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(Revision of
IEEE Std 1193-1994)

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IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators

IEEE Standards Coordinating Committee 27

Sponsored by the
IEEE Standards Coordinating Committee 27 on Time and Frequency

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(Revision of
IEEE Std 1193-1994)

IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators

Sponsor

IEEE Standards Coordinating Committee 27
on Time and Frequency

Approved 12 June 2003

IEEE-SA Standards Board

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Abstract: Standard frequency generators that include all atomic frequency standards, quartz oscillators, dielectric resonator oscillators, yttrium-iron-garnet oscillators, cavity oscillators, sapphire oscillators, and thin-film resonator based oscillators are addressed.
Keywords: atomic clock, atomic frequency standard, environmental sensitivities, frequency standard, oscillator, quartz crystal oscillator, standard frequency generator

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Introduction

(This introduction is not part of IEEE Std 1193-2003, IEEE Guide for Measurement of Environmental Sensitivites of Standard Frequency Generators.)

Techniques to characterize and measure the frequency and phase instabilities in frequency and time devices and in received radio signals are of fundamental importance to all manufacturers and users of frequency and time technology.

In 1988, the IEEE Standards Coordinating Committee 27 (SCC27) Time and Frequency, issued IEEE Std 1139™-1988, Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology, which defined and confirmed those measures of instability in frequency generators that had gained general acceptance by researchers, designers, and users throughout the world. In 1999, the SCC27 issued a revision of this standard, IEEE Std 1139™-1999.

After issuing IEEE Std 1139-1988, SCC27 then embarked on a much more ambitious effort aimed not only at codifying proper terminology, but also at providing guidelines for the characterizations and use of frequency and time standards in realistic environments. In 1994, the SCC27 issued the result of this work, IEEE Std 1193™-1994, which covered all important environmental conditions to which time and frequency devices are normally exposed. This standard aids the designer and manufacturer in characterizing their product and helps the user to properly accept, test, and confirm the specified behavior of devices in a variety of environmental conditions.

This standard is a revision of IEEE Std 1193-1994, which had been prepared by a previous SCC27 consisting of Helmut Hellwig, Chair; John R. Vig, Vice Chair; David Allan; Arthur Ballato; Michael Fischer; Sigfrido Leschiutta; Joseph Suter; Richard Sydnor; Jacques Vanier; and Gernot M. R. Winkler. Many sections of the 1994 standard remain unchanged.

Participants

The following is a list of participants in the IEEE Standards Coordinating Committee 27 (SCC27) Time and Frequency.

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IEEE Guide for Measurement of Sensitivities of Standard Frequency Generators

1. Overview

1.1 Scope

Standard frequency generators include atomic frequency standards, quartz oscillators, dielectric resonator oscillators (DROs), yttrium-iron-garnet (YIG) oscillators, cavity oscillators, sapphire oscillators, and thin-film resonator (TFR) based oscillators. Excluded are oscillators with a frequency stability worse than approximately 10^{-4}, as well as all other active and passive electronic equipment such as receivers, amplifiers, filters, and so on.

There are three distinctly different areas of concern for environmental testing and specifications listed as follows:

a) Fitness for specific user needs and actual environments (tests attempt to mimic the anticipated environments)

b) Characterization of the unit (tests attempt to provide "pure" coefficients for the various environments)

c) Reliability and survival (tests attempt to stress the unit by either going to extremes of operating ranges or by repeated application of stimuli, e.g., cycling)

This document puts emphasis on b) above. It provides guidance and a conceptual framework rather than a prescription of procedures that must be followed. It emphasizes proper methodology and practice; it cautions against pitfalls. It also is concerned with economic issues, i.e., the potential resource requirements and their minimization in test and measurement. In summary, this IEEE guide is not a specification document, but rather a resource document for deriving specification statements.

1.2 Purpose

This document describes the nature of the environmental effects, as well as of the test methods to evaluate, quantify, and report (i.e., in specifications) the sensitivity of the frequency of standard frequency generators under environmental influences such as magnetic fields, atmospheric pressure, humidity, shock, vibration, acceleration, temperature, ionizing radiation, and intermittent operation. Its primary purpose is to aid in writing specifications and to verify specified performance through measurement. In addition, this document

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will help to assure consistency and repeatability of environmental sensitivity measurements, and the portability of results on particular frequency sources between the various segments of the time and frequency community.

1.3 Summary

The very broad scope of this guide makes it desirable to introduce the many individual environmental phenomena in summary fashion. The following subclauses will assist the user of this guide in rapidly identifying those passages of this document that are relevant.

1.3.1 General considerations in the metrology of environmental sensitivities (refer to Clause 3)

Environmental effects on precision oscillators may be evaluated by

a) Identification of relevant parameters and transducing factors through correlation and spectral analyses

b) Control or removal of systematic effects (through curve-fitting, differentiation, etc.)

c) Evaluation of residual random errors by means of two-sample variances and covariances and an error budget analysis

Given an adequate measurement system, frequency reference, and control over experimental conditions, optimal data reduction involves choices as to parameter range, sampling time, averaging process, and mathematical model. Matters may be complicated by nonlinear responses, intercorrelations, different time constants, transient effects, and aging. If quasi-state conditions are not applicable, explicit account should be taken of the temporal and spatial profile of the stimulus.

1.3.2 Acceleration effects (refer to Clause 4)

The effects of acceleration on atomic standards and other precision frequency sources are reviewed, and guidelines are provided for the specification and testing of oscillator acceleration sensitivities. The discussion includes steady-state acceleration effects, gravitational change effects, shock effects, and vibration effects. The vibration effects subclause includes sinusoidal vibration, random vibration, and acoustic noise effects. Also discussed are the effects of frequency multiplication and modulation index, the effects on short-term stability, spectral responses at other than the vibration frequency, interactions with other environmental effects, and other pitfalls.

1.3.3 Temperature, humidity, and pressure (refer to Clause 5)

In addition to vibration effects, variations in temperature, humidity, and/or pressure (THP) are the most common environmental perturbations on terrestrial precision oscillators. (Radiation is another environmental effect of particular relevance in space applications; refer to Clause 7.) These environmental perturbations typically adversely affect the long-term behavior of oscillators. In general, the effects of THP on frequency are nonlinear 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. The purpose is to arrive at guidelines and precautions for test methods used in determining the dependence of the output frequency of precision oscillators on THP that are tractable (non-burdensome). Overspecification, underspecification, or the lack of specifications will lead to miscommunication. A perspective is offered for the manufacturer and the designer, as well as for the user, so that clear understanding and communication can occur. These guidelines and precautions encourage consistency and repeatability for measurement and specification of these environmental sensitivities.

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1.3.4 Electric and magnetic fields

Guidelines are formulated for test methods leading to practical and factual specifications for electromagnetic effects on standard frequency generators. Electromagnetic effects include, for the purpose of this guideline, electric fields, magnetic fields, and electromagnetic interference (EMI). In all cases, the effect will be considered a "black box" effect; i.e., the internal response of various components to the stimulus is not considered; only the overall response of the device to the stimulus is taken into account.

1.3.5 Ionizing and particle radiation (refer to Clause 7)

Characterization of the response of frequency standards to ionizing and particle radiation, such as those encountered aboard a spacecraft, should be based on a thorough understanding of the radiation environment (proton, electron, neutron, flash X-ray radiation, and single event upset) and radiation scenarios (dose/anneal cycle and combined environments). Specifically, the stimulation of radiation-induced effects in low-earth-orbit requires a simulation of actual exposure periods followed by annealing periods. Frequency standards have exhibited greater sensitivities to this form of radiation because mobile contaminant ions, which freed themselves during the anneal period, can interact again with subsequent ionizing radiation. For enhanced environments, the radiation from a burst can be classified both according to time of production, prompt or delayed, and type of radiation. This document presents, in detail, the various forms of radiation existing or produced in the low-earth-orbit and enhanced environments. In particular, emphasis is placed on flux, fluence, dose rate levels, and interaction mechanisms as pertaining to realistic radiation exposure scenarios. In addition, selection criteria for radiation sources are presented, including dosimetry and procedures for the radiation testing of frequency standards. A subclause is also included on the effects of nuclear-burst-generated electromagnetic pulses.

1.3.6 Aging, warm-up time, and retrace (refer to Clause 8)

An important characteristic of a precision frequency source or a standard frequency generator is the variation of its output frequency caused either by internal changes or alterations of operating conditions. The character of these changes and the number of their causes are very large. Aging, warm-up time, and retrace characteristics of precision oscillators are examined in connection with their definition, methods of reporting their size in a given device, and recommended techniques of measurements.

2. References

This guide shall be used in conjunction with the following publications.

Glossary of Time and Frequency Terms issued by Comite Consultatif International de Radio Communication—International Telecommunications (CCITT) Union, Geneva, Switzerland.[1]

IEEE Std 1139™-1999, IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology—Random Instabilities.[2]

MIL-0-55310, General Specification for Military Specification, Oscillators, Crystal, Military Specifications and Standards.[3]

[1]CCITT publications are available from the International Telecommunications Union, Sales Section, Place des Nations, CH-1211, Genève 20, Switzerland/Suisse (http://www.itu.int/). They are also available in the United States from the U.S. Department of Commerce, Technology Administration, National Technical Information Service (NTIS), Springfield, VA 22161, USA.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

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MIL-STD-202, Test Methods for Electronic and Electrical Component Parts.

MIL-STD-810, Environmental Test Methods and Engineering Guidelines.

3. General considerations in the metrology of environmental sensitivities and relativistic effects

3.1 General

The basic principle governing the physical measurement of time is demarcation of equal time intervals by observation of a repeating process. More than one such process or clock may be required for statistical inter-comparison (to achieve precision). Isolation of each clock from the rest of the universe is essential for identical process repetition (to achieve stability). Analysis of residual errors attributable to environmental influences allows corrections to a standard system (to achieve accuracy).

Resonances of macroscopic resonators such as quartz crystals and other precision resonators are determined by the type and dimensions of the material, the material method excitation, and other factors. However, changes in the environment such as temperature that affect those dimensions and factors, as well as other external stimuli, such as radiation, inevitably introduce frequency error at some level. Likewise, although isolated atoms at rest have fixed resonant frequencies, any force acting on them inside an atomic oscillator (e.g., due to exciting microwaves, cavity walls, or magnetic fields) can cause a frequency shift of the resonance. In practice, the apparent resonant frequency of ensembles of atoms can also vary because of such effects as dimensional changes or mistuning of the resonant cavity, imperfections in the detector, and distortions due to the electronics. If any of these effects varies with time, the result is frequency instability. Thus, the instability of a well-adjusted precision oscillator depends on a number of (perhaps, interacting) factors mostly related to the stability of the environment.

It is well known that the frequencies and accuracy of high-precision frequency standards are susceptible to changes in ambient conditions, necessitating their operation in a controlled environment. The most important effects have been found to be acceleration (including vibration) (refer to Clause 4), temperature, humidity, barometric pressure (refer to Clause 5), load impedance, power-supply voltage, electric and magnetic fields (refer to Clause 6), and radiation (refer to Clause 7).

For the user, it is of utmost importance to know the magnitudes of an oscillator's sensitivity to each external influence and the accuracy that can be anticipated under all expected operating conditions. Accordingly, the manufacturer should employ test methods and evaluation criteria that are reasonably standardized, that accurately predict the performance of the product, and that clearly define the limits on its accuracy imposed by the environment. It is also necessary to understand the source of these sensitivities if ways are to be found to reduce them. For the system's designer, it is necessary to appreciate the relative importance of these sensitivities in order to make the optimal tradeoffs. Standardization of environmental test methods should ease device specification, simplify test plans, clarify test results, and lead to improved oscillator performance and application. The need for greater knowledge about environmental sensitivities has increased with the increasing accuracy of timing and positioning systems, especially in the extreme environments encountered in land- and sea-mobile, airborne, and spaceborne applications.

3.2 Analytical methods

Instabilities in an oscillating system may be analyzed deterministically and stochastically. In the deterministic part of the analysis, systematic effects are modeled by an analytic method such as curve-fitting or Kalman-filtering the time or frequency data relative to some reference, yielding the derivative (frequency or frequency drift) and higher order or otherwise nonlinear trends. After the systematic variation is

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documented and removed, random errors are evaluated by measures such as the two-sample (Allan) variance in the time domain (refer to Allan [B1], Ferre-Pikal et al. [B15], IEEE Std 1139™-1994 [B25], and Rutman [B37][4]) or the spectral density function in the frequency domain (refer to IEEE Std 1139-1995 [B25], Percival [B33], and Greenhall [B19]).

In the stochastic approach, trends such as a rate (frequency) drift can often be removed by differentiating the function or differencing the series one or more times. For example, the instantaneous frequency *y(t)* of a clock is the first derivative of its phase *x(t)* and is approximated by the first difference in the time. Random errors may then be characterized by the autocorrelation function, the power spectrum, or Allan variance.

Given a continuous signal *x(t)*, such as a clock's phase relative to some reference, the *autocorrelation function* is

$$\Phi_{xx}(k) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{+T/2} x(t+k)x(t)dt \tag{1}$$

where

t is the time,
k is the lag time.

As the data are usually discrete and equally spaced, the signal can be replaced with a time series and the autocorrelation function with the *k*th *autocorrelation coefficient* as follows:

$$p_k = \frac{\sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x})}{\sum_{t=1}^{n} (x_t - \bar{x})^2} \tag{2}$$

where

$\bar{x}$ is the mean of *x(t)*,
n is the number of data samples.

Some sampling error has been necessarily introduced due to our time steps and finite data length. A plot of p_k vs *k* is called the *autocorrelogram*.

A sinusoidal appearance to the autocorrelogram indicates the presence of periodic phenomena, either internal or environmental in origin. Internal variations (which also include spontaneous phenomena such as phase jumps and relaxation effects) plus statistical noise constitute the inherent noise of the system. Before environmental effects can be investigated, these noise processes can be calibrated (on the basis of system performance in steady state) and corrected. Such correction is better done during postprocessing than in real time because of the superior determination of constant and periodic characteristics through averaging and modeling (e.g., with ARIMA [B10] or Fourier analysis) and clearer recognition of spontaneous changes (such as by forward and backward filtering).

Time-series analysis generally involves the assumption of ergodicity and stationarity. An ergodic process has the property that sample (or time) averages of observations may be used as approximations to the corresponding ensemble (or population) averages. A stationary series is one whose mean, variance, and higher statistical moments do not change significantly with time. Generally, approximate ergodicity and

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stationarity of the mean, variance, and autocorrelation coefficients for low lag times are sufficient in practice. Approximate stationarity can often be achieved by differentiation or a change of variable, such as use of first differences or logarithms. For example, replacing the phase *x(t)* above with its first difference *y(t)* may make the series sufficiently stationary. Stationarity is indicated by rapid damping of the autocorrelation coefficients. Drifts with time in the characteristics of a disturbing signal may invalidate the assumptions of ergodicity and stationarity.

Generally, the input *x(t)* and output *y(t)* of a linear time-invariant system can be related as follows:

$$y(t) = \lim_{T\to\infty} \int_{-T}^{t} w(t-t')x(t')dt' \tag{3}$$

where

w(t) is called the system's impulse response function.

The Fourier transforms of *y(t)*, *w(t)*, and *x(t)*, namely, *Y(f)*, *W(f)*, and *X(f)*, are related similarly as follows:

$$Y(f) = W(f)X(f) \tag{4}$$

where

f is the Fourier frequency,

W(f) is referred to as the system's frequency response function.

The response of a system, or a quantity under measurement, may be affected by other variables called input (or influence) quantities, which may be internal or external. The latter are of concern, in particular those that depend on time, and hence, may affect our time- or frequency-measuring process. If one can deduce the environmental factors likely to be of significance and has concurrent data on their magnitude, the environmental influences may be investigated with least-squares (refer to 3.5) or cross-correlation techniques (refer to Box and Jenkins [B10] and Breakiron et al. [B11]). The latter can be compromised if there are different (e.g., thermal) time constants involved (refer to Clause 5).

Providing the dependence can be modeled, a correlation coefficient (or, equivalently, a covariance) can be computed whose significance can be tested statistically. When the correlation is significant, the coefficient of dependence can usually be determined with sufficient accuracy to correct for most of the effect. In this case, the residuals (e.g., phases) should be Gaussian and their derivatives (e.g., frequencies) are white noise; i.e., they are neither autocorrelated nor cross-correlated.

Nonlinear responses can greatly complicate determination of environmental sensitivities and may invalidate statistical measures of frequency stability. Examples of nonlinear behavior are the following:

a) Gross changes in the magnitude and sense of the temperature coefficient of quartz oscillators near "activity dips"

b) The electric field sensitivity of crystal oscillators

c) The magnetic field sensitivities of many types of oscillators

After all relevant environmental influences have been identified, the sensitivity coefficients (or factors) can usually be determined from an analysis of the oscillators frequency variations Δf as a linear function of the relevant driving variables z_j as follows:

$$\frac{\Delta f}{f} \approx \sum_j \frac{1}{f}\frac{\delta f}{\delta z_j}\Delta z_j \tag{5}$$

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Equation (5) is valid for a steady state or very slowly varying system. Equation (5) also assumes a Taylor series expansion about the mean of each variable, at which the derivatives are evaluated, and keeps only the first-order terms; significant nonlinearity would require higher order terms.

Some variables act through transducing factors; e.g., a hydrogen maser cavity's frequency variation may be related to the cavity's dimension *D* and temperature *T* as follows:

$$\Delta f = \frac{\delta f}{\delta D}\frac{\delta D}{\delta T}\,\Delta T \tag{6}$$

If these influences can be measured or predicted and their effects modeled, *f* can be corrected for them. For example, the frequency of a temperature-compensated crystal oscillator (TCXO) is automatically corrected for thermal effects on the basis of a predetermined temperature dependence (Stein and Vig [B40]).

3.3 Measurement methods

A published measurement should always be accompanied by its associated uncertainty, and to ensure that both of these are meaningful and reproducible, the physical and statistical methods involved should be clearly documented, including all limitations, correction factors, and error sources.

One cannot measure and should be careful not to specify the environmental sensitivity of an oscillator more precisely than is permitted by the fundamental instability of that oscillator. As stability generally depends on sampling time, test procedures should allow sufficient measurement time before and after application of environmental stimuli for the oscillator to reach a given stability level (refer to Ferre-Pikal et al. [B15], IEEE Std 1139-1999 [B25], and Howe et al. [B24]). This limitation can be overcome somewhat by repeated measurements and use of correlation techniques.

Complete, unambiguous tests should include measurements of time and frequency offset, phase noise, amplitude noise, and frequency stability (e.g., Allan variance) before, during, and after environmental changes over a range of frequencies and for a length of time adequate to average down the noise and contain the lowest frequencies of interest (Allan [B2], Ferre-Pikal et al. [B15], and IEEE Std 1139-1999 [B25]). The sampling (Nyquist) frequency must be greater than twice the highest frequency present in the data; otherwise, higher frequencies will be misinterpreted as lower frequencies ("aliasing") (Howe et al. [B24]). The frequency bandwidth (spectral window) should be narrow enough and properly shaped by weighting factors for sufficient resolution and minimal bias and leakage, and yet wide enough for adequate smoothing (Oppenheim and Willsky [B32]).

The frequency stability of a precision oscillator is best measured with a computerized system consisting of a frequency reference; frequency multiplier, divider, or synthesizer, time interval and/or frequency counter or heterodyne arrangement; and spectrum analyzer. Phase noise may be measured with a double-balanced mixer and a phase-locked reference oscillator. In some cases, it may be necessary to use a two-channel cross-correlation technique to measure the phase noise (refer to Howe et al. [B24], Stein [B38], Walls et al. [B46], and Walls [B47]). Control of experimental conditions is critical to obtaining reproducible results. All critical equipment, environmental control, and test units should be powered by an uninterruptible power source (Sydnor et al. [B41]).

All frequency measurements depend on a reference frequency, which should be as stable and accurate as required in view of the basic performance being measured. Any trend in the data should be removed first with curve-fitting or other techniques. Every oscillator has a characteristic behavior of Allan variance vs sampling time according to the types of noise present (refer to Allan [B1], Ferre-Pikal et al. [B15], IEEE Std 1139-1999 [B25], Howe et al. [B24], and Allan [B2]). Over increasingly longer sampling times, the Allan variance eventually increases due to environmental influences and aging, if aging has not been removed (refer to Clause 8). Over long sampling times, one must refer to a "paper timescale" computed as a

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filtered average from an ensemble of clocks (refer to Allan et al. [B3], Percival [B34], and Stein and Evans [B39]) or utilize a time signal, say, via common-view GPS (Lewandoski and Thomas [B29]), from an official timing center whose master clock might be steered in frequency toward a paper timescale. In the latter case, the effects of steering may have to be removed by reference to International Atomic Time (TAI), although TAI is only available every ten days, two months after the fact.

Any analysis using time or frequency differences between oscillator pairs yields only the vector sum of their stabilities (neglecting intercorrelation). An "n-cornered-hat analysis" of Allan variances may be used to separate the individual oscillator errors, assuming measurements are simultaneous and statistically independent and neglecting noise added by the measurement system. For the case of *n* oscillators, the variance σ_i^2 of an oscillator *i* may be computed from the following:

$$\sigma_i^2 = \frac{1}{n-2}\left(\sum_{j=1}^{n}\sigma_{ij}^2 - A\right) \tag{7}$$

where

σ_{ij}^2 is the variance of the differences between oscillators *i* and *j*, $\sigma_{ii}^2 = 0$, and

$$A = \frac{1}{n-1}\sum_{\substack{k=1 \\ j<k}}^{n}\sigma_{jk}^2 \tag{8}$$

(refer to Allan [B2], Barnes [B6], and Gray and Allan [B18]). The method works best when the oscillators are comparable in stability. Even so, intercorrelations among the oscillators and errors associated with the variance determinations may result in the computation of negative variances (refer to Stein [B38] and Yoshimura [B48]), which may be avoided by taking explicit account of the intercorrelations (Tavella and Premoli [B42], Premoli and Tavella [B35], Torcaso et al. [B43], Ekstrom and Koppang [B14]). Measurement system noise may be rejected by an equivalent method that utilizes cross-correlation (Groslambert et al. [B20]).

Interactions between adjacent oscillators (e.g., a test unit and its local reference or a field unit and its backup) may occur as a result of electric field coupling, magnetic field coupling, common ground currents, and feedback through control loops where circuit isolation is deficient (Zaduszliwer et al. [B26]). These interactions are elusive to measurement, except by use of three independent references in dual-bridge circuits capable of picosecond to femtosecond phase measurements using heterodyne techniques for interactions $\leq 10^{-14}$ in frequency. Physical separation of the independent oscillators is especially important if the electrical or magnetic shielding of the oscillators is inadequate. The ambient conditions can also cause correlated behavior, whose common errors will be impossible to detect without recourse to an external reference. Any correlation between two oscillators reduces the variances obtained, resulting in their underestimation.

When a precision oscillator is under test, its resonance frequency and phase noise at a particular drive level and bandwidth are determined; then, as ambient conditions are varied, measurements are made of the oscillator's characteristics (e.g., its frequency vs temperature curve, its electrical parameters after compensation for the impedance of the measuring system, etc.; Kinsman and Rydback [B28]). Abrupt changes in ambient conditions, such as oven turn-on, have protracted effects until the oscillator stabilizes at a particular frequency. Also, AM noise generated by environmental effects can mask or mimic phase noise.

In passive atomic frequency standards like a cesium or a rubidium clock/crystal oscillator (RbXO), a voltage-controlled quartz crystal oscillator is locked to an atomic resonator, which generates a highly stable frequency reference based on an atomic transition. Of the many transitions available, the ones selected are those least sensitive to environmental (in particular, magnetic) disturbances and to which a crystal oscillator

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may be conveniently locked (Vanier and Audion [B44]). The environmental sensitivity of such a frequency standard is theoretically given by the crystal's sensitivity modified by the transfer function (refer to Box and Jenkins [B10] and Breakiron et al. [B11]) of the frequency- or phase-locked servo-loop or filter. In practice, only total system testing can ascertain system behavior because the atomic resonator is environmentally sensitive as well. The short-term stability is generally determined by the crystal oscillator and the long-term stability by the atomic resonator, with the crossover behavior and the point from uncontrolled to resonator controlled conditions being determined by the design and frequency response of the feedback control loop (Vanier and Audion [B44] and De Marchi et al. [B12]).

The difficulties involved in clearly relating the amount of frequency change to variations in environmental conditions may require each unit to be tested individually. The individual components of a frequency standard might be tested separately, although there will still be influences from connections and component interactions.

One difficulty is to measure effectively the property of the element under test, and not the property of the environmental sensor or transducer (e.g., oven). Consequently, the sensor and transducer should be as closely coupled to the oscillator as possible, or alternatively, it should be located and/or buffered so as to duplicate as closely as possible the experience of the oscillator as it will be deployed in actual field use.

3.4 Interactions among environmental stimuli

If more than one environmental factor proves to be of significance, all other such factors should be held constant while the dependence of each is being determined. As the relevant factors are not always obvious, and as unrecognizable influences can obscure the effect of a given parameter, it is best to control as many of the ambient conditions as possible, e.g., by isolating the frequency standard and measurement system in an environmental chamber with good thermal insulation, humidity control, air circulation, and magnetic shielding. Regarding the latter, residual magnetic fields inside the shields can be evaluated and the frequency possibly reset whenever changes in the external magnetic field occur, e.g., after moving the device. The magnetic shields may also have to be demagnetized.

Even so, coupling between the parameters may necessitate the use of special statistical techniques like multivariate analysis. The following are examples:

a) Temperature, humidity, and barometric pressure effects are interrelated. Temperature changes can cause significant changes in humidity both inside an environmental chamber and inside a frequency standard, especially if the chamber is not humidity controlled. Temperature and humidity affect the characteristics of electrical components in frequency standards (refer to Audion et al. [B4], Riley [B36], Mattison [B31], and Walls and Gagnepain [B45]). Condensation and even ice can form inside a unit and permeate materials, which can affect electrical properties and cause shorts and other damage to sensitive electronics and other components. Condensation can be eliminated by testing under a vacuum, but the concomitant removal of convection alters the temperature distribution, and electrical discharges may occur at very low pressures that will affect performance and even damage components. The time constants for humidity changes within the unit are not necessarily equal to the thermal time constants, possibly causing erratic results with regard to both humidity and temperature. The unit may have critical areas that are not well vented and, hence, have local time constants that differ substantially from the global time constants of the unit (refer to Clause 5) (Hellwig [B23]). These problems can be circumvented by the stochastic approach mentioned in 3.2, even in the presence of nonlinearities, because very small random disturbances would avoid responses in the nonlinear region.

b) Oscillators are often hermetically sealed against humidity, e.g., the absorption cell of a rubidium standard, the resonant cavity of a hydrogen maser, or the mounting structure of a crystal oscillator. However, changes in barometric pressure or ambient magnetic field can deform this packaging, alter the heat transfer conditions, and affect the frequency (refer to Clause 5) (refer to Riley [B36], Matison [B31], and Walls and Gagnepain [B45]).

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c) Acceleration effects are usually measured by changing the orientation of a frequency standard relative to gravity. However, because a significant portion of the heat transfer inside a unit is by air convection, such a reorientation ("*2g tipover*") will alter the internal heat distribution, resulting in thermal effects. There may also be effects due to altering the direction of the magnetic field. If the data desired are really for tipover, the test is still valid, even though it is not exclusively a measurement of acceleration sensitivity (refer to 4.2.1.3) (Hellwig [B23]). It is generally possible to separate these effects from the thermal effects by looking at the transient variation of frequency because thermal effects will have a significant time constant, and gravitational and magnetic effects will appear instantaneously (Walls and Gagnepain [B45]).

d) Movement, acceleration, or vibration can lead to magnetic or electric effects, if such fields are present, by changing the orientation of the resonator therein.

e) In passive atomic standards, vibrations at the servo-loop modulation frequency, its subharmonics, and even-harmonics can affect the crystal oscillator, harmonic generator, microwave power, power supply, and other electronics.

f) The temperature of a crystal oscillator affects its sensitivity to vibration (refer to Clause 4) (Hanson and Wickard [B22]).

g) If an oscillator receives a dose of radiation in a period of time short in comparison to its thermal time constant, the internal heating caused by the radiation will have effects that are particularly noticeable when measurements are made within a period of time less than the thermal time constant of the unit (Hellwig [B23]).

h) Power-supply fluctuations, filtered by voltage regulators, can lead to lagged secondary effects such as changes in the internal power dissipation and, hence, heat distribution, producing thermal effects.

i) In a rubidium standard, the microwave excitation field, radio frequency power, temperature distribution, C-field, and pumping light intensity are interrelated, so that inhomogeneities in any of these shift the region of optimal signal, resulting in a frequency change (Riley [B36]).

j) Oscillating (ac) magnetic fields can induce voltages that interfere with vibration-sensitivity tests and can also cause thermal effects because any transient magnetic field dissipates energy proportional to the area of the hysteresis cycle in the material. Eddy current losses also add heat. Air cooling during centrifuge tests can cause thermal effects as well.

k) The permeability of typical magnetic materials and, hence, the magnetic field sensitivities of oscillators may in general depend on temperature and the oscillator's history.

l) Residual magnetic fields may arise from oven heaters. Magnetic effects may be induced if the oscillator is not sufficiently protected from strong ac fields associated with vibration test equipment and centrifuges. The residual dc magnetic field of an oven heater may cause a pseudo-temperature coefficient. A useful diagnostic technique for this effect is to reverse the polarity of the voltage running the oven (thus reversing the direction of the current), which will then reverse the dc magnetic field.

m) Coils in shake tables used for vibration testing induce ac and dc magnetic fields (refer to 4.4.1).

n) Temperature or vacuum chambers exhibit vibration, and this may cause additional effects on the frequency stability.

Other factors that can complicate evaluation of a given type of sensitivity are changes due to hysteresis and, in the long term, aging and maintenance adjustments.

The testing of mathematical models for the environmental dependences should start with the simplest form (in number and order of terms) and proceed by the addition of single terms (in decreasing order of importance). The model chosen should be that which yields the best chi-square to the observed frequency behavior, provided that the reduction in the variance of the fit accompanying the incorporation of each new term exceeds the increase in the Allan variance [given by Equation (9)] caused by having to solve for the additional term (refer to Eichhorn and Williams [B13] and Berger and Jefferys [B9]). This often, but not always, yields the same result as retaining those parameters whose coefficients exceed their associated standard errors. The most consistently successful models reflect parsimony of parameters (Box and Jenkins [B10]).

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If error residuals are normally distributed, the values of the sensitivity coefficients and their standard errors may be determined by least-squares. In the case of errors that have non-Gaussian but well-determined distributions, the coefficients may be estimated by the maximum likelihood method or the method of moments.

If individual measurements differ significantly in precision, each should be weighted by its estimated variance. If different types of measurements are combined in a solution, each type should be weighted by its respective variance. In order to have least-squares normal equations that are well-conditioned against the accumulation of round-off errors, the variable involved must be linearly transformed such that the coordinate origins are in the data range. The most stable solutions are provided by the method of singular value decomposition (Forsythe et al. [B16]). However, the older method of orthogonal polynomials does have the advantage that the residuals from one solution may be analyzed for additional roots without affecting the values of roots already obtained.

If any of the variables are significantly correlated, the covariance matrix should be included in the solution. Although multivariate analytical methods exist for the circumvention of covariance determination, the correlations are too interesting in themselves to recommend these. If a correlation between two quantities arises because they are functions of some other quantity, it might be preferable (depending on the acceptable number of parameters) to incorporate the latter quantity in the model, thereby eliminating the correlation.

In the case of nonlinearities, hysteresis, and dynamic effects, plots may be more informative than models. The extra cost of performing complicated tests, rather than simple ones, or of repeated tests to average down errors, might exceed the value of the results to the user.

3.5 Error budgets

In principle, variation of all the parameters on which the results of a measurement depend should yield the total variation in the measured value. The total variance would be just the vector sum of the variances and covariances of the parameters and of any other sources of error. However, time and resource constraints usually require that the measurement uncertainty be evaluated using a mathematical model and the law of propagation of errors. Assuming the errors are random, if a variable f is a function of other variables z_1, z_2, …, z_j, …, z_p, then the law of propagation of error states

$$\sigma^2(f) \approx \sum_{j=1}^{p}\left[\frac{\delta f}{\delta z_j}\right]^2 \sigma^2(z_j) + 2\sum_{j=1}^{p}\sum_{k<j}\frac{\delta f}{\delta z_j}\frac{\delta f}{\delta z_k}\phi(z_j, z_k) \tag{9}$$

or, approximately,

$$\sigma^2(f) \approx \sum_{j=1}^{p}\left[\frac{\delta f}{\delta z_j}\right]^2 \sigma^2(z_j) + 2\sum_{j=1}^{p}\sum_{k<j}\frac{\delta f}{\delta z_j}\frac{\delta f}{\delta z_k} r(z_j, z_k)\sigma(z_j)\sigma(z_k)$$

where

$\sigma^2(z_j)$ is the variance of z_j,

$\phi(z_j, z_k)$ is the covariance between z_j and z_k,

$r(z_j, z_k)$ is the linear correlation coefficient between z_j and z_k.

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This assumes a steady-state or very slowly varying system. Also, as in the case of Equation (5), it involves a Taylor series expansion about the mean of each variable, at which the partial derivatives are evaluated, and keeps only the first-order terms, so again significant nonlinearity (or nonlinear intercorrelations) would require higher order terms.

In the special case where the derivatives are unity and the intercorrelations are zero, Equation (9) becomes

$$\sigma^2(f) = \sum_{j=1}^{p} \sigma^2(z_j) \tag{10}$$

Further, if f is strictly a product and quotient of the input quantities, then all the variances may be expressed as relative variances as follows:

$$\frac{\sigma^2(f)}{f^2} = \sum_{j=1}^{p} \left[\frac{\sigma^2(z_j)}{z_j} \right]^2 \tag{11}$$

In Equation (9), let f be the frequency, z_j, z_k, … the environmental parameters at time t, and $\sigma^2(z_j)$ the two-sample variance, as follows:

$$\sigma^2(z_j) = \frac{1}{2(n-1)} \sum_{t=1}^{n-1} \left[z_j(t+1) - z_j(t) \right]^2 \tag{12}$$

for n observations, and $\phi(z_j, z_k)$ the two-sample covariance is as follows:

$$\phi(z_j, z_k) = \frac{1}{2(n-1)} \sum_{t=1}^{n-1} \left[z_j(t+1) - z_j(t) \right] \left[z_k(t+1) - z_k(t) \right] \tag{13}$$

One could then use Equation (9) to predict how variations in the ambient conditions transduce into variations in the frequency, as well as how intercorrelations between the parameters affect the frequency. Also, one could use this method to measure environmental effects stochastically. The two-sample variance $\sigma^2(f)$ is just the Allan variance. More often, the Allan variance is expressed as a relative uncertainty, i.e., $\sigma^2(f)/f^2$, usually logarithmically.

In order to properly evaluate the overall instability of a system in the presence of all the sources of error that might reasonably be expected to be present, one should perform an "error (or uncertainty) budget" analysis. After identifying all such significant sources, say, correlation studies, the individual contributions to the combined uncertainty $\sigma^2(f)$ by each of the parameter variances $\sigma^2(z_j)$, $\sigma^2(z_k)$, … and their covariances $\phi(z_j,z_k)$,… may be evaluated by actual measurement of the variances and covariances. Sometimes the functional relationships are clear theoretically [e.g., Equation (6)] and sometimes they must be modeled empirically [e.g., Equation (5)] ("Guide to the expression of uncertainty in measurement" [B21]).

Some error sources are not available or amenable to repeated measurements and statistical analysis. Still, variances for them should be estimated as well as possible on the basis of published information or experience (as should be stated) ("Guide to the expression of uncertainty in measurement" [B21]).

Substituting one-time parameter variations Δz_j, z_k, … in Equation (5) permits one to predict the effects of changes in the individual parameters, but it is a further approximation; in such cases, the derivatives must be evaluated at the parametric values. Ideally, the effects should be modeled by varying the parameters randomly over their operational ranges, as in the stochastic method. Use of Equation (9) would then allow the apportioning of an error budget among the relevant contributing sources. Any detailed report about

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uncertainties should consist of a complete list of the error components, the numerical value of each standard error, the method used to determine it, and the number of degrees of freedom. If the measured quantities are significantly correlated, the correlation coefficient matrix, the covariance matrix, or preferably both should be given ("Guide to the expression of uncertainty in measurement" [B21]).

Although it is generally necessary to vary each parameter throughout its operational range to determine properly the coefficient of dependence, as a rule, it is preferable to keep each parameter as constant as possible during routine operation rather than to attempt to correct for the effect of the variation during postprocessing. This is because of the uncertainties associated with the coefficients, the intercorrelation among the parameters, and dynamic effects.

The total uncertainty may be expressed either as a tolerance (a specified number of standard errors) or as a confidence limit (a specified probability percentage). For the former to be meaningful and for the latter to be determinate at all, the probability distribution of the total error residuals must be known, at least approximately. Hence, it is preferable to correct the data first for systematic (nonstochastic) effects so the residuals will be normally (Gaussian) distributed, assuming that the number of degrees of freedom is greater than about 30; for cases fewer than that, random residuals should follow Student's distribution. In either case, the hypothesis that the residuals are randomly distributed may be tested, as with a chi-square test or normal probability plot. The presence of uncorrected systematic effects may be recognized in residuals that depart significantly from a normal distribution. The corrections for systematic effects have their own uncertainties that should be included in any error budget ("Guide to the expression of uncertainty in measurement" [B21]).

Reliance on internal errors, i.e., failure or inability to use an external reference (or at least independent determinations), risks miscalibrations and oversights of error sources that generally cause one to underestimate one's errors. If, on the other hand, such systematic effects (uncorrected departures from random Gaussian errors) are present in the measurements, the errors will generally be overestimated, especially as the errors are computed relative to the mean rather than from consecutive residuals (two-sample variances and covariances). Increasing the amount of data under a variety of conditions reduces the random errors (true white noise having a stationary mean), but risks systematic errors if parameter dependences are not properly modeled (e.g., through incorrect linear or higher order differentials or neglect of significant parameter intercorrelations), usually resulting in underestimation of predicted frequency variations.

3.6 Transient effects and aging

Specifications of environmental sensitivities generally assume quasi-static conditions. The following are examples:

a) The frequency source has stabilized and is in equilibrium with its surroundings before the ambient change occurs.

b) After application of the stimulus, the frequency standard has again reached a new equilibrium with its environment.

As the idealized conditions would require both infinite time periods before and after application of the stimulus, as well as infinitely slow application of the stimulus itself, acceptable procedures must be found to approximate the quasi-static condition. Furthermore, measures of frequency stability are theoretically based on infinite time averages, so enough data for a statistically meaningful result must be acquired over a period of time during which sufficiently quasi-static conditions can be said to apply (Hellwig [B23]).

Measurement under nonequilibrium conditions generally occurs when the time constants involved in the transfer of the environmental stimulus into the sensitive components of the frequency source are longer than the period of time between the application of the stimulus and the measurement. In such a case, the result is highly dependent on the exact temporal and spatial profile of the stimulus (e.g., whether the unit is in direct

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contact with a heating element or separated from it by circulating air) and the transfer function of the oscillator (e.g., dependence on the internal temperature gradient). Also, if fast ramping and close coupling are involved, the final results will depend on the initial condition of the oscillator (Hellwig [B23]). For example, the time required by the correction cycle of a microprocessor-compensated crystal oscillator (MCXO) limits the system's ability to follow rapid temperature variations (Benjaminson [B8]). These firmware-driven devices depend heavily on internal digital compensation of environmental effects; therefore, careful testing is needed to uncover software problems, and gross errors are possible under certain conditions.

If the user is specifically interested in the effect of a dynamic environment, test methods would probably have to conform to the exact profile of the stimulus in question. In such cases, experience has shown that one cannot extrapolate reliably the effects from one profile to another. In general, use of statistical measures in nonequilibrium situations should be avoided (Hellwig [B23]). Nonetheless, dynamic effects can be at least approximately quantified by differentiating Equation (5) with respect to time and determining the resulting coefficients. When more than one time constant is involved, the effect on the frequency can be very complex. A slow, complete sweep and retrace through the range of an environmental parameter is necessary to characterize dynamic response and to check for local nonlinearities such as crystal "activity dips."

Inability to maintain quasi-static conditions can frequently be traced to external changes such as power-supply fluctuations. When filtered by voltage regulators, such fluctuations lead to lagged secondary effects such as changes in the internal power dissipation and temperature distribution. The resulting temperature gradients can cause frequency variations as well as further changes in the power consumption of the major modules. Thus, the frequency standard may never achieve equilibrium but always has a "flicker" floor of frequency modulation (FM) noise, if it is not a noise type of even higher variance. Flicker also results in part from environmental shocks, although the latter mainly produce random-walk FM noise (Ferre-Pikal et al. [B15], IEEE Std 1139-1999 [B25], and Howe et al. [B24]).

In passive atomic oscillators, susceptibility to power-supply ripples and electromagnetic interference (EMI) is generally worst at the fundamental and higher even-harmonics of the servo-loop modulation frequency; large frequency shifts are possible due to interference with the servo. System turn-on and turn-off transients may also cause problems, often exhibiting exponential behavior and requiring modeling with time constants (Lu and Tsuzuki [B30]).

Frequency measurements for environmental tests should be made when the oscillator is beyond any significant initial relaxation, but it has not yet shown any significant aging effects or spontaneous changes (e.g., FM random walk), unless these are unavoidable or can be adequately corrected. Also, unless such corrections are well known, the environmental variations should be restricted to intervals small in comparison to that over which significant aging occurs, or over which a spontaneous change is likely to occur. Well-behaved frequency drift, such as that due to aging, need not limit system usage if it is measured and corrected. Frequency drift is usually most accurately determined from the mean of nonoverlapping phase second differences rather than from a linear fit to frequency first differences or a quadratic fit to phase first differences (Barnes [B7]). Most oscillators, except crystals, have a useful lifetime (varying significantly from unit to unit), at the end of which aging effects are extreme and unpredictable (refer to Clause 8).

In addition, each type of oscillator is subject to frequency variations as the result of changes and distortions in the electronics, such as those in voltage references, power supplies and amplifiers, resistors, diodes, capacitors, and so on, which in turn are sensitive to variations in ambient conditions (Audion et al. [B4], Riley [B36], Mattison [B31], and Walls and Gagnepain [B45]. Power-supply and load impedance changes affect crystal oscillator circuitry and, indirectly, the crystal's drive level and load reactance. A change in load impedance changes the amplitude or phase of the signal reflected into the oscillator loop, which changes the phase and frequency of the oscillation. Similar effects occur in most oscillators. These effects can be minimized through voltage regulation and the use of buffer amplifiers (Stein and Vig [B40]). In cesium clocks, changes and distortions in the electronics and power supply propagate into the microwave field, the frequency servo-loop, and the slaved crystal oscillator (De Marchi et al. [B12] and Audion et al. [B4]).

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3.7 Additional considerations

3.7.1 Relativistic effects on clocks

Relativistic effects are ordinarily negligible for most frequency sources except for those in a spacecraft environment, where velocity and gravitational potential effects can be significant (Jorgensen [B27] and Riley [B36]). Time dilation causes the frequency of a moving clock to appear to run more slowly by an amount

$$\frac{\Delta f}{f} \approx -\frac{v^2}{2c^2} \tag{14}$$

where v is the clock velocity and c is the velocity of light. For a GPS satellite in a 12-hour circular orbit, the fractional frequency change is -8.35×10^{-11}. Gravitation redshift causes a clock to run more slowly in a stronger gravitational field by an amount

$$\frac{\Delta f}{f} = \frac{\mu}{c^2}\left(\frac{1}{R} - \frac{1}{r}\right) \tag{15}$$

where m is the Earth's gravitational constant (3.986×10^{14} m^3/s^2, R is the Earth's radius, and r is the orbital radius. This is about 1×10^{-16}/m at the Earth's surface, an amount that must be taken into account by terrestrial laboratories when comparing high-performance frequency references. For a GPS satellite, the gravitation redshift is 5.28×10^{-10}, and the net relativistic frequency change is $+4.45 \times 10^{-10}$.

Other relativistic effects may need to be considered in the context of an environmental factor as clock performance improves, especially for space applications (Audion and Guinot [B5]). It is recommended that a professional relativist be consulted whenever this is a possibility.

3.7.2 Testing microprocessor-driven clocks

Clocks incorporating an embedded digital hardware and software architecture have the potential of presenting unusual validation and verifications problems. Traditionally, testing techniques have treated hardware and software as independent entities, even though the requirements are specified as a system. These techniques have tended to focus on the environmental sensitivities, failures, and/or degradation of the physical components only. This approach does not reflect the actual operating conditions where the hardware and software function as an integrated system. The problem arises from the complexity of the software used to run the clock and the difficulty in exhaustively testing the software. Such problems are most likely to be seen in developmental clocks where the software is still being optimized but could also occur in production units. An example of how this situation could arise during environmental testing would be a case where an environmental factor such as temperature or magnetic field causes several internal parameters of the clock to change to values away from nominal at the same time that an unrelated factor such as an external data readout command occurs. The combination of factors can cause the software to branch to an unexpected state and give undesired results. The condition may appear to be unrepeatable simply because the tester does not know what factors were involved and thus cannot recreate the exact scenario. New validation techniques suitable for analyzing the behavior of embedded hardware and software systems are needed. This will be an unusual and difficult problem. One approach could be for the developer, in addition to the traditional design verification testing, to use modeling to verify hardware and software interactions. The results become part of the clock's reference material. The independent system tester can conduct environmental sensitivity and stress testing at the system level. This way, any anomalous performance observed will be evaluated independent of the source, hardware, or software.

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4. Acceleration effects

4.1 Description of the phenomena

All precision frequency sources, even atomic, are affected by acceleration. The magnitude of an oscillator's acceleration-induced frequency shift is proportional to the magnitude of the acceleration. It also depends on the direction of the acceleration and on the acceleration sensitivity of the oscillator. It has been shown, empirically, that the acceleration sensitivity of a quartz crystal oscillator is a vector quantity (Filler [B54] and Walls and Gagnepain [B77]). The same is probably true of all precision oscillators. Therefore, the frequency during acceleration can be written as a function of the scalar product of two vectors as follows:

$$f(\vec{a}) = f_o(1 + \vec{\Gamma} \cdot \vec{a}) \tag{16}$$

where

$f(\vec{a})$ is the resonant frequency of the oscillator experiencing acceleration $\vec{a}$,

f_0 is the frequency with no acceleration (often called the "carrier frequency"),

$\vec{\Gamma}$ is the acceleration-sensitivity vector of the oscillator defined with respect to a specified axis system.

The frequency of an accelerating oscillator is a maximum when the acceleration is parallel to the acceleration-sensitive vector. The frequency shift, $f(\vec{a}) - f_0 = \Delta f$ is zero for acceleration in the plane normal to the acceleration-sensitive vector, and it is negative when the acceleration is antiparallel to the acceleration-sensitive vector. The frequency change due to acceleration is usually expressed as a normalized frequency change, where, it follows from Equation (16) that

$$\frac{\Delta f}{f_o} = (\vec{\Gamma} \cdot \vec{a}) \tag{17}$$

Typical values of $|\vec{\Gamma}|$ for precision crystal oscillators are in the range of 10^{-9} per g (i.e., 10^{-10} per m/s^2), where g is the earth's gravitational force. $|\vec{\Gamma}|$ is independent of acceleration amplitude for the commonly encountered acceleration levels (i.e., at least up to 20 g [200 m/s^2]); however, high acceleration levels can result in changes in the crystal unit (e.g., in the mounting structure) that can lead to $|\vec{\Gamma}|$ being a function of acceleration. $|\vec{\Gamma}|$ can also be a function of temperature (Hanson and Wickard [B56]).

In a passive atomic frequency standard, the frequency of a voltage-controlled crystal oscillator (VCXO) is multiplied and locked to the frequency of an atomic resonance. The effects of acceleration on atomic standards can be divided into crystal oscillator effects, atomic resonance effects, and servo-loop effects. The extent to which an acceleration-induced VCXO frequency shift affects the output frequency of the atomic standard depends on the rate of change of acceleration relative to the atomic resonance-to-crystal oscillator servo-loop time constant, t_o. Fast acceleration changes ($f_{vib} >> 1/2\pi t_o$) will cause the atomic standard's acceleration sensitivity to be that of the VCXO, because the servo-loop will not be fast enough to correct the VCXO. Slow acceleration changes ($f_{vib} << 1/2\pi t_o$) will have little effect on the output frequency to the extent that the servo-loop gain is sufficient to correct the VCXO frequency to that of the atomic resonance. However, it has been observed that a constant frequency offset may appear in the case where the atomic standard is submitted to a periodic vibration, even if its frequency is lower than $1/2\pi t_o$. This is a servo-loop effect, and it occurs when the acceleration-induced frequency change shows a distortion, with a component at twice the acceleration frequency in addition to that at the fundamental vibration frequency. An analysis of this effect can be found in Appendix A of Vig et al. [B73], [B74]. In the case $f_{vib} >> 1/2\pi t_o$, the spurious constant frequency offset is very efficiently attenuated when the value of t_o is decreased.

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In general, vibration near the servo-loop modulation frequency f_{mod} (i.e., within the servo loop bandwidth or near even multiples or submultiples of f_{mod}) can cause significant frequency offsets in passive atomic frequency standards. In the case of rubidium frequency standards, vibration of the physics package at f_{mod} can modulate the light beam, producing a spurious signal that can confuse the servo system and, thereby, cause a frequency offset (in a manner identical to that for cesium standards). Vibration of the VCXO at even multiples of f_{mod} produces sidebands on the microwave excitation to the resonator that causes a frequency offset via an intermodulation effect (refer to Riley [B68], Lynch and Riley [B64], Kwon and Hahn [B61], Kwon et al. [B63], and Kwon et al. [B62]). A loss of microwave excitation power can occur at low vibration frequencies, as is shown in an example in Appendix B of Vig et al. [B74].

At low acceleration levels, properly designed atomic resonators possess very low acceleration sensitivities; however, high acceleration levels (e.g., >10 g [100 m/s^2]) can produce significant effects. For example, in a rubidium standard, the acceleration can change the location of the molten rubidium inside the rubidium lamp, and it can cause mechanical changes that result in deflection of the light beam (Riley [B68] and Lynch and Riley [B64]). Both effects can result in a change in light and signal output that, due to light shift and servo offset mechanisms, can cause a frequency shift. Mechanical damage can cause radio frequency (RF) power changes that, due to the RF power shift effect, can cause a frequency shift.

In a cesium standard, high acceleration levels can affect the accuracy and stability of the output frequency through mechanisms that modify the position of the atomic trajectory with respect to the tube structure (Audion et al. [B49], [B50]). This is most serious when the vibration frequency is near the servo modulation frequency. The vibration modulates the amplitude of the detected beam signal. The net effect of this phenomenon is normally of no consequence because the perturbing vibration must be located at or very near the servo modulation frequency and must be stable in frequency as well. When the acceleration is very near the servo modulation frequency, the vibration-induced amplitude perturbation of the detected beam can be synchronously detected, leading to large output frequency errors. It should be noted that this problem is of minimal concern in actual applications due to the requirements on the precision and stability of the frequency of the perturbing acceleration.

A more subtle problem arises from the effects on the position of the beam with respect to the microwave interrogating cavity via distributed cavity phase shift effects. Another subtle effect arises from the potential to modify the detected velocity distribution. The magnitude of these effects is small when compared to the vibration-induced amplitude modulation perturbations described above.

Acceleration effects can also cause frequency offsets in cesium frequency standards via degradation of the amplitude of the interrogating microwave signal. This can happen as a result of detuning of the frequency multipliers. Good mechanical design and thorough qualification of the design will minimize problems in this area.

In hydrogen masers, the most acceleration-sensitive part is the microwave cavity (Mattison [B65]). A deformation of the cavity structure causes a shift of the cavity resonant frequency. This induces a change of the maser frequency via the cavity-pulling effect. A cavity autotuning system is able to suppress this effect if the acceleration rate of change is sufficiently smaller than $1/2\pi t_o$, where t_o is the cavity servo-loop time constant.

When a crystal oscillator is subjected to vibration, the primary cause of the resultant output signal frequency modulation is the acceleration sensitivity of the quartz crystal resonator. However, in both crystal oscillators and atomic frequency standards, vibration-induced mechanical motion in other circuit components and in the circuit board, can also result in output signal frequency and/or phase modulation. In general, these effects are more pronounced in higher frequency oscillators due to a combination of the following:

a) Increased circuit signal phase sensitivity to mechanical motion (i.e., increased phase shift for a given amount of circuit reactance variation due to a larger resonator C_1)

b) Decreased crystal quality factor (Q)

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If the vibration-induced circuit phase shift occurs inside the oscillator feedback loop, there will be a conversion of phase-to-frequency modulation for vibration frequencies within the resonator half-bandwidth. The phase-to-frequency conversion is related to the resonator group delay (i.e., loaded *Q*). For vibration frequencies in excess of the resonator half-bandwidth, the vibration-induced phase modulation sidebands may or may not be further attenuated, depending on whether the induced modulation is occurring in a portion of the circuit signal path that is subject to resonator frequency selectivity.

Methods for minimizing these effects include use of multiple circuit board chassis mounting points, circuit potting, wire and cable tie down, elimination of adjustable components or post-tuning cementing in place of adjusters, avoidance of nonpotted and nonshielded inductors, and avoidance of very high circuit nodal impedances that are sensitive to nodal capacitance variation. As an example, measurements on a 100 MHz SC-cut crystal oscillator (SC is the designation of a particular crystallographic orientation of the crystal cut) indicate that, when these precautions are taken, sustaining stage carrier signal phase shift sensitivity to vibration on the order of 10^{-6} radians per g (10^{-7} radians per m/s^2) can typically be obtained. This represents a situation where sustaining stage variation-induced signal phase modulation becomes dominant (as compared to resonator frequency modulation effects) only at vibration frequencies in excess of approximately 50 kHz.

4.2 Effects and test methods

4.2.1 Quasi-static acceleration

4.2.1.1 Steady-state acceleration

When an oscillator is subjected to steady-state acceleration, the normalized frequency shifts by $\vec{\Gamma} \cdot \vec{a}$, per Equation (17). Steady-state acceleration occurs, for example, during the launching of a rocket, in an orbiting satellite, in a centrifuge, and in a gravitational field.

4.2.1.2 Gravity change effects

The frequency shift described in Equation (17) is also induced by the acceleration due to gravity. One manifestation occurs when an oscillator is turned upside down (on earth). This is commonly referred to as *2g tipover*. During 2*g* tipover, the magnitude of the gravity field is 1*g* in the direction toward the center of the earth. The magnitude of acceleration is in units of g, i.e., the magnitude of the earth's gravitational acceleration at sea level, 9.8 m/s^2. Use of Equation (16) and Equation (17) for gravitational field effects necessitates defining the acceleration of gravity as pointing away from the center of the earth so that the direction of $\vec{\Gamma}$ is consistent with the direction one obtains for conventional acceleration (Vig et al. [B73], [B74]).

When an oscillator is rotated 180 degrees about a horizontal axis, the scalar product of the gravitational field and the unit vector normal to the initial "top" of the oscillator changes from –1*g* to +1*g*, i.e., by 2*g*. Figure 1 shows actual data of the fractional frequency shifts of an oscillator when the oscillator was rotated about three mutually perpendicular axes in the earth's gravitational field. For each curve, the axis of rotation was horizontal. The sinusoidal shape of each curve is a consequence of the scalar product being proportional to the cosine of the angle between the acceleration-sensitive vector and the acceleration due to gravity (refer to Vig et al. [B73], [B74]).

Another type of gravity change effect occurs when, for example, a spacecraft containing an oscillator is sent into space. The oscillator's frequency will, again, change in accordance with Equation (16).

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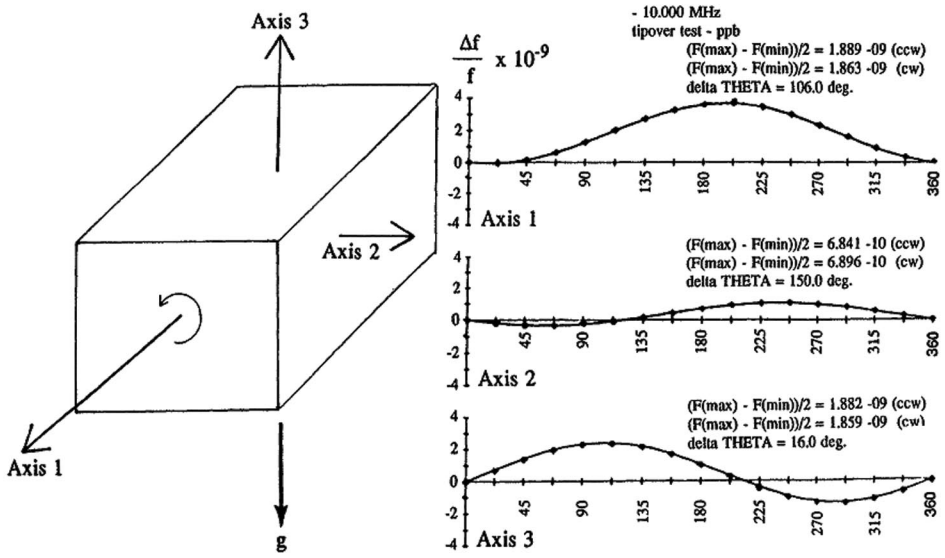


Figure 1—2*g* tipover test—frequency change vs rotation in the earth's gravitational field for three mutually exclusive perpendicular axes

4.2.1.3 2*g* tipover test

In the past, the 2*g* tipover test has often been used by manufacturers (and researchers) to characterize an oscillator's acceleration sensitivity. This test method is deceptively simple because, if not used carefully, it can yield false and misleading results.

The simple 2*g* tipover test consists of measuring the frequency changes when an oscillator is turned upside down three times, about three mutually perpendicular axes. The magnitude of the acceleration sensitivity is then the vector sum (square-root of the sum of the squares) of the three frequency changes per *g* (where, for each axis, the frequency change per *g* is one-half of the measured frequency change).

Some serious problems with using the 2*g* tipover test are as follows:

a) The test is applicable only to high-quality oven-controlled oscillators because in nontemperature-controlled oscillators, the frequency-shifts due to ambient temperature changes will exceed the acceleration-induced frequency changes and, thereby, make the test results worthless.

b) Many oven-controlled oscillators are not suitable for characterization by the 2*g* tipover test because rotation of the oscillator results in temperature changes (due to air convection) inside the oven that can mask the effects due to acceleration changes; similarly, in atomic standards, changes in internal thermal distribution resulting from the tipover will mask acceleration effects.

c) The results are poor indicators of performance under vibration when the vibration frequencies of interest include resonances (refer to 4.4.1).

d) As magnetic fields can change the frequencies of crystal oscillators ~10^{-10} to 10^{-9} per millitesla (Brendel et al. [B51]), rotation in the earth's magnetic field can produce significant errors while measuring (unshielded) low-acceleration-sensitivity crystal oscillators.

e) In atomic frequency standards, the effects of the earth's magnetic field can dominate the results. The results will be irrelevant to the performance under vibration if during 2*g* tipover testing the acceleration changes faster than the servo-loop time constant.

The interfering thermal effects can be minimized by performing the 2*g* tipover test rapidly. Acceleration (and magnetic field) effects are virtually instantaneous, whereas the thermal effects are relatively slow. When thermal effects are a problem, a sudden change in an oscillator's altitude results in an instantaneous

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frequency change due to the oscillator's acceleration sensitivity followed by a gradual frequency change due to the oscillator's temperature sensitivity.

A 2*g* tipover test that is far more reliable than the simple test described above consists of measuring the fractional frequency changes corresponding to small changes in orientation with respect to the earth's gravitational field, e.g., as shown in Figure 1. The oscillator is first rotated, e.g., in 22.5-degree increments, 360 degrees about an axis (which is usually one of the major axes of the oscillator). From the frequency changes during this rotation, one can determine two out of the three components of $\vec{\Gamma}$ [keeping in mind that $\vec{a} = -\vec{g}$ in Equation (16) and Equation (17)]. The oscillator is then similarly rotated 360 degrees about a second axis that is perpendicular to the first. From the frequency changes during this second rotation, one can determine the third component of $\vec{\Gamma}$ and, simultaneously, obtain a self-consistent check for one of the other two components (i.e., the one that is normal to both the first and second axes of rotation). The frequency changes during rotation about the third axis can provide additional self-consistency checks for the two components of $\vec{\Gamma}$ that are normal to the third axis. If the measurements are not self-consistent, and if there are large deviations in the $\Delta f(\theta)$ vs θ from the best fit to a sinusoidal function, as will generally be the case if, for example, the resonator's temperature changes during the test, then the 2*g* tipover test result is unreliable. It should be noted that, in this 2*g* tipover test too, the earth's magnetic field can produce significant errors if the oscillator is unshielded and if the oscillator possesses low acceleration sensitivity. Further details about the analysis of 2*g* tipover test data can be found in Appendix B of Vig et al. [B73].

4.2.2 Vibration effects

The effects of vibration on frequency stability are summarized in 4.2.2.1 through 4.2.2.4 (see Filler [B54], Vig et al. [B73], and Vig et al. [B74]):

4.2.2.1 Sinusoidal vibration

For a small modulation index,

$\beta = \Delta f / f_v = (\vec{\Gamma} \cdot \vec{A}) f_o / f_v < 0.1$, sinusoidal vibration produces spectral lines at $\pm f_v$ from the carrier

where

f_v is the vibration frequency.

The spectral lines $\mathcal{L}'(f_v)$ are described by

$$\mathcal{L}'(f_v) = 20 \log\left(\frac{\vec{\Gamma} \cdot \vec{A} f_o}{2 f_v}\right) \tag{18}$$

NOTE—$\mathcal{L}'(f_v)$ are spectral lines (i.e., delta functions), not spectral densities. Most of the power is in the carrier, a small amount is in the first spectral line pair, and the higher order spectral lines are negligible.

4.2.2.2 Random vibration effects

For a small modulation index, the contribution of random vibrations to phase noise is given by

$$\mathcal{L}(f) = 20 \log\left(\frac{\vec{\Gamma} \cdot \vec{A} f_o}{2 f}\right) \tag{19}$$

where

$\left|\vec{A}\right| = [(2)(PSD)]^{1/2}$,

PSD is the power spectral density of the vibration.

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The use of $\mathcal{L}'(f)$ is in conformance with IEEE Std 1139-1999.[5] Vibration platforms can cause severe phase noise degradation.

Not only does random vibration degrade the spectrum, but the time errors due to random vibration also accumulate. The time (or phase) errors do not completely average out because the white frequency noise is integrated to produce random walk of the phase. The noise of an oscillator produces time prediction errors of $\sim\tau\sigma_y(\tau)$ for prediction intervals of τ (Stein and Vig [B70]).

4.2.2.3 Acoustic noise effects

Acoustic noise can produce vibration in equipment similar to that produced by mechanically transmitted vibration. In an acoustic noise field, pressure fluctuations impinge directly on the equipment. The attenuation effects of mechanical transmission are missing, and the response of the equipment can be significantly greater. Further, components that are effectively isolated from mechanical transmission will be excited directly (refer to MIL-STD-810D). Examples of acoustically induced problems are as follows:

a) Failure of microelectronics component lead wires
b) Chafing of wires
c) Cracking of printed circuit boards

In addition to these problems, the response of an oscillator to acoustic-noise-induced acceleration is the same as the response to any other type of vibration; i.e., the acoustic noise modulates the oscillator's frequency (Renoult et al. [B67]). The modulation (or phase noise degradation) is a function of the acoustic-noise-induced vibration's amplitudes, directions, and frequencies.

Acoustic noise can have a broad spectrum. For example, in a missile environment, it may extend to frequencies above 50 kHz. An effect of such noise, e.g., in 100 MHz fifth overtone resonators, may be the excitations of flexural modes (microphonics) in the crystal plate (Weglein [B80]). These flexural modes in turn can produce undesirable spectral lines in the phase noise spectrum. The magnitudes of these lines are independent of the resonator and depend chiefly on the plate geometry and mounting structure.

Acoustic noise can be especially troublesome in certain applications. For example, when an extremely low noise oscillator was required in an aircraft radar application system, designers built a three-level vibration isolation system to isolate the oscillator from the vibration of the aircraft. They then discovered, however, that the isolation system failed to deliver the expected phase noise of the oscillator because the isolation system failed to deal with the acoustic noise in the aircraft; i.e., the isolation system was effective in isolating the isolator from the vibrations of the airframe, but it was ineffective in blocking the intense sound waves that impinged on the oscillator.

4.2.2.4 Vibration tests

The sidebands generated by sinusoidal vibration can be used to measure the acceleration sensitivity. In Equation (18)

$$\Gamma_i = \left(\frac{2f_v}{A_i\, f_o}\right)10^B \tag{20}$$

where

$B = \mathcal{L}'_i(f_v) / 20$

where

Γ_i and A_i are the components of the acceleration sensitivity vector and of the acceleration, respectively, in the $\hat{i}$ direction.

[5]Information on references can be found in Clause 2.

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Measurements, along three mutually perpendicular axes, are required to characterize $\vec{\Gamma}$, which becomes

$$\vec{\Gamma} = \Gamma_i \hat{i} + \Gamma_j \hat{j} + \Gamma_k \hat{k} \tag{21}$$

with a magnitude of

$$\left|\vec{\Gamma}\right| = \left(\Gamma_i^2 + \Gamma_j^2 + \Gamma_k^2\right)^{1/2} \tag{22}$$

One scheme for measuring $\vec{\Gamma}$ is shown in Figure 2. The local oscillator is used to mix the carrier frequency down to the range of the spectrum analyzer. If the local oscillator is not modulated, the relative sideband levels are unchanged by mixing. The frequency multiplier is used to overcome dynamic range limitations of the spectrum analyzer, using the 20 log *N* enhancement (refer to 4.3). The measured sideband levels are adjusted for the multiplication factor. A sample measurement output and calculation is shown in Figure 3.

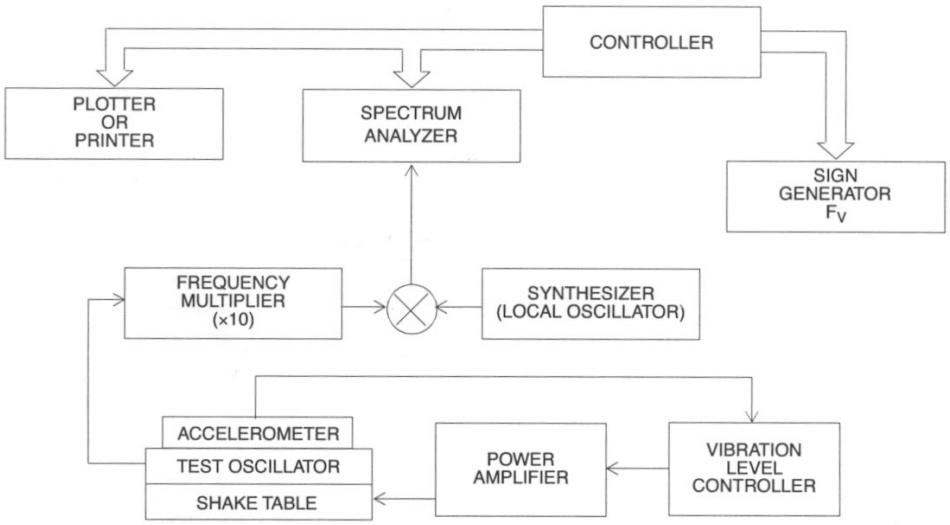


Figure 2—Acceleration sensitivity measurement system

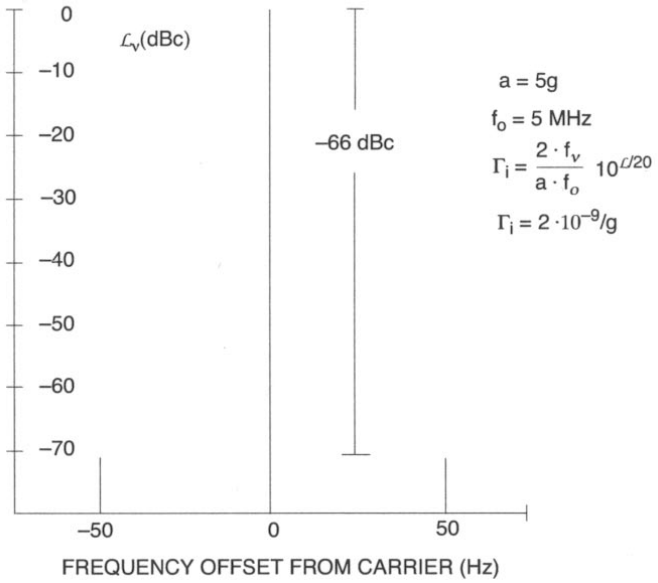


Figure 3—Acceleration sensitivity test result and calculation example

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In order to detect frequency sensitivities, such as those due to vibration resonances, the sideband levels need to be measured at multiple vibration frequencies. An alternative to using a series of vibration frequencies is to use random vibration (see Healy et al. [B58]).

The method depicted in Figure 2 (see Driscoll [B53] and Watts et al. [B79]) provides for minimization of measurement errors due to cable vibration. The method also allows measurement of acceleration sensitivity of the resonator alone. The resonator is mounted on the shake table and is connected to the oscillator circuitry via a quarter wavelength cable. The oscillator circuitry remains at rest while the resonator is vibrated.

In the results of the vibration-induced-sideband method of measuring acceleration sensitivity, there is a 180 degree ambiguity in the direction of $\vec{\Gamma}$; i.e., the results cannot distinguish between two oscillators, the $\vec{\Gamma}$s of which are antiparallel. In the method of Watts et al. [B79], the sensitivity of doubly rotated quartz resonators to voltages applied to the electrodes is used to resolve the ambiguity. When the proper magnitude applied voltage is in-phase with the applied acceleration, the sidebands are increased. When the applied voltage is 180 degrees out of phase with the acceleration, the sidebands are decreased. The method allows not only the determination of the sign of $\vec{\Gamma}$, but also the elimination of cable vibration effects.

4.2.3 Shock

4.2.3.1 Shock effects

When a crystal oscillator experiences a shock, frequency (and phase) excursions result that, in a properly designed oscillator, are due primarily to the quartz resonator's stress sensitivity. The magnitude of the excursion is a function of resonator design and of the shock-induced stresses on the resonator. (Resonances in the mounting structure will amplify the stresses.) A permanent frequency offset may result that can be due to shock-induced stress changes (when some elastic limits in the resonator structure are exceeded), the transfer of (particulate) contamination to or from the resonator surfaces, and changes in the oscillator circuitry, e.g., due to changes in stray capacitances.

The shock-produced phase excursions can be calculated from Equation (17) (see Vig et al. [B73], [B74]), with the proviso that at high acceleration levels, $\vec{\Gamma}$ may be a function of the acceleration $\vec{a}$. For example, for a half-sine shock pulse of duration D

$$\Delta\phi_{peak} = 2Df_o(\vec{\Gamma} \cdot \vec{a}) \tag{23}$$

Upon frequency multiplication by N, the $\Delta\phi_{peak}$ becomes N times larger, so in systems where the frequency is multiplied to microwave (or higher) frequencies, the shock-induced phase excursion can cause serious problems, such as loss of lock in phase-locked loop (PLL) systems, and bit errors in phase shift keying (PSK) systems.

4.2.3.2 Shock tests

The shock testing of a frequency source generally consists of measuring the frequency or phase of the source before and after exposing the device to the specific shock. The phase deviation resulting from the shock (which is the time integral of the fractional frequency change) can provide useful information about the frequency excursion during the shock (including the possible cessation of operation).

Survival under shock (and under vibration) is primarily a function of resonator surface imperfections. Even minute scratches on the surfaces of the quartz plate result in orders of magnitude reductions in the resonator's shock resistance (Vig et al. [B75]). Chemical-polishing-produced scratch free resonators have survived shocks of up to 36 000 g [360 km/s^2] in air gun tests and have survived the shocks due to being fired from a 155 mm howitzer (16 000 g [160 km/s^2], 12 ms duration) (Filler et al. [B55]).

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In atomic frequency standards, a shock-induced phase excursion of the VCXO can result in a transitory loss of lock; however, this is not a problem when the shock duration is smaller than the servo loop time constant, which is often the case. When a loss of lock does occur, the recovery time is a function of the servo-loop time constant. The phase excursions of the VCXO, and of the output crystal filter, can have a significant effect on the clock output, which can disturb the host system. Shock-induced mechanical damage can cause changes (e.g., light and RF power changes in rubidium standards) that can produce a permanent frequency offset. For atomic standards employing Ramsey interrogation, large (2×10^{-8}) shock-induced permanent frequency shifts of the VCXO can cause false lock acquisition to the satellite peaks in the Ramsey resonance.

4.3 Other effects

4.3.1 Frequency multiplication

Upon frequency multiplication by a factor N, the vibration frequency f_v is unaffected because it is an external influence. The peak frequency change due to vibration, Δf, however, becomes

$$\Delta f = (\vec{\Gamma} \cdot \vec{A}) N f_o \tag{24}$$

The modulation index β is therefore increased by the factor N. Expressed in decibels, frequency multiplication by a factor N increases the phase noise by 20 log N.

When exposed to the same vibration, the relationship between the vibration-induced phase noise of two oscillators with the same vibration sensitivity and different carrier frequencies is

$$\mathcal{L}_B(f) = \mathcal{L}_A(f) + 20 \log (f_B / f_A) \tag{25}$$

where

$\mathcal{L}_A(f)$ is the sideband level, in dBc/Hz (or dBc for sinusoidal vibration), of the oscillator at frequency f_A,

$\mathcal{L}_B(f)$ is the sideband level of the oscillator at frequency f_B.

For the same acceleration sensitivity, vibration frequency, and output frequency, the sidebands are identical, whether the output frequency is obtained by multiplication from a lower frequency or by direct generation at the higher frequency. For example, when a 2×10^{-9}/g (2×10^{-10} per m/s^2) sensitivity 5.0 MHz oscillator's frequency is multiplied by a factor of 315 to generate a frequency of 1575 MHz, its output will contain vibration-induced sidebands that are identical to those of a 1575 MHz surface acoustic wave (SAW) oscillator that has the same 2×10^{-9}/g (2×10^{-10} per m/s^2) sensitivity.

4.3.2 Large modulation index

A large modulation index, i.e., $\beta > 0.1$, can occur in ultra high-frequency systems and at low vibration frequencies. When the modulation index is large, it is possible for the sidebands to be larger than the carrier. At the values of β where $J_o(\beta) = 0$, e.g., at $\beta = 2.4$, the sidebands-to-carrier power ratio goes to infinity (refer to Vig et al. [B73], [B74]), which means that all of the power is in the sidebands and none is in the carrier. Such "carrier collapse" can produce catastrophic problems in some applications. In general, the power in the carrier relative to the total power is $e^{-\beta^2}$ (Walls and DeMarchi [B76]).

4.3.3 Two-sample deviation

The two-sample deviation (refer to IEEE Std 1139-1999 [B59]) (or square-root of the Allan variance) $\sigma_y(\tau)$ is degraded by vibration because the vibration modulates the oscillator's output frequency. The typical degradation due to sinusoidal vibration varies with averaging time, as shown in Figure 4. As a full sine wave averages to zero, the degradation is zero for averaging times that are integer multiples of the period of the

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vibration. The peaks occur at averaging times that are odd multiples of half the period of vibration. The $\sigma_y(\tau)$ due to a single-frequency vibration is

$$\sigma_y(\tau) = \frac{\vec{\Gamma} \cdot \vec{a}}{\pi} \frac{\tau_v}{\tau} \sin^2\left(\pi \frac{\tau}{\tau_v}\right) \tag{26}$$

where

τ_v is the period of vibration,
τ is the measurement averaging time,
$\vec{\Gamma}$ is the acceleration sensitivity vector,
$\vec{a}$ is the acceleration.

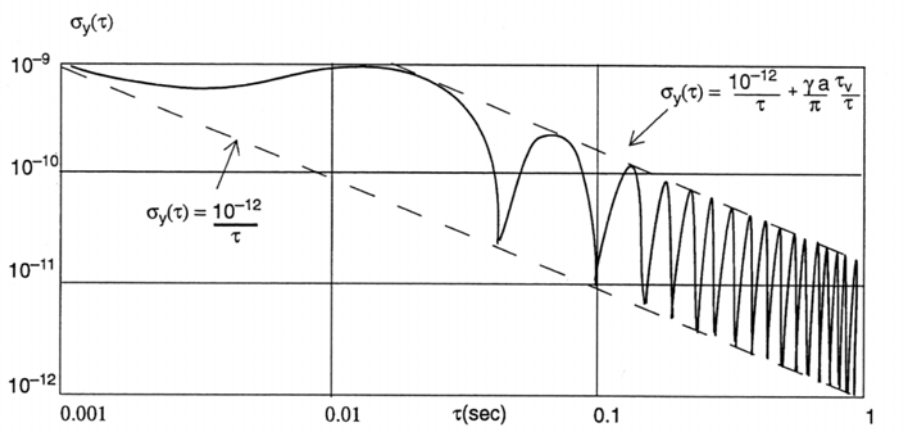


Figure 4—Vibration-induced Allan variance degradation example (f_v = 20 Hz, |a| = 1.0 *g*, $|\vec{\Gamma}|$ = 1 x $10^{-9}/g$ [10^{-10} per m/s^2])

4.3.4 Integrated phase noise, phase excursions, jitter, and wander

Specialists in crystal resonators and oscillators generally characterize phase noise by $S_\phi(f)$ or $\mathcal{L}(f)$ (refer to IEEE Std 1139-1999 [B59]). Some users of crystal oscillators, however, characterize phase noise in terms of "phase jitter." In digital communications, the terms jitter and wander are used in characterizing timing instabilities. Jitter refers to the high-frequency timing variations of a digital signal, and wander refers to the low-frequency variations. The dividing line between the two is often taken to be 10 Hz. Wander and jitter, whether caused by vibration or otherwise, can be characterized by the appropriate measurement of the rms time error of the clock. For very high Fourier frequencies or short integration times, it may be necessary to calculate the jitter from the spectrum rather than to measure it directly. For example, the mean-square timing jitter δt accumulated over a time interval τ is given by $\tau\sigma_y(\tau)$, which can be computed from $S_\phi(f)$ using

$$\delta t = \tau\sigma_y(\tau) = \left(\frac{\sqrt{2}}{\pi\nu_o}\right)\left[\int_0^\infty H_\phi(f)[S_\phi(f)] \sin^4(\pi f\tau)\, df\right]^{1/2} \tag{27}$$

where *H(f)*, the transfer function of the system, generally has a low-pass character at high frequencies (Stein and Vig [B70] and Walls and Walls [B78]).

The mean-squared phase jitter for a measurement bandwidth of f_1 to f_2 is given by

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$$\Delta\phi^2 = \int_{f_1}^{f_2} S_\phi(f)\,df \tag{28}$$

For random vibration, it can be shown that

$$S_\phi(f) = \frac{1}{2 f_v^2}(PSD)(|\vec{\Gamma}|\ f_o)^2 \tag{29}$$

When the oscillator is subjected to a simple sinusoidal vibration, the peak excursion follows from Equation (17) (refer to Vig et al. [B73], [B74]), i.e.,

$$\Delta\phi_{peak} = \Delta f / f_v \tag{30}$$

In a phase-locked loop, for example, the magnitude of the phase excursion determines whether the loop will break lock under vibration. For example, if a 10 MHz, 1 x $10^{-9}/g$ (10^{-10} per m/s^2) oscillator is subjected to a 10 Hz sinusoidal vibration of amplitude 1 *g*, the peak vibration-induced phase excursion is 1 x 10^{-3} radian. If this oscillator is used as the reference oscillator in a 10 GHz radar system, the peak phase excursion at 10 GHz will be 1 rad. Such a large phase excursion can be catastrophic to the performance of many systems, such as those which employ phase-locked loops (PLL) or phase-shift keying (PSK).

4.3.5 Spectral responses at other than the vibration frequency

Spectral responses at other than the vibration frequency may arise from a nominally sinusoidal vibration source of frequency f_v if the source is not a pure sinusoid (Weglein [B80]). This usually occurs when the source is driven hard to generate vibration near its maximum output power, so that it operates in the nonlinear regime. Under these circumstances, the spectrum of the vibration source itself will contain not only the spectral line at frequency f_v, but also lines at harmonic frequencies, $2f_v$, $3f_v$, etc. A spectrum check of the vibration source is recommended in such cases.

Even if the vibration source is a pure sinusoid at frequency f_v, it is still possible to excite oscillator vibration responses at harmonically related vibration frequencies $2f_v$, $3f_v$, etc. if the vibration level is excessive so as to drive materials in the oscillator into the nonlinear range. This situation is readily identified by observing the effect of reducing the vibration source amplitude.

Oscillator spectral responses at other than the vibration frequency have also been observed in cases where the oscillator is subjected to a random vibration spectrum. These responses are excited at frequencies much higher than the exciting spectrum and are the result of nonlinear phenomena in the crystal plate and/or the oscillator. The responses are in the form of spectral lines at carrier offset frequencies that correspond to the flexural modes of the crystal plate. The flexural mode frequencies are determined in decreasing order of importance by the number of crystal plate support posts, the plate thickness, and the crystal cut. For example, the typical spectral response range in a 100 MHz, four-post supported crystal plate extends upward from 12.2 kHz, the fundamental mode flexural frequency (Weglein [B80]). It has been observed that these responses are minimized in a crystal plate that is compliantly supported rather than hard-mounted.

4.3.6 Acceleration effects on crystal filters

Some frequency sources, such as synthesizers, atomic frequency standards, and precision crystal oscillators with post-filters, contain crystal filters. In these applications, they are often called spectrum cleanup filters; however, under vibration, such filters modulate the signals passing through them, adding as well as removing vibration-related sidebands. Hence, spectrum cleanup filters should be used with great care in systems subject to vibration. Often it is better to use notch filters to remove unwanted spurious signals, as the vibration will primarily modulate the amount of spurious suppression, not the PM noise of the carrier.

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It is well known that the principal vibration effect in crystal filters is phase modulation, although some amplitude modulation may also occur (Clark and Yurtseven [B52], Smythe [B69],and Vig et al. [B74]).

4.4 Special user notes

4.4.1 Interactions with other environmental effects and other pitfalls

The two major influences that can interact with the effects of acceleration during testing are thermal effects and magnetic field effects. If the oscillator's temperature changes during acceleration-sensitivity testing, then the temperature-induced frequency shifts can interfere with measurement of the acceleration-induced frequency shifts, as is discussed in 4.2.1.3, for example. Another example of interference by thermal effects is the cooling due to increased air flow during testing in a centrifuge.

Similarly, ac magnetic fields can produce sidebands that can interfere with the vibration-induced sidebands, and dc magnetic fields can produce frequency offsets in atomic frequency standards. Two sources of magnetic field are the earth's magnetic field and the magnetic field of a shake table, which can affect frequency-determining circuitry, e.g., varactors, gain control circuits, and power supplies. As the frequency of a vibration-induced ac voltage is the vibration frequency, the sidebands due to ac voltages are superimposed on the vibration-induced sidebands of main interest. One solution to shake-table-produced magnetic fields is to use hydraulic shakers. Such devices are less commonly available than are electrodynamic shakers and have a lower frequency range.

Resonance phenomena can lead to other pitfalls in the determination and specification of acceleration sensitivity. Resonances can occur not only within the oscillator, but also in the test setup and in the platform where the oscillator is to be mounted. Figure 5 shows test results for an oscillator that had a resonance at 424 Hz. (The resonance was traced to a flexible circuit board within the oscillator.) The resonance amplified the acceleration sensitivity at 424 Hz by a factor of 17. It is therefore important to test oscillators at multiple vibration frequencies (with either a series of sinusoidal vibration frequencies or with random vibration) in order to reveal resonances. It is also important to determine the resonances in the platform where the oscillator is to be mounted, and to take that information into account during the specification of acceleration sensitivity.

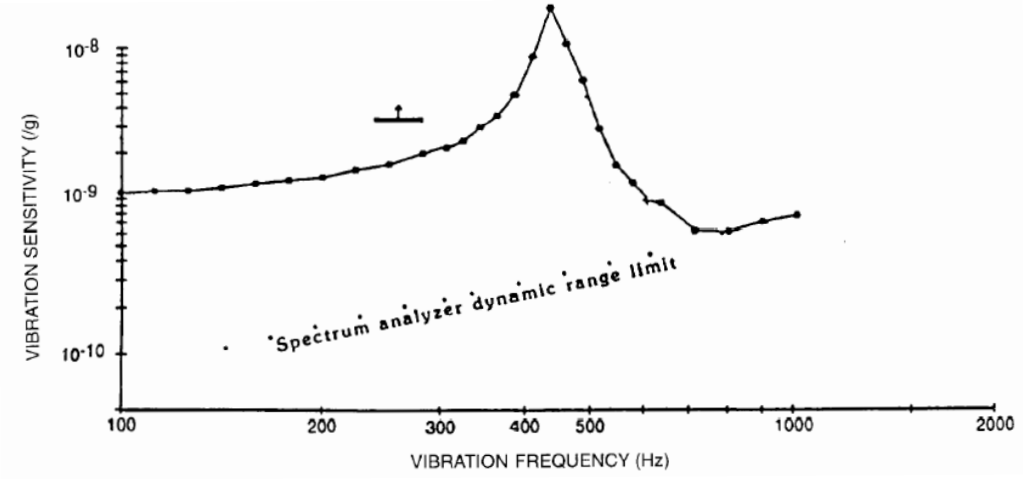


Figure 5—The effect of a resonance on the measurement of acceleration sensitivity vs vibration frequency

The accelerometers used in vibration-sensitivity testing have nonideal frequency responses, usually at both low (near dc) and high frequencies. The useful frequency range at the high end is limited by resonances in the accelerometer. The limitations of the accelerometer can be measured and can also usually be obtained

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from the manufacturer. The limitations should be taken into account during acceleration-sensitivity testing. Similarly, the limitations of other components in the test setup, e.g., the spectrum analyzer, the signal generator, and the shake table, must be taken into account (e.g., the shake table may produce vibrations transverse to the intended direction; Kosinski and Ballato [B60]). Another factor to consider is that spectral responses at other than the vibration frequency can occur, as was discussed earlier.

Vibration isolation has been proposed as the "fix" for the acceleration sensitivity of frequency sources. The pitfalls of using such a "fix" are as follows:

a) Isolation systems have a limited frequency range of usefulness; outside this range, the isolation systems amplify the problem.

b) A single isolator isolates the vibration primarily along a single direction.

c) Isolation systems add size, weight, and cost.

d) Most isolation systems are ineffective against acoustic noise.

Figure 6 illustrates the frequency response of a typical passive vibration isolator. It shows that although such a device can be effective at high vibration frequencies, it amplifies the problem at low vibration frequencies in the region of the isolator's resonant frequency.

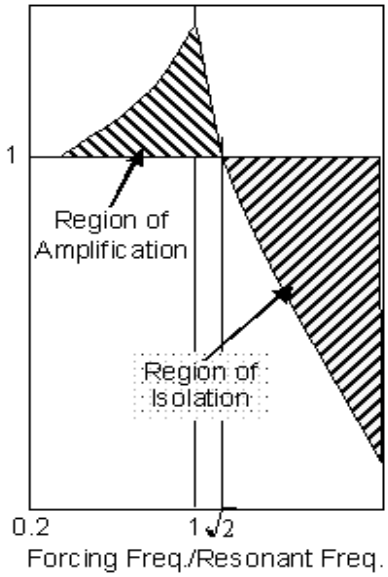


Figure 6—Vibration isolator frequency response

4.4.2 Safety issues

During acceleration sensitivity testing, one must ensure both the operator's and the equipment's safety. Exposing the operator to high intensity noise may cause permanent hearing loss. In the United States, safety regulations (refer to Occupational Safety and Health Administration [B66]) require employers to provide protection against the effects of high noise exposures and to administer "a continuing and effective hearing conservation program" whenever the noise exposures exceed specified levels. The permissible noise exposures are functions of the sound levels, its frequency (especially infrasound; frequency below 10 Hz), and the exposure durations.

For both the operator's and the equipment's safety, all parts subjected to testing should be securely fastened. The forces generated during vibration testing can be high enough to shear the bolts that hold down the equip-

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ment. General information on shock and vibration testing can be found in suitable publications (refer to Harris [B57], Steinberg [B71], and Tustin and Mercado [B72]).

5. Temperature, humidity, and pressure

5.1 Description of the phenomena

In addition to 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 (refer to Bava et al. [B82], Becker [B83], Breakiron [B85], [B86], Coffer and Camparo [B87], De Marchi [B88], De Marchi and Rubiola [B89], Dorenwendt [B90], Gagnepain [B91], Goldberg et al. [B92], Gray et al. [B93], Hellwig [B94], Iijima et al. [B95], MIL-0-55310C [B96], Tavella and Thomas [B97], Thomas and Tavella [B98], and Walls and Gagnepain [B99]). In general, the effects of THP on frequency are nonlinear 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 a given type of device. Our purpose here is to arrive at traceable (nonburdensome) guidelines and precautions for test methods used in determining the dependence of the output frequency of precision oscillators on temperature, humidity, and pressure.

The quantity *y(t)* is defined in the usual way as the relative frequency (refer to IEEE Std 1139-1999). This is the actual time-dependence 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*.

The THP frequency dependence is defined as the causal effect on *y(t)* as follows:

$$y(t) = f(T, H, P) \tag{31}$$

It is recognized that there may be other environmental parameters that are dependent on one or more of the THP parameters. This problem is addressed later. Nonetheless, Equation (31) 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 THP are studied.

Because the environment is so important to the long-term performance of precision oscillators, and in some cases even to the short-term performance, it is very important 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 dependences 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 those items that are important to the manufacturer, designer, or user and that are most significant.

First, define some nominal operating values of T, H and P. Call these T_o, H_o, and P_o. Then, expand the fractional frequency about these nominal values using a Taylor series:

$$y(T, H, P) = y(T_o, H_o, P_o) + \sum_{n=1}^{\infty} \frac{1}{n!} \left(\delta T \frac{\partial}{\partial T} + \delta H \frac{\partial}{\partial H} + \delta P \frac{\partial}{\partial P} \right)^n y(T, H, P) \Big|_{T_o, H_o, P_o} \tag{32}$$

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breaking out the n = 1 term, and defining Δy: $\Delta y \equiv y(THP)-y(T_oH_oP_o)$, Equation (32) becomes

$$\Delta y = \delta T \left.\frac{\partial y}{\partial T}\right|_{T_o,H_o,P_o} + \delta H \left.\frac{\partial y}{\partial H}\right|_{T_o,H_o,P_o} + \delta P \left.\frac{\partial y}{\partial P}\right|_{T_o,H_o,P_o} + \tag{33}$$

$$\sum_{n=2}^{\infty} \frac{1}{n!}\left(\delta T \frac{\partial}{\partial T} + \delta H \frac{\partial}{\partial H} + \delta P \frac{\partial}{\partial P}\right)^n y(T,H,P)\Big|_{T_o,H_o,P_o}$$

For small values of δT, δH, and δP, the terms of n = 2 and higher can be ignored. Thus, Equation (33) has a clear meaning as to how it is to be implemented. To account for the interactions among THP, terms of n = 2 and higher in the sum are retained. However, as stated later in Clause 5, typically there is one sensitivity that dominates the other two. As an example, assume that the oscillator's temperature dependence is much greater than its humidity or pressure dependence. Then, expanding Equation (33) to second order, terms of order δH^2, $\delta H \delta P$, and δP^2 can be ignored compared to terms of order δT^2, $\delta T \delta H$, and $\delta T \delta P$. In this approximation, Equation (33) can be written as

$$\Delta y \cong (a_T + \beta_T\, \delta T)\delta T + (a_H + \beta_{TH}\, \delta T)\delta H + (a_P + \beta_{TP}\, \delta T)\delta P \tag{34}$$

It is straightforward to evaluate Equation (34). First, H and P are held constant, and Δy is plotted as a function of $\delta T = (T–T_o)$; the quadratic dependence of Δy on δT yields α_T and β_T. Then, keeping P constant and armed with this knowledge, the humidity and temperature dependence of $\Delta y_c = [\Delta y - (\alpha_T + \beta_T \delta T)\delta T]$ are examined; and specifically, $\Delta y_c/\delta H$ is determined at several temperatures. Plotting $\Delta y_c/\delta H$ as a function of δT, α_H and β_{TH} are then obtained. The procedure is repeated keeping H constant and examining $\Delta y_c/\delta P$.

The manufacturer has the responsibility to state which of these coefficients are the most important and for which type of oscillator. A similar solution may be performed for the parameter variances as part of an error budget analysis, although if a parameter cannot be varied independently, then covariance terms must be included (refer to 3.5). 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. Some suggestions regarding this problem will be made.

The above equations deal will coefficients that may depend on the values of parameters other than THP and, hence, will not be constant coefficients. In cases where there is a significant dependence of THP on some other environmental condition, that needs to be stated.

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. It is clear that a detailed modeling could become intractable. The models should be kept as simple and useful as possible. If unconventional models are used, there should be good motivation (e.g., unusual dependences) to do so.

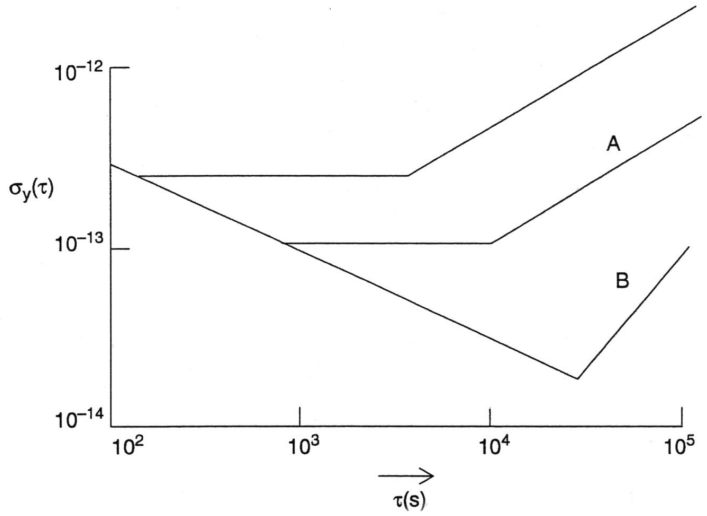
5.2 Effects and test methods

5.2.1 Effects of temperature, humidity, and pressure (THP)

Often at "turn-on" or during certain transient situations, the output frequency behaves in a logarithmic way. This is often caused by the THP parameters restabilizing to new values. Where this is the case, the time constant of a particular model gives another method of describing the frequency behavior. In general, it is needed to distinguish between turn-on or transient behavior and steady-state behavior (Coffer and Camparo [B87]).

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In general, those coefficients that are most important for different categories of oscillators should be identified in Equation (34). Some general statements about the different types of oscillators can be made, 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. Figure 7 is a classic example of environmental effects on a rubidium gas-cell frequency standard. Cesium-beam frequency standards may be affected by both temperature and humidity. The long-term frequency stability of most cesium-beam frequency standards can be improved by stabilizing the temperature and humidity environment.



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CURVE B: IMPROVED MAGNETIC SHIELDING, COMPENSATION AND BAROMETRIC SEALING

A frequency drift of approximately 1 x 10^{-13} per day is removed from the data.

Figure 7—Time-domain frequency stability of a rubidium standard for different environmental conditions

Based on very preliminary experiments, 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 of both atomic standards and quartz oscillators has been recognized as a significant environmental perturber (refer to Bava et al. [B82], Walls and Gagnepain [B99], and Gray et al. [B93]).

As, 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 nonrepeatability of the situation, it is best to simulate the dynamics of the space environment over some appropriate range of temperature.

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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 that is most sensitive to THP and then to control the systems with a THP sensor. If this is not practical, then temperature gradients in the environment should be minimized.

5.2.2 Test methods for temperature, humidity, and pressure

Given the complexity of the problem, 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 possible to specify temperature and other dependences 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 water 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.

White noise 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. As 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 the environmental parameter being evaluated should be changed and the integration time should be repeated to measure the frequency change. The precision with which the change in frequency with a change in an environmental parameter can be determined may be improved 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 $N^{-1/2}$. One should respect the settling times after changing a parameter's value, as well as other systematics affecting the measurement.

In order to separate and determine the dominant effect, the variables T, H, and P are allowed to assume high and low values in a defined pattern (Bhote and Keki [B84]). 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. 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 is a general set of guidelines:

a) Do a crude experiment to determine the dominant effect.

b) 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).

c) 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.

d) Document the major environmental effects, test conditions, and responses. Graphs are essential here. Three-dimensional graphing software makes this relatively easy.

e) Define the overall accuracy and the terms under which it was derived. Identify it explicitly as an rms value, additive worst-case, or other type of desired description.

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5.2.3 Guidelines for documenting results

A user will typically have a range of THP and other environmental parameters over which a clock or oscillator should meet a certain set of performance requirements. In general, let us suppose the model for the frequency stability of a particular product is affected by *n* environmental parameters. If the manufacturer could state that for any combination of some peak-to-peak range of each of the *n* environmental parameters, the stated performance specification will be met, this would be very useful to the designer and the user.

The *n*-parameter box approach has the effect of eliminating the need for a parametric expression, gives the user a direct measure of the worst-case performance, and is a valid and useful way of expressing the environmental performance. This approach automatically takes care of any nonlinearities and cross coupling, assuming that the proper verification experiments have been done by the manufacturer. On the negative side, the *n*-parameter box technique does not allow optimization of performance availability when environmental parameters vary less than the assumed peak-to-peak values.

If significant nonlinearities are a problem with any of the environmental parameters, then additional information can be obtained in the following way. If in the environmental test procedures, the greatest slope within the specification range for that environmental parameter could be determined, then the specification could reflect that result. As an example, $dy(t)/dT$, the temperature coefficient, is not larger than some value over the operating range of the unit. In contrast, if there was a particular region of the *n*-parameter space where the product was particularly well behaved, then the specification could reflect that. In as much as some users can set their environments, this would be very useful to them.

5.3 Special user notes

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. 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.

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 “red-shift” 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. If the relative humidity is given, then the applicable temperature must also be known and stated.

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. Small factors such as fans in a room or a test chamber moving the air around an experiment can make a big difference in time constants and apparent temperature and humidity responses of the output frequency.

5.3.1 Device positioning

Any change in the orientation of the oscillator during testing can invalidate the data because 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.

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5.3.2 Temperature gradients

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 erroneously ignores the thermal configuration. 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 (e.g., a baseplate) 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 it 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 a 2*g* tipover, the stronger effect on the frequency seems to be the change in temperature gradients because the convection currents flow in the opposite direction for many of the components. Sometimes acceleration and THP effects can be separated because of the different time constants involved.

The effect of thermal gradients in a rubidium standard 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.

5.3.3 Sealed devices

Oscillators that are hermetically sealed show a totally different character than those that are open or sealed with gaskets that are permeable to moisture or different gases. 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.

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

5.3.4 Quartz crystals

Changes in orientation, temperature, pressure, humidity, magnetic field, and gravitational field all produce significant frequency shifts. Magnetic field effects are the result of using ferromagnetic materials in either the crystal mount or the crystal plating. Proper sealing of the case can reduce pressure and humidity shifts, but it 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 by rerouting high-current leads.

In quartz crystal oscillators, "activity dips" may occur. An "activity dip" occurs when a $y(t)$ vs temperature (T) curve of an unwanted mode intersects the $y(t)$ vs T curve of the wanted mode. Such activity dips generally become worse when the quartz crystal resonator is being driven at higher power levels; the load

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reactance will shift the location of activity dips in the frequency vs temperature curve. 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. It is important to note that SC-cuts, as compared to AT-cuts, are largely free of activity dips.

Conventional measurement of activity dips requires that the crystal be adequately mounted to a temperature-controlled stage. Several years ago, activity dips that occurred over a millidegree temperature range were reported. Therefore, it becomes critical that the temperature-controlled stage be of high precision. As the temperature is slowly scanned in a deliberate, controlled manner, if either an anomalous frequency or resistance change is observed, an activity dip most likely is present. Detection of the frequency or resistance change can be done with conventional electronic testing instruments such as a counter or voltmeter if the crystal is driven by an oscillator during testing. Greater accuracy with less uncertainty due to the oscillator electronics is possible by measuring the crystal by itself using a passive method.

Manufacturers obviously have a responsibility to indicate the presence of activity dips and to specify their impact on the oscillator's 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.

Thermal hysteresis is also found in quartz crystal oscillators, much more so in devices using AT-cuts as compared to SC. This means that the frequency vs temperature plot generated as the temperature is increased will not be the same as that generated while decreasing the temperature.

5.3.5 Rubidium devices

Rubidium oscillators exhibit all of the effects observed in quartz oscillators, most of which can be reduced by proper sealing. The impact of all effects is reduced by one or two orders of magnitude over that in quartz because of the fundamental use of an atomic resonance. One potentially unique problem for rubidium is that the effect of atmospheric gases (diffusing into the gas cell) may show up as a frequency drift (e.g., atmospheric helium) (Goldberg et al. [B92]). Another effect that should be considered in rubidium frequency standards is the barometric sensitivity of the absorption cell, which is caused mostly by "oil-canning" of the cell windows. This sensitivity has a typical value of $1pp10^{10}$ per atmosphere.

5.3.6 Cesium beam devices

Cesium standards typically have long time constants and contain significant internal heat sources. At one end is an oven at roughly 100 °C; at the other end is a hot-wire ionizer at about 1000 °C. Full thermal equilibrium may take many hours to reach. Temperature probably affects the physics package more than any other variable. Humidity affects high-impedance current amplifiers. All three parameters (THP) affect power delivered by the harmonic generator.

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.

Limited experience with the frequency dependence on humidity in cesium standards indicates that the coefficients may be dependent on the individual unit; e.g., two units with adjacent serial numbers can have very different coefficients, and these even may be of opposite sign.

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5.3.7 Hydrogen masers

As 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 on 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.

5.3.8 Frequency drift and THP

THP effects frequently are a cause of long-term frequency drift. Polynomial modeling can be misleading in estimating frequency drift (Barnes [B81]). 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 (refer to Weiss et al. [B101] and Weiss and Hackman [B100]). 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 phase modulation (PM) or white frequency modulation (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 better confidence on the estimate of the drift as well (refer to Barnes [B81], Weiss et al. [B101], and Weiss and Hackman [B100]).

5.3.9 Some pitfalls

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 dependent. The number of model parameters should be kept as low as practicable and still provide useful quantitative information.

For many standards, it appears that there is a maximum frequency shift with pressure change followed by a relaxation period. This may depend on 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.

Pressure effects typically have not been as important as temperature effects for precision oscillators. However, some important lessons have been learned. Atmospheric pressure changes can cause changes in the output frequency of hydrogen masers and rubidium gas-cell frequency standards due to cavity-pulling.

With all types of clocks and oscillators, it is unfortunately true that the environmental sensitivities are critically dependent on the fine details of the instrument's adjustments; thus, careful measurements on one instrument will not necessarily predict the performance of another even if taken from the same production lot.

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6. Electric and magnetic field effects

6.1 Description of the phenomena

6.1.1 Electric field effects

This effect results in the change in frequency of a frequency standard due to changes in the ambient electric field. Such changes in the ambient field may be caused by the buildup of static charge on structures in the vicinity of the frequency standard or by positioning of the frequency standard near high-voltage conductors.

The electric field sensitivity of a device is the change in frequency due to a change in the applied electric field. The electric field is not the field measured at the device but the free space field measured at the location of the device with the device removed.

6.1.2 Magnetic field effects

This effect results in the change in the frequency of a frequency standard due to changes in the ambient magnetic field. For static fields such as may be caused by the proximity of magnetic material (racks, vehicles, etc.), the effect is an offset in the operating frequency from the unperturbed frequency. For dynamic fields (caused by leakage fields from power supplies florescent lighting ballasts and the like), the effect results in frequency modulation of the standard at the frequency of the interfering field.

The static (dc) magnetic field sensitivity of a device is the change in frequency due to a change in the applied magnetic field. The magnetic field is not measured at the device, but it is instead the free space field in the same location as the device but with the device removed. The utility of the static sensitivity measurement is the determination of the effect of differing magnetic environments on the performance of the device.

The dynamic magnetic field sensitivity of a device has the same units as the static, but the measurement technique and analysis of the data are, out of necessity, different. The applied field is characterized in the same manner as in the static case, but the field is now an alternating field and the measurements are usually made using a spectrum analyzer. The value of the dynamic sensitivity measurement is the ability to ascertain the effect of power line and related fields on the device.

6.1.3 Electromagnetic interface (EMI) effects

This effect results in the change in frequency of a frequency standard due to an impressed electromagnetic field. Such fields may leak through the joints in an instrument case or be conducted into the interior of the frequency standard via power lines or cables. The resulting effect may be either a change in the frequency of the standard or production of sidebands on the standard frequency output.

6.2 Effects and test methods

6.2.1 Electric fields

Electric field sensitivity has not been reported in the literature. Although the individual components within the frequency standard (e.g., quartz crystals, atoms) are sensitive, the frequency standards are encased in a metallic structure that effectively shields the standard from the field and eliminates the effect. There is, in general, no need to test for this effect.

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6.2.2 Magnetic fields

6.2.2.1 Nonlinearities and hysteresis

As the sensitivities are different in different directions, the measurements should be made and results given in the three dimensions, *x*, *y*, and *z*. The changes in frequency of a device are the result of interaction of the applied field either with atomic states in an atomic device or with magnetic materials in the electronics of all devices. It is to be expected that the effect will be nonlinear and will exhibit some hysteresis. Enough measurement points should be made so that an adequate characterization of the effect may be made. It is important that the range of fields be traversed several times so that hysteresis effects may be characterized.

6.2.2.2 Effects of other environmental parameters

The permeability of typical magnetic materials (mu-metal, moly-permalloy, ferrite) varies with temperature. If it is necessary to completely characterize the magnetic susceptibility of the device, the magnetic sensitivities may be measured over the range of temperatures that are considered normal for the application. For a normal room temperature of 25 °C, measurements at 20, 25, and 30 degrees may be adequate. This effect is small, and for most normal applications, it may usually be neglected.

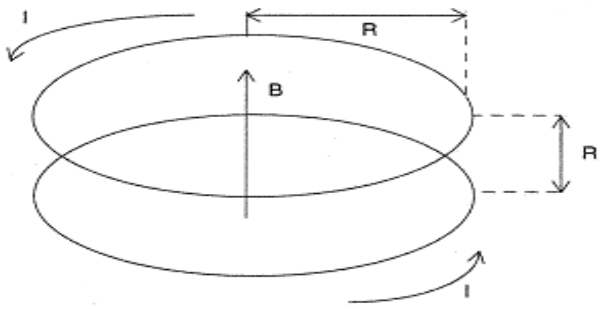
6.2.2.3 Time effects

There is some indication that the shielding efficiency of some magnetic materials improves slightly with time. Probably no measurements need be made of this effect, but awareness of it may be useful.

6.2.2.4 Steady-state (dc) field tests

The traditional test uses a Helmholtz coil as shown in Figure 8. As a rule of thumb, the Helmholtz coils should have a diameter at least twice as large as the maximum dimension of the device under test (DUT); three or four times larger is better. The standard spacing between the coils is one radius [B103]. The earth's field is on the order of 40 μT (400 mG) and varies in direction depending on the location on the globe. As the purposes of measuring the effect of magnetic field are to

a) Determine the changes in frequency that will occur in a given environment.
b) Determine the frequency that the standard will produce in a given environment, a single Helmholtz coil is adequate to completely characterize the standard.



$$B = \frac{32\pi 10^{-7} NI}{5\sqrt{5}}, \text{ TESLAS}$$

Figure 8—Classical Helmholtz coil

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A three-axis Helmholtz coil as shown in Figure 9 is recommended. The fields and currents are the same as in the single-axis coil. The field in the center may be set to zero, nullifying the earth's field, and then varied around this point by large enough changes in the applied field to cover the expected amount that the DUT may experience in actual operation. A variation of ±200 μT (2 G) is usually adequate. The DUT must be kept in the same orientation for all tests (preferably the normal operating position) to eliminate the effects of varying gravitational forces and changes in thermal gradients that may also affect the frequency standard and give erroneous results for the magnetic field sensitivity. The length of the measurement period for a given magnetic field is governed by the two-sample deviation curve for the standard. A measurement period should be chosen that corresponds to an averaging time in the area of the two-sample deviation curve that is near the minimum. Typical times might be 100 s for a quartz crystal standard, 2000 s for a hydrogen maser, and 10^5 s for a cesium-beam standard. The measured sensitivity may depend on the prior magnetic "history" of the tested device and, thus, can show hysteretic characteristics.

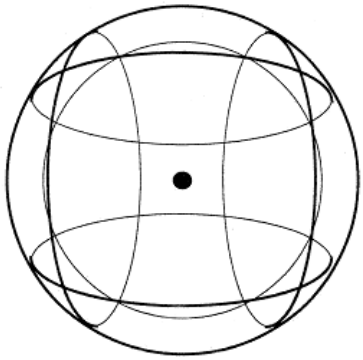


Figure 9—Three-axis Helmholtz coil

6.2.2.5 Alternating field tests

If the Helmholtz coil used for the static field tests is made on a nonmetallic form, it may also be used for the dynamic field tests. One calculates the applied field in a manner similar to the calculation of the static field, except that the current will be an alternating current. For the purposes of standardization, peak reading instruments will be assumed in the calibration of the impressed field. If other instruments are used, proper conversion to peak values should be applied. The applied field is given by

$$B = \frac{\left(4\pi 10^{-7} 2NI \sin \Omega t\right)}{5\sqrt{5}R} \tag{35}$$

where

I is the peak value of the current in the coils (expressed in amperes),
N is the number of turns in each coil,
R is the radius of the coils in meters,
B is the field in teslas.

By examining the resulting spectrum of the output signal, sidebands may be observed at the excitation frequency (and possibly at its harmonics). As the field is known, the expression for the amplitude of the sidebands is

$$P = 20 \log\left(\frac{\alpha}{2\sqrt{2}}\right) \tag{36}$$

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in dBc, where

α is Bs_m,

B is the magnetic field in teslas,

s_m is the magnetic sensitivity of the oscillator in relative frequency change per tesla.

The desired equation for the sensitivity is then

$$s_m = 2\sqrt{2}\, 10^{(P/20)} B \tag{37}$$

As the magnetic field sensitivities are nonlinear functions of the field intensity, the test should be made over the range of fields that might be expected in practice. In a standard relay rack that is full of various electronic equipment, the field can be of the order of 5 μT (50 mG) at the power line frequency or its second harmonic. Ordinary laboratory environments may have power-line-related field intensities on the order of 0.5 μT, whereas areas in the vicinity of large motors or transformers can have field intensities as high as 100 μT.

6.2.2.6 Alternative methods

An alternative method for pseudo-static tests utilizes a very slowly varying field with a sinusoidal variation of period commensurate with the lowest noise portion of the two-sample deviation curve for the standard in question. The data can then be analyzed with a spectral analysis computer program to achieve improved sensitivity (Brendel et al. [B102]).

6.2.3 Electromagnetic interference

By impressing a specified amplitude EM (electromagnetic) field on the frequency standard and determining the effect of the field on the standard, a measure is made of the sensitivity of the standard to the applied field. In general, measurement of the susceptibility is the same as the standard EMI test applied to other devices; i.e., a field is produced in the location of the standard, and changes in the output are detected. The normal means of performing this test uses a swept frequency field generator that spans a large segment of the radio frequency (RF) spectrum. The entire test is performed in an RF anechoic chamber to prevent erroneous results due to standing waves. The spectrum, frequency, and phase of the output is monitored during the test to determine what effect the applied field has on the device.

The purpose is to determine existing electrical leakage, the existing internal resonances that can be excited by the leakage, and the effect this combination of leakage and resonances has on the operation of the device.

An additional test is necessary in the case of frequency standards because they may have susceptibilities that occur in extremely narrow bands and will be missed during the fast sweep of frequencies that is normal for EMI tests. A very slow sweep through these bands is necessary in order to determine the susceptibility of the frequency standard in these frequency ranges. The sweep should cover a band approximately 10 times the resonator bandwidth and should be at a rate approximately $f_o/100Q$ of the resonator; this assures that the rate is also slow compared to the time constant of the servo loop. For example, a 5 MHz oscillator with a resonator Q of 2×10^6 would have a resonator bandwidth of $\approx$ 2 Hz. The sweep should cover 5 MHz ± 20 Hz and should be at a rate of 0.02 Hz/s. An example of the results of such a test is given in Figure 10. The variation in the slope of the phase-time curve indicates that the oscillator was being affected by the impressed electromagnetic field.

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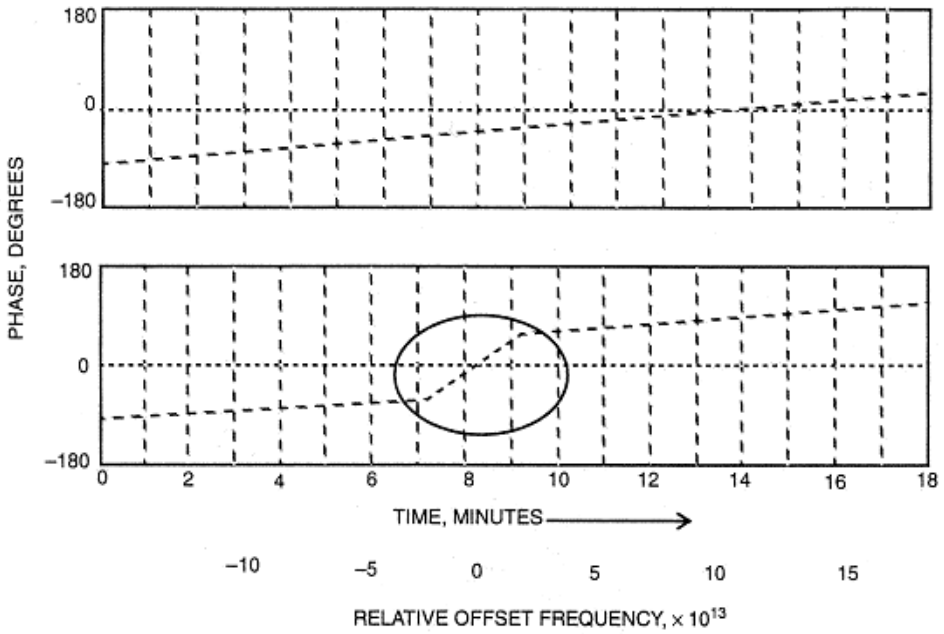


Figure 10—EMI test, example data

The actual bands that must be investigated depend on the type and design of the frequency standard: a quartz crystal oscillator should be tested in a band around the crystal resonances and submultiples of the resonant frequencies, and a passive frequency standard (e.g., cesium beam), should be tested at the crystal oscillator frequency and the various frequencies used in the frequency multiplier as well as the frequency modulator frequency and its multiples, especially the even ones.

A standard level of excitation does not exist for radiating the device under test. Usually, a level is used that is specified based on the expected operational environment. The required level for equipment that is to be used in a field radar installation is different from the required level for laboratory equipment. Levels on the order of one volt per meter are in the general range of testing. Figure 11 is an example of an EMI test requirement for a spacecraft oscillator.

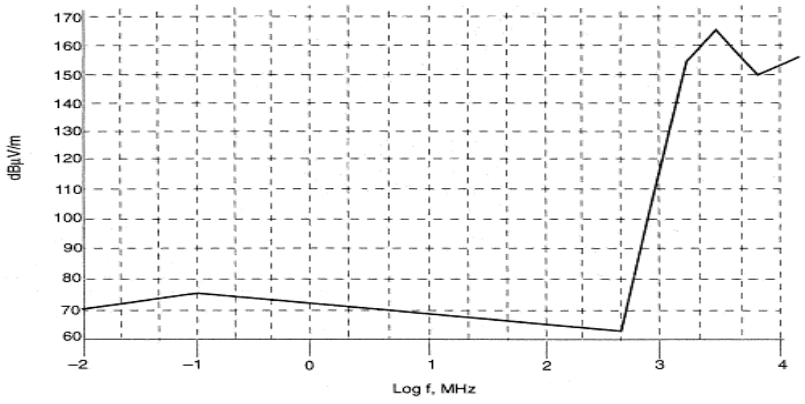


Figure 11—EMI test, example of applied field strength

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6.3 Some pitfalls

If there are nonlinearities and hysteresis, the effect of a magnetic field in one direction is affected by the magnitude of the field in other directions. For most frequency standards, this is not the case for fields in the normal range. Some standards have magnetic shielding, and this shielding may exhibit such effects. In this case, the characterization of the standard's sensitivity is very complicated and the measurements should be made with the impressed field corresponding to the ambient field at the location wherein the standard is to be located.

7. Ionizing and particle radiation

7.1 Description of the phenomena

7.1.1 General discussion

The susceptibility of frequency standards to radiation should be addressed in the design stage. The exact radiation environments should be characterized with respect to dose, dose rate, flux, fluence, and energy spectrum. The design of the frequency standard and the hardness of its physics package and electronics should be based on geometrical modeling so that the dose levels at various locations inside the standard will be well understood. Radiation testing of a mechanical mock-up will assist in confirming the geometrical calculations.

Actual radiation testing of atomic or quartz crystal frequency standards can only be performed after obtaining a thorough understanding of the environment, including dose and anneal cycles. Tests should be conducted using reference frequency standards with a stability of at least one order of magnitude better than the standard under test or the radiation-induced frequency shifts. Radiation experiments must measure the frequency standard's frequency shift versus dose and dose rates, recovery during annealing intervals, clock signal outages during burst, and flash X-ray and pulsed neutron events. Data should be obtained on the recovery of the frequency standard after radiation exposure. The radiation hardness of frequency standards is environment-related, and generalization of test results from specific radiation tests can therefore lead to erroneous interpretations, which may cause costly overdesigns or the construction of frequency standards that are not adequately hardened. As mentioned previously, the radiation hardening of frequency standards starts with a full knowledge of the environment outside the standard as well as that which is created internally.

7.1.2 Previous investigations

The susceptibility of quartz oscillators and atomic frequency standards to natural and enhanced ionizing and particle radiation is an important parameter in predicting the short- and long-term performance of these standards in spacecraft. Many studies have been conducted to establish a relationship among the radiation sensitive components, like quartz, and the radiation response of resonators made from quartz (refer to Flanagan [B108], Flanagan and Wrobel [B110], Halliburton et al. [B112], King and Koehler [B116], and Lipson et al. [B118]). These studies involved ionizing and particle radiation at specified dose and dose rates employing gamma-rays from cobalt 60 sources (1.25 MeV photons), electrons, protons, flash X-rays, and neutrons (refer to Suter et al. [B132], Flanagan and Leadon [B109], and Riley and Vaccaro [B127]). The primary goal of these investigations was to establish a base of experimental data that often addressed the radiation hardening requirements for specific spacecraft missions. Therefore, it was often difficult to extend the results of these radiation tests to a more general understanding of the radiation susceptibility of frequency standards. For example, extensive radiation tests on quartz crystal resonators with ionizing radiation have shown no correlation between the aluminum impurity content of the quartz crystal and its susceptibility to low dose levels [<100 rad (Si)] and dose rates [<1 rad (Si) per min] (King and Koehler [B116]). However, the radiation response to higher doses and dose rates is dependent on the aluminum impurity content (refer to Flanagan and Wrobel [B110], Suter et al. [B135], Suter and Maurer [B130], and Suter and Maurer [B131]).

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7.2 Effects and test methods

7.2.1 Total dose due to ionization

7.2.1.1 Types of sources

Effects due to total radiation dose are simulated using sources of ionizing radiation. The most common such sources in the natural environment are X-rays, gamma-rays, electrons, and protons. As the electrons are not very massive and the protons prefer to lose their energy in a dense media via ionization (see Table 1), it has been found (refer to Suter et al. [B135] and Passenheim [B125]) that cobalt 60 gamma-rays can be used to simulate the natural space environment. It is recommended that low dose rate (10^{-4} to 10^{-2} rads (Si)/s) be used for simulating the space environment because time or frequency shifts may have dose rate as well as accumulated total dose dependence.

Table 1—Radiation interaction mechanisms

Radiation type	Interaction mechanisms
Gamma radiation and X-rays	Photoelectric effect (E_k < 10 MeV) Compton scattering (1 MeV < E_k < 10 MeV) Pair production (E_k > 10 MeV)
Protons, electrons, ions	Rutherford scattering Straggling Nuclear reactions Electronic collisions Atomic collisions Bremsstrahlung (electrons and heavy ions) Ionization (secondary electrons) Capture (electrons)
Neutrons	(In) elastic nuclear collisions

In contrast, for the weapons or burst environments, high dose rate sources such as flash X-ray machines should be employed to deposit the total dose. In practical cases, the ionizing dose rate is not high enough to cause any thermal effects, such as an increase in temperature of a quartz crystal resonator. One must be careful when simulating burst environments in that noise or high magnetic fields produced by the simulator do not upset the precision frequency source under test. A noise shot (one that produces no ionizing radiation at the test sample) should be made in order to quantify any such effects.

7.2.1.2 Parameter monitoring

For the natural space environment, it is also important to study the dose/anneal cycle that will occur, particularly in low-earth-orbits (refer to Suter et al. [B134] and Suter [B129]). For these missions, accurate clocks are necessary to carry out reliable surveillance. Due to the contamination inherent in some precision frequency sources, additional dose periods after annealing periods can reveal greater sensitivity to radiation because some mobile contaminant ions have freed themselves during the anneal/recovery period and can interact again with subsequent ionizing radiation.

The most important parameter to be monitored during radiation exposure is the output frequency of the source, both over long and short time periods. The frequency behavior over long time periods is represented by the drift rate. Over shorter periods such as 1 s or 10 s, frequency stability is measured using the Allan variance. Before and after total dose exposures, it is also important to measure and compare the single sideband phase noise. During burst environment testing, the amplitude and phase of the frequency source output must be monitored so that any interruptions of function or losses of time can be determined.

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An adequate warm-up period (about 24 h) is necessary in order that the precision frequency source has stabilized before radiation exposure is begun. Similarly, it is often critical that the recovery of the source be monitored after the radiation exposure has been completed. Usually one is interested in the time it takes for the frequency source to regain its original drift rate and short-term stabilities as well as whether a residual frequency offset remains between the time lines before and after irradiation.

7.2.1.3 Selection of ionization sources

The discussion of total dose testing will be finished by commenting on the various ionization sources. Cobalt 60 facilities often have the advantage of being relatively inexpensive and offer the possibility of adjusting the dose rate, either by using shielding or varying the distance between the device under test and the source. Electron beams can be used in either a continuous mode for steady-state total dose of a pulsed mode primarily to stimulate burst phenomena. Proton beams produce a continuous flux through the device under test, but an energy spectrum simulating a low-earth-orbit environment can be produced (Suter et al. [B133]) by a modulating wheel so that the experimenter is not confined to a monoenergetic source. In the case of both electrons and protons, low flux beams (to simulate low dose rates) of good uniformity are difficult to achieve, and shielding may produce unwanted and uncollimated secondaries (Passenheim [B125]).

In addition to the total dose effects on the frequency source itself, one should be aware of the sensitivity of the associated electronic circuitry to ionizing radiation.

Electron and proton beams from accelerators are generally monitored by Faraday cup techniques. Knowing the beam flux and energy, the total dose in silicon or quartz is readily computed. For cobalt 60 irradiations or gamma cells, an ionization chamber is quite useful because it is calibrated to read dose rate directly. When dealing with cobalt 60, one finds that if the source strength is known at a given time, measurements of dose rate just verify the law of radioactive decay (see Table 2) (Hubbell [B114]).

Table 2—Radiation sources and dosimetry

Radiation	Source	Dosimetry
1.25 MeV gamma	Co60	-Thermoluminescent dosimeters -Law of radioactive decay -PIN diodes -Fibers -Calorimeters
Protons	Cyclotrons, Linacs Synchrotrons Van de Graaff	-Radiochromic dyes -PIN diodes -Ionization chambers
Electrons	Linac Van de Graaff	-Faraday cup -Ionization chambers -PIN diodes -Radiochromic dyes
X-rays	Van de Graaff	-Film -Ionization chambers
Neutrons	Nuclear Reactor (fission) Radionuclides	-Activation foils -Sulphur [S32(n, p)P^{32}] -Scintillators
Heavy ions	Van de Graaff	-Faraday cup

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7.2.2 High dose rate environments

This environment is discussed in 7.2.1.1 through 7.2.1.3. High dose rate (flash X-ray or gamma-ray sources) testing is done to simulate the burst environment. Primarily one is looking for transient upsets or interruptions of the frequency source. Such upsets may cause a loss of time for a spaceborne clock (Breuner [B105]). Also of interest is the quickness and completeness of the recovery from such an upset.

Precision frequency sources and their associated electronic circuitry can be expected to exhibit thresholds with respect to the dose rate causing upset, and to be dependent on the dose rate beyond threshold with respect to the amplitude of the upset. In addition to upset thresholds, burnout thresholds are a consideration due to photocurrents generated in associated electronics at very high dose rates.

Finally, in a weapons environment combining both high dose rate ionization and neutron displacement damage pulses, the dose rate effects on frequency shifts can be expected to be of greater amplitude but of shorter duration than the induced effects due to neutrons. Refer to Figure 12 (Suter et al. [B132]).

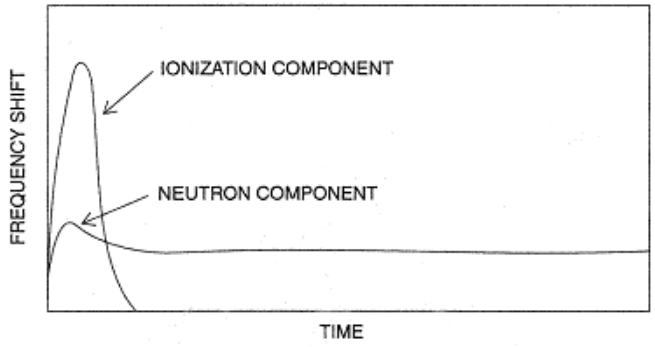


Figure 12—Nuclear burst environment

Several flash X-ray or gamma-ray facilities exist in the U.S. (refer to Suter et al. [B132], Gordon and Behman [B111], and Passenheim [B125]). Two sites providing such testing are at Aberdeen Proving Grounds and the Naval Surface Weapons Center. Potential facilities need to be compared to see if the dose rate amplitude and pulse width are appropriate to simulate the desired burst environment. Table 3 presents a summary of these test facilities.

Measurement of the dose deposited at critical locations within the target equipment is carried out employing thermoluminescent dosimeters (TLDs). These devices are made from lithium or calcium fluoride, giving up light after irradiation in a TLD reader. Doses monitored by TLDs are generally only accurate to 10%–15% (refer to Suter et al. [B132] and Verhey et al. [B137]).

7.2.3 Electromagnetic pulse (EMP) effects

Electromagnetic pulse (EMP) describes the phenomena by which electromagnetic fields are generated when X-rays and gamma-rays induce Compton and photoelectrons in electronic systems. These X-rays and gamma-rays are the product of a nuclear burst. Surface-generated EMP (SGEMP) describes the generation of electromagnetic pulses created by Compton and photoelectrons emitted from the mechanical surfaces of the system. SGEMP differs from EMP because source electrons generate the electromagnetic fields, rather than the surrounding air or other material. Induced EMP (IEMP) is the generation of transient electromagnetic pulses inside electrically conductive enclosures. These pulses are mainly produced by electron currents that flow on any conductive surfaces from which electrons were ejected. The magnitude of these currents is dependent on the electrical characteristics of the material and on X-ray and gamma-ray energies.

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Table 3—Test facilities (selected)

Radiation type	Facility	Characteristics[a]
Gamma	Co^{60}—usually local, GSFC	1.17 MeV (50%) and 1.33 MeV (50%) photons
Proton	Harvard University	E_{max} = 154 MeV $\Phi_{max} = 10^{10}$ p/cm^2/min d_{max} = 12 cm Low-earth-orbit simulation
	University of California at Davis	E_{max} = 65 MeV d_{max} = 10 cm
Electron	GSFC	E_{max} = 3MeV
	NRL	E_{max} = 65 MeV $\Phi_{max} = 10^{11}$ rad(Si)/s d_{max} = 0.4 cm
Neutron	Aberdeen Proving Ground	E > 10 keV $\Phi_{max} = 8 \times 10^{14}$ n/cm^2/s Gamma-ray dose 3.9×10^5 rad (Si) per pulse
X-rays	ARL Febatron	Dose 100 rad/cm2 Pulse width = 4 ns V_{max} = 600 keV

[a]E_{max}, Φ_{max}, and d_{max} are the maximum kinetic energy, flux, and beam diameter.

When a space system is located in the vicinity of a nuclear burst, SGEMP will most likely be the phenomena of interest (refer to Figure 13). In this case, no atmosphere is present to absorb the lower energy X-rays emitted from the weapon's burst (Higgens et al. [B113]). However, the higher energy X-rays are the primary energy source in nuclear bursts because most of the kinetic energy is radiated as X-rays when no intervening atmosphere is present. An SGEMP analysis involves a study of the X-ray transport through the structure, generation, and transport of primary and secondary electrons, generation of electromagnetic fields, and electronic circuit response.

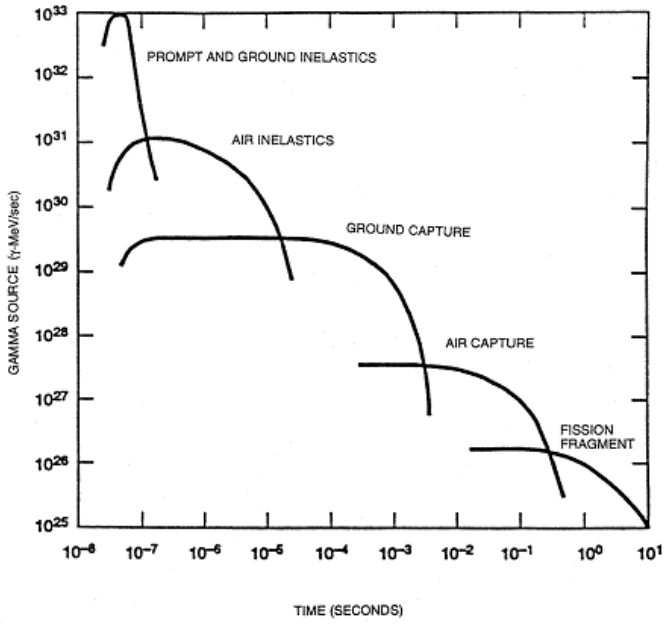


Figure 13—Total gamma source strength versus time for nominal 1-megaton surface burst [B120]

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Photoelectrons are generally generated by soft X-rays (<10 keV), and therefore, SGEMP tests should use soft X-ray transient pulses. Furthermore, because SGEMP phenomena depend heavily on the exact geometry, orientation, and composition of a system, tests should be conducted on the exact system configuration.

Table 4 lists a series of tests conducted at several representative spacecraft locations using a plasma radiation source with an 8 ns rise time (Van Lint et al. [B136]). Table 4 shows the location characteristics as well as the electron yield (k) and average electron energy E, as previously mentioned. X-rays and gamma-rays interacting with electronic enclosures generate photo or Compton currents, leading to internal electromagnetic pulse effects (refer to Figure 14). These currents produce net electrical charges in metallic enclosures, and they generate peak potentials (V) at the center of the enclosure equal to

$$V = \frac{JL^2}{8\varepsilon_0 \bar{v}} \tag{38}$$

where

J is the current density,
L is the enclosures height,
$\bar{v}$ is the average electron velocity,
ε_0 is the electrical permittivity (refer to Longmire [B119], [B120]).

Table 4—SGEMP photon source, electron yield (k), and average electron energy (E)

Location	Emitting material	E (keV)	k(mC/cal)
External	Al, SiO^2	1.2	16
Behind thermal blankets	Al	1.8	0.034

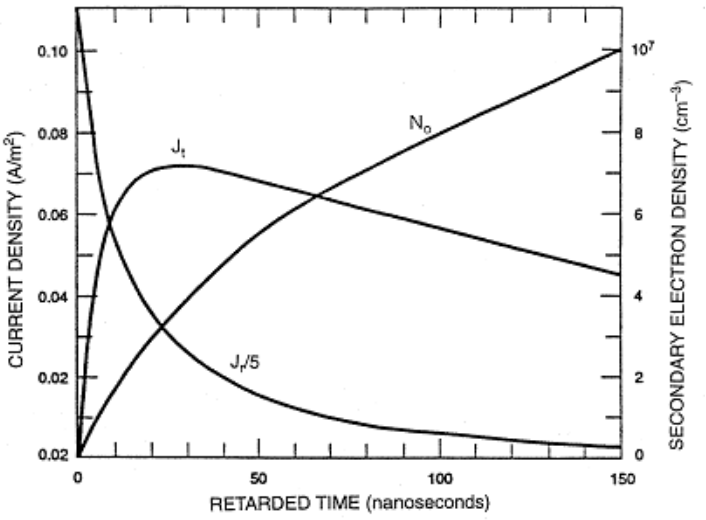


Figure 14—Radial and transverse Compton currents for EMP

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IEMP testing of frequency standards is therefore best conducted using flash X-ray facilities offering control of energy levels, fluence, spectrum, pulse width, and pulse duration. If the system will find application other than the vacuum of space, the gamma-ray effects will dominate due to their lower absorption in air. In this situation, IEMP effects should be simulated using high-energy bremsstrahlung sources (>3 MeV).

Besides the generation of IEMP inside conductive enclosures, virtually all circuit boards, connecting cabling harnesses, and dielectric materials can generate so-called printed circuit board IEMP. Radiation-induced currents will flow between conductive patterns on these circuit boards because photoelectric and Compton currents will be emitted from every radiation-exposed surface. This type of IEMP falls into one of the following three categories:

a) Direct

b) Inductive

c) Capacitive coupling

IEMP effects can be reduced by radiation shielding of the enclosure, which limits the creation of photoelectric and Compton currents. Furthermore, the use of air and vacuum gaps between metallized surfaces and dielectrics will decrease IEMP effects. The basic source of IEMP, and for that matter SGEMP, is the production of a current density when incident photons interact with various materials in the system, causing electron emission.

Therefore, reducing the X-ray and gamma-ray radiation levels at the enclosure, using shielding when practical, is an efficient way of reducing these EMP effects. Further methods for minimizing SGEMP are to reduce voltage clipping and use decoupling networks (series resistors and zener diodes). The design of a frequency standard should include a minimization of ground loops and the placement of components close to the ground planes (Suter et al. [B132]).

7.3 Special user notes

7.3.1 Response of frequency standards to radiation

Significant progress has been made with respect to the evaluation of the response of quartz crystal oscillators and atomic frequency standards to natural and enhanced radiation. The overall situation is approximately summarized as follows:

a) The response of a frequency standard to low doses of radiation cannot be extrapolated from the result of high dose rate radiation tests and is highly nonlinear (Flanagan [B108] and Suter et al. [B135]).

b) Different radiation response mechanisms are activated for various accumulated doses; the behavior of a frequency standard in one dose region cannot be extrapolated from the behavior in another (Flanagan [B108] and Suter et al. [B135]).

c) The susceptibility of frequency standards, in particular quartz crystal oscillators, to low levels of ionizing radiation [<100 rad (Si)], is not determined by the electronic components in the oscillator circuit. Most electronic components are capable of surviving, without any significant degradation, accumulated doses up to several krad (Si). Therefore, the response of these standards to low dose radiation, as encountered in earth orbits, is controlled by the frequency determining element (quartz resonator, and physics package) (refer to King and Koehler [B116], Flanagan and Wrobel [B110], Riley and Vaccaro [B127], Suter and Maurer [B130], and Nichols et al. [B123]).

d) The radiation sensitivity of atomic frequency standards and quartz oscillators to enhanced environments, like accumulated doses greater than 1 krad (Si), peak prompt dose rates of 10^{10} rad (Si)/s, and neutron fluences (1 MeV) in the order of 10^{11} to 10^{13} neutrons per cm^2, is not only determined by the quartz resonator or physics package, but also by the hardness of the oscillator electronics. This includes components in the oscillator circuit, voltage-controlled oscillators, tuning

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circuitry, and thermal control. Design limits must be established to minimize the effects of radiation on these devices. Order-of-magnitude estimates of radiation induced frequency shifts can be established by assuming that these limits increase linearly with electrical parameter changes and that they act independently (Breuner [B106]).

e) The radiation response of quartz resonators is related to the various steps in the fabrication process of the quartz crystal resonators (refer to King and Koehler [B116] and Suter et al. [B135]). These processes are difficult to control and have resulted in different responses of crystals, made from the same quartz bar, to identical levels and types of radiation (Suter et al. [B135]).

f) Frequency standards on spacecrafts are, in general, intermittently exposed to both natural and enhanced radiation. In the case of low-earth-orbits, a significant amount of radiation is delivered to the frequency standard during that part of the orbit when the satellite passes through the South Atlantic Anomaly and, to a lesser degree, when it passes through the Northern and Southern Horns (refer to Flanagan and Leadon [B109], Suter [B129], Stassinopoulos and Barth [B128], Aguero [B104]). Annealing effects during radiation-free orbit segments should be studied carefully in any radiation hardening study, since they affect the long term stability and frequency offset in different ways. This is also true for enhanced environments, since multiple radiation events may occur, spaced over different time intervals, resulting in cumulative effects increasing the likelihood of timing errors in clocks (refer to Stassinopoulos and Barth [B128], Aguero [B104], and March et al. [B121]).

g) Depending on the ephemeris of the satellite, single event upsets (SEUs) and latch-up may occur due to high-energy particles traveling through integrated circuits [B117]. The induced current pulses can create SEUs and latch-ups, resulting in data errors due to a malfunctioning of voltage-controlled oscillator circuitry and microprocessor systems or a change in information in storage registers.

7.3.2 Test procedures

In radiation testing of frequency standards, the methods used to measure changes in output frequency involve customary equipment such as reference standards, frequency multipliers, mixers, and frequency counters. As shown in Figure 15, the RF output signal from a frequency standard is compared with that of a reference by first multiplying its output signals to a higher frequency. Multiplication prior to frequency mixing may yield a greater resolution of the beat frequency signal from the mixer (refer to Suter et al. [B132], [B135]).

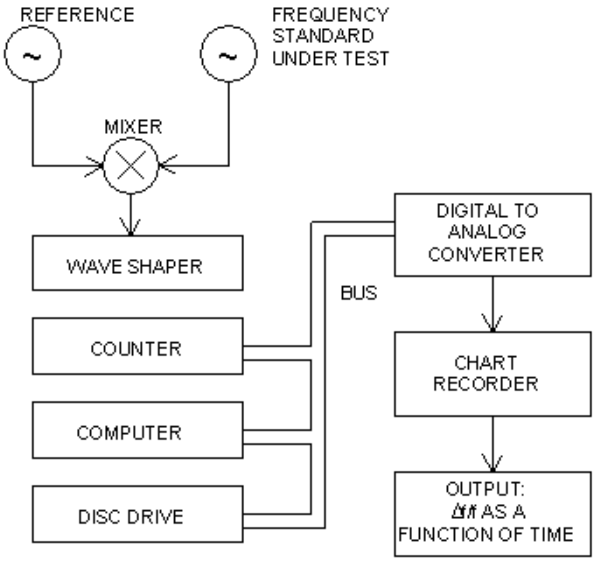


Figure 15—Frequency shift data acquisition system

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Typical systems mix the two frequencies so that their beat frequency is in the audio frequency range (20 Hz–4000 Hz). A frequency counter, together with a data acquisition system, is then used to calculate the frequency shift and Allan variance as a function of time and accumulated dose.

In order to observe radiation-induced frequency shifts in real time, an analog strip chart recorder may be needed to display the frequency standard's fractional frequency shift as compared to the laboratory reference. Previous experiments have indicated that radiation-induced frequency shifts (*df/f*) can be as small as 1.0 part in 10^{-12}/rad. Hence, the reference source should have a stability that is at least one order of magnitude better than the device under test.

To observe the recovery characteristics of the frequency standard after a radiation exposure, the reference standard should have a drift rate that is also at least a factor of ten better than the standard under test.

Prompt radiation can often introduce momentary outages in a frequency standard, which results in a possible loss of time. Figure 16 shows a method for measuring the magnitude of this time loss. The time difference between two clocks, one referenced to the laboratory standard and one to the device under test in terms of 1pps, are input to a counter. The time difference, either a loss or gain of the device under test relative to the standard during a radiation event, is then monitored by the counter. The resolution of this system should be better than 1 ns [B132].

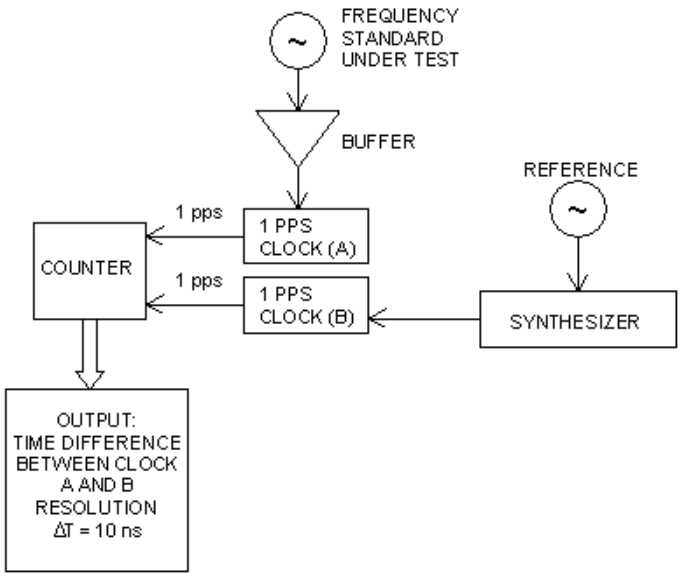


Figure 16—A method for measuring time loss due to momentary outages caused by prompt radiation

The difference in phase between the test and reference standard should also be continuously monitored before, during, and after the radiation tests. For example, using a vector voltmeter, the difference in phase between the standards can be recorded by using a high-speed recorder. The phase measurement systems supplied not only information on the phase difference, but also the possible time loss between the test standard and reference (refer to Figure 17).

In prompt radiation tests, a fourth experimental setup is recommended. This monitoring system records not only the frequency standard's output, but also flash X-ray and neutron pulses as a function of time. Figure 18 shows the experimental arrangement of this test system.

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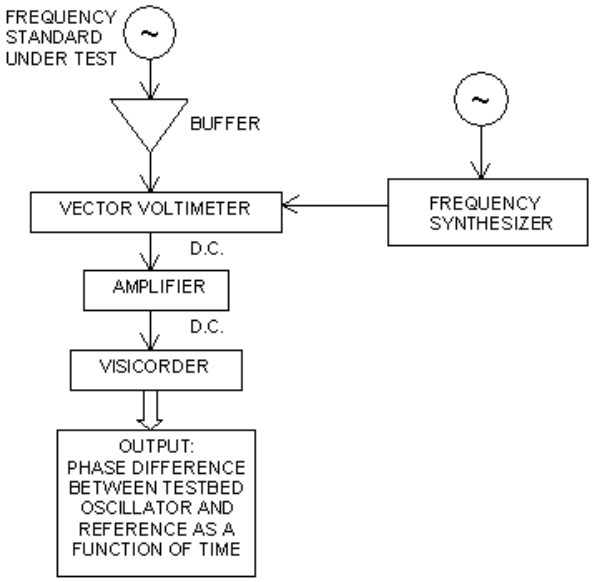


Figure 17—Phase measurement system

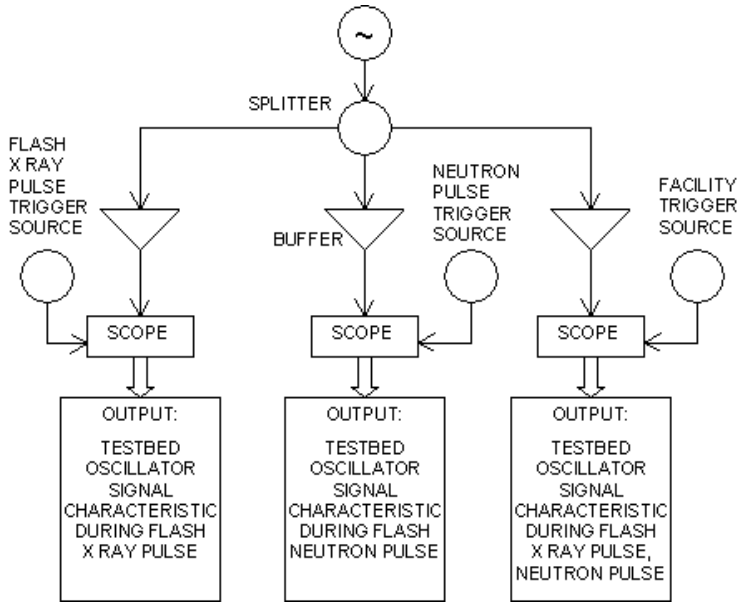


Figure 18—Test set-up for recording frequency standards output during flash X-ray and neutron pulses

7.3.3 Radiation test facilities

Protons, with a limited kinetic energy range, can be generated at a radiation test facility (refer to Table 3) using, for example, cyclotrons (Gordon and Behman [B111]). The cyclotron at Harvard University accelerates protons to a fixed energy of 158 MeV (Suter et al. [B133]). The extracted beam is scattered and shaped to uniformly cover fields up to 21 cm in diameter.

Specific dose vs depth curves can be shaped using a range modulator system to emulate low-earth-orbit proton exposures (Burke [B107]). For example, Figure 19 and Figure 20 show the total dose and orbit

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radiation profile for the TOPEX orbit (Stassinopoulos and Barth [B128]). A modulator wheel is rotated across the proton beam with its axis parallel to, but not concentric with, the beam (refer to Figure 21). The time-averaged energy spectrum is then a composite determined by the geometry of the steps in the wheel. A specific low-earth-orbit radiation environment can be emulated. Making use of standard range-energy tables, the relative transmitted flux and degraded energy of protons passing through the layers of the modulator wheel can be calculated (refer to Packer [B124] and Katz and Penhold [B115]).

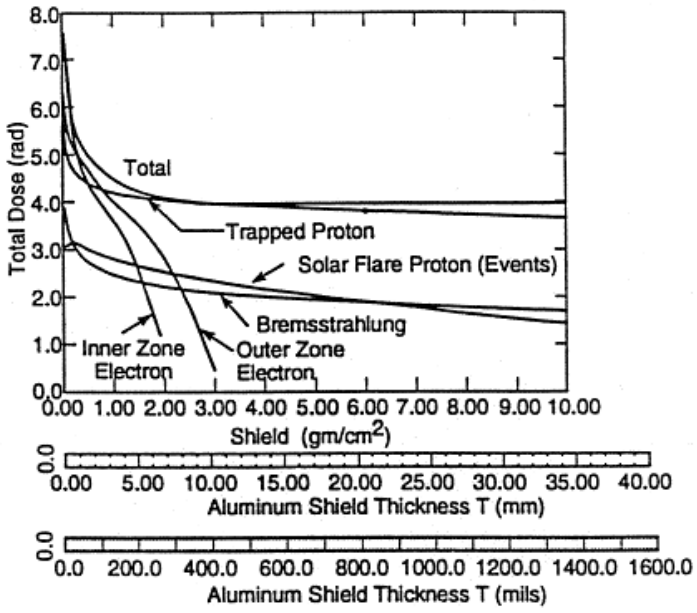


Figure 19—TOPEX orbit total dose (after Stassinopoulos and Barth [B128])

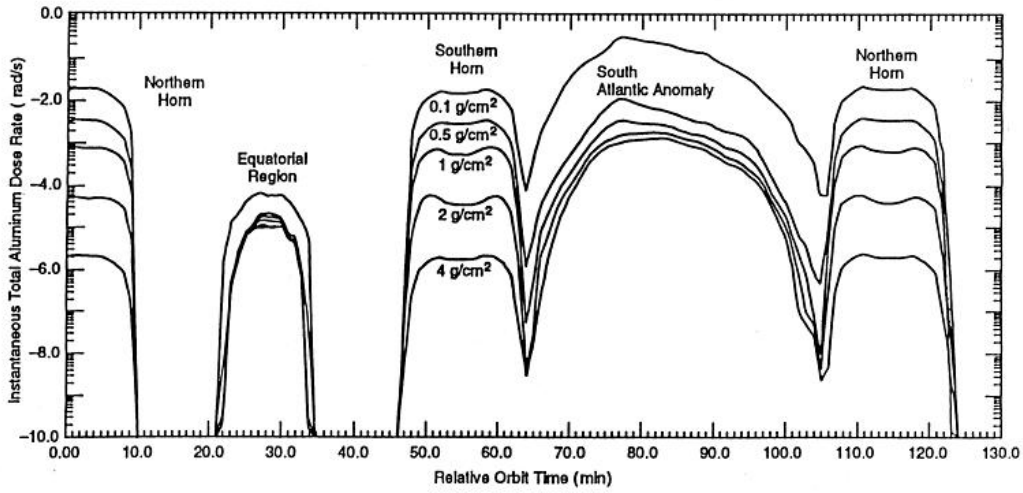


Figure 20—- TOPOEX orbit radiation profile (after Stassinopolous and Barth [B128])

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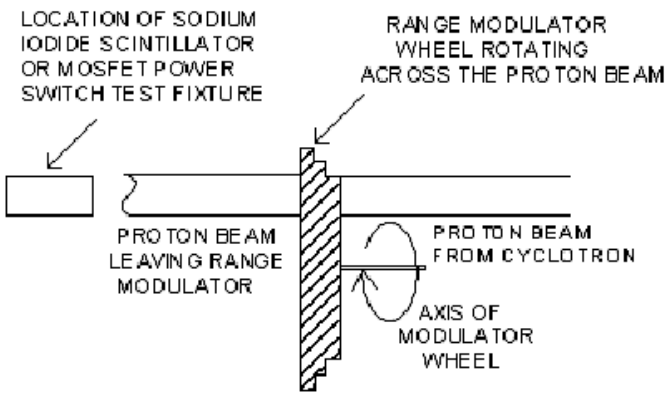


Figure 21—Range modulator system for determining specific dose vs depth

Let E_n by the calculated energy in MeV after degrading through n layers of the modulator wheel material. Lef f_n be the relative transmitted flux through n layers; let t_n be the relative dwell time with a total of n thicknesses as the wheel spins; and let $(dN/dE)E_n$ be the proton flux at an energy E_n in the space environment. Then, t_n is determined as follows:

$$t_n = (dN/dE)E_n f_n^{-1} \Delta E_n \tag{39}$$

where

$$2\Delta E_n = E_{(n+1)} - E_{(n-1)} \tag{40}$$

This method of calculation neglects mixing between adjacent energy bins. As the range distribution of the Harvard cyclotron proton beam shows a spread of about ±0.25 g/cm^2 in plastic, the choice of 0.25 in stock thickness (0.59 g/cm^2) makes reasonably sure that mixing between bins will not distort the overall spectrum. Another calculation using range as the parameter instead of energy should give a very similar result.This method of calculation neglects mixing between adjacent energy bins. As the range distribution of the Harvard cyclotron proton beam shows a spread of about ±0.25 g/cm^2 in plastic, the choice of 0.25 in stock thickness (0.59 g/cm^2) makes reasonably sure that mixing between bins will not distort the overall spectrum. Another calculation using range as the parameter instead of energy should give a very similar result.

Figure 22 shows the actual proton energy distribution produced with the modulator and measured with a sodium iodide scintillator. The intended profile and measured energy distribution agree generally to within 10%. This natural environment spectrum has a typical mean proton kinetic energy of 40 MeV and covers the range from 1 to 500 MeV. The simulated spectrum covers a kinetic energy range from 5 to 120 MeV, which includes the most damaging kinetic energies of the proton radiation.

Proton radiation dosimetry can be accomplished with thimble ionization chambers to measure dose as a function of overlying materials. Absolute calibration of such a chamber is established by exposing it to a standard proton field whose flux and mean proton range are measured with a Faraday cup and a set of aluminum absorbers. This method of absolute calibration can then be checked using an intercomparison with other accelerator facilities (Verhey et al. [B137]).

7.3.4 Single event phenomena

In the case of precision frequency sources, single event phenomena can be expected to occur only in the associated digital electronic circuitry or in the power metal on silicone field effect transistor (MOSFETs). Individual cosmic-ray ions or solar or trapped protons can produce enough ionization near critical nodes in solid state circuitry to cause a change of the logic state. In bulk CMOS integrated circuits, a destructive burnout due to latch-up can occur. Single event-induced burnout has also been observed in power MOSFETs (Kinnison et al. [B117]).

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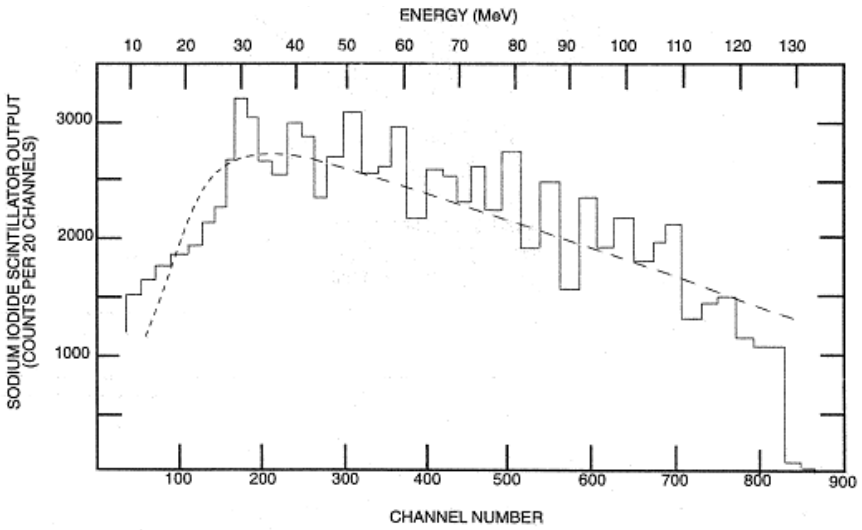


Figure 22—Actual proton energy distribution produced with the modulator and measured with a sodium iodide scintillator

In the majority of cases, it should be possible to screen the proposed parts list for integrated circuits susceptible to single event phenomena and to replace them with ICs that are immune to such effects. Hardened MOSFETs and digital logic families are now readily available but at substantially increased cost.

Testing could be performed at the system level to verify the immunity of the frequency reference system to single event effects. As contrasted to such systems as data handling in which some upsets can be tolerated, it is recommended that critical frequency reference and clock systems be immune or bulletproof with respect to single event effects.

The recommended facility for single event upset testing is the Brookhaven National Laboratory Tandem Van de Graaff Single Event Upset Facility. The Van de Graaff accelerates heavy ions to hundreds of MeV, providing particles that can deposit picocoulombs of charge in microns of silicon. After the usual focusing and switching, the beam enters a target room dedicated to single event upset testing. Delidded parts are placed in a large vacuum chamber with the beam entering through a pipe with a shutter. Beam and target control is achieved via a facility computer, whereas the results of the upset testing are monitored by the experimenter's computer.

Dosimetry is provided by the Brookhaven facility and consists of four separate Faraday cups measuring the intensity and uniformity of the beam flux near the target chamber.

8. Aging, warm-up time, and retrace

8.1 Description of the phenomena

8.1.1 Aging

The frequency of a typical precision frequency source may vary with time as shown in Figure 23. In the graph, a long-term change of the frequency in one direction is observed after the turn-on transient.

Shorter term fluctuations generally superimposed on the long-term changes are not shown. These shorter term fluctuations may sometimes be correlated with temperature or barometric fluctuations. In such cases, their origin is known, and with adequate techniques, they can be remedied if a need is expressed. The longer term variations in many cases, however, are more troublesome, and it may prove to be impossible to remedy them. They may be caused, for example, by internal changes of the controlling element of the precision frequency source, e.g., relaxation or outgassing of the quartz crystal in a quartz oscillator or the evolution of the cell in a rubidium frequency standard. In general, these effects are called aging.

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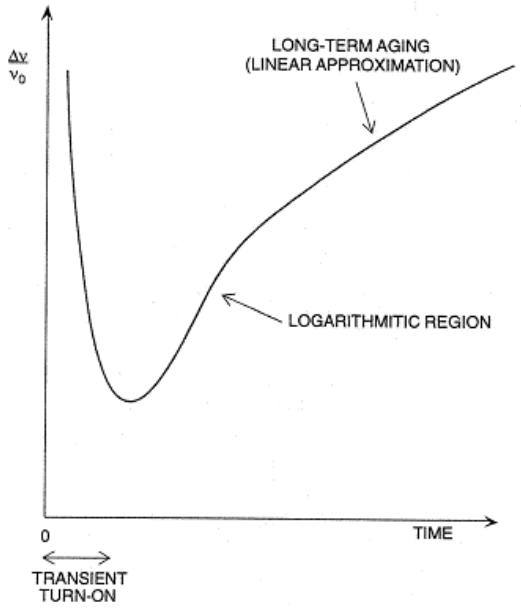


Figure 23—Illustration of the aging characteristics of a precision frequency source

8.1.2 Warm-up time

The warm-up time (T_{wu}) of an oscillator is characterized by various properties that are normally grouped under the form of a table. Similar oscillators are generally given the same fundamental and environmental specifications that include, for example, accuracy, frequency stability, temperature sensitivity, magnetic field sensitivity, and so on. These specifications are usually quoted for steady-state operation, reached only after a sufficient period of continuous operation, as illustrated in Figure 24. This period is called warm-up time.

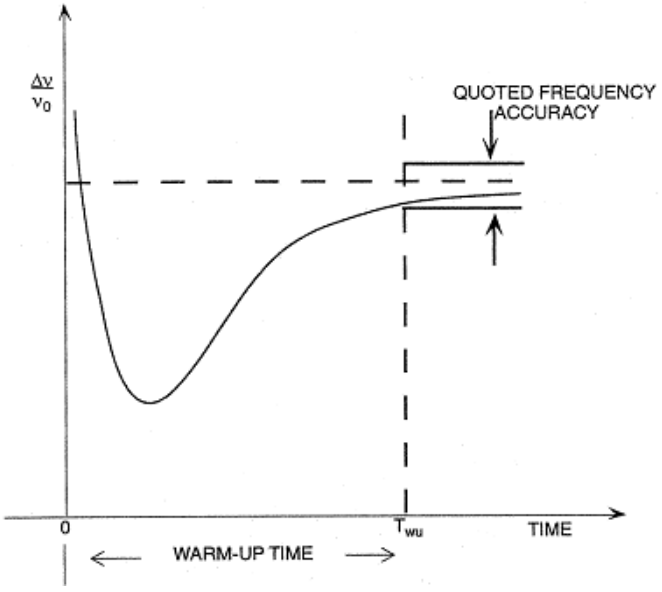


Figure 24—Illustration of the warm-up characteristic of a precision frequency source

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8.1.3 Retrace

Oscillators are subject to many environmental changes, of which a drastic one is an interruption of operation called *on/off* operation. In general, for most oscillators, most specifications such as frequency stability, magnetic field sensitivity, and several others will reproduce closely upon on/off cycling (after the appropriate warm-up period). However, the frequency may be different after such an operation to an extent that makes it clearly measurable; i.e., the retrace (R) is greater than the variation caused by its inherent frequency instability, as illustrated in Figure 25.

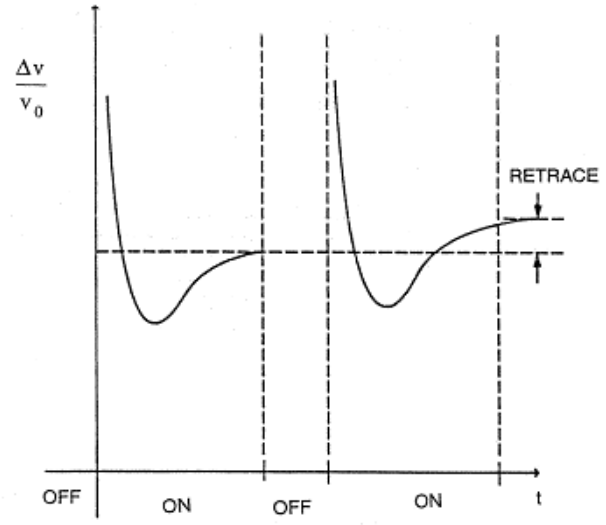


Figure 25—Illustration of the retrace characteristic of a precision frequency source

8.2 Effects and test methods

8.2.1 Aging

Aging is the systematic change in frequency with time due to internal changes in the oscillator. This excludes frequency fluctuations caused by environmental changes as well as frequency fluctuations caused by malfunctioning oscillator components that could be improved or repaired. Aging in this context is thus a property of a type or class of oscillators and not of a defective unit or changing environment.

An aging measurement shall, to the greatest extent practical, avoid the effects of environmental sensitivities (such as temperature and barometric pressure), noise, and reference error. The aging data can be continuous or sampled. In the latter case, measurements shall be made often enough to resolve the true shape of the aging characteristic. Supplementary continuous data (or data taken at shorter intervals) may be necessary to establish the absence of environmental and other disturbances faster than, or synchronous with, the normal sampling interval. All measurements shall extend over sufficient time that the noise inherent in the measurements is less than the aging to be measured (or specified). Measurements should start after all transient frequency changes caused by the turn-on of the oscillator have become negligible compared to the aging itself. The identity of the reference shall be stated, as well as the measurement averaging time, the measurement interval, and any data averaging that is done.

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The measurement of aging thus requires the following:

a) Ascertaining the integrity of the frequency source

b) The stabilization of environmental parameters to levels below those which cause frequency changes of the order of magnitude of the observed aging (i.e., drift and aging must be identified)

The aging measurement shall extend over a period of time sufficient to show the intended information. The measurement of the aging of a frequency source over a certain period requires data over at least that length of time. Extrapolation shall not be used unless explicitly stated. For example, a statement that the aging rate is 3 x 10^{-10}/month implies that data were taken for at least 1 month, and that this is the average linear aging over a month. It should be neither the result of only one week's data nor the slope at the end of one month. The latter should be expressed as, say, 1 x 10^{-11}/day after 30 days. Continuous operation of the source is assumed.

In general, the long-term behavior of frequency with time of a precision frequency source is nonlinear. In quartz crystal oscillators and in well-behaved rubidium frequency standards, for example, the change in frequency after turn-on may be represented by a logarithmic equation. After a period of time, characteristic of the particular source, the change may be approximated by a linear equation. In most atomic frequency standards, except in rubidium standards, there are not sufficient data to conclude on a given law, and thus, long-term behavior is normally characterized by means of a linear equation.

a) In the logarithmic model, the frequency change is represented by

$$\frac{\Delta \nu}{\nu_0} = A \cdot \ln\left[B \cdot (t - t_0) + 1\right] \tag{41}$$

where

$$\Delta\nu = \nu - \nu_0$$

ν is the frequency at time t,

ν_0 is the frequency at $t = t_0$ normally taken as the time at which turn-on transients have decayed to a negligible level.

A and B are determined by a fitting process. A is dimensionless, whereas B has the units of inverse time.

a) In the linear model, the frequency change is represented by

$$\frac{\Delta \nu}{\nu_0} = C(t - t_0) \tag{42}$$

where

C is the aging rate (refer to 5.3.8) reported on the basis of per day, per month or per year,

and the other symbols are defined as above.

Effects of environmental and short-term fluctuations must be removed from the specifications; i.e., they either must be controlled to be sufficiently small or they must be measured and the data correspondingly adjusted.

8.2.2 Warm-up time (T_{wu})

Warm-up time (T_{wu}) is the time taken by an oscillator after turn-on to reach a steady state in which the quoted specifications are met. The concept "steady state" is important because of possible overshoot in the

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oscillator characteristics. In such a case, damped oscillations may even be present in the characteristics after turn-on. Steady state may be claimed to exist only after these oscillations have decayed to a level such that specifications are continually met at subsequent times.

It is worth mentioning that warm-up depends on the environmental history of the oscillator before turn-on, in particular, on its actual temperature.

Warm-up time may be given in minutes, days or other units of time that appear most appropriate. The environmental temperature at which the specification applies should be given, and it is assumed that the oscillator while off has reached thermal equilibrium with its environment at the time of turn on. An example for stating a warm-up time specification is

T_{wu} = less than 12 min for temperatures between –25 °C and 0 °C

T_{wu} = less than 5 min for temperatures between 0 °C and 25 °C

The warm-up behavior may be strongly dependent on the operating conditions, particularly on environmental temperature and/or electrical supply voltage. All such factors should be considered. The device should be allowed to soak long enough to reach complete equilibrium. This is particularly important for a device with a well-insulated internal oven.

The warm-up characteristics of interest can span a range of second to days (or longer). The data often take the form of strip-chart records of such variables as input current and frequency. As a minimum, these variables should be recorded at intervals not exceeding one-tenth of the specified warm-up time.

8.2.3 Retrace

Retrace (R) is the change of frequency of an oscillator after exposure to specified on/off operations measured after the specified warm-up time, and at the specified temperature. This is somewhat restrictive because it does not include, for example, other cycling operations such as on/off magnetic fields and abrupt cycling changes in temperatures. The term *retrace* has also been used in certain instances for characterizing other phenomena such as hysteresis in the frequency/temperature characteristics of a crystal oscillator when subjected to temperature cycling. The use of the term *retrace* is discouraged for such situations.

The off-time duration should be specified to be much larger than the warm-up time, and it shall be given as part of the specification. If the warm-up time is not given, the specification should include detailed data on the assumption made including the time of turn-off and turn-on. The specification should also give the range of environmental conditions that are relevant and over which retrace specifications apply if more limited than the environmental ranges otherwise specified, e.g., temperature, pressure, humidity, magnetic field intensity, and so on. With the exception of aging, the unit may not move outside its retrace specification during continuous operation or discontinuous operation within the given environmental constraints. The specification should also mention if the unit is sensitive to repetitive on/off cycling. For example, a specification could read

> Retrace or $R = \pm 5 \times 10^{-11}$ for any turn-off time greater than 6 h. (Specification applies after operating more than 4 hours.) Specification applies for temperatures between –20 °C and + 30 °C, barometric pressure between 50 kPa and 105 kPa, and relative humidity between 20% and 65%. This statement is required when warm-up specification is not given.

Although the retrace requirement can involve a number of environmental and other factors, retrace, by definition, implies a return to exactly the same operating conditions. For example, a typical retrace test might involve turning a device off and on a number of times while measuring the variation in stabilized frequency. The operating conditions (temperature, supply voltage, orientation, etc.) of the device should not change between runs. The test should emphasize the consistency of the retrace and whether the unit shows any accumulative frequency change (trend). A sufficient number of runs should be made to show this (as opposed to fewer runs under different operating conditions). Sufficient off time should be allowed so that all internal

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parts of the unit reach ambient temperature. Sufficient on time should be allowed for the unit to fully restabilize.

A related factor is the on/off and/or thermal-power cycling endurance of the frequency source. This is especially important for a device such as a rubidium-controlled crystal oscillator (refer to 8.3.4) that is intended for many on/off cycles. A design verification test consisting of thousands of on/off and thermal power cycles may be necessary to qualify such a device.

8.3 Special user notes

8.3.1 Drift vs aging

Aging should be differentiated from the much broader concept of frequency drift. The frequency of an oscillator may drift with time for several reasons. For example, a long-term continuous change in the environment temperature may cause a long-term change in the oscillator frequency. The size of the frequency change will depend on the oscillator control element temperature sensitivity and the gain of the oscillator temperature controls. This may go on for a long period (until the temperature variations change) and, with limited measurement capability, could be mistakenly identified as "aging." The concept of aging is reserved for changes in the fundamental intrinsic properties of the control element of the oscillator, a property that characterizes, for example, a class of oscillators fabricated by means of similar manufacturing processes. There are some areas where the distinction between aging and drift may become blurred, sometimes because of superimposed effects difficult to assess. For example, a hydrogen maser's frequency may drift because of changes in its cavity frequency. If the cavity material creeps slowly with time, the frequency change observed appears as aging of the maser. However, the effect can be readily corrected by a simple re-tuning of the cavity, which can be done automatically, and the "aging" disappears. On the other hand, some bulb coatings have been known to change characteristics with time, with the consequence that the maser frequency varies (ages) in a continuous fashion for very long periods of time without any ability to remedy this condition operationally. Similar discussions can be held in connection with Rb frequency standards, quartz oscillators, and Cs-beam frequency standards.

8.3.2 Crystal oscillators

The relatively low noise and high aging of a typical crystal oscillator may result in a well-defined fit to an aging model. The aging is usually determined by such processes as stress relaxation and redistribution of contamination that decrease with time. Some units exhibit a change in sign of aging. This is because there is more than one source of aging of opposite signs.

8.3.3 Rubidium frequency standards

The relatively low aging of a typical rubidium frequency standard can easily be masked by noise or environmental sensitivities. The early aging is usually determined by such stabilization processes as rubidium redistribution in the cells, and a logarithmic model may be used. The later aging is usually low and steady, and a linear model may be used.

The warm-up of a rubidium frequency standard is often defined as the time to atomic lock and/or a certain absolute frequency tolerance (after prior calibration). This is generally a few minutes, and it depends strongly on the environmental temperature and the supply voltage. Lockup time should be stated as the time to reach and remain in atomic lock, as indicated by a status signal. The energy required to attain a certain accuracy may be important for battery-backed applications. The reference point for reaching a certain frequency accuracy during warm-up is most often based on the "final" frequency—the settled value after no significant additional change takes place. The warm-up criterion is usually such that a stabilized value is quickly attained. It is unusual, however, to have a warm-up requirement related to attaining/regaining a certain aging rate.

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The controlling element being the atomic resonance of the rubidium gas, retrace is generally a characteristic that makes rubidium frequency standards the units of choice in some specific applications. In some types of design, retrace may be of the order of the aging rate that is barely measurable. However, in some other types of design, rubidium redistribution upon turn-off, cooling, and warming may cause important changes in the characteristics of the standards, with resulting measurable frequency shifts.

8.3.4 Rubidium-crystal oscillators

The aging of a rubidium-crystal oscillator (RbXO) is that of its crystal oscillator during low-power operation between synchronizations and that of its rubidium reference during full-power operation and over the long term.

The syntonization time and energy is critical for many RbXO applications, and the specification should be clear on this question.

The retrace characteristic of the rubidium reference is critical because, for intermittent operation, it is the retrace rather than the aging that determines the long-term stability.

8.3.5 Hydrogen masers

The aging of a hydrogen maser is still a question of debate. For masers with automatic or continuous tuning of their cavities, sometimes a change of wall shift yet to be identified causes a continuous aging. A linear model is often used.

The warm-up of hydrogen masers is ordinarily very long. Generally these devices are kept in continuous operation, and warm-up conditions are not necessarily given. These devices are not designed in such a way as to optimize this parameter.

Unless it has been turned off for a long period, the question of retrace of a hydrogen maser is normally connected to the ability to reproduce or retrace the microwave cavity. For very long periods, wall shift drift may have some importance.

8.3.6 Cesium-beam frequency standards

An exceptionally stable reference and control of environmental conditions is necessary to measure the aging of these devices. The relatively high noise requires a long averaging time. In general, the very low aging of a cesium beam tube frequency standard is considered to be consistent with zero.

The warm-up of a cesium frequency standard is usually associated with its attaining a specified frequency accuracy. All other characteristics are assumed to be reached upon warm-up unless specified otherwise.

In general, cesium-beam frequency standards are used for their long-term stability and as primary reference standards in the frequency domain. Their accuracy is given and their retrace is closely connected to their quoted accuracy.

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Annex A

(informative)

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The following bibliography is provided solely for the purposes of informing the user of this guide about available literature that may offer in-depth coverage of particular technical aspects. The accuracy of this listing has not been verified; furthermore, this listing is not intended to be all-inclusive because only a subset of the relevant literature was selected for this purpose. The bibliography is structured to correspond to Clause 3 through Clause 8 of this guide.

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