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THE EFFECT OF HUMIDITY ON COMMERCIAL CESIUM BEAM ATOMIC CLOCKS

by

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Summary

Because a dependence of the frequency of commercial cesium beam clocks on humidity has been observed by others, NBS chose to control the humidity in one of the environmental chambers for the NBS clock ensemble. On 9 February 1988 the relative humidity was changed from a few percent to 48%. All of the clocks underwent a change in frequency. The resulting frequency changes were of different sign and of varying magnitudes among the clocks. In some, the changes were an order of magnitude larger than the flicker noise FM levels associated with the corresponding clocks.

The implications of such changes are quite significant in the generation of International Atomic Time (TAI) and of Universal Coordinated Time (UTC). The possibility of annual variations in the time scales of the principal timing centers as well as in TAI and UTC will be discussed. These results imply the potential for improved long-term frequency stability performance for individual clocks as well as for clock ensembles.

Introduction

The authors know of only two primary timing centers that have actively controlled the humidity around their clocks, the University of Graz in Austria and PTB in the Federal Republic of Germany. The latter discontinued humidity control a few years ago due to equipment failure. A recent analysis by Bava et. al. [1] at the Instituto Elettrotecnico Nazionale at Corso, Italy documented the clear effect of humidity on the frequency of the clocks in the IEN clock ensemble. Work by Freon at the Paris Observatory has indicated both a cause and a possible cure for this problem [2], The presence of an apparent annual term in the International Atomic Time (TAI) scale has been a concern for several years. Figure 1 is a plot of TAI versus Guinot's optimally smoothed 1988 post analysis time scale, Terrestrial Time scale of the Bureau International des Poids et Mesures (TTBIPM88). Over the ten year period, ten cycles are apparent with amplitudes of a few parts in 10^{14}.

Because of the above results and concerns, NBS made a decision to conduct an experiment involving servo control of the humidity in one of the environmental chambers (EC2) in the NBS clock ensemble.

Effect of Humidity on NBS Clock Ensemble (Internal Estimate)

On 9 February 1988, a humidistat was turned on in one of the chambers of commercial cesium beam frequency standards which are a part of the National Bureau of Standards atomic time scale ensemble. The relative humidity increased from its dry season value of 12% to a controlled value of 42%, while the temperature remained stabilized at 23 degrees Celsius. The sensor used was a commercial capacitive-type with a manufacturer's stated accuracy of 4%. There were four cesium standards in the chamber at the time, and each of them shifted to a new frequency within about two hours after the humidity control was turned on. The frequency shift was estimated by comparing the average frequency measured during the first two weeks of humidification with that during the previous two weeks. Assuming that the frequency change is linearly proportional to the change in relative humidity, we can express the results as humidity coefficients.[1]

SERIAL NUMBER	FREQUENCY SHIFT	COEFFICIENT PER %
HP323	+1.1 E-13	+3.6 E-15
HP324	-1.8 E-13	-6.1 E-15
HP2165	-1.3 E-13	-4.4 E-15
HP2315	-0.5 E-13	-1.6 E-15

Using these coefficients, we can calculate the extent to which seasonal variations in humidity should have affected the frequency of these clocks, and then compare the actual frequency variations with those predicted. For a period of about 400 days before the humidistat was turned on, we read the humidity off a commercial strip-chart recorder (capacitive-type sensor) once a week. The humidity varies slowly in our laboratory, so that a weekly reading should adequately represent the conditions in the chamber. The manufacturer of the recorder claims the instrument to be accurate to 4% between 20% and 80% relative humidity. About half of our readings are below 20% so that the accuracy of this recorder is questionable. However, we have two recorders and they have always agreed with one another within the 1% resolution that we can read the strip-charts. A more accurate (1%) commercial instrument was utilized in the servo controlling the humidity. This instrument featured a Dunmore type hygro-scopic salt detection method. In steady state its reading was 48% -- differing from the 42% of the capacitive- type sensor. Since the above coefficients are based on a change in humidity, the capacitive-type instrument was used for those calculations -- the particular Dunmore-type sensor we had purchased was limited in range in order to achieve the 1% accuracy.

Figure 2 shows the recorded humidity in the chamber during the 400 days. We multiply this recorded humidity by the coefficient for HP323 to find the effect of humidity on the frequency of HP323. Figure 3 shows the humidity effect plotted on the same scale as the observed frequency of HP323. The frequency measurements are one week averages. The appearance of figure 3 suggests that humidity variations are the principal cause of seasonal variations in the frequency of HP323.

Although HP324 is of the same make, model and adjacent serial number, its behavior during the 400 days is rather different. Its frequency responds to two influences with about equal magnitude. One of them is the humidity, and the other is the signal level in its electronics, as indicated by the "second harmonic" reading on its panel meter. During the 400-day interval, we increased the amplifier gain to compensate for the decline in signal amplitude with ageing of the cesium-beam tube. At that time, we observed a frequency shift of +2.3 E-13 for a change in the second harmonic reading from 15 to 40. We can form an amplitude coefficient with this information just as we did with the humidity. The amplitude coefficient is +9.2 E-15 per unit on the second-harmonic meter. Multiplying this coefficient by the recorded amplitude gives the expected variation in frequency due to variation in signal amplitude. It has the form of a sawtooth, declining as the tube ages, and rising sharply when we increase the amplifier gain. To explain the behavior of HP324, we must add this amplitude effect to the humidity effect. Figure 4 shows the result. These two effects together account for most of the frequency variations of HP324 during the 400-day period.

We have no long-term data for HP2165 because of repeated repair problems. HP2315 was in operation during the later part of the 400-day period. Figure 5 shows that its frequency begins to shift at day 47100 for unknown reasons. Humidity is clearly not the only cause of frequency shifts in this clock.

The data presented so far indicates that variations in humidity generally affect the frequency of cesium beam standards but is not necessarily the only cause of frequency variations. We also consider the behavior of the other clocks in our time scale ensemble. These are located in another chamber, where the humidity has never been intentionally altered. Consequently, we do not know the humidity coefficients of the clocks in this chamber. Nevertheless, we can examine the long-term variations in their frequencies and compare these variations with the humidity record for the chamber. In many instances, the resemblance of the two curves is so great that we are sure humidity variations are the major cause of the observed frequency variations. We can even estimate the magnitude of the humidity coefficient -- whatever is needed to make the two curves match. This indirect procedure permits us to extend our observations to a larger population of clocks, though with less confidence in the certainty of the results.

Figures 6 & 7 show two instruments that seem to be affected by humidity.[2] The frequency curve for FTS 113 did not resemble the humidity curve.[3] Figure 8 shows the last few months of the life of the cesium tube in FTS 217.[4] The record is short, and the humidity profile so simple, that we cannot be sure whether we are seeing a humidity effect. Figure 9 shows OSQ61, whose frequency appears to track the humidity.[5]

The humidity coefficients for these four instruments have been chosen to match the calculated curve to the measured frequency curve. The value for FTS217 is particularly uncertain, but it is included because it is the only example we have of an option 004 instrument of this make. We can be reasonably confident of the other coefficients.

SERIAL NUMBER	COEFFICIENT PER %
HP1316	+3.8 E-15
HP352	-11. E-15
FTS217	-9. E-15
OSQ61	+40. E-15

Changes in relative humidity cause significant changes in the frequency of most of the commercial cesium beam frequency standards that we have examined. For some of the most stable of these clocks, changing relative humidity is the predominant cause of long term instability. The sensitivity of each clock to changes in humidity seems to be an individual matter. Clocks of the same make, model and even adjacent serial numbers do not necessarily behave the same. For this reason, we caution the reader not to suppose that the numbers given here are typical of the makes and models mentioned. We simply do not have enough information for such generalizations. We do suggest that users of such instruments should consider the possibility that their instruments may vary in frequency with changes in humidity, even though our data are too limited to predict it.

The frequency measurements reported here are made with respect to our AT1 time scale. We have neglected the humidity coefficient of this time scale. The coefficients given above contain an error to the extent that AT1 has a non-zero humidity coefficient. We can now estimate that coefficient. AT1 is a weighted average of the members of its ensemble. We can multiply each clock's humidity coefficient by its weight in AT1 and add them up. This simplified procedure overlooks the effect of the non-commercial devices that contribute to AT1, and it overlooks the fact that the composition of AT1 changes as the assortment of available clocks changes. Nevertheless, the coefficient obtained in this way is enough of an approximation to give us a rough idea of the magnitude of the error it contributes to the coefficients given above. We estimate the humidity coefficient of AT1 to be +0.9 E-15 per percent. The humidity coefficients of the several clocks have cancelled to some extent. This coefficient not only represents an error in the reported values of the clock humidity coefficients given above, but it also estimates the effect of the humidity in our laboratory upon UTC(NBS), which is obtained from AT1 by adding coordination corrections. Apparently, UTC(NBS) goes about 0.1 microsecond early during our summer and about 0.1 microsecond late during our winter. These deviations should be reduced in the future to the

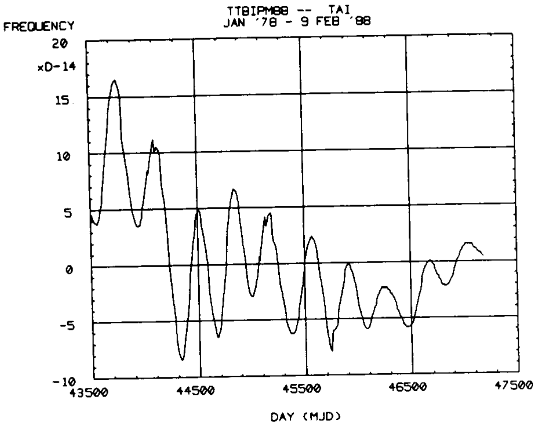

FIGURE 1. FREQUENCY OF (TTBIPM--TAI) JANUARY 1978 - FEBRUARY 1988

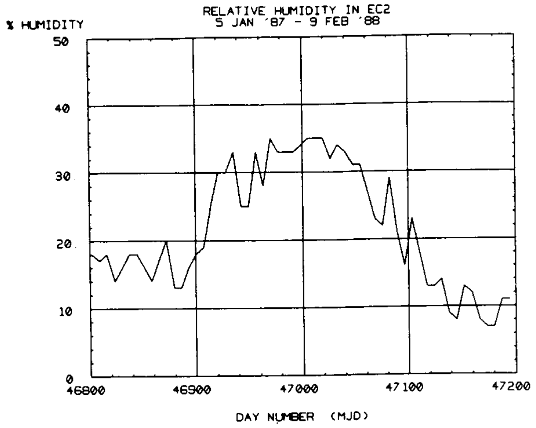

FIGURE 2. RELATIVE HUMIDITY IN CHAMBER EC2

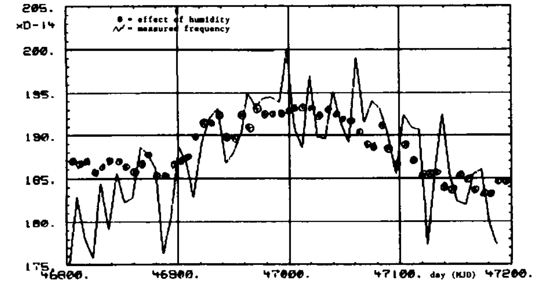

FIGURE 3. HP323 - EFFECT OF HUMIDITY

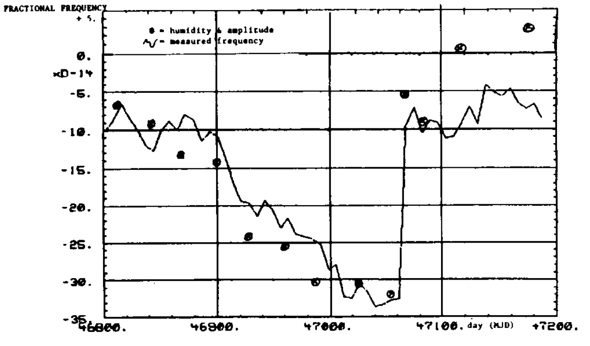

FIGURE 4. HP324 - EFFECTS OF HUMIDITY AND SECOND HARMONIC AMPLITUDE

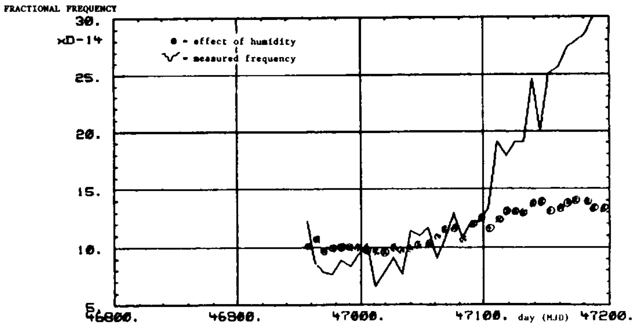

FIGURE 5. HP2315 - EFFECT OF HUMIDITY

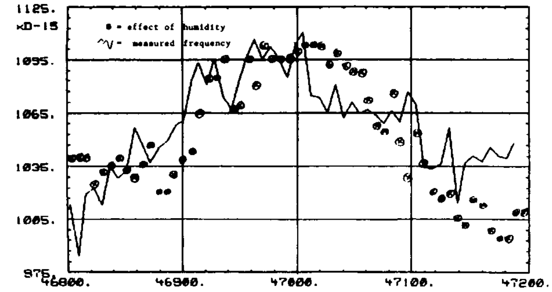

FIGURE 6. HP1316 - EFFECT OF HUMIDITY

extent that we apply humidity control to the clocks of our ensemble.

External Estimate of the Humidity Dependence of Clocks

The internal estimate discussed above overlooks any humidity-induced effects which may be common to all of the NBS clocks. For that reason, it is especially interesting to compare NBS(AT1) with other time scales. Probably the best external scale for comparison is the TTBIPM88 scale. Figure 10 is a plot of the frequency of this terrestrial time scale versus the NBS(AT1) ensemble. Comparing figure 10 with figure 2 shows an apparent correlation. An approximate estimate of the coefficient is minus three parts in 10^{15} per percent change of the relative humidity. This is of opposite sign and about three times larger than what was estimated from internal measurements as stated above. The frequency stability between these two time scales is plotted in figure 11. From the humidity coefficient, one can infer a fractional frequency stability caused by humidity acting on the NBS ensemble. This humidity-caused instability is plotted in figure 12. Figures 11 and 12 agree within the uncertainties, showing that the model is self-consistent.

One may conclude that the NBS clock ensemble probably has been perturbed in the past by environmental humidity variations. Since 9 February 1988, the environmental chamber EC2 has been controlled within about 1% at 48% relative humidity. The effect of humidity on these clocks should therefore not degrade the stability of NBS ensemble to more than a few parts to 10^{15} due to this cause. Environmental chamber number three is yet to be dealt with.

Several of the clocks contributing to international atomic time are not protected from variations in humidity. Most of these clocks are in the northern hemisphere and they could have seasonal intercontinental correlations due to this effect. The annual variations plotted in figure 1 could well be driven by this effect. The fact that the internal and external estimate of the humidity coefficients for NBS(AT1) were of opposite sign and a factor of three different in magnitude could be explained if the annual variations were not in NBS(AT1), but in TTBIPM88. There is additional evidence for that possibility as discussed in reference [3]. In actuality there are probably some annual variations in both time scales. Another possible explanation is that all of the NBS clocks have a humidity coefficient much larger than measured because relative measurements detect only differences between clocks, rather than the full effect. Further study is needed to ascertain, with some degree of certainty, where these annual variations come from. The probability that relative humidity changes are an important concern for time scale environments seems now evident.

Conclusion

The data presented in this paper indicate that variations in relative humidity are a major contributor to the long-term instabilities in at least some cesium atomic clocks. Several of the atomic clocks contributing to the NBS ensemble have been affected, and the same kind of clocks are used in the generation of International Atomic Time as well as at the primary timing centers throughout the world.

There are insufficient data at this point to conclude where the annual variations are. A study is underway to answer some of these questions. It seems probable that seasonal humidity variations could be an important cause of the annual variations observed between time scales.

Long-term instabilities in earth-bound time systems have become increasingly important with the discovery of millisecond pulsars. The effects of humidity may cause terrestrial time scales to change a few parts in 10^{14} over the course of half a year. This is the level of estimated instabilities in the millisecond pulsar PSR 1937+21 for the same integration time. At an integration time of one year this pulsar has an estimated instability of about one part in 10^{14}. This pulsar may assist in determining the sources of these annual variations. Now that variations in relative humidity are recognized as a probable cause of annual variations in terrestrial time scales, controlling the humidity or compensating for the effect of humidity should improve the long-term performance of earth bound atomic clocks. This improvement may be very important for characterizing the long-term performance of millisecond pulsars.

Footnotes

[1] Each of these four clocks was a model 5061A option 004 made by Hewlett Packard. Identification of a commercial company does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that any identified entity is the only or the best available for the purpose.

[2] Serial HP1316 is a Hewlet-Packard 5061A option 004, and serial number HP352 is a Hewlett-Packard 5061A containing a standard tube.

[3] Serial number FTS113 is a Frequency and Time Systems model 4050.

[4] Serial number FTS217 is a Frequency and Time Systems model 4050 option 004.

[5] Serial number OSQ61 is an Oscilloquartz model 3200.

References

[1] E. Bava, F. Cordara, V. Pettiti, and P. Tavella, "Analysis of the Seasonal Effects on a Cesium Clock to Improve the Long-Term Stability of a Time Scale," 19th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, December 1-3, 1987, Redondo Beach, CA.

[2] Dr. W. Lewandowski, private communication.

[3] D. W. Allan, "A Study in Long-term Stability of Atomic Clocks," 19th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, December 1-3, 1987, Redondo Beach, CA.

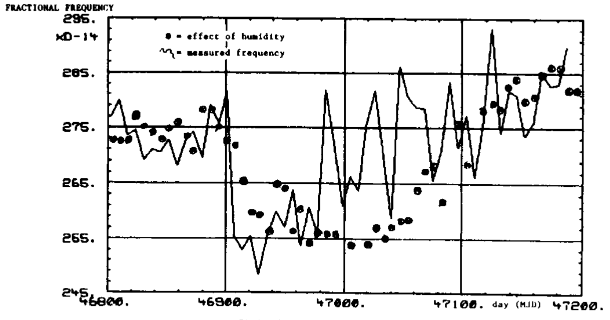

FIGURE 7. HP352 - EFFECT OF HUMIDITY

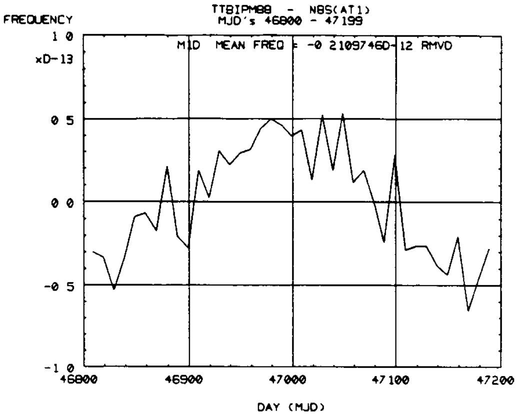

FIGURE 10. FREQUENCY OF (TTBIPM88 - NBS(AT1) MJD 46800 - 47199

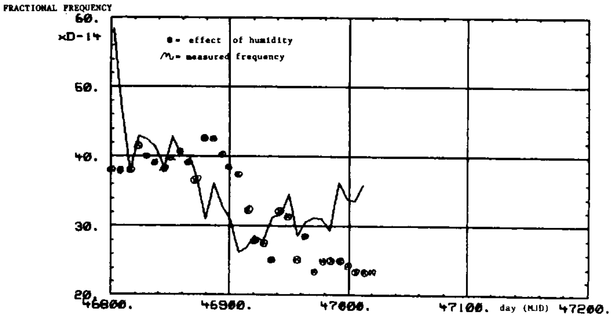

FIGURE 8. FTS217 - EFFECT OF HUMIDITY

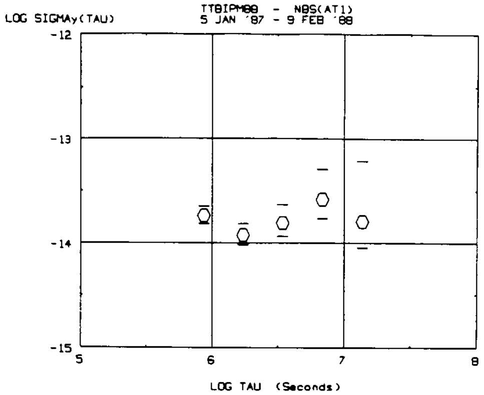

FIGURE 11. INSTABILITY OF NBS(AT1) vs. TTBIPM88

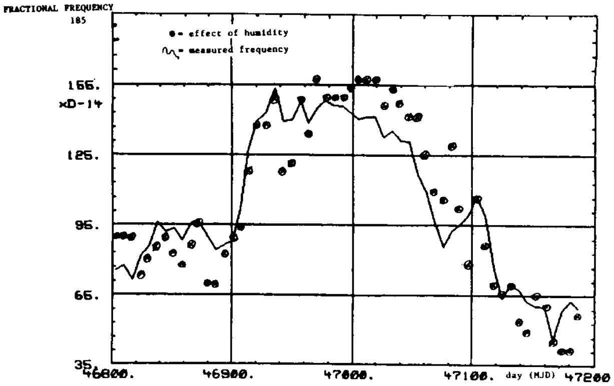

FIGURE 9. OSO61 - EFFECT OF HUMIDITY

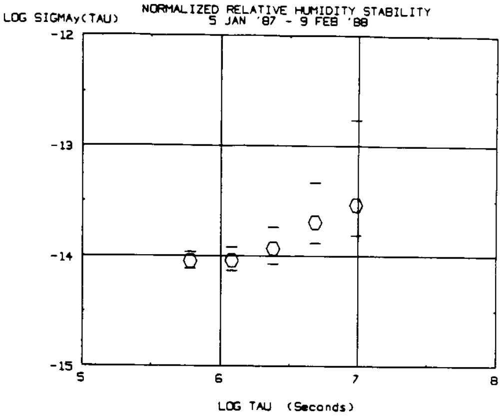

FIGURE 12. HUMIDITY-INDUCED INSTABILITY PREDICTED FOR NBS(AT1) FROM EXTERNAL ESTIMATE OF HUMIDITY VERSUS FREQUENCY COEFFICIENT