“Precision Oscillators: Dependence of Frequency on Temperature, Humidity and Pressure”

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PRECISION OSCILLATORS: DEPENDENCE OF FREQUENCY ON TEMPERATURE, HUMIDITY AND PRESSURE

WORKING GROUP 3 OF THE IEEE SCC27 COMMITTEE

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Abstract

Excluding vibration effects, variations in temperature, humidity and pressure (THP) are the most common environmental perturbations on precision oscillators. Thus the modeling, measurement and understanding of how these variations affect the frequency outputs of such devices are very important -- particularly for long-term behavior. In general, the effects of THP on frequency are non-linear and interdependent. For example, the temperature coefficient of a frequency standard is often directly dependent on the level of humidity. Hence, to obtain a complete model for even a single device, let alone a whole model line, would be incredibly complex.

Our purpose here is to arrive at tractable (non-burdensome) guidelines, standards, and precautions for test methods used in determining the dependence of the output frequency of precision oscillators on temperature, humidity, and pressure. Over specification, under specification, or the lack of proper specification will miscommunicate. We offer a perspective for the manufacturer and the designer, as well as the user so that clear understanding and communication can occur. The guidelines, standards and precautions encourage consistency and repeatability for measurement and specification of these environmental sensitivities. We believe very large cost savings will be appreciated if these guidelines, standards and precautions are followed.

INTRODUCTION AND DEFINITIONS

Excluding vibration effects, variations in temperature, humidity and pressure (THP) are the most common environmental perturbations on precision oscillators. Thus the modeling, measurement and understanding of how these variations affect the frequency outputs of such devices are very important -- particularly for long-term behavior. [1-6] In general the effects of THP on frequency are non-linear and interdependent. For example, the temperature coefficient of a frequency standard is often directly dependent on the level of humidity.

Given this complexity and nonlinear interdependence of these three environmental parameters, it is generally not possible to obtain a complete model for even a single device. Obtaining a general model for just the THP parametric dependence for a given type of device would be incredibly complex. There is also the danger that specifications might indicate that all is known in this regard. This would be very misleading. Our purpose here is to arrive at tractable (non-burdensome) guidelines, standards, and precautions for test methods used in determining the dependence of the output frequency of precision oscillators on temperature, humidity, and pressure.

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This is not a specification document for these parameters, but a resource document which gives guidelines for deriving specification statements and for developing methodology that will be efficient and cost effective for the manufacturer, designer and user. In addition, the information herein is intended to help the researcher, those developing precision oscillators and those wanting to get the best possible performance out of a precision oscillator.

We define, in the usual way, y(t) as the relative frequency (ref IEEE Standard 1139-88). This is the actual time dependent frequency minus the nominal frequency all divided by the nominal frequency. Hence, y(t) is a dimensionless number describing the instantaneous frequency offset from the nominal at time t.

We define the THP frequency dependence as the causal effect on y(t):

$$y(t) = f(T,H,P). \qquad (1)$$

We recognize that there may be other environmental parameters which are dependent on one or more of the T, H or P parameters. This problem is addressed later. Nonetheless, equation (1) is a useful conceptual model. In addition, the actual y(t) of an oscillator, of course, will be driven by internal effects. These other effects need to be adequately understood, be held constant or be sorted out in some appropriate way as the effects of T, H and/or P are studied.

In this document "quartz" will typically mean a precision quartz-crystal oscillator, "rubidium" will mean a rubidium gas-cell frequency standard, "cesium" will mean a cesium-beam frequency standard, and "hydrogen" will mean an active hydrogen-maser frequency standard. We now list a set of specific issues before we discuss general issues, guidelines, precautions and design issues.

* In quartz crystal oscillators, "activity dips" may occur. An activity dip occurs when a y(t) versus temperature (T) curve of an unwanted mode intersects the y(t) versus T curve of the wanted mode. Such activity dips are usually highly dependent on the way the quartz crystal resonator is being driven and on the load reactance in the oscillator circuit.

* Thermal hysteresis is also found in quartz crystal oscillators. This means that the frequency versus temperature plot generated as the temperature is increased will not be the same as that generated while decreasing the temperature.

* The pressure effect on a clock should not be confused with an altitude effect. For a high-accuracy clock, frequency will change with altitude due to the gravitational, relativistic "redshift" as measured against a clock at a fixed gravitational potential. This effect is small--about 1×10^{-16} per meter.

* It is preferable to measure the absolute humidity. Since often the relative humidity is given, the temperature must also be known.

* Because of the interdependence of the frequency of precision oscillators on various environmental parameters, it is always good practice to record all relevant data during a measurement. It is also wise to record what may seem to be trivial experimental conditions. Little things, like fans in a room moving the air around an experiment can make a big difference in time constants and apparent temperature and humidity responses of the output frequency.

* Most buyers of a product specify worst-case performance. It is also true that most design specifications are not necessarily written on the same basis. Our general practice is to use a statistical approach where the expected performance plus a guard band is listed as the specification. Companies differ widely in the size of the guard band. The specification is usually derived from a root-mean-square (rms) approach for all of the expected environmental parameters. In other words, in determining the effect of THP on an oscillator, it is not uncommon to assume that the full environmental range will never be met and that it is suitable to take the environmental influence on overall accuracy as the rms value of the individual environmental effects. In some cases this may result in a conflict between the designer and user. For a view of this, observe the data sheets of most typical quartz oscillators.

- We recommend the arithmetic-sum, worst-case approach, as we believe it is more realistic and honest. Its major fault is that it assumes linear dependence and no interaction between external effects. For frequency standards where interactions between outside influences dominate performance, this approach might be too aggressive. This approach also places additional financial burden on the manufacturer to do additional testing, but it should result in happier designers and users. Of course, the best approach lies in characterizing the standard as completely as possible.

GENERAL ISSUES

Because the environment is so enormously important to the long-term performance of precision oscillators and in some cases even to the short-term performance, it is very desirable to quantify the dependence of the oscillator frequency on the relevant environmental parameters. In this regard, it will be useful to come up with models describing these dependencies given the environmental perturbations. To handle all of them in a single model would be very difficult. It is better to break the problem into pieces and consider only those items that are important to the manufacturer, designer and user.

In the following equation we write a general description of the fractional frequency dependence of a precision oscillator as a function of temperature, humidity and pressure:

$$y(T,H,P) = \alpha_0 + \alpha_1 T + \alpha_2 H + \alpha_3 P + \alpha_4 TH + \alpha_5 TP + \alpha_6 HP + \alpha_7 THP. \qquad (2)$$

From this we obtain:

$$\begin{aligned} dy = {} & \alpha_1 dT + \alpha_2 dH + \alpha_3 dP \\ & + \alpha_4 TdH + \alpha_4 HdT \\ & + \alpha_5 TdP + \alpha_5 PdT \\ & + \alpha_6 HdP + \alpha_6 PdH \\ & + \alpha_7 THdP + \alpha_7 TPdH + \alpha_7 HPdT. \qquad (3) \end{aligned}$$

If the parameter cannot be varied independently, then covariance term must be included [7]. The manufacturer has the responsibility to state which ones of these coefficients are most important and for which type of oscillator. Although the assumption of linearity is almost always useful over small ranges, one of the problems in current commercial specifications of any of the THP parameters is the assumption that the parameters are linear over a large range. We will make some suggestions regarding this problem.

The above equations deal with coefficients which may depend upon the values of parameters other than T, H, or P, and hence will not be constant coefficients. In cases where there is a significant dependency of T, H or P on some other environmental condition, that needs to be stated.

We could write another set of equations that would describe the dynamics. For example, we could use a set of coefficients that are functions of the rates of change of each of the above parameters. Furthermore, in most precision oscillators there will be more than one time constant, hence the frequency-temperature dependence will be a very complex function as it involves the dynamics of the environment. If a non-standard model is used, there should be good motivation (e.g., unusual dependencies) to do so.

Often at "turn on" or during certain transient situations, the output frequency behaves in an exponential way. Where this is the case, the time constant of a particular model gives another method of describing the frequency behavior. In general, we need to distinguish between turn-on or transient behavior and steady-state behavior.

Although mathematical models can be powerful tools, we encourage practical (measurable) specifications and simple models and measurement methods.

Most users tend to prefer specification of worst-case performance; i.e., outer limits which must be met over a range of environmental parameters. However, this often leads to over-specification and undue expenditure. We strongly encourage a dialogue between user and designer so that the final oscillator meets the actual needs at affordable costs of manufacture and test.

There are always those who wish to carry the analysis and the modeling as far as they can. For those so inclined, we will give cautions, guidelines and suggestions that, hopefully, will be helpful in their analysis. However, we will primarily address the typical user, designer, developer and manufacturer.

GUIDELINES

Given the complexity of the problem, as much as practical, it is important to develop methods that will keep all parameters constant, except the one under test. In the case of humidity in precision quartz oscillators, it may be impossible to specify temperature and other dependencies in an open environment where the humidity is not held constant.

In general, the temperature coefficient of quartz oscillators is a strong function of humidity. If a quartz crystal oscillator is sealed against changes in humidity, then the temperature coefficient can be reasonably obtained. Condensed H_2O in a unit can cause drastic changes in performance and should be avoided. This can occur as significant temperature cycling occurs. Another problem with units open to the atmosphere is that the time constant associated with humidity change can be very long. Also, pressure changes can alter the mechanical stress on internal components. To cover this potential sensitivity, measurements of the pressure effect at one temperature are probably required, and this can probably only be done for a sealed unit.

In addition to holding other parameters constant, it is important to achieve steady-state conditions after any change in the parameter under test. Time constants for achieving steady state can vary enormously, but unless steady state is achieved, the transient effects can seriously cloud the estimates of the dependence on a particular environmental parameter.

Obtaining and separating these time constants is one of the first challenges in properly characterizing the effects of the environment. Time constants range from minutes in quartz oscillators (thermal transients lasting up to hours may be a dominant effect in non-SC-cut oscillators) to days in some atomic standards.

In order to separate and determine the dominant effect,we suggest using methods related to statistically controlled design of experiments. One of the simplest views of this is outlined in Bhote [8]. In this book, the dominant effect is known as the "Red X." Assuming that the constants are properly understood, in a relatively crude experiment the major effects can be determined. In this methodology, the variables, T, H, and P, are allowed to assume high and low values in a defined pattern. No real precision is sought, rather the goal is to determine the magnitude of the largest effect whether a single environmental parameter or a combination of them is important.

Once we know the dominant effect, we can then systematically explore it. In some cases there may be no single dominant effect, at least within some measurement precision. At this point, the next step may be to explore each of the variables separately with more precision.

The following are a general set of guidelines:

* Do a crude experiment to determine the dominant effect.

* Examine the dominant effect variable to determine its time constant (careful plotting and analysis are necessary to determine whether there is more than one time-dependent process present).

* Measure both dynamic and static responses to changes in the dominant effect with all other variables held constant. Once valid data are obtained, follow statistical procedures to eliminate the effect of the existing dominant effect, and find the next most significant factor, measure it, eliminate it, and continue to iterate as required.

* Write a specification that outlines the major environmental effects, test conditions and responses. Graphs here are essential. Three-dimensional graphing software make this relatively easy.

* Define an overall accuracy specification and the terms under which it was derived. Identify it explicitly as an rms specification, additive worst-case specification, or whatever other type of specification is being defined.

In general, in equations (2) and (3) above we should identify those terms that are most important and least important for different categories of oscillators. We can make some general statements about the different types of oscillators, but, as with all general statements, there will be exceptions. For example, temperature effects are the dominant factor in most, but not all, quartz crystal oscillators. In rubidium gas-cell frequency standards, T, H, and P are all important, with another caveat regarding the constituents of the atmospheric gasses. With the improper choice of glass, trace helium content becomes a dominant effect in apparent aging. Figure 1 is a classic example of environmental effects on a rubidium gas-cell frequency standard. Cesium-beam frequency standards, prior to recent optimization concepts, were dependent on both temperature and humidity.

RUBIDIUM FREQUENCY STABILITY WITH ENVIRONMENTAL CHANGES

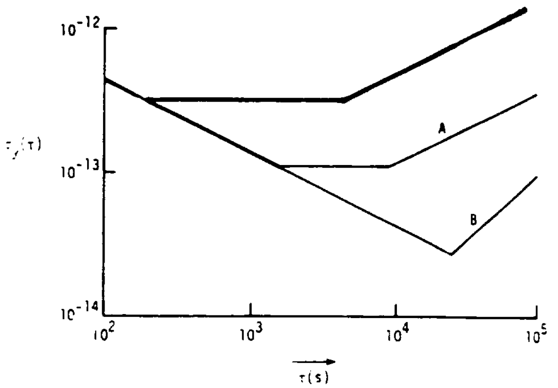

Figure 1. A plot of the random instabilities of a commercial rubidium gas-cell frequency standard with changing environmental conditions. The better the environmental parameters were controlled the better was the long-term frequency stability performance. The top curve is the frequency stability for nominal laboratory environment. Curve (a) additional magnetic shielding and temperature compensation was provided. Curve (b) was with the additional magnetic shielding, temperature compensation and with barometric sealing (pressure control). A frequency drift of approximately 1 part in 10^{13} per day was removed from the data before analyzing the stability.

From most experience, it seems that it is not relative humidity, but absolute humidity that is more important. It has only been in recent years that the humidity dependence on both atomic standards and quartz oscillators has been recognized as a very significant environmental perturber. (see Appendix)

Given the nonlinearities occurring, especially with temperature, it has been suggested that a coefficient be expressed such that the slope, dy/dT would not exceed some value over some specification range. If such significant nonlinearities exist, then the appropriate time constants need to be respected as the effects of these nonlinearities are determined. In general, nonlinearities will be very different between the different types of oscillators.

Since, in most cases, a frequency standard will have more than one thermal time constant, a measurement of steady-state thermal effects should not be made until waiting twice as long as the longest time constant, which takes it 86% of the way to its final value. If more precision is wanted, then the metrologist should wait as long as needed to accomplish the goal.

In some applications the dynamic effects may be more important. In space applications of clocks, because of expense and non-repeatability of the situation, it is best to simulate the dynamics of the space environment over some appropriate range of temperature.

For those pushing the performance of a standard as far as they reasonably can, it is very important to first know the part of the oscillator which is most sensitive to T, H or P, and then control the system with a T, H or P sensor at that point. If this is not practical, then temperature gradients in the environment should be minimized.

THP effects frequently are a cause of long-term frequency drift. Polynomial modeling can be misleading in estimating frequency drift [9]. Having an accurate measurement of frequency drift in precision oscillators is very important for both the manufacturer and the user. If an efficient estimator of the drift is used, this can save large amounts of time and money in the manufacturing process. It has been shown that misleading estimates are all too often obtained using a quadratic least-squares fit to the phase or a linear least-squares fit to the frequency, given the kinds of long-term random variations that are superimposed on top of the drift. Long-term random spectral density models for the frequency modulation are usually 1/f or random-walk in character. For these kinds of random residuals, a second-difference estimator for the drift is typically more efficient than the two methods mentioned above [10].

The mean second-difference estimate may be somewhat contaminated by higher Fourier frequencies than from the pure random-walk or 1/f model. For example, if white PM or white FM are also present (as they often are) these noise processes can significantly degrade the confidence of the mean second-difference drift estimate. However, a simple second-difference estimate using the first, middle and end data point from the time or phase residuals is very close to an optimum estimator for the above cases. This approach gives a much better confidence on the estimate of the drift as well [10].

White FM tends to be the predominant noise model for integration times of the order of a second out to several thousand seconds in both cesium and rubidium frequency standards. In the case of cesium this model may be appropriate for integration times of the order of a day and even longer. Measuring THP coefficients in the presence of this kind of noise presents a practical signal-to-noise problem. Since the optimum estimate of the mean of a white process is the simple mean, when measuring the effect of changes in these environmental parameters it is best to hold them constant and average the frequency for an interval such that the $\sigma_y(\tau)$ curve starts changing from $\tau^{-1/2}$ toward a flattening (flicker floor) where τ is the integration time over which the frequency is averaged. Then change the environmental parameter being evaluated and repeat the integration time to measure the frequency change. We may improve the precision with which we can determine the change in frequency with a change in an environmental parameter by reiterating the above process several times -- following the above rule for integration time. In principle, if "N" is the number of changes back and forth, then the confidence on the frequency change is the value of $\sigma_y(\tau)$ times $1/\sqrt{N}$. One must respect the settling times after changing a parameter's value as well as other systematics affecting the measurement.

PRECAUTIONS

Setting up proper measurement configurations is critically important. It will always be important to measure the "real" temperature. The exteriors of most frequency sources are not isothermal. Gradients depend on conductive and convective heat transfer; convection especially depends on the presence or absence of forced circulation in the surrounding atmosphere. Most testing in environmental chambers ignores this. In addition, the size of a unit is very important. Typically, the smaller the unit the less important will be the effect of temperature gradients.

The temperature at (and within) a device depends on the interplay between the external heat (or cooling) source and its conductive paths and the internal heat-generating mechanisms (internal ovens, electrical losses, etc.), and their respective conductive paths. Furthermore, the degree of coupling of both external and internal sources determines the various time constants, and thus is critical when one attempts to define quasi-static conditions.

In some instances temperature gradients may be more important than the actual temperature coefficient. For example, if a commercial cesium beam standard is turned upside down to measure the effects of a 2-g tip-over, what seems to be the stronger effect on the frequency is the change in temperature gradients since the convection currents flow in the opposite direction for many of the components. These effects can often be separated because of the difference in time constants.

The effect of thermal gradients in rubidium can easily be the dominant effect in its performance. The frequency drift rate is a strong function of the temperature gradients inside the physics package. As gradients change, the drift rate can change in magnitude and even in sign.

Oscillators that are hermetically sealed should show a totally different character than those that are open or sealed with gaskets that are permeable to moisture or different gasses (especially helium). Manufacturers should specify whether an oscillator is or is not sealed against changes in pressure, humidity and helium. Most plastic and rubber gaskets are permeable to moisture and helium. Open units and those with permeable gaskets will show many nonlinear and transient effects that are not present in sealed units. At high humidity, moisture can condense inside the unit and alter many of the electrical parameters. This effect will persist long after the high humidity has been removed because of the high heat capacity and relatively low vapor pressure of water.

Any change in the orientation of the oscillator during testing can invalidate the data since frequency changes due to acceleration and magnetic field can range up to 10^{-8}. Orientation of the oscillator under test also enters into the characterization. Physically inverting a quartz crystal oscillator has the potential of significantly changing the test results via temperature gradient, magnetic field and gravitational field. Therefore, repeating tests in different orientations may be necessary.

Polynomial modeling has its drawbacks and is not universally recommended. Actual devices may exhibit polynomial behavior in one property, exponential behavior in another, and something else in a third. In other words, the mathematical model chosen is probably as important as the coefficients used in understanding environmental coefficients. Polynomial modeling with too many coefficients may make the model too device dependant. The number of model parameters should be kept as low as practicable and still provide useful quantitative information.

Intuitively, we might think that we can learn the frequency dependence of a clock by exposing it to a white spectrum of temperature variations. By taking the Fourier transform of the frequency variations cross-correlated with the known temperature spectrum, we might hope to determine the impulse response function. Unfortunately, as clever as this experiment seems, it will fail because the coefficients are usually nonlinear. In addition, there are typically several different thermal time constants for almost any precision oscillator which complicates reaching the end goal.

For many standards, it appears that there is a maximum frequency shift with pressure change followed by a relaxation period. This may depend upon the time rate of change of pressure. Perhaps a maximum allowed shift for a specific pressure change could be easily measured. This might avoid some of the nonlinear characterization problems.

Particular concerns associated with each type of frequency standard are as follows:

Quartz

> Orientation, temperature, pressure, humidity, magnetic field and gravitational field all produce significant frequency shifts. Proper sealing of the case can reduce pressure and humidity shifts, but might actually exacerbate orientationally dependent thermal-gradient effects. Over the years, some of these thermal gradient effects have been reduced by relocating heaters and thermistors, and rerouting high-current leads. "Activity dips" in quartz crystal oscillators can cause adverse temperature dependence. If not properly included in a manufacturer's specifications, a system could fail, when in fact the specifications might indicate that the oscillator should work in a normal temperature-dependent fashion over some range of temperature. For example, when an activity dip occurs, there are cases where the magnitude of the temperature coefficient increases by as much as an order of magnitude and even changes sign. The oscillation amplitude may also change, and in the worst case the device might cease oscillation.

Measurement of "Activity dips" is adequately addressed by software designed to implement ANSI/EIA-512 [11]. Following this software design, one scans over a range of frequencies near the desired resonance thus determining the unwanted modes. The additional requirement is that the crystal should be monitored on a temperature-controlled stage. Several years ago activity dips were reported which occurred over millidegree temperature ranges. Therefore, it becomes critical that the temperature-controlled stage be of high precision.

Manufacturers obviously have a responsibility to indicate the presence of activity dips and to specify their impact on the oscillators performance as well as the range of temperatures over which they might occur. If it is believed that none are present over some range of performance, then that also should be stated.

In quartz oscillators, pressure effects should be very small for all sealed units. Oscillators that are sealed in vacuum should have the best pressure performance since outside pressure changes will not have an effect on the internal pressure. Units with small dimensions and/or a strong enclosure should show little response to changing pressure. There is the possibility that pressure changes could alter the mechanical stress on internal components. To cover this potential sensitivity, measurements of the pressure effect at one temperature are probably required.

Rubidium

These oscillators exhibit all of the effects of quartz, most of which can be reduced by proper sealing. The impact of all effects are reduced by one or two orders of magnitude over that in quartz because of the fundamental use of an atomic resonance in addition to a much higher line-Q. One unique problem for rubidium is that the effect of atmospheric gasses (diffusing into the gas cell) may show up as an unwanted change in frequency drift. The presence of helium in the ambient atmosphere can be devastating to rubidium standards.

Cesium

Cesium standards typically have long time constants. The Ramsey cavity is usually copper or a copper alloy. At one end is an oven at roughly 100° C. At the other end is a hot-wire ionizer at 950-1100° C. Full thermal equilibrium of the cavity may take many hours to reach. Temperature probably affects the physics package more than any other variable. Humidity affects high-impedance, beam-current, output amplifiers. All three parameters (THP) affect power delivered by the harmonic generator, although newer electronic circuit designs reduce these effects.

For cesium beam frequency standards, the temperature coefficient for the harmonic generator can be much larger than that for the power supply controlling the cesium oven, and each will have very different time constants.

The limited experience that we have with the frequency dependence on humidity in cesium standards indicates that the coefficients may be quite linear, and the coefficients seem to not be production line dependant; e.g. two units with adjacent serial numbers can have very different coefficients and these may be even of opposite sign.

Hydrogen

Since cavity pulling is a significant concern in hydrogen-masers, much effort has gone into stabilizing these cavities. The cavities must be stable to about 10^{-8} cm in order to have a frequency stability of the order of 1×10^{-14}. Much progress has been made in this area and frequency stabilities of the order of 1×10^{-15} are common for averaging times of the order of 100 s and longer -- in some cases as long as several days. Both temperature and pressure can detune the cavity. Long thermal time constants, similar to those in cesium, are often present in masers.

DESIGN ISSUES

Some specific design issues for the different types of precision oscillators are given here.

Quartz

Seal the device. Use insulation liberally to reduce convection inside the oscillator. Use SC-cut quartz. Evacuate the can. Keep it small.

Rubidium

If possible, seal the unit. Pre-age thermistors. Reduce convection currents if possible. Evacuate the unit if possible. Use a good quartz oscillator and second order integration loops to minimize the effect of changes in the quartz oscillator on the overall rubidium accuracy. If the unit is not sealed, use a glass for the storage bulb that has low permeability to helium and to the gasses in the bulb.

Cesium

Proper design can optimize performance to minimize most environmental effects. Use a good quartz oscillator and second order integration loops. Special attention should be given to THP offsets on the output level of the microwave power generation.

APPENDIX

Shown in Figure 2 is a year's worth of recent data comparing (through GPS) the various national standards and two commercial cesium standards in a temperature-controlled chamber. In

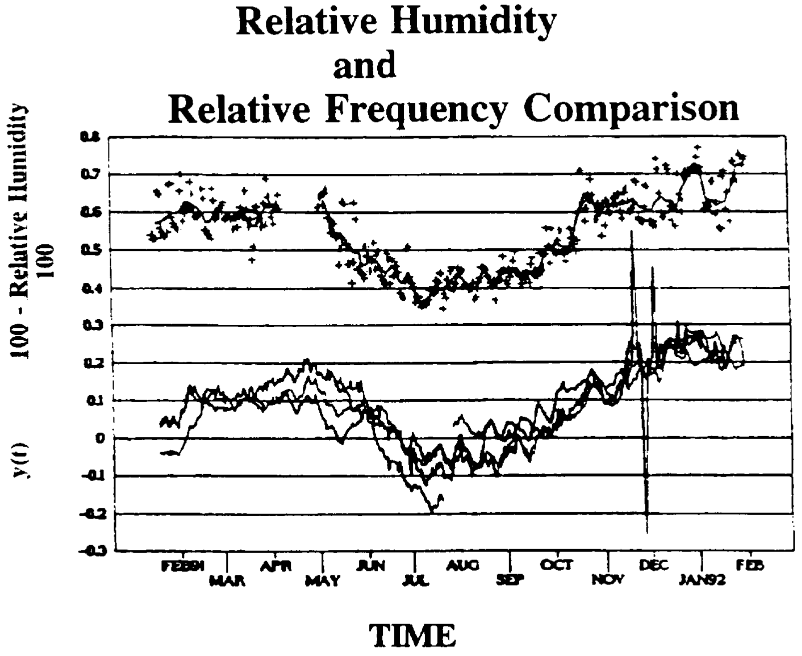

Figure 2. The plot is of both frequency, y(t), and the negative of the relative humidity versus time as measured in the laboratory. The top set of curves "+" are the negative of the relative humidity with a smoothed average plotted as well. The smoothing is a seven day average. Given that the temperature was relatively constant (to about ±0.5°C.) the change in relative humidity is directly proportional to the absolute humidity. The bottom set of four curves are of two commercial cesium-beam frequency standards, located in Geneva Switzerland, being compared with three independent timing centers (PTB, OP and USNO) via GPS in the common-view mode. The correlation is self-evident. The coefficient is about -1×10^{-14} per percent of relative humidity change. The environmental temperature was about 21°C.

this case the two commercial standards (both the same model number) had similar humidity coefficients. That is not always the case. Two other units with the same model numbers and differing by only one in their serial numbers had quite different humidity coefficients.

Figures 3 and 4 show the nonlinearity of frequency vs. temperature for AT-cut and SC-cut quartz crystal resonators. The advantages of the SC cut are evident. A variety of ways have been found to take advantage of these profiles. It is beyond the scope of this document to cover these, except to mention, since our main goal is to reduce environmental sensitivity, that controlling the temperature to a place where dy/dT is zero is obviously ideal. Not only does the SC-cut crystal have a larger plateau where this condition is approximately met, but the linear coefficient is usually about an order of magnitude smaller and the dynamic temperature coefficient is approximately one hundred times smaller. The turnover temperature for SC-cut resonance is also more desirable for many applications.

The development of the SC-cut crystal illustrates an important point. The best way to improve performance is to reduce the sensitivity of the basic frequency determining element rather than trying to provide better and better environmental control. The latter can be more and more expensive and also impractical for many field applications.

A related situation exists in cesium standards. One of the reasons for a temperature coefficient in cesium is that temperature affects the electronics causing a change in the micro-wave power output feeding the Ramsey cavity. The transition

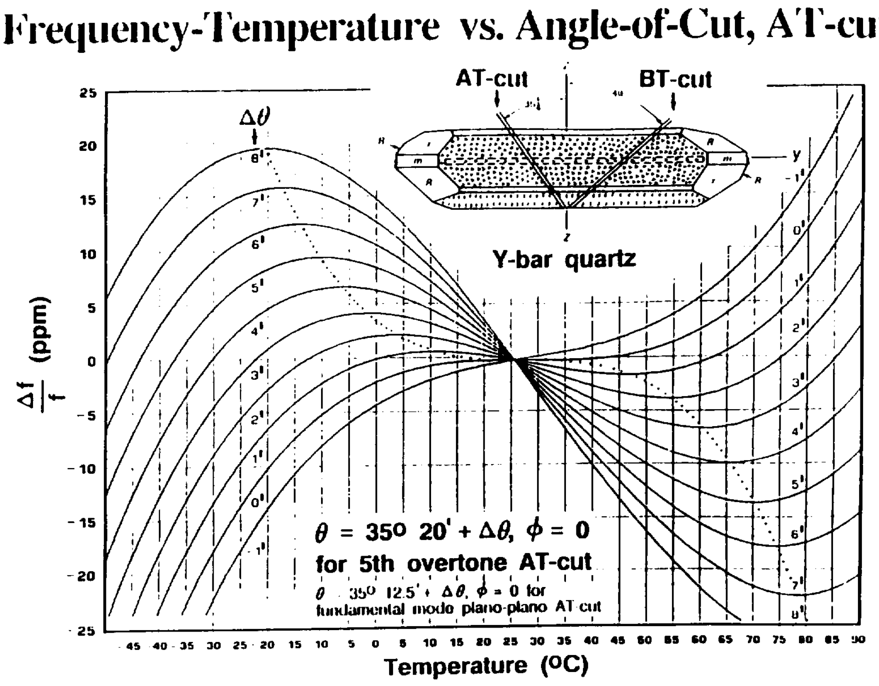

Figure 3. A family of plots of frequency versus temperature for AT-cut quartz-crystal resonators with differing angles of cut.

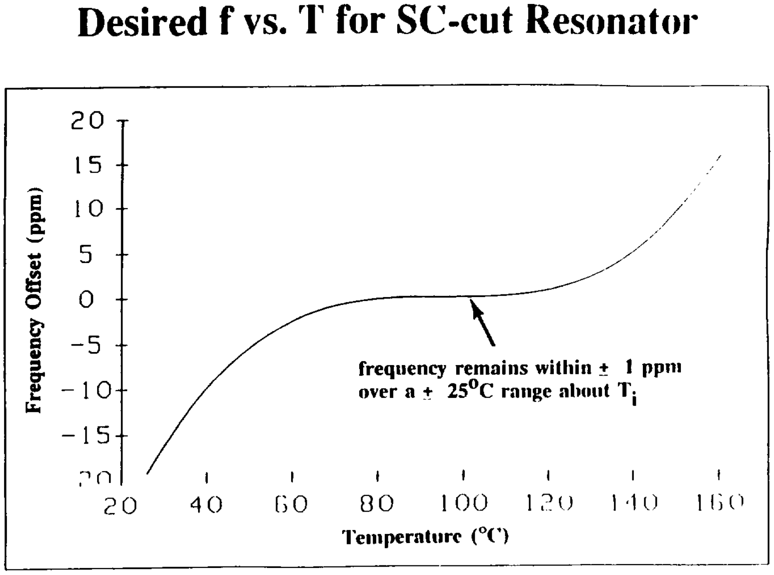

Figure 4. A plot showing the reduced temperature dependence of SC-cut quartz crystal resonators. Not only can a wider and more useful range of temperature operation be achieved, but the coefficient is about an order of magnitude smaller. The dynamic temperature coefficient is approximately 100 times smaller.

probability is a function of power, hence different velocities of atoms will be chosen with such change. If there is a non-zero cavity phase-shift across the Ramsey cavity (which there always is), this causes a frequency shift. As the velocity changes, the frequency shift changes. Figure 5 illustrates this sensitivity. The first sidelobe of the Ramsey spectrum is displaced by v/ℓ, where v is the nominal atom velocity and ℓ is the length of the Ramsey cavity. Hence, the microwave power can be servoed to a velocity corresponding to optimum power by sampling this sidelobe. By adapting such control, the overall temperature sensitivity is reduced [12,13].

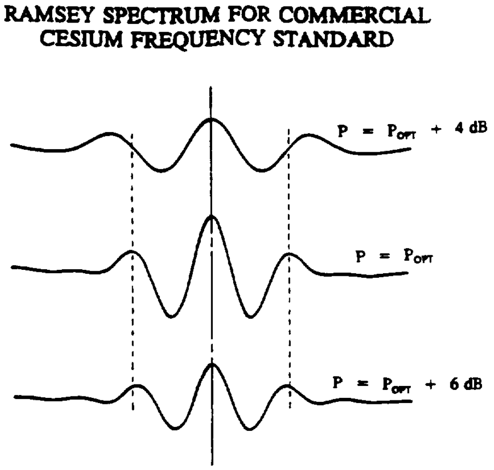

Figure 5. A plot of the Ramsey spectrum at three different microwave power levels in a commercial cesium standard. The velocity selection changes dramatically with changes in microwave power, causing a change in the spectrum. The value of P_{opt} is chosen as that power which gives best signal-to-noise.

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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 Times Scale," Proc. of the 19th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Redondo Beach, CA, Dec. 1-3, 1987, pp. 185-202.

[2] S. Iijima, K. Fujiwara, H. Kobayashi, and T. Kato: "Effect of environmental conditions on the rate of a Cs Clock-Annals of Tokyo Astronomical Observatory," vol. XVIII n1.

[3] G. Becker: Zeitskalenprobleme: jahreszeitliche Gangswankugen von atomuhren, PTB Mitteilungen 92 2/82.

[4] K. Dorenwendt: Das verhalten kommerzielle caesium atomuhren und ide zeitskalen der PTB-PTB Mitt. 94.

[5] J.-J. Gagnepain, Characterization Methods for the Sensitivity of Quartz Oscillators to the Environment, Proc. of 43rd Annual Symposium on Frequency Control, 1989, pp. 242-247.

[6] Fred L. Walls, and J.-J. Gagnepain, "Environmental Sensitivities of Quartz Crystal Oscillators," IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 39, pp. 241-249, March 1992.

[7] L. A. Breakiron, L. S. Cutler, H. W. Hellwig, J. R. Vig, and G. M. R. Winkler, "Environmental Metrology for Precision Oscillators," these proceedings.

[8] Keki, R. Bhote, World Class Quality, AMA Membership Publication #2334, American Management Association, New York, 1988.

[9] J. A. Barnes, "The Measurement of Linear Frequency Drift in Oscillators," in NIST Technical Note 1337, pp. 264-295, 1990.

[10] M. A. Weiss, D. W. Allan, and D. A. Howe, "Confidence on the Second Difference Estimation of Drift," these proceedings.

[11] ANSI/EIA-512, Standards Methods for Measurement of Equivalent Electrical Parameters of Quartz Crystal Units, 1 kHz to 1 GHz, 1985. Order from: Naval Publication & Form, Center or General Services Administration Business Service Centers in major U. S. Cities. See also Military Standard MIL-0-55310B,

Oscillators, Crystal, Gen Spec for. Order from: Military Specifications and Standards, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

[12] D. W. Allan and M. Garvey, "Microwave Power Level Stabilizing Circuit for Cesium Beam Frequency Standards," U. S. Patent No. 4,331,933, issued May 25, 1982.

[13] L. S. Cutler and R. P. Giffard, "Architecture and Algorithms for New Cesium Beam Frequency Standard Electronics," these proceedings.