THE VARIANCE OF PREDICTABILITY OF HYDROGEN MASERS AND OF PRIMARY CESIUM STANDARDS IN SUPPORT OF A REAL TIME PREDICTION OF UTC

by

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ABSTRACT

The need for global synchronization has increased rapidly over the last few years. These needs have arisen from the telecommunications industry and from the monitor and control stations associated with navigation systems. This paper presents a possible solution for a real-time predicted estimate of UTC based on some of the best clocks in the world. It specifically addresses the variance of time predictability utilizing the excellent resources now available. These resources include the very stable hydrogen masers and the primary cesium-beam frequency standards located at several timing centers around the world.

One problem in providing a real-time estimate of UTC is the uncertainty in comparing the time and frequency of widely separated clocks. Based on real data, we will show the time predictability in a variance sense of the outstanding clocks available independent of this problem. Then we will discuss how an accuracy of about 10 ns for a real-time prediction of UTC can potentially both be achieved and be disseminated internationally.

I. OUTLINE AND PERSPECTIVE

The need for global synchronization has increased rapidly over the last few years, largely driven by the telecommunication and power industries and needs for synchronized monitor and control stations associated with navigation systems. These new timing needs are not yet being met. This paper will present possibilities for meeting these needs.

The most desirable solution is for users to have ready access to a common real-time time scale. Universal Coordinated Time (UTC) is the international time scale generated by the Bureau International des Poids et Mesures (BIPM) in France. It is not a real-time scale, being provided about two months after the fact because of the care needed in its computation. To keep the best accuracy of the SI second as defined in the international system of units, UTC must be calculated after the fact. It is not possible to have a real-time UTC without compromising its reliability, stability, and rate accuracy. On the other hand, to be practically useful, a real-time estimate of UTC needs to be readily available. If UTC is needed in real time, it must be predicted forward in time [1,2].

All measurement units except time can be post-processed with effectiveness. The standard for time is different in that, by its very nature, it is most accurately realized when the prediction interval used to estimate the current time is minimized. For this reason, the BIPM is currently studying the calculation interval to determine whether it can be reduced to one month. Several timing centers provide real-time predictions of UTC (with the current two month delay in data), some keeping their real-time scale within approximately 100 ns of where UTC will be after it is computed.

This paper presents a method for obtaining a real-time prediction of UTC through combining some of the best clocks in the world using optimal estimation and prediction techniques. The clocks used include the very stable active hydrogen masers with cavity tuning and the primary cesium-beam frequency standards located at various timing centers around the world. We will show that it is possible to reduce the errors of prediction to the order of 10 ns, an uncertainty of the same order as the measurement noise. This uncertainty would be small enough to satisfy most current user needs.

In addition, the accessibility to this real-time prediction can be enhanced. We show how different national time scales, the UTC(k)'s, where "k" denotes a particular timing center, can be synchronized to about 10 ns. The value for users would be reduced concern about where they obtain a reference time. Such improvement would provide a reference one to two orders of magnitude better than is currently available. For example, within the USA the telecommunications industry has declared UTC as the official reference for time. However it cannot be used because it is not available in real time. Instead, UTC(NIST) and UTC(USNO MC), which track UTC to within about 100 ns, are used as secondary references. The synchronization needs of this industry are increasing. Hence, better coordination of the different sources of UTC is now needed. If the UTC(k)'s were commonly held within 10 ns of UTC, it could significantly assist international telecommunications.

II. THE VARIANCE OF TIME PREDICTION

This section describes the theory used to accomplish an improved real-time prediction of UTC [2,3,4]. For optimum time prediction there are two issues.

First, the systematics errors in a clock must be optimally estimated. These typically include the time offset, the frequency offset and the frequency drift. Second, the random variations need to be modeled. Optimum prediction algorithms can be constructed from these models. We then combine the optimum estimates of the systematic errors with the optimum estimation procedures for the modeled random processes. This parameterization of each clock can, in principle, be used to provide an independent estimate of a real-time UTC.

Once a prediction is obtained for each clock, the values are combined as a weighted set. If the clocks are independent, the optimum weighting factor for each clock is proportional to the reciprocal of the mean-squared prediction error for that clock. An optimum estimate of the systematic parameters will depend on the models used for the stochastic processes. Hence, the first step is to discuss these stochastic models.

Three noise processes provide parsimonious modeling for the random behavior of the clocks we will use. These are white-noise frequency modulation (FM), 1/f or flicker-noise FM and random-walk FM. The measurement noise also enters, and we will address this issue later.

Assuming an optimum algorithm is used, the optimum prediction error is given approximately by $\tau\,\sigma_y(\tau)$. Optimum means minimum squared error. This expression is exactly the optimum prediction error for white-noise FM and for random-walk FM. For flicker-noise FM the optimum prediction error is given by $\tau\,\sigma_y(\tau) / \sqrt{(\ln 2)}$.

The optimum estimate of clock frequency offset from a reference for white FM is the simple mean. The optimum time prediction value is the last time offset measurement. The optimum frequency drift estimate can be calculated from the linear regression to the residual frequency-offset measurements. New commercial cesium-beam frequency standards have negligible frequency drift and are dominated by white FM. In practice, the normalized mean frequency may be calculated by taking the last time offset measurement minus the first time offset measurement divided by the elapsed time [5].

The optimum algorithm for flicker noise FM requires a filter which converts the noise type to white noise FM, and then takes the mean. The filter is then inverted for prediction. This can be quite complicated. But there are two simple algorithms which are very close to optimum. The first is an exponential-filtered frequency estimate. This is particularly useful if the clock is well modeled by a composite of white noise FM and flicker noise FM [6]. The second is called a second-difference predictor. If τ is the prediction interval, it is simply formed by

$$x_p(t+\tau) = 2\,x(t) - x(t-\tau), \qquad (1)$$

where x(t) is the last known value of the clock relative to UTC. The value of τ

in our example would be two months with the current procedure for computing UTC two months after the fact. The BIPM is studying the impact of reducing this delay to one month.

The optimum algorithm for random-walk FM is the last value for the time error, the last slope for computing the frequency offset, and the mean second difference for computing the frequency drift. The difficulty is that, in practice, one model is never adequate. From Kalman-Busie theory [7], an exponential filter can be shown to be optimum for a composite of white FM and random-walk FM. If, for example, a clock is modeled by white noise FM for shorter integration times and by random-walk noise FM for longer integration times, then the optimum drift estimate is given by a three-point, second-difference estimate [8]. The three points are the first, the middle, and the last time readings.

Given a set of clocks which are independent of each other, the individual instabilities can be computed using an N-cornered hat approach [9,10]. We might also use a time scale algorithm to estimate the internal noise processes for each of the contributing clocks. [6] We will use this latter approach here, because it avoids negative variances.

We use a unique method to treat data from different locations taken at different times. Under the assumption of independence, we combine the prediction error variances to arrive at an estimate of the total prediction error for a real-time UTC. In this way we discover potential prediction accuracy, independent of time links. We will discuss the impact of this assumption later.

III. APPLICATION USING THE CURRENT BEST CLOCKS AVAILABLE

To study the performance of the best frequency standards available, we generated three experimental time scales, the first two using clocks colocated at particular sites, the third using time transfer to bridge two sites. At these sites we had access to clock data with outstanding performance. We used the TA2 time scale algorithm to generate these three independent time scales. TA2 is a retrospective smoothing algorithm, which runs a time scale both forward and backward in time. It combines the forward- and backward-calculated values and obtains a post-processed scale optimized for frequency stability [11,12]. This provided a reference for studying the instability of some of the most stable clocks in the world. The one-directional time scale algorithm, AT2 [13], is an extension of AT1, the algorithm used to generate the real-time unsteered time scale at NIST, with the addition of an estimate of confidence of the frequency estimate. This confidence estimate allows the forward and backward AT2 estimates of frequency to be combined into a smoothed estimate of frequency. A third pass in the forward direction uses this smoothed estimate of the frequency offset of each clock to estimate the time offsets. For estimating the predictability of clocks we are interested in their behavior only forward in time.

We obtained estimates of clock predictability from the TA2 algorithm only after compensating for the advantage gained from retrospective smoothing.

The clocks we used were active hydrogen masers (with cavity autotuning) and primary cesium-beam frequency standards. The first site was PTB (Physikalisch-Technische Bundesanstalt), which operates two laboratory primary cesium-beam frequency standards and two active hydrogen masers with cavity tuning. The time scale we generated from the PTB data we refer to as TA2PTB. The second site is the former Soviet Union (SU) timing center north of Moscow. We had the data from five active cavity-tuned hydrogen masers at this site. We call the time scale we generated from the data from these masers, TA2SU. The third scale combined two hydrogen-masers at the United States Naval Observatory (USNO) linked with one hydrogen-maser at NIST (National Institute of Standards and Technology) using the GPS common-view time transfer technique. We call the time scale generated from these measurement data, TA2M1.

The masers at PTB and at SU use a cavity tuning technique where the atomic line width of one maser is modulated and the cavity frequency adjusted under servo control until its oscillation frequency as measured against the other maser is independent of atomic line width. The reference maser and tuned maser are then reversed so that the cavity frequencies of both masers are autotuned. The masers at USNO and NIST use a different technique where the cavity frequency is modulated. A servo system then tunes the cavity frequency until the oscillation frequency is independent of small mistunings. This approach does not require an external frequency reference. Either approach is designed to remove the effects of cavity mistuning. Removing the effects of cavity mistuning is very important in achieving long-term frequency stability and time predictability. Cavity detuning is the major cause of frequency drift in conventional masers. [14,15,16] The cavity tuning usually reduces the frequency drift by more than an order of magnitude.

The variances of the clocks in this study were computed against their respective scales. The true variance of a clock is larger than the variance of that clock when measured against an ensemble containing that clock, since the ensemble is in part defined by that clock. An estimate of the true variance can be obtained by adjusting the measured variance for correlation with the scale. The relationship is

$$\sigma^2_{true} = \frac{\sigma^2_{measured}}{1-w}, \qquad (2)$$

where w is the normalized weight of the clock in the ensemble [17].

Figure 1a shows the estimated true variances for the clocks at PTB as seen by the TA2PTB scale. The data cover the period from MJD 48700 - 49050 (19 March 1992 - 4 March 1993). A short period of anomalous performance was removed from the PTB H1 maser data (MJD's 48921 - 48953), to enable determination of the steady-state performance. Figure 1b shows the variances with estimated drifts removed. The drift values are tabulated in Table I below along with the confidence on each estimate [18]. The confidence intervals on the variance estimates are omitted from the plot to allow the variances to be seen clearly. We discuss the 10 d confidence below, since we use that to determine confidence on the 10 d prediction errors.

The TA2SU scale ran from MJD 48835 - 49000 (01 August 1992 - 13 January 1993). Figures 2a and 2b show the uncorrelated estimates of the true variances for the clocks at SU using the TA2SU time scale without and with frequency drift removed, respectively. As for the data from PTB, the drift values and confidences are tabulated in Table I.

The TA2MI scale linked masers at NIST and USNO with once-per-day measurements from MJD 49050 - 49349 (4 March 1993 - 28 December 1993). The resultant variances for the masers as referenced by TA2MI and adjusted for correlation are plotted in figure 3a, while the variances with drift removed from USNO maser N4 are plotted in figure 3b. The time transfer technique added measurement noise in the form of a time step in the comparison technique of the order of 1 ns. Such a shift in the measurement system would appear as white noise FM of the order of $1.2 \cdot 10^{-14} \cdot \tau^{-1/2}$. To help stabilize the TA2MI scale three other masers at NIST were added for short periods each, as they were available. The result is that the TA2MI algorithm assigned the time transfer noise to the USNO masers. The variances of the masers themselves are not visible until after τ=10 days. The measurement noise is averaged down for longer values of τ.

To estimate the error in prediction we ran the scales again, with data selected once every 10 days. We also added a "clock" to the TA2MI scale which was an average of 33 commercial primary cesium-beam frequency standards. Figures 4 - 6 show the actual rms prediction errors for each clock versus its respective ensemble, adjusted to decorrelate clocks from their respective scales according to equation (2). We further adjusted the prediction errors to account for TA2 being a retrospective smoother. Since the prediction errors from TA2 are the root mean square of the forward and backward time prediction errors, we have multiplied the TA2 prediction errors by $\sqrt{2}$. We note in TA2MI that for this run there is only one maser at NIST and effectively three clocks at USNO. For this reason, the algorithm confused the time transfer noise with the NIST maser. It appears that at τ = 10 days there is still some measurement noise contaminating the prediction error estimate of the NIST maser. Also note that the NIST H1 maser was out of the measurement system for some days for adjustments. When it came back in, the prediction error took a large jump until the scale learned the new frequency of the maser.

The values of the 10-day prediction errors after each clock reached steady-state were combined in a root-mean-square sense for the entries in Table II from the three different ensemble time scales. We determine confidence on these values from the confidence on the $\sigma_y(\tau)$ values and the fact that the optimum prediction error is proportional to $\tau \cdot \sigma_y(\tau)$. The confidence interval for variance or prediction error is asymmetric. The 95% confidence fractional uncertainty at 10 d for the variances against each of the ensembles were: 0.83 - 1.2 for TA2PTB, 0.75 - 1.5 for TA2SU, and 0.8 - 1.4 for TA2M1. These values give the confidence intervals in Table II.

An optimum combination of these 10 d prediction errors -- excluding time transfer measurement noise -- would yield a 10 day prediction uncertainty of less than 1 ns. If we were limited by flicker-noise FM for prediction times longer than 10 days, then we would have a one-month prediction uncertainty of about 3 ns. If we were limited by random-walk FM, then the one-month prediction uncertainty would be about 5 ns.

IV. THE SIGNIFICANCE OF TIME TRANSFER TECHNIQUES

Since the high quality clocks used in the analyses are not colocated, transferring their frequency and time optimally is an important part of combining their readings. Obviously, the combined readings could give us the best prediction of UTC. This would also give us the advantage of independent clocks at separated sites. We could then better test for correlated effects that might exist between clocks at a given site [19]. Also, the more clocks we have, the better we can detect abnormal behavior in any one of the clocks. Such detection would minimize the effect on the composite prediction from the set of clocks we choose for minimizing the errors of prediction of UTC.

Currently, the best operational method for time transfer is obtained using GPS in the common-view mode. A receiver capable of participating in this kind of time transfer has been installed by the BIPM at VNIIFTRI (National Scientific and Research Institute for Physical-Technical and Radiotechnical Measurements) near Moscow. This is where the official SU time scale is generated. All of the sites used for the analysis in this paper participate in this method of time transfer. The measurement noise for this method is slightly dependant on location and the base-line distance between the two sites being compared. Typical numbers are 1 to 6 ns from day to day [10]. The measurement noise is typically white noise PM; hence, it will average as the square root of the inverse averaging time. If optimum filtering on the noise is utilized, it need not impact the prediction times for prediction intervals of one month. Sometimes the measurement noise is as dispersive as 1/f (flicker) PM, and even in this case it should average sufficiently so that its contribution will be significantly less than 10 ns at one month.

Having a high-confidence current estimate of UTC would provide several advantages. We have illustrated that less than 10 ns is probably achievable. Hence, each timing center could, in principle, steer their UTC(k) to this accuracy. If this were the case, industries like telecommunication could obtain a synchronization reference from any key timing center -- a significant advantage for international telecommunication particularly for countries where multiple servers are employed.

If a high-confidence estimate of UTC were available in real time, then the disseminated time UTC(USNO) from GPS would track UTC corresponding to the confidence of the estimate. Hence, GPS could become a more accurate source of UTC, even as GPS is becoming more readily available. Recent work has shown that for timing, the SA modulation on GPS can be filtered to the order of 1 ns [20]. SA is the Selective Availability modulation which degrades the GPS broadcast signal as used by the civil sector. Since SA can be filtered to low levels, as UTC(USNO) steers more closely to UTC, GPS can provide a high accuracy, indirect access to UTC at a level of better than 10 ns [2].

Other time transfer techniques are being developed. The two-way satellite time and frequency transfer technique shows promise of 1 ns accuracy and subnanosecond day-to-day stability. It is now being developed among several time standards laboratories [21]. However, it is relatively expensive. There are possibilities for transmitting a time service from INMARSAT satellites which could potentially supply UTC world wide [22]. It could become the first UTC distribution method. The potential accuracy of INMARSAT timing could be 10 ns -- consistent with the confidence level for time prediction of UTC presented in this paper. Further, INMARSAT would operate in the receive-only mode, making it easier and less expensive to use than the two-way technique.

Another possibility is the use of the telecommunications system for precise time and frequency transfer. A number of telecommunication companies are studying two-way time transfer in optical fiber between nodes in their network [23]. Optical fibers have been shown to be an excellent media for time transfer [24]. Eventually, if the telecommunication industry has ready access to UTC, they in turn could become very accurate suppliers of UTC as well.

V. CONCLUSIONS, REVIEW AND PERSPECTIVE

In the last few years, clocks have been introduced with outstanding long-term stability. This long-term frequency stability translates to exceptional time predictability when optimum or near optimum prediction algorithms are used. These clocks include laboratory cesium-beam frequency standards and active hydrogen masers with cavity tuning capability. In addition, a particular commercial cesium-beam frequency standard now rivals the laboratory standards of recent years.

The analysis in this paper considered a subset of available clocks to demonstrate the thesis -- that UTC can be predicted a month in advance to an accuracy of less than 10 ns. This, of course, assumes that the rate of UTC will be stable to this same level. The subset we used were the two primary cesium-beam frequency standards (operating as clocks) at the PTB and hydrogen masers located at NIST, USNO, PTB and VNIIFTRI. Figures 4-6 show the 10 d prediction errors for these clocks relative to their respective experimental time scales as the scales evolve into steady-state performance. The values after each clock reached steady-state were averaged for the entries in Table II.

There are now about 50 improved commercial cesium-beam frequency standards, like the ensemble of 33 at USNO, contributing as clocks to TAI and UTC. The specification of these can be characterized with a frequency stability, $\sigma_y(\tau) = 8 \cdot 10^{-12} \cdot \tau^{-1/2}$ for $10\ s < \tau < 10\ d$. In some cases this white noise FM is lower and persists for even longer values of τ. Using the optimum time prediction procedures outlined in this paper, the rms prediction error at 10 d for a single standard would be 7.4 ns. If all 50 of these standards were operating within their specification and were independent, optimally combining them would yield an rms dispersion of $7.4\ ns/\sqrt{50} = 1\ ns$. Of course in real manufacturing and laboratory conditions there may be problems causing correlations and improper performance of standards. The ensemble of 33 such cesium-beam frequency standards at USNO showed a predictability of 3 ns at 10 d, relative to the ensemble including them and 3 H-masers. The number of 3 ns is perhaps larger than it could be, since the clocks were combined as a simple average without regard to individual performance. Given a predictability of 3 ns for 33 standards, if we increase to 50 independent standards we find a predictability of $(\sqrt{33}/\sqrt{50}) \cdot 3 = 2$ ns at 10 d. For τ values longer than 10 d, we may conservatively assuming both a 10 d predictability of 2 ns and a model of flicker noise FM past 10 d. For this model the dispersion grows as time, and under the assumption of optimum prediction outlined herein, we would have 7.2 ns for a one-month prediction interval from these commercial cesium-beam frequency standards without the masers.

From the actual clocks analyzed herein, we have shown that a time scale can be created using three to five active hydrogen masers and/or laboratory cesium-beam frequency standards. Against such time scales the predictability of several masers taken together reached 1 ns for a 10 d prediction interval. We also saw that the noise type of many such systems was flicker noise FM at under $3 \cdot 10^{-15}$ out to one month or longer. Since the time dispersion due to flicker noise FM is proportional to τ, we can forecast a time dispersion at one month for a scale based on an ensemble of similar clocks. Shortly, there may be 25 such cavity-tuned masers in the world available for use in an ensemble approximately a factor of 5 greater than what we use in our study here to obtain 1 ns predictability at 10 d. If they are properly linked, an ensemble of independent standards with drift modeled perfectly should be $\sqrt{5}$ times better than what we have demonstrated here. Using a model of flicker noise FM from 10 d to 30 d, we find a one-month predictability of

$$\frac{3}{\sqrt{5 \cdot \ln(2)}} = 1.6\, ns.$$

If drift can be estimated to $5 \cdot 10^{-17}$/d as indicated in Table I, this could add a time dispersion of 2.2 ns for each maser. Conservatively, it is not unreasonable to expect a one month rms prediction error of less than 3 ns for such an ensemble. For UTC to be that predictable it would need to have a flicker floor at about $1 \cdot 10^{-15}$. This is not currently available. If standards can be predicted below the 3 ns level at one month, it seems reasonable to expect that UTC will improve as it uses these standards, commensurate with their predictability.

While clocks are being improved, methods of time comparison need to be improved as well. It will take time to reach the goals demonstrated in this paper, but the prospects seem very good.

At the present time, practical consideration such as time steps and frequency steps in clocks, and uncertainty in estimating frequency drift limit predictability of UTC to significantly more than 1 ns. In addition, UTC is still only available with about a two-month delay. The noise in the two-month region might be as dispersive as random-walk FM. This would cause the time prediction error to grow as $\tau^{3/2}$. This might bring us up to about the 10 ns region at the present time using the best clocks available. This is still about an order of magnitude better than the current performance of most of the UTC(k)s.

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Table I

Standard	Lab	Estimated Linear Frequency Drift
CS1	PTB	$(-2.9 \pm 0.8) \cdot 10^{-16}$/d
H1	PTB	$(1.4 \pm 0.4) \cdot 10^{-16}$/d
H2	PTB	$(1.3 \pm 0.2) \cdot 10^{-16}$/d
H50	SU	$(-0.6 \pm 0.3) \cdot 10^{-16}$/d
H51	SU	$(0.7 \pm 0.3) \cdot 10^{-16}$/d
H53	SU	$(-0.2 \pm 0.3) \cdot 10^{-16}$/d
N4	USNO	$(1.0 \pm 0.2) \cdot 10^{-16}$/d

Table II

Measurement	RMS Uncorrelated Prediction Error at 10 d 95 % confidence limits:	lower	upper
For PTB, 21 points used from end of data, MJD's 48840 - 49050			
CS1 - TA2PTB	8 ns	7	10
CS2 - TA2PTB	5 ns	4	6
H1 - TA2PTB	2 ns	2	2
H2 - TA2PTB	3 ns	2	4
For SU, 8 points used from end of data, MJD's 48915 - 48985			
H47 - TA2SU	2 ns	2	3
H49 - TA2SU	2 ns	2	3
H50 - TA2SU	2 ns	2	3
H51 - TA2SU	1 ns	1	2
H53 - TA2SU	2 ns	2	3
For TA2M1, 16 points used from end of data, MJD's 49171 - 49321			
N4 - TA2M1	2 ns	2	3
N5 - TA2M1	1 ns	1	1
33Cs - TA2M1	3 ns	2	4
NIST H1 - TA2M1	3 ns	2	4

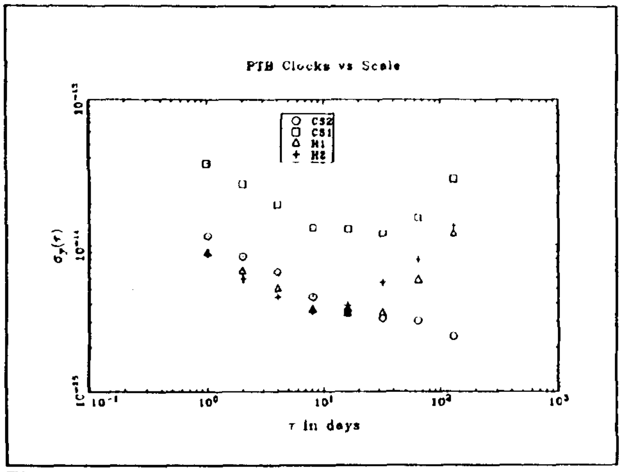

Figure 1a

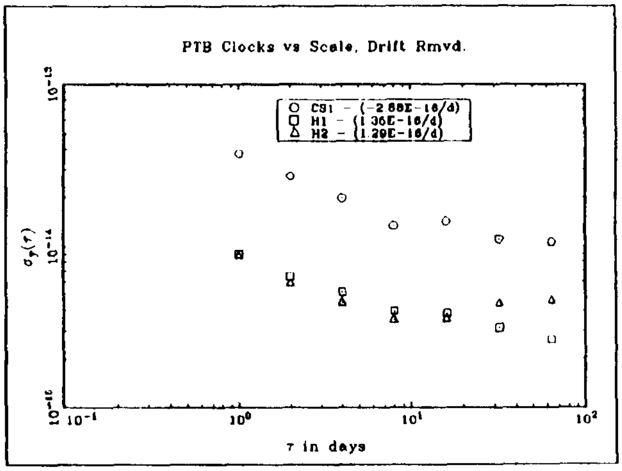

Figure 1b

Figures 1a and 1b use the data from the PTB primary cesium-beam frequency standards operating as clocks and two hydrogen masers. Figure 1a is a plot of the estimate of the unbiased instability, $\sigma_y(\tau)$, as inferred from measuring each clock against an ensemble -- then removing the bias resulting from membership of that clock as a member of the ensemble. Figure 1b is the same as figure 1a except a frequency drift has been subtracted from the data.

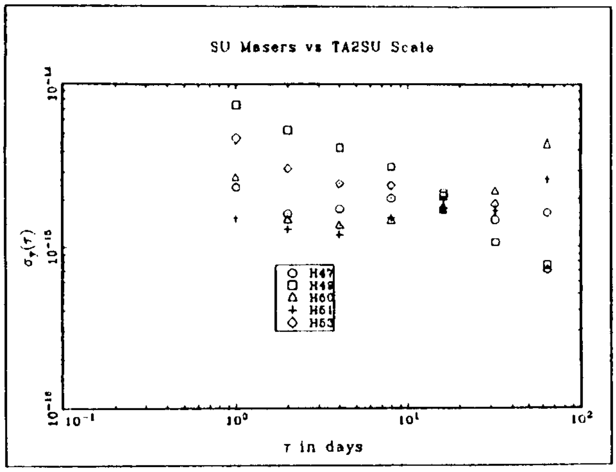

Figure 2a

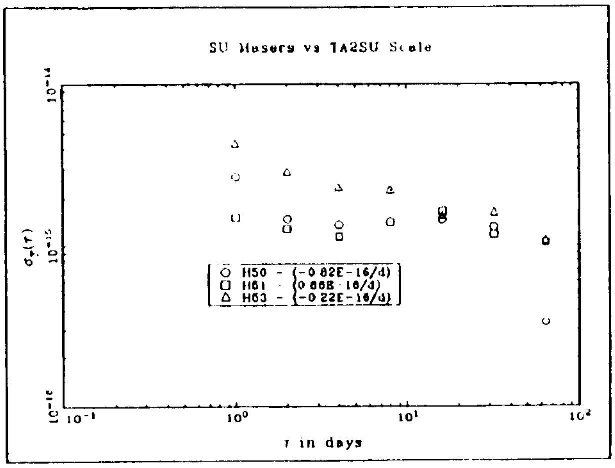

Figure 2b

Figures 2a and 2b use the data from clocks located at VNIIFTRI (the former Soviet Union reference time scale is still maintained for the different Unions). These are all hydrogen masers. Figure 2a is a plot of the estimate of the unbiased instability, $\sigma_y(\tau)$, as inferred from measuring each clock against an ensemble -- then removing the bias resulting from membership of that clock as a member of the ensemble. Figure 2b is the same as figure 2a except a frequency drift has been subtracted from three of the clocks which indicated some drift.

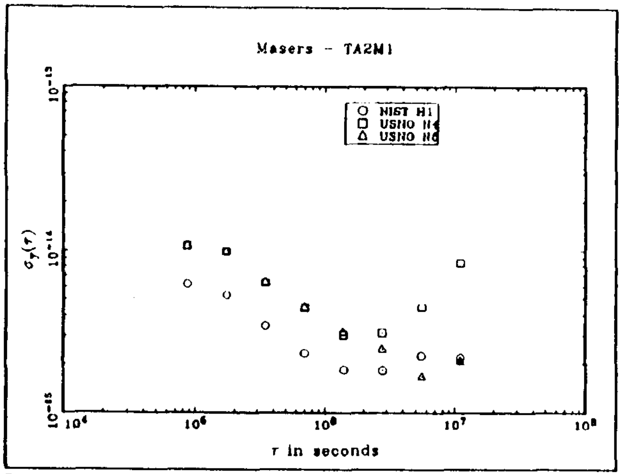

Figure 3a

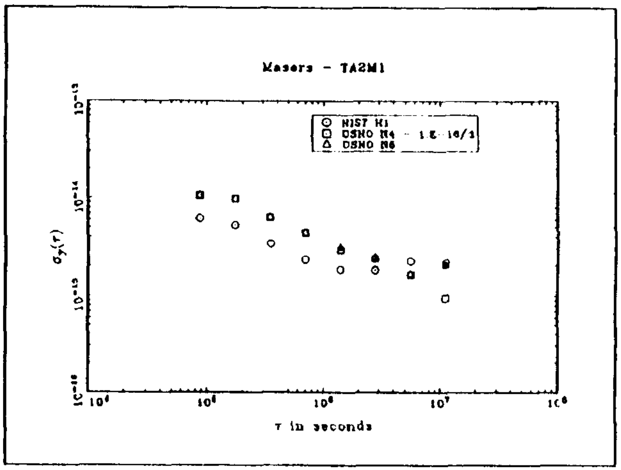

Figure 3b

Figures 3a and 3b use the data from clocks located at both USNO and NIST. The GPS common-view technique was used to compare the clocks at the two sites. Figure 3a is a plot of the estimate of the unbiased instability, $\sigma_y(\tau)$, as inferred from measuring each clock against an ensemble -- then removing the bias resulting from membership of that clock as a member of the ensemble. Figure 3b is the same as figure 3a except a frequency drift has been subtracted from the data for the N4 maser. For this data set the measurement noise contaminates the stability of the NIST maser.

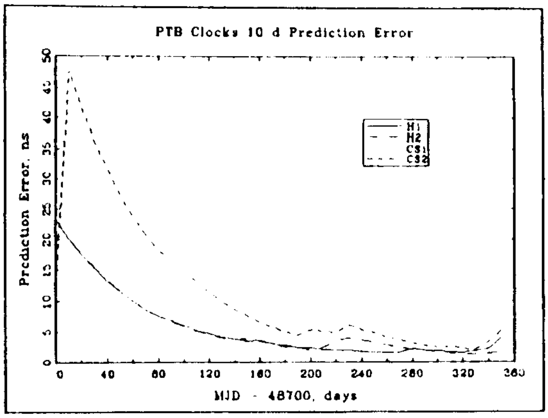

Figure 4

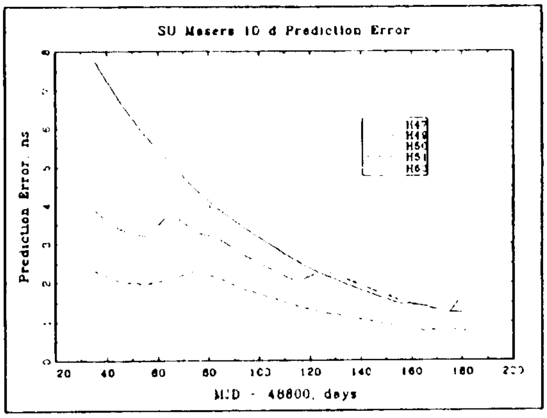

Figure 5

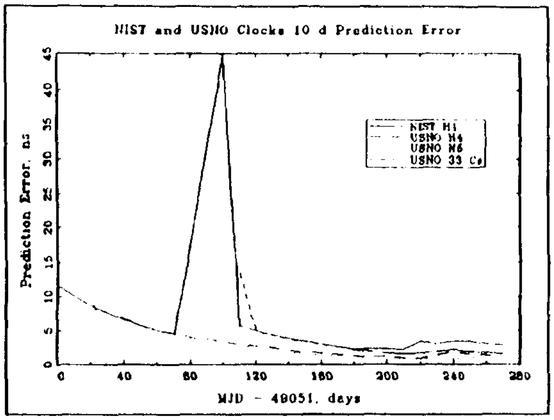

Figure 6

Figure 4 - 6 These three figures all estimate the 10 day rms prediction error as determined (internally) with respect to the TA2 time-scale algorithm. The figures correspond to the stability data shown in figures 1 - 3. Note, there is a turn on transient and occasional adverse perturbations in some of the clocks. Table 1 lists a root-mean-square of the asymptotic average for each of the clocks.