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Standard Time and Frequency Generation

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Abstract—The basic properties of atomic primary frequency standards are reviewed. A continuously running frequency source combined with counting, storage, and display devices results in a clock. Time scales are obtained by setting clocks with respect to a convenient origin. The accuracy of a primary frequency standard is a combined theoretical and experimental assessment of the uncertainties of all known possible sources of bias from the idealized definition. Recommended standard measures for the stability are the spectral density of fractional frequency fluctuations (frequency domain) and the two-sample no-dead time Allan variance (time domain). The operation of atomic frequency standards is based on various methods of particle interrogation to observe the transitions, particle confinement to obtain sufficient interaction time, and particle preparation to obtain the desired energy level populations. Passive resonator and active oscillator (maser) modes of operation are discussed; the former has some fundamental advantages.

A review of the state of the art and current practice shows that cesium beam resonator standards have the best documented accuracy capability (5×10^{-13}) and, in their commercial versions, are presently the best available clocks.

There are three concepts related to time: time interval, date, and synchronization. In order to assign dates to events, time scales have to be established. The steadily growing need for a very precise and uniform time scale has resulted in a new internationally coordinated time scale, IAT.

Frequency metrology will have increasing impact on both length and voltage metrology in the near future.

I. INTRODUCTION

IN THIS PAPER we shall review the basic properties (Section II) and current performance (Section III) of atomic frequency standards. Section IV gives a very brief account of the historical background. In the following Section V, we discuss the relevant aspects of time scales. In the last section we mention the possible future impact of frequency metrology on the definition of the meter and the volt.

Time and frequency are closely interrelated, the unit of one being the inverse of that of the other. However, since the introduction of primary atomic frequency standards, the more basic quantity is the frequency related to the atomic resonance. Time intervals can then be defined by counting definite numbers of periods. By combining continuously running frequency sources with counters, storage and display devices, we obtain *clocks*. A time scale is obtained by choosing an appropriate origin, which is a pure matter of convention. Any desired degree of reliability can be reached by the use of a sufficiently large ensemble of clocks, operated at various locations.

The many powerful techniques of time and frequency dissemination treated in the other papers of this issue not only provide accurate time and frequency to the user but also provide an important contribution to the increasing accuracy and reliability of timekeeping itself.

II. BASICS OF FREQUENCY STANDARDS

We have restricted our discussion to primary frequency standards having the highest possible accuracy. Atomic frequency standards are based on a fundamental property of nature. The principles of quantum mechanics tell us that the interaction of electromagnetic radiation with atoms or molecules leads to interchanges of energy in discrete steps, changing the energy of the absorbing or emitting particle between discrete energy levels. The frequency ν_0 of the emitted or absorbed wave packet (photon) is related to the energy difference between levels p and q by the relation

$$h\nu_0 = W_q - W_p$$

where $h = 6.63 \times 10^{-34}$ Js is Planck's constant.

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For unperturbed atoms or molecules, the energies W_p and W_q, and, therefore, the frequency ν_0 can be regarded as constants, since no experiment has yet shown any secular variation or aging of these values with time.

Any physical experiment or apparatus devised to measure or generate a frequency ν_0 introduces perturbations and errors, not only of a random but also of a systematic nature. The concepts of *accuracy* and *stability* are used to describe the departures of a practical standard's performance from the assumed ideal. The following descriptions of these concepts are used in evaluating and comparing the performance of different types of standard frequency sources:

Accuracy: The *accuracy* of a primary frequency standard is a measure of its ability to generate a frequency whose relation to the ideal value ν_0 is known within the narrowest possible limits. Obviously, this property can be assessed only by means of a thorough investigation of all known possible perturbing effects. Any potential departure from the assumed nominal value ν_0 is called a *bias.* The uncertainty of each bias contributes to the total uncertainty. The results of the investigations of all biases and their uncertainties are usually arranged into an *error budget* and the result of an appropriately weighted combination of the bias uncertainties is an estimate called the *accuracy capability* of the evaluated standard. The task of evaluating the accuracy capability of a primary standard is at best tedious and time consuming. Furthermore, some duplication of effort in different laboratories is not only desirable but necessary in order to compare the results of independent evaluations. This reduces the danger of unnoticed biases and errors. Ideally the comparisons between laboratories (external estimate) should be in accord with the individual evaluations (internal estimates).

Stability: The *stability* of the generated frequency can be more readily determined by experiment, at least within limited periods of time. In the time domain, stability can be described by the variance of a series of measurements, taken as a time series. Statistical models and methods of analysis have been developed [1], which take account of the type of fluctuation spectra, the duration of individual samples, and the dead time between measurements. Both frequency-domain and time-domain analysis techniques can be used to investigate frequency fluctuations of standard frequency sources. Practical considerations concerning readily available instruments usually limit the possibility of either approach. Frequency-domain analysis using spectrum analyzers is most appropriate for the study of rapid fluctuations (periods shorter than 1 s, i.e., Fourier frequencies larger than 1 Hz). Time-domain analysis, i.e., calculating variances and standard deviations as a function of sampling time, is most adequate for the investigation of slow fluctuations, but there is a range in between where both methods are feasible. Considering this dual approach, two related measures of frequency stability have recently been proposed for adoption as IEEE standard definitions for frequency stability by the Subcommittee on Frequency Stability of the IEEE Group on Instrumentation and Measurement [1]. These recommended measures of frequency stability can be summarized as follows.

Consider a signal generator having the instantaneous output voltage

$$V(t) = [V_0 + \epsilon(t)] \sin [2\pi\nu_0 t + \phi(t)] \tag{1}$$

where V_0 and ν_0 are the nominal amplitude and frequency, respectively. Provided that $\epsilon(t)$ and $d\phi/dt$ are sufficiently small for all time t, the fractional instantaneous frequency deviation from nominal is defined as

$$y(t) = \frac{1}{2\pi\nu_0} \frac{d\phi}{dt} \cdot$$

Then the recommended definition for the stability measure in the *frequency domain* is the one-sided spectral density $S_y(f)$ of the time dependent variable $y(t)$. $S_y(f)$ is defined as

$$S_y(f) = 4 \int_0^\infty R_y(\tau) \cos 2\pi f\tau \, d\tau \tag{2}$$

with $R_y(\tau) = s\langle y(t)y(t-\tau)\rangle$ being the autocorrelation function of $y(t)$, $\langle \cdot \rangle$ denoting an infinite average.

As an alternative measure in the time domain, the use of the two-sample Allan variance [2]:

$$\sigma_y^2(\tau) \equiv \langle \sigma_y^2(2, \tau, \tau) \rangle = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle \tag{3}$$

is recommended. This variance is a special case of the general N-sample Allan variance:

$$\langle \sigma_y^2(N, T, \tau) \rangle = \left\langle \frac{1}{N-1} \sum_{n=1}^{N} \left(\bar{y}_n - \frac{1}{N} \sum_{k=1}^{N} \bar{y}_k \right)^2 \right\rangle \tag{4}$$

where

$$\bar{y}_k = \frac{1}{\tau} \int_{t_k}^{t_k+\tau} y(t) dt$$

is the kth individual sample averaged over a sampling time τ, T is the time interval between the beginnings of two successive samples, $(t_{k+1} = t_k + T)$, and $(T - \tau)$ is therefore the dead time between measurements. N is the number of samples used in the computation of the variance. Cutler [1] has shown that under reasonable conditions of convergence, the general N-sample variance is related to the spectral density $S_y(f)$ by the following expression:

$$\langle \sigma_y^2(N, T, \tau) \rangle = \frac{N}{N-1} \int_0^\infty df S_y(f) \left(\frac{\sin \pi f T}{\pi f \tau} \right)^2 \left(1 - \frac{\sin^2 \pi r f N \tau}{N^2 \sin^2 \pi r f \tau} \right) \tag{5}$$

where $r = T/\tau$. The reasons for restricting the number of samples to $N = 2$ are not only the simplicity of computation but also the fact that the general N-sample variance has no finite limit for $N \to \infty$ for certain commonly encountered types of noise spectra. In particular, the integral of (5) diverges for infinite N if $S_y(t)$ contains f^{-1} or f^{-2} (flicker noise, random walk) terms. Furthermore, the system bandwidth (high and low cutoff frequencies) has to be specified for certain types of noise.

The influence of different noise sources and mechanisms (white phase, white frequency, flicker of phase and flicker of frequency, random walk of frequency) can be combined into a fairly realistic model which is defined by a truncated power series representation for $S_y(f)$:

$$S_y(f) = h_{-2}f^{-2} + h_{-1}f^{-1} + h_0 + h_1 f + h_2 f^2 \tag{6}$$

for $0 \leq f \leq f_h$ and $S_y(f) = 0$ for $f > f_h$, f_h being the upper frequency cutoff limit which is not only necessary for convergence of the integral in (5) but also reasonable for a practical measuring setup.

For this frequency domain model, there exists a simple relation to the time domain, as shown by Allan [2] and Vessot [3]. For every term of $S_y(f)$ of the form $h_\alpha f^\alpha$, the corresponding variance

TABLE I

Terms Describing Different Types of Noise

α	Phase	Frequency	μ
-2	--	Random Walk	1
-1	--	Flicker	0
0	Random Walk	White	-1
1	Flicker	--	-2
2	White	--	-2

$\sigma_y^2(\tau)$ is proportional to τ^μ, with

$$\begin{aligned} \mu &= -\alpha - 1, & -3 < \alpha < 1 \\ \mu &= -2, & 1 \leq \alpha. \end{aligned} \tag{7}$$

In most cases, several different noise generating processes are present which lead to one or several terms of the form $h_\alpha f^\alpha$. If these processes are uncorrelated, the combined total spectral density and corresponding variance can be obtained by simple addition of the terms as in (6). Table I shows the usual terms describing the different types of noise.

A. Principles of Operation

The purpose of the frequency standard is always the generation of a periodic signal having a frequency which is as stable and accurate as possible. Various ways of achieving this goal are possible, each having its own particular advantages and weaknesses, which we shall briefly discuss without going into detailed design features since abundant literature on this subject exists. The discussion in Sections II-A through II-E is based on a recent review [4] of the possibilities of future primary frequency standards, but restricted to the systems in current use or showing considerable promise for the future. Figs. 1–4 are taken from [4]. First, two main categories can be distinguished, namely the *active* and the *passive* mode of operation. The active mode is obtained by using the maser or laser principle, i.e., coherent stimulated emission of the radiation within a suitable resonant structure (cavity resonator). In the passive mode, an ensemble of particles (i.e., atoms or molecules) undergoing the desired quantum transition is used as a resonator. An auxiliary source of radiation (commonly called the "slave oscillator") is required to produce the transitions which occur with maximum probability when the frequency of the radiation is, in principle, near ν_0. The simplest example is an absorption experiment, but there are various other ways to observe the transitions.

Three major steps are required in order to implement either the active or the passive mode of operation:

1) "particle interrogation," which is the way of observing the interactions;
2) "particle confinement," which keeps the particles in the region of interaction for a sufficiently long time so that the transitions can take place and produce a narrow line;
3) "particle preparation," in order to obtain a sufficient initial population difference for the observation of a net effect of the transitions. If there were no initial population difference (at least in certain regions), emission and absorption would cancel and no net effect would be observed.

The accomplishment of each of these three steps is associated with several undesired side effects which lead to biases in the generated standard frequency. Fluctuations of these biases and additional sources of noise limit the accuracy as well as the stability of all real devices.

B. Particle Interrogation

It is only here that the active mode, i.e., laser or maser operation, can be distinguished from the passive mode. In the active mode, a coherent signal output is produced by stimulated emission within a resonant cavity. In the passive mode, the transitions can be observed in various ways:

absorption;
reemission (amplification of radiation);
detection of particles having made a transition;
indirect detection (variation of intensity in pumping radiation).

In all these cases, the properties of the slave oscillator play an important role in the total performance of the device. The active maser oscillator frequency stability, for frequencies where $h\nu \ll kT$, is ultimately limited by the thermal noise in the resonant cavity [6], with

$$\langle \sigma_y^2 \rangle \approx \frac{1}{Q^2} \frac{kT}{2P_T} \cdot \tag{8}$$

Q is the effective "Q" of the quantum transition and thus directly related to the interaction time which in turn depends on particle confinement. P is the power generated by the device. On the other hand, the frequency stability of a standard operating in the passive mode is limited by shot noise perturbing the frequency of the slave oscillator and can be written as [5]:

$$\langle \sigma_y^2 \rangle \approx \frac{1}{4Q^2} \frac{h\nu}{P_T} \tag{9}$$

where $P = nh\nu$ is the average power exchanged between the radiation field and the particles, assuming that we detect n transitions per unit of time.

It appears, therefore, that for equal Q and equal rate of transitions the passive mode of operation leads to a superior stability, at least in the lower frequency range where $h\nu \ll kT$. Another factor in favor of the passive mode of operation is cavity pulling. In masers and lasers the frequency of oscillation ν is related to the cavity resonance frequency ν_c by [6]:

$$\nu - \nu_0 = \frac{Q_c}{Q}(\nu - \nu_c) = \frac{W}{W_c}(\nu - \nu_c) \tag{10}$$

where Q, Q_c, W, W_c are the Q factors and half-power linewidths of the transition and the cavity, respectively. Active oscillators require, furthermore, a high Q_c (low-loss cavity) in order to allow self-oscillation. In passive systems operating far below the level of self-oscillation, the pulling relation [7] can be approximated[1] by

$$\nu - \nu_0 = \left(\frac{Q_c}{Q}\right)^2 (\nu - \nu_c) \left(2 \frac{\Delta P}{P_0}\right) \tag{11}$$

where $\Delta P/P_0$ is the fractional departure in excitation power from nominal and there is, at least in principle, no lower limit for Q_c below which the device would fail to operate.

At infrared and optical frequencies, where $h\nu \gg kT$, i.e., in laser oscillators, the frequency is almost entirely determined by the cavity resonant frequency. Lasers can, therefore, practically be

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[1] The factor $[2(\Delta P/P_0)]$ in (11) is valid for beam devices such as cesium beams but not for storage devices [8].

ruled out as active frequency standards, but they may well serve as slave oscillators (kind of an "optical klystron") locked to a passive resonator.

However, (9) sets a limit only for the case of an ideal slave oscillator locked to the resonance. For a complete system and time intervals short compared to the servo response time, the slave oscillator determines the fluctuations of the output frequency [9]. The apparent advantages of a passive system can, therefore, only be realized in practice within the performance limits of available slave oscillators. Passive frequency standards require a servo system controlling the frequency of the slave oscillator to the atomic resonance. Frequency biases due to servo errors are proportional to the resonance linewidth. With high-Q resonators and careful design of the servo, these errors can be kept smaller than those inherent to the resonator.

C. Particle Confinement

The linewidth (and therefore the Q) of the ensemble of particles (atoms or molecules) interacting with the radiation field is given approximately by the relation

$$W \approx 1/T_r$$

where T_r is the average interaction time (lifetime, relaxation time). The purpose of particle confinement techniques is to make T_r as large as possible, and to reduce uncontrollable motion of the particles with respect to the interrogating radiation field. Three main techniques can be distinguished (in order of increasing sophistication):

absorption cell,
particle beam,
storage devices: coated storage cell,
    buffer gas cell,
    electromagnetic field containment.

The simple absorption cell is not very suitable for microwave standards, but has regained considerable importance in the infrared and visible region through the introduction of saturated absorption techniques [10], [11]. The very high frequency leads to high Q values even for short interaction times, together with large signal-to-noise ratios due to the large number of transitions involved.

Particle beam techniques are commonly used in the most accurate microwave frequency standards, i.e., cesium beam resonators. A possible limit of accuracy is the difficulty of knowing the exact velocity distribution which is required to calculate the bias due to second-order Doppler shift [12]. Storage techniques are used in several devices. Coated cells are used for confining hydrogen atoms in hydrogen masers and, more recently, hydrogen storage beam resonators. Buffer gas cells are used in connection with optical pumping [13] in rubidium frequency standards and magnetometers.

Ion storage in electromagnetic fields has been used in high-resolution spectroscopy [14]; however, an interrogation method competitive with other approaches still remains to be developed. There are also problems in determining the mean square velocity of the stored particles and hence the uncertainty of second-order Doppler shift.

The main problems in storage devices using wall coatings or buffer gases are the biases introduced by collisions, which in the case of rubidium gas cells are so large that they preclude their use as primary standards and introduce some aging. Wall collision shifts in hydrogen storage devices limit the accuracy of these standards.

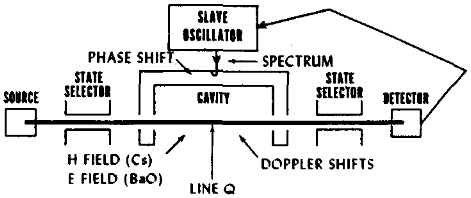

Fig. 1. Atomic beam (principle).

D. Particle Preparation

The creation of a sufficient difference in energy level population is necessary only for low-transition frequencies (microwave region) where $h\nu \ll kT$. At infrared and optical frequencies, the population difference in a gas at thermal equilibrium is sufficiently large that absorption experiments can be done efficiently. The most important methods of particle preparation currently in use are spatial state selection in a beam [15], optical pumping [13], and particle collisions [16], [14].

State selection in a beam can be obtained by means of inhomogeneous magnetic or electric fields interacting with magnetic or electric dipole moments of the particle used. The existence of a dipole moment, however, implies the dependence of the energy on the applied field, i.e., Zeeman and Stark effects, which lead to bias and require careful shielding and control of the applied fields. Magnetic hyperfine transitions in hydrogen and in alkali metal atoms provide energy levels which have a purely quadratic Zeeman effect and negligibly small Stark effect, so that at low magnetic fields the dependence on the field strength is small.

At high fields (>3000 A/cm), the magnetic dipole moment approaches 1 Bohr magneton (9.27×10^{-24} J/T) and is of opposite sign for the two levels of interest, so that state selection by magnetic beam deflection or focusing of the higher level by multipole magnets becomes easy and relatively efficient.

Optical pumping methods are usually much more efficient than beam state selection provided that an appropriate spectral intensity of the pumping light source can be obtained. In optically pumped alkali vapor cells, microwave transitions can be observed with high signal-to-noise ratios through the change in absorption of the pumping light. However, the simultaneous application of the pumping light and the microwave interrogating field leads to coupling between transitions and thus to biases depending on the spectral characteristics of the pumping light, which are difficult to control.

Population enhancement of certain energy levels by particle collisions are widely used in gas lasers. The same technique is also used in ion storage experiments.

E. Types of Frequency Standards

The following types of standard frequency sources have reached some maturity and some show considerable promise for the future:

cesium-beam resonators,
hydrogen masers,
hydrogen storage beam tube,
methane saturated absorption cells,
rubidium vapor cells.

Furthermore, quartz-crystal oscillators, without being accurate frequency standards, are of high importance as slave oscillators in all radio-frequency standards.

Cesium-Beam Resonator (Fig. 1): The cesium atomic beam is produced from a heated oven containing liquid cesium. The first state selector allows only atoms of a selected hyperfine state to pass through the interaction region, where transitions are produced by a pair of separated oscillating fields (Ramsey method [15]) in a microwave cavity ($\nu_0 = 9.2$ GHz). (Some cesium beams use both emission and absorption, but in this configuration atoms in the two states are spatially separated.) Simultaneously a weak uniform magnetic field (C field) is applied in order to separate the different sublevels of the hyperfine state, so that transitions occur only between the two levels ($m_F = 0$), where the Zeeman effect is purely quadratic. The second state selector allows only atoms that have completed the transition to the other hyperfine state to be detected. The cesium atoms are detected by surface ionization on a hot-metal ribbon. Usually the ion current is amplified by means of a secondary electron multiplier. As a function of excitation frequency, the output current shows a sharp resonance peak.

Hydrogen Masers (*Fig. 2*): Atomic hydrogen is produced in an RF-discharge source and the beam is formed in a collimator. Atoms in the upper hyperfine state are focused into a coated storage bulb by means of a multipole magnet. The storage bulb is located in the uniform RF field region of a high-Q cavity. A weak uniform C field is applied for the same reasons as in a cesium tube. The condition of oscillation depends on various relaxation processes, the flux ratio of atoms in the desired and undesired states, and the loaded Q of the tuned cavity.

Hydrogen Storage Beam Tubes (*Fig. 3*): This is a new device [5] based on old ideas [17], which combines the advantages of the passive resonator with those of hydrogen atom storage in a coated bulb. Source and first state selector are similar to those of a hydrogen maser. An output collimator is added to the storage bulb, means for avoiding direct transit of atoms are provided, and a second state selector and hydrogen atom detector are added. The future of this device depends on the development of a high-efficiency detector. In principle, its feasibility has been demonstrated [18].

Rubidium Vapor Cell (*Fig. 4*): A light beam from an Rb^{87} lamp, filtered by a vapor cell containing Rb^{85}, depopulates one of the two hyperfine levels of Rb^{87} atoms stored in another cell which is located inside a cavity. Application of the microwave field changes the hyperfine level populations and hence the absorption of pumping radiation. A photodetector provides the resonance signal for locking the slave oscillator. With high levels of pumping light, appropriate choice of buffer gases [19], and a high-Q cavity, maser oscillation can be obtained. In practical applications, however, the passive mode of operation is the only one used. This is the simplest and least expensive type of atomic frequency standard and it has found wide acceptance for those applications where its aging with time is no inconvenience. An even simpler variety, using natural rubidium in a resonance cell without additional filter cell, has recently been described [20]. The simplicity is gained, however, at the expense of performance.

Methane Saturated Absorption Cell (*Fig. 5*): This very recent development [10] is included in our review because of its potential future as a high-accuracy frequency standard in the infrared region and as an example for the potential applications of frequency metrology in the definitions of other physical quantities (see Section VI).

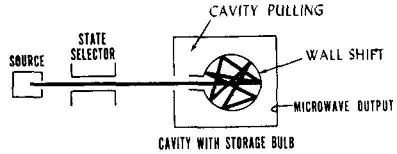

Fig. 2. Hydrogen maser (principle).

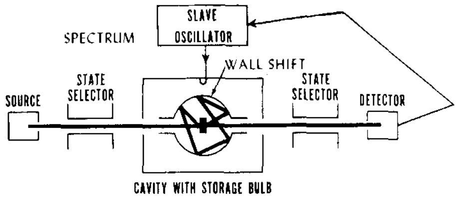

Fig. 3. Hydrogen storage beam (principle).

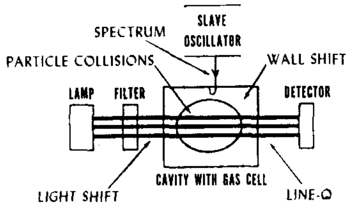

Fig. 4. Rubidium vapor cell (principle).

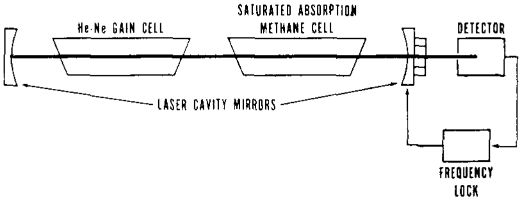

Fig. 5. Methane saturated absorption (principle).

A gas cell filled with methane is mounted with a ^3He–^{20}Ne gain cell between the two mirrors of a laser cavity. The He–Ne laser can be made to oscillate at a frequency of approximately 88 THz (wavelength 3.39 μm) which coincides with a resonance of the methane molecule. With appropriate methane pressure, strong absorption occurs over the whole range of oscillation of the laser. Methane molecules in the cell interact with both running waves forming the standing wave pattern, provided that their velocity is nearly perpendicular to the laser beam (i.e., parallel to the wavefronts). With sufficient intensity, these molecules are saturated, and a narrow "hole" is "burned" in the absorption profile [21]. A Q factor of 10^9 is easily obtained. A photodetector provides the resonance signal used for locking the laser frequency to the resonance.

III. Device Performance

A. State of the Art

In this section we shall review the state of the art of frequency standards used in national standards laboratories with consideration of future possibilities. The current practice, reflected in the performance of commercial devices, will be treated in the next section.

The state of the art as of the time of writing this paper is reflected in Table II where the published and projected values for the accuracy capability of the various types of standards we discussed in the previous sections are indicated. The experimental values are all based on published results and the corresponding references are indicated in the table. In the last column the major effects limiting the accuracy and, to some degree, also the long-term stability are mentioned in order to identify the areas of current and future research.

Information on measured stability performance over a wide range of sampling times is given in Fig. 6. The accuracy capa-

TABLE II

Accuracy Capability of Present and Potential Future Primary Frequency Standards

Type	Experimental 1 - σ Estimates	Potential Limits	Major Causes of Bias
Cesium Beam	5×10^{-13} [24]	$< 1 \times 10^{-13}$	Cavity Phase Shift, C-Field, Second Order Doppler Shift, Excitation Spectrum [7], [24], [25].
Hydrogen Maser	2×10^{-12} [26]	$< 1 \times 10^{-12}$	Wall Collision Shift, Cavity Pulling [4], [26].
Hydrogen Storage Beam	Not yet available	$< 1 \times 10^{-12}$	Wall Collision Shift, Excitation Spectrum [5], [26].
Methane Cell	1×10^{-11} [10]	$< 1 \times 10^{-12}$	Photon Recoil [27], Excitation Spectrum, Pressure Shift [10]

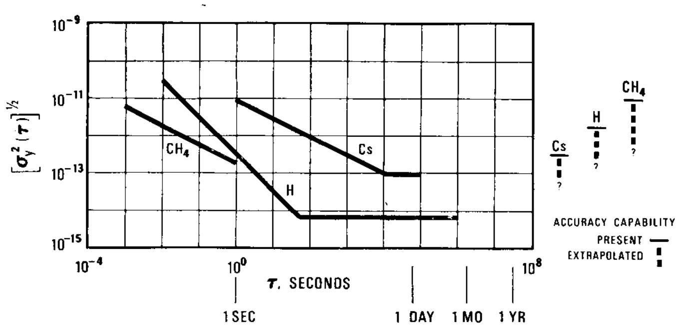

Fig. 6. Stability and accuracy data on laboratory frequency standards. The data are based on experimental results published in the following references: methane (CH_4), [11]; cesium (Cs), [24]; hydrogen (H), [38].

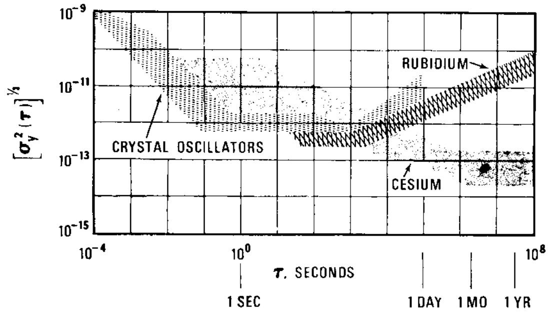

Fig. 7. Stability data on commercial frequency standards, indicating the margin between specified data and performance of selected units.

bilities are repeated as vertical bars in the right-hand margin, indicating the range between the established and projected values. Fig. 6 shows that there is no single approach which is significantly superior in every respect. All systems which generate a standard radio frequency require a quartz crystal oscillator.

In the time domain region from $\tau = 10^2$ s up to $\tau = 10^6$ s the stability of hydrogen masers is superior to that of other frequency sources. For shorter times than 10^2 s the stability shown is that of the crystal oscillator locked to the maser. Over longer times, stability data have not yet been published either for hydrogen masers or for laboratory type cesium beam standards. As indicated in Fig. 7, some commercial cesium beam devices operated as clocks in a controlled environment show σ_y values of a few parts in 10^{14} over times as long as 1 year or more [22], [23]. In the very short term, the methane device shows the best stability yet reported.

B. Current Practice

The users of frequency and time generating equipment are at least as interested in the performance of currently available commercial equipment as in the state of the art of a few leading laboratories. The availability of high-performance standard frequency generators at reasonable cost leads to increased demands on the methods of time and frequency dissemination used to reference local standards to some higher accuracy reference. In a commercial frequency standard, accuracy is not the prime design objective, since other factors as size, weight, environmental behavior, reliability, power consumption, and cost (i.e., initial investment and operation costs) have an influence on the choice of the principle and on its implementation. For the user, the choice of a particular type of frequency standard is not only a problem of device design and characteristics but rather one of systems design and optimization.

Fig. 7 shows the stability performance of commercial cesium and rubidium frequency standards and of high-quality crystal oscillators. In each case, some spread in the data has been allowed for. The more conservative limit corresponds to data specified in manufacturers' data sheets. The better values correspond to measurements reported on selected units. For crystal oscillators, the best available values on short-term stability are those reported in [28] by Brandenberger, Hadorn, Halford, and Shoaf. The indicated stability data of rubidium vapor frequency standards are those reported by Throne [29] for values of $\tau < 10^4$ s; the longer term data are estimated from the expected aging of the rubidium cell system. The best values for cesium beam standards are based on data reported by Hyatt, Throne, Cutler, Holloway, and Mueller [30] for values of τ up to 10^5 s. The longer term values are based on data reported by Winkler, Hall, and Percival [22] and by Allan [23].

Cost (initial and support), stability, reliability, and production experience on the major types of standard frequency generators are given in Table III [31] as relative figures with reference to commercial cesium beam standards. These figures are the result of several years' experience in the U. S. Navy and Coast Guard and they are valid for relatively quiet environments, especially the frequency stability figures of quartz crystal oscillators which are relatively most sensitive to shock and vibration. The combined

TABLE III

RELATIVE COMPARISONS OF STANDARD FREQUENCY GENERATORS

Code	Parameter	Cesium Standard	Hydrogen Maser	Rubidium Vapor Cell	Quartz Crystal
a	Initial Cost	1	5.00	0.5	0.10
b	Support	1	10.00	0.5	0.10
c	Stability	1	10.00	0.1	0.01
d	Reliability	1	0.20	1.0	10.00
e	Production Experience	1	0.1 *	0.5	10.00
	Figure of Merit ($F = \frac{c \cdot d \cdot e}{a \cdot b}$)	1	0.004	0.2	100.0

* Actually not commercially available.

"figure of merit" is therefore somewhat arbitrary but it can serve as a guideline. It must be kept in mind that for each new application the choice of the most adequate instrument requires a careful study of all pertinent factors involved.

IV. HISTORICAL BACKGROUND

In this section we shall briefly review the historical background of atomic frequency standards and atomic clocks only. The earlier history of time measurement and the history of quartz crystal oscillators and clocks are not only well documented but also less relevant to this paper.

Several lines of development can be traced as far back as the late 1920's [32] when Darwin first linked the quantized orientation of spins in a magnetic field to a resonance phenomenon. In the 1930's the first spectroscopy experiments were made in the microwave range. In 1936 Cleeton and Williams first described the inversion line of ammonia at about 1-cm wavelength and in the same year Rabi at Columbia University developed the atomic and molecular beam resonance techniques for investigations in spectroscopy.

The technological breakthroughs in microwave techniques during World War II led to a very fruitful activity in microwave spectroscopy after the war, and in 1948 Harold Lyons of NBS built the first "atomic clock" based on microwave absorption in ammonia. In the same 5-year period around 1950, the application of atomic-beam spectroscopy to frequency definition and measurement was developed [33]. In 1953 the first maser action was reported, marking the early beginnings of the now wide field of quantum electronics. The first practical application of a cesium beam apparatus was made around 1955 and the first commercial cesium beam frequency standards appeared around 1956. In the years from 1955 to 1970, the accuracy capability of cesium beam primary frequency standards has been improved by roughly one order of magnitude every 5 years. Numerous attempts to find better solutions using other techniques and other atoms and molecules were undertaken during the same period. Significant work has been done in Canada, Czechoslovakia, France, Germany, Great Britain, Italy, Japan, the Soviet Union, Switzerland, and the United States.

On the international level, the new definition of the second based on the hyperfine transition of the cesium atom was given final adoption in October 1967 by the General Conference on Weights and Measures, thus legalizing the advent of the era of atomic time.

V. TIME SCALES

It has often been pointed out that the single word "time" embodies at least two different concepts. There is the concept of time interval or duration and there is the concept of date. As examples, one might make an appointment to meet a person "in 5 hours from now." This is time interval. Similarly, one might make an appointment for July 27, 1972, A.D., 2 P.M. EDT. This is date.[2]

This section is specifically concerned with establishing the means of assigning dates to events; that is, with establishing time scales.

Two Different Uses for Time Scales: Within the single concept of date, one can identify two very different uses for schemes for assigning dates—i.e., two very different uses for time scales.

First, there is the importance of simply having a universally accepted convention of assigning dates. If I make an appointment to meet a person on July 27, 1972, A.D., at 2 P.M. EDT, it is important that both of us use essentially the same convention or we will be unable to keep the appointment. With the development of very high speed digital telecommunications systems involving time multiplexing, the precision needed for this conventional dating scheme may be very stringent. Nowadays, one can find stated needs for time synchronization (i.e., needs for a time scale convention) at the microsecond and submicrosecond levels.

The second use for time scales is in navigation and astronomy. Historically, the common time scales have been related to the sun's apparent position. The calendars were constructed to count the daily cycles of the sun and clocks were constructed to measure fractions of days and to extrapolate the sun's position when it was not visible. This type of a time scale is basically tied to the earth's angular position in space and is important to anyone who is concerned with earth position. For example, a person on a ship at sea might be able to observe stars in particular positions in the sky. If this person knows what time it is (i.e., if he knows earth position) and he has suitable astronomical tables, he can determine his position on the earth. Except for relatively few sophisticated users, most of the needs for an earth-based time scale can be limited in accuracy in the vicinity of about 1 s. It is also important to note that earth time is perhaps 10 000 times *less* uniform than atomic time.

An Analogy with the Calendar: As we know, there are not a whole number of days in a year and we do not want the seasons to get out of step with the calendar. By the occasional addition of a day to the calendar (leap year), it is possible to keep the calendar and the seasons in approximate step. We note that the exact beginning of spring is not of great importance to most people as long as the seasons do not get badly out of step with the calendar. But the convention of assigning names to the days is important to almost everyone. We are all interested in the calendar.

The leap year situation is analogous to the present requirements of precise timekeeping: We want very precise time synchronization which exploits the full capabilities of atomic clocks, but we also want approximate agreement with the sun for the benefit of navigators. As it is more completely discussed in the

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[2] In the U. S. literature on navigation and satellite tracking and geodesy the word "epoch" is sometimes used in a similar manner. There is some ambiguity, however, in the word "epoch" and the authors prefer the use of the word "date," the precise meaning of which is neither ambiguous nor in conflict with other, more popular uses.

paper on international time scale coordination [34], the new Universal Coordinated Time (UTC) system incorporates the concept of a "leap second" to accomplish these goals. The point of this discussion here is to establish the basis and the criteria of evaluation for an atomic time scale which ultimately becomes an integral part of a universally accepted dating scheme. It is now possible to state explicitly the goals one is attempting to accomplish with atomic clocks.

A. Principles of Generation, Performance, and Reliability

As was previously pointed out, the date of an event on an earth-based time scale is obtained from the number of cycles (and fractions of cycles) of the apparent sun counted from some agreed-upon origin. Similarly, atomic time scales are obtained by counting the cycles of a signal in resonance with certain kinds of atoms. The major difference between these two methods is that the cycles of atomic clocks are much, much shorter than the daily cycles of the apparent sun. Thus the atomic clock requires more sophisticated devices to count cycles than are required to count solar days. The importance of this difference is a matter of technological convenience and is not terribly profound.

Of technological significance are the facts that atomic clocks can be read with many thousands of times the precision of the earth clock with much greater ease and the reading of an atomic clock can be predicted with about 10 000 times better accuracy than the earth clock. To be practical, however, atomic time must be reliable and readily available. Thus the establishment of an atomic time scale must involve the concepts of accuracy of rate, uniformity, and reliability.

Accuracy: Since 1967 the internationally accepted definition of the unit of time (interval), the second, ". . . is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom."

In general, a primary frequency standard (e.g., a cesium beam) is routinely subjected to an accuracy evaluation in order to assess any changes in device performance. While this routine reevaluation is most desirable from an accuracy standpoint, it is not directly amenable to the reliable and stable operation of a clock. Thus one normally finds that the primary standard of frequency is separate from a clock ensemble which is calibrated as to rate with the primary frequency standard. Thus there is a distinction between a *frequency standard* and a *time standard* which must logically include both stable clocks and a primary frequency standard to calibrate the clocks.

There are some clock ensembles [22] which do not themselves incorporate primary frequency standards. These time scales might be very uniform, but their rate accuracy is normally traced to other laboratory-type frequency standards which undergo routine evaluation. In particular, the International Atomic Time (IAT) scale maintained by the International Time Bureau (BIH) is an international average of various national time standards and time scales.

Uniformity and Reliability: Uniformity (i.e., frequency stability) and reliability are normally obtained by grouping several high-quality oscillator clocks into the system. Theoretically, it is possible to average several clocks and obtain a time scale which is more uniform than any one of the individual clocks alone could generate. Unless one carefully accounts for differences in the individual clock performances, however, this might not be realized.

It is possible today to operate a group of 4 or 5 high-quality clocks to define an atomic time scale with almost no risk of a complete failure or significant time loss. Currently, the preferred clocks to be used are commercial cesium beam devices.

In actual practice, an algorithm (i.e., a specific method of computation) is used to average the times of the various clocks in the ensemble and to test for failures in any of the individual clocks. These algorithms are implicitly based on models of ideal clock performance and some ideas of possible clock failures.

For the future, one may well expect that the models of clock performance will become much more sophisticated, comprehensive, and well verified. The results should be that substantially more uniform and reliable time scales can be generated with fewer clocks in the ensemble than at present, and that the actual performance will be better understood and documented than at present.

B. Independent and Coordinated Time Scales

There are several laboratories which generate independent atomic time scales. These laboratories include the National Bureau of Standards, U. S. Naval Observatory, Physikalisch Technische Bundesanstalt, Observatory of Neuchâtel, Commission Nationale de l'Heure, National Research Council, and Royal Greenwich Observatory. These independent time scales, however, are not widely disseminated although the pertinent data are made available to interested people. Instead, an international atomic time scale, IAT, is constructed by the BIH from the independent atomic time scales.

Standard frequency and time signals (such as WWV, CHU, and WWVH) which are broadcast by many countries in conformance with International Radio Consultative Committee (CCIR) regulations are coordinated with the BIH time scale, AT [34]. Thus there does exist a single very precise time scale which is coordinated internationally, is highly reliable and precise, and is readily available. The accuracy of rate of IAT is subject to periodic evaluation and correction.

VI. IMPORTANCE OF FREQUENCY METROLOGY NOW AND IN THE FUTURE

The already wide and increasing field of application of accurate frequency and time metrology is covered in the other papers in this issue. However, we would like to mention in this review two further subjects to which the application of frequency metrology will almost certainly be extended in the near future.

A. Definition of the Meter

Historically, the unit of length was the first unit to be based on a quantum transition. This has been discussed since the pioneering work of Michelson at the end of the last century. More than 60 years later, the present definition based on the wavelength of a spectral line in Krypton 86 was at last adopted. The advent of the methane-stabilized laser having an accuracy capability (as a frequency standard) which is several orders of magnitude better than that of the Krypton lamp offers new and far-reaching possibilities. Recent research efforts on frequency multiplication from microwave frequencies up to infrared frequencies [35], [36] show that it may become possible to relate microwave standard frequencies to infrared and visible frequencies with the same high precision and accuracy available in frequency standards work. The speed of light in a vacuum c might then become a defined quantity and the basic units of time and length could be based on the same primary standard. If separate standards for length and frequency were to continue, the most accurate value of c would possibly come from a *frequency* measurement of the length standard.

B. Definition of the Volt

In the ac-Josephson effect [37], the frequency ν of oscillations generated in a superconducting weak link is related to the applied voltage V by

$$\nu = \frac{2eV}{h}$$

where e and h are the charge of the electron and Planck's constant, respectively. This is a simple voltage–frequency relation which contains the ratio of two fundamental constants. Until proof to the contrary we may again assume this ratio to be invariant with time and thus useful as a working standard for the volt. Voltage measurement could then be reduced to frequency measurements.

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