4 TH EUROPEAN FREQUENCY AND TIME FORUM NEUCHÂTEL - 13 - 14 - 15 MARCH 1990

Session APP-04 Number 1

REMOTE TIME AND FREQUENCY COMPARISONS NOW AND IN THE FUTURE

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ABSTRACT

Time metrology has moved from milliseconds to picoseconds in the last four decades, and frequency metrology has moved from nine significant digits to sixteen. The ability to synchronize remote clocks has improved dramatically as well. With the implementation of GPS (Global Positioning System), the full long-term frequency stability, as well as the frequency accuracy of the best atomic clocks, can now be transferred to remote sites. In the future, GPS's selective availability, an intentional degradation of system performance, will adversely affect the usefulness of GPS time and frequency transfer for the average civilian user.

This paper discusses various alternatives for clock synchronization and syntonization, and makes some comparisons between various techniques used in synchronizing and syntonizing clocks. In the process, it reviews concepts of time stability and accuracy, and frequency stability and accuracy. The future of comparison systems is considered. An Appendix of definitions is provided to support the concepts developed.

INTRODUCTION

The synchronization of clocks is a subject which has been widely treated throughout the years. With the development of very accurate means for satellite time transfer, the subject has substantially gained in importance.

Time transfer systems (or clock synchronization systems) are often given a single numeral designation, characterizing their precision, or accuracy, in microseconds or nanoseconds. This characterization is often ambiguous or inadequate, and thus it is now important to clarify the factors involved in clock synchronization or comparison systems.

BACKGROUND

Characterizing the measurement system is essential if a remote (slave) clock is intended to be optimally synchronized or syntonized to a master clock. In this situation, optimum design of the servo which locks the slave to the master clock requires a characterization of all of the contributing elements. We are not here generally concerned with measurement noise (divider or counter-noise), although such noise can be problematic in some instances.

A free-running clock can almost always be better characterized than one whose output is servo controlled to another clock. Hence, it is better to have the servo control be a computed output or an external micro-phase stepper in order to provide a synchronized or syntonized output which does not perturb the free-running clock. [1] A local set of clocks can be better characterized if there are at least three of them of about the same quality. [2] Algorithms can be employed to intelligently combine the readings of a set of clocks so that the algorithm-computed time and/or frequency can be more stable than that of the best clock in the set. In addition, algorithms can be designed to test for abnormal clock behavior and for desensitizing the computed time to any abnormal behavior or failures. [3]

If the clocks, as well as the comparison system, are well characterized, then an ensemble of clocks can be constructed from a set of remotely located clocks. With full characterization of all components, the system of clocks and its associated comparison can be optimized for overall performance. While often applied to local ensembles, this concept has apparently not yet been applied to an ensemble whose member clocks are in different locations. There are some long-term plans to do this using GPS. Potentially significant gains are available in the proper application of this concept to the generation of TAI.

Figure 1 illustrates a straightforward comparison system or time-and-frequency-dissemination system which measures the time-and-frequency differences between Clock 1 and Clock 2. The word comparison will be used for simplicity to represent any generic dissemination system. Of concern is the characterization of the full noise in the comparison, including measurement noise, clock noise, and noise introduced in the comparison path and system. In figure 2, an additional concern arises in designing a servo loop to slave a remote clock to a master clock. The data from the comparison may not be available immediately; hence in the feedback loop the measurement noise, path deviations, and delay in acquiring the comparison data will affect the servo design very fundamentally. Practical delays in acquiring comparison data range from milliseconds to times longer than a month. For example, the delay time (data acquisition time) for servo controlling Coordinated Universal Time at NIST (UTC(NIST)) to the international UTC scale is more than 1 month. Although this paper does not address servo design theory, it is important to stress that the measurement noise and path noise characteristics, and the delay in acquiring comparison data, play very important roles in servo design.

Appendix A provides a few relevant definitions (for example, "precision," "accuracy," "stability"). In characterizing systems for comparing clocks which are located remotely from each other, it is important to consider concepts such as time accuracy, time stability, time prediction error, frequency accuracy, and frequency stability. Each has a unique interpretation.

Conceptually, time accuracy is the time difference between the readings of two clocks at some time in a given reference frame. One of the clocks is often defined as perfect, so that the assessment is of the accuracy of a clock relative to that "ideal" clock. We can imagine the transport of a perfect, portable clock to accomplish this time-difference measurement. Time accuracy is often limited by systematic errors in the comparison system, such as uncertainties in cable delays and propagation-path-length uncertainties. In addition, systematic differences between clocks will contribute to time inaccuracy. Time accuracy can never be better than time stability and is often much worse.

One of the best ways to observe time stability is to plot the time residuals, often denoted x(t), that exist between two clocks after the systematic errors have been subtracted. In addition to the usual kinds of random variations which affect clock and comparison system performance, time stability is often affected by environmental variations. People commonly measure time stability as the rms deviation of the time residuals from a linear regression to the time deviations. This practice, which can be very misleading, is discussed in some detail in the body of this paper. If there are periodic terms affecting a time comparison system, then the spectral density of the time or the phase fluctuations may be a very good measure. We may also measure the effect of these periodic terms using $\sigma_y(\tau)$. [2] For time stability there is often a τ (averaging-time) dependence. Also, $\tau \mathrm{mod}\sigma_y(\tau)$ is a useful measure of the time stability of a comparison system.

The quantity $K\tau\sigma_y(\tau)$ is a useful measure for estimating the time prediction error of a clock. Often a particular power-law, spectral-density model is dominant for the signal variations from the clocks and/or the comparison system. Under the assumption of optimum prediction over the data spacing interval, τ_0, the value of K is $1/\sqrt{3}$ for white-noise PM, 1 for white-noise FM and for random-walk FM, and 1.2 for flicker-noise FM. In the case of white-noise phase modulation, the quantity $\tau \mathrm{mod}.\sigma_y(\tau)/\sqrt{3}$ is the optimum rms time prediction error for an average of n x(t) measurements ($\tau = n\tau_0$).

Frequency accuracy for a given primary standard is not a function of integration time and is properly stated as a single number. But the ability of a comparison system to determine absolute frequency difference between two standards is often a function of the sampling, or integration time τ. The frequency accuracy of a comparison system is also a function of the data processing method. This leads to the idea that there is an optimum method for estimating the absolute frequency difference between two remote clocks or for controlling the frequency of a remote clock.

Frequency stability, like time stability, is observed by looking at a plot of the fractional frequency offset, y(t), where $y(t) = (\nu(t)-\nu_o)/\nu_o$; $\nu(t)$ is the time varying frequency output of a clock and ν_o is the clock's nominal frequency. In practice, measured values of y(t) are observed over some averaging time, τ. It is often very useful to observe a y(t) plot at different averaging times. The frequency stability of a comparison system can be quantified in the same way clocks are characterized, using a $\sigma_y(\tau)$ or $\mathrm{mod}\sigma_y(\tau)$ plot. It is sometimes useful to measure the spectral density of the frequency fluctuations to supplement the time-domain methods, in order to ascertain the presence of different kinds of noise. The kind of noise observed in comparisons between two clocks, and the noise which may be added by the comparison system, will determine how to optimize estimates of characterization parameters (both systematic errors and noise) for the clocks and the comparison system. One important example of a characterization parameter is the relative frequency drift between two clocks. See reference [2] for examples.

CHARACTERIZATION OF COMPARISON SYSTEMS

Figure 3 shows the improvement in the U.S. primary frequency standard since the development of cesium beam technology. The trend line shows an improvement of about a factor of 10 every seven years. Further improvement is expected--although not certain. There are now good indications that standards based on trapped and cooled ions will yield dramatic improvements. The estimated ultimate potential for these devices is an accuracy of about one part in 10^{18}, but practical considerations will make this limit difficult to achieve.

In the past, the accuracy of operational comparisons between primary standards lagged behind the accuracy of the standards. Further improvements in primary standards were thus of limited use. However, during the last decade, the development and application of GPS time transfer and two-way satellite time transfer dramatically changed the picture. With the excellent comparison accuracy available in the GPS common-view technique or in the two-way technique, comparison accuracy at integration times of a few days and longer is now ahead of clock accuracy. This was a major breakthrough for international time and frequency comparisons, and the GPS common-view technique has become the defacto international standard for comparisons. [5] A decision by GPS system operators to intentionally degrade performance as observed by civilian users (called selective availability) raises questions which are important in time transfer applications.

Time transfer using the two-way satellite technique now appears very attractive alternative to primary timing centers. More information is needed on the accuracy and long-term stability of this comparison technique since primary investigations have not focused on these. [6], [7] Most of the published results concern short-term time stability.

Important factors for all of these comparison systems include cost, simplicity of use, and means for correctly assessing comparison accuracy. The ideal comparison system is one which provides the time difference, the frequency difference, and the relative time and frequency stability of the clocks and which makes clear the uncertainties associated with the comparison system. If the comparison system is to be widely used, the cost should be low. Of course, there is no single system which now meets this ideal. Figure 4 illustrates the performance of some of the common comparison techniques now being used. Both $\sigma_y(\tau)$ and mod$\sigma_y(\tau)$ are used to characterize the frequency stability of these comparison systems, because, in some cases, white-noise phase modulation (PM) is the limiting random process and therefore characterization using $\sigma_y(\tau)$ is ambiguous.

When white-noise phase modulation is the predominant noise in a comparison system, some important equations for optimal estimation of time and frequency differences between the clocks are

$$\hat{x}(i) = a_0 + a_1 \cdot i \quad \text{and} \tag{1}$$

$$s_x = \sqrt{\frac{1}{N-2} \sum_{i=1}^{N} (x(i) - \hat{x}(i))^2} \quad . \tag{2}$$

Here $\hat{x}(i)$ is the optimal estimate of the time difference between the clocks at the measurement point i. The coefficients a_o and the a_1 are determined by minimizing the variance around the linear regression line, so the meaning of optimum is for a minimum variance. The x(i)'s are the measured time differences over the N measurements. The confidence of the estimate of the intercept a_o is

$$s_0 = 2s_x/\sqrt{N}, \tag{3}$$

and the confidence of the estimate of the mean value $x = \frac{1}{N} \sum_{i=1}^{N} x(i)$ is $s_{mean} = s_x/\sqrt{N}$.

The confidence of the estimate of the slope (a_1, the frequency difference) is

$$s_1 = \frac{\sqrt{12}}{\tau_o \; N^{3/2}} s_x = 2 \, \text{mod}\sigma_y(\tau). \tag{4}$$

Equation 1 is the classical equation for a linear regression, which is often computed as a fit to the time residuals. The application of this equation is optimal only for white noise processes. It is assumed that there are N values each separated by τ_o. In this case, the standard deviation (given by equation 2) is a measure of the time stability at the data sampling rate -- sometimes called the precision of the time difference measurements. The expression N-2 in the denominator shows that two degrees of freedom have been removed with the estimation of a_0 and a_1 in equation 1. The mean-value confidence interval in Equation 4 is half that of the intercept and is the optimum estimate of the time difference between the clocks at the midpoint time., Clearly, it is more efficient to use the mean rather than the intercept to cite the time difference in a comparison. The solution to equation 1 at the midpoint is equal to the mean value. Equation 5 shows the value of using mod$\sigma_y(\tau)$ to determine the confidence of the estimate of the frequency difference, a_1. If the residuals are not white, then the τ dependence will not be $\tau^{-3/2}$, and the linear regression will not give the optimum estimate of the time and frequency difference of the clocks. If the residuals are white, the value of mod$\sigma_y(\tau)$ gives the proper value of the confidence for any averaging time, τ. The rapid improvement ($\tau^{-3/2}$) gained in estimating the absolute frequency difference by increasing the averaging time is clearly illustrated by the use of mod$\sigma_y(\tau)$.

Linear regression analysis is often used to model processes whose residuals do not have a white spectrum. In this case, the linear regression coefficients and their confidences can often be very misleading. A mod$\sigma_y(\tau)$ diagram will indicate whether or not using linear regression analysis is legitimate; if not, then it gives a measure of the effects of the degradation (caused by the actual random processes) on the estimate of the frequency difference between the two remote clocks.

Figure 5 is a plot of the rms time prediction error seen in currently available clocks and oscillators. The data has been used in an optimum fashion to predict the future over an interval, τ_p. The rms time deviation can be defined in many ways. This is one useful approach. The next four Figures, 6, 7, 8, and 9, are plotted with exactly the same ordinate and abscissa as Figure 5. They can be overlaid to see the various systematic effects, either in the clocks or in the comparison system. Figure 6 shows that the ordinate is labeled with both the white PM level (usually arising from the comparison system) and the time inaccuracy. The time accuracy number provides a hard limit for comparing the time difference between two clocks. In contrast, the white PM level is a function of integration time, and, if other processes are not limiting, knowledge of the time difference improves as the square root of the number of measurements averaged -- consistent with equation 4. If the residuals are white PM, we may also write (from the concept of time averaging of measurements) the following equation

$$s_{rms}(\tau_o) = \frac{\tau^{3/2}}{\sqrt{3 \; \tau_o}} \text{mod}\sigma_y(\tau), \tag{5}$$

where s denotes the classical standard deviation of x(i) taken τ_o apart ($\tau = n\tau_o$) as in Equation (2). Since the numerator in Eqüation (5) is constant for white PM, the improvement in $s_{rms}(\tau_o)$ is proportional to $\tau_o^{-½}$. This is not surprising since τ_o is the period over which the phase (or the time) has been averaged. If τ_o becomes the full data length, then, as expected, equation 5 is the standard deviation of the mean. Here again, a mod$\sigma_y(\tau)$ diagram provides a good visualization of the estimate of the time difference uncertainty and of the time stability (as limited by the clocks and/or the comparison system).

Figures 5, 7, 8, and 9 are included for the reader's convenience. Figure 7 shows the time difference as a function of time for two clocks whose frequencies differ by various fixed amounts. In this case the abscissa could also be the prediction interval. Figure 8 shows the rms time deviation as a function of the prediction interval as caused by flicker noise frequency modulation (FM) (a common noise in clocks). Notice that the slope is the same as for frequency offset. The factor 1.2 is the K factor for flicker noise where optimum prediction has been assumed. Figure 9 shows the large time deviation that results from frequency drift. The labels for the different lines are fractional frequency drifts per day expressed as powers of 10. The quadratic nature of the time deviation resulting from frequency drift often causes this kind of error to be the predominant long-term systematic error.

Figure 10 is a plot of τmod$\sigma_y(\tau)$ as a function of τ. With $\tau = n\tau_0$, this shows whether or not we benefit from averaging n values of the x(i) time difference measurements. This new approach illustrates the benefit of averaging the time difference measurements, whether the instabilities are in the comparison system or in the clocks. If the measurement noise residuals represent a white PM process, then the time stability will improve as the square root of τ. If it is a flicker PM process, there will be no improvement with averaging. If the plot degrades with increasing τ (slope greater than 0), then there are probably nonstationary processes perturbing the comparison system. In the case of Loran-C, we see a double hump at one half day and at one half year caused by diurnal variations and annual variations. There are longer-term, common-view GPS data than are plotted showing that the time stability does not continue to improve as the square root of τ. In this latter case, the nonstationary processes are probably related to ionospheric modeling errors and errors in the Kalman estimates of the satellites' ephemerides. Multipath distortion at the antenna can sometimes cause several nanoseconds of bias in the time accuracy, but does not change the slope or the level in a τmod$\sigma_y(\tau)$ plot (that is, the bias is constant).

For two-way satellite time transfer, the noise limit does not continue decreasing as indicated by the short-term results in Figure 10. Daily deviations of the order of a few nanoseconds have been observed, but these will likely be reduced as the systems are improved and better characterized. This characterization of the two-way satellite time transfer technique will be very important for the future -- especially for averaging beyond one day. A determination of the time transfer accuracy of this technique will be very important as well. Theoretically, for both the time stability and the time accuracy, two-way satellite time transfer should provide the best operational means for comparing widely separated clocks. The primary drawback to this technique is the need for broadcasting from each station, a requirement which adds cost and involves licensing with government agencies.

THE FUTURE OF COMPARISON SYSTEMS

The best means for comparing widely separated clocks involves satellite techniques. For clocks in proximity (that is, within a modest number of kilometers) perhaps optical fibers will provide the best comparisons. [8] As higher accuracy and more stable clocks are developed, it will be necessary to use higher frequencies to achieve better phase resolution in the comparisons.

It appears that the GPS system could be pushed to a time accuracy approaching a few nanoseconds. For short-baseline comparisons, studies suggest that we might achieve errors as low as 0.1 ns. [9] Time stabilities for GPS common-view comparisons yield τmod$\sigma_y(\tau)$ of about 1 nanosecond times $\tau^{-1/2}$, where τ is in days. At $\tau = 1$ day, this product actually ranges from 0.8 to 8 ns for the many international time stability measurements which use the GPS common-view method. With ionospheric measurement receivers, and more exact post-ephemeris data for the satellites, the GPS common-view technique could yield a comparison limit for frequency accuracy approaching 10^{-17}. This would require about three months of integration under the assumption of ideal white-noise phase modulation. Codeless-ionospheric-measurement receivers, which measure the real-time, path-dependent ionospheric delay, are now becoming available for GPS. There is also the promise that precise post-measurement ephemerides will be made available to the civilian sector. With these advances the GPS common-view, time-and-frequency transfer could be even better than it is today. But the price for this will be additional processing and significant delay in access to data needed to calculate all errors. Table I summarizes the errors in GPS common-view transfers in the face of selective availability, both with and without additional compensation for errors.

How well the systematic errors in two-way satellite time transfer can be understood is yet to be determined. In theory, this technique should be better in both time stability and time accuracy than the GPS common-view technique. The method could provide an order of magnitude of improvement in performance.

An older, often overlooked experiment which has significant bearing on time transfer improvement is the Scout Rocket Experiment which involved flight of a hydrogen maser. [10], [11] This experiment used a microwave Doppler cancellation method and an ionospheric calibration system. From the published data it is estimated that time stability, τmod $\sigma_y(\tau)$ over several hours was about 10 ps. With the stability available from a satellite-borne hydrogen maser, cycle ambiguity of the clock's microwave signal could be resolved from pass to pass or from day to day. Such performance in an operational satellite could yield frequency comparisons over 24 hours of 1 part in 10^{-16}. If the residuals for the comparison were white PM from day to day, it would take only a few weeks to measure frequency difference of a few parts in 10^{-18}. At this level, relativity considerations become very important, and they will be very difficult to calculate.

CONCLUSION

In order to synchronize (or syntonize) a system of clocks optimally, it is necessary to characterize both the stability of the clocks and those of the comparison system. The characterization of the random variations in clocks is pretty well understood, but that of comparison systems is not. Often the standard deviation of the time residuals for both clocks and comparison systems is not convergent, in which case this is not a useful measure. This paper has presented some effective ways to describe and to characterize comparison systems. These allow us to better specify time and frequency comparisons. This issue is becoming more important as system synchronization and syntonization requirements become more stringent.

We have described time accuracy, time stability, time predictability, frequency accuracy, and frequency stability as separate and distinct concepts, with important relationships between these concepts being presented. These ideas have implications for accurate time comparisons. For example, knowing the kinds of random instabilities in clocks and in the comparison system or dissemination system allows us to optimally estimate absolute time and frequency differences between widely separated clocks. With the anticipation of more accurate frequency standards, very careful design as well as characterization of comparison and dissemination systems will be required to take advantage of the improved standards. Even with the current accuracy of time comparisons, there is a need for better specification of the performance of comparison and dissemination systems. We have presented one approach here with the hope that discussion will be stimulated leading to the adoption of a standard method for characterizing the accuracy and stability of the comparison or dissemination process.

ACKNOWLEDGEMENTS:

The author is indebted to Wilfred K. Klemperer, Trudi K. Peppler, Donald B. Sullivan and Matt Young for contributions and suggestions. Marc A. Weiss and Dick D. Davis helped with the data acquisition and analysis for which I am grateful. Thomas Weissert was extremely helpful with the figures.

APPENDIX:

DEFINITIONS

ACCURACY

The degree of conformity of a measured or calculated value to its definition (see Uncertainty).

AGING

The systematic change in frequency with time caused by internal changes in the oscillator.

DRIFT

The systematic change in frequency of an oscillator with time.

ERROR

The difference of a value from its assumed correct value.

FREQUENCY INSTABILITY

The spontaneous and/or environmentally caused frequency change within a given time interval.

PRECISION

The degree of mutual agreement among a series of individual measurements; often, but not necessarily, expressed by the standard deviation.

REPRODUCIBILITY

(A) With respect to a set of independent devices of the same design, the ability of these devices to produce the same value.
(B) With respect to a single device, put into operation repeatedly without adjustments, the ability to produce the same value.

UNCERTAINTY

The limits of the confidence interval of a measured or calculated quantity.

REFERENCES:

[1] D.W. Allan, M.A. Weiss, and T.K. Peppler, "In Search of the Best Clock," IEEE Transactions on Instrumentation and Measurement," IM-38, 624-630 (1989).

[2] D.W. Allan, "Time and Frequency (Time-Domain) Characterization, Estimation, and Prediction, of Precision Clocks and Oscillators," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, UFFC-34, 647-654 (1987).

[3] M.A. Weiss and T. Weissert, "A New Time Scale; AT1 Plus Covariance," submitted to Proc. of 20th Annual Precise Time and Time Interval Planning Meeting (PTTI), Redondo Beach, CA, Nov. 30 - Dec. 1, 1989.

[4] D.J. Wineland, J. Bergquist, J. Bollinger, W. M. Itano, D. Heinzen, S. Gilbert, C. Manney, and C. Weimer, "Progress at NIST Toward Absolute Frequency Standards Using Stored Ions," Proc. of 43rd Annual Symposium on Frequency Control, Denver, CO, May 31-June 2, 1989, pp. 143-150.

[5] D. W. Allan, et. al., "Accuracy of International Time and Frequency Comparisons via Global Positioning System Satellites in Common-View," IEEE Transactions on Instrumentation and Measurement, IM-34, 118-125 (1985).

[6] D. Hanson, "Fundamentals of Two-Way Time Transfers by Satellite," Proc. of 43rd Annual Symposium on Frequency Control, Denver, CO, May 31-June 2, 1989, pp. 174-178; D.A. Howe, et al., "NIST-USNO Time Comparisons Using Two-Way Satellite Time Transfers," 43rd Annual Symposium on Frequency Control, Denver, CO, May 31 - June 2, 1989, pp. 193-198.

[7] M. Imae, H. Okazawa, T. Sato, M. Urazuka, K. Yoshimura, and Y. Yasuda, "Time Comparison Experiments with Small K-Band Antennas and SSRA Equipments via a Domestic Geostationary Satellite," IEEE Transactions on Instrumentation and Measurement, IM-32, 199-203 (1983).

[8] G. Lutes and M. Calhoun, "Simultaneous Transmission of a Frequency Reference and a Time Code Over a Single Optical Fiber," submitted to Proc. of 20th Annual Precise Time and Time Interval Planning Meeting (PTTI), Redondo Beach, CA, Nov. 30-Dec. 1, 1989.

[9] P.F. MacDoran, D.J. Spitzmesser, L.A. Buennagel, "SERIES: Satellite Emission Range Inferred Earth Surveying," Proc.of the Third International Geodetic Symposium on Satellite Positioning," Las Cruces, N. Mexico, February 1982.

[10] R.F.C. Vessot and M.W. Levine, Gen. Relativ. Gravit. 10 (1979) 181;
R.F.C. Vessot, et al., Phys. Rev. Lett. 45 (1980) 2081.

[11] D.W. Allan, C.O. Alley, N. Ashby, R. Decher, R.F.C. Vessot and G.M.R. Winkler, Ultra-Accurate International Time and Frequency Comparison Via an Orbiting Hydrogen-Maser Clock, Journal De Physique, Colloque C8, 395-413, 1981.

TABLE I. GPS COMMON-VIEW TIME-TRANSFER ERROR SOURCES

(WITH SELECTIVE AVAILABILITY ON)

SOURCE	COMMENTS	RMS TIME ACCURACY (ns)
CLOCK DITHER	CANCELS IN C-V MODE	--
EPSILON	DEPENDS ON THE BASE-LINE	30 to 50
IONOSPHERE (BDCST)	DEPENDS ON TOD AND COORD.	5 to 40
TROPOSPHERE	DEPENDS ON ELV. AND WEATHER	2 to 5
MULTIPATH	DEPENDS ON GROUND PLANE AND REFL.	4 to 8
RECEIVER	DEPENDS ON THE MAKE AND MODEL	1 to 100
C-V TIME TRANSFER ERRORS (NO COMPENSATION)		**31 to 120**

(WITH SELECTIVE AVAILABILITY ON AND WITH COMPENSATION)

SOURCE	COMMENTS	RMS TIME ACCURACY (ns)
CLOCK DITHER	CANCELS IN C-V MODE	--
EPSILON	COMPUTED EPHEMERIS (Some Days After)	3 to 5
IONOSPHERE	WITH IONOSPHERIC CALIBRATOR	2 to 3
TROPOSPHERE	DEPENDS ON ELV. AND WEATHER	2 to 5
MULTIPATH	WITH CHOKE-RING ANTENNA GND. PLANE	2 to 4
RECEIVER	DEPENDS ON THE MAKE AND MODEL	1 to 100
C-V TIME TRANSFER ERRORS (WITH COMPENSATION)		**5 to 100**

The right column lists rms estimates for each of the time accuracy error elements with the sum at the end of each column being the square root of the sum of the squares. EPSILON is the intentional insertion of errors in the broadcast ephemeris. The meanings of other terms in the table are:

C-V	GPS common-view mode	Elv.	Elevation
TOD	Time of Day	Refl.	Reflections
GND	Ground	BDCST	As Broadcast

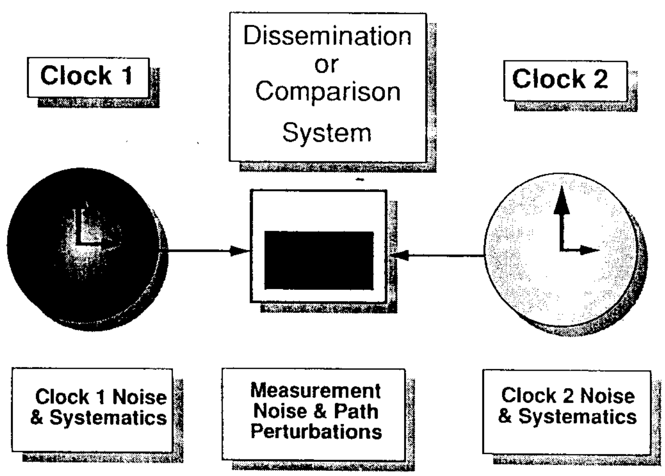


Figure 1. This figure shows two clocks, some arbitrary distance apart, being compared by some generic comparison system. In principle, the comparison system can be co-located with either or both of the clocks or be apart from both. In general, the measured values coming from the comparison system will have variability due to clock noise, delay variations in the connecting links, and variations in the comparison system itself. Characterizing the performance of the links and the comparison system is important. Otherwise, the determination of what variations come from the clocks and what come from the comparison system and the links would be impossible.

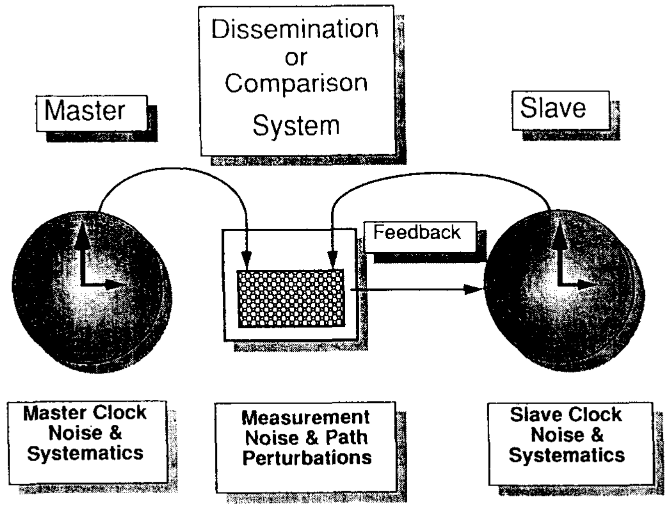


Figure 2. This figure is similar to Figure 1. Again, we are measuring the time and frequency difference between two clocks located some distance apart. In this case we wish to servo control the time and/or frequency of the slave to the master. A proper characterization of the links between the clocks in combination with the comparison system is essential for the proper design of a feedback system to control the slave clock. Another important parameter for the feedback design is the delay associated with acquisition of data by the comparison system.

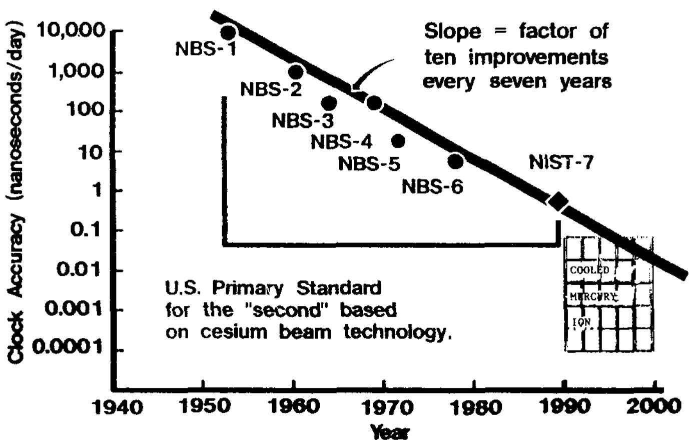


Figure 3. Improvement in atomic frequency standards of the U.S. The overall trend is a factor of 10 improvement every seven years. If this trend line continues, and there is good indication that it may, then more careful attention is needed both in the design as well as in the proper characterization of systems used to compare these with other national standards. Note: one nanosecond per day corresponds to a fractional frequency change of about a part in 10^{14}.

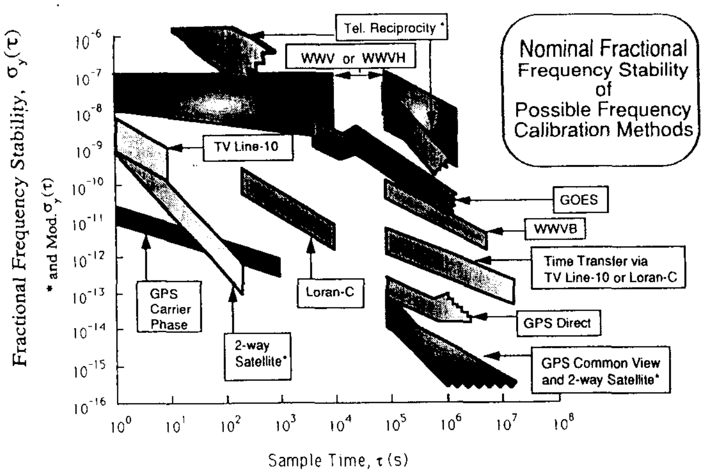


Figure 4 (Caption to follow)

Figure 4. Nominal frequency stability for several important comparison systems. The stabilities are characterized using $\sigma_y(\tau)$ except where indicated by an "*" in which case Mod$\sigma_y(\tau)$ is used. The latter case Mod $\sigma_y(\tau)$ was used in those involves situations where white noise PM is predominant for some range of sample times τ. The "Tel. Reciprocity" data were analyzed under the assumption of reciprocity of the path (measure the round trip time and divide by two to calibrate the path delay). The short-term data were measured locally and the long-term data were measured between Colorado and Hawaii via communication satellite. We often found that telephone modems contributed more noise than the path. What is plotted is the composite. The WWV and WWVH time-and-frequency transmissions at 2.5, 5, 10 and 15 MHz (WWV also broadcasts at 20 MHz) are limited in their stabilities by sky-wave-path variations. GOES East and GOES West are NOAA weather satellites broadcasting UTC(NIST) on two slightly different frequencies near 468 MHz. Here, the stability is limited by the knowledge of the satellites' ephemerides. WWVB is NIST's 60 kHz time-and-frequency broadcast service; in this case the propagation path stability is limited by the fluctuations in the earth-ionosphere waveguide. The TV Line-10 method involves line-of-sight transmissions in the TV band. It can operate with an atomic clock at the transmitter or with two clock sites receiving the TV Line-10 arrival times concurrently and subtracting one set of numbers from the other. Stability limitations here are often caused by the receiving equipment. Loran-C is a ground-wave navigation signal (at 100 kHz) operated by the U.S. Coast Guard. The time is monitored and controlled with respect to UTC(USNO). The stability is limited by propagation path variations. Two-way satellite time transfer uses spread-spectrum modems operating with different up-link and down-link carrier frequencies in one of several different bands (C, Ku, and K). The short-term stability for two-way satellite time transfer is basically limited by signal-to-noise and bandwidth considerations. Currently, the long-term performance seems to be limited by equipment instabilities. One can only extract frequency information from the "GPS Carrier Phase" measurements, and the stability seems to be limited by the GPS on-board clocks. Time and frequency stability of directly received GPS signals is limited mainly by variations in the GPS Kalman-state estimates for the system. If one is using an L1 GPS timing receiver only, then the ionospheric modeling errors can contribute additional instabilities. In some cases, signal multipath errors and/or receiver instabilities can also contribute significant instabilities. Using GPS in the common-view mode cancels out the GPS clock instabilities and cancels some of the broadcast satellite-ephemeris instabilities. The stability limits for the common-view mode arise from the same mechanisms as for GPS direct measurements except that some errors are reduced by common-mode cancelation.

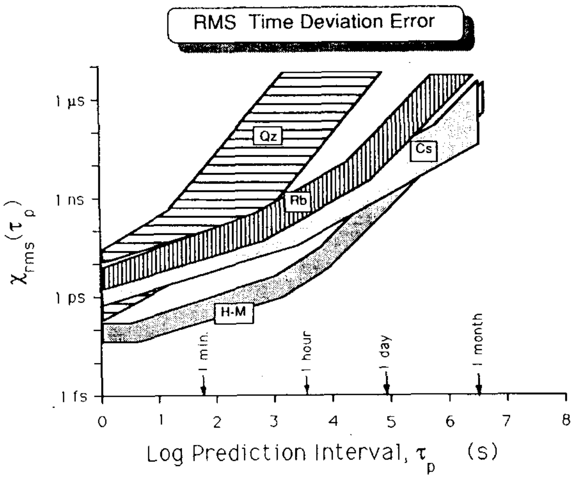
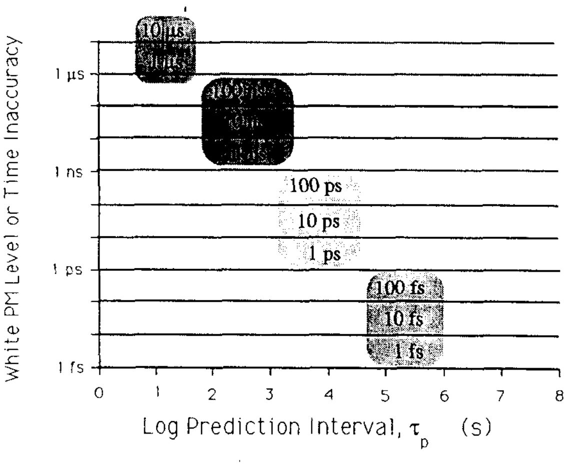
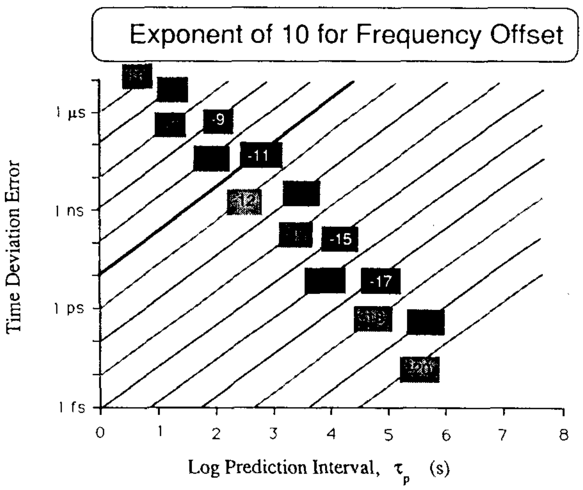
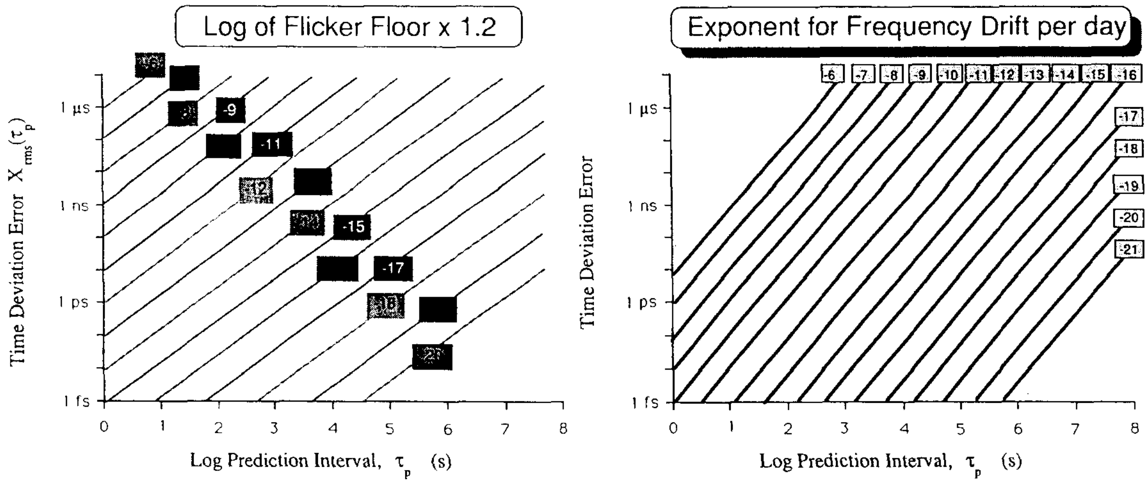


Figure 5. Time prediction error, $x_{rms}(\tau_p)$, as a function of the prediction interval for commercially available precision clocks. Qz denotes quartz-crystal-oscillator clock; Rb denotes rubidium gas-cell clock; Cs denotes cesium-beam clock; and H-M denotes active hydrogen maser clock. The prediction error is calculated from $K\tau\sigma_y(\tau)$ with K chosen for an optimum prediction estimate. The value of K depends on the noise type.





Figures 6 and 7 (caption to follow)



Figures 6, 7, 8 and 9. The ordinates and abscissas of these four plots are the same as those for Figure 5. Figure 6 can represent either the time accuracy or the white noise PM level. The time accuracy is often limited by systematic effects and averaging does not improve it. The white noise PM is well represented by the standard deviation of the measurements, and, if this is the limiting noise, then averaging will improve the knowledge of the time as the square root of the number of values averaged. Figure 7 is the time accumulation over some interval, τ_p, due to a systematic frequency difference (or offset) between two clocks being compared. Figure 8 is the rms time deviation resulting from a random flicker FM process -- often observed in long-term clock comparisons. The 1.2 ($1/\sqrt{\ln 2}$) factor is the K factor for flicker noise FM. "Flicker Floor" means the value of $\sigma_y(\tau)$ where there is a τ^0 dependance, that is, where there is no further improvement in stability with increasing τ. The curves in Figures 7 and 8 have the same slope (+1) even though they arise from different mechanisms. Figure 9 demonstrates the long-term significance of time deviation errors resulting from a linear frequency drift in a clock. The plus-two (+2) slope corresponds to the quadratic departure of the time of a drifting clock. If frequency drift exists in a clock, this error along with environmental perturbations is often the main cause of long-term time error.

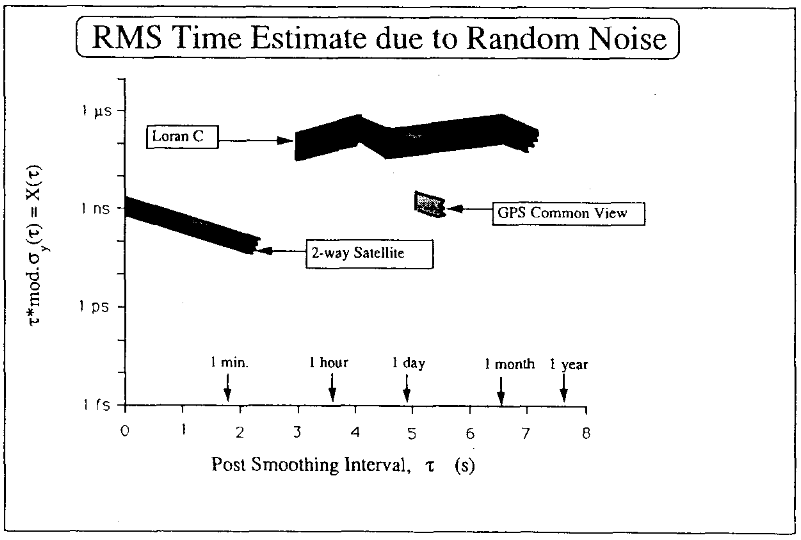


Figure 10. This type of plot can be used to determine whether or not smoothing or averaging the data is beneficial. We have here defined the time stability as the product τ mod $\sigma_y(\tau)$. For flicker noise PM, white noise FM, flicker noise FM and random-walk noise FM the standard deviation of the time residuals grow without bound as the data length increases. Hence, the standard deviation is not a good measure. The above product is a good measure since it is convergent and is data-length independent. This measure can also show the effects of systematic errors and of environmental perturbations as well as the different kinds of noise processes that may be driving the instabilities in the comparison system and/or in the clocks. The different comparison methods are explained in the caption of Figure 4.