DOCUMENT 214-09

Range
Commanders
Council

TELECOMMUNICATIONS
AND TIMING GROUP

DEFINITIONS OF FREQUENCY AND TIMING TERMS, SATELLITE NAVIGATION AND TIMING SYSTEMS AND THE BEHAVIOR AND ANALYSES OF PRECISION CRYSTAL AND ATOMIC FREQUENCY STANDARDS AND THEIR CHARACTERISTICS

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PREFACE

This document presents the results of efforts by the Telecommunications and Timing Group (TTG) of the Range Commanders Council (RCC).

Over the past several decades, atomic clocks have advanced from the laboratory stage to large-scale use in government and industry. There have also been significant improvements in quartz crystal oscillator technology. The improvement in time transfer techniques has largely been due to the improvement in frequency standards. In this document, an effort was made to provide substantial agreement with the accepted definitions found in the literature, as authored by leading experts in the field of precise time and frequency techniques. The terms and definitions contained herein relied heavily on the references at the end of this document.

This document, which is a revision of RCC Document 214-94, contains definitions of frequency and timing terms, time transfer techniques and analysis, and behavior of crystal and atomic frequency standards. The document serves as a common reference for acceptable definitions, current terminology, and proper use of frequency and timing terms. It is also a guide for preparing procurement specifications and requirements for time and frequency equipment as well as preparing other technical documents. Use of this document will help greatly in mitigating uncertainty, ambiguity, and misunderstanding of terminologies.

For compiling this document from numerous sources listed in the reference section and from private communications with individuals prominent in the Precise Time and Time Interval (PTTI) field, the RCC gives special acknowledgement to:

Mr. Clark Wardrip
Associate Representative, TTG
NASA/Goddard Space flight Center (retired)
Naval Research Laboratory (SFA, Inc.)
726 Foxwood Drive
Santa Maria, CA 93455-4221
Telephone: (805) 937-6448
E-mail: skyclark1@msn.com

Please direct any questions to:

Secretariat, Range Commanders Council
ATTN: TEDT-WS-RCC
100 Headquarters Avenue
White Sands Missile Range, New Mexico 88002-5110
Telephone: (575) 678-1107, DSN 258-1107
E-mail: usarmy.wsmr.atec.list.rcc@mail.mil

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ACRONYMS

AVAR	Allan Variance
BCD	Binary Coded Decimal
BIPM	Bureau International des Poids et Mesures
BIPM	International Bureau of Weights and Measures
DGPS	Differential GPS
Emf	Electromotive force
ESA	European Space Agency
ET	Ephemeris Time
EU	European Union
fs	Femtosecond
GLONASS	Global Orbiting Navigation Satellite System (a Russian GPS system)
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite System (a space-based navigation and timing system)
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronic Engineers
IERS	International Earth Rotation Services
IRIG	Inter-range Instrumentation Group
ITU	International Telecommunication Union
ITU-R	ITU- Radiocommunication (Sector)
JD	Julian Day or Julian Date
LF	Low Frequency
LORAN	Long Range Aid to Navigation
MCXO	microcomputer-compensated crystal oscillator
MHz	Megahertz
MJD	Modified Julian Day
MVAR	Modified Allan Variance
NIST	National Institute of Standards and Technology
ns	Nanosecond
OCVCXO	Oven controlled/voltage controlled crystal oscillator
OCXO	Oven controlled crystal oscillator
PM	Phase modulation
ps	Picosecond
PTTI	Precise Time and Time Interval
RbXO	Rubidium crystal oscillator
RCC	Range Commanders Council
RMS	Root mean squared
SI	International System of Units
TA	Atomic Time
TAI	International Atomic Time
TCVCXO	Temperature compensated/voltage controlled crystal oscillator
TCXO	Temperature Compensated Crystal Oscillator
TJD	Truncated Julian Day
TT	Terrestrial Time

TTG	Telecommunications and Timing Group
TWSTFT	Two-Way Satellite Time and Frequency Transfer
U.S.	United States
USNO	U.S. Naval Observatory
UT	Universal Time
UTC	Coordinated Universal Time
VCXO	Voltage controlled crystal oscillator
XO	Crystal oscillator

CHAPTER 1

DEFINITIONS OF FREQUENCY AND TIMING TERMS, SATELLITE NAVIGATION SYSTEMS, AND TIMING SYSTEMS

1.1 General Terms Defined

1.1.1 List of General Terms.

Accuracy
Allan Deviation
Allan Variance (AVAR)
Atomic Clock
Atomic Oscillator
Atomic Time (TA)
Binary Coded Decimal (BCD) Time Code
Bureau International des Poids et Mesures (BIPM)
Calibration
Clock
Clock Ensemble
Clock Time Difference
Coordinated Clock
Coordinated Time Scale
Coordinated Universal Time
Differential GPS (DGPS)
Disciplined Oscillator
DUT1
Ephemeris Time (ET)
Epoch
Error
Femtosecond (fs)
Fractional Frequency Difference
Fractional Frequency Offset
Frequency
Frequency Accuracy and Stability
Frequency Aging
Frequency Deviation
Frequency Difference
Frequency or Phase Jitter
Frequency Offset
Frequency Shift
Frequency Standard
Galileo
Global Positioning System (GPS)
GPS Common-View
GLONASS
Global Navigation Satellite System (GNSS)
Greenwich Mean Time (GMT)
IEEE 1588
International Atomic Time (TAI)
Jitter
Julian Day of Julian Date (JD)
Leap Second
Leap Year
Long Range Aid to Navigation (LORAN-C)
Mean Solar Time
Microsecond
Millisecond
Modified Allan Variance (MVAR)
Modified Julian Day (MJD)
Nanosecond (ns)
National Institute of Standards and Technology (NIST)
Nominal Value
Offset
On-time
Phase
Phase Coherence
Phase Deviation
Phase Jump
Phase Shift
Phase Signature
Picosecond (ps)
Primary Frequency Standard
Precise Time and Time Interval (PTTI)
Resolution of a Time Code
Second
Secondary Frequency Standard
Sidereal Time
Solar Time
Stratum Clock Family
Stratum 0 Clock
Stratum 1 Clock
Stratum 2 Clock
Stratum 3 Clock
Stratum 4 Clock
Terrestrial Time
Time Code
Time Code Generator
Time Comparison
Time Interval
Time Marker
Time Reference
Time Scale
Time-scales in Synchronism
Time Standard
Time Step
Truncated Julian Day (TJD)
Two-Way Satellite Time and Frequency Transfer (TWSTFT)
Uncertainty
Universal Time (UT) Family
U.S. Naval Observatory (USNO)
Zulu Time

1.1.2 Definitions of General Terms.

Accuracy: The degree of conformity of a measured or calculated value to its definition. Accuracy is related to the offset from an ideal value. In the world of time and frequency, accuracy is used to refer to the time offset or frequency offset of a device. For example, time offset is the difference between a measured on-time pulse and an ideal on-time pulse that coincides exactly with Coordinated Universal Time (UTC). Frequency offset is the difference between a measured frequency and an ideal frequency with zero uncertainty. This ideal frequency is called the nominal frequency.

Allan Deviation: The standard method of characterizing the frequency stability of oscillators in the time domain (both short and long term). This statistical method is sometimes called the Allan Variance, but since it is the square root of the variance, its proper name is Allan Deviation. The equation for the Allan Deviation for a finite sample set is given below.

$$\sigma_y\,(\tau) = \sqrt{\frac{1}{2(M-1)}\ \sum_{i=1}^{M-1}(y_{i+1} - y_i)^2}$$

$$\sigma_y\,(\tau) = \sqrt{\frac{1}{2(M-1)}\ \sum_{i=1}^{M-1}(y_{i+1} - y_i)^2}$$

Where:

M = the number of samples.
Y = the fractional frequency averaged over the time interval τ.

Note: all averaged fractional frequency values are from adjacent measurements.

Allan Variance (AVAR): Allan Variance is the Allan Deviation squared (see Figure 2-12). The equation for the Allan Variance is given below.

$$\sigma_y^2(\tau) = \frac{1}{2(M-1)}\ \sum_{i=1}^{M-1}(y_{i+1} - \ y_i)^2$$

Where:

M = the number of samples.
Y = the fractional frequency averaged over the time interval τ.

Note: all averaged fractional frequency values are from adjacent measurements.

Atomic Clock: A clock that is referenced to an atomic oscillator. The only clocks that qualify as atomic clocks are those having an internal atomic oscillator. However, the term is sometimes used to refer to radio clocks that receive a signal referenced to an atomic oscillator at a remote location such as the National Institute of Standards and Technologies (NIST) radio stations WWV and WWVB, with transmissions on 100 kHz.

Atomic Oscillator: An oscillator that uses the quantized energy levels in atoms or molecules as the source of its resonance. An electromagnetic field at a particular frequency can boost an atom from one energy level to a higher one. Conversely, an atom at a high energy level can drop to a lower level by emitting energy. The resonance frequency (*f*) of an atomic oscillator is the difference between the two energy levels divided by Planck's constant (*h*).

$$f = \frac{E_2 - E_1}{h}$$

In theory, the atom is a perfect "pendulum" whose oscillations are counted to measure time interval. The first atomic oscillator was developed in 1949 by the NIST, which was previously the National Bureau of Standards (NBS). The oscillator's resonance frequency was derived from an absorption line in the ammonia molecule. The NIST national frequency standards derive their resonance frequency from the cesium atom, and use cesium beam or cesium fountain technology. NIST has used several other atoms to build experimental atomic standards, including mercury and calcium. Rubidium standards are the lowest priced and most common atomic standards, but cesium beam and hydrogen maser atomic standards are also sold commercially.

Atomic Time (TA) scale: A time scale based on atomic or molecular resonance phenomena. Elapsed time is measured by counting cycles of an atomic frequency standard source (i.e. cesium standard) rather than on the earth's rotation. Coordinated Universal Time (UTC) is an atomic time scale, since it defines the second based on the transitions of the cesium atom.

Binary Coded Decimal (BCD) Time Code: A code, usually digital, that contains sufficient binary bits to convey enough information to determine UTC time. The code may contain year, day of year, hours, minutes, seconds, and fractions of seconds. A list of Inter-range Instrumentation Group (IRIG) serial time code documents can be found at the RCC web site. At the present time, the web site is being relocated and the reader should contact the RCC Secretariat for site-access information.

Bureau International des Poids et Mesures (BIPM): The BIPM (International Bureau of Weights and Measures) is located near Paris, France. The task of the BIPM is to ensure worldwide uniformity of measurements and their traceability to the International System of Units (SI). The BIPM averages data from about 50 laboratories, including NIST and the U.S. Naval Observatory (USNO), to produce a time scale called International Atomic Time (TAI). When corrected for leap seconds, TAI becomes UTC, or the true international time scale. The BIPM publishes the time offset or difference of each laboratory's version of UTC relative to the international average. For example, the BIPM publishes the time offset between UTC and UTC (NIST) and UTC (USNO). The work of the BIPM makes it possible for laboratories to adjust their standards so that they agree more closely with the true international time scale.

Calibration: The process of identifying and measuring time or frequency errors, offsets, or deviations of a clock/oscillator relative to an established and accepted time or reference frequency standard such as UTC(USNO) or UTC(NIST).

Clock: A device for maintaining and displaying time. The frequency standard is the rate generator and the "clock" is the accumulator and displayer of time.

Clock Ensemble: A collection of clocks, not necessarily in the same physical location, operated together in a coordinated way to maximize the performance of a time scale (time accuracy and frequency stability).

Clock Time Difference: The difference between the readings of two clocks at the same instant. To avoid confusion in sign, algebraic quantities are given using the following convention:

> At time T of a reference time scale,
>   let $\underline{a}$ denote the reading of the time scale A,
>   let $\underline{b}$ denote the reading of the time scale B,
> Then,
>   The time scale difference is expressed by $A - B = \underline{a} - \underline{b}$ at time T.
>
> Note: The same convention applies to the case in which A and B are clocks. Therefore a positive difference between A and B indicates that A was ahead of (earlier than) B.

Coordinated Clock: A clock synchronized within stated limits to a spatially separated reference clock.

Coordinated Time Scale: A time scale synchronized within stated limits to a reference time scale.

Coordinated Universal Time (UTC): The international atomic time scale that serves as the basis for timekeeping for most of the world; UTC is a 24-hour timekeeping system. The hours, minutes, and seconds expressed by UTC represent the time-of-day at the earth's prime meridian (0° longitude) located near Greenwich, England. Leap seconds are added or subtracted to the UTC scale to keep in synchronism with UT1 to within ± 0.9 seconds. UTC is maintained by the BIPM.

Differential Global Positioning System (DGPS): A way to improve the accuracies of the received Global Positioning System (GPS) measurements for a user whose GPS receiver has the capability to receive and apply the transmitted DGPS corrections. The underlying premise of DGPS is that any two receivers that are relatively close together, within a few hundred kilometers, will experience similar atmospheric errors. Differential GPS requires that a GPS receiver be set up on a precisely known location and designated the base or reference station. The base/reference station receiver calculates its position based on received GPS satellite signals and compares the computed location to the known location. The difference (correction) is transmitted from the base station to a second GPS receiver, known as the roving receiver, in order to correct its measurements. The corrected information can be applied to data from the roving receiver either in real time, in the field, or through post-processing to provide improved accuracy.

Disciplined Oscillator: An oscillator with a servo loop that has its phase and frequency locked to an external reference signal with a memory of the last sampled reference frequency. If the reference frequency is temporarily unavailable, the phase and frequency of the oscillator will continue in close agreement with the extrapolated reference.

DUT1: The predicted difference between UT1 and UTC, calculated as DUT1 = UT1-UTC. The values of DUT1 are given by the International Earth Rotation Services (IERS) in integral multiples of 0.1s. The magnitude of DUT1 should not exceed ±0.9 s

Ephemeris Time (ET): An obsolete time scale based on the ephemeris second, which served as the SI second from 1956 to 1967. Used mainly by astronomers, ET was replaced by Terrestrial Time (TT) in 1984.

Epoch: An epoch signifies the beginning of an era (or event) or the reference date of a system of measurements.

Error: The difference of a measured value from the true or correct value.

Femtosecond (fs): One quadrillionth of a second (10^{-15} s).

Fractional Frequency Difference: The ratio of the difference between the actual frequency (f_1) and the nominal frequency (f_2) divided by the nominal frequency, expressed as:

$$\frac{\Delta f}{f} = \left(\frac{f_1 - f_2}{f_2} \right)$$

Fractional Frequency Offset: The level of agreement of the frequency of a clock with the ideal frequency. Alternatively, a measure of the deviation of the frequency of a signal from the reference, expressed as a ratio:

$$|(f - fr)/ fr|$$

Where:

f = the actual frequency output of signal.

fr = the reference frequency.

Frequency: The rate at which a repetitive phenomenon occurs over time. If T is the period of a repetitive phenomenon, then the frequency is $f = 1/T$. In the SI, the period is expressed in seconds (s) and the frequency in hertz (Hz). One hertz equals the repetitive occurrence of one “event” per second.

Frequency Accuracy and Stability: The concepts of frequency accuracy and frequency stability are often not well understood. An oscillator can be very accurate but have high instability. In this case, at any given moment the oscillator's frequency could be slightly inaccurate. However, for long time periods, its average frequency would be highly accurate. Conversely, an oscillator could be slightly inaccurate and very stable. In this case, one would have high confidence in knowledge of the instantaneous frequency, even if it were not at the preferred nominal frequency. An oscillator with lesser frequency accuracy and better frequency stability is often preferred over one with better frequency accuracy and lesser frequency stability because it is relatively easy to compensate for accuracy errors and more difficult to compensate for random frequency fluctuations. See Figure 2-1 for a pictorial presentation.

Frequency Aging and Frequency Drift: Frequency Aging is the systematic change in frequency with time due to internal changes in the oscillator. Aging is the frequency change when factors external to the oscillator are kept constant. Aging has many possible causes including buildup of foreign material on the crystal, changes in electronics or changes in the quartz material or crystal structure. Frequency drift is what is observed and aging is the underlying, internal part of what is observed. Frequency drift is due to aging plus external changes such as environment, power supply, and other changes. In practice, it is very difficult to separate the causes of aging and drift.

Frequency Deviation: The difference between frequency values of the same signal at two different times or between the instantaneous signal frequency and the average signal frequency.

Frequency Difference: The difference between frequency values of two different signals.

Frequency or Phase Jitter: The abrupt and unwanted variations of one or more signal characteristics, such as the interval between successive pulses, the amplitude of successive cycles, or the frequency or phase of successive cycles. Although widely used in fields such as telecommunications, the term jitter is seldom used in time and frequency metrology, since terms such as phase noise are more descriptive.

Frequency Offset: The frequency difference between the realized value and a reference frequency value.

Frequency Shift: An intentional (or unintentional) change in frequency from a reference.

Frequency Standard: A precise frequency generator that normally uses the quantized energy levels in atoms or molecules as the source of its resonance to discipline a crystal oscillator, which provides accurate and stable frequency signals. A high quality free-running crystal oscillator can also be a frequency standard.

Galileo: A joint program by the European Union (EU) and the European Space Agency (ESA) that provides a space-based radio-navigation system for position and timing information. The system is similar to the Global Positioning System (GPS) is available to users worldwide.

Global Positioning System (GPS): A space-based radio-navigation system that nominally consists of a minimum constellation of 24-satellites that provides navigation and timing information to military and civilian users worldwide. GPS is controlled, operated and maintained by the United States (U.S.) Department of Defense (DoD) and consists of three segments (space, control, and user).

GPS Common-View: A measurement technique used to compare two clocks or oscillators. The common-view method involves a single reference transmitter (R) (i.e. GPS satellite) and two receivers (A and B), each referenced to a local clock. The transmitter (GPS satellite) is in common view of both receivers. Both receivers compare the simultaneously received signal to their local clock and record the data. Receiver A receives the signal over the path d_{ra} and compares the reference to its local clock (R - Clock A). Receiver B receives the signal over the path d_{rb} and records (R - Clock B). Errors from the two paths d_{ra} and d_{rb} that are common to the reference cancel out, and the uncertainty caused by path delay is nearly eliminated. The result of the measurement is (Clock A - Clock B) - (d_{ra} - d_{rb}). This method enables clocks to be compared over short or transcontinental distances, with uncertainties of just a few nanoseconds.

Global Navigation Satellite System (GNSS): A space-based navigation and timing system. Examples of a GNSS include GPS, Galileo, and GLONASS.

Global Orbiting Navigation Satellite System (GLONASS): A space-based navigation and timing system that is similar to the GPS and is operated by the Russian Space Forces. The GLONASS system was officially declared operational on September 24, 1993.

Greenwich Mean Time (GMT): A 24-hour time keeping system whose hours, minutes, and seconds represent the time-of-day at the earth's prime meridian (0° longitude) located near Greenwich, England. Technically speaking, GMT no longer exists since it was replaced by other astronomical time scales many years ago. Those astronomical times scales were superseded by the atomic time scale UTC in 1992. However, the term GMT is still used incorrectly by the public. When heard today, it should be considered as a synonym for UTC (and also Zulu time).

Institute of Electrical and Electronic Engineers (IEEE) 1588: Addresses the clock synchronization requirements of measurement and control systems. The objective of IEEE 1588 is defined in the 'Scope' section of the Project Authorization Request approved by the Standard Board of the IEEE as follows:

> *"This standard defines a protocol enabling precise synchronization of clocks in measurement and control systems implemented with technologies such as network communication, local computing and distributed objects. The protocol will be applicable to systems communicating by local area networks supporting multicast messaging including but not limited to Ethernet. The protocol will enable heterogeneous systems that include clocks of various inherent precision, resolution and stability to synchronize. The protocol will support system-wide synchronization accuracy in the sub-microsecond range with minimal network and local clock computing resources. The default behavior of the protocol will allow simple systems to be installed and operated without requiring the administrative attention of users."*

International Atomic Time (TAI): An atomic time scale based on data from a worldwide set of clocks and is the internationally agreed to time reference. The TAI is maintained by the BIPM in Paris, France, the USNO, and other national observatories and laboratories. Its epoch was set such that TAI was in approximate agreement with UT1 on 1 January 1958. The TAI accumulates at 86,400 seconds per day.

Jitter: The short-term phase variations of timing signals from their ideal position in time.

Julian Day or Julian Date (JD): An integer day number obtained by counting days from the starting point of noon on 1 January 4713 B.C. (Julian Day zero). It is one way of telling what day it is with the least possible ambiguity. The Modified Julian Date (MJD) has a starting point of midnight on November 17, 1858. You can obtain the MJD by subtracting exactly 2,400,000.5 days from the JD.

Leap Second: Civil time is occasionally adjusted by one-second increments to insure that the difference between the uniform time-scales defined by TAI and UTC do not differ from the earth's rotational time by more than 0.9 seconds. To date, 37 leap seconds have been added to keep UTC in synchronization with the rotation of the earth. In 1980, when the GPS became operational, it was synchronized to UTC. However, GPS time does not add leap seconds, and consequently, as of 2008, GPS time is fourteen seconds ahead of UTC. If required, leap seconds are added on December 31 and on June 30 at one second after 23:59:59 hours to 00:00:00.

Leap Year: According to the Gregorian calendar, which is the civil calendar in use today, years that are evenly divisible by four (4) are leap years with the exception of century years that are not evenly divisible by 400. This means that years 1700, 1800, 1900, 2100, 2200, 2300 and 2500 are NOT leap years and that years 1600, 2000, and 2400 are leap years. To summarize:

a. Every year that is divisible by four is a leap year;

b. of those years, if it can be divided by 100, it is not a leap year, unless

c. the year is divisible by 400, then it is a leap year.

Long Range Aid to Navigation, Version C (LORAN-C): A ground based radio navigation system that operates in the low frequency (LF) radio spectrum at a carrier frequency of 100 kHz, with a bandwidth from 90 to 110 kHz. LORAN-C broadcasts are referenced to cesium frequency standards and are widely used as a source for frequency calibrations. It is also possible to synchronize a LORAN-C receiver so that it produces an on-time UTC pulse. However, the broadcast does not contain a time code, so time-of-day cannot be recovered using LORAN-C. Typical timing accuracies using LORAN-C are 1µs, and 50 to 200 nanoseconds root mean squared (RMS).

Mean Solar Time: Apparent solar time corrected for the effects of orbital eccentricity and the tilt of the earth's axis relative to the ecliptic plane; the correction is made by a mathematical formula known as the equation of time. The equation of time is defined as the hour angle of the true sun minus the hour angle of the mean sun.

Microsecond (µs): One millionth of a second (10^{-6} s).

Millisecond (ms): One thousandth of a second (10^{-3} s).

Modified Allan Variance (MVAR): Modified Allan Variance was introduced to further distinguish noise processes for the normal Allan Variance. The MVAR is the same as the normal Allan variance (AVAR) except that it includes an additional phase-averaging operation and has the advantage of being able to distinguish between white and flicker phase modulation (PM) noise. In addition, the time deviation measurements are averaged with each interval equal to *t*. The confidence interval of an MVAR determination is also dependent on the noise type. The equation for MVAR is:

$$\sigma_y^2(\tau) = \frac{1}{2}\left(\overline{y_{i+1} - y_i}\right)^2$$

Where:

y = the fractional frequency averaged over the time interval τ.

Note: all averaged fractional frequency values are from adjacent fractional frequency periods.

Modified Julian Day (MJD): The number of days that have elapsed since midnight at the beginning of Wednesday, November 17, 1858. The MJD is often more useful than conventional calendar dates for record keeping over long periods of time, since the MJDs of two events can easily be subtracted to determine the time difference in days. Usually, the MJD is specified as a number with five significant digits. For example, the MJD for 1 January 1995 is 49718, meaning that this many days have elapsed between 17 November 1858 and 1 January 1995. In terms of the Julian day:

MJD = JD - 2,400,000.5

Nanosecond (ns): One billionth of a second (10^{-9} s).

National Institute of Standards and Technology (NIST): An agency of the U.S. Department of Commerce that maintains the primary frequency standard for the U.S. in the Time and Frequency Division in Boulder, Colorado. The Division maintains advanced measurement and calibration facilities, and is involved with extensive research and development of atomic frequency standards such as cesium fountains.

Nominal Value: The expected value of a measurement or property when operating in a normal expected environment. For example, the nominal value of a 51 ohm, 20% resistor operating at room temperature is 51 ohms. However, the actual resistance of any single 51 ohm, 20% resistor may be any value between 46 and 56 ohms.

Offset: The difference between the realized value and a reference value.

On Time: The state of any bit (in a time code) being coincident with the standard time reference (i.e. UTC, TAI, etc.).

Phase: A measure of a fraction of the period of a repetitive phenomenon, measured with respect to some distinguishable feature of the phenomenon itself.

Phase Coherence: Phase coherence exists if two periodic signals of frequency M and N resume the same phase difference after M cycles of the first and N cycles of the second, where M/N is a rational number.

Phase Deviation: The difference of the phase from a reference.

Phase Jump: A sudden phase change in a signal.

Phase Shift: An intentional (or unintentional) change in phase from a reference.

Phase Signature: A deliberate phase offset to identify a signal. For example, NIST's radio station WWVB broadcast is deliberately phase shifted at 10 minutes after the hour, so a person knows that he is tracking the WWVB signal as opposed to a different signal.

Picosecond (ps): One trillionth of a second (10^{-12} s).

Primary Frequency Standard: A standard whose frequency corresponds to the adopted definition of the second with its specified accuracy achieved without external calibration of the device. The cesium standard can be a primary frequency standard since the SI second is defined from the resonance frequency of the cesium atom (^{133}Cs), which is 9,192,631,770 Hz. This defines the second. However, special laboratory standards such as the long tube cesiums and the cesium fountains are also defined as primary standards.

Precise Time and Time Interval (PTTI): The accepted term for Time and Frequency.

Resolution of a Time Code: The smallest increment of time or least significant bit that can be defined by a time code word or sub-word.

Second: The basic unit of time or time interval in the International System of Units (SI) that is equal to the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium-133 atom.

Secondary Frequency Standard: A frequency standard that requires external calibration. For example, a crystal oscillator is considered a secondary frequency standard.

Sidereal Time: In general terms, the measure of time defined by the apparent diurnal motion of the vernal equinox; hence, it is a measure of the rotation of the earth with respect to the reference frame that is related to the stars rather than the sun. Two types of sidereal time are used in astronomy (mean sidereal time and apparent sidereal time). A mean sidereal day is approximately 23 hours, 56 minutes, and 4.090 seconds of mean solar time. In addition, a solar year contains 366.2422 sidereal days, equal to 365.2422 mean solar days.

Solar Time: A measure of time defined by the apparent diurnal motion of the sun. There are two types of solar time: apparent solar time and mean solar time. The mathematical formula to convert the local solar time into local mean solar time is known as the equation of time.

Stratum Clock Family: The accuracy requirements placed on frequencies in five stratum levels. The accuracy of stratum frequencies refers to "clocking" performance when the communications device receives no input reference frequency.

> **Stratum 0:** The Master Clock ensemble located at the USNO with inputs from GPS.
>
> **Stratum 1:** A clocking source with an inherent frequency accuracy equal to or greater than $1x10^{-11}$. A true Stratum 1 source shall maintain Stratum 1 accuracy for days to weeks without reference (or discipline) to another frequency source. GPS receivers are often incorrectly called Stratum 1 sources. If the GPS receiver cannot maintain Stratum 1 accuracy without its reference signal(s) (i.e. signals from GPS satellites), it is not a Stratum 1 accuracy source.
>
> **Stratum 2:** A clocking source that has, or can be adjustable to, a free running minimum frequency accuracy of $1.6x10^{-8}$. The Stratum 2 clocking source should be capable of being frequency disciplined to a Stratum 1 clocking source and provide essentially Stratum 1 performance while disciplined. If the external reference is not available or fails, the clock shall detect this absence of signal and enter into a holdover mode, where it maintains at least Stratum 2 accuracy.
>
> **Stratum 3:** A clocking source that has or can be adjustable to a free running minimum frequency accuracy of $4.6x10^{-6}$. The Stratum 3 clocking source should be capable of being frequency disciplined to a Stratum 1 or Stratum 2 clocking source and provide essentially Stratum 1 or Stratum 2, performance while disciplined. If the external reference is not available or fails, the clock shall detect this absence of signal and enter into a holdover mode, where it maintains at least Stratum 3 accuracy.
>
> **Stratum 4:** A clocking source that has or can be adjustable to a free running minimum frequency accuracy of $3.2x10^{-5}$. The Stratum 4 clocking source should be capable of being frequency disciplined to a Stratum 1, 2 or 3 clocking source and provide essentially Stratum 1, 2 or 3, performance while disciplined. If the external reference is not available or fails, the clock shall detect this absence of signal and enter into a holdover mode, where it maintains at least the Stratum 4 accuracy.

Terrestrial Time (TT): An astronomical time scale that equals approximately TAI + 32.184 s. The uncertainty of TT is ± 10 microseconds. In 1984, TT replaced the now obsolete Ephemeris Time scale.

Time Code: A system of symbols (digital or analog) used for identifying specific instants of time. This system is an information format used to convey time information.

Time Code Generator: Instrumentation that outputs time coded signals. Normally, this instrumentation includes the ability to be synchronized to an external source and accepts (or contains) a high quality frequency source.

Time Comparison: The determination of a time or time-scale difference.

Time Interval: The duration between two time instants read on the same time scale.

Time Marker: A reference event enabling the assignment of the date and time on a time scale.

Time Reference: The basic repetition rate chosen as the common time reference for all instrumentation in a system.

Time Scale: A reference system for specifying occurrences with respect to time. A system of unambiguous ordering of events. A time scale is meant to be stable and homogeneous.

Time Scale Difference: The difference between the readings of two time scales at the same instant. See Clock Time Difference

Time Scales in Synchronism: Two time scales are in synchronism when they assign the same time to an instant. If the time scales are produced in spatially separated locations, the propagation time of transmitted time signals and relativistic effects, including the reference coordinate frame, are taken into account.

Time Standard: A continuously operating device used for the realization of a time scale in accordance with the definition of the second and with an appropriately chosen origin.

Truncated Julian Day (TJD): Introduced by the National Aeronautics and Space Administration (NASA) for the space program. The TJD was zero at midnight UT at the beginning of May 24, 1968. It has a repetition period (recycle time) of 10,000 days (27.379 years) and first recycled on 9 October 1995. TJD defined by NASA as:

$$\text{TJD} = \text{JD} - 2440000.5 \bmod 10000$$

> This calculation was chosen so the number would resemble the MJD but be only four digits long. TJD exceeded four digits on October 10, 1995, and NASA now uses five digit TJDs. In the NASA scheme, at midnight April 2, 2007, TJD was 14192.838391.

Two-Way Satellite Time and Frequency Transfer (TWSTFT): Time and frequency difference determination of two ground stations (often separated by many hundreds of miles), utilizing a geostationary satellite. This is also commonly called Two Way Satellite Time Transfer (TWSTT).

Uncertainty: The limits of the confidence interval of a measured or calculated quantity. Note: The probability of the confidence limits should be specified, preferably by the 1 sigma value.

U.S. Naval Observatory (USNO): The official source for time for the DoD and the GPS. The USNO time scale, UTC(USNO), is based on an ensemble of atomic clocks that include cesium frequency standards and hydrogen masers. The UTC(USNO) is usually kept within 10 nanoseconds of UTC.

Universal Time (UT) Family: Before the acceptance of atomic time scales such as TAI and UTC in the 1960s, astronomical time scales were used for everyday timekeeping. These time scales are still used today, but mostly for applications related to astronomy. They are based on mean solar time. The mean solar second is defined as 1/86,400 of the mean solar day, where 86,400 is the number of seconds in the mean solar day. This mean solar second provides the basis for Universal Time (UT). Several variations of UT have been defined:

- **UT0:** The original mean solar time scale, based on the rotation of the earth on its axis. The UT0 scale was first kept by pendulum clocks. As better clocks based on quartz oscillators became available, astronomers noticed errors in UT0 due to polar motion, which led to development the UT1 time scale.
- **UT1:** The most widely used astronomical time scale, UT1 is an improved version of UT0 that corrects for the shift in longitude of the observing station due to polar motion. Since the earth’s rate of rotation is not uniform, UT1 is not completely predictable, and has an uncertainty of +/- 3 milliseconds per day.
- **UT2:** Mostly of historical interest, UT2 is a smoothed version of UT1 that corrects for known deviations in the earth’s rotation caused by angular momenta of the earth’s core, mantle, oceans, and atmosphere.

Zulu Time: A term sometimes used in the military and in navigation as a synonym for UTC or GMT. In military shorthand, the letter Z follows a time expressed in UTC. Zulu time is not an official time scale. The term originated because the word “zulu” is the radio transmission articulation for the letter Z, and the time zone located on the prime meridian is designated on many time zone maps by the letter Z.

1.2 Time Codes Defined

1.2.1 List of Time Codes.

Binary coded decimal
Binary number system
Bit
Bit transition time
Identification bits (ID)
Inhibit/read bit
IRIG Time Codes
IRIG Time Code Standards
Parity bit

Sub-Word
Time
Time Code
Time Code Word
Time Frame
Time Interval
Time Reference
Time T0

1.2.2 Definitions of Time Codes.

Binary Coded Decimal: A numbering system that uses decimal digits encoded in a binary representation.

Binary Number System: A numbering system that has two as its base and uses two symbols, usually denoted by 0 and 1.

Bit (Binary + Digit): A fundamental unit of information having just two possible values, either binary 1 or a binary 0.

Bit Transition Time: The time required for a bit in the time code or sub-word to change from one logic level to the next such as a logic 0 to a logic 1 or vice versa.

Identification (ID) Bits: Bits with a fixed state (logic level) used for time-code identification information.

Inhibit/read Bit: A bit, generated with the time code, that can be used to prohibit a user from reading the code during the time code update.

Parity Bits: The confidence bits derived from and generated with the bits in the time code word or sub-word.

Sub-word: A subdivision of the time code word containing only one type of time unit such as days, milliseconds, or microseconds.

Time: Signifies epoch, which is the designation of an instant of time on a selected time scale such as astronomical, atomic, or UTC.

Time Code: A system of symbols used for identifying specific units of time.

Time Code Word: A specific set of time code symbols that identifies one instant of time. A time code word may be subdivided into sub-words.

Time Frame: The time interval between consecutive reference markers that contains all the bits that determine the time code format.

Time Interval: The duration between two instants read on the same time scale, usually expressed in seconds or in a multiple or sub multiple of a second.

Time Reference: The basic repetition rate chosen as the common time reference for all instrumentation timing (usually 1pps).

Time T_0: The initial time $0^h\ 0^m\ 0^s$, January 1, or the beginning of an epoch.

1.3 IRIG Time Codes and Standards.

1.3.1 IRIG Time Codes.

The time codes originally developed by the former Inter-Range Instrumentation Group (IRIG), are now maintained by the Telecommunications and Timing Group (TTG) of the Range Commanders Council (RCC), and are used in government, military and commercial fields. There are many formats and several modulation schemes, but they are typically amplitude modulated on an audio sine wave carrier. The most common version is probably IRIG-B, which sends year, day of year, hour, minute, and second data on a 1 kHz carrier frequency, with an update rate of once per second. For a list of all RCC standards and TTG (IRIG) time codes, go to the RCC web site to find and download documents; however, the public web site is currently being upgraded and the reader should contact the RCC Secretariat office for site-access information.

1.3.2 IRIG Time Code Standards.

The IRIG Time Code Standards are listed below. BCD minimum design goal standards are shown in Table 1-1.

a. 200-04 IRIG Serial Time Code Formats.

b. 204-96 Instrumentation Timing Systems.

c. 205-87 IRIG Standard Parallel Binary and Parallel Binary Coded Decimal Time Code Formats.

d. 209-90 Event Count Status Code Formats.

e. 212-00 IRIG J Asynchronous ASCII Time Code Formats.

f. 214-09 Glossary of Frequency and Timing Terms and a Pictorial Representation of terms used in the Behavior and Analysis of Frequency Standards (this document).

TABLE 1-1. TIME CODE GENERATOR HARDWARE: MINIMUM DESIGN CONSIDERATIONS

IRIG Serial Time Codes	Level (dc) Pulse Rise Time Between the 10% and 90% Amplitude Points	Jitter: Modulated at Carrier Frequency	Jitter: Level (dc) Shift, Pulse-to-Pulse
Format A	≤ 200 ns	≤1%	≤100 ns
Format B	≤ 1 µs	≤1%	≤200 ns
Format D	≤ 1 µs	≤1%	≤200 ns
Format E	≤ 1 µs	≤ 1%	≤200 ns
Format G	≤ 20 ns	≤ 1%	≤ 20 ns
Format H	≤ 1 µs	≤1%	≤200 ns

CHAPTER 2

THE BEHAVIOR AND ANALYSES OF PRECISION CRYSTAL AND ATOMIC FREQUENCY STANDARDS AND THEIR CHARACTERISTICS

Below are links to a series of diagrams, illustrations, and narratives to describe and clarify the behavior and analysis of precision crystal and atomic frequency standards and their characteristics.

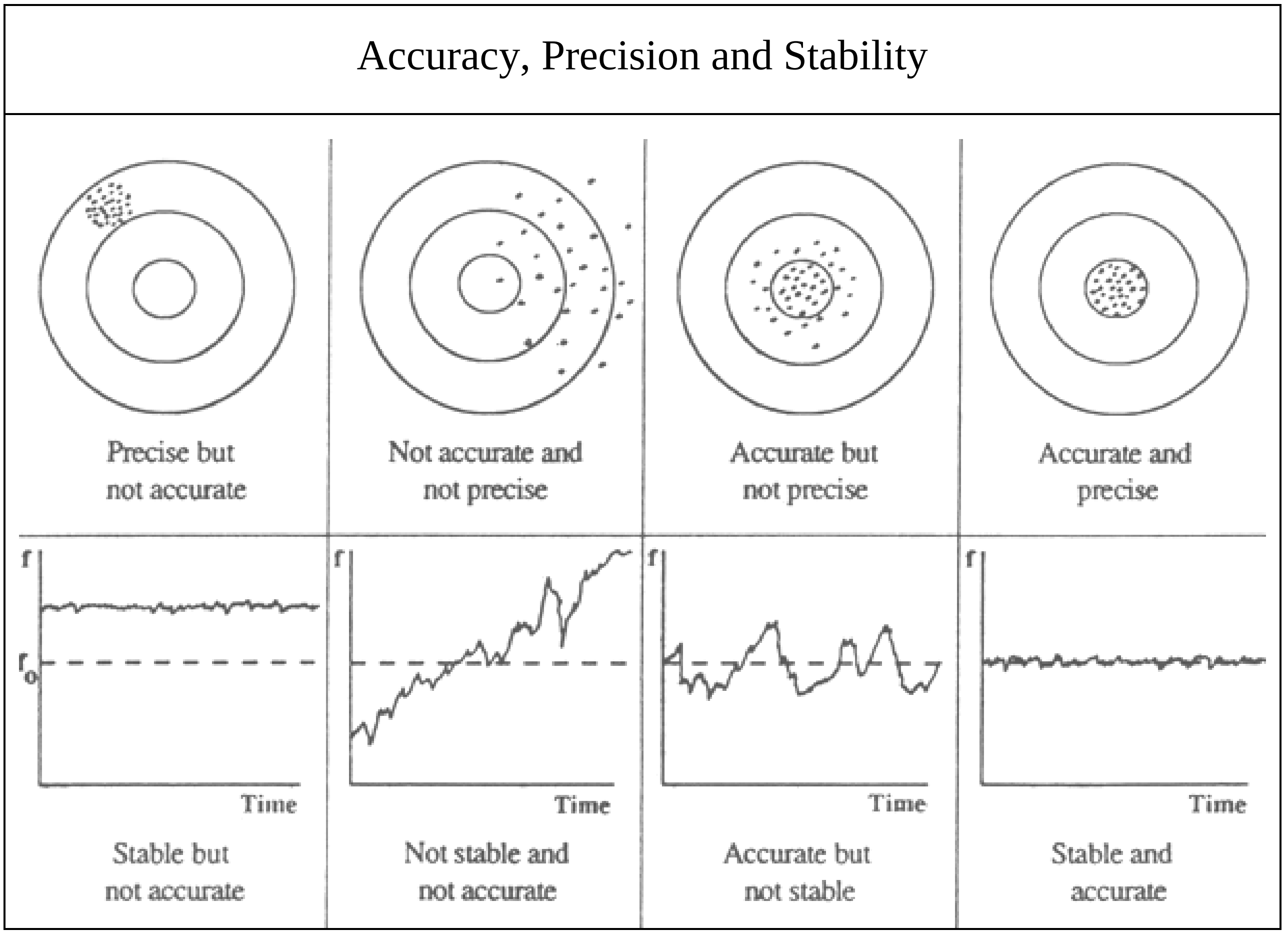
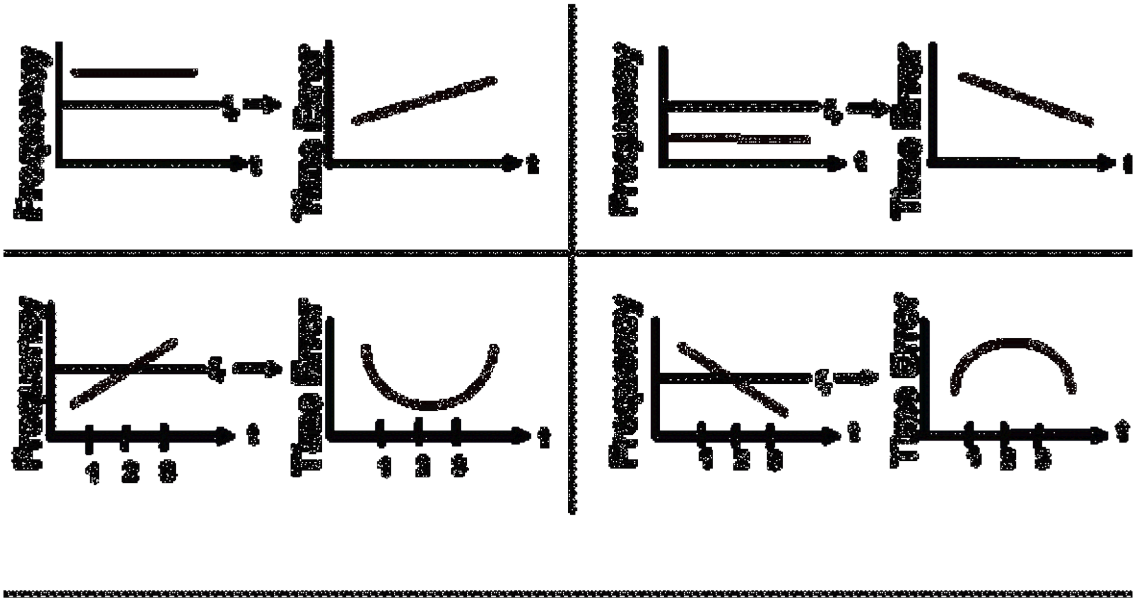

Accuracy, Precision and Stability

Figure 2-1. Accuracy, precision, and stability.

Frequency Error Versus Time Error



f_r = reference (i.e., the "correct") frequency

Figure 2-2. Frequency error versus time error.

Influences on Oscillator Frequency

- **Time**
    - Short term (noise) Intermediate term (e.g., due to oven fluctuations)
    - Long term (aging)
- **Temperature**
    - Static frequency vs. temperature
    - Dynamic frequency vs. temperature (warm-up, thermal shock)
    - Thermal history ("hysteresis," "retrace")
- **Acceleration**
    - Gravity (2g tipover)
    - Acoustic noise
    - Vibration
    - Shock
- **Ionizing radiation**
    - Steady state
    - Photons (X-rays, γ-rays)
    - Pulsed
    - Particles (neutrons, protons, electrons)
- **Other**
    - Power supply voltage
    - Humidity
    - Magnetic field
    - Atmospheric pressure (altitude)
    - Load impedance

Figure 2-3. Influences on oscillator frequency.

Idealized Frequency-Time-Influence Behavior

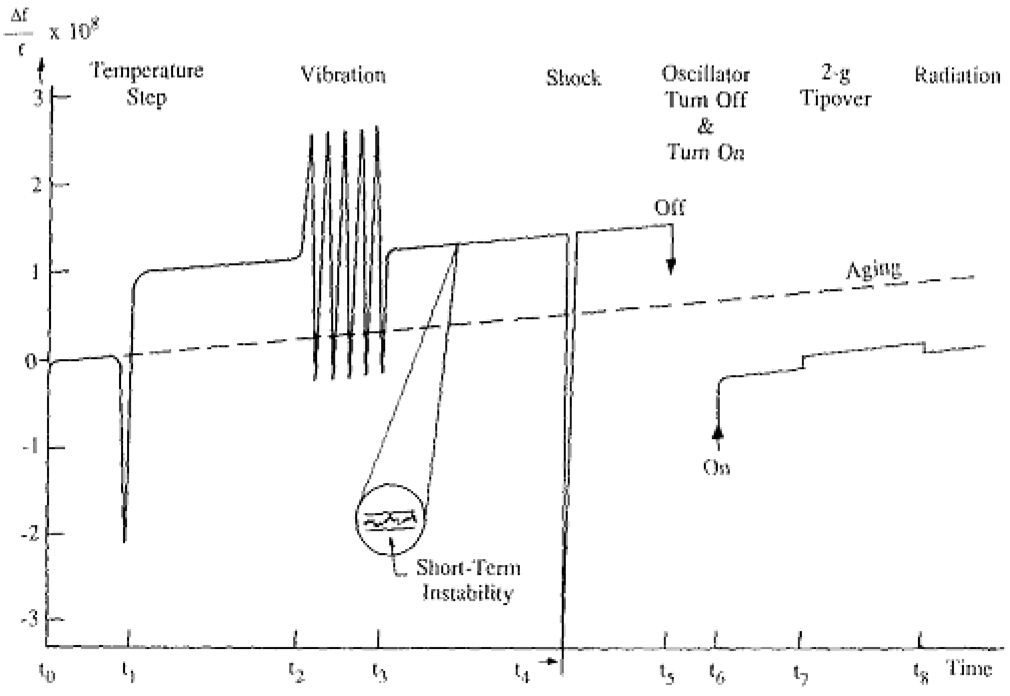


Figure 2-4. Idealized frequency-time-influence behavior.

Aging and Short-Term Stability

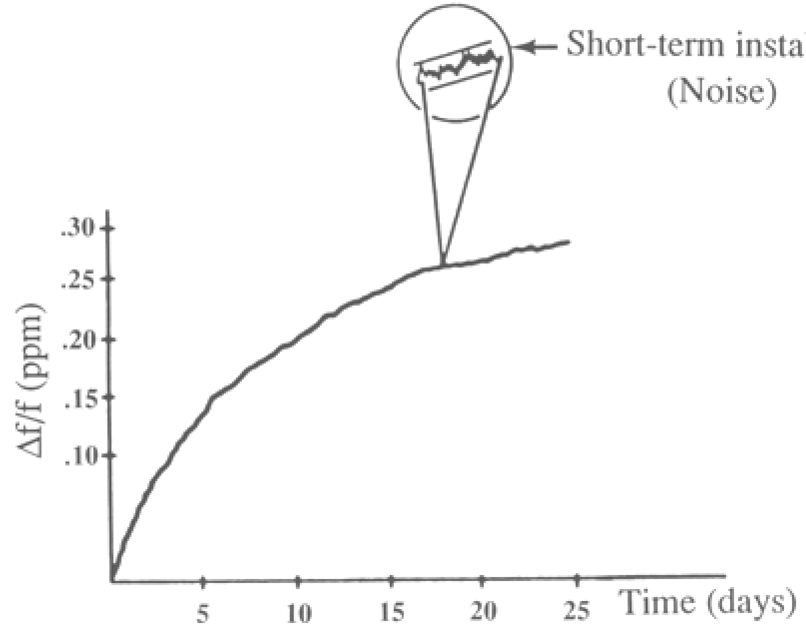
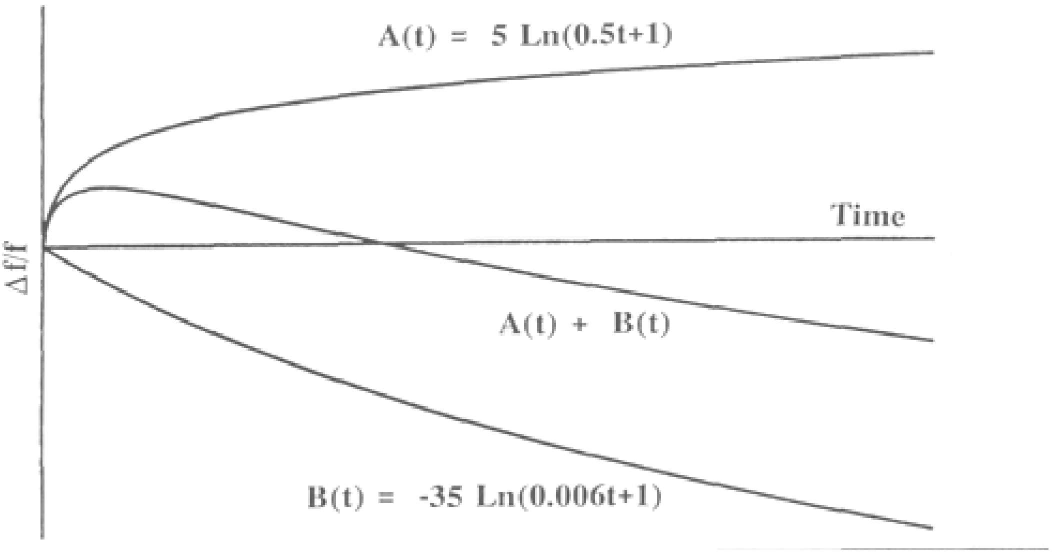


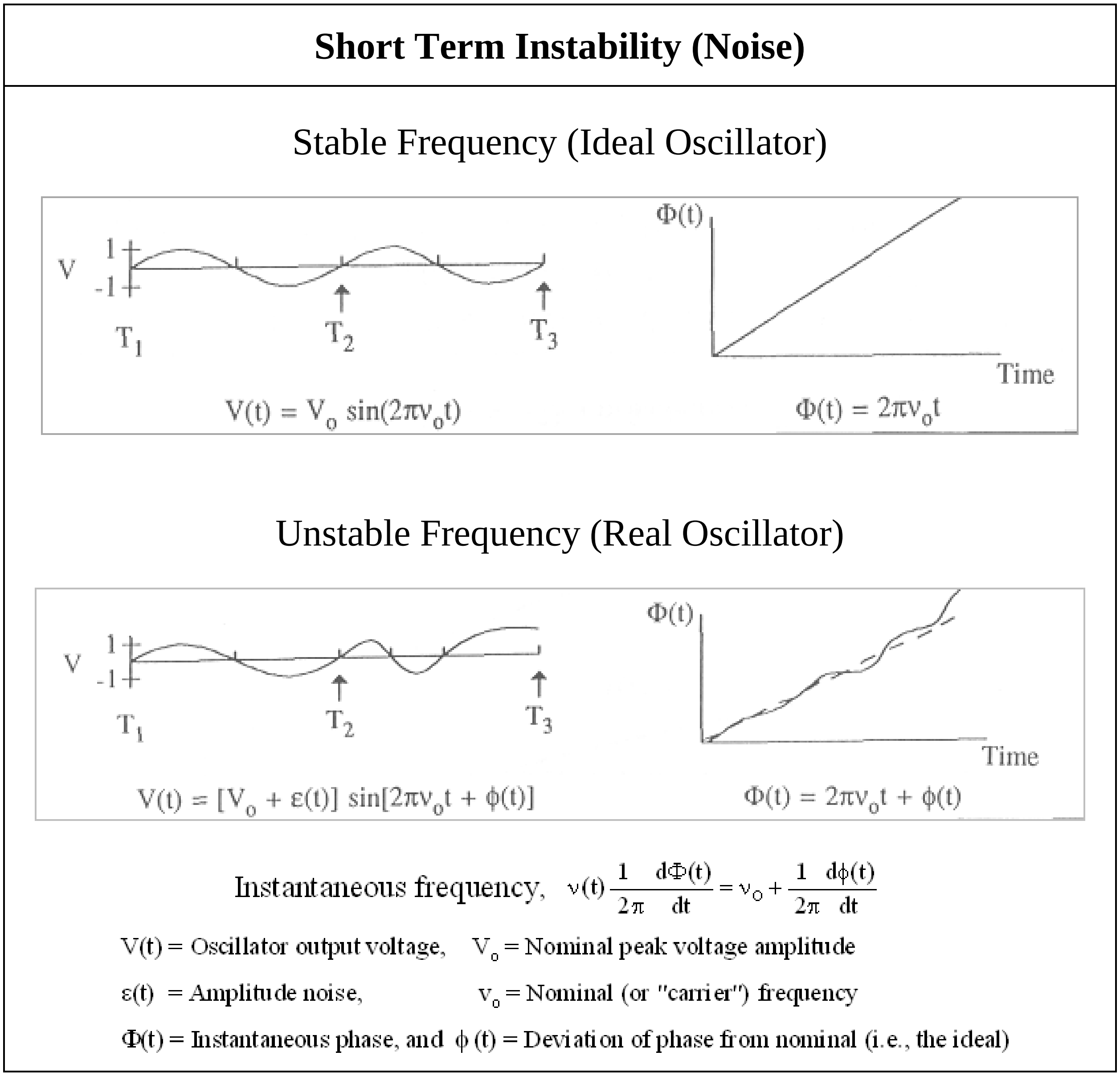
Figure 2-5. Aging and short-term stability.

Typical Aging Behaviors



Aging can be positive or negative. Occasionally, a reversal of aging direction is observed. The above (computer-generated) curves illustrate the three types of aging behaviors. The curve showing the reversal is the sum of the other two curves. Reversal indicates the presence of at least two aging mechanisms.

Figure 2-6. Typical aging behaviors.



Short Term Instability (Noise)

Stable Frequency (Ideal Oscillator)

$V(t) = V_o \sin(2\pi\nu_o t)$ $\Phi(t) = 2\pi\nu_o t$

Unstable Frequency (Real Oscillator)

$V(t) = [V_o + \varepsilon(t)] \sin[2\pi\nu_o t + \phi(t)]$ $\Phi(t) = 2\pi\nu_o t + \phi(t)$

Instantaneous frequency, $\nu(t)\frac{1}{2\pi}\frac{d\Phi(t)}{dt} = \nu_O + \frac{1}{2\pi}\frac{d\phi(t)}{dt}$

$V(t)$ = Oscillator output voltage, V_o = Nominal peak voltage amplitude

$\varepsilon(t)$ = Amplitude noise, ν_o = Nominal (or "carrier") frequency

$\Phi(t)$ = Instantaneous phase, and $\phi(t)$ = Deviation of phase from nominal (i.e., the ideal)

Figure 2-7. Short-term instability (Noise).

Impacts of Oscillator Noise

- Limits the ability to determine the current state and the predictability of precision oscillators
- Limits syntonization and synchronization accuracy
- Limits receivers’ useful dynamic range, channel spacing, and selectivity; can limit jamming resistance
- Limits radar performance (especially Doppler radar’s)
- Causes timing errors [$\sim\tau\sigma_y(\tau)$]
- Causes bit errors in digital communication systems
- Limits number of communication system users, as noise from transmitters interfere with receivers in nearby channels
- Limits navigation accuracy
- Limits ability to lock to narrow line width (atomic) resonances
- Can cause loss of lock; can limit acquisition/reacquisition capability in phase-locked-loop systems

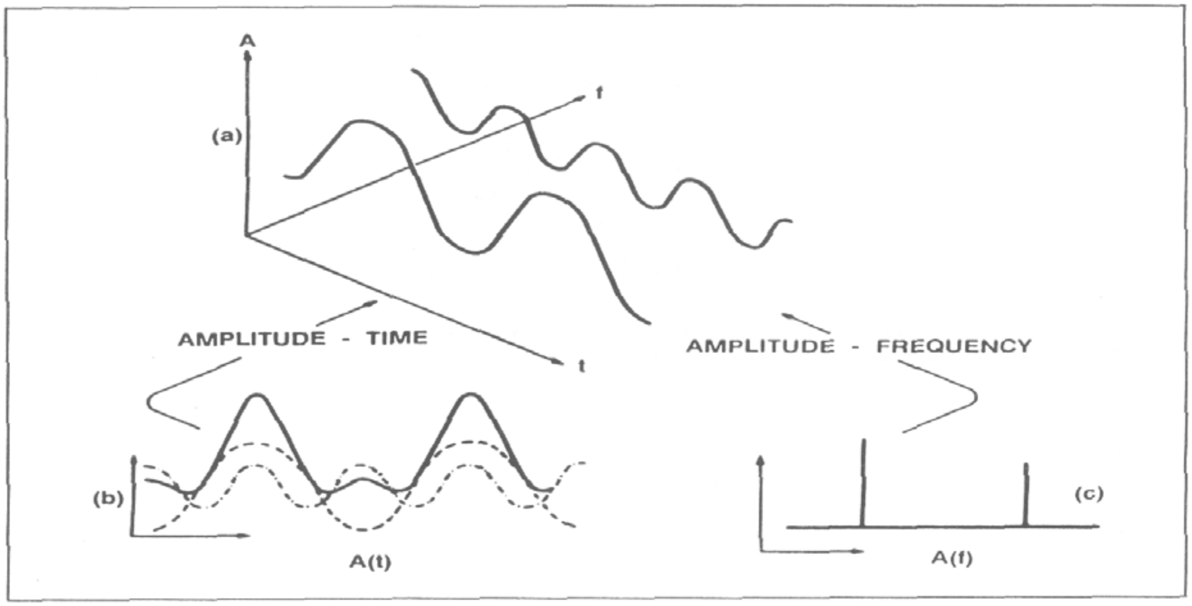
Figure 2-8. Impacts of oscillator noise.

Causes of Short Term Instabilities

- Temperature fluctuations –
    - thermal transient effects
    - activity dips at oven set-point
- Johnson noise (thermally induced charge fluctuations (i.e., "thermal electromotive force (emf)" in resistive elements).
- Acoustic losses (i.e., Q)
- Random vibration
- Fluctuations in the number of adsorbed molecules
- Stress relief, fluctuations at interfaces (quartz, electrode, mount, bond)
- Noise due to oscillator circuitry (active and passive components)
- Shot noise in atomic frequency standards

Figure 2-9. Causes of short term instabilities.

Time Domain - Frequency Domain



Example (a) shows a sine wave and its second harmonic. A signal consisting of the sum of the two waves is shown in the time domain (b), and in the frequency domain (c). In the time domain, all frequency components are summed together. In the frequency domain, signals are separated into their frequency components and the power level at each frequency is displayed.

Figure 2-10. Time domain - frequency domain.

Short-Term Stability Measures

Measure	Symbol
deviation (square-root of Allan Variance)	Two-sample $\sigma_y(\tau)$ *
of phase deviations	Spectral density $S_\phi(f)$
of fractional frequency deviations	Spectral density $S_y(f)$
*	Phase noise L(f)

**Most frequently found on oscillator specification sheets*

$$f^2 S_\phi(f) = \nu^2 S_y(f),$$

$$L(f) \equiv 1/2\, [S_\phi(f)] \text{ (per IEEE Std. 1139-1988)},$$

and $$\sigma_y^2(\tau) = \frac{2}{(\pi\nu\tau)^2} \int_0^\infty S_\varphi(f) \sin^4(\pi f \tau) df$$

Where:
τ = Averaging time
f = Fourier frequency, or "frequency from the carrier"
ν = Carrier frequency

Figure 2-11. Short-term stability measures.

Allan Variance (AVAR)

The **two-sample deviation**, or square-root of the "**Allan Variance**," is the standard method of describing the short-term stability of oscillators in the time domain. It is usually denoted by $\sigma\gamma(\tau)$,

Where: $$\sigma_y^2(\tau) = \frac{1}{2} < (y_{k+1} - y_k)^2 > .$$

The fractional frequencies, $y = \frac{\Delta f}{f}$ are measured over time interval τ;

$(y_{k+1}-y_k)$ are the differences between pairs of successive measurements of y, and, ideally, < > denotes a time average of an infinite number of $(y_{k+1}-y_k)^2$.

A good estimate can be obtained by a limited number, m, of measurements ($m \geq 100$).

$\sigma_y(\tau)$ generally denotes $\sqrt{\sigma_y^2(\tau, m)}$, i.e.,

$$\sigma_y^2(\tau) = \sigma_y^2(\tau, m) = \frac{1}{m} \sum_{j=1}^{m} \frac{1}{2} (y_{k+1} - y_k)_j^2$$

Figure 2-12. Allan Variance (AVAR).

Why Allan Variance?

- **Classical variance**, $\sigma^2 = \frac{1}{m-1}\sum\left(y_i - \bar{y}\right)^2,$
  - diverges for commonly observed noise processes, such as random walk, i.e., the variance increases with increasing number of data points.
- **Allan variance:**
  - Converges for all noise processes observed in precision oscillators.
  - Has straightforward relationship to power law spectral density types.
  - Is easy to compute.
  - Is faster and more accurate in estimating noise processes than the Fast Fourier Transform.

Figure 2-13. Why Allan Variance?

Frequency Noise and $\sigma_y(\tau)$

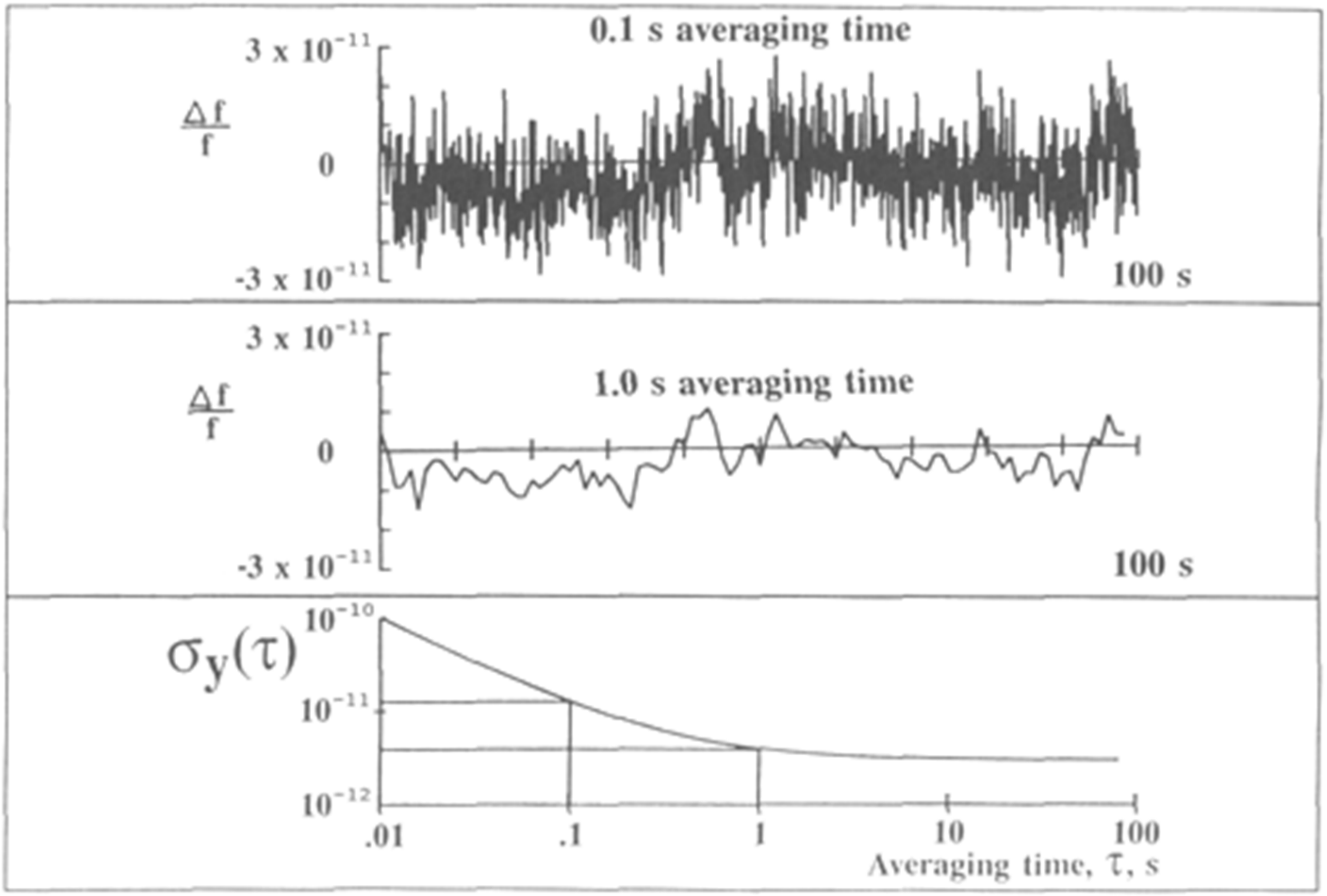


Figure 2-14. Frequency noise and $\sigma_y(\tau)$.

Time Domain Stability

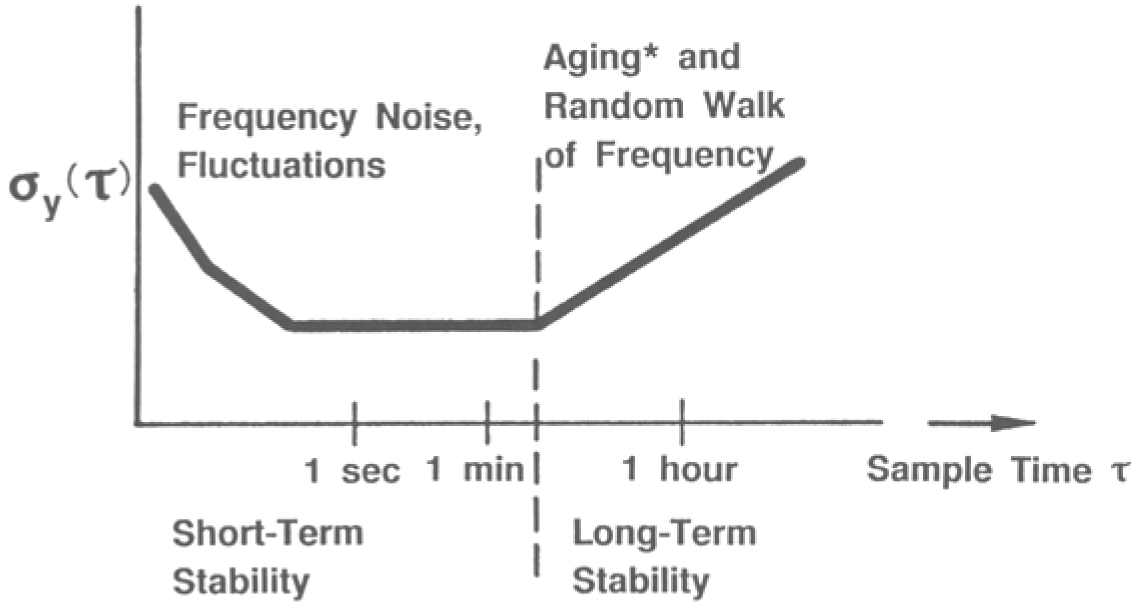


Figure 2-15. Time domain stability.

Spectral Densities

$$V(t) = [V_0 + \varepsilon(t)]\sin[2\pi\nu_0 t + \phi(t)]$$

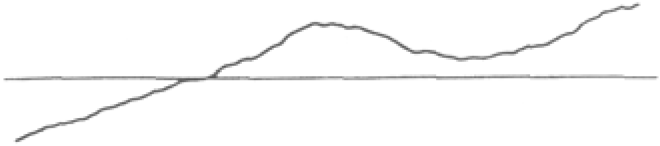
- In the frequency domain, due to the "phase noise," ϕ(t), some of the power is at frequencies other than v_0. The stabilities are characterized by "spectral densities." The spectral density $S_v(f)$, the mean-square voltage $<V^2(t)>$ in a unit bandwidth centered at f, is not a good measure of frequency stability because both ε(t) and ϕ(t) contribute to it, and because it is not uniquely related to frequency fluctuations (although ε(t) is usually negligible in precision frequency sources).

- The spectral densities of phase and fractional-frequency fluctuations, $S_\phi(f)$ and $S_y(f)$, respectively, are used to characterize stabilities in the frequency domain. The spectral density $S_g(f)$ of a quantity g(t) is the mean square value of g(t) in a unit bandwidth centered at f. Moreover, the RMS value of g^2 in bandwidth BW is given by:

$$g_{RMS}^2(t) = \int_{BW} S_g(f)\,df.$$

Figure 2-16. Spectral densities.

Pictures of Noise

Plot of z(t) versus t	**$S_z(f) = h_\alpha f^\alpha$**	**Noise Name**
	$\alpha = 0$	White
	$\alpha = -1$	Flicker
	$\alpha = -2$	Random walk
	$\alpha = -3$	

Plots show fluctuations of a quantity z(t), which can be, e.g., the output of a counter (Δf vs. t) or of a phase detector ($\phi[t]$ vs. t). The plots show simulated time-domain behaviors corresponding to the most common (power-law) spectral densities; $h\alpha$ is an amplitude coefficient.

Note: since $S\Delta f = f^2 S\phi$,e.g., white frequency and random walk of phase are equivalent.

Figure 2-17. Pictures of noise.

Types of Phase Noise

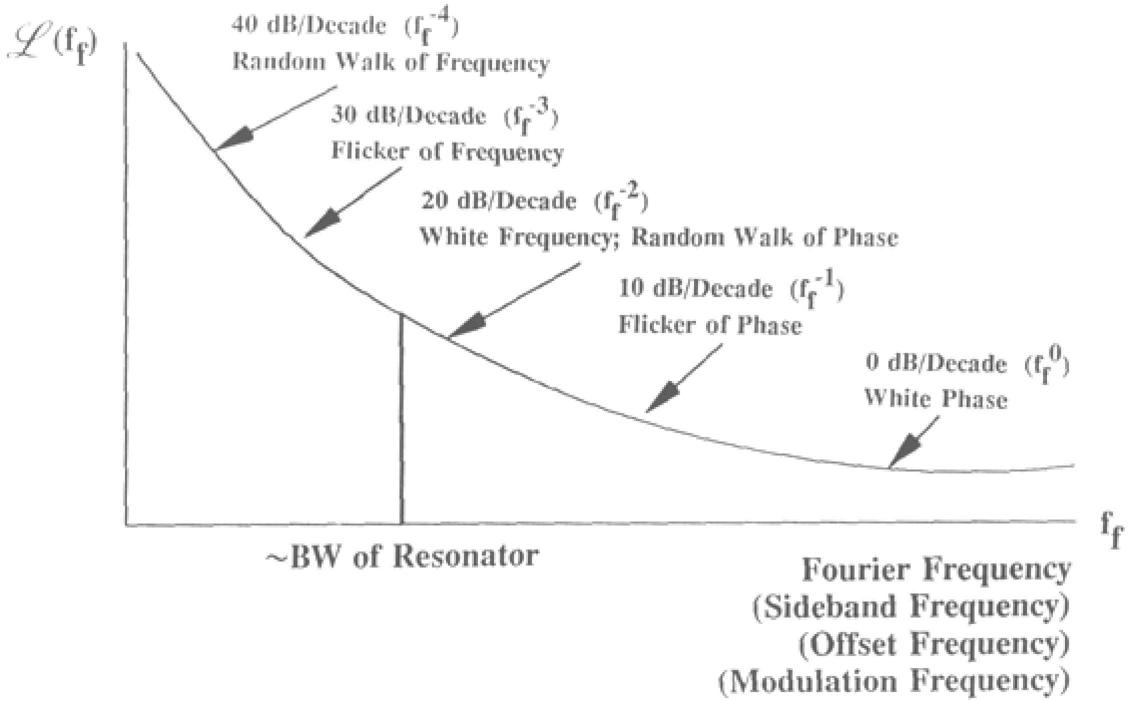


Figure 2-18. Types of phase noise.

Natural Frequencies of Oscillators

Oscillator Type	Resonance Frequency (Hz)
Pendulum	1
Quartz Wristwatch	32 768
Hydrogen Maser	1 420 405 752
Rubidium	6 834 682 608
Cesium	9 192 631 770

The natural frequency of several types of oscillators is shown above. The resonance frequency is usually either divided or multiplied to produce the output frequency of the oscillator. The above list shows the resonance frequency for several types of oscillators. A high resonance frequency leads to a higher quality factor Q, and generally improves the stability. The quality factor, Q, of an oscillator is defined as its resonance frequency divided by its resonance width.

Figure 2-19. Natural frequencies of oscillators.

Crystal Oscillator

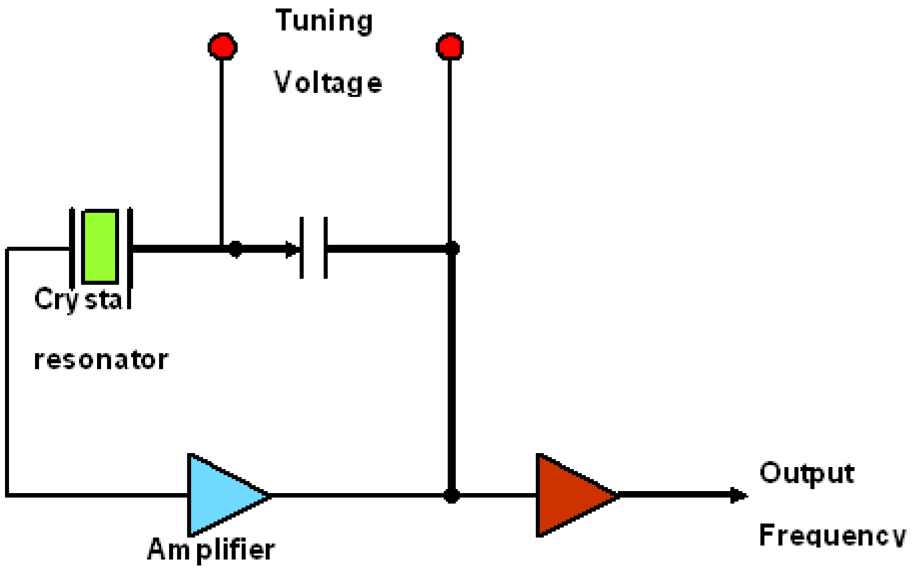


Figure 2-20. Crystal oscillator.

Oscillation

- At the frequency of oscillation, the closed loop phase shift = $2n\pi$.

- When initially energized, the only signal in the circuit is noise. That component of noise, the frequency of which satisfies the phase condition for oscillation, is propagated around the loop with increasing amplitude. The rate of increase depends on the excess; i.e., small-signal, loop gain and on the BW of the crystal in the network.

- The amplitude continues to increase until the amplifier gain is reduced either by nonlinearities of the active elements ("self limiting") or by some automatic level control.

Figure 2-21. Oscillation.

Atomic Frequency Standard Basic Concepts

When an atomic system changes energy from an exited state to a lower energy state, a photon is emitted. The photon frequency v is given by Planck's law:

$$V = (E_2 - E_1)/h$$

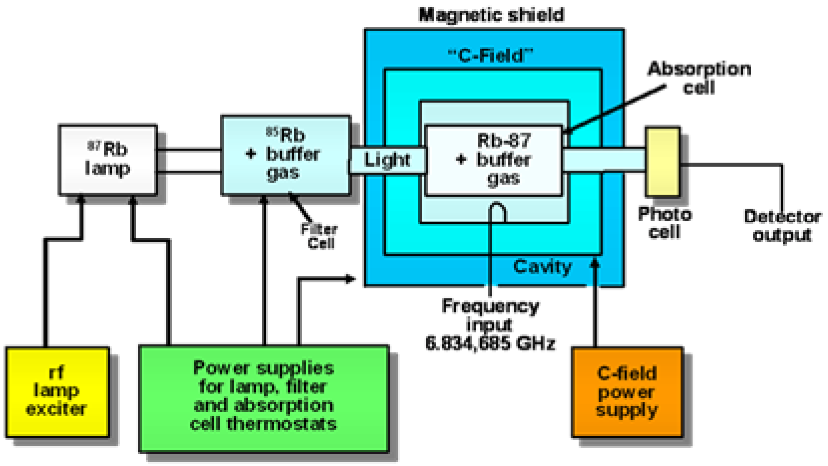
Where:
E_2 and E_1 are the energies of the upper and lower states, respectively, and
h is Planck's constant.

An atomic frequency standard produces an output signal the frequency of which is determined by this intrinsic frequency rather than by the properties of a solid object and how it is fabricated (as it is in quartz oscillators).

The properties of isolated atoms at rest, and in free space, would not change with space and time. Therefore, the frequency of an ideal atomic standard would not change with time or with changes in the environment. Unfortunately, in real atomic frequency standards: 1) the atoms are moving at thermal velocities, 2) the atoms are not isolated but experience collisions and electric and magnetic fields, and 3) some of the components needed for producing and observing the atomic transitions contribute to instabilities.

Figure 2-22. Atomic Frequency Standard basic concepts.

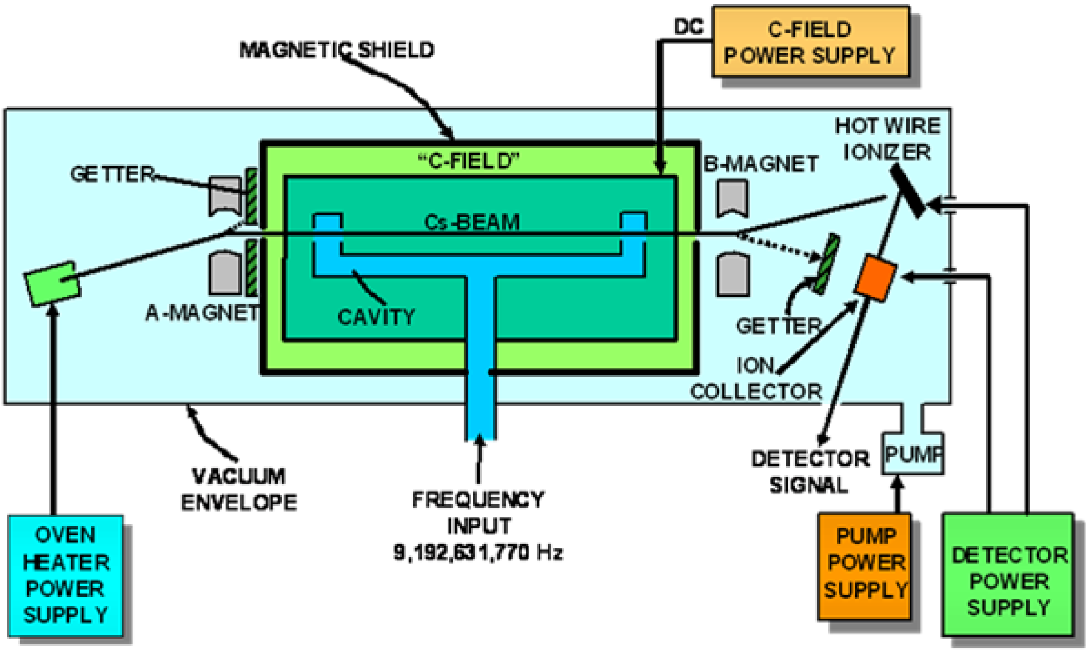
Rubidium Oscillator Operation



The lowest priced members of the atomic oscillator family, rubidium oscillators operate near 6.83 GHz, the resonance frequency of the rubidium atom (^{87}Rb), and use the rubidium frequency to control the frequency of a quartz oscillator. The optical beam from the rubidium lamp pumps the ^{87}Rb buffer gas atoms into a particular energy state. Microwaves from the frequency synthesizer induce transitions to a different energy state. This increases the absorption of the optical beam by the ^{87}Rb buffer gas. A photo cell detector measures how much of the beam is absorbed and its output is used to tune a quartz oscillator to a frequency that maximizes the amount of light absorption. The quartz oscillator is then locked to the resonance frequency of rubidium, and standard frequencies are derived from the quartz oscillator and provided as outputs as shown above. Additional information can be found at the National Institute of Standards and Technology (NIST) web site, http://tf.nist.gov/.

Figure 2-23. Rubidium Cell schematic diagram (atomic resonator).

Cesium Beam Frequency Standard Operation



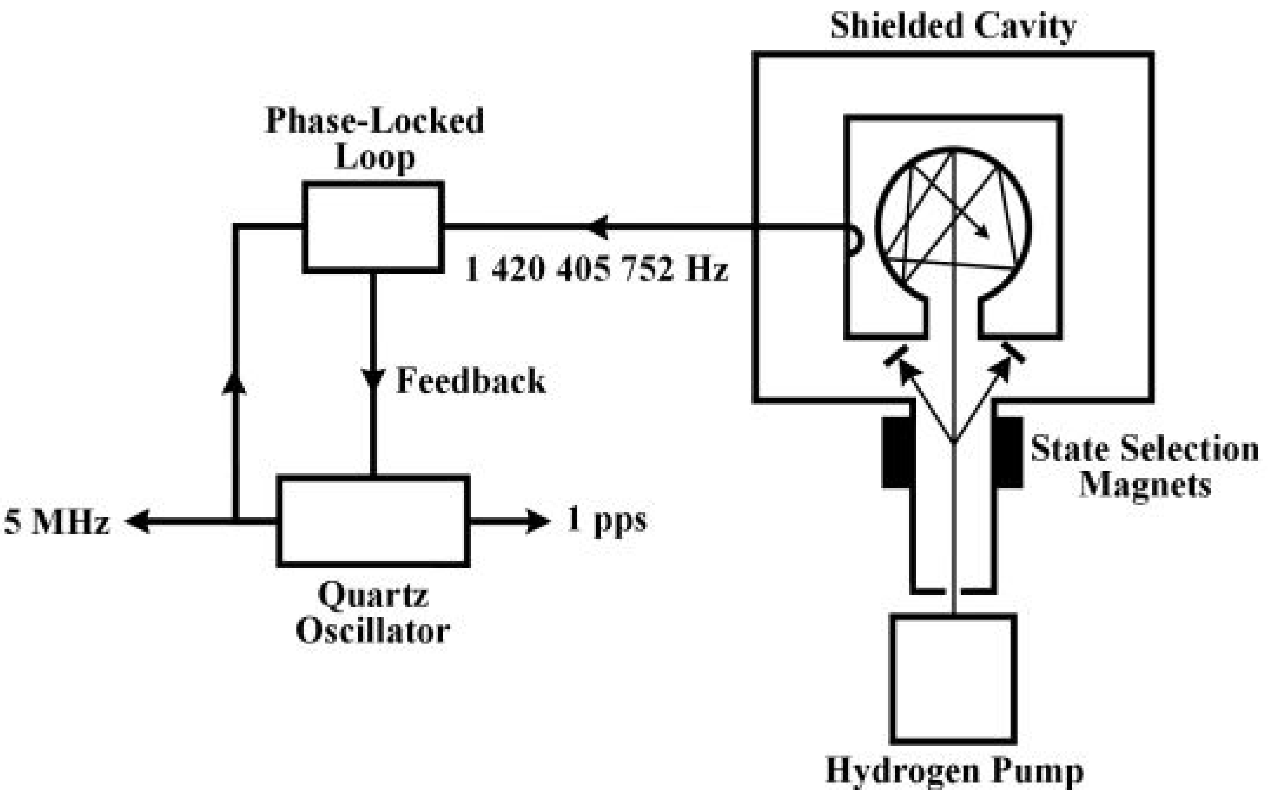
Cesium oscillators can be primary frequency standards since the SI second is defined from the resonance frequency of the cesium atom (^{133}Cs), which is 9,192,631,770 Hz. A properly working cesium oscillator should be close to its nominal frequency without adjustment, and there should be no change in frequency due to aging. However, environmental conditions (motion, vibration, magnetic fields, and so on) do cause small frequency shifts.

Commercially available oscillators use cesium beam technology. Inside a cesium oscillator, ^{133}Cs atoms are heated to a gaseous state in an oven. Atoms from the gas leave the oven in a high-velocity beam that travels through a vacuum tube toward a pair of magnets. The magnets serve as a gate that allows only atoms of a particular magnetic energy state to pass through a gate into a microwave cavity, where they are exposed to a microwave frequency derived from a quartz oscillator. If the microwave frequency matches the resonance frequency of cesium, the cesium atoms change their magnetic energy state.

The atomic beam then passes through another magnetic gate near the end of the tube. Only those atoms that changed their energy state while passing through the microwave cavity are allowed to proceed to a detector at the end of the tube. Atoms that did not change state are deflected away from the detector. The detector produces a feedback signal that continually tunes the quartz oscillator in a way that maximizes the number of state changes so that the greatest number of atoms reaches the detector. Standard output frequencies are derived from the locked quartz oscillator as shown above. Additional information can be found at the National Institute of Standards and Technology (NIST) web site, http://tf.nist.gov/.

Figure 2-24. Cesium-Beam Frequency Standard (Cs atomic resonator schematic diagram).

Active Hydrogen Maser Operation

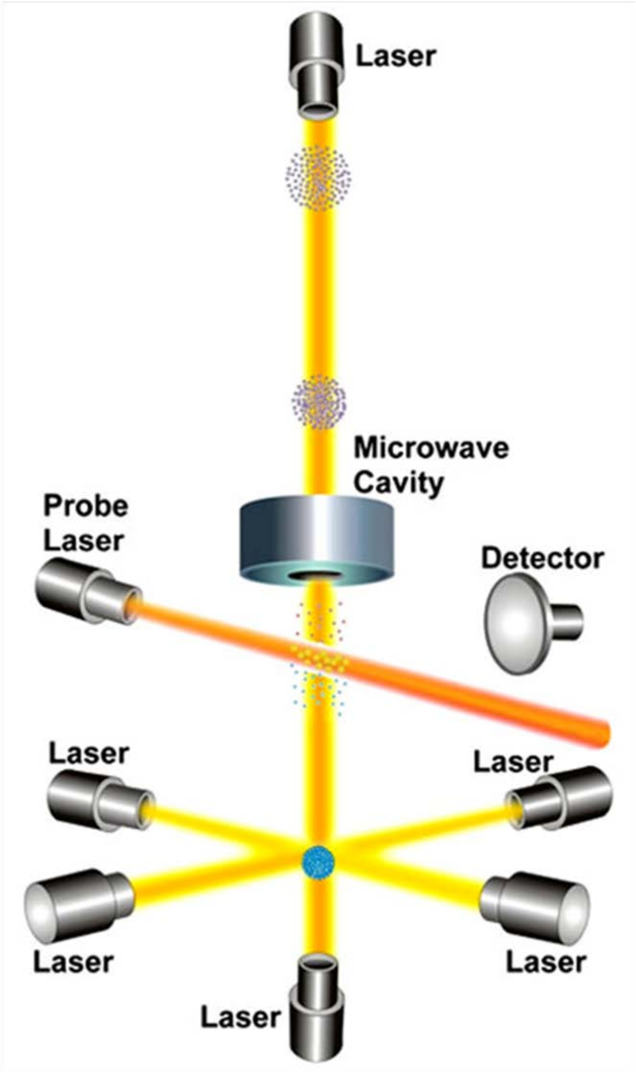


The hydrogen maser is the most elaborate and expensive commercially available frequency standard. The word maser is an acronym that stands for microwave amplification by stimulated emission of radiation. Masers operate at the resonance frequency of the hydrogen atom, which is 1,420,405,751.688 Hz.

A hydrogen maser works by sending hydrogen gas through a magnetic state selector that only allows atoms in certain energy states to pass through. The atoms that make it through enter a Teflon coated storage bulb surrounded by a tuned, resonant cavity. Once inside the bulb, some atoms drop to a lower energy level, releasing photons of microwave frequency. These photons simulate other atoms to drop their energy level and they in turn release additional photons. In this manner, a self-sustaining microwave field builds up in the bulb. The tuned cavity around the bulb helps to redirect photons back into the system to keep the oscillation going. The result is a microwave signal that is at the resonance frequency of the hydrogen atom and that is continually emitted as long as new atoms are fed into the system. A tunable quartz crystal oscillator is phase locked to this RF signal through a down conversion receiver. The output frequency is usually either 5MHz or 1MHz. Additional information on the hydrogen maser is located within the National Institute of Standards and Technology (NIST) web site, http://tf.nist.gov/general/enc-no.htm

Figure 2-25. Hydrogen Maser schematic.

Cesium Fountain Frequency Standard Description



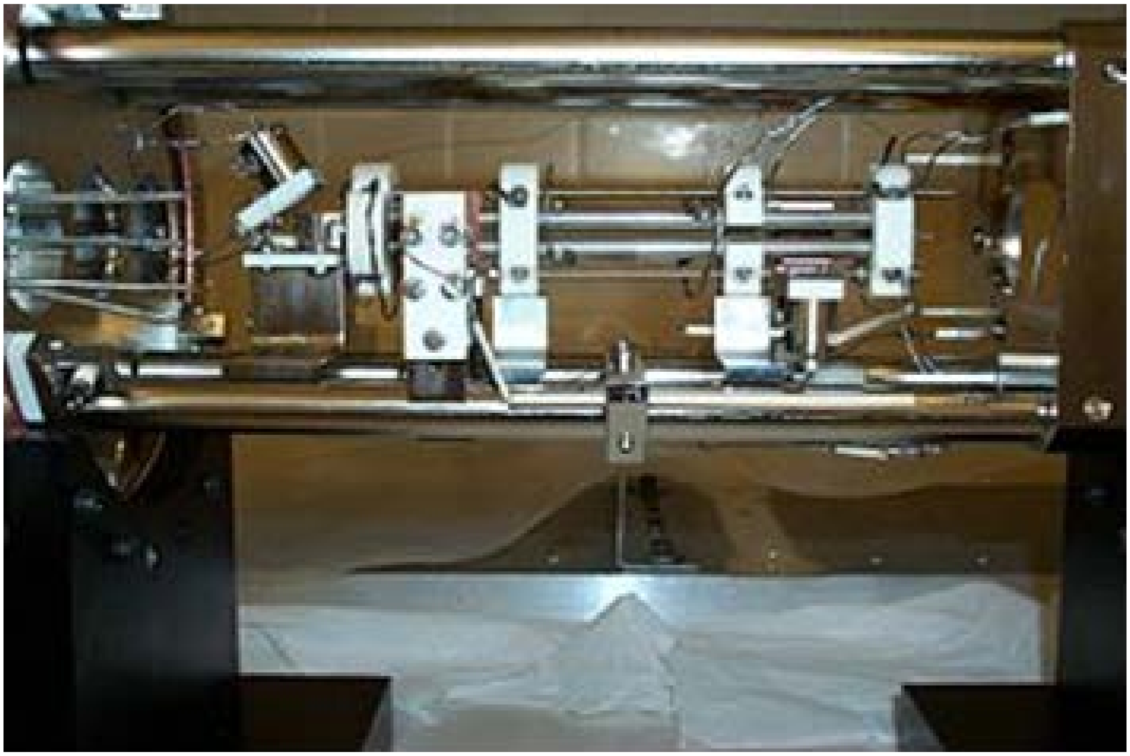
The current state-of-the-art in frequency standard technology is the cesium fountain, which is named after its fountain-like movement of cesium atoms. A cesium fountain, named, NIST-F1 serves as the primary standard of time interval and frequency for the United States.

A cesium fountain works by releasing a gas of cesium atoms into a vacuum chamber. Six infrared laser beams are directed at right angles to each other at the center of the chamber. The lasers gently push the cesium atoms together into a ball. In the process of creating this ball, the lasers slow down the movement of the atoms and cool them to temperatures a few millionths of a degree above absolute zero. This reduces their thermal velocity to a few centimeters per second.

Vertical laser beams gently toss the ball upward and then all of the lasers are turned off. This little push is just enough to loft the ball about a meter high through a microwave-filled cavity. Under the influence of gravity, the ball then stops and falls back down through the microwave cavity. The round trip up and down through the microwave cavity lasts for about 1 second, and is limited only by the force of gravity pulling the atoms downward. During the trip, the atomic states of the atoms might or might not be altered as they interact with the microwave signal. When their trip is finished, another laser is pointed at the atoms. Those atoms whose states were altered by the microwave signal emit photons (a state known as fluorescence) that are counted by a detector. This process is repeated many times while the microwave signal in the cavity is tuned to different frequencies. Eventually, a microwave frequency is found that alters the states of most of the cesium atoms and maximizes their fluorescence. This frequency is the cesium resonance. Accuracy is approximately 1×10^{-15} or 1 second in 30 million years. $1\text{x}10^{-16}$ is achievable. Go to: the National Institute of Standards and Technology (NIST) web site http://tf.nist.gov/cesium/fountain.htm

Figure 2-26. Cesium Fountain.

Linear Ion Trap at the University of Calgary



Linear ion traps use a set of quadrupole rods to confine ions radially and a static electrical potential on end electrodes to confine the ions axially. The linear form of the trap can be used as a selective mass filter, or as an actual trap by creating a potential well for the ions along the axis of the electrodes. Advantages of the linear trap design include increased ion storage capacity, faster scan times, and simplicity of construction (although quadrupole rod alignment is critical, adding a quality control constraint to their production. This constraint is additionally present in the machining requirements of the 3D trap). Additional information on the hydrogen maser is located within the National Institute of Standards and Technology (NIST) web site, Ion Storage Group NIST.

Figure 2-27. Linear Ion Trap.

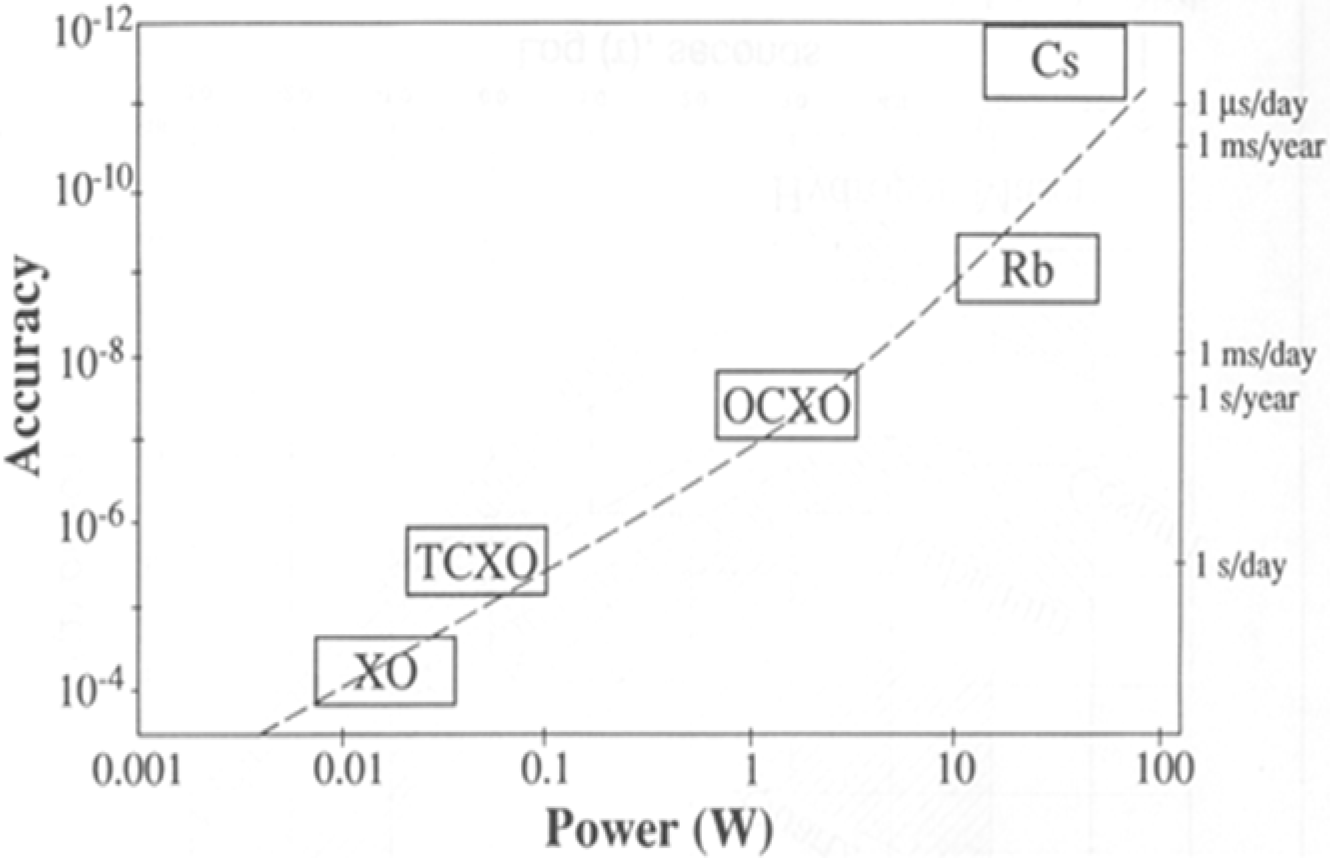
Oscillator Comparison

	Quartz Oscillators			**Atomic Oscillators**		
	TCXO	MCXO	OCXO	Rubidium	RbXO	Cesium
Accuracy* (per year)	2 x 10^{-6}	5 x 10^{-8}	1 x 10^{-8}	5 x 10^{-10}	7 x 10^{-10}	2 x 10^{-11}
Aging/Year	5 x 10^{-7}	2 x 10^{-8}	6 x 10^{-9}	2 x 10^{-10}	2 x 10^{-10}	0
Temp. Stab. (range, ºC)	5 x 10^{-7} (-55 to +85)	2 x 10^{-8} (-55 to +85)	1 x 10^{-9} (-55 to +85)	3 x 10^{-10} (-55 to +68)	5 x 10^{-10} (-55 to +85)	2 x 10^{-11} (-28 to +65)
Stability, $\sigma y(\tau)$ (τ=1s)	1 x 10^{-9}	1 x 10^{-10}	1 x 10^{-12}	3 x 10^{-11}	5 x 10^{-12}	5 x 10^{-11}
Size (cm3)	10	50	20-200	800	1200	6000
Warm-up Time (min)	0.1 (to 1 x 10^{-6})	0.1 (to 2 x 10^{-8})	4 (to 1 x 10^{-8})	3 (to 5 x 10^{-10})	3 (to 5 x 10^{-10})	20 (to 2 x 10^{-11})
Power (W) (at lowest temperature.)	0.05	0.04	0.25 -4	20	0.35	30
Price (~$)	100	1,000	2,000	8,000	10,000	40,000

*Including environmental effects (note that the temperature ranges for Rb and Cs are narrower than for quartz).

Figure 2-28. Oscillator comparison.

Accuracy vs. Power-Requirement*



- Note: Accuracy vs. size, and accuracy vs. cost have similar relationships.

Figure 2-29. Accuracy versus power requirement.

Stability Ranges of Various Frequency Standards

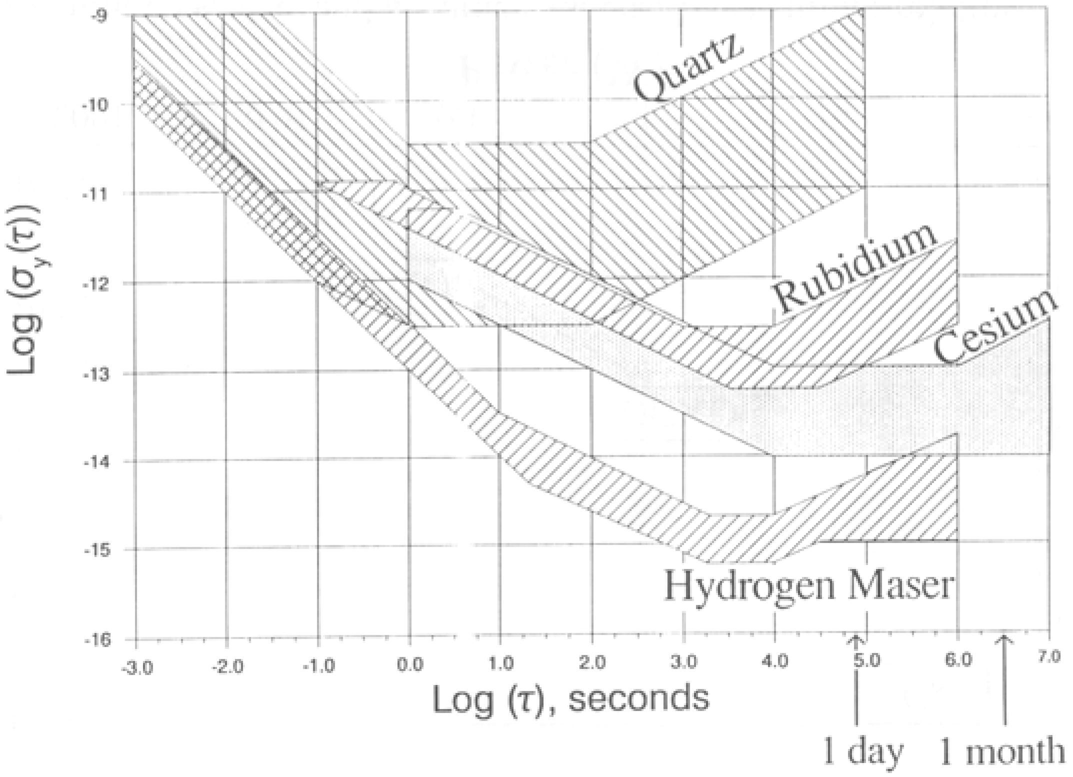
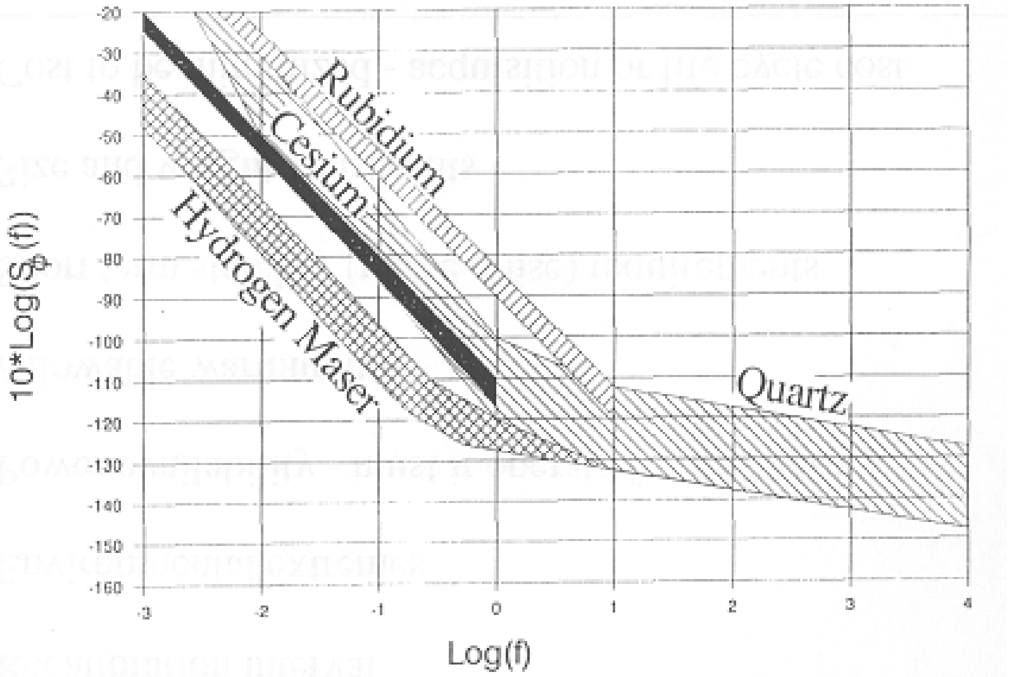


Figure 2-30. Stability ranges of various frequency standards.

Phase Instabilities of Various Frequency Standards



Typical One-sided Spectral Density of Phase Deviation versus Offset Frequency, for Various Standards, Calculated at 5 MHz.

Figure 2-31. Phase instabilities of various frequency standards.

Oscillator Selection Considerations

- Frequency accuracy or reproducibility requirement
- Recalibration interval
- Environmental extremes
- Power availability: must it operate from batteries?
- Allowable warm-up time
- Short term stability (phase noise) requirements
- Size and weight constraints
- Cost to be minimized: acquisition or life cycle cost

Figure 2-32. Oscillator selection considerations.

Oscillator Acronyms

XO	Crystal Oscillator
VCXO	Voltage Controlled Crystal Oscillator
OCXO	Oven Controlled Crystal Oscillator
TCXO	Temperature Compensated Crystal Oscillator
TCVCXO	Temperature Compensated/Voltage Controlled Crystal Oscillator
OCVCXO	Oven Controlled/Voltage Controlled Crystal Oscillator
MCXO	Microcomputer Compensated Crystal Oscillator
RbXO	Rubidium-Crystal Oscillator

Figure 2-33. Oscillator acronyms.

Crystal Oscillator Categories

The three categories, based on the method of dealing with the crystal unit's frequency vs. temperature characteristic, are:

- XO, crystal oscillator, which does not contain means for reducing the crystal's f versus T characteristic (also called PXO - packaged crystal oscillator).

- TCXO, temperature compensated crystal oscillator, in which the output signal from a temperature sensor (thermistor) is used to generate a correction voltage that is applied to a voltage-variable reactance (varactor) in the crystal network. The reactance variations compensate for the crystal's f vs. T characteristic. Analog TCXO's can provide about a 20X improvement over the crystal's f versus T variation.

- OCXO, oven controlled crystal oscillator, in which the crystal and other temperature sensitive components are in a stable oven which is adjusted to the temperature where the crystal's f vs. T has zero slope. OCXO's can provide a >1000X improvement over the crystal's f versus. T variation.

Figure 2-34. Crystal oscillator categories.

Hierarchy of Oscillators

Oscillator Type*	Accuracy**	Typical Applications
● Crystal oscillator (XO)	10^{-5} to 10^{-4}	Computer timing
● Temperature compensated crystal oscillator (TCXO)	10^{-6}	Frequency control in tactical radios
● Microcomputer compensated crystal oscillator (MCXO)	10^{-8} to 10^{-7}	Spread spectrum system clock
● Oven controlled crystal oscillator (OCXO)	10^{-8}	Navigation system clock & frequency standard, MTI radar
● Small atomic frequency standard (Rb, RbXO)	10^{-9}	C^3 satellite terminals, bistatic and multistatic radar
● High performance atomic standard (Cs)	10^{-12} to 10^{-11}	Strategic C^3, EW

Notes:

* Sizes range from less than 5 cm^3 for clock oscillators to more than 30 liters for Cs standards.
Costs range from less than $5 for clock oscillators to more than $40,000 for Cs standards.

** Including the effects of military environments and one year of aging.

Figure 2-35. Hierarchy of oscillators.

REFERENCES

NOTE

Many of the graphs and charts in Chapter 2 were obtained from Dr. John R. Vig of the U.S. Army Research Laboratory (retired) and the National Institute of Standards and Technology (NIST). The IEEE web site shows a pictorial representations and analysis of terms used in the behavior of crystal and atomic frequency standards. Go to http://www.ieee-uffc.org/fc , then on the **bar** at the top click on **frequency Contro**l, then on the left column click on **Teaching Resources** and scan down to the tutorial by John R. Vig on "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications." Other tutorials and topics of interest are on the same web site.

NOTE

For a more comprehensive discussion of topics covered in the definitions and frequency standard analysis, the Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting and the IEEE Frequency Control Symposium Proceedings are excellent references, as are the Symposia on Frequency Standards and Metrology and those of the proceedings of the annual European Frequency and Time Forum (EFTF).

1. Vig, J. (August 1993). *Quartz Crystal Resonators and Oscillators*. Report Number SLCET-TR-88-1 (Rev. 6.1), U.S. Army Research Laboratory AD-A269372.

2. Jespersen, J. (December 1991). *Introduction to the Time Domain Characterization of Frequency Standards*. National Institute of Standards and Technology (NIST) in Tutorials, pgs 83-102, the Twenty-Third Annual Precise Time and Time Interval Applications and Planning Meeting (PTTI), December 3-5, 1991, AD-A254745.

3. Stein,S., Vig, J. (1991). *Frequency Standards for Communications*. U.S. Army Laboratory Command (LABCOM), Report Number SLCET-TR-91-2 (Rev. 1), October 1991, AD-A243211.

4. Vig, J., Audoin, L., Cutler, et al, (July 1992). *The Effects of Acceleration on Precision Frequency Sources*. (proposed for IEEE Standards Project P1193), U.S. Army Laboratory Command (LABCOM), Research and Development Technical Report SLECT-TR-91-3 (Rev. 1), AD-A255465.

5. Sullivan, D., Allan, D. Howe D., Walls, F., (March 1990). *Characterization of Clocks and Oscillators*. NIST Technical Note 1337, March 1990.

6. Piezo Crystal Company, (September 1990). *Frequency Sources That Set the Standard*.

7. International Telecommunication Union (ITU), ITU-T (September 1997). Recommendation G.811 Document, *Timing Characteristics of Primary Reference Clocks. From Series G: Transmission Systems and Media, digital Systems and Networks*.

8. ITU Radiocommunication Sector (ITU-R). One of the three sectors (divisions or units) of the International Telecommunication Union (ITU) and is responsible for radio communication.

9. U.S. Department of Commerce/National Bureau of Standards (NBS), (May 1974). *Time and Frequency: Theory and Fundamentals*. NBS Monograph 140.

10. U.S. Department of Commerce/National Bureau of Standards (NBS), (June 1972). *Precision Measurements and Calibration: Frequency and Time*. NBS Special Publication 300, Volume 5.

11. U. S. Naval Observatory (USNO): official source of time for Department of Defense (DOD) and the Global Positioning system (GPS), and a standard of time for the United States (U.S.). The web site is: http://tycho.usno.navy.mil/frontpage.html.

12. U.S. National Institute of Standards and Technology (NIST). The web site provides an overview of activities at NIST including the time and frequency activities. The web site is: www.boulder.nist.gov..

13. U.S. Coast Guard Navigation Center (NAVCEN) web site has a description of LORAN and future activities. http://www.navcen.uscg.gov/loran/default.htm.

14. IEEE, *IEEE Standard Dictionary of Electrical and Electronic Terms*, IEEE Standard 100-1972-ANSI C42.100-1072.

15. International Organization for Standardization (ISO), International Electrotechnical Commission (IEC), International Organization of Legal Metrology (OIML), International Bureau of Weights and Measures (BIPM) (June 1992). *Guide to the Expression of Uncertainty in Measurement*. ISO/TAG 4/WG 3.

16. International Astronomical Union (edited by Hughes, J. A., Smith, C. A., Kaplan, G. H., (October 14-20, 1990). *Proceedings of the 127th Colloquium of the International Astronomical Union*. Held in Virginia Beach, Virginia, USA (hosted by the U.S. Naval Observatory, Washington, DC).

17. Guinot, B., *Report of the Sub-Group on Time*. Proceedings of the 127th Colloquium of the International Astronomical Union (Reference 11).

18. U.S. Naval Observatory, Time Service and Astrometry Departments, *Explanatory Supplement to the Astronomical Almanac*, edited by P. K. Seidelmann. A Revision to the Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac, University Science Books, Mill Valley, California.

19. U.S. Naval Observatory (1981). *The Astronomical Almanac*, *Glossary*, (pp. M5 and M12).

20. Smart, W. M., *Textbook on Spherical Astronomy*. Cambridge University Press, 6th ed, (pp. 137-143 and 147-150).

21. Clarke, A. Roy, D., *Astronomy: Principles and Practice*. Adam Hilger Publication, 3rd ed, (p. 78).

22. Kartaschoff, P., (1978). *Frequency and Time*. Academic Press, ISBN 0-12-40150-5.

23. Gerber, E. A., Ballato, A., (1985). *Precision Frequency Control*. Academic Press, ISBN 0-12-280601-8.

24. Draft Proposal American National Standard - *Synchronization Interface Standard* (Revision of ANSI T1.101-1987), December 1991.

25. Hurn, J., (1993). *Differential GPS Explained*. Trimble Navigation.

26. Hurn, J., (1989). *GPS: A Guide to the Next Utility*. Trimble Navigation.

27. *Tutorials from the Twenty-Third Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*. Pasadena, California, December 3-5, 1991, and tutorials from 1992 to 2006. See Reference 42 for the USNO PTTI web site.

28. Horn, F., Bellcore, Red Bank, NJ, (September 25, 1991). *Draft Proposed American National Standard - Synchronization Interface Standard*. Sixth Revision of ANSI T1.101-1987.

29. Consultative Committee on Space Data System (CCSDS), (April 1990). *Time Code Formats, Blue Book Issue 2*, CCSDS 301.0-B-2.

30. International Telecommunications Union. *Handbook Selection and use of Precise Frequency and Time systems* and *Time Signals and Frequency Standard Emissions*, TF series of the ITU Handbook.

31. Precise Time and Time Interval (PTTI) Systems and Applications Meeting website, (papers from 1991 to the present). Reference http://tycho.usno.navy.mil/ptti/index.html

32. BIPM in Paris, France is another website with additional timing/frequency information. Go to: http://www.bipm.fr/en/home and http://www.bipm.org

33. Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy has additional information on Timing: http://www.ien.it

34. National Institute of Standards (NIST). *Glossary of frequency and time terms.*: http://tf.nist.gov/general/glossary.htm.

35. U. S. Coast Guard Navigation Center (NAVCEN) Website, http://www.navcen.uscg.gov/ , contains significant information on LORAN and DGPS. The site is a wealth of information on many topics.

36. Megapulse (Magazine), good site for *Loran-C information in WGS 84 Coordinates* http://www.megapulse.com/chaininfo.html.

37. For Leap Year/Leap Second Conventions go to: http://timeanddate.com/date/leapyear.html and http://aa.usno.navy.mil/faq/docs/leap_years.html.

38. USNO. *History of accumulated leap seconds*: ftp://maia.usno.navy.mil/ser7/tai-utc.dat.

39. IEEE 1588. Additional information may be obtained from Kang Lee, the IEEE Technical Committee on Sensor Technology of the Instrumentation and Measurement Society sponsor of IEEE 1588. Contact: Kang Lee, NIST, 301-975-6604, kang.lee@nist.gov.

40. IEEE Frequency Control Website (since 1956). Proceedings of the Frequency Control Symposiums. Contains the full text of all the papers ever published by the group. Some of the information is openly available, and some is available to IEEE UFFC Society members only. To join, see www.ieee.org/join.

41. IEEE Electronic Library; contains more than 1.2 million documents. Full text access is provided to journals, magazines, transactions and conference proceedings as well as active IEEE standards. Membership is required for most publications. Go to: www.ieee.org/ieeexplore.

42. Precise Time and Time Interval (PTTI); web site list Programs and Abstracts for PTTI 1999 and PTTI 2000. Past PTTI meeting programs are listed from 2001 to 2006. There are many other web sites listed of interest. Go to: http://tycho.usno.navy.mil/what.html.

43. GPS World Magazine; is an excellent source for information on GPS technology. The magazine is free to qualified subscribers. Their web page is: www.gpsworld.com.

44. Space and Tech; Comprehensive summary of GLONASS satellite system. In addition, the March/April 2007 issue of “Inside GNSS” has an excellent article on PS/GALELEO/GLONASS. Go to: www.insidegnss.com and http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml.

45. Börjesson, J., GLONASS Contributions to Space Geodesy (thesis), Department of Radio and space Science, Chalmers University of Technology, Goteborg, Sweden. Refer to http://www.oso.chalmers.se~geo/introduction or contact at: Jorgen@melcogot.com.

46. GLONASS. An excellent summary is at: http://search.msn.com/results.aspx?q=glonass&FORM=USNO.

47. Hanson, D. W. (1989). Fundamentals of Two-Way Transfer by Satellite. NIST Time and Frequency Division, presented at the 43rd Symposium on Frequency Control - 1989.

48. Ultrasonics, Ferroelectrics, and Frequency Control Society. UFFC Frequency Control Review Papers/Tutorials. See the following web site: http://www.ieee-uffc.org/fcmain.asp?view=review.

49. International Telecommunications Study Group, Working Party 7A (26 April 2001). Glossary and Definition of Time and Frequency Terms, Document 7A/17-E.

50. Range Commanders Council (RCC), Electronic Trajectory Measurements Group, (2000). Standard Report Format for Global Positioning System (GPS) Receivers and System Accuracy Tests and Evaluations (IRIG Document 261-00).

51. Range Commanders Council (RCC), GPS Range Safety Applications Ad Hoc Group (1998). IRIG Document 322-98: Guidelines Document: Global Positioning System (GPS) as a *Real-Time Flight Safety Data Source*.

52. IEEE Society on Instrumentation and Measurements, IEEE Standard No. 1139-1988 on Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology.

53. International Telecommunications Union (ITU), (1994). Measures for Random Instabilities in Frequency and Time (Phase), ITU Recommendation ITU-R TF.538-3.

54. NASA Jet Propulsion Laboratory (JPL). Time and Frequency activity; see the Frequency and Timing Advanced Development Group: http://horology.jpl.nasa.gov.

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