

IEEE Std 1193™-2003

(Revision of
IEEE Std 1193-1994)

IEEE Standards

1193™

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



Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

12 March 2004

Print: SH95139
PDF: SS95139

Recognized as an
American National Standard (ANSI)

IEEE Std 1193™-2003
(Revision of
IEEE Std 1193-1994)

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**IEEE Standards Coordinating Committee 27
on Time and Frequency**

Approved 12 June 2003

IEEE-SA Standards Board

Approved 17 September 2003

American National Standards Institute

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

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Print: ISBN 0-7381-3710-3 SH95139
PDF: ISBN 0-7381-3711-1 SS95139

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Introduction

(This introduction is not part of IEEE Std 1193-2003, IEEE Guide for Measurement of Environmental Sensitivities 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.

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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

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.

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 Comité 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

¹CCITT 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.

²IEEE 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/>).

³MIL publications are available from Customer Service, Defense Printing Service, 700 Robbins Ave., Bldg. 4D, Philadelphia, PA 19111-5094.

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

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

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

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:

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

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

⁴The numbers in brackets correspond to those of the bibliography in Annex A.

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:

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

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:

$$Y(f) = W(f)X(f) \quad (4)$$

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:

$$\frac{\Delta f}{f} \approx \sum_j \frac{1}{f} \frac{\delta f}{\delta z_j} \Delta z_j \quad (5)$$

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:

$$\Delta f = \frac{\delta f}{\delta D} \frac{\delta D}{\delta T} \Delta T \quad (6)$$

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

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:

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

where

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

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

(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 (Gros Lambert 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

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], Mattison [B31], and Walls and Gagnepain [B45]).

- 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]).

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 $z_1, z_2, \dots, z_j, \dots, z_p$, then the law of propagation of error states

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

or, approximately,

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

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 .

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

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

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:

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

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

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

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

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

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 $\Delta z_j, z_k, \dots$ 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

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

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]).

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

$$\frac{\Delta f}{f} \approx -\frac{v^2}{2c^2} \quad (14)$$

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

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

where m is the Earth's gravitational constant ($3.986 \times 10^{14} \text{ m}^3/\text{s}^2$), R is the Earth's radius, and r is the orbital radius. This is about $1 \times 10^{-16}/\text{m}$ 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.

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:

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

where

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

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

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 ($f_{vib} \gg 1/2\pi t_o$) 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 ($f_{vib} \ll 1/2\pi t_o$) 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 $f_{vib} \gg 1/2\pi t_o$, the spurious constant frequency offset is very efficiently attenuated when the value of t_o is decreased.

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., $>10\text{ g}$ [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)

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 *2g tipover*, the magnitude of the gravity field is $1g$ 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 $-1g$ to $+1g$, i.e., by $2g$. 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).