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TIME AND FREQUENCY METROLOGY: CURRENT STATUS AND FUTURE CONSIDERATIONS

By

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ABSTRACT

Over the last three decades we have seen methods evolve for the characterization of clocks and oscillators. The principal progress has been made in the time domain, but significant clarification has occurred in the frequency domain as well. We now have a CCIR recommendation and an IEEE standard for clock characterization. However, as we see the frontiers pushed forward, we can see a demand for even more exacting characterization of oscillators and clocks. The effect of environmental perturbations on clocks and oscillators is likely to become even more important as it effects the long-term stability. In addition, we see an important need to characterize measurement systems. To date, there is no standard for the proper characterization of measurement systems. Yet often the techniques for comparing either laboratory or remotely separated clocks may limit their frequency or time stability. As we look a decade ahead, these measurement concerns become even more important. Hence, there is a clear need to arrive at measures for characterizing measurement systems. In addition, we need to refine our ability to characterize the advanced clocks we anticipate in the coming years. Stronger ties with the telecommunications industry, where system timing and synchronization needs are high, will be mutually beneficial to both fields. This paper reviews some of the highlights of time and frequency metrology, makes recommendations for some needed standardization, and calls attention to certain unresolved problems.

INTRODUCTION

There is a need to be still more definitive in the measures we use to describe time and frequency (T/F) devices, and comparison systems. There are now a useful IEEE standard (No. 1139-1988) and a consistent CCIR recommendation for characterizing clocks and oscillators. [1] There is not, however, a similar measurement standard for time and frequency measurement systems (which might include clocks and oscillators).

Since the construction of the first atomic clock in 1948 we have seen about a factor-of-10 improvement in accuracy of primary standards every seven years. We expect this trend to continue. This will place new demands on metrology within the lab as well as on comparisons of clocks remote to each other.

In addition, as we design servo electronics, we cannot optimize system design unless we have properly characterized both the frequency standards involved and the measurement electronics. Within the laboratory environment this is often done well. However, when servo-controlling clocks remote from each other, serious mistakes are often made.

FOUR AREAS OF T/F METROLOGY

There are four general categories of time and frequency metrology as shown in Table 1. The first category involves frequency sources. Many advances, large and small, over the years have produced devices of remarkable stability and accuracy. A recent example is the work of Andrea De Marchi [2], who showed how Rabi pulling in cesium-beam frequency standards degrades the long-term frequency stability of these devices. Understanding these effects, he then showed how to reduce environmental perturbations on cesium standards. A significant improvement in long-term frequency stability and accuracy is now available.

The second category is turning a frequency standard into a reliable clock. At first thought, counting cycles from a frequency standard seems straightforward. But there are problems knowing absolute delays through critical parts of the measurement equipment. At the sub-nanosecond scale and over long distances, knowing these delays poses significant challenges. In addition, there is promise for a frequency standard in the optical region of the spectrum. We are probably decades away from being able to count optical frequencies without degradation. A breakthrough is needed.

Included within this second category is the important problem of properly using combining algorithms. When there is more than one clock, how should the readings be combined? Here again characterizing both the clocks as well as the measurement systems is essential for algorithm optimization. Caution is necessary because algorithms can make matters worse. Properly used, algorithms can provide improved reliability and performance. Past work has demonstrated that for intermediate and long-term frequency stability, the output of an algorithm can be better than the best physical clock in the system. Now,

Table 1. Areas of Time & Frequency Metrology

Frequency Sources	Time Keeping Metrology	Measurement Systems	Analysis and Modeling
ISSUES			
State preparation	Counting	Time interval & frequency counters	Systematics
Interrogation	Frequency dividers	Dual-mixer time difference	Stochastic
Particle detection	Delays absolute stable	Direct	Frequency domain
Frequency multiplication	Trigger points	Heterodyne	Time domain
Servo electronics	Balanced zero-crossing detectors	Homodyne	Optimum estimation
Spectral purity	Distortion	Dead time	Time & frequency stability & accuracy
Signal-to-noise	Dispersion	Hardware Filters Bandpass High pass Low pass	Abnormal behavior detection
Internal & external perturbations	Combining algorithms	Dissemination & comparision systems	Digital filters
			Distribution of error

the short-term stability of a good individual clock is better than can be achieved with an algorithm. This is due to digitization noise and long servo response times. As digitization speeds improve, the short-term stability of an algorithm's output may eventually be better than any of the contributing clocks.

Because of the high stability and accuracy of time and frequency devices, direct measurement methods almost always add significant measurement noise. A common example is the use of time-interval counters. If, for example, a counter has 1 ns resolution, it may require hours or even days of integration before the digital measurement noise is less than that of a precise clock. Such a measurement arrangement cannot be used to determine the intermediate or short-term stability of good clocks. There are more cost-effective, stable and accurate ways to characterize precise clocks. In general, it is desirable that the measurement system noise be less than the noise of the clock or oscillator. This is especially important for those regions of integration or sample time of interest. [1]

I cannot do full justice to analysis methods here, but I will present a few problems as examples. Consider the 1 ns counter mentioned above. If this is the measurement equipment used, and we want to measure the frequency difference between the clocks, then the data should be taken at the maximum rate possible; this is so because if the counter's measurement noise is well modeled as white noise PM (phase modulation), then the uncertainty of the frequency estimate is

$$s = \frac{\sqrt{12}\,\sigma}{\tau_0 N^{3/2}}, \qquad (1)$$

where σ is the standard deviation of N time measurements spaced τ_0 apart. Since the uncertainty decreases as $\tau_0 N^{3/2}$ grows, there is significant gain in taking as many points as possible, yet this is seldom done. Similarly, the optimum time difference estimate is best taken as the mean of as large a set of independent individual measurements as is practicable. The confidence of this estimate is the standard deviation of the mean. Such measurements often include systematic effects which make the classical estimates invalid. Characterizing these systematics is important, but is seldom done. Another common analysis error is made in processing time or phase differences between cesium beam clocks, rubidium gas-cell clocks, or any of the passive atomic standards where the intermediate-term stability is characterized by white-noise FM. White noise FM is the same as random walk PM. Analysts will often calculate a linear regression on the time difference measurements to estimate the frequency difference. This is far from optimum. It is equivalent to throwing away a significant percentage of the data as compared to an optimum estimator. The linear regression on the time differences is optimum for white-noise PM. This noise is found in the very short term for quartz oscillators and active hydrogen masers. Hence, in general, this linear regression on the phase or time difference measurements may give much less than optimum results.

MEASURES FOR STANDARDS AND MEASUREMENT SYSTEMS

Figure 1 illustrates a generic phase locked loop or time (phase) difference measurement system. This figure is a concept diagram. It could apply, for example, to phase locking a local oscillator, comparing data between remote clocks or synchronizing a network. First, consider that the two clocks involved have frequency determining elements. In general, the basic physical quantity of interest in a clock is its frequency, not its phase or

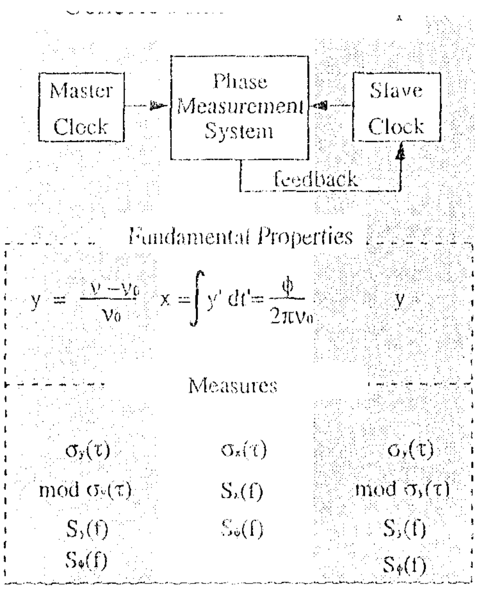


Fig.1. A fundamental concept diagram showing the properties and measures for clocks in contrast to measurement systems. The measurement system can be in the laboratory or it can be a comparison system for measuring clocks remote from each other. These concepts could also apply to a phase-locked servo system or a time dissemination system.

time. If the clocks are ideal the residuals around the mean frequency will have a white-noise FM spectrum (random-walk PM) in some useful regions of Fourier space. In contrast, for a measurement system the basic quantity of importance is the phase or time difference and not the frequency with a few exceptions. Hence, in the case of an ideal measurement system the residuals will have a white-noise PM spectrum.

Our conclusions from this distinction is that $S_y(f)$, $\sigma_y(\tau)$ or mod$\sigma_y(\tau)$ are useful measures for characterizing most clocks and frequency standards (y is the relative frequency and x is the time residuals gotten by integrating y). Similarly, we conclude that $S_x(f)$, $S_\phi(f)$, $\mathcal{L}(f)$ and $\sigma_x(\tau)$ are useful measures for characterizing typical measurement systems. $S_\phi(f)$ or $\mathcal{L}(f)$ are often used to characterize precise oscillators and have been shown to have useful properties. However, because frequency is basic and phase or time is proportional to the integral of frequency, the spectrum of the phase or the time will behave like the frequency spectrum divided by f^2. Walls and Percival [3] have shown that, within a finite analyzer band-width, significant biases (several decibels) can occur as a result of the steeper slopes typically used in modeling the phase or time spectral density for precision oscillators. Of course, corrections can be made for this, but the potential for error is greater. In general, if a spectrum is more nearly flat, then these biases will be negligible. It might well be wise to limit the use of these latter measures ($S_\phi(f)$ and $\mathcal{L}(f)$) for measurement system characterization. In the time domain the preference for measuring the frequency stability of a measurement system or of a time and frequency comparison or dissemination system is mod$\sigma_y(\tau)$.

dissemination system is mod$\sigma_y(\tau)$.

For the frequency domain, IEEE Standard 1139-1988 recommends the measures given in Table 2. [1] From the arguments above we conclude that these form a good set of measures for frequency standards and clocks as well as for measurement systems. In the time domain we conclude that the measures recommended are a good set for frequency standards and clocks. But these are deficient for characterizing measurement systems. Table 3 lists the recommended measures along with a proposed time stability (TVAR) measure which satisfies this deficiency. Table 4 lists the spectral density relationships for this measure and the range of convergence. For a finite data set an estimate of this measure (TVAR) is

$$\sigma_x^2(\tau) \approx \frac{1}{6n^2(N-3n+1)} \sum_{k=1}^{N-3n+1} \left(\sum_{i=k}^{n+k-1} (x_{i+2n} - 2x_{i+n} + x_i) \right)^2, \quad (2)$$

where $\tau = n\tau_0$.

Equation (2) and Table 3, show that the subscript i denotes data taken from the original set, whereas the subscript k denotes an average over n values of the x_is. The averaging of the x_is has the effect of digitally narrowing the bandwidth in the software to $f_s = f_h/n$, where f_h is the hardware bandwidth of the measurement system. [1][4][5][6]

Figures 2, 3 and 4 are the time-to-frequency domain mappings for $\sigma_y^2(\tau)$, mod$\sigma_y^2(\tau)$ and for $\sigma_x^2(\tau)$, respectively. Each of the three figures shows the usual range of applicability for precision oscillators and for measurement systems. In Figure 4 we immediately see an advantage of using $\sigma_x(\tau)$.

Table 2. IEEE Standard 1139 (1988)

Frequency Domain Spectral Densities

$S_y(f)$, $S_\phi(f)$, $S_{\dot\phi}(f)$, or $S_x(f)$

Relationships:

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

$$S_{\dot\phi}(f) = (2\pi f)^2 S_\phi(f)$$

$$S_x(f) = \frac{1}{(2\pi\nu_0)^2} S_\phi(f)$$

$$S_y(f) = (2\pi f)^2 S_x(f).$$

Table 3. IEEE Standard 1139 (1988)

Time Domain Variances

AVAR:

$$\sigma_y^2(\tau) = \frac{1}{2}\langle(\bar{y}_{i+1} - \bar{y}_i)^2\rangle$$

$$= \frac{1}{2\tau^2}\langle(x_{i+2} - 2x_{i+1} + x_{ik})^2\rangle$$

MVAR:

$$\mathrm{mod}.\sigma_y^2(\tau) = \frac{1}{2\tau^2}\langle(\bar{x}_{k+2} - 2\bar{x}_{k+1} + \bar{x}_k)^2\rangle$$

Proposed

TVAR:

$$\sigma_x^2(\tau) = \frac{\tau^2}{3}\,\mathrm{mod}.\sigma_y^2(\tau)$$

$$= \frac{1}{6}\langle(\bar{x}_{k+2} - 2\bar{x}_{k+1} + \bar{x}_k)^2\rangle$$

Table 4. Spectral Density and Time Domain Relationships

$$S_x(f) \sim f^{\beta},$$

$$\sigma^2_x(\tau) \sim \tau^{\eta},$$

$$\beta = -\eta - 1,$$

$$-5 < \beta \le 1$$

where $S_x(f)$ is the spectral density of the time difference measurements, x, and β denotes the kind of power-law spectrum.

$$S_y(f) \sim f^{\alpha}$$

$$\alpha = \beta + 2,$$

$$-3 < \alpha \le +3$$

where y is the normalized frequency.

Since the usual types of measurement noise are centered around $\beta = 0$, this gives a near-zero dependence on τ (a desirable trait for a good measure). Other useful characteristics of this measure are:

- it is equal to the classical standard deviation of the time difference measurements for $\tau = \tau_0$, for white-noise PM;
- it equals the standard deviation of the mean of the time difference measurements for $\tau = N\tau_0$ (the data length), for white-noise PM;
- it is convergent and well behaved for the random processes commonly encountered in time and frequency metrology;
- the τ dependence indicates the power-law spectral density model appropriate for the data;
- the amplitude of $\sigma_x(\tau)$ at a particular value of τ, along with the assumption of one of the five power-law spectral-density models (β = -4, -3, -2, -1, 0), provides enough information to estimate the corresponding level in the frequency domain for any of the recommended IEEE-standard spectral-density measures.

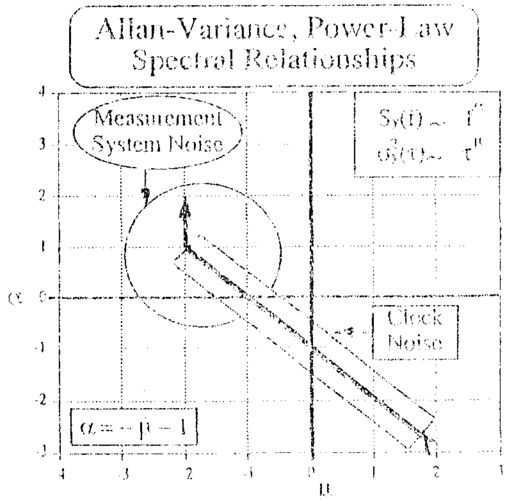


Fig. 2. The broad line represents the corresponding value of α for each value of μ. The rectangle is to graphically illustrate where the broad line is applicable for clock noise. Similarly, the circle is to graphically illustrate where the broad line is applicable for measurement system noise.

Other important considerations for a measurement, comparison, or dissemination system are time accuracy, frequency accuracy and frequency stability. For a measurement system, frequency accuracy will typically be a function of the averaging time as well as the processing method. As shown before, this can be very important. I will give another illustration later.

Whereas the discussion above has focused on time and frequency stability measures, time and frequency accuracy are also very important to metrology. Frequency accuracy as it relates to the fundamental definition of the second seems to be well in hand. However, there is a deficiency in the literature in relation to the definition of and use of time accuracy. Limited work has been done. [7] Absolute frequency has meaning in physics, but absolute time does not. Time accuracy has meaning only as a measurement is traceable to some defined or agreed-upon time standard or reference. Time accuracy can be thought of, for example, as the transport of a perfect portable clock from the agreed upon

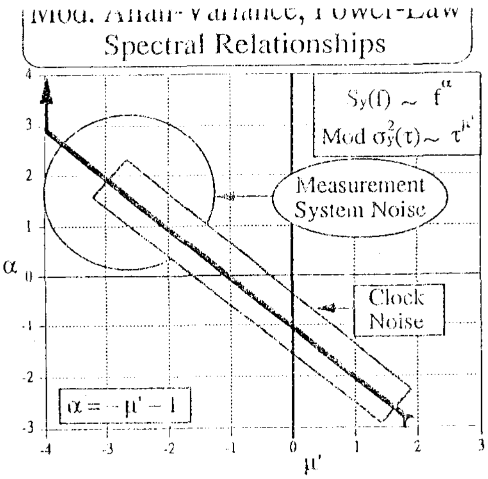


Fig. 3. The broad line represents the corresponding value of α for each value of μ'. The rectangle is to graphically illustrate where the broad line is applicable for clock noise. Similarly, the circle is to graphically illustrate where the broad line is applicable for measurement system noise.

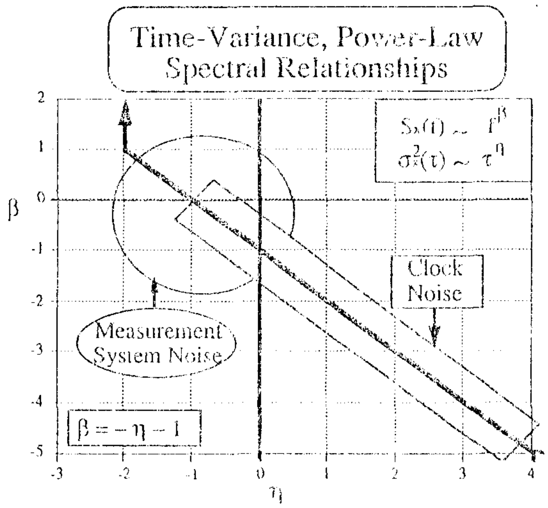


Fig. 4. The broad line represents the corresponding value of β for each value of η. The rectangle is to graphically illustrate where the broad line is applicable for clock noise. Similarly, the circle is to graphically illustrate where the broad line is applicable for measurement system noise.

reference to a desired point including all relativistic effects. The accuracy of transferring time from an agreed upon standard to another point is often hard to evaluate or estimate at high levels of precision. Unknown systematic delays and delay variations often become very important in this regard.

CHARACTERIZATION OF SYSTEMATICS EFFECTS

Properly characterizing the stochastic processes allows optimal estimation of the environmental perturbations due to temperature, humidity or other factors. If, for example, we see white-noise FM ($\alpha = 0$) in a cesium standard, the optimum estimator the frequency and not a quadratic on the time residuals or on the phase residuals. Often we see random-walk FM ($\alpha = -2$) as the long-term behavior of cesium or rubidium standards. If we wish to estimate frequency drift in the presence of this noise, the optimum estimator is a second-difference operator, rather than a simple linear regression. [1]

If a modulation side-band is found in the data, due, for example, to a diurnal effect, then such a side-band can be clearly seen when analyzed in the frequency domain. It can also be observed in the time domain. Figure 5 shows the effect of modulation on a $\sigma_x(\tau)$ plot. The effect of modulation decays as $1/\tau$, whereas the white-noise PM background decays only as $\tau^{-1/2}$.

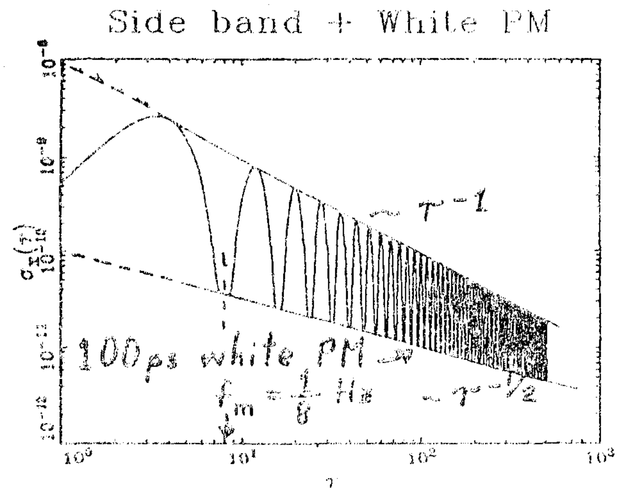


Fig. 5. An illustration of the effect of a modulation side band on top of a white-noise PM background. The solid straight lines are the theoretical maximum and minimum limits for $\sigma_x(\tau)$.

COMPARISON OF $\sigma_y(\tau)$ AND $\sigma_x(\tau)$

The IEEE and CCIR definition for $\sigma_y^2(\tau)$ is

$$\sigma_y^2(\tau) = \tfrac{1}{2}\langle(\bar{y}_{j+1} - \bar{y}_j)^2\rangle, \qquad (3)$$

where

$$\bar{y}_j = \frac{x_{j+1} - x_j}{\tau}. \qquad (4)$$

This estimate for y is an optimum estimate if the spectrum of the residuals is white-noise FM. This noise is the theoretically expected noise for a passive atomic frequency standard. The first-difference operator allows this measure to remain convergent for the low-frequency divergent power-law spectra met in modeling precision oscillators. Other advantages of $\sigma_y^2(\tau)$ are that it is equal to the classical variance for white FM. It is theoretically derivable from any of the commonly occurring spectral density models in precise oscillators. It is intuitive in that it is a measure of the change in frequency over some interval τ as may be germane, for example, in determining the optimum attack time for a servo design or for choosing the appropriate oscillator for a radar returned signal. In addition to these theoretical and practical advantages, we have from the arguments above an additional intuitive feeling for why $\sigma_y(\tau)$ is a good measure for clocks and oscillators. It is an optimum estimation of frequency change for white-noise FM.

The principal disadvantage of $\sigma_y(\tau)$ is the ambiguity for power-law processes with $\alpha \geq +1$ where we cannot easily distinguish between white-noise PM and flicker-noise PM. This ambiguity was the main motivation for the development of $\mathrm{mod}\sigma_y(\tau)$. As shown above, $\sigma_y(\tau)$ differences adjacent optimum frequency estimates (for white-noise FM) each measured over an interval τ. While this is a good measure for frequency stability, it has limitations as a measure where time or phase is the basic quantity, such as for measurement systems or for the synchronization of networks.

Since $\sigma_x(\tau)$ is derived directly from $\mathrm{mod}\sigma_y(\tau)$, it has all the associated advantages. For example, $\sigma_x(\tau)$ can be used to differentiate between white and flicker-noise PM. The second-difference expression for $\sigma_x(\tau)$ is

$$\sigma_x(\tau) = \left[\frac{1}{6}\langle(\bar{x}_{k+2}-2\bar{x}_{k+1}+\bar{x}_k)^2\rangle\right]^{1/2}. \tag{5}$$

The equivalent second-difference equation for $\sigma_y(\tau)$ is similarly

$$\sigma_y(\tau) = \left[\frac{1}{2\tau^2}\langle(x_{j+2}-2x_{j+1}+x_j)^2\rangle\right]^{1/2}. \tag{6}$$

$\sigma_x(\tau)$ is proportional to the rms second difference of time (phase) averages rather than the rms second difference of the time (phase) measurement points as in $\sigma_y(\tau)$. If we have white-noise PM, then the optimum estimate of the time from a set of time readings is the simple mean. Since $\sigma_x(\tau)$ is proportional to the rms change in the mean value of the time difference measurements averaged over an interval τ with respect to a similar average taken just before and just after τ, we see that it is an optimum estimator of changes in time (phase) over the interval τ. Hence, this measure is most useful where time or phase differences are the basic quantity of interest. Examples of application include network synchronization, time and phase difference measurements, phase-locked servo systems, remote time transfer and comparison systems, and time distribution systems.

A look at the transfer function for $\sigma_y(\tau)$ and $\mathrm{mod}\sigma_y(\tau)$ for different values of τ provides a good insight into their usefulness. We can show that, for $\tau = n\tau_0$ and $n = 2^i$ (i = 0, 1, 2,...), the set of resultant transfer functions form a nearly orthogonal set as viewed from the frequency domain. Figures 6 and 7 are the composite transfer functions for i = 0 to 8. For $\sigma_y^2(\tau)$ the composite transfer function is nearly square and flat within about 5% over more than two decades. One of the features of $\mathrm{mod}\sigma_y(\tau)$ is that it changes the bandwidth within the software; hence the composite transfer function is a little less flat than that for $\sigma_y(\tau)$. It is also more nearly square at the high frequency end.

The time-domain, frequency-domain relationships are known for $\sigma_y(\tau)$ and for $\mathrm{mod}\sigma_y(\tau)$ [1]. Since $\sigma_x(\tau) = \tau\, \mathrm{mod}\sigma_y(\tau)/\sqrt{3}$, these known relationships can be used for $\sigma_x(\tau)$ as well.

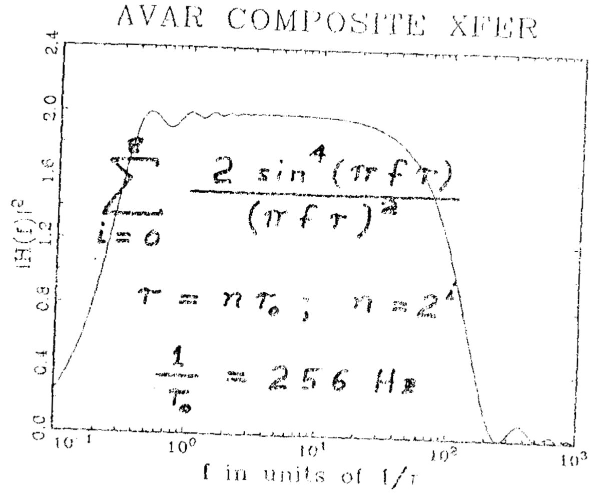


Fig. 6. A plot of the sum of nine individual transfer functions for $\sigma_y^2(\tau)$. The number of transfer functions included in the sum, of course, is arbitrary. The approximate square window, as viewed from the frequency domain, can be made as wide as one wishes -- limited by the data length. The value of n must be less than or equal to N/2.

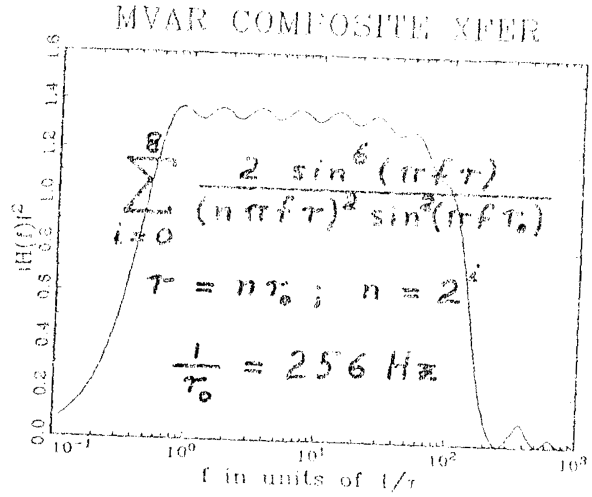
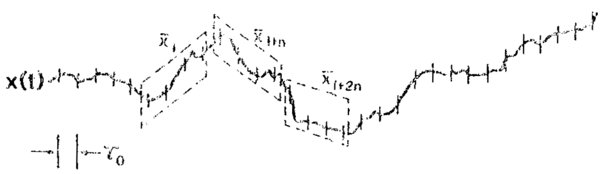


Fig. 7. A plot of the sum of nine individual transfer functions for $\mathrm{mod}\sigma_y^2(\tau)$. The number of transfer functions included in the sum, of course, is arbitrary. The approximate square window, as viewed from the frequency domain, can be made as wide as one wishes -- limited by the data length. The value of n must be less than or equal to N/3. Notice that Figure 7 has a slightly sharper high-frequency edge than Figure 6.

SOFTWARE CONSIDERATIONS FOR $\mathrm{mod}\sigma_y(\tau)$ AND $\sigma_x(\tau)$

The computation time for these two measures is essentially the same. They differ only by a factor. However, because of the double sum in equation (2), a direct software implementation of this form of the equation will take substantial CPU time for large data sets. 10^6 data points may take several hours to process on a main-frame machine, and the CPU time grows as the number of points squared. There are two procedures that can reduce the computation time enormously.

The first procedure can be conceptualized by looking at Figure 8. This Figure illustrates a case where n = 4, and the windows show which time points (spaced τ_0 apart) are used to make up each window's time average. The averages from the three windows provide the entries for one second-difference. An rms of these second differences is computed across all possible sets for a particular n. Equation (2) implies that we recompute the sums over the x_is each time we move the second difference one point forward. However, instead of repeating the sum, we can drop a point at the back end of each window in Figure 8, add the point dropped to the previous window (windows 1 and 2), and add a new point to the third window to the right. This properly implements the sum much more efficiently. This procedure reduces the CPU time to be proportional to the number of points rather than to the number of points squared as above.



$$\mathrm{Mod.}\ \sigma_y^2(\tau) = \frac{1}{2\tau^2}\langle(\Delta^2 \bar{x}_i)^2\rangle$$

$$\tau = n\tau_0$$

Fig. 8. A plot illustrating a set of x(t) values measured τ_0 apart. The windows block out a single set of these measurements as they are combined to construct a single second difference of the average value taken from each window's set of x(t) readings. For a given value of n, the three windows are moved from the beginning of the data to the end to obtain an estimate of the infinite-time average of these sqared second differences.

The second procedure is probably useful only for very large data sets - on the order of 10^5 or more points. It takes advantage of the confidence of the estimate obtainable from such large sets. It is not necessary to take all possible averages and second-difference combinations to get a very good confidence of the estimate from a large data set. For example, the original data points could be averaged in nonoverlapping blocks of 128 (n = 128) to form a new data set. The number of data points in this new set would be N/128, where N is the original number in the set. This process can, of course, be repeated as many times as needed and for any value of n. As argued before, the set $n = 2^i$ ($i = 0, 1, 2, \ldots$ log(N/3)/log2) is a nearly orthogonal set as viewed in the frequency domain. The data can then be analyzed in blocks. If this is done the rms values can be obtained across all blocks for the whole set along with an internal estimate of the confidence interval as calculated from the standard deviation of the mean of the variances at a particular value of n. This internal estimate of the confidence also provides a check on the hetero-schedasticity of the modeling; that is, are the measures and the model well behaved with time. The sacrifice in using this procedure is small for white-noise PM. Fortunately, this is the ideal noise met in time or phase measurement systems. This second procedure also gives a significant reduction in computation time. For large data sets the penalty in loss of confidence of the estimate is typically very small.

SOME PRACTICAL APPLICATIONS

Figure 9 is a $\mathrm{mod}\sigma_y(\tau)$ plot for comparing a passive hydrogen maser at NBS (now NIST) against the NRC (National Research Council) primary cesium standard, Cs 5. Two features are worth noting. First, there is excellent agreement between the theoretical curves and the experimental data. And second, with optimum combining algorithms and analysis procedures, we can see a white-noise PM modulation of $\sigma_x(\tau = 1\ \text{day}) = 0.8$ ns and a relative stability for the clocks of $\mathrm{mod}\sigma_y(\tau = 8\ \text{days}) = 2 \times 10^{-15}$. This experiment was repeated three times with similar results. As an aside, it is apparent that optimally weighted time transfer data using the GPS common-view method serves this comparison of geographically separated clocks quite well.

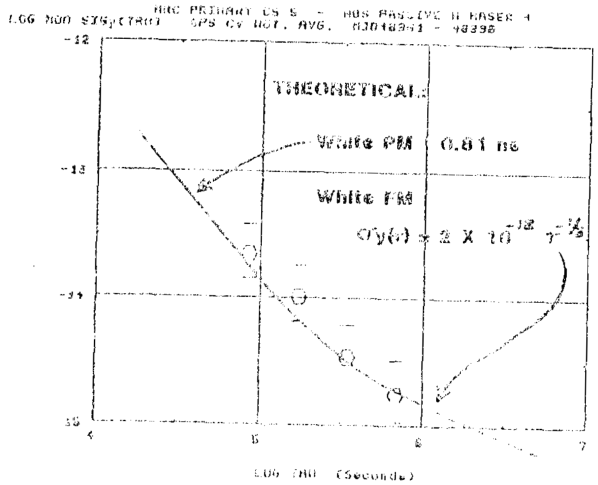


Fig. 9. A $\mathrm{mod}\sigma_y(\tau)$ plot of the frequency stability between a passive-hydrogen maser located in Boulder, Colorado and the Cs 5 Primary Frequency Standard of NRC located in Ottawa, Canada. The distance between these timing centers is about 3 Mm. The measurement system was an optimally weighted set of GPS satellites used in the common-view mode.

Figure 10 is a combined $\sigma_y(\tau)$ and mod$\sigma_y(\tau)$ diagram showing performances for the usual kinds of measurement, dissemination, and comparison systems. Figure 11 is a $\sigma_x(\tau)$ diagram for a subset of these measurement and comparison systems along with the performance of typical atomic clocks. The noise seen in the two-way satellite time transfer technique is outstanding for τ equal one second to a few minutes. Unfortunately this white-noise PM behavior does not persist for larger τ values due to systematic effects in the transmitting and receiving equipment. This

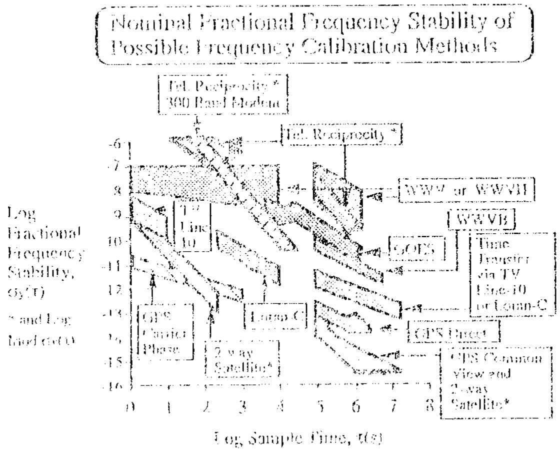


Fig. 10. A plot showing the frequency transfer capability of various comparison and dissemination systems. The accuracy with which frequency can be transfered is obviously a function of τ. Where white-noise PM was an appropriate model, mod$\sigma_y(\tau)$ was used as the measure as indicated by the asterisk, *.

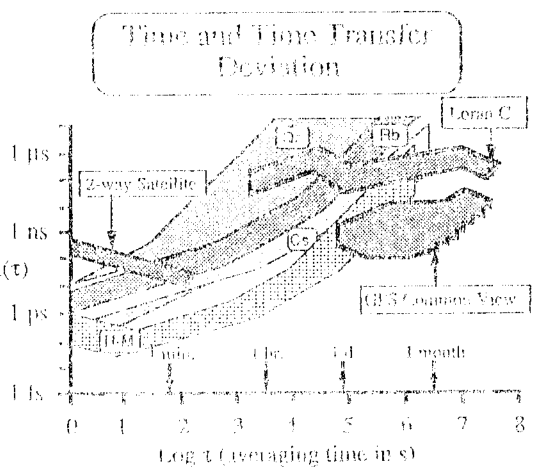


Fig. 11. A $\sigma_x(\tau)$ plot of a subset of comparison or dissemination systems shown in Figure 10. Also plotted are the time stabilities of commonly used precise clocks. It becomes obvious that the measurement noise is often the limiting factor.

problem is currently being addressed, and with the aid of proper measurement techniques a significant resolution is expected. Loran-C shows a double hump due to the combination of a diurnal term and an annual term. These annual variations plagued international time comparisons and the generation of TAI for many years. When we thought the averaging time was sufficiently long to see the behavior of two widely separated clocks, doubts arose about whether the variations were caused by annual or seasonal variations in Loran-C or similar variations in the clocks. The top part of the GPS common-view curve is from an around-the-world comparison performed over several years. We see again an annual term. This is apparently due to annual variations in the errors associated with the ionospheric model broadcast from the satellites. The bottom of the curve reflects results of the NBS/NRC (NBS is now NIST) comparison shown in Figure 9. It is easy to see why GPS has been widely accepted for international time comparison.

As we look forward to the development of advanced clocks and frequency standards with accuracies and stabilities beyond one part in 10^{15}, we face significant challenges in performing comparisons of widely separated clocks and frequency standards (see Figure 11). Table 5 is a list of some of current time comparison techniques as well as some proposed. Important improvements are needed for measurement and comparison systems as we prepare for future clocks and frequency standards.

Table 5. Time & Frequency Transfer Research

Type	$\sigma_x(\tau = 1\ d)$	mod$\sigma_y(\tau = 30\ d)$
GPS	<50 ns	10^{-13}
GPS C-V	1-6 ns	10^{-15}
2-Way Sat.	1-10 ns	10^{-15}
Trilateration	<10 ns	10^{-15}
LASSO	<0.1 ns	10^{-16}
STIFT	<0.02 ns	10^{-17}

The first three types are currently operating systems. The last three are proposed. Trilateration is a specific service being built up by NIST. It will operate in the receive only mode at the KU band. It will use a transponder on board a geostationary satellite. The satellites position will be actively determined using triangulation from three known timing centers. Both the LASSO and STIFT proposed time and frequency transfer techniques have been published.

CONCLUSIONS

The progress in time and frequency metrology over the last three decades is impressive. An excellent bibliography covering the measurements used is the reference list in a paper by Walls and Rutman. [8] Advances in frequency and time sources have been similarly impressive. As we review the past and look to the future, we see a continuum of change. There will be a need to better characterize clocks and oscillators, for outlooks on performance advances are good.

The current standards for characterizing clocks, oscillators, measurement systems, and dissemination systems are useful and adequate except in two areas. These deficiencies are (1) the characterization and modeling of environmentally induced perturbations, which often cause long-term instabilities in clocks and oscillators, and (2) the characterization of the time-domain behavior of measurement, dissemination, and comparison systems. A time-domain time stability measure, $\sigma_x(\tau)$, has been studied, tested and is proposed as a measure which will help resolve these deficiencies. Dealing with both these deficiencies is a necessary step to improve time and frequency metrology and to keep up with the new clocks and oscillators anticipated in the future.

As we develop new international time transfer systems, such as the two-way satellite time-transfer system, it will be extremely helpful to have a common language, as well as common and needed measures to characterize performance. Additional tools may also be needed as we move to higher levels of accuracy and stability.

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