CLOCKS IN TELECOMMUNICATIONS

The concept of time flow is related to the possibility of arranging events in an ordered sequence, that is, saying which of two events comes earlier (1). Then, a timescale is a system of labeling events with real numbers according to their sequence. The labeling law is quite arbitrary, given that the order of events is left unchanged, but for practical purposes it must use equal intervals (two time intervals are defined equal if equal processes take place during these two intervals) for its successive scale intervals (*uniform time scale*).

Clocks are devices able to measure the time, that is, to produce time markers together with identification of these markers (1). Under different forms, they are widespread in everyday life and penetrate a surprisingly wide range of applications. Beyond ruling human (and automated) activities worldwide, for example, clocks provide the timing of digital electronics in almost all of the commonly used electronic equipment and synchronize the nodes of telecommunications systems and networks. The performance of such systems heavily relies on the quality of the synchronization signals.

The oldest historical examples of clocks date back to 1400 B.C. and are a sun dial and a clepsydra (water clock) made by Egyptians. With several technical improvements, sun dials (based on measuring the rotation of a shadow with the sun) and clepsydrae (based on measuring the level of water in a vessel with a regulated flow of water as input or output) had been in use until the Middle Ages. On the other hand, early mechanical clocks date back to the thirteenth century, and the first pocket watches, based on a spring mechanism, were constructed in the fifteenth century. However, the true milestone was the invention of pendulum clocks due to Galileo and Huygens and the introduction of the swing wheel as an oscillating element. After that, until the introduction of electrical clocks and then of clocks based on quartz and atomic oscillators, mechanical clocks did not change substantially, at least in their operating principle, until today.

From a theoretical viewpoint, the operating principle of clocks of any kind consists of a generator of oscillations and an automatic counter of such oscillations. Although differing in capability, the oscillator can be based on *any* (pseudo-)periodic physical phenomenon. The swinging of a pendulum or a wheel in mechanical clocks, the vibration of atoms in a crystal around their minimum-energy position in quartz clocks, the radiation of specific quantic atomic transitions in atomic clocks are the best known examples because of their wide application, but are not the only ones. Recently, even the rotation period of pulsars, after some (although not trivial) data processing, has been used to design clocks of the highest precision, comparable to that of the best atomic clocks.

CLOCK SIGNALS AND THEIR TIMING RELATIONSHIPS

A clock is a device supplying a *timing signal,* or *chronosignal,* defined as a pseudoperiodic (ideally periodic) signal for controlling the timing of actions. Examples of applications are the timing of digital hardware systems (gates, chips, or boards), where the operation of different modules must be synchronized to ensure proper transfer of binary symbols, and the timing of telecommunications systems, where digital signals are multiplexed, transmitted, and switched.

Typical chronosignal waveforms are sine and square waves. A general expression describing a pseudoperiodic waveform which models the timing signal $s(t)$ at the output of clocks is given by (2,3)

$$s(t) = A(t)\sin\Phi(t) \tag{1}$$

where $A(t)$ is the instantaneous amplitude (in the following, without loss of generality, we assume $A(t) \cong A_0$), $\Phi(t)$ is the total phase, and the instantaneous frequency $\nu(t)$ is given by

$$\nu(t) = \frac{1}{2\pi}\frac{d\Phi(t)}{dt} \tag{2}$$

Obviously, in the ideal case, when the pseudoperiodic timing signal is periodic, the total phase increases linearly with time, that is,

$$\Phi(t) = 2\pi\nu_{\mathrm{n}}t \tag{3}$$

where ν_{n} is the nominal frequency. In the actual case, other components may affect the total phase increase, including frequency offset, drifts, and purely random fluctuations. This topic is thoroughly discussed in the section Characterization and Modeling of Clocks.

A chronosignal fulfils its duty by triggering events, that is, timing the controlled process. From this point of view, a timing signal can be also modeled by a series of pulses spaced T apart, at special instants called *significant instants.* The timing signal triggers the controlled process at those instants. Suitable significant instants can be identified, for example, at the signal zero-crossing instants for ease of implementation.

Synchronous and Asynchronous Clock Signals

Two *synchronous* (from the Greek etymon $\sigma\upsilon\gamma\chi\rho o\nu o\varsigma$, built by $\sigma\upsilon\nu$ = *with* and $\chi\rho o\nu o\varsigma$ = *time*) clock signals have the same frequency, at least on average, and a precisely controlled phase relationship (i.e., with phase offset $\Delta\Phi$ = constant, at least on average). The expression "at least on average" points out that some zero-mean small fluctuations may be accepted as unavoidable in real systems.

Conversely, two clock signals are *asynchronous* if they are not synchronous.

Mesochronous Clock Signals

Two *mesochronous* (from the Greek etyma $\mu\epsilon\sigma o\varsigma$ = *medium* and $\chi\rho o\nu o\varsigma$ = *time*) clock signals are asynchronous timing signals which have the same frequency, at least on average, but no control of the phase relationship. It is worth noting that because the phase fluctuation function is proportional to the integral of the frequency fluctuation function, the phase error $\Delta\Phi$ is not theoretically limited over an infinite time interval, even for small zero-mean frequency fluctuations (thus, $\Delta\Phi$ = any value).

Plesiochronus Clock Signals

Two *plesiochronous* (from the Greek etyma $\pi\lambda\theta\sigma\iota o\varsigma$ = *close* and $\chi\rho o\nu o\varsigma$ = *time*) clock signals are asynchronous timing signals that have the same frequency values only nominally, but actually are different within a given tolerance range.

Heterochronous Clock Signals

Two *heterochronous* (from the Greek etyma $\epsilon\tau\epsilon\rho o\varsigma$ = *different* and $\chi\rho o\nu o\varsigma$ = *time*) clock signals are asynchronous timing signals that have different nominal frequencies.

Practical Examples

To give sound examples of the above abstract concepts, a phase-locked loop (PLL), locked to its reference, outputs a timing signal that is synchronous with the input signal because of the feedback control on the phase error between the signals. A frequency-locked loop (FLL), which is a feedback system operating like a PLL, but which instead controls the frequency error between the input and the output signals, outputs a signal that is mesochronous with the input. Two oscillators, even designed and built as equal by the same supplier, output plesiochronous timing signals because of unavoidable manufacturing tolerances. In telecommunications networks also, two digital signals that have the same nominal bit rate (e.g., two 2.048 Mb/s digital signals) are always plesiochronous unless generated by the same piece of equipment (driven, in this case, by a single clock). On the other hand, two digital signals with different rates (e.g., 2.048 Mb/s and 8.448 Mb/s signals) are heterochronous.

NETWORK SYNCHRONIZATION STRATEGIES

Network synchronization deals with the distribution of time and frequency over a network of clocks spread over a wide geographical area (4). The goal is to align the time and frequency scales of all of the clocks by using the communications capacity of the links interconnecting them (e.g., copper cables, fiber optics, radio links). In particular, network synchronization plays a central role in modern digital telecommunications (5,6) and has a determining influence on the quality of most services offered by the network operator to its customers.

Many intriguing examples of synchronizing a large number of oscillators are found in nature. Lindsey et al. (4) pointed out as one of the most spectacular ones the synchronous fireflies described by Buck and Buck (7). These fireflies flash their light organs at regular but individual and independent intervals if they are not close together. Though, if many of these insects are placed in a relatively close proximity, they synchronize their light organs until they flash in unison.

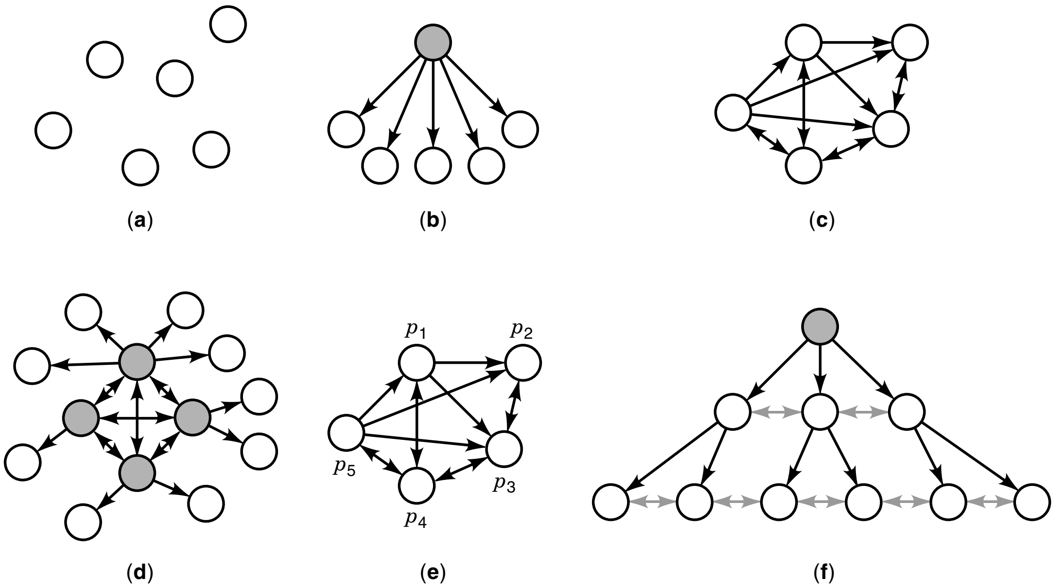


Figure 1. Network synchronization strategies. (a) Full plesiochrony; (b) Master-slave synchronization (despotism); (c) Mutual synchronization (democracy); (d) Mixed mutual/master–slave synchronization (oligarchy); (e) Hierarchical mutual synchronization (hierarchical democracy); (f) Hierarchical master–slave synchronization (hierarchical despotism).

Other biological examples are the synchronization of individual fibers in heart muscles to produce the familiar heartbeat or the resting and active periods of mammals, which exhibit rhythms.

During the last few decades, many different network synchronization strategies have been conceived, mainly for synchronizing the nodes of telecommunications networks, nowadays the most demanding application of network synchronization. The main features of such strategies are now summarized briefly, pointing out for each one its sociopolitical analogy. Such an analogy may be helpful in understanding immediately the pros and cons of each strategy, because it may be more direct to assess a form for governing human beings rather than clocks.

Full Plesiochrony (Anarchy)

The full plesiochronus strategy is actually a *no-synchronization strategy,* that is, does not involve any synchronization distribution to the network of clocks. Each clock is independent of the others (*autonomous clocks*), as shown in Fig. 1(a), hence the expression synchronization *anarchy.*

Anarchy is the easiest form of government, but it relies on the good behavior of the single elements. Because of the lack of any timing distribution, the synchronization of the processes in different nodes is entrusted to the accuracy of the network's autonomous clocks, which therefore must feature excellent performance.

In the late 60s, this strategy was generally considered the most promising for synchronizing telecommunications networks because of the decreasing cost of atomic oscillators and the limited synchronization requirements envisaged then. Nevertheless, as the cost of such oscillators became stable and the new digital transmission and switching techniques demanded increasing timing performance, this strategy was eventually abandoned.

Master-Slave Synchronization (Despotism)

The principle of master–slave (MS) strategies is based on the distribution of the timing reference from a clock (*master clock*) to all of the other clocks of the network (*slave clocks*), directly or indirectly as shown in Fig. 1(b). Although the master clock must be an expensive high-precision oscillator (usually based on an atomic frequency standard), slave clocks can be much less expensive. A slave clock is usually implemented as a PLL, mostly based on a quartz crystal oscillator and locked to the reference timing signal coming from the master. In PLLs, the output timing signal is kept synchronous with the input reference by a feedback control on the phase error between them.

The loop time constant of the PLL controls its filtering properties from the phase fluctuations of the input reference and of the internal oscillator. Further details can be found in the section "Characterization and Modeling of Clocks" and in Refs. 8–11. Therefore, an important step in designing a MS synchronization network is to design the loop time constants of the slave clocks in different nodes, according to specific requirements.

Despotism may look unethical, but it is certainly effective in ensuring very tight control on the slaves. A MS network is synchronous with the master clock and stable by definition. Therefore, MS-based strategies are currently the most widely adopted in many applications. Questions may arise, nevertheless, on what happens if the unique master fails. The hierarchical MS strategy has been conceived for this purpose.

Mutual Synchronization (Democracy)

Mutual synchronization is based on direct, *mutual control* among the clocks, so that the output frequency of each one is the result of the "suggestions" of the others, as shown in Fig. 1(c). Such pure democracy looks appealing. There are no masters and no slaves, but mutual cooperation exists, though the "discipline" of the mutually controlled elements is hard to guarantee.

Modeling the behavior of such networks or even ensuring the stability of the control algorithms (the control algorithm must damp the transient impairments, preventing them from propagating indefinitely) can be a very complex task (4,12,13). Thus networks so designed are quite expensive, but they are extremely reliable. Hence, till now, the field of application of mutual synchronization has been limited mostly to special cases, for example, military networks.

Mixed Mutual/Master-Slave Synchronization (Oligarchy)

In this mixed solution, the mutual synchronization strategy is adopted for the main clocks of the network, and the MS strategy is adopted for the peripheral clocks, as shown in Fig. 1(d).

Oligarchy is a compromise that aims at mitigating the absolutism of despotism. Greater reliability is achieved, and the peripheral MS synchronization substantially simplifies the system control architecture compared with pure mutual synchronization.

Hierarchical Mutual Synchronization (Hierarchical Democracy)

Hierarchical mutual synchronization is a generalization of the democratic strategy. In hierarchical democracy, some count more than others.

All of the network nodes are given a relative weight p_i ($0 \le p_i \le 1$, $\Sigma_i\, p_i = 1$), as shown in Fig. 1(e). When all of the weights are equal, this strategy becomes pure mutual synchronization. When the weight of one clock is equal to one and all of the others are equal to zero, this strategy becomes a MS synchronization.

Hierarchical Master-Slave Synchronization (Hierarchical Despotism)

The Hierarchical Master-Slave (HMS) synchronization strategy is a variant of the pure MS strategy. A master clock synchronizes the slave clocks, directly or indirectly, and these are organized in two or more hierarchical levels [see Fig. 1(f)]. Protective mechanisms against link and clock failures are allowed through alternative transversal synchronization routes. If the master fails, another clock takes its place according to a hierarchical plan.

The HMS strategy is currently the most widely adopted for synchronizing modern digital telecommunications networks because of the excellent timing performance and reliability which is achieved at limited cost.

Mixed Plesiochronous/Synchronous Networks (Independent Despotic States)

Although most national administrations adopted the HMS strategy for synchronizing their national networks, locking all of them to a supranational timing reference is not feasible (it is worth noting that the GPS can take this role from a *technical* point of view, but for *political* reasons it is hardly accepted as first-choice reference by most national administrations). Therefore, the current arrangement is to have several synchronous HMS networks, each plesiochronous relative to the others. The political analogy is a set of independent despotic states.

CHARACTERIZATION AND MODELING OF CLOCKS

Designing such complex systems as networks of clocks or specifying the quality requirements of clocks suitable for a given application is not an obvious task. To face these issues effectively, first it is necessary to identify a proper mathematical model of the clock and of the timing signals generated and distributed. This section supplies this background knowledge. Simplified models of autonomous and slave clocks are described and the basics of time and frequency stability characterization are provided.

Timing Signal Model

A general expression describing a pseudoperiodic waveform that models the timing signal $s(t)$ at the output of clocks is given by Eq. (1). A common and comprehensive model used to characterize $\nu(t)$, defined by Eq. (2), is given by [see the ideal case of Eq. (3)]

$$\begin{aligned}\nu(t) &= \nu_0 + \nu_{\mathrm{d}}(t) + \nu_{\mathrm{a}}(t)\\ &= \nu_{\mathrm{n}} + \Delta\nu + \sum_{k=1}^{K-1} \frac{q_k t^k}{k!} + \frac{1}{2\pi}\frac{d\varphi(t)}{dt}\end{aligned} \tag{4}$$

The *nominal frequency* ν_{n} (design goal) and the *starting frequency offset* $\Delta\nu$ (also called *synchronization error*) make up the starting frequency ν_0 of the oscillator:

$$\nu_0 = \nu_{\mathrm{n}} + \Delta\nu \tag{5}$$

The term $\nu_{\mathrm{d}}(t)$ is the deterministic (for a given oscillator) time-dependent component, modeling the *frequency drift* mainly caused by oscillator aging as a power series:

$$\nu_{\mathrm{d}}(t) = \sum_{k=1}^{K-1} \frac{q_k t^k}{k!} \tag{6}$$

The coefficients q_i ($k = 1, 2, \ldots, K - 1$) are time-independent, random variables that are fixed for a given oscillator. The frequency drift in real clocks is caused by complex phenomena (14,15), but in practice, for simplicity, the previous summation is often truncated to the first term, so that

$$\nu_{\mathrm{d}}(t) \cong q_1 t = D\nu_{\mathrm{n}} t \tag{7}$$

where D is the *linear, fractional-frequency drift* rate.

Finally, the term $\nu_{\mathrm{a}}(t)$ is the random time-dependent component

$$\nu_{\mathrm{a}}(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \tag{8}$$

where $\dot{\varphi}(t)/(2\pi)$ and $\varphi(t)$ are stochastic processes, respectively, the *random frequency deviation* and the *random phase deviation* that model oscillator intrinsic phase-noise sources.

Basic Quantities

Two functions strictly related to $\dot{\varphi}(t)$ and $\varphi(t)$ are used in treating random frequency and time fluctuations: the *random* *fractional-frequency deviation* $y(t)$ and the *random time deviation* $x(t)$, defined as

$$\begin{aligned} y(t) &= \frac{1}{2\pi\nu_{\rm n}}\frac{d\varphi(t)}{dt} \\ x(t) &= \frac{\varphi(t)}{2\pi\nu_{\rm n}} \end{aligned} \tag{9}$$

These functions, together with the model and definitions provided in the previous section, have been widely adopted by specialists since the 60s (2,16). More recently, needs in particular in the telecommunications field for designing synchronization equipment and networks led to the introduction of the following other basic functions, more oriented to the timing aspects of clocks.

The generated *time* function $\mathrm{T}(t)$ of a clock is defined in terms of its total instantaneous phase as

$$\mathrm{T}(t) = \frac{\Phi(t)}{2\pi\nu_n} \tag{10}$$

It is worth noting that for an ideal clock $\mathrm{T_i}(t) = t$ holds, as expected. For a given clock, the *time error* function $\mathrm{TE}(t)$ between its time $\mathrm{T}(t)$ and a reference time $\mathrm{T_r}(t)$ is defined as

$$\mathrm{TE}(t) = \mathrm{T}(t) - \mathrm{T_r}(t) \tag{11}$$

Whereas the time error variation over an interval of duration τ starting at time t (i.e., the error committed by the clock in measuring an interval τ with respect to the reference clock) is called *time interval error* $\mathrm{TIE}_t(\tau)$ and is defined as

$$\begin{aligned} \mathrm{TIE}_t(\tau) &= [\mathrm{T}(t+\tau) - \mathrm{T}(t)] - [\mathrm{T_r}(t+\tau) - \mathrm{T_r}(t)] \\ &= \mathrm{TE}(t+\tau) - \mathrm{TE}(t) \end{aligned} \tag{12}$$

Now, it must be pointed out that $x(t)$ and $\mathrm{TE}(t)$ have very similar definitions, but they differ in that the $\mathrm{TE}(t)$ function takes into account both deterministic [the $\Delta\nu$ and $\nu_{\rm d}(t)$ terms in Eq. (4)] and random phase-noise components, whereas $x(t)$ depends only on random components. Finding the deterministic components in the TE measured data may not be straightforward, and the result can depend greatly on the parameter estimation technique adopted (14,17,18).

Basic Concepts of the Quality of Clocks

Characterizing the *quality* of a clock (or equivalently of its timing signal) is one of the most complex and debated tasks in coping with the issues involved in practical applications of clocks. In the most common sense, one simple term is used to refer to clock quality: the *precision,* somehow denoting how close the timing signal of the clock under test is to a reference timing signal. From a more technical viewpoint, the quality of a clock is usually defined by two other basic terms: stability and accuracy. Although it must be recognized that researchers and engineers working in different fields may understand these two terms with subtly different meanings, the definitions provided in the following can be considered quite general.

The *stability* of a clock deals with measuring the random and deterministic variations of the instantaneous frequency (or of the time) of the output timing signal, compared to the nominal value (i.e., in practice, to a reference clock), over a given observation interval. With reference to the mathematical model of Eq. (4), the clock stability depends on the random phase noise $\varphi(t)$, the frequency offset $\Delta\nu$, and the frequency drift D (and all the coefficients q_i). The relative weights of such parameters in affecting stability depend on the observation interval. If it is short, the frequency drift is negligible.

When the observation interval is small, the expression *short-term* stability is commonly used. Otherwise the expression *long-term* stability applies. What should be the meaning of the word "small", that is, where the boundary between short and long term is, depends on the specific application. For example, in the time metrology field, it is common to consider observation intervals longer than one day as long-term, whereas in telecommunication applications observation intervals over 100 s are also definitely considered long term.

Since the 1960s, several quantities have been defined that aim at characterizing clock stability. Although they differ in applicability, they highlight distinct phenomena in the phase noise or they are more oriented to some application. A few details are given in the following subsections.

Accuracy, on the other hand, denotes the maximum frequency error $\Delta\nu_{\rm MAX}$ compared to the nominal value, which may be measured in general over the entire clock life (e.g., twenty years), unless specified differently. It must be pointed out that accuracy also depends in principle on the previously mentioned parameters $\varphi(t)$, $\Delta\nu$, and the coefficients q_i, but in this case the observation interval is so long that in practice the only relevant quantities are the frequency offset and drift. Accuracy is usually expressed by the dimensionless ratio $\Delta\nu_{\rm MAX}/\nu_{\rm n}$ and is often measured in 10^{-6} units (μHz/Hz), in engineering practice also called parts per million and abbreviated as ppm (not a SI unit).

Autonomous Clocks

An *autonomous clock* is a device for generating a timing signal, suitable for measuring time intervals, starting from a periodic physical phenomenon.

Examples of state-of-the-art autonomous clocks are atomic frequency standards (such as the rubidium or cesium-beam or hydrogen-MASER oscillators) and crystal quartz oscillators. Some of them (the rubidium and the quartz oscillators) may also be locked to a reference timing signal and thus work as slave clocks.

A simplified model of an autonomous clock is shown in Fig. 2. Here, according to the timing signal model of Eq. (4), the

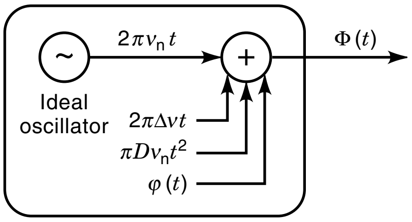


Figure 2. Simplified model of autonomous clock.

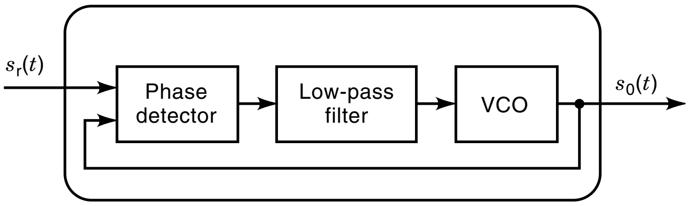


Figure 3. Scheme of the principle of a phase-locked loop (PLL).

total output phase $\Phi(t)$ consists of three deterministic terms that model the phase generated by an ideal oscillator, the frequency offset $\Delta\nu$, and the frequency drift D, together with the random phase noise $\varphi(t)$.

The parameter $\Delta\nu$ decreases with more accurate clock calibration procedures (this is part of the production process). Such calibration procedures aim at making the clock generate an output frequency as close as possible to the nominal frequency. As for the frequency drift coefficient D, it is worth noting that it is practically null in cesium-beam oscillators, but it cannot be neglected in rubidium and quartz oscillators, at least in the most demanding applications. Finally, some details above the characteristics of the random phase-noise process $\varphi(t)$ are provided in the section Common Types of Clock Noise.

Slave Clocks

A *slave clock* is a device for generating a timing signal, suitable for measuring time intervals whose phase (or much less frequently frequency) is locked to a reference timing signal at its input. They are usually implemented as PPLs (or FLLs).

Slave clocks are very widely employed (see Network Synchronization Strategies) in synchronization networks and in digital telecommunication equipment. Such a widespread application of slave clocks calls for a somewhat detailed description of their models and properties. Therefore, the next subsections deal with the main characteristics of PLLs and the operating modes of slave clocks in synchronization networks.

Phase-Locked Loops. A device that implements phase locking to a reference timing signal commonly uses loop architecture, based on the negative feedback principle, where the output signal keeps tracking the phase fluctuations of the input reference. Such a device is called *phase-locked loop* (PLL).

A scheme of the principle of PLL operation is depicted in Fig. 3. In this scheme, the following functional blocks are used:

- *phase detector,* which supplies a signal proportional to the phase error between the PLL output signal $s_o(t)$ fed back and the input reference $s_r(t)$;
- *low-pass filter* (*loop filter*), whose task is canceling the high-frequency phase fluctuations at the output of the phase detector;
- *voltage-controlled oscillator* (VCO), which supplies a periodic signal that has a frequency dependent on its input signal; the VCO, with null input signal, oscillates with angular frequency ω_F (VCO free-run angular frequency).

To summarize, the phase detector supplies a signal proportional to the phase error between $s_o(t)$ and $s_r(t)$. This signal is low-pass filtered and feeds the VCO to control its oscillation frequency and keep the phase error between $s_o(t)$ and $s_r(t)$ around zero.

Analysis of the PLL operation is very complex because of the nonlinear phase-detector block. A detailed analysis of its properties can be found in Refs. 8–10. Moreover, Ref. 11 glances at practical implementation. In this section, only the main features of PLL are overviewed.

Assuming that the phase error between $s_o(t)$ and $s_r(t)$ remains small (PLL locked to the reference), the system can be described by a linear model. Therefore, its input-output transfer function $H(s)$ between the input and output phase-modulation signals in the Laplace-transform domain can be evaluated. The transfer function $H(s)$ is typically of the second-order low-pass type (because the loop filter is typically first-order), with cutoff frequency B (PLL bandwidth). It is characterized by the natural angular frequency ω_n and the damping factor ζ and thus has the form

$$H(s) = \frac{\phi_o(s)}{\phi_r(s)} = \frac{Cs + D}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{13}$$

where C and D are constants dependent on the particular PLL characteristics.

The PLL tracks the phase modulation of the reference signal $s_r(t)$ if the bandwidth of the phase-modulation signal is lower than B. Under static lock conditions (i.e., $s_r(t)$ is ideally periodic), the phase detector supplies a time-constant signal which makes the VCO oscillate at the same frequency of $s_r(t)$. The values ω_n and ζ are determined by the design of the PLL blocks, and they control the duration, amplitude, and shape of the transients in the PLL response $s_o(t)$ to disturbances in $s_r(t)$.

Noise in PLLs. Characterizing noise sources in a PLL is a very important topic that aims at evaluating slave clock performance. The linear model, depicted in Fig. 4, approximates PLL behavior by pointing out the main internal noise sources (a more thorough analysis is provided in Ref. 10). This model holds under the assumptions that the PLL is locked to the reference and that the noise amplitudes are small, compared to the signals.

In Fig. 4, ϕ_o and ϕ_r (rad) are the phase noises in $s_o(t)$ and $s_r(t)$, respectively, ϕ_{VCO} (rad) is the phase noise generated by the VCO, V_{DF} (V) is the tension noise produced by the phase detector and the loop filter, and $F(s)$ is the transfer function of the low-pass loop filter (all quantities in the Laplace domain).

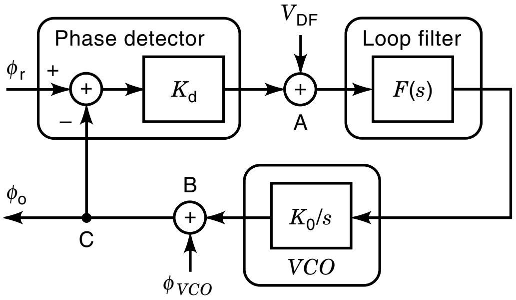


Figure 4. Linear model in the Laplace-transform domain of a phase-locked loop (PLL) with the main internal noise sources.

By analyzing this model, considering one input at a time, the following transfer functions can be evaluated:

$$H(s) = \frac{\phi_o(s)}{\phi_r(s)} = \frac{K_0 K_d F(s)}{s + K_0 K_d F(s)} \tag{14}$$

$$H_A(s) = \frac{\phi_o(s)}{V_{DF}(s)} = \frac{K_0 F(s)}{s + K_0 K_d F(s)} \tag{15}$$

$$H_B(s) = \frac{\phi_o(s)}{\phi_{VCO}(s)} = \frac{s}{s + K_0 K_d F(s)} \tag{16}$$

The transfer functions $H(s)$ and $H_A(s)$ are low-pass, and $H_B(s)$ is high-pass (because the loop filter $F(s)$ is low-pass). Therefore,

- the phase noise in the reference signal $s_r(t)$ and the internal tension noise produced by the phase detector and the loop filter are low-pass filtered to the output signal $s_o(t)$;
- the internal phase noise produced by the VCO is high-pass filtered to the output signal $s_o(t)$.

Key Parameters of PLLs. Four key parameters describe the performance of a PLL (here, the angular frequencies ω are considered, but the equivalent frequencies f can also be considered because $\omega = 2\pi f$):

- the *hold-in range* $\Delta\omega_{HI}$, defined as the maximum deviation of the frequency of the input signal $s_r(t)$ from the VCO free-run angular frequency ω_F within which the PLL can track slow (quasi-stationary) variations of the input frequency;
- the *pull-out range* $\Delta\omega_{PO}$, defined as the maximum deviation of the input frequency from ω_F within which the PLL can track fast variations (e.g., like steps) of the input frequency;
- the *lock-in range* $\Delta\omega_{LI}$, defined as the maximum deviation of the input frequency from ω_F within which the PLL can lock fast (i.e., faster than $1/\omega_F$ seconds) to the new input frequency;
- the *pull-in range* $\Delta\omega_{PI}$, defined as the maximum deviation of the input frequency from ω_F within which the PLL can lock in any time to the new input frequency.

Typically, $\Delta\omega_{LI} < \Delta\omega_{PO} < \Delta\omega_{PI} < \Delta\omega_{HI}$.

Operating Modes of Slaves Clocks. A slave clock may operate in the following three modes in a synchronization network:

- *Locked Mode.* The PLL tracks the input frequency, which is always within the hold-in and pull-out ranges. The lock mode may be *ideal,* if the reference signal is always available and stable, or *real* (stressed), if the reference is affected by impairments of various kinds.
- *Free-Run Mode.* If the reference signals fails, the clock works autonomously, supplying the free-run frequency ω_F of the internal oscillator (VCO) that works with null control tension. Generally, the nominal ω_F is designed equal to the nominal reference frequency.
- *Hold-Over Mode.* As in the free-run mode, if the reference signals fails, the clock works autonomously, supplying the frequency generated by the VCO. In this case, nevertheless, the last control tension value at the input of the VCO before the reference failure is maintained, so as to hold over the last output frequency value. More sophisticated clocks even store several subsequent samples of the VCO control tension, so that after entering the hold-over mode the VCO is controlled with variable tension extrapolated from the last data. Excellent hold-over accuracy can be achieved in this way, even under a substantial VCO nonlinear frequency drift.

Clock Stability Characterization

The background work on clock stability characterization is immense and broad in range. By the late 1960s, the pressure from clock manufacturers, time and frequency metrologists, and application engineers, all demanding a common set of frequency stability characterization parameters, led the IEEE to convene a committee to recommend uniform measures of frequency stability (2,16). Before and after this breakthrough, since the 1960s, several quantities have been defined aimed at characterizing clock stability. Although differing in ability, they highlight distinct phenomena in the phase, time, or frequency noise, or they are more oriented to some applications. A thorough and detailed treatise on time and frequency stability characterization and measurement is beyond the scope of this article. Refs. 2, 3, and 17–24 provide further information about this topic.

Frequency-Domain Versus Time-Domain Characterization. The characterization of clock stability is usually carried out by characterizing, by suitable analytical tools, the random processes $\varphi(t)$, $x(t)$, TE(t), $y(t)$, or $\nu(t)$ [see Eq. (4), Eq. (9), and Eq. (11)].

Historically, a dichotomy became established between the characterization of such processes in the *Fourier frequency domain* and in the *time domain.* The inadequacy of measurement equipment strengthened the barriers between these two characterizations of the same noise process. Though these barriers are mainly artificial, nevertheless, it is not always possible to translate unambiguously from any quantity in one domain to any in the other.

Examples of stability measures in the frequency domain are the one-sided power spectral densities (PSDs, or more simply spectra) of phase, time, and frequency fluctuations, as functions of the Fourier frequency. On the other hand, the variances of the fluctuations averaged over an observation interval (e.g., the Allan variance), apart from the fact that they are evaluated starting from samples of time error or of instantaneous frequency, are examples of stability measures in the time domain as functions of the observation interval (time).

Clock Stability Characterization in the Frequency Domain: Power Spectral Densities. The most straightforward and intuitive way to characterize the stability of a timing signal $s(t)$ is to evaluate directly its two-sided spectrum, often denoted as $S_s^{RF}(f)$ (spectrum in radio frequency), or more precisely its low-pass representation. The variable f is the Fourier frequency. Positive values of f denote frequencies above ν_n. Negative values denote frequencies below ν_n. The spectrum $S_s^{RF}(f)$ is a continuous-time function proportional to the timing signal power per unit of bandwidth centered around f. The spectrum

$S_s^{\mathrm{RF}}(f)$ is definitely *not* a good tool to characterize clock frequency stability. Unfortunately, given $S_s^{\mathrm{RF}}(f)$, it is not possible to determine unambiguously if the power at the various Fourier frequencies results from amplitude rather than phase fluctuations in the timing signal $s(t)$.

Commonly used stability measures in the frequency domain are, instead, the one-sided PSDs of $\varphi(t)$, $x(t)$, and $y(t)$, denoted as $S_\varphi(f)$ (rad^2/Hz), $S_x(f)$ (ns^2/Hz) and $S_y(f)$ (Hz^{-1}), respectively, because they describe the time and frequency stability characteristics directly. The following relationships hold:

$$\begin{aligned} S_y(f) &= \frac{f^2}{\nu_\mathrm{n}^2} S_\varphi(f) \\ S_x(f) &= \frac{S_\varphi(f)}{(2\pi\nu_\mathrm{n})^2} \\ S_y(f) &= (2\pi f)^2 S_x(f) \end{aligned} \tag{17}$$

For a long time, the analog measurement of these PSDs in the frequency domain has been the main technique for studying the behavior of oscillators. More recently, the introduction of high-resolution digital instrumentation for the measurement in the time domain (time counters) made time-domain measurement more appealing in most applications. As a matter of fact, the recent telecommunication standards recommend time-domain quantities evaluated starting from measured samples of time error as standard stability measures.

Clock Stability Characterization in the Time Domain: Telecommunications Standard Quantities. Although the previous frequency-domain characterization has proven very meaningful and complete in studying the behavior of oscillators, it is important to point out that the main concern in many modern applications, for example, in digital telecommunications, lies in controlling *time* deviations over given observation intervals (the buffer fill level in digital telecommunications equipment is proportional to the time error cumulated between the write and read clocks). Therefore, the time-domain stability quantities, basically a sort of prediction of the expected time and frequency deviations over an observation interval τ, are more oriented to this purpose.

Because of the prominent role of timing and synchronization in modern digital telecommunications and therefore the increasing interest in clock stability time-domain characterization far beyond the narrow circle of oscillator designers and time and frequency metrologists, this section focuses in particular on the time-domain quantities adopted for telecommunication standards to specify clock stability.

Among the several quantities defined in the literature for characterizing time and frequency stability, the following five in the time domain have been considered by telecommunication international standard bodies (25,26) for specifying timing interface requirements: the *Allan Deviation* (ADEV) $\sigma_y(\tau)$ square root of the Allan Variance (AVAR); the *Modified Allan Deviation* (MADEV) mod$\sigma_y(\tau)$ square root of the Modified Allan Variance (MAVAR); the *Time Deviation* (TDEV) $\sigma_x(\tau)$ square root of the Time Variance (TVAR); the *root-mean-square of Time Interval Error* (TIErms); and the *Maximum Time Interval Error* (MTIE). For the formal definitions of the first three quantities and the relevant theoretical background, the reader is referred to the works cited (2,3,19–24). The last two quantities, on the other hand, have been widely used by telecommunication engineers and look somewhat "exotic" to the traditional world of time and frequency metrology. A rather detailed analysis of their properties is available in Refs. 27 and 28.

For the practical purposes of telecommunications clock stability measurement (29), processes TE(t) and $x(t)$ are considered synonymous [see Eqs. (9) and (11)]. Therefore, based on a sequence of N TE samples, defined as

$$x_i = x[t_0 + (i-1)\tau_0] \qquad i = 1, 2, \ldots, N \tag{18}$$

that is measured with sampling period τ_0 over a measurement interval $T = (N-1)\tau_0$ starting at an initial observation time t_0, the following five standard estimators have been defined by the ITU-T (25) and ETSI (26) bodies:

$$\begin{aligned} \mathrm{ADEV}(\tau) &= \sqrt{\frac{1}{2n^2\tau_0^2(N-2n)} \sum_{i=1}^{N-2n} (x_{i+2n} - 2x_{i+n} + x_i)^2} \\ n &= 1, 2, \ldots, \left\lfloor \frac{N-1}{2} \right\rfloor \end{aligned} \tag{19}$$

$$\begin{aligned} &\mathrm{MADEV}(\tau) \\ &\quad = \sqrt{\frac{1}{2n^4\tau_0^2(N-3n+1)} \sum_{j=1}^{N-3n+1} \left[\sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2} \\ &n = 1, 2, \ldots, \left\lfloor \frac{N}{3} \right\rfloor \end{aligned} \tag{20}$$

$$\begin{aligned} &\mathrm{TDEV}(\tau) \\ &\quad = \frac{\tau}{\sqrt{3}} \mathrm{MADEV}(\tau) \\ &\quad = \sqrt{\frac{1}{6n^2(N-3n+1)} \sum_{j=1}^{N-3n+1} \left[\sum_{i=j}^{n+j-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2} \\ &\quad n = 1, 2, \ldots, \left\lfloor \frac{N}{3} \right\rfloor \end{aligned} \tag{21}$$

$$\mathrm{TIErms}(\tau) = \sqrt{\frac{1}{N-n} \sum_{i=1}^{N-n} (x_{i+n} - x_i)^2} \quad n = 1, 2, \ldots, N-1 \tag{22}$$

$$\begin{aligned} \mathrm{MTIE}(\tau) &= \max_{1 \le k \le N-n} \left[\max_{k \le i \le k+n} x_i - \min_{k \le i \le k+n} x_i \right] \\ n &= 1, 2, \ldots, N-1 \end{aligned} \tag{23}$$

where $\tau = n\tau_0$ is the *observation interval* and $\lfloor z \rfloor$ denotes "the greatest integer not exceeding z."

Common Types of Clock Noise

Experimental measurements on clocks may exhibit a wide variety of types of noise, either generated by physical processes intrinsic to the oscillator hardware or caused by external phenomena, such as environmental perturbations, mechanical vibrations, residual ripples in the power supply, signal coupling via power supplies and ground paths, and electromagnetic interference.

Power-Law Noises

In the frequency domain, the model most frequently used to represent the output phase noise measured on clocks is the so-called *power-law model* (3). In terms of the one-sided PSD of $x(t)$, this model is expressed by

$$S_x(f) = \begin{cases} \dfrac{1}{(2\pi)^2} \displaystyle\sum_{\alpha=-4}^{0} h_{\alpha+2} f^{\alpha} & 0 \leq f \leq f_h \\ 0 & f > f_h \end{cases} \tag{24}$$

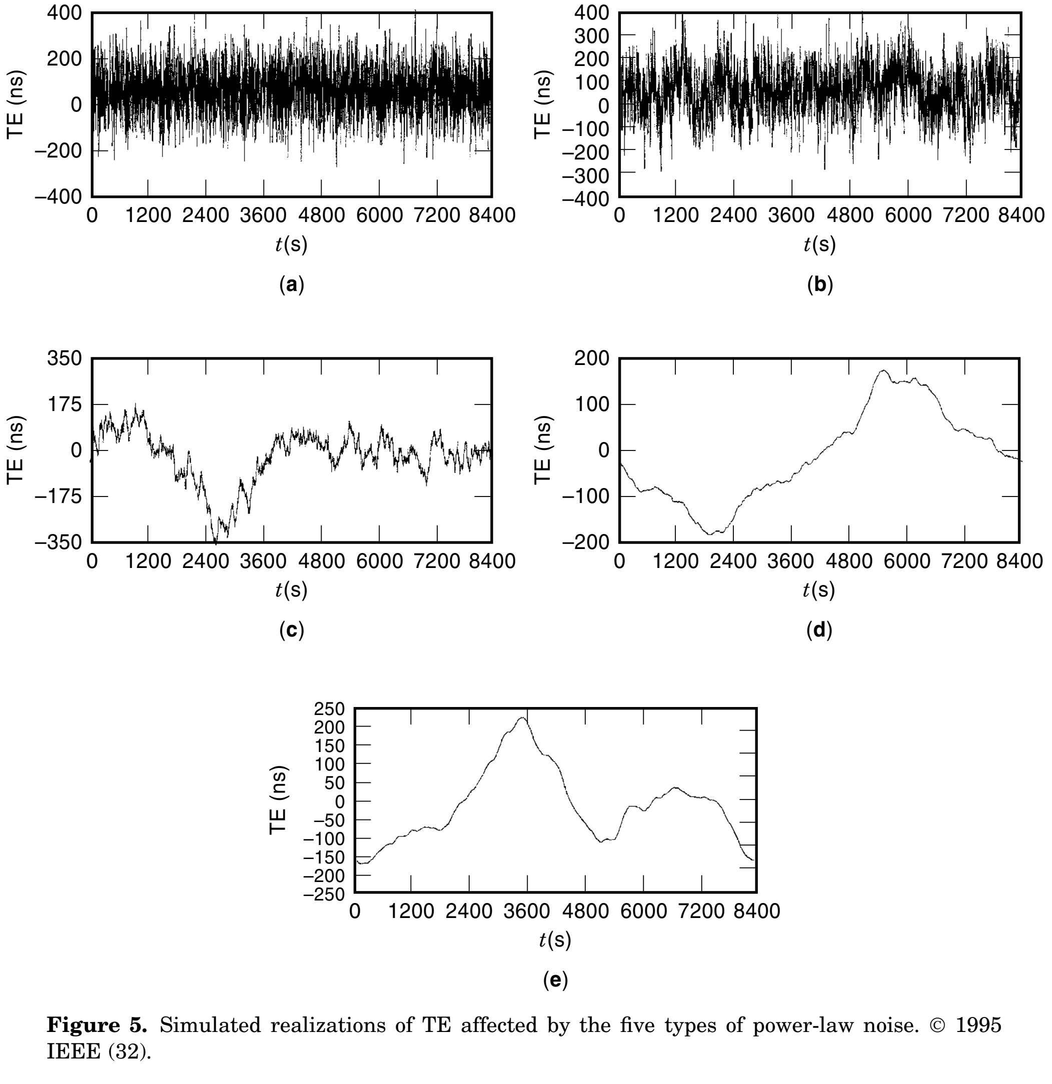
where the coefficients h_{-2}, h_{-1}, h_0, h_{+1}, and h_{+2} are device-dependent parameters [the reason for the subscript $\alpha + 2$, for $\alpha = -4, -3, -2, -1, 0$, is that, historically, the coefficients h_{-2}, h_{-1}, h_0, h_{+1}, and h_{+2} have been used in defining the power-law model in terms of $S_y(f)$], and f_h is an upper cutoff frequency, dependent mainly on low-pass filtering in the oscillator and in its output buffer amplifier. This clock upper cutoff frequency is usually in the range of 10 kHz to 100 kHz in precision frequency sources (30).

The five noise types of this model are White Phase Modulation (WPM) for $\alpha = 0$; Flicker Phase Modulation (FPM) for $\alpha = -1$; White Frequency Modulation (WFM) for $\alpha = -2$; Flicker Frequency Modulation (FFM) for $\alpha = -3$; and Random Walk Frequency Modulation (RWFM) for $\alpha = -4$. All of the stability quantities cited are sensitive, according to different laws, to the presence of these noises in the timing signal (3,27).

According to this model, the PSD $S_x(f)$, plotted on a log-log diagram, results approximately in a broken line composed of straight segments, one per each noise type and each having a slope equal to the corresponding power α. In the time domain, on the other hand, the random realizations of the noise process of each single type have characteristic trends which can be recognized at a glance by an experienced eye. To give an idea, Fig 5(a) through (e) shows sample realizations of TE affected, respectively, by the five types of power-law noise, simulated according to the procedure outlined in Ref. 31. Each realization is made of 4096 random TE samples, normally distributed and having a spectrum that obeys the law of Eq. (24) according to the value of α specified.

These noise processes may be from different physical causes (17) and, on a particular oscillator, they may all be recognized or some may not. The main features and the origin of each of the five types of power-law noise are now summarized as follows:

Random Walk Frequency Modulation (h_{-2}/f^4). Difficult to measure as close to the carrier (the ideal timing signal).



(a)

(b)

(c)

(d)

(e)

Figure 5. Simulated realizations of TE affected by the five types of power-law noise. © 1995 IEEE (32).

It is mostly ascribed to environmental effects. If RWFM noise dominates, then it is likely that frequent perturbations like mechanical shocks or temperature variations cause random shifts in the oscillation frequency.

Flicker Frequency Modulation (h_{-1}/f^3). The causes of this type of noise are not fully understood, but they are ascribed mostly to the physical resonance mechanism of an active oscillator or to phenomena in the control electronic devices. FFM noise is commonly recognized in high-quality oscillators but can be hidden by WFM or FPM noise in lower quality oscillators.

White Frequency Modulation (h_0/f^2). This is a type of noise commonly recognized in passive-resonator frequency standards, based on a slave oscillator (mostly a quartz) locked to a resonance of another device. Cesium-beam and rubidium standards feature a dominant WFM noise.

Flicker Phase Modulation (h_1/f^1). Although it may be related to a physical resonance mechanism of the oscillator, this noise is added mostly by noisy electronics, especially in the output amplification stages and in the frequency multipliers.

White Phase Modulation (h_2). This noise has little to do with the clock resonance mechanism, but it is added mainly by noisy electronics. In the past, this type of noise was often negligible in high-quality clocks, featuring very low-noise output stages. Nowadays, conversely, the spreading of clocks based on digital control electronics (such as the Digital PPLs, DPLLs) made the WPM noise the most commonly found in several applications, for example on telecommunications clocks, which are maybe the most impressive case of wide application of high-precision frequency sources. The substantial WPM noise in DPLLs is caused by the quantization error in the phase-lock loop, which produces a broadband white noise in the output timing signal. Moreover, WPM is the test-bench background noise caused by the trigger and quantization errors of time counters in the digital measurement of the TE.

Periodic Noise. Though the power-law model has proved very general and suitable for describing most measurement results, yet other types of noise may result in experimental measurements. Periodic noises are quite common. They may be typically caused by 50/60 Hz ac power line interference, diurnal temperature variations, or sensitivity to acoustic or mechanical vibrations, but they may be also due to intrinsic phenomena, such as special frequency control algorithms in DPLLs.

An example of real periodic noise is provided in Fig. 6, which shows the PSD $S_x(f)$ estimated from the TE data (N = 79000 samples spaced τ_0 = 23 ms over a total measurement period of T = 1800 s) measured on a telecommunications equipment [synchronous digital hierarchy (SDH) STM-16 Line Terminal] slave clock in the synchronized clock configuration (25) according to the procedure outlined in Ref. 29. This PSD exhibits several discrete terms (spikes) in the frequency domain at harmonic frequencies of about 1 Hz, superposed on a power-law noise.

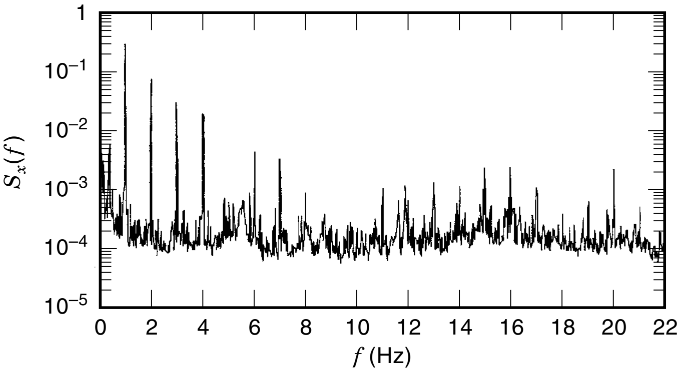


Figure 6. Experimental results featuring periodic noise. This graph shows the PSD $S_x(f)$ measured on a telecommunications equipment slave clock (SDH STM-16 Line Terminal). Several spikes are evident at harmonic frequencies of about 1 Hz. © 1997 IEEE (30).

TECHNOLOGY OF CLOCKS

Clocks are implemented by exploiting a physical mechanism of resonance generating a (pseudo-)periodic signal. In early clocks the oscillation was mechanical (e.g., pendulum clocks). Nowadays in high-precision clocks, on the other hand, the oscillation of atoms around their minimum-energy position in a quartz crystal or the atomic transition between two quantum energy levels is exploited. This section simply summarizes the physical operating principles of high-precision clocks. For a closer look at the physics and technology of quartz and atomic oscillators and their performance, the reader is referred to Refs. 32–37 and to the wide bibliography cited by the articles of Ref. 32.

Quartz Crystal Oscillators

Quartz oscillators are based on the piezoelectric effect discovered by P. Curie in 1880 (Nobel prize, 1903): a mechanical strain in the crystal yields an electrical field and vice versa. Thus a crystal oscillator (XO) is based on exciting a quartz crystal with a periodic electric signal at the resonance frequency (10 kHz to 100 MHz). The resulting resonator has a quality factor quite high (10^3 to 10^6) and, used in a feed-back circuit, allows generating a timing signal featuring excellent short-term stability (in particular over observation intervals smaller than one second). Because it performs well and is inexpensive, it is widely employed in most electronic equipment, for example, as voltage-controlled crystal oscillator (VCXO) in PLLs.

Temperature-Compensated Crystal Oscillators. The main problem with a plain XO is that its natural frequency depends on aging (around 10^{-7}/day in plain models) and on the temperature (typical values are on the order of 10^{-7}/°C or above). To overcome the latter problem, temperature-compensated crystal oscillators (TCXOs) implement feedback control on the oscillation frequency, based on measuring the crystal temperature. Such a device achieves frequency stability of 10^{-7} over a temperature interval from 0° to 50°C. Through digital control, more sophisticated models achieve frequency stability on the order of 10^{-8} in the temperature interval from 0° to 70°C.

Table 1. Typical Performance Data and Characteristics of Commonly Available Quartz Oscillators

	XO	TCXO	OCXO
Short-term stability $\sigma_y(\tau = 1\ \text{s})$		$1 \cdot 10^{-9}$	$1 \cdot 10^{-13}$ to $2 \cdot 10^{-11}$
Linear drift D	$>1 \cdot 10^{-6}$/year	$5 \cdot 10^{-7}$/year	$5 \cdot 10^{-9}$/year
Accuracy, 1 year	$2 \cdot 10^{-6}$ to $1 \cdot 10^{-5}$	$2 \cdot 10^{-6}$	$1 \cdot 10^{-8}$ to $1 \cdot 10^{-7}$
Temperature sensitivity	$>1 \cdot 10^{-7}$/°C	$>5 \cdot 10^{-7}$ (−55° to 85°C)	$1 \cdot 10^{-9}$ (−55° to 85°C)
Warm-up time		10 s (to $1 \cdot 10^{-6}$)	1 hour (to $1 \cdot 10^{-8}$)
Lifetime (performance guaranteed)	10 years to 20 years	>5 years	10 years to 20 years

Oven-Controlled Crystal Oscillators. Far better than compensating temperature variations with a feedback control is to insulate the oscillator thermally and to make it work in a constant-temperature oven. Such clocks are called oven-controlled crystal oscillators (OCXOs). Thus frequency stability values exceeding 10^{-9}/day are achieved. State-of-the-art OCXOs, based on a double-oven temperature control and on a special technology of crystal excitation, may even achieve frequency stability on the order of 10^{-10}/day.

Performance and Characteristics of Crystal Oscillators. Table 1 summarizes some typical performance data and characteristics of quartz oscillators (for further data see Refs. 35–37). Performance is expressed in terms of the short-term stability (Allan variance) over one second, of the linear drift D (in parts $\Delta\nu_{\text{MAX}}/\nu_{\text{n}}$ per year), of the accuracy expected over one year ($\Delta\nu_{\text{MAX}}/\nu_{\text{n}}$) and of the temperature sensitivity. Moreover, the warm-up time is expressed in terms of the time needed to achieve the accuracy specified between brackets.

Atomic Frequency Standards

The operating principle of passive atomic frequency standards is based on achieving a resonance frequency maximizing the number of atomic transitions between two quantum energy levels A and B (characterized by different magnetic moments of one unpaired electron). The energy difference $E_{\text{B}} - E_{\text{A}}$ between the two states is proportional to Planck's constant h and to the frequency ν_0 of the electromagnetic radiation that excites the transition, according to Bohr's law

$$E_{\text{B}} - E_{\text{A}} = h\nu_0 \tag{25}$$

A feedback control, aiming at maximizing the number of atomic transitions from A to B, then allows the system to synchronize on the frequency ν_0 (in the microwave range) within the frequency width given by Heisenberg's uncertainty principle. Hence, the accuracy of the output timing signal is determined solely by the atomic physical properties of the element adopted, that is, on fundamental constants which do not depend on space and time (within known relativistic effects).

Cesium-Beam Frequency Standard. The scheme of the principle of a basic cesium-beam frequency standard is shown in Fig. 7. An oven with a few grams of the isotope 133 of cesium (^{133}Cs) effuses cesium atoms uniformly distributed among 16 quantum energy levels, and the resonator is based on the transition between the levels characterized by magnetic moments $F = 4$ (level A) and $F = 3$ (level B). The nonhomogeneous magnetic field in magnet 1 (polarizer) deflects only the level B atoms through the resonant cavity, where a microwave signal at frequency $\nu_0 = 9.192631770$ GHz stimulates their transition to level A. The nonhomogeneous magnetic field in magnet 2 (analyzer) deflects only the level A atoms to a detector. Thus the atom flux detected is proportional to the transition probability from level B to level A. Finally, the signal output by the detector is used to control a quartz VCXO, from which the microwave radiation and the output timing signal are synthesized, aiming at maximizing the number of transitions. Therefore the VCXO is locked to the atomic resonance frequency. The excellent short-term stability of the quartz oscillator is coupled with the excellent long-term stability of the atomic resonator.

Hydrogen MASER Frequency Standard. The operating principle of a hydrogen MASER (Microwave Amplification by Stimulated Emission of Radiation) frequency standard is based on the stimulated emission of electromagnetic radiation at the frequency ν_0 corresponding to the transition of hydrogen atoms between states that have magnetic moments $F = 1$ and $F = 0$. As shown in Fig. 8, the hydrogen atoms in the state $F = 1$ are deflected by a nonhomogeneous magnetic field of intensity 1 T into a storage bulb surrounded by a high-Q microwave resonant cavity, which is exposed to another internal magnetic field of intensity 10^{-7} T designed to resonate at the transition frequency $\nu_0 = 1.420450751$ GHz. Then the hydrogen atoms decay to state $F = 0$ by bouncing inside the bulb, and microwave electromagnetic radiation at frequency ν_0, stimulated by the magnetic field, is emitted and detected by

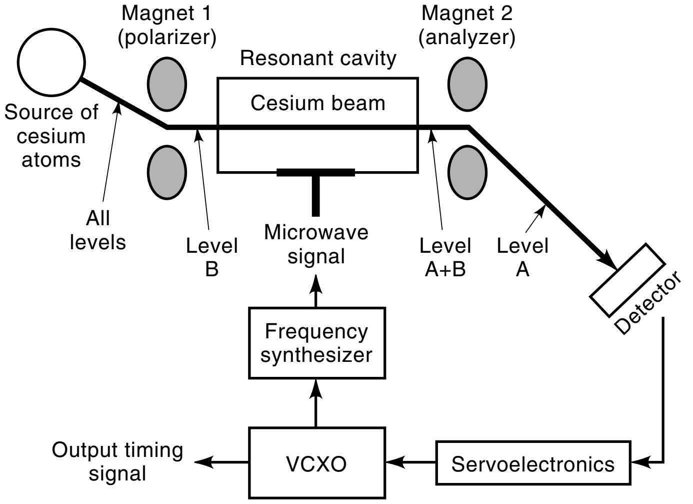


Figure 7. Scheme of the principle of a cesium-beam frequency standard.

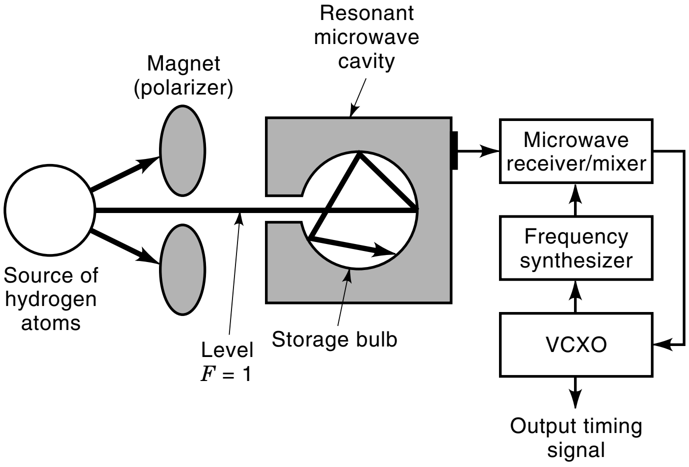


Figure 8. Scheme of the principle of a passive hydrogen MASER frequency standard.

an antenna. Finally, a quartz VCXO is kept locked to this signal to produce the output timing signal.

Rubidium Gas-Cell Frequency Standard. This frequency standard is based on the transition of atoms of ^{87}Rb between the base levels characterized by magnetic moments $F = 1$ and $F = 2$. A scheme of the principle of a rubidium gas-cell frequency standard is shown in Fig. 9. Light from a lamp filled with ^{87}Rb is filtered through a cell (hyperfine filter) containing ^{85}Rb vapor before it excites ^{87}Rb gas atoms in a cell (absorption cell) inside a resonant microwave cavity. The filter cell allows only the light spectrum component that excites the level $F = 1$ to reach the absorption cell, where this level is thus depopulated as ^{87}Rb atoms absorb the light radiation and migrate to the upper level and then down to both the base levels $F = 1$ and $F = 2$ (optical pumping). If the level $F = 1$ is depopulated by light absorption, the cell becomes transparent, but microwave radiation at $\nu_0 \cong 6.834682613$ GHz is applied to the atoms and excites the transition again to level $F = 1$. In resonance, when the frequency of the applied microwave radiation is exactly ν_0, the signal at the photodetector shows a minimum. Thus the VCXO is driven accordingly to keep light absorption at its maximum.

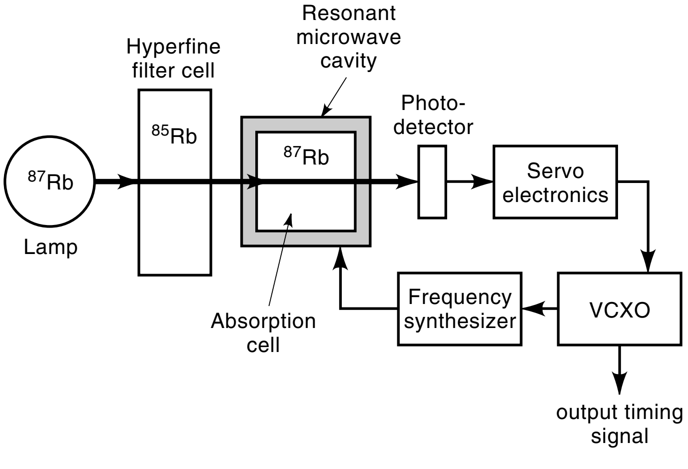


Figure 9. Scheme of the principle of a rubidium gas-cell frequency standard.

The center frequency generated may deviate considerably (10^{-9}) from the theoretical value because of several kinds of environmental causes. For this reason, Rb frequency standards are not suited as *primary* standards, but need to be calibrated against cesium-beam or hydrogen masers, though their short-term stability is usually much better than that of Cs standards.

Performance and Characteristics of Atomic Frequency Standards. Table 2 summarizes typical performance data and characteristics of atomic frequency standards (for further data, see Refs. 35–37). As in Table 1, performance is expressed in terms of the short-term stability (Allan variance) over one second, of the linear drift D (in parts $\Delta\nu_{\mathrm{MAX}}/\nu_{\mathrm{n}}$ per year), of the accuracy expected over one year ($\Delta\nu_{\mathrm{MAX}}/\nu_{\mathrm{n}}$) and of the temperature sensitivity. Moreover, the warm-up time is expressed in terms of the time needed to achieve the accuracy specified between brackets.

The Ground Positioning System

The Ground Positioning System (GPS) is not actually a *clock,* but rather a complex system of clocks and satellites. Because it supplies, beyond the positioning service, the most accurate timing reference signal available worldwide, it is treated in this section as it can be considered, broadly speaking, a sort of *superclock.*

GPS is a satellite radio system providing continuous and real-time three-dimensional position, velocity, and time information to suitably equipped users anywhere on the surface of the earth. Born essentially as a navigation and positioning tool, it is used also as a pure time reference (e.g., in telecommunications).

The NAVSTAR system operated by the US Dept. of Defense is the first GPS system available to civilian users. It has been in design since 1973 to take the place of the older navigation system LORAN-C and was completed in 1994, when the last satellites were launched. The Russian GPS system, called GLONASS, is very similar to NAVSTAR. These systems consist of three segments, the space, the control, and the user segments.

This section provides a quite general overview of GPS. A starting point for further details on GPS and its applications are Refs. 38 and 39. Nice and thorough overviews, moreover, are available on the Internet web, in particular at the addresses (40,41). Official pages on the web are provided by the US Air Force on NAVSTAR (42) and by the Russian Space Forces on GLONASS (43), together with almost real-time information (e.g., satellite status reports).

Space Segment. The space segment consists of a set of satellites (constellation), equipped with Cs or Rb atomic clocks, controlled by earth, and transmitting radio signals which can be received by user equipment.

The NAVSTAR constellation is composed of 21 satellites (plus three on-orbit spares) on six orbital planes. The satellites operate in 20200 km circular orbits with an inclination angle of 55° and a period of 12 h. The spacing of satellites in orbit is arranged so that a minimum of four satellites are in view to users worldwide at any time. Using spread-spectrum

Table 2. Typical Performance Data and Characteristics of Commonly Available Atomic Frequency Standards

	Rubidium Oscillator	Cesium-Beam Oscillator	Hydrogen MASER Oscillator
Short-term stability $\sigma_y(\tau = 1\ \text{s})$	$2 \cdot 10^{-11}$ to $5 \cdot 10^{-12}$	$\sim 10^{-11}$	$1 \cdot 10^{-13}$ to $1 \cdot 10^{-12}$
Linear drift D	$5 \cdot 10^{-11}$/year to $5 \cdot 10^{-10}$/year	0	$<10^{-13}$/year to $5 \cdot 10^{-13}$/year
Accuracy, 1 year	$5 \cdot 10^{-10}$	$2 \cdot 10^{-11}$ to $1 \cdot 10^{-14}$	$\sim 10^{-13}$
Temperature sensitivity	$1 \cdot 10^{-11}$/°C	$1 \cdot 10^{-13}$/°C	$1 \cdot 10^{-14}$/°C
Resonance frequency ν_0	6.834682613 GHz	9.192631770 GHz	1.420450751 GHz
Warm-up time	2 min to 5 min (to $5 \cdot 10^{-10}$)	30 min (to $3 \cdot 10^{-12}$)	24 hours (to $1 \cdot 10^{-12}$)
Lifetime (performance guaranteed)	5 years to 10 years	5 years	3 years
Basic wear-out mechanism	Rb lamp and cavity life (15 years)	Cs beam tube (5 years)	Ion pumps and H_2 source depletion, cavity resonance shift (7 years)
Portability and intended location	Space, air, ground	Ground and lab. oriented	Definitely ground and lab. oriented
Average size	8 cm × 8 cm × 12 cm	50 cm × 30 cm × 14 cm	50 cm × 30 cm × 50 cm
Weight	0.5 kg to 2 kg	10 kg to 30 kg	>50 kg
Power consumption	10 W to 50 W	25 W to 50 W	70 W to 100 W

techniques, each satellite broadcasts a pair of L-band RF signals, that is, L1 (1575.42 MHz) and L2 (1227.6 MHz). The L1 signal carries a Precise (P) code and a Coarse/Acquisition (C/A) code, whereas L2 carries only the P code. The P code is normally encrypted so that only the C/A code is available to civilian users.

On the other hand, the GLONASS constellation is composed of 24 satellites on three orbital planes. The satellites operate in 19100 km circular orbits with an inclination angle of 64.8° and a period of 11 h and 15 min. Each satellite transmits on two L frequency groups (the L1 group centered on 1609 MHz and the L2 group centered on 1251 MHz) on a unique pair of frequencies. Unlike NAVSTAR, the GLONASS signals carry both a P code and a C/A code. The P code is encrypted for military use and the C/A code is available for civilian use.

Control Segment. The control segment is composed of all of the GPS facilities on the ground that monitor and control the satellites. The NAVSTAR system consists of five monitor stations, a master control station (MCS), and unlink antennas. The monitor stations (located at Colorado Springs, Hawaii, Ascension Island, Diego Garcia, and Kwajalein) passively track all GPS satellites in view, collect ranging data from each satellite, and send these raw data in real time to the MCS for processing. The MCS (located at Falcon Air Force Base, Colorado) evaluates clock and ephemeris changes in the satellites and uploads such correction data with other maintenance commands to each satellite once or twice each day by the ground-based uplink antennas (located in Ascension Island, Diego Garcia, and Kwajalein).

User Segment. A GPS receiver calculates its four-dimensional position (space and time) on the basis of the radio signals received from at least four satellites in view. GPS receivers come in many different sizes, shapes and price ranges, according to their performance and the application for which they are intended. For positioning, for example, inexpensive palm-receivers determine their positions with 95% accuracy (i.e., the value of two standard deviations of radial error from the actual antenna position under specified test measurement conditions) on the order of 100 m, whereas highly sophisticated receivers for military applications may achieve even subcentimetric resolution.

Use of GPS as Timing Reference. Because of the MCS control, GPS provides a timing signal traceable to the Universal Time Coordinated (UTC). Its main problem is very poor short-term stability (95% time accuracy is guaranteed to be 340 ns for the NAVSTAR civilian standard positioning service) together with the possibility of transitory local signal unavailability. Therefore, GPS timing supplies are equipped with a slave quartz oscillator to couple the excellent short-term performance of the latter with the long-term accuracy of GPS. One of the most important applications of GPS receivers as timing supplies is in telecommunications networks to synchronize the nodes of networks spread over long distances.

Clocks in Digital Telecommunications Networks

As mentioned previously, clocks and network synchronization play a central role in modern digital telecommunications (5,6) because they have a determining influence on the quality of the services provided. Clocks used in telecommunications are mainly primary reference clocks and slave clocks in synchronization networks, equipment clocks, and real-time clocks. The next subsections give some detail on this topic.

Architecture of Synchronization Networks for Digital Telecommunications Networks

As mentioned previously in the section Network Synchronization Strategies, among the several network synchronization strategies conceived, the HMS strategy is the most widely adopted worldwide for synchronizing modern digital telecommunications networks (and it is indicated as the standard choice by Ref. 44). The master–slave architecture is organized hierarchically in at least two levels:

- at level 0, one (or more, for reliability) master *Primary Reference Clock* (PRC) generates the reference signal by running in autonomous mode;
- at the lower levels, slave clocks are synchronized by the signals coming from the upper level (thus traceable to the PRC) and synchronize the clocks of the lower level.

Such slave clocks are called *Synchronization Supply Unit* (SSU) or *Stand-Alone Synchronization Equipment* (SASE) in Europe and in the ITU-T Recommendations. In North

America they are commonly known as *Building Integrated Timing Supply* (BITS). These clocks are deployed in telecommunications offices to distribute their timing signal to all of the equipment in the building.

Each piece of equipment in a telecommunications network is provided with an *Equipment Clock* (EC) that distributes the timing to all of the cards and modules of the apparatus. The task of a synchronization network is to synchronize all the equipment clocks in the telecommunications network exactly.

The timing is carried from one clock to another of the synchronization network through *synchronization trails,* which may be direct digital links or even chains of SDH/SONET equipment clocks (44). Direct digital links are usually primary-level signals of the plesiochronous digital hierarchy (PDM) that is the European 2.048 Mb/s (E1) or the North-American/Japanese 1.544 Mb/s (T1), in some cases through a multiplexer-demultiplexer chain. Alternatively, they may be SDM/SONET signals (46) on optical fibers. Within an office, on the other hand, timing is usually distributed as analog 2.048 MHz signals.

Clocks in Synchronization Networks

According to their different roles in a synchronization network, PRCs and SASEs pose different requirements to designers. They are specified, respectively, by the new ITU-T Recommendation G.811 and G.812, which substitute for the previous ones, denoted by the same number, in the Blue Book series.

PRCs are autonomous clocks which are masters of the entire network (level 0). Therefore, they must have the highest long-term accuracy and stability. *Cesium-beam clocks* are well suited to this and therefore are adopted as a national reference.

SASEs are slave clocks designed to filter effectively the synchronization impairments in the incoming reference and have very good or even excellent stability in the hold-over mode, should all of the references fail. They pose different requirements according to their level in the synchronization network. At level 1, *rubidium clocks* are usually adopted, because of their excellent long-term stability coupled with lower cost compared to cesium clocks. At level 2 and below, *quartz OCXO clocks* are mostly adopted. The loop time constant of SASEs is usually on the order of 100 s to 10000 s.

GPS receivers are often used as additional reference at the input of SASEs (as noted previously, many national Administrations do not accept GPS as a first-choice primary reference for political reasons, because it is controlled by a foreign government), especially in very wide area networks to face the issue of timing transfer over long distances.

Equipment Clocks

ECs are designed to run mainly in the slave mode and take their reference either from a synchronization network or from another EC (e.g., the previous EC in a chain). Therefore, on the one hand, their long-term stability in hold-over is specified more loosely than for PRCs or SASEs. On the other hand, their noise filtering capabilities meet different requirements according to the specific type of equipment and network architecture.

As a first example, the ECs of user primary digital multiplexers, which are located at the lowest level of the synchronization hierarchy, are synchronized by an external reference or an incoming digital multiplex signal but do not distribute their timing to any other equipment. Their clocks are usually inexpensive quartz oscillators (XO) with poor accuracy in free run (just better than 50 μHz/Hz).

The clocks of digital switching exchanges meet tighter requirements because they need to control the slips in the input digital signals by a suitable network synchronization strategy (usually HMS). Most commonly, such exchanges are equipped with high-precision OCXOs whose loop time constant is set to at least 100 s (1000 s is common) to filter out a substantial amount of phase noise on the input reference.

Finally, SDH Equipment Clocks (SECs) are the ECs which must comply with the tightest and best specified requirements. The ITU-T Recommendation G.813 (46) is devoted to their specification, especially as for their output noise and noise filtering capabilities. SECs are usually TCXOs, with a free-run accuracy better than 4.6 μHz/Hz and loop bandwidth on the order of 1 Hz to 10 Hz.

Real-Time Clocks

Real-time clocks are a very special kind of equipment clock, strictly related to network and equipment management. Modern telecommunications equipment performs quite sophisticated management functions (e.g., configuration and fault management, performance monitoring) through a local terminal or a remote control center which may even manage several networks of different kinds.

Management messages sent to the local terminal or to the remote control center must include the key information, the *date and time* (with one second resolution) on which the fault, the data error, the configuration change, etc. occurred, to allow the network manager to correlate events reported from different nodes and after variable delays. This information is given in each node by the local real-time clock.

It is essential that the real-time clocks of the whole network be synchronized, otherwise it would become impossible to correlate meaningfully different messages (which may be *numerous* and come from different parts of the network) under a common label (i.e., the actual event that happened or the issue that the network manager is interested in knowing). Synchronizing the real-time clocks of a network is a very special issue of network synchronization.

The network synchronization addressed to SASEs and EC has the target of minimizing time error fluctuations among the clocks and mostly achieves deviations not greater than 10 ns or 100 ns, regardless of the starting phase offset. This implies that *synchronous timing signals* (e.g., sine waves) are distributed.

The network synchronization addressed to real-time clocks, on the other hand, is conceptually different: the *absolute time* information (e.g., 23 Dec 1998, 01.32.04 AM) is needed, but a time alignment error of a few ms can be allowed. Here, synchronization is often distributed through software messages carrying the date-and-time message to the network nodes, according to suitable algorithms, as reported, for example, in Refs. 47–49.

BIBLIOGRAPHY

1. G. M. R. Winkler, Timekeeping and its applications, *Adv. Electron. Electron Phys.,* **44**: 1977.

2. J. A. Barnes et al., Characterization of frequency stability, *IEEE Trans. Instrum. Meas.,* **IM-20**: 105–120, 1971.
3. J. Rutman and F. L. Walls, Characterization of frequency stability in precision frequency sources, *Proc. IEEE,* **79**: 952–960, 1991.
4. W. C. Lindsey et al., Network synchronization, *Proc. IEEE,* **73**: 1445–1467, 1985.
5. P. Kartaschoff, Synchronization in digital communications networks, *Proc. IEEE,* **79**: 1019–1028, 1991.
6. J. C. Bellamy, Digital network synchronization, *IEEE Commun. Mag.,* **33** (4): 70–83, 1995.
7. J. Buck and E. Buck, Synchronous fireflies, *Sci. Amer.,* May, 1976.
8. F. M. Gardner, *Phaselock Techniques,* New York: Wiley, 1967.
9. R. E. Best, *Phase Locked Loops,* New York: McGraw-Hill, 1984.
10. V. F. Kroupa, Noise properties of PLL systems, *IEEE Trans. Commun.,* **COM-30**: 2244–2252, 1982.
11. P. Horowitz and W. Hill, *The Art of Electronics,* Cambridge, England: Cambridge University Press, 1980, Sects. 9.28–9.33.
12. J. P. Moreland, Performance of a system of mutually synchronised clocks, *Bell Syst. Tech. J.,* **50** (7): 2449–2464, 1971.
13. W. C. Lindsey and J. H. Chen, Mutual clock synchronization in global digital communication networks, *Eur. Trans. Telecommun.,* **7** (1): 25–37, 1996.
14. J. A. Barnes, The measurement of linear frequency drift in oscillators, *Proc. 15th Annu. Precise Time Time Interval PTTI Meet.,* 1983.
15. R. L. Filler and J. R. Vig, Long term aging of oscillators, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control,* **40**: 387–393, 1993.
16. IEEE Stand. 1139, *IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology,* approved October 20, 1988.
17. D. A. Howe, D. W. Allan, and J. A. Barnes, Properties of signal sources and measurement methods, *Proc. 35th Annu. Freq. Control Symp.,* 1981.
18. S. R. Stein, Frequency and time—their measurement and characterization, in E. A. Gerber and A. Ballato (eds.), *Precision Frequency Control,* New York: Academic Press, 1985, vol. 2, chap. 2, pp. 191–232.
19. D. W. Allan, Statistics of atomic frequency standards, *Proc. IEEE,* **54**: July, 1966.
20. L. S. Cutler and C. L. Searle, Some aspects of the theory and measurement of frequency fluctuations in frequency standards, *Proc. IEEE,* **54**: February, 1966.
21. W. C. Lindsey and C. M. Chie, Theory of oscillator instability based upon structure functions, *Proc. IEEE,* **64**: 1652–1666, 1976.
22. P. Lesage and C. Audoin, Characterization of frequency stability: Uncertainty due to the finite number of measurements, *IEEE Trans. Instrum. Meas.,* **IM-22**: 157–161, 1973.
23. P. Lesage and T. Ayi, Characterization of frequency stability: Analysis of the modified Allan variance and properties of its estimate, *IEEE Trans. Instrum. Meas.,* **IM-33**: 332–336, 1984.
24. L. G. Bernier, Theoretical analysis of the modified Allan variance, *Proc. 41st Annu. Freq. Control Symp.,* 1987.
25. ITU-T Rec. G.810, *Definitions and Terminology for Synchronisation Networks,* Geneva, 1996 and later editions.
26. ETSI Draft ETS 300 462, *Generic Requirements for Synchronisation Networks,* Bonn, 1996.
27. M. Carbonelli, D. De Seta, and D. Perucchini, Characterization of timing signals and clocks, *Eur. Trans. Telecommun.,* **7** (1): January–February, 1996.
28. S. Bregni, Measurement of maximum time interval error for telecommunications clock stability characterization, *IEEE Trans. Instrum. Meas.,* **IM-45**: 900–906, 1996.
29. S. Bregni, Clock stability characterization and measurement in telecommunications, *IEEE Trans. Instrum. Meas.,* **46**: 1284–1294, 1997.
30. F. L. Walls and A. De Marchi, RF spectrum of a signal after frequency multiplication: Measurement and comparison with a simple calculation, *IEEE Trans. Instrum. Meas.,* **IM-24**: 210–217, 1975.
31. S. Bregni, L. Valtriani, and F. Veghini, Simulation of clock noise and AU-4 pointer action in SDH equipment, *Proc. IEEE GLOBECOM '95,* Singapore, 1995.
32. Special Issue on Time and Frequency, *Proc. IEEE,* **79** (7): July, 1991.
33. E. A. Gerber and A. Ballato (eds.), *Precision Frequency Control.* New York: Academic Press, 1985.
34. J. Vanier and C. Audoin, *The Quantum Physics of Atomic Frequency Standards,* Bristol: Adam Hilger, 1989, Vol. 1.
35. J. Vig, *Quartz Crystal Resonators and Oscillators—A Tutorial,* Tech. Rep. SLCET-TR-88-1, Fort Monmouth, NJ: U.S. Army Electron. Technol. Devices Lab., 1992.
36. *Precision Time and Frequency Handbook,* Irvine, CA: Ball Corp., Efratom Time and Frequency Products, 1993.
37. *Handbook Selection and Use of Precise Frequency and Time Systems,* Geneva: ITU-R, 1997.
38. I. A. Getting, The global positioning system, *IEEE Spectrum,* **30** (12): 36–38, 43–47, 1993.
39. E. Kaplan, *Understanding GPS: Principles and Applications,* London: Artech House, 1996.
40. J. T. Beadles, *Introduction to GPS Applications,* 1997. Available: URL: http://ares.redsword.com/gps/
41. P. H. Dana, *Global Positioning System Overview,* Department of Geography, University Texas, Austin, 1997. Available: URL: http://www.utexas.edu/depts/grg/gcraft/notes/gps/gps.html
42. US Air Force, NAVSTAR GPS HOMEPAGE. Available: URL: http://www.laafb.af.mil/SMC/CZ/homepage/
43. Russian Space Forces, *Welcome to the Coordinational Scientific Information Center of the Russian Space Forces!* Available: URL: http://mx.iki.rssi.ru/SFCSIC/SFCSIC-main.html
44. ITU-T Rec. G.803, *Architectures of Transport Networks Based on the Synchronous Digital Hierarchy SDH,* Geneva, 1993, §6.
45. IRU-T Revised Rec. G.707, *Network Node Interface for the Synchronous Digital Hierarchy SDH,* Geneva, 1996.
46. ITU-T Rec. G.813, *Timing Characteristics of SDH Equipment Slave Clocks SEC,* Geneva, 1996.
47. J. Levine, An algorithm to synchronize the time of a computer to universal time, *IEEE/ACM Trans. Network.,* **3**: 42–50, 1995.
48. S. R. Jefferts et al., Two-way time and frequency transfer using optical fibers, *IEEE Trans. Instrum. Meas.,* **IM-46**: 209–211, 1997.
49. D. L. Mills, Precision synchronization of computer network clocks, *ACM/SIGCOMM Comput. Commun. Rev.,* **24** (2): 28–43, 1994.

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CMOS AND BICMOS TECHNOLOGIES. See GATE DIELECTRICS.

CMOS LOGIC. See BIPOLAR AND MOS LOGIC CIRCUITS; TRANSISTOR-TRANSISTOR LOGIC.

COATINGS, THERMAL SPRAY. See THERMAL SPRAY COATINGS.