block of coefficients in Table 1 consists of three rows of data displaying the semi partial correlation coefficients with time delays of 12 and 24 hours added to most of the the frequency offset data. A 48-hour time delay was added to the data set for MJD 47973. The data for MJD 48189 do not include time delay calculations because the humidity, barometric pressure, and frequency offset curves are nearly identical as measured.

The temperature in the laboratory where the masers were operated was maintained at 23±2°C throughout this investigation. This is a level of control easily accomplished with a computer room air conditioning system. Intimately surrounding the NR maser's resonant cavity with the thermally isolating quartz sleeve has reduced temperature-induced frequency offsets to a second order effect (at least in a laboratory environment), and examination of the coefficients in the temperature column of Table 1 is all that is necessary to convince oneself that ambient temperature fluctuations had no significant effect on the performance of the NR masers in this investigation. It is the interrelation of the barometric pressure and humidity with the frequency offset that is interesting.

As is visible in Table 1, both the humidity and pressure can be strongly correlational with maser frequency offset, but there are critical differences between the two correlations. The humidity does not consistently show significant correlation to the frequency offset; moreover, whenever the correlation seems significant, a time delay of up to 48 hours has been added to the frequency offset data to maximize the coefficients. The optimal time delay is not fixed. In the MJD 47973 data set, a 48-hour delay maximizes the correlation coefficient. Similarly, a time delay of 24 hours in the MJD 48314 data set maximizes the semi partial correlation coefficients between humidity and frequency offset.

One would expect that if humidity changes were significantly affecting maser frequency offset, the relation between the cause and effect would be more consistent. In many of the data sets presented in Table 1, the semi partial correlation coefficient between humidity and frequency offset is insignificant in comparison with that between the barometric pressure and frequency offset irrespective of the time delay used. It seems probable, therefore, that the occasional correspondence between humidity and frequency offset is being caused by a third variable influencing both the humidity and frequency offset.

In all observed cases where the humidity shows significant correlation with the frequency offset, the barometric pressure is also strongly interrelated with the frequency offset. A meteorological relationship exists between the barometric pressure and ambient humidity. It is this relationship that could account for the observed correlation between the humidity and frequency offset. Because of the inconsistency and unpredictability of the correlation between humidity and frequency offset, it seems apparent that what is being seen in the data is the often unpredictable correlation of humidity and barometric pressure in East Coast weather.

In sharp contrast to the humidity-frequency offset relationship, the observed barometric pressure-frequency offset correlation exhibits consistency. The changes in pressure and frequency offset are always observed to occur simultaneously. In addition to the data presented here, correlational analyses were performed on other data sets in which the environmental conditions and frequency offset were sampled at 5-minute intervals. Even in these cases, the semi partial correlation coefficients were maximized without adding time delays to the frequency offset.

The calculated semi partial correlation coefficients between barometric pressure and frequency offset presented in Table 1 are consistently on the order of -0.7. Correlation coefficients of this magnitude are seen for all sorts of barometric pressure patterns, including large, rapidly moving low-pressure fronts as depicted by Figure 1A; gradually increasing or decreasing pressures such as illustrated in Figures 3A and 5A; and semisinusoidal patterns as shown in Figure 4A.

Semi partial correlation coefficients near -0.7 are seen when the variation in the pressure is large (typically a variation $\geq$ 0.3 inch over a few days). The coefficients become smaller, and the relationship less linear, for smaller pressure fluctuations. This occurs because NR maser performance in stable conditions is one or two parts in 10^{15} over a 24-hour period, and this is the magnitude of the frequency offset effect one would expect to see from such small pressure variations. In Figure 1A, for example, it is clear that the barometric pressure is associated with frequency offsets as large as 9 parts in 10^{14} in response to the strong pressure front. During the first few days presented in Figure 1A, where the pressure variations are small, the frequency offset remains in the small parts in 10^{15} range.

Although correlational analysis cannot prove cause and effect, the findings that the semi partial correlation coefficients between pressure and frequency offset are consistently stronger than -0.7

and that the pressure and frequency offset change simultaneously give good reason to suspect a causal relationship between pressure and NR hydrogen maser frequency offset.

CONCLUSION

Since March 1990, the frequency offset of three NR hydrogen masers has been recorded synchronously with the environmental conditions in the laboratory enclosing the masers. Using these data, semi partial correlation coefficients were calculated between maser frequency offset and various environmental conditions (temperature, barometric pressure, and humidity). The statistical analysis revealed a strong correlation between large changes in the barometric pressure and changes in maser frequency offset.

Large variations in barometric pressure are consistently associated with changes in NR maser frequency offset as large as 9 parts in 10^{14}. The correlation is a negative one, so decreasing pressure is associated with a positive change in the frequency offset, and vice versa. When the barometric pressure variation is greater than approximately ± 0.3 inch of mercury over a few days, the calculated semi partial correlation coefficients are consistently near -0.7.

REFERENCES

[1] H. Helwig, **Precision Frequency Control**, Vol. 2, E. A. Gerber and A. Ballato, Eds. Orlando, FL: Academic Press, 1985, p. 159.

[2] R. A. Dragonette and J. J. Suter, *"Barometric Pressure-Induced Frequency Offsets in Hydrogen Masers"* Proc. 45th Annu. Symp. Freq. Control, 1991, p. 586.

[3] D. Harnett and A. Soni, **Statistical Methods for Business and Economics**, 4th ed. Reading, MA: Addison-Wesley, Inc., 1991.

TABLE 1
Semi Partial Correlation Coefficients Between The Temperature, Pressure And Humidity, And The Frequency Offset

	Mean Julian Date (# DAYS)	Semi Partial Correlation Coefficients: Temperature	Pressure	Humidity
	47973			
Frequency Offset	(17)	.11	-.75	-.16
Frequency Offset (12h)		.12	-.64	.02
Frequency Offset (24h)		.12	-.51	.21
Frequency Offset (48h)		.19	-.22	.47
	48076			
Frequency Offset	(7)	-.01	-.86	-.08
Frequency Offset (12h)		-.24	-.77	-.07
Frequency Offset (24h)		-.33	-.41	0
	48094			
Frequency Offset	(6.5)	.10	-.66	.20
Frequency Offset (12h)		-.22	-.36	.19
Frequency Offset (24h)		-.02	-.03	.34
	48189			
Frequency Offset	(6.5)	-.20	-.49	.30
	48280			
Frequency Offset	(6)	.08	-.88	-.10
Frequency Offset (12h)		-.18	-.49	-.41
Frequency Offset (24h)		-.19	-.09	-.48
	48314			
Frequency Offset	(5.5)	-.01	-.61	-.22
Frequency Offset (12h)		.03	-.31	.10
Frequency Offset (24h)		.20	.00	.45
	48438			
Frequency Offset	(6)	-.07	-.61	-.17
Frequency Offset (12h)		-.08	-.33	-.22
Frequency Offset (24h)		-.03	.08	-.34
	48540			
Frequency Offset	(7)	.01	-.83	-.41
Frequency Offset (12h)		-.17	-.61	-.13
Frequency Offset (24h)		-.29	-.28	-.29
	48550			
Frequency Offset	(7)	.03	-.76	.07
Frequency Offset (12h)		-.32	-.25	-.13
Frequency Offset (24h)		-.56	.13	-.07

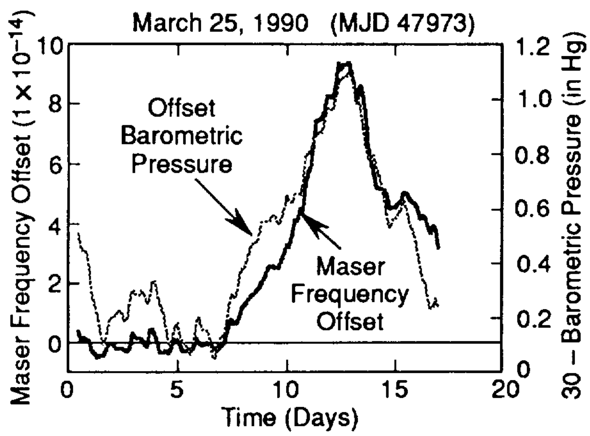

Figure 1A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

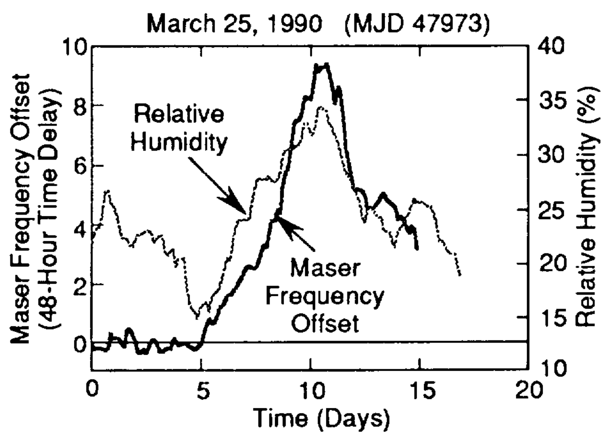

Figure 1B. Maser Frequency Offset and Relative Humidity Versus Time. (Note: The frequency offset curve has been delayed by 48 hours with respect to the relative humidity curve.)

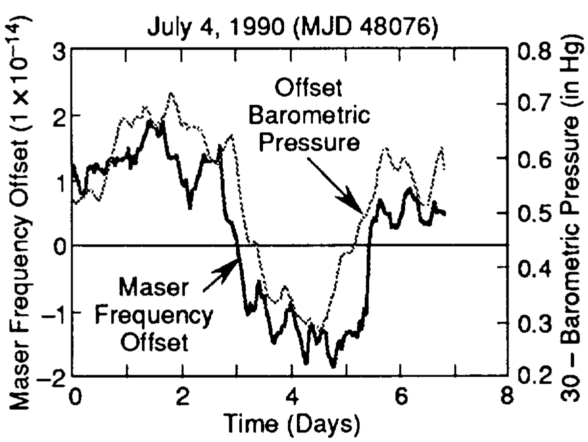

Figure 2A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

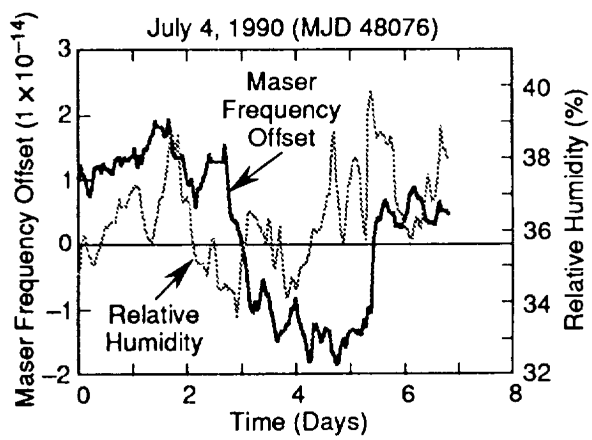

Figure 2B. Maser Frequency Offset and Relative Humidity Versus Time.

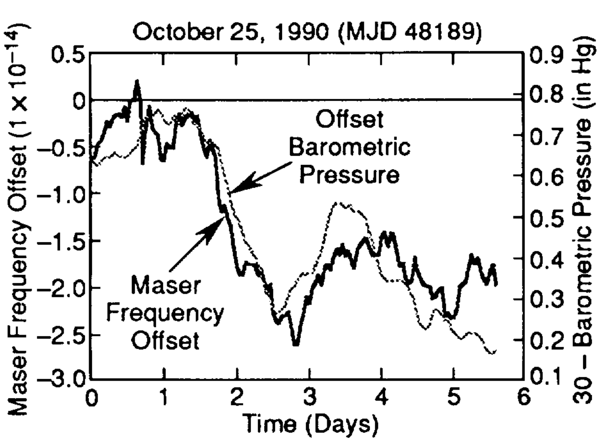

Figure 3A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

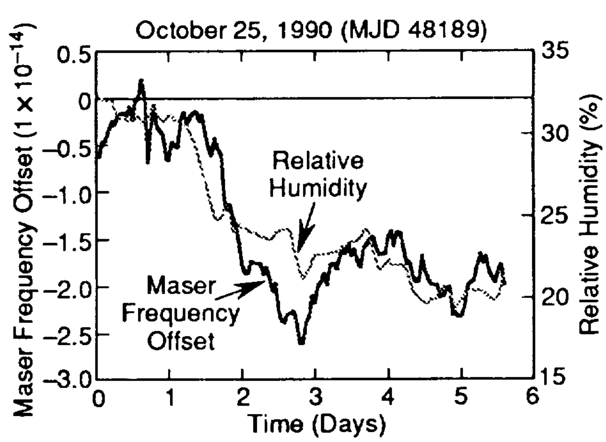

Figure 3B. Maser Frequency Offset and Relative Humidity Versus Time.

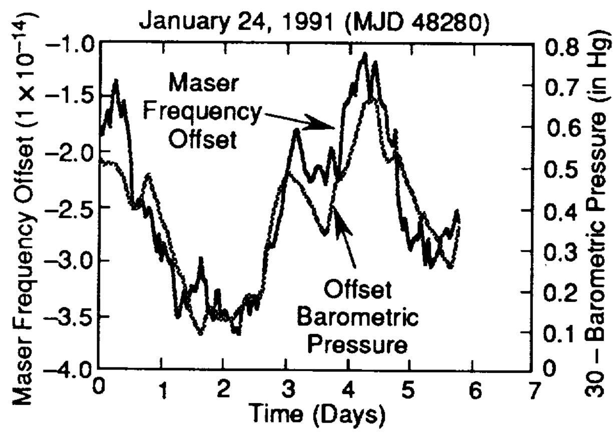

Figure 4A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

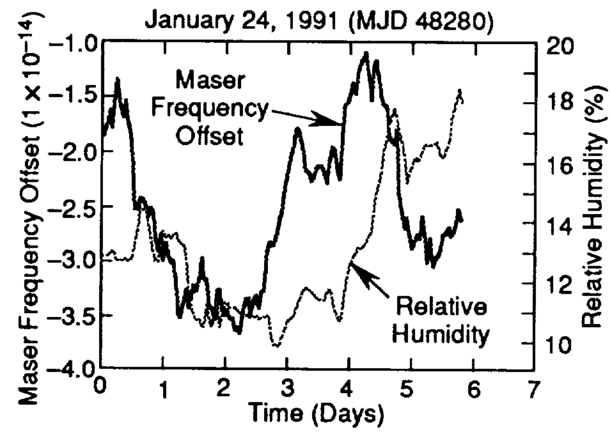

Figure 4B. Maser Frequency Offset and Relative Humidity Versus Time.

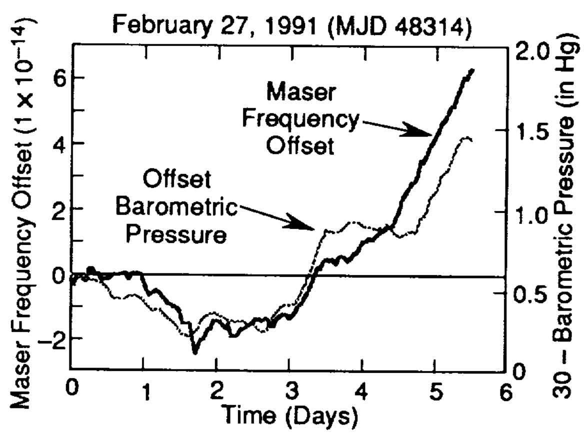

Figure 5A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

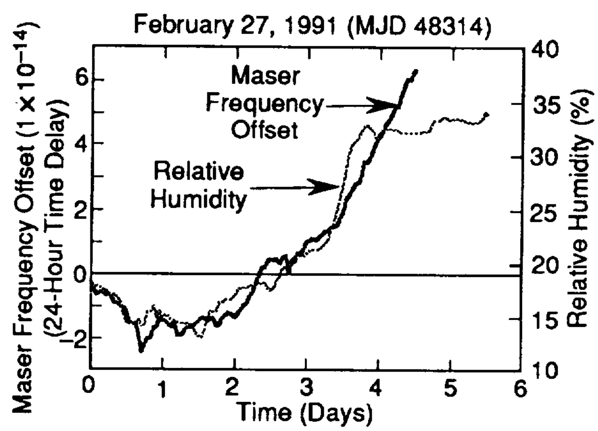

Figure 5B. Maser Frequency Offset and Relative Humidity Versus Time. (Note: The frequency offset curve has been delayed by 24 hours with respect to the relative humidity curve.)

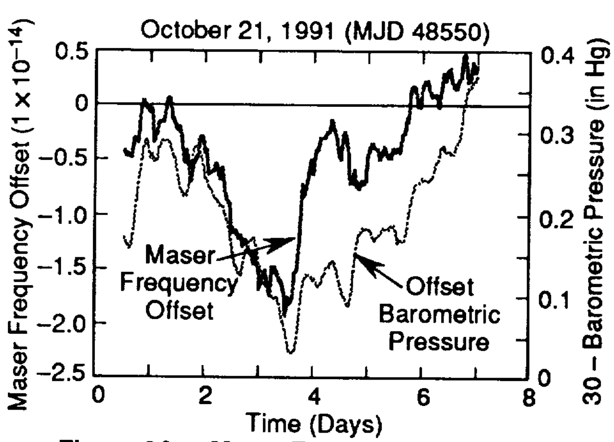

Figure 6A. Maser Frequency Offset and Offset Barometric Pressure Versus Time.

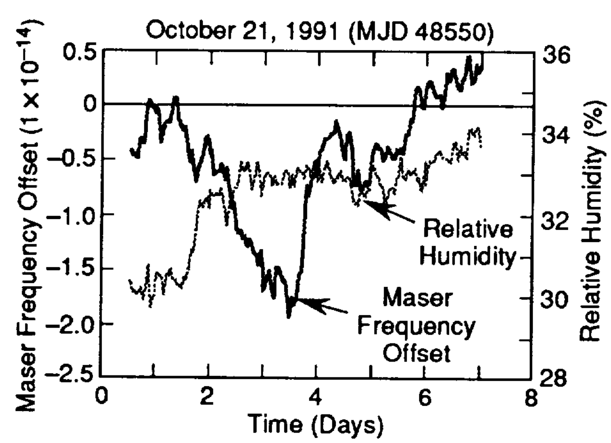

Figure 6B. Maser Frequency Offset and Relative Humidity Versus Time.

QUESTIONS AND ANSWERS

Harry Peters, Sigma Tau: I think that it is only fair to point out that what you are seeing is probably cavity frequency variations. This would not necessarily be characteristic of a maser which uses autotuning. That is, frequency variations due to atmospheric pressure variations would be eliminated in a maser which uses cavity autotuning, so this is not necessarily characteristic of all hydrogen masers.