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-nanoscale 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

<table>
<thead>
<tr>
<th>Frequency Sources</th>
<th>Time Keeping Metrology</th>
<th>Measurement Systems</th>
<th>Analysis and Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>State preparation</td>
<td>Counting</td>
<td>Time Interval &amp; Frequency Measurement</td>
<td></td>
</tr>
<tr>
<td>Investigation</td>
<td>Frequency dividers</td>
<td>Synthetic</td>
<td></td>
</tr>
<tr>
<td>Particles detection</td>
<td>Delay</td>
<td>Multi-channel time differences</td>
<td></td>
</tr>
<tr>
<td>Frequency multi-detection</td>
<td></td>
<td>Frequency domain</td>
<td></td>
</tr>
<tr>
<td>Serve electronics</td>
<td>Trigger probes</td>
<td>Clock</td>
<td></td>
</tr>
<tr>
<td>Spectral purity</td>
<td>Balanced two-measuring detectors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal-to-noise</td>
<td>Distortion</td>
<td>Heterodyne</td>
<td></td>
</tr>
<tr>
<td>Input &amp; external</td>
<td>Interference</td>
<td>Heterodyne</td>
<td></td>
</tr>
<tr>
<td>perturbations</td>
<td>Coexisting algorithms</td>
<td>Dead time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hardware Filters</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>High pass</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low pass</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distribution of error</td>
<td></td>
</tr>
</tbody>
</table>

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 low source 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 a resolution of five days of integration before the digital measurement noise is less than that of a precision 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 precision clocks. To date, 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.

\[ s = \frac{2}{\pi} \sigma \]  

where \( s \) is the standard deviation of \( N \) time measurements spaced \( t_p \) apart. Since the uncertainty decreases as \( \sigma_N \) grows, there is significant gain in taking as many points as possible. Let this be stated: that the optimum time difference estimate is best taken as the mean of a large set of independent individual measurements x. This facilitates ease of the standard deviation of the mean. Such measurements often include systematic effects which make the classical estimates invalid characterizing these systematic effects is important. Another common analysis error is made in processing time or phase noise between central time clocks, which are not time clocks, or any of the practical atomic standards where the intermediate-term stability is characterized by white-noise NN. While \( \sigma_N \) is the mean on random walk NN, analysis 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 NN. This noise is found in the very short time for spurs oscillators and active microwave circuits. 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 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
dissemination system in \( \text{mod}_0(r) \).

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

\[
\sigma_v^2(t) = \frac{1}{6n^2(N-3n+1)} \sum_{f_1}^{n-1} \left( \sum_{f_2}^{n-1} \frac{(X_{1+n}^2 - 2X_{1+n}X_f)}{f} \right)^2
\]

where \( r = m_v \).

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 \( x_h \). The averaging of the \( x_h \) has the effect of digitally narrowing the bandwidth in the software to \( f_n = f_m/n \), where \( f_m \) 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 \( \sigma_v^2(t) \), \( \text{mod}_0^2(r) \) and for \( \sigma_v^2(t) \), 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 \( \sigma_v^2(t) \).

Table 2. IEEE Standard 1139 (1988)

<table>
<thead>
<tr>
<th>( Y(f) ), ( \Phi(f) ), ( S_y(f) ), or ( S_k(f) )</th>
<th>Relationships</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_y^2(f) )</td>
<td>( \frac{f^2}{\nu_0} S_y^2(f) )</td>
</tr>
<tr>
<td>( S_f^2(f) )</td>
<td>( (2\pi f)^2 S_f^2(t) )</td>
</tr>
<tr>
<td>( S_k^2(f) )</td>
<td>( \frac{1}{2n^{2p}} S_k^2(f) )</td>
</tr>
<tr>
<td>( S_v^2(f) )</td>
<td>( (2\pi f)^2 S_v^2(f) )</td>
</tr>
</tbody>
</table>

Figures 2, 3, 4 and 5 are the time-to-frequency domain mappings for \( \sigma_v^2(t) \), \( \text{mod}_0^2(r) \) and for \( \sigma_v^2(t) \), 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 \( \sigma_v^2(t) \).
Table 3. IEEE Standard 1139 (1988)

<table>
<thead>
<tr>
<th>Time Domain Variances</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVAR:</td>
</tr>
<tr>
<td>$a_y^2(r) = \frac{1}{2} \left\langle (y_{i+1} - y_i)^2 \right\rangle$</td>
</tr>
<tr>
<td>$= \frac{1}{2\tau} \left\langle (x_{i+1} - 2x_{i+1} + x_i)^2 \right\rangle$</td>
</tr>
<tr>
<td>MVAR:</td>
</tr>
<tr>
<td>$\text{mod.} a_y^2(r) = \frac{1}{2\tau} \left\langle (x_{i+1} - 2x_{i+1} + x_i)^2 \right\rangle$</td>
</tr>
</tbody>
</table>

Proposed

<table>
<thead>
<tr>
<th>TVAR:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_x^2(r) = \frac{1}{3} \text{mod.} a_y^2(r)$</td>
</tr>
<tr>
<td>$= \frac{1}{6} \left\langle (x_{i+1} - 2x_{i+1} + x_i)^2 \right\rangle$</td>
</tr>
</tbody>
</table>

Table 4. Spectral Density and Time Domain Relationships

- $S_f(f) = f^\alpha$,
- $\sigma_x^2(r) = r^\beta$,
- $\beta = -\eta - 1$,
- $\eta < \beta \leq 1$

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

\[ S_f(f) = f^\alpha \]
\[ \sigma_x^2(r) = r^\beta \]
\[ \alpha = \beta + 2, \]
\[ -3 < \alpha \leq 3 \]

where $\gamma$ is the normalized frequency.

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

- It is in equal to the classical standard deviation of the time difference measurements for $r = \tau_0$, for white-noise PN:
- It equals the standard deviation of the mean of the time difference measurements for $r = \frac{1}{n}$ (with different length), for white-noise PN.
- It is convergent and well behaved for the random processes commonly encountered in time and frequency metrology.
- The $r$ dependence indicates the power-law spectral density model appropriate for the data.
- The amplitude of $a_y(r)$ at a particular value of $r$, along with the assumption of one of the five power-law spectral density models ($\beta = -1, -2, -3, -4$), provides enough information to estimate the corresponding level in the frequency domain for any of the recommended IEEE standard spectral-density measures.

![Alien-Variance, Power-Law Spectral Relationships](image)

Fig. 2. The broad line represents the corresponding value of $a$ for each value of $\mu$. 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 disimulation 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 if a measurement is meaningful for a specific, well-defined standard or reference. Time accuracy can be thought of, for example, as the transport of a perfect portable clock from the standard.
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 for the frequency and not a quadratic on the time residuals or on the phase residuals. Often we see random-walk FM ($\alpha = -\frac{1}{2}$) 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.\footnote{[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 $\sigma_j(t)$ plot. The effect of modulation decays as $1/t$, whereas the white-noise FM background decays only as $t^{-1/2}$.

**Fig. 3.** The broad line represents the corresponding value of $\alpha$ for each value of $\mu'$. 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 $\beta$ for each value of $\eta$. 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. 5.** An illustration of the effect of a modulation side-band on top of a white-noise FM background. The solid straight lines are the theoretical maximum and minimum limits for $\sigma_j(t)$.

**COMPARISON OF $\sigma_j(t)$ AND $\sigma_j'$**

The IEEE and CCIR definition for $\sigma_j'(t)$ is

\[ \sigma_j'(t) = \frac{1}{2} \left( \overline{y}_j(t) - \overline{y}_j(t+1) \right)^2, \]  

where

\[ \overline{y}_j = \frac{X_j - X_0}{t}. \]  

This estimate for $\gamma$ 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 $\sigma_j'(t)$ 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 precision oscillators. It is intuitive in that it is a measure of the change in frequency over some interval $t$ 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 return signal. In addition to
these theoretical and practical advantages, we have from the arguments above an additional intuitive feeling for why $\sigma_i(r)$ is a good measure for clocks and oscillators. It is an optimum estimate of frequency change for white-noise PM.

The principal disadvantage of $\sigma_i(r)$ is the inability for power-law processes with $a \leq 1$ where we cannot easily distinguish between white-noise PM and flicker-noise PM. This inability was the main motivation for the development of mode($r$). As we've seen above, $\sigma_i(r)$ differences adjacent optimum frequency estimates (for white-noise PM) each measured over an interval $n$. 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 $\sigma_i(r)$ is derived directly from mode($r$), it has all the associated advantages. For example, $\sigma_i(r)$ can be used to differentiate between white and flicker-noise PM. The second-difference expression for $\sigma_i(r)$ is

$$\sigma_i(r) = \frac{1}{n^2} \sum (\Delta \Delta \phi_i)$$

The equivalent second-difference equation for $\sigma_i(r)$ is similarly

$$\sigma_i(r) = \frac{1}{n^2} \sum (\Delta \Delta \phi_i)$$

$\sigma_i(r)$ is proportional to the two second differences of the time (phase) measurements above the mean square deviation of the data from the mean. Since $\sigma_i(r)$ is proportional to the mean square deviation of the time (phase) measurements above the mean, $\sigma_i(r)$ is an optimum estimate of the time (phase) difference over an interval $n$ with respect to a similar sequence taken before and after $n$. Since $\sigma_i(r)$ is an optimum estimate of the time (phase) difference, $\sigma_i(r)$ is a measure of the basic quantity of interest. Examples of application include network synchronization, time and phase difference measurements, phase-locking servo systems, macro time transfer and comparison systems, and time distribution systems.

A look at the transfer functions for $\sigma_i(r)$ and mode($r$) for different values of $i$ provides a good insight into their usefulness. We can show that, for $r = n$ and $a = 1$, the set of resultant transfer functions form a nearly orthogonal set used from the frequency domain. Figure 6 and 7 are the composite transfer functions for $i = 0$ to 8. For $i = 0$, the composite transfer function is nearly identical and flat within about $1\%$ over more than two octaves. One of the features of mode($r$) is that it changes the bandwidth within the software; hence the composite transfer function is a little less flat than that for $\sigma_i(r)$. It is also more nearly square at the high frequency end.

The time-domain, frequency-domain relationships are known for $\sigma_i(r)$ and for

\[\text{mode}(r) \] since $\sigma_i(r) = r \text{mode}(r)/i$. These known relationships can be used for $\sigma_i(r)$ as well.

Fig. 6. A plot of the sum of nine individual transfer functions for $\sigma_i(r)$. 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 $1/2$.

Fig. 7. A plot of the sum of nine individual transfer functions for $\text{mode}(r)$.

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 $1/2$. Notice that Figure 7 has a slightly sharper high-frequency edge than Figure 6.
SOFTWARE CONSIDERATIONS FOR MODE, (1) AND
0, (r)

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

1 apart) are used to make up each window time average. The averages from the three

windows provide the entries for one second-difference. An average of these second
differences is computed across all possible sets for a particular n. Equation (2)
implies that we recalculate the sums over the

X's 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.

The second procedure is probably useful only for very large data sets - on the order

of 10^6 or more points. It takes advantage of the confidence or the estimate obtainable

from each large set. 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 125 (n = 128) to form a new data set. The number of data points in this new set

would be 1/128, 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 = 2^11 1 (i.e., log(N)/log2) is a nearly orthogonal set viewed in the frequency
domain. The data can then be analyzed in blocks. If this is done the raw value can be obtained using

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

heteroskedasticity of the modeling, that is, are the measures and the model well

behaved with time. The procedure in using this procedure is small for white-noise input. Unfortunately, this is the ideal noise set 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 mode, (r) 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 modulation of a (r = 1
day) = 0.6 ns and a relative stability for the clock of about (r = 1 day) = 2 X 10^-7.

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. 8. A plot illustrating a set of X(t)

values measured 1 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 squared second

differences.

Fig. 9. A mode, (r) plot of the frequency

stability between a passive-hydrogen maser

located in Boulder, Colorado, and the Cs 5

primary frequency standard also located in

Boulder, Colorado. The distance between these

two clocks is about 3 km. The

measurement system was an optimally weighted

set of GPS satellites used in the common-view

mode.
Figure 10 is a combined \( d_f(t) \) and \( \text{mode}(t) \) diagram showing performances for the usual kinds of measurement, dissemination, and comparison systems. Figure 11 is a \( d_f(t) \) 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 \( t = 1 \) second to a few minutes. Unfortunately this white-noise FM behavior does not persist for larger \( t \) values due to systematic effects in the transmitting and receiving equipment. This

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 the widely separated clock pairs, it appeared whether the variations were caused by annual or seasonal variations in location or satellite variations in the clocks. The top part of the GBS common-view curve is from an around-the-world comparison performed over a few 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 HRS/TAC (HRS is now HST) comparison shown in Figure 9. It is easy to see why GPS has been widely accepted for international time comparisons.

As we look forward to the development of advanced clocks and frequency standards with accuracies and stabilities beyond one part in \( 10^9 \), we face significant challenges in performing comparisons of widely separated clocks and frequency standards (see Figure 11). Table 6 is a list of some current time comparison techniques as well as some important improvements are needed for measurement and comparison systems as we prepare for future clocks and frequency standards.

**Table 6. Time & Frequency Transfer Research**

<table>
<thead>
<tr>
<th>Type</th>
<th>( \sigma_f(\tau = 1 \text{~d}) ) ( \text{mode}(\tau = 30 \text{~d}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>0.5 ns \quad 10^{-13}</td>
</tr>
<tr>
<td>GPS e-0</td>
<td>1.5 ns \quad 10^{-15}</td>
</tr>
<tr>
<td>2-Way TAC</td>
<td>1.5 ns \quad 10^{-15}</td>
</tr>
<tr>
<td>Trilateral</td>
<td>10 ns \quad 10^{-15}</td>
</tr>
<tr>
<td>LASSO</td>
<td>0.1 ns \quad 10^{-16}</td>
</tr>
<tr>
<td>SMST</td>
<td>0.02 ns \quad 10^{-16}</td>
</tr>
</tbody>
</table>

The first three types are currently operating systems. The last three are proposed. Trilateral is a specific service being built up by HST. It will operate in the receiver only mode at the MHz band. It will use a transponder on board a generation satellite. The satellite position will be actively determined using triangulation from three ground tracking centers. Both the LASSO and SMST proposed time and frequency transfer techniques have been published.

**CONCLUSIONS**

The progress in time and frequency metrology over the last three decades is impressive. To recent bibliography covering the measurements used in the reference list in a report by Miller and Hubbard. [1] Advances in frequency and time scales have been steadily impressive. As we review the past and look to the future, we see a constant of change. There will be 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, $\sigma(t)$, 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.

ACKNOWLEDGEMENTS

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References:


