

CLOCKS AND MEASUREMENTS OF TIME AND FREQUENCY*

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SUMMARY

After a brief historical review, the present state of the art in frequency and time standards of high performance will be reviewed.

Precision oscillators used in precision time and time interval applications include quartz crystal, rubidium gas cell, cesium beam, and hydrogen maser oscillators. A general characterization and comparisons of these devices is given, including accuracy, stability, environmental sensitivity, etc. Areas of special concern in practical applications are identified, and a projection of future performance is given. An attempt is made to predict physical and performance characteristics of new designs potentially available in the near future, such as novel crystal standards, superconducting cavity devices, etc.

Methods for measuring frequency stability are discussed. The terms which are useful to characterize frequency stability are recommended by the IEEE subcommittee on Frequency Stability of the Technical Committee on Frequency and Time of the IEEE Group on Instrumentation. The methods employed for measuring frequency are designed to include state-of-the-art oscillators; they are fairly simple, and commonly available components can be used in the measurement system.

Physical interpretations of common noise processes are discussed, and it is shown how frequency domain stability characteristics may be translated to time domain stability characteristics.

A brief survey of the capabilities of available and potentially available time and frequency transfer techniques is given, including portable clocks, satellite methods, and radio broadcasts.

PREFACE

This paper is intended as a review of the field of time and frequency. Most of its text is not original but taken, with only minor changes, directly from several publications by researchers of the National Bureau of Standards. The reader is encouraged to go back to these referenced originals for more detail and additional literature references.

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1. HISTORICAL REVIEW

Today's precision clocks and frequency standards are exclusively based on quartz crystal and atomic resonators. Quartz crystal oscillators became available in the 1920's and were soon developed into precision devices, and put in service as workhorses in numerous applications involving time and frequency. Because of systematic frequency changes with time, displayed by all crystal resonators, crystal clocks never became true timekeeping clocks but remained interpolating devices for limited time periods in need of recalibration and resetting. The calibration reference, i.e., the primary frequency and time standard, remained the rotating earth via astronomical observations.

The idea of atomic clocks, i.e., clocks based on natural resonance phenomena in atoms or molecules, was actively studied after the second world war, when the needed microwave technology became widely available. At this time, accuracies in the 10^{-9} to 10^{-10} region were predicted with great excitement--for the first time it appeared possible to build a clock better than the rotating earth. Working experimental devices based on the ammonia molecule and the cesium atom were built and tried. In the mid-1950's it was experimentally shown that cesium devices indeed were usable as clocks surpassing the performance of astronomical "clocks." As a consequence, new time scales called Atomic Time (AT) were established, to be maintained in parallel with the official "astronomical" time (or Universal Time, UT).

The increasing availability of commercially produced clocks since the late 1950's caused an increasing number of laboratories to generate atomic time scales. The demonstrated uniformity of the atomic cesium clocks exceeded the uniformity of "astronomical" ones by orders of magnitude. This ultimately led to an international agreement to redefine the length of the Second in terms of the cesium resonance, executed in 1967, as "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 a logical move thereafter, the internationally coordinated time scales, Atomic Time, and Coordinated Universal Time, were "unified." Today, two time scales are available worldwide: the

International Atomic Time (TAI) and the Coordinated Universal time (UTC). TAI is generated by the International Time Bureau (BIH) in Paris from the input of numerous timekeeping laboratories around the world. UTC is derived from TAI, also by the BIH, using information on UT obtained by several dozen astronomical observatories of worldwide distribution. UTC is based on the same unit of time as TAI, i.e., on the atomic second. However, UTC's dating differs from TAI by an integral number of seconds in order to approximate, to better than one second, the actual astronomical UT.

The official or legal time made available by the responsible laboratories in the different countries is almost always an excellent approximation to UTC, often differing by only a few microseconds from it.

The types of standards which are in actual use as frequency standards and clocks in science and industry have not changed during the past decade. We still find hydrogen masers, cesium beam tubes, rubidium gas cells, and quartz crystal oscillators. However, considerable technological advances have significantly improved the performance and other physical characteristics of these standards. More improvements are possible; and, in fact, a considerable amount of effort is being expended in this direction by industry, universities, and government. These improvements of the past and the present naturally have been and are being paralleled by corresponding advances in measurement methods and techniques as well as in the dissemination of time and frequency.

2. FREQUENCY STABILITY OF PRECISION OSCILLATORS^{1,2}

We will concern ourselves in this chapter only with those devices which are commercially available and/or have direct importance for applications; i.e., we will discuss only crystal oscillators, cesium beam devices, rubidium gas cell devices, and hydrogen masers.

Figure 1 is adapted from Ref. 2, but updated. It includes crystal oscillators and various types of laboratory and commercial atomic frequency standards. Figure 1 shows that for short sampling times quartz crystal oscillators are the oscillators of choice. For medium-term stability, the hydrogen maser is superior to any other standard which is available today. For very-long-term stability or clock performance, cesium standards are presently the devices of choice. Rubidium standards are not superior in any region of averaging times; however, they excel in the combination

of good performance, cost and size. It should be noted that in Figure 1 the best available stabilities (usually obtained in a laboratory environment) are listed for each class of standards, regardless of other characterization of the devices.

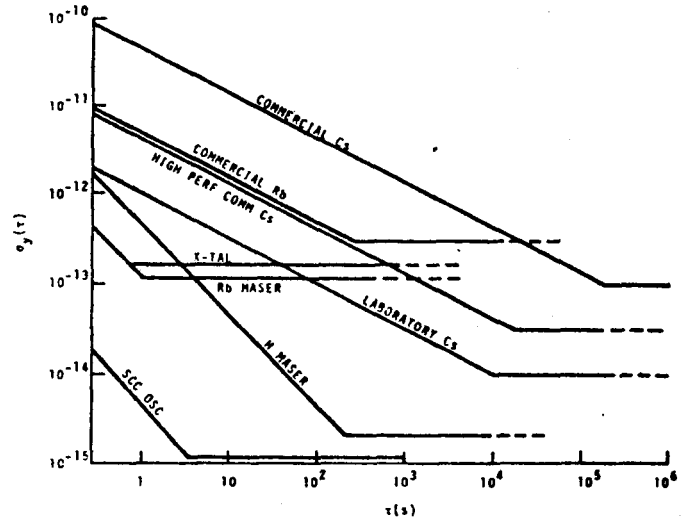


Figure 1

Figure 1 illustrates that the choice of atomic frequency standards should be a matter of very careful consideration and weighing of the trade-offs and actual requirements. For any system application of precision oscillators, it is important to first determine the actually needed stability performance of the devices; secondly, to consider the environmental conditions under which the standard has to perform; and thirdly, the size, weight, cost, and turn-on characteristics of the standard. Occasionally, a system designer will find that a standard with all the characteristics needed is not available on the market. In this case, the designer has two alternatives: either to adjust his system parameters to accommodate one of the available standards or to choose a combination of these standards to fulfill his need. The systems concept as a solution to a design problem is a very powerful tool, and it can be realized technically at no sacrifice to the performance of the individual components of the system. The only actual restrictions may be physical size and cost. It should be noted here that many time scale generating systems are based on clock ensembles which feature not only several clocks of the same type but a combination of clocks of different design. For example, at the National Bureau of Standards we routinely use a combination of crystal oscillators and cesium standards when testing precision oscillators.

An important design and application topic is the tunability of an oscillator. It can be generalized that for any oscillator, crystal or

atomic, there is a trade-off between tunability and stability (and accuracy). The addition of tunability introduces into the oscillator a variable element which is also frequency determining and thus degrades to the degree of tunability the primary function of the crystal or atomic resonator as the only frequency-determining element. Quantitative values of this degradation depend strongly on the particular engineering-solution. As an example, a varactor tunability over a range of 10^{-7} in a crystal oscillator will likely preclude any possibility of reaching into the 10^{-13} region with such a device.

3. QUARTZ CRYSTAL OSCILLATORS¹

Two deleterious effects, among others, are important in the design of crystals and crystal oscillators (Fig. 2) and limit their usefulness. The first is the temperature dependence of the quartz crystal resonance frequency; the second is a slow change of the resonance frequency with time (drift, aging).

The temperature dependence is caused by a slight change in the elastic properties of the crystal with temperature. However, certain crystallographic orientations of the crystal minimize this effect over a rather wide range of temperatures; best known in this regard are the so-called "AT" cuts. Temperature coefficients of less than 10^{-8} per degree are possible. Nevertheless, this effect demands certain precautions in the design of a crystal oscillator if very high frequency stabilities over longer times (hours or days) are desired and/or if large environmental temperature fluctuations are to be tolerated. Hence, many crystals are enclosed in electronically regulated ovens which maintain a constant temperature. In certain crystal oscillators this is done to better than 1/1000 of a degree.

A different solution to the temperature problem is the so-called temperature-compensated crystal oscillator or TCXO. An additional frequency-determining element in the oscillator (often a varactor or mechanically tunable capacitor) gives the opportunity to tune the oscillator over a limited range. The applied corrective signal is derived from a temperature-sensing circuit. The TCXO thus does not necessarily require further temperature control by an oven. However, we see the drawback of this approach. In adding a further frequency-determining element, the crystal resonator has to relinquish a corresponding part of its control on the output frequency of the whole oscillator. We, therefore, realize that the stability performance of a TCXO will degrade the more, the wider the temperature range of compensation is made. The long-term stability (days) of TCXO's is therefore below that of crystals with a good oven control. We find TCXO's in small, usually portable units of relative low performance.

The drift, or aging, is a common behavior of all crystal oscillators. It is a nearly linear change in resonance frequency with time, which frequently is negative (i.e., the resonance frequency decreases). A frequency decrease could be interpreted as an increase in the crystal size. Many physical mechanisms have been considered as the cause: contamination of the surfaces (deposition of foreign material); changes associated with the electrodes or the metallic plating; reformation of loose (from grinding and etching) surface material; changes in the internal crystal structure, etc.--all of this possibly caused or enhanced by the vibrating motion of the oscillating crystal. Careful fabrication and electrode design combined with clean vacuum enclosures have led over the years to a reduction of the aging to about 10^{-11} per day and better for the best crystals.

Two more effects on crystal resonators are to be considered. One is its relative sensitivity to gravitational forces and acceleration; frequency changes will occur because of the stresses in the crystal caused by these forces. This influence depends on the direction of the force relative to the crystallographic axes and thus can be minimized for certain orientations. The magnitude of the effect is typically of the order of 10^{-9} for accelerations corresponding to the earth's gravitation.

The other effect is related to intermittent operation. If a crystal oscillator is turned off and, after some time, put back into operation, it will not oscillate immediately at the original frequency but will exhibit first a "warm-up" due to temperature stabilization of the crystal resonator and its oven and then for some time (as long as many days) a large but diminishing drift until it reaches its previous aging performance. The frequency at which it will then operate might also be substantially different from its frequency before the interruption (retrace).

Crystal resonators have Q-values which are typically, in the range from $Q = 10^4$ to almost $Q = 10^7$. These are very high Q-values as compared to most other resonators, except, most notably, atomic resonators. The high performance devices presently use 5 MHz or 2.5 MHz crystal resonators with Q-values of more than one million.

These high Q-values are an essential prerequisite for the excellent stability performance of crystal oscillators. The best presently available devices show stabilities of nearly one part in 10^{13} for sampling times of the order of seconds. There is experimental evidence that some crystal resonators may perform better. For times shorter than one

second, the stability is often determined by additive noise in the output amplifiers and can then be reduced by a crystal filter in the output or by different circuit design. The long-term stability beyond several hours' sampling time is determined by aging and by external influences such as line voltage variations, temperature fluctuations, etc. The reliability of crystal oscillators is usually not limited by the crystal; it is comparable to the reliability of any electronic circuit of equivalent sophistication.

4. ATOMIC CLOCKS^{1,2}

Before we discuss effects which might cause changes in the output frequency of an atomic standard, we should make a very important statement: The atomic resonance frequency itself is given to us by nature; it will not drift nor age. Hence, atomic resonators with Q-values of 10^8 or higher may be expected to "naturally" have accuracies of one part in 10^8 or better because we will not be able to pull the resonance frequency further away than the linewidth of the resonance.

a. Cesium Standards

The basic design of a cesium standard is shown in Fig. 2. The cesium beam emerges from an oven into a vacuum, passes a first-state selecting magnet, traverses a Ramsey-type cavity where it interacts with a microwave signal

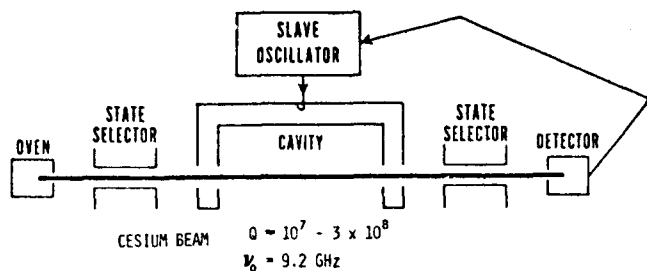


Figure 2

derived from a slave oscillator. The microwave signal changes the distribution of states in the atomic beam, which is then analyzed and detected by means of the second-state selector magnet and the atom detector. The detector signal is used in a feedback loop to automatically keep the slave oscillator tuned. The beam tube can be either a single conventional beam or a multiple beam as has been developed recently in some commercial beam tubes. This allows a

high beam intensity without too much sacrifice in the ability of the designer to control and predict the functions of the beam optics. The line Q is determined by the interaction time between the atoms and the microwave cavity. Thus, a beam of slow atoms and a long cavity leads to a high line Q. Commercial devices which for obvious reasons are restricted in total size have line Q's of a few 10^7 ; whereas, high-performance laboratory standards with an overall device length of up to 6-m feature line Q's of up to 3×10^8 .

b. Hydrogen Maser Standards

Hydrogen masers are rather simple devices as shown in Fig. 3. The hydrogen is produced usually by a radio frequency discharge from molecular hydrogen. The beam then emerges in a vacuum, passes a state-selecting hexapole magnet, and enters a quartz vessel whose inside is lined with a fluorocarbon coating. This storage bulb is located inside of a microwave cavity. If the cavity losses are low enough

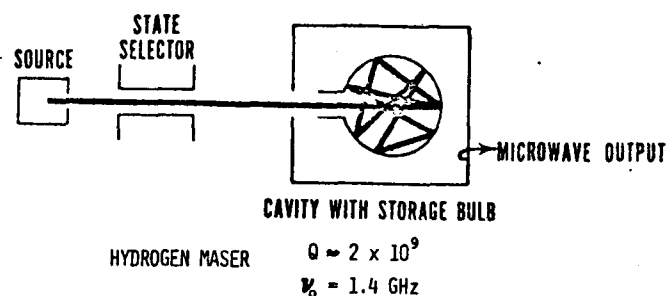


Figure 3

and the intensity of the state-selected hydrogen beam high enough, self-sustained oscillations occur and a microwave output is generated. This microwave output is used to lock a crystal oscillator to the hydrogen transition frequency via a frequency synthesizer and a phase comparator. Storage times of up to 1 second can be realized ultimately, limited by recombination of hydrogen and relaxation of the state-selected hydrogen atoms after too many wall bounces. The Q values of hydrogen masers are the highest of all the traditional frequency standards and are typically 2×10^9 , which accounts for the excellent stability of hydrogen masers as listed in Fig. 1.

c. Rubidium Standards

The basic design of a passive rubidium gas cell standard is depicted in Fig. 4.

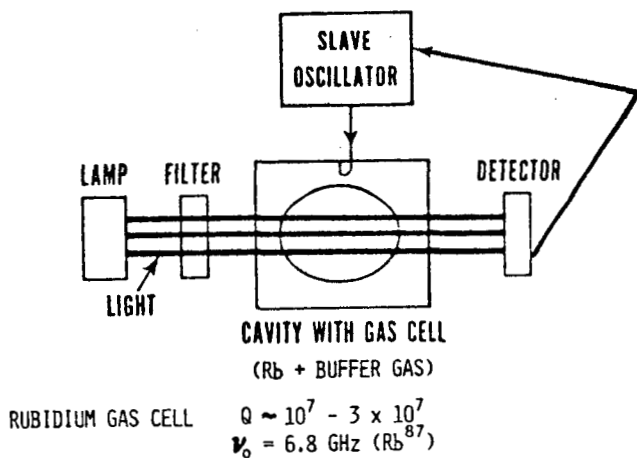


Figure 4

Rubidium and some buffer gas is contained within a storage cell located within a microwave cavity. The storage cell is completely sealed off. A lamp emits light at an optical transition of the rubidium. It is transmitted through a filter which contains a rubidium isotope, then through the rubidium cell to a photodetector. If the signal injected from a slave oscillator into the cavity coincides with the microwave transition, the light intensity is changed due to the simultaneous action of the microwave radiation and the light radiation on the same energy level. Thus the detector signal can be used in a feedback network to keep the slave oscillator on the rubidium resonance frequency. If the cavity is of sufficiently low loss, and the rubidium content and the lamp intensity are sufficiently high, the system is capable of self-sustained oscillations (rubidium maser oscillator).

The system can be built rather compactly and thus has led to several commercial devices of rather small size, weight, and low cost as compared to the other atomic frequency standards. Rubidium standards exhibit a long-term performance including aging and drift which is considerably inferior to that of the other atomic standards. It is likely that this behavior is due to small changes in buffer gas composition, rubidium density, light intensity, spectral distribution of the light, etc., as the standard ages. However, new developments appear to yield some better handling of these long-term processes.

Some general statements can be made concerning the physical effects which may cause frequency changes in atomic clocks. In the following, we are not exhaustive, but list only the major perturbing effects:

(1) Electronic noise and offsets: Random noise in the crystal oscillator (slave oscillator), the detector, the microwave cavity, the

modulation and servo circuits, and the frequency synthesizer will cause corresponding fluctuations of the output frequency. Voltage offsets, especially in the modulation and servo circuits can cause frequency offsets, which may vary with time affecting the long-term stability and potentially causing some aging.

(2) Cavity pulling: The microwave cavity is itself a resonator. Thus we have an additional frequency-determining element besides the atoms. It influences the output frequency by pulling the combined resonance frequency to a value which usually lies between the resonances of the atom and cavity. The requirements for tuning will be relaxed if the Q-value of the atomic resonance is as high as possible and the cavity-Q as low as possible. For all practical purposes, only the hydrogen maser suffers in this regard, whereas the cesium and rubidium standards display negligible effects due to the fact that the atomic resonance is not monitored via the microwave signal but via atomic beam or light detection, respectively. In this case the pulling factor is the square of the Q-ratios of cavity-Q and atomic-resonance-Q (in hydrogen masers it is directly the ratio). The pulling factors in Cs and Rb are therefore typically of the order of 10^{-8} or smaller as compared to at best 10^{-5} in hydrogen masers.

(3) Microwave spectrum: If the exciting microwave signal has not a symmetric but an asymmetric distribution of frequencies, a frequency pulling occurs which conceptually is related to the mechanism of cavity pulling. By careful design in the electronics, this effect can be made negligible, and it is not present in the hydrogen maser oscillator.

(4) Collisions: Collisions between the atoms, and between the atoms and the walls of a vessel (gas cell) in which the atoms may be contained, will not only shorten the duration of the oscillation but also cause a frequency shift. Obviously, these effects can be minimized by having low atom densities and no walls, if possible, such as in the case of the cesium beam.

(5) Doppler effect: The apparent change in frequency if the emitter moves relative to an observer is the first order Doppler effect. Here, the moving objects are the oscillating atoms and the observer is the microwave cavity. The Doppler effect can be highly reduced by choosing a right-angle orientation of the atomic beam with respect to the direction of the oscillating magnetic microwave radiation, or by placing a gas cell inside of the cavity. The change in frequency due to the fact that the moving "clock" goes slower as measured from an observer at rest is called the second-order or relativistic Doppler effect. In contrast

to the first order effect it is independent of the direction of movement. It should be noted that experimental verifications of this effect have not yet been carried out to much better than 1 percent.

(6) Magnetic field: Of the effects which we discuss here, this is the only one which directly affects the atomic resonance. All present atomic standards use magnetic dipole transitions; therefore, the atomic resonance frequency changes in a magnetic field. This necessitates magnetic shielding, which is a characteristic design feature of all presently used atomic frequency standards. The shielding is usually quite elaborate and reduces the external magnetic fields, e.g., the earth's magnetic field, to 1 percent or less of its external value. This residual magnetic field can shift the output frequency fractionally by an amount of the order of 10^{-10} , typically, as compared to the frequency of the atom in a zero magnetic field. However, the magnitude of the magnetic field can be measured quite precisely, actually to an accuracy which is much better than required in view of the other discussed limitations. This measurement uses the atom itself as the magnetometer. In Fig. 5, which illustrates cesium, the clock transition is indicated by the solid line; the magnetic field H can be measured very precisely by measuring the "magnetic field dependent" or Zeeman resonances at higher or lower frequencies

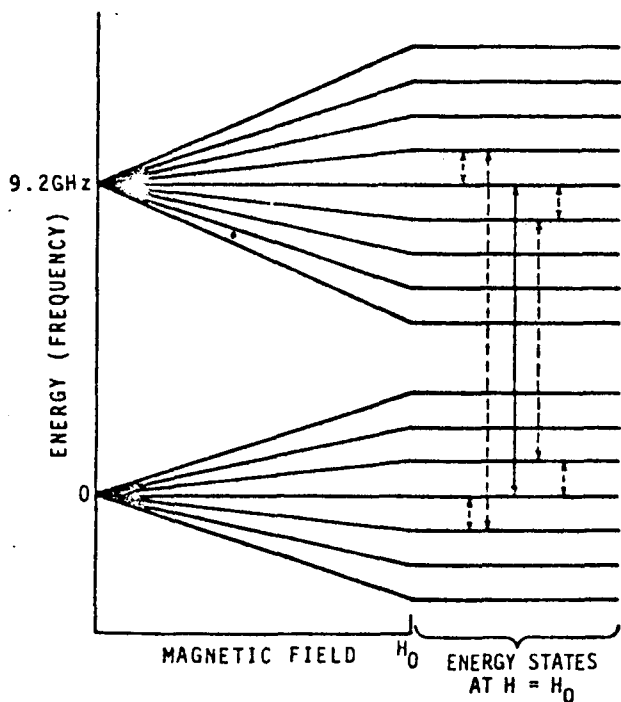


Figure 5

as indicated by the dotted lines between the energy levels. The corresponding magnetic field dependencies are given by the following equations (ν or f in Hz, H in T) for the shift in the clock transition:

$$\nu - \nu_0 = K_1 H^2$$

$$[\text{Rb}:K_1 = 5.73 \times 10^{10};$$

$$\text{H}:K_1 = 27.5 \times 10^{10};$$

$$\text{Cs}:K_1 = 4.27 \times 10^{10}]$$

for the "magnetic field dependent" resonance:

$$\nu_M - \nu_0 = K_2 H$$

$$[\text{Rb}:K_2 = 1.4 \times 10^{10};$$

$$\text{H}:None;$$

$$\text{Cs}:K_2 = 0.7 \times 10^{10}]$$

for the low frequency resonance:

$$f_M = K_3 H$$

$$[\text{Rb}:K_3 = 0.7 \times 10^{10};$$

$$\text{H}:K_3 = 1.4 \times 10^{10};$$

$$\text{Cs}:K_3 = 0.35 \times 10^{10}].$$

We can thus obtain the magnetic field H by measuring $\nu_M - \nu_0$ or f_M , and can then apply the proper frequency shift correction in the clock transition according to the first of the above equations.

The output frequency has to be corrected to reflect the frequency of the magnetically unperturbed atom. This can be done either by calculations or, as in most commercial devices, by hardware implementation within the synthesizer, which is necessary in any event to produce a standard 5 MHz output frequency. The magnetic field can, in principle, be also adjusted in order to adjust the output frequency of the device. This is sometimes done in commercial frequency standards; however, it is not recommended for high-precision devices, since any change of the magnetic field, voluntary or involuntary, will cause a change in the behavior of the magnetic shielding of the device. It may necessitate a degaussing cycle in the instrument, and certain drift or transitory behavior in the output frequency of the device may result. Also, the residual magnetization of the shields (especially the innermost one) may exhibit changes due to not-well-understood aging mechanisms.

5. PRECISION OSCILLATORS POTENTIALLY AVAILABLE IN THE FUTURE^{2,3,4}

a. Near Future: existing oscillators

As was outlined in the introduction, we list here only those devices and improvements which appear to be easily realizable within today's technology. We expect stability improvements of about 1 order of magnitude in all four devices: crystal oscillators, hydrogen masers, cesium beam tubes, and rubidium standards. In the case of crystals, this is due to better understanding and control of the noise behavior in the crystal resonator itself and, more importantly, in the design of the electronic circuits and the selection of electronic components. Also, new crystal cuts are being developed which promise superior performance with regard to stress phenomena; i.e., they may be better in warm-up, temperature gradients, accelerations, etc. In the case of hydrogen, we expect an even better control of the cavity-pulling effects which transduce temperature, pressure, and vibrational effects into frequency fluctuations. Also, significantly improved methods for long-term temperature control of the cavity, as well as improvements in the coating method of the storage bulb and the incorporation of sensors and servos for control of possible changes in the wall properties will play an important part. A better understanding and control of the aging of rubidium cells due to improved control of the lamp intensity, as well as the gas composition in the cells appears possible. In cesium an understanding of the flicker noise performance is expected, as well as improved signal levels. Flicker noise effects may be due to cavity temperature gradients, microwave interrogation power fluctuations, magnetic field variations, etc., all of which can be controlled to higher precision than is presently done. The rigorous application of good magnetic shielding techniques and improved understanding of magnetization changes with time in magnetic material will significantly impact on the performance, especially in long term, of all atomic standards.

b. Near Future; new devices

Five new concepts of devices are already in various stages of perfection: cesium gas cells, dual crystal standards, passive hydrogen masers, simple atomic standards, and superconducting cavity oscillators.

The cesium gas cell device is very much like the rubidium gas cell device, except that cesium is used, which necessitates a different lamp/filter arrangement. There is the potential that some aging effects may be better controllable with a cesium device because its different filter permits better control and higher symmetry

of the optical spectrum. However, aside from this, the cesium gas cell device is expected to have characteristics similar to the projected performance of rubidium gas cell devices.

The dual-crystal concept consists of a crystal oscillator which is locked to a crystal resonator with a reasonably long time constant. The advantage of a combination of a passive crystal with an active crystal oscillator lies in the realization of exceedingly high short-term stability in the oscillator, while the crystal resonator can be specifically designed for excellent long-term stability. In crystal oscillators short-term and long-term stability have been opposing goals because high short-term stability typically requires low drive levels at the crystal resonator. A combination using two crystals could optimize on both in the same package.

The passive hydrogen maser has been studied in detail and has demonstrated feasibility. The device is similar to a conventional active maser except that its advantages rely to a high degree on reduction of cavity pulling. As was mentioned already, cavity pulling serves as the transducer for temperature fluctuations, pressure fluctuations, mechanical stress fluctuations, etc., into frequency fluctuations. An increased environmental insensitivity coupled with a simplified design and excellent long-term stability without very high demands on the temperature stability can be realized. The hydrogen resonance is interrogated by a signal derived from a crystal oscillator. The signal is used to lock the crystal to the hydrogen resonance. A low cavity Q can be realized by using a lossy cavity, which may be a small dielectrically loaded cavity. This would lead to considerably smaller devices, i.e., a volume of the order of 100 μ appears possible.

Small and inexpensive atomic frequency standards appear possible. Traditionally, atomic frequency standards have been devised, designed, and built in order to achieve performances impossible to reach with crystal oscillators. Thus, the selection of the atomic resonance as well as the whole design concept was directed toward achieving the utmost in stability and accuracy. A different design philosophy, however, appears possible. Crystals require calibration and show environmental sensitivity, in particular, with regard to temperature and acceleration. If the atomic resonance is viewed only as a means to reduce or eliminate these negative performance characteristics of a crystal oscillator, we are not necessarily constrained to resonances which lead to utmost stability and accuracy performance, but others may be considered that lead to simpler designs.

Such a simple atomic standard could be built based on the well-known inversion transition in ammonia. Ammonia will not permit the design of a standard exceeding significantly a 10^{-10} performance level in stability, accuracy, and environmental insensitivity; however, up to the 10^{-10} a rather simple design concept should be realizable. The oscillator has not necessarily to be a crystal oscillator. If the standard is to operate under severe acceleration and vibration, the sensitivity of a crystal against these influences may cause loss of lock to the atomic resonance. Therefore, it may be advantageous to use other oscillator concepts such as a conventional LC or a Gunn effect oscillator. The device will have a performance which is in certain ways inferior to that of laboratory-type crystal oscillators, but it is projected that a combination of low cost, size, and environmental sensitivity can be obtained which is not presently available with any other design solution.

The superconducting cavity oscillator concept already demonstrated a stability performance which exceeds that of any other known oscillator. In fact, stabilities in the 10^{-16} region have been realized at averaging times of hundreds of seconds. The superconducting cavity oscillator appears adaptable to commercial design and would be the best performer for medium-term stabilities (averaging times to 100 s). It could therefore be of interest to users such as those engaged in very long baseline interferometry. It appears, however, unlikely that the superconducting cavity oscillator can become a very small and rugged device, and it is equally unlikely that its environmental sensitivity (especially against vibrations) can be reduced significantly.

c. Distant Future

In Table 1 is given a summary of classes of devices which are presently known to participate in the "competition" for potentially excellent performance in the more distant future. They will include classes where we find devices already available today (e.g., cesium) but also novel concepts. The reader should consult References [3,4] for more detail.

6. FREQUENCY STABILITY AND ITS MEASUREMENT^{4,5,6}

Most important to most frequency and time metrologists is probably the stability of a standard. Stability can be characterized in the frequency domain or in the time domain. The instantaneous fractional frequency deviation $y(t)$ from the nominal frequency ν_0 is related to the instantaneous phase deviation $\phi(t)$ from the nominal phase $2\pi\nu_0 t$ by definition

$$y(t) \equiv \frac{\phi(t)}{2\pi\nu_0} \quad (1)$$

a. Frequency Domain:

In the frequency domain, frequency stability is conveniently defined as the one-sided spectral density $S_y(f)$ of $y(t)$. More directly measurable in an experiment is the phase noise or, more precisely, the spectral density of phase fluctuations $S_\phi(f)$ which is related to $S_y(f)$ by

$$S_y(f) = \frac{f^2}{\nu_0^2} S_\phi(f) \quad (2)$$

For the above, f is defined as the Fourier frequency offset from ν_0 .

Of course, $S_\phi(f)$ cannot be perfectly measured; however, useful estimates of $S_\phi(f)$ can easily be obtained. One useful experimental arrangement to measure $S_\phi(f)$ is given in Fig. 6.

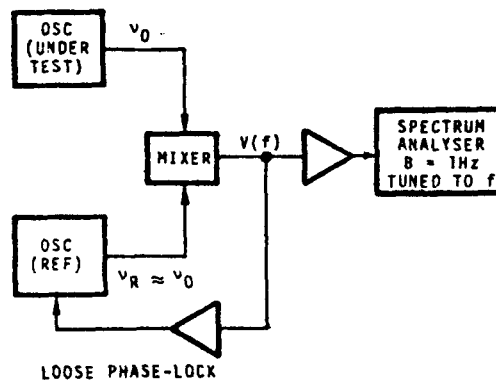


Figure 6

If the measured oscillator and the reference oscillator are equal in their total performance, and if the phase fluctuations are small, i.e., much less than a radian, then, for one oscillator

$$S_{\phi}(f) \approx 2 \frac{V^2(f)}{V_R^2} \quad (3)$$

where $V(f)$ is the rms voltage at the mixer output due to the phase fluctuations within a 1 Hz bandwidth at Fourier frequency f , V_R is a reference voltage which describes the mixer sensitivity and is equivalent to the sinusoidal peak-to-peak voltage of the two oscillators, unlocked and beating. The phase lock loop is only necessary to keep the signals in phase-quadrature at the mixer; it must be a sufficiently loose lock, i.e., its attack time (corresponding to the unity-gain condition) is long enough to not affect all (faster) fluctuations to be measured.

b. Time Domain

The relationship between the frequency and time domain, essentially a Fourier transformation, is extensively covered in Ref. (5). In the time domain, frequency stability is defined by the sample variance:

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

where $\langle \rangle$ denotes an infinite time average, N is the number of frequency readings in measurements of duration τ , and repetition interval T, B is the bandwidth of the measurement system. Some noise processes contain increasing fractions of the total noise power at lower Fourier frequencies; e.g., for flicker or frequency noise the above variance approaches infinity as $N \rightarrow \infty$. This, together with the practical difficulty to obtain experimentally large values of N , led to the convention of using always a particular value of N . In recent years, frequency stability has become almost universally understood as meaning the square root of the two-sample variance (Allan Variance) $\sigma_y^2(\tau)$, defined as in Eq. (4) for $N = 2, T = \tau$.

$$\sigma_y^2(\tau) = \left\langle \frac{(\bar{y}_{k+1} - \bar{y}_k)^2}{2} \right\rangle \quad (5)$$

$\sigma_y(\tau)$ is convergent for all noise processes commonly found in oscillators. It should be noted that even for Eq. (5) B remains an important parameter which must be taken into consideration. Fig. 7 depicts three different measurement systems which may be used to determine $\sigma_y(\tau)$.

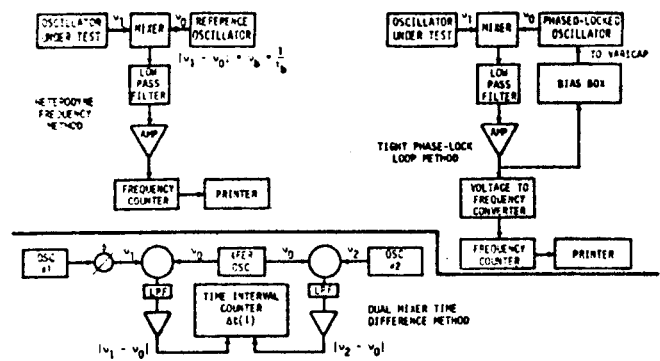


Figure 7

Very often it is useful to resort to a technique illustrated in Fig. 8. The frequencies of the oscillator under test and the reference oscillator are both multiplied to higher frequencies, e.g., into the GHz region, before the beat frequency is obtained and then analyzed. This has the effect of an expansion of the phase or frequency fluctuations by the frequency multiplication factor. This relaxes considerably the demand on the beat-frequency analysis equipment but introduces the multipliers as additional noise sources. This frequency multiplication technique is useful for measurements in the frequency domain as well as in the time domain. Commercial equipment based on this technique is on the market.

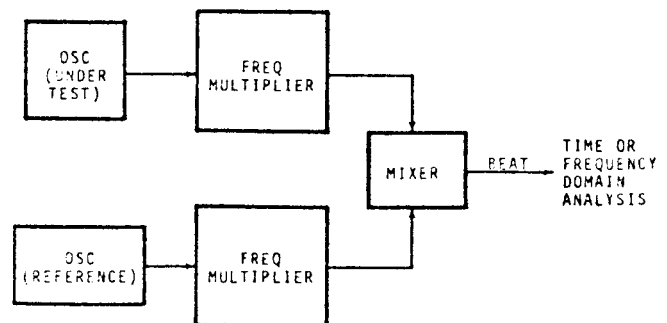


Figure 8

7. NOISE PROCESSES

Noise processes are models of precision oscillator noise that produce a particular slope on the spectral density plot. We often classify these noise processes into one of five categories. For plots of $S_\phi(f)$, they are:

1. Random walk FM (random walk of frequency), S_ϕ plot goes down as $1/f^4$.
2. Flicker FM (flicker of frequency), S_ϕ plot goes down as $1/f^3$.
3. White FM (white of frequency), S_ϕ plot goes down as $1/f^2$.
4. Flicker ϕM (flicker of phase), S_ϕ plot goes down as $1/f$.
5. White ϕM (white of phase, S_ϕ plot is flat.

The spectral density plot of a typical oscillator's output usually is a combination of different power-law noise processes.

We can make the following general remarks about power-law noise processes:

1. Random walk FM ($1/f^4$) noise is difficult to measure, since it is usually very close to the carrier. Random walk FM usually relates to the oscillator's physical environment. If random walk FM is a predominant feature of the spectral density plot, then mechanical shock, vibration, temperature, or other environmental effects may be causing "random" shifts in the carrier frequency.
2. Flicker FM ($1/f^3$) is a noise whose physical cause is usually not fully understood but may typically be related to the physical resonance mechanism of an active oscillator or the design or choice of parts used for the electronics, or even environmental properties. Flicker FM is common in high-quality oscillators, but may be masked by white FM ($1/f^2$) or flicker ϕM ($1/f$) in lower quality oscillators.
3. White FM ($1/f^2$) noise is a common type found in passive-resonator frequency standards. These contain a slave oscillator, often quartz, which is locked to a resonance feature of another device which behaves much like a high-Q filter. Cesium and rubidium standards have white FM noise characteristics.
4. Flicker ϕM ($1/f$) noise may relate to a physical resonance mechanism in an oscillator, but it usually is added by noisy electronics. This type of noise is common, even in the highest quality oscillators,

because in order to bring the signal amplitude up to a usable level, amplifiers are used after the signal source. Flicker ϕM noise may be introduced in these stages. It may also be introduced in a frequency multiplier. Flicker ϕM can be reduced with good low-noise amplifier design (e.g., using rf negative feedback) and hand-selecting transistors and other electronic components.

5. White ϕM (f^0) noise is broadband phase noise and has little to do with the resonance mechanism. It is probably produced by similar phenomena as flicker ϕM ($1/f$) noise. Stages of amplification are usually responsible for white ϕM noise. This noise can be kept at a very low value with good amplifier design, hand-selected components, the addition of narrowband filtering at the output, or increasing, if feasible, the power of the oscillator.

A measured curve of $S_\phi(f)$ can be translated into $\sigma_y(\tau)$. The following is a brief introduction and aid to these very useful and important translations.

First, consider $S_y(f)$, the spectral density of frequency fluctuations. There are two quantities which completely specify $S_y(f)$ for a particular power-law noise process: (1) the slope on a log-log plot for a given range of f and (2) the amplitude. The slope we shall denote by " α "; therefore, f^α is the straight line (on log-log scale) which relates $S_y(f)$ to f . The amplitude will be denoted " h_α "; it is simply the coefficient of f for a range of f . When we examine a plot of spectral density of frequency fluctuations, we are looking at a representation of the addition of all the power-law processes. Knowing how to measure $S_\phi(f)$ for a pair of oscillators, let us see how to translate the power-law noise process to a plot of $\sigma_y^2(\tau)$:

In the beginning of this section, five power-law noise processes were outlined with respect to $S_\phi(f)$. One obtains from Eq. 2

1.	Random Walk FM	(f^{-2})	...	$\alpha = -2$
2.	Flicker FM	(f^{-1})	...	$\alpha = -1$
3.	White FM	(1)	...	$\alpha = 0$
4.	Flicker ϕM	(f)	...	$\alpha = 1$
5.	White ϕM	(f^2)	...	$\alpha = 2$
		↑		↑ slope
		with respect to $S_y(f)$		

Table 2 is a list of coefficients for translation from $\sigma_y^2(\tau)$ to $S_y(f)$ and from $S_\phi(f)$ to $\sigma_y^2(\tau)$. The left column is the designator for the power-law process. Using the middle column, we can solve for the value of $S_y(f)$ by computing the coefficient " a " and using the measured time domain data $\sigma_y^2(\tau)$. The rightmost column yields

a solution for $\sigma_y^2(\tau)$ given frequency domain data $S_\phi(f)$ and a calculation of the appropriate "b" coefficient.

In order to execute such a translation with a real measured oscillator performance, the data points in an $S_\phi(f)$ (or $S_y(f)$) or a $\sigma_y(\tau)$ plot must first be connected by one or more straight lines. This is illustrated in Fig. 9, a $\sigma_y(\tau)$ plot of a real, measured oscillator and its translation into a $S_y(f)$ plot (Fig. 10).

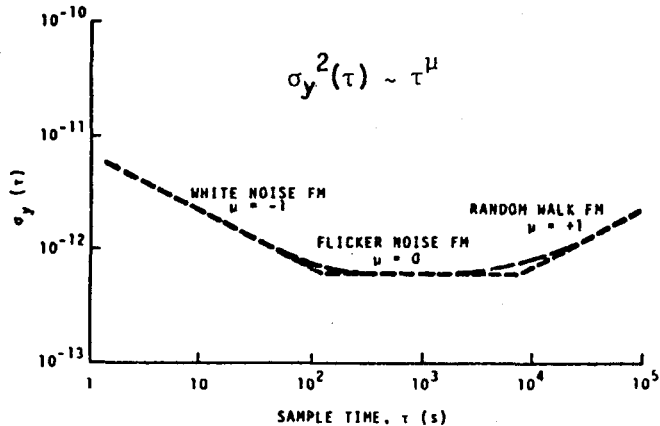


Figure 9

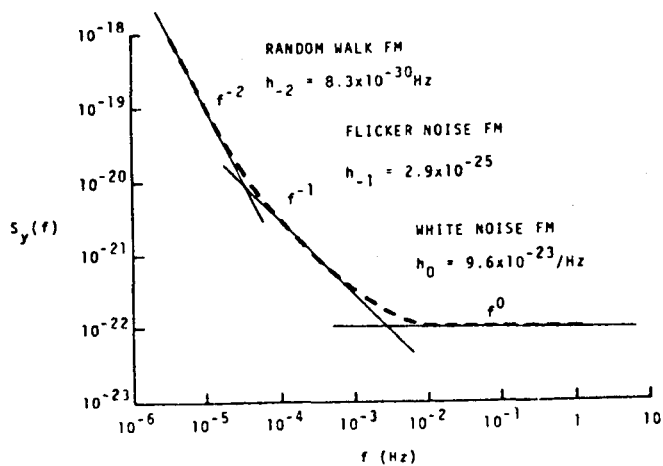


Figure 10

8. SUMMARY OF TIME AND FREQUENCY DISSEMINATION TECHNIQUES^{7,8,9,10}

An excellent survey of the area of time dissemination can be found in Ref. (8). A summary table from this survey is reproduced here for the benefit of the reader (Table 3).

Since the date of this survey, 1973, two noteworthy developments have begun which will significantly affect future time-dissemination procedures.

- a. Smaller, less expensive atomic clocks with less power demand have become commercially available. This is expected to lead to commercially produced portable clock systems with 10 to 20 hours of battery operation in packages which should allow their use via airline carry-on luggage by a single traveler. First experimental attempts in this direction already have demonstrated this. The costs per trip will thus reduce substantially, and the number of users and frequency of comparisons will increase significantly (including service of relatively remote locations).
- b. It appears that future worldwide time services as well as the most precise time comparison techniques will rely largely on satellites. A survey of relevant techniques and developments is given in Ref. (9). Tables 4 and 5, reproduced from this reference, may help the reader to appreciate these developments and their technical potential.

CLASS OF DEVICES	DOCUMENTED ACCURACY (ORDER OF MAGNITUDE)	COMMENTS
MICROWAVE BEAMS	(C ₁) 10 ⁻¹³	BEST DOCUMENTED. REALIZATION OF THE DEFINITION OF THE SECOND
ATOM STORAGE (M)	10 ⁻¹²	COATED STORAGE VESSEL ONLY USABLE FOR FEW SELECTED ATOMS
ION STORAGE (Mg, Ba, Pt, etc.)	10 ⁻⁹	SIGNAL-TO-NOISE PROBLEMS WITH PRESENT TECHNIQUES
SATURATED ABSORPTION (Ca, I ₂ , SF ₆ , etc.)	10 ⁻¹²	USEFULNESS AS "TRUE" TIME/FREQUENCY STANDARDS CRITICALLY DEPENDENT ON PRECISION MICRO-WAVE/INFRARED/VISIBLE FREQUENCY SYNTHESIS
TWO PHOTON TRANSITIONS (Na, H, etc.)		
INFRARED & OPTICAL BEAMS (Mg, Ca, I ₂ , etc.)	10 ⁻¹¹	

TABLE 1. Summaries of devices promising accuracies < 10⁻¹³

$S_y(f) = 1_a f^0$	$S_y(f) = a \sigma_y^2(\tau)$	$\sigma_y^2(\tau) = b S_\phi(f)$
(white phase)	$\frac{(2\pi)^2 \tau^2 f^2}{3 f_h}$	$\frac{3 f_h}{(2\pi)^2 \tau^2 v_0^2}$
(flicker phase)	$\frac{(2\pi)^2 \tau^2 f}{3.81 + 3 \ln(\omega_h \tau)}$	$\frac{[3.81 + 3 \ln(\omega_h \tau)] f}{(2\pi)^2 \tau^2 v_0^2}$
(white frequency)	2τ	$\frac{f^2}{2 \tau v_0^2}$
(flicker frequency)	$\frac{1}{2 \ln(2) + f}$	$\frac{2 \ln(2) + f^2}{v_0}$
(random walk frequency)	$\frac{6}{(2\pi)^2 \tau f^2}$	$\frac{(2\pi)^2 \tau f^4}{6 v_0^2}$

TABLE 2. Conversion table from time-domain to frequency-domain and from frequency-domain to time-domain for common kinds of integer power law spectral densities; f_h ($= \omega_h/2\pi$) is the measurement system bandwidth. Measurement response should be within 3 dB from D.C. to f_h (3dB down high-frequency cutoff is at f_h).

METHOD	SATELLITES & SATELLITE SYSTEMS
A Broadcast from synchronous satellites	ATS (Applications Technology Satellite) SMS/GOES (Synchronous Meteorological Satellite/ Geostationary Operational Environmental Satellite)
B Clock carry/fog satellites	Transit - TIP (Transit Improvement Program) Timation NTS (Navigation Technology Satellite) GPS (Global Positioning System)
C Satellite relays	DSCS (Defense Satellite Communications System)

TABLE 4. Satellite time dissemination systems⁹

METHOD	SATELLITES & SATELLITE SYSTEMS	ACCURACY	
		no corrections	realized
A	ATS SMS/GOES	tens of ms tens of ms	tens of μ s tens of μ s
B	Transit - TIP Timation NTS - GPS	tens of ms	30 ns 0.1 μ s 0.1 μ s
C	DSCS	-----	100 ns

TABLE 5. Time accuracy from satellite systems⁹

DISSEMINATION TECHNIQUES		STATUS	ACCURACY FREQUENCY SYNCHRONIZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY	COVERAGE FOR STATED ACCURACY	% OF TIME AVAILABLE	RELIABILITY	RECEIVER COST FOR STATED ACCURACY	COST PER CALIBRATION	NUMBER OF USERS THAT CAN BE SERVED	OPERATOR SKILL REQUIRED FOR STATED ACCURACY
VLF RADIO	COMMUNICATION SFB GER. NVA WHVWL	0	1-10 ¹¹	ENVELOPE 300 μs	PHASE ~50 μs	GLOBAL						
	NAVIGATION SYSTEM OMEGA	0/P	<1-10 ¹¹	≤ 10 μs	PROPOSED 1 YR ~100 μs	GLOBAL						
LF RADIO	STANDARD FREQ BROADCAST (WWVB)	0	1-10 ¹¹ (PHASE 24h)	ENVELOPE ~50 μs	1 YR	USA (WWVB) LIMITED			MODERATE		USA (WWVB), EUROPE OTHERS	
	NAVIGATION SYSTEM LORAN C	0	1-10 ¹² GND	~1 μs (GND) 50 μs (SKY)	50ms PHASE 10 μs	SPECIAL AREAS					SPECIAL AREAS	
HF/MF RADIO	STANDARD FREQ BROADCASTS (WWV)	0			1 DAY	HEMISPHERE						
	NAVIGATION SYSTEM LORAN A	0	5-10 ¹¹	2.5 μs NOT UTC	0.5 min	LIMITED AREAS						
TELEVISION (VHF/SHF RADIO)	PASSIVE LINE 10	0	1-10 ¹¹ (24h)	~1 μs	1 DAY	NETWORK COVERAGE					USA FOR EXAMPLE	
	ACTIVE LINE 1 (NBS TV TIME SYSTEM)	E	1-10 ¹¹ (<30 min)	<100ns	1 DAY	NETWORK COVERAGE					USA FOR EXAMPLE	
SATELLITES (VHF/UHF/SHF RADIO)	STATIONARY SATELLITES (TRANSPONDER) ONE WAY	E 0	1-10 ¹⁰ (24h)	10-50 μs	DEPENDS ON FORMAT	HEMISPHERE						
	STATIONARY SATELLITES (TRANSPONDER) TWO WAY	E 0	1-10 ¹² (24h)	~100ns	DEPENDS ON FORMAT	HEMISPHERE						
SHF RADIO	ON BOARD CLOCK (ACTIVE) ONE WAY LOW ALTITUDE	0	~1-10 ¹⁰ (24h)	0.5-50 μs	DEPENDS ON FORMAT	WORLD						
	MICROWAVE	E 0	~1-10 ¹³ (PER WEEK)	≤ 100ns	PHASE COMPARISON	HEMISPHERE						
PORTABLE CLOCKS	VLEI	P	5-10 ¹⁴	~1ms	DEPENDS ON FORMAT	HEMISPHERE						
	PHYSICAL TRANSFER	0	1-10 ¹²	100ns	1 DAY	LIMITED BY TRANSPORTATION						
PULSARS	AIRCRAFT FLYOVER 2 WAY	E	1-10 ¹²	≤ 100ns	DEPENDS ON FORMAT	LIMITED BY TRANSPORTATION						
	OPTICAL SIGNAL → NP 0537	P	1-10 ¹⁰	~10 μs	~33ms	HEMISPHERE						
AC POWER LINE	POWER NETWORK SYSTEM	P	1-10 ⁹		16.7ms	CONTINENTAL USA						

GOOD FAIR POOR

TABLE 3 Evaluation of selected time/frequency dissemination techniques

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