RECENT IMPROVEMENTS IN THE ATOMIC TIME SCALES OF THE NATIONAL BUREAU OF STANDARDS

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ABSTRACT

Coincident with the installation of a new measurement system, the National Bureau of Standards has also developed a new philosophy for the generation of both UTC(NBS) and atomic time, TA(NBS). Several benefits have resulted from this new direction. First, a more uniform UTC(NBS) scale was achieved in order to meet the increased requirements of our users. Second, improved synchronization of UTC(NBS) with UTC (Universal Time Coordinated) has been achieved. The frequency stability of UTC(NBS) is typically about 1×10^{-14} for averaging times of one day and longer and synchronism is now maintained to within about 1 microsecond of UTC indefinitely. Previously five microseconds was a realistic goal. Third, a new Kalman type algorithm with more robust performance is used to generate TA(NBS) totally independent of the generation of UTC(NBS). TA(NBS) is still steered in rate toward the frequency given by the NBS primary frequency standards. Fourth, a significantly improved working time and frequency reference is readily available. This reference supports the research and development of new frequency standards, and also supports our calibration services. This improved time and frequency reference is constructed by computing UTC(NBS) in final form every two hours. A real-time output signal is then steered in frequency to keep its time within a few nanoseconds of the officially computed value. And fifth, a very stable frequency reference is obtained by using all of the clocks available in the NBS clock ensemble. This time scale -- denoted AT1 -- is used for all of the NBS frequency stability calibrations, and is also used to generate UTC(NBS). This new approach has been tested for more than a year and the resulting improvements have now been documented.

INTRODUCTION

As of MJD 45195.5 (14 Aug. '82) NBS has been generating three time scales: UTC(NBS), TA(NBS), and AT1. Frequency steps introduced in the past to synchronize UTC(NBS) with UTC were objectionable to some of the NBS's more sophisticated users. These steps have been reduced by an order of magnitude and the frequency stability and the time accuracy of the new UTC(NBS) have been improved by about an order of magnitude. With the introduction of a new measurement system (1) with a measurement precision of about 1 picosecond, UTC(NBS) is computed every two hours, and a real-time clock is kept within a few nanoseconds of this computed time. The coordination of UTC(NBS) is accomplished with a one year time constant so that the monthly frequency steps introduced to maintain synchronization are of the order of one part in 10^{14} comparable to the order of the noise and hence are imperceptible. Coordination with UTC has been enhanced by more than an order of magnitude by placing into operation, in July of 1983, the measurement of UTC - UTC(NBS) via global positioning system satellites in common-view between Boulder, Colorado and Paris, France (2,3). The measurement precision of this technique is about 10 ns.

The "second" used in generating the independent and proper time scale, TA(NBS) continues to be steered toward the NBS "best estimate" of the SI second as determined by periodic calibrations with the NBS primary frequency standard (4). Hence, this time scale is syntonized with the definition of the second as realized at Boulder, Colorado--limited only by the inaccuracies of the NBS primary frequency standards and the alogrithms involved, currently 8 x 10^{-14}. At the last calibration (July 1983) -- after applying the 1.8 x 10^{-13} gravitational potential correction of Boulder, Colorado with respect to the geoid -- the second used in UTC and TAI was found to be too long by 3 x 10^{-14} with respect to the NBS "best estimate". The algorithm employed in generating TA(NBS) is based on Kalman filter and prediction techniques (5). Though it uses measurements from the same set of clocks, its operating algorithm is independent of that used to generate UTC(NBS) and AT1. A new clock noise parameter estimation procedure has also been introduced (6,7), which has provided better clock noise model development and noise parameter estimation for each of the clocks in the NBS ensemble. This improvement in parameter estimation has enhanced the frequency stability of all three time scales.

The AT1 time scale is a proper time scale designed to run in real time with state-of-the-art frequency stability. UTC(NBS) differs from AT1 by a preset (steering) time and frequency offset. AT1 is a totally independent scale generated by a choice of optimum weighting factors for each of the clocks in the NBS ensemble so that, in principle, the scale's stability is better than that of the best clock in the ensemble. This scale provides a local frequency reference for NBS research and development efforts, and also for clocks being calibrated by NBS. These clocks may be either on site or at remote locations. When the clocks are at remote locations, they are compared with the NBS time scales via the GPS in common-view technique or via Loran-C. The frequency stability of AT1 is estimated to be about 1 x 10^{-14} for sample times of one day to about one month.

The body of the paper will give the details of the formulation and the performance of the above three scales. Figure 1 is a block diagram illustrating how the time scales are generated.

The Time Scale UTC(NBS)

An International Radio Consultative Committee (CCIR) regulation states that all UTC(i) scales should be synchronized to within 1 millisecond of the international scale, UTC, maintained by the BIH (8). Well within that regulation and in accordance with the intent to minimize the disparity between scales, NBS has designed UTC(NBS) to be synchronous with UTC within practical limits. In the past that limit has been 5 µs. With the new UTC(NBS), the goal is 1 µs. UTC(NBS) is also kept nearly as stable as AT1, a scale designed specifically for optimum frequency stability. Because UTC(NBS) is synchronous with UTC in long term, the syntonization accuracy of UTC(NBS) is approximately the same as that of the international primary frequency standards utilized in the determination of the SI second for TAI (currently CS1 at the PTB, CS5 at the NRC, and NBS-6 at the NBS all with accuracies equal to or less than 1 x 10^{-13}). UTC is derived from TAI by subtracting "leap seconds" as needed in order to keep UTC within 0.9 seconds of the earth time scale UT1.

Synchronizing to UTC presents two challenging logistic problems: 1) In the past the measurement noise using the Loran-C navigation chain as the time transfer mechanism required averaging times of the order of several months before the instabilities of state-of-the-art clocks began to appear. With GPS satellites used in common-view, that measurement noise becomes negligible for sample times of a few days and longer. However, this technique is currently only available to a small set of timing laboratories. 2) There have been indications that either the propagation noise and/or temperature coefficients in the clocks involved in the generation of TAI may be causing an annual variation to appear. The BIH is paying strict attention to the temperature environment of the clocks involved in order to reduce any potential effect from that source. While this problem is being worked out, NBS has adopted a steering servo technique with a one year time constant in order to average out any annual term which may be present. This servo technique has been applied since November 1982, and the improved performance is illustrated in Figure 2. The GPS satellite data used in common-view between Boulder, CO and Paris, France has only been available since July 1983. As more of this data becomes available the smoothness and synchronization accuracy of UTC(NBS) should continue to improve. Theoretical estimates indicate that frequency stabilities in the range of 1×10^{-14} may be maintained for sample times from one day to a month and longer for UTC(NBS). Synchronization accuracies should drop well below a microsecond as annual term problems in the clocks and in the propagation are solved.

The most stringent users of UTC(NBS) desire it to be as smooth and accurate as possible. Time steps to synchronize it to UTC would be objectionable. Excellent frequency stability and time accuracy can be obtained simultaneously by inserting imperceptible frequency steps (of the same size as the noise) on a monthly basis in order to steer it toward UTC. Prior to this new procedure for steering UTC(NBS), only annual frequency steps were inserted. They were sufficiently large so that they became objectionable to NBS's most stringent users such as the NASA Deep Space Network. Table 1 lists the steering corrections published in the NBS Time and Frequency Bulletin, yielding the results shown in Figure 2.

The Time Scale TA(NBS)

The NBS goal is to smoothly syntonize TA(NBS) with the frequency given by the NBS primary frequency standard -- currently NBS-6. TA(NBS) is a proper time scale in the sense of general relativity -- its time being determined only by the clocks and standards in the NBS laboratories. Since frequency steps are objectionable for this time scale, frequency syntonization is achieved for TA(NBS) by inserting frequency drift of the order of the noise (≤ 1 part in 10^{13} per year). The frequency drift inserted is computed using an algorithm (4) which uses the periodic calibrations of the primary frequency standards. The relationship between the frequencies of TA(NBS) and UTC(NBS) are listed in the right column of Table 1.

The algorithm used in generating TA(NBS) employs the same clock data used in generating the other two time scales. However, the algorithm has been developed using Kalman filter and prediction techniques (5). The noise model for the clocks in the ensemble used to generate the NBS time scales is composed of two coefficients:

a coefficient which gives the level of white noise frequency modulation (FM) and a coefficient which gives the random walk FM. A maximum likelihood parameter estimation procedure is used to estimate these coefficients for each of the clocks. Their values are listed in Table 2. A test for whiteness of the residuals has been conducted to assess the goodness of the model. The test was affirmative indicating the model is statistically adequate to describe the behavior of the clocks in the NBS ensemble.

Equation 1 gives the relationship of these coefficients to the "Allan Variance".

$$\sigma_y^2(n\tau_o) = \frac{\sigma_\varepsilon^2}{n\tau_o^2} + \frac{\sigma_\eta^2\,(2n^2+1)}{6n\tau_o^2}, \tag{1}$$

where the sample time $\tau = n\tau_o$, τ_o is the measurement and prediction interval and σ_ε and σ_η are measures of the magnitude of the rms prediction error in the clock over an interval τ_o for the white noise FM and the random walk noise FM respectively.

The Time Scale AT1

AT1 is a basic time and frequency metrology tool for the Time and Frequency Division of NBS. It is also used as a stable frequency reference for remotely measuring and calibrating clocks as well as for measuring and calibrating clocks sent to the NBS.

AT1 is automatically computed every two hours. The computation algorithm uses an "optimum" weighted set of the data from each of the clocks in the NBS ensemble. The time differences are measured with a precision of the order of a picosecond. A two-parameter representation of the noise characteristics is also used in this algorithm. There is a one-to-one correspondence between these two parameters and the two parameters referenced above. (See Table 2) The values of these parameters, their relationships, and how the algorithm works is described elsewhere (9).

To evaluate a clock such as AT1 which is designed to be better than the best clock available is a very difficult task. However, there are ways to estimate the frequency stability of AT1: First, by simulation, using the clock models estimated from the maximum likelihood approach; second, by measuring against an independent clock, either remote or local; third, by using the three corner-hat (10) technique with three nominally comparable and independent clocks or time scales. One further twist on the last option is to permute three separate algorithms around three independent clock ensembles, allowing one to independently estimate the performance of each of the algorithms and each of the ensembles. The data available were only sufficient to perform the first two options.

Figure 3 shows the frequency stability model for each of the clocks in the NBS ensemble. Once the model elements had been estimated using the maximum likelihood technique, each clock was simulated and then processed through the AT1 algorithm as if the data were real. The computed time could then be compared against perfect (true) time since the data were simulated. Two different sets were simulated and processed and the resulting frequency stability is indicated by the squares in this figure. One estimates that for sample times ranging from about one day to about a month, the stability of AT1 so computed should be of the order of or below about 1×10^{-14}.

Using the second option and the GPS common-view technique we have measured the frequency stability of AT1 versus UTC(USNO MC) an operational time scale provided by the U.S. Naval Observatory. The time difference so deduced is shown in Figure 4 for the period July through October 1983. The $\sigma_y(\tau)$ analysis of these data is shown in Figure 5 with and without an apparent frequency drift being removed. The frequency drift is tiny -- amounting to only -8×10^{-16} per day. For sample times of one, two, and four days, the stability values are probably significantly contaminated by measurement noise. A probable proper conclusion from this data set is that both time scales are better than about 2×10^{-14} for 4 days $\leq \tau \leq$ 1 month.

Because of the previously determined white phase measurement noise present when using the GPS in common-view technique (11), it is appropriate to use the modified $\sigma_y(\tau)$ analysis technique (12). Using this technique, Figure 6 shows AT1 versus both UTC(USNO MC) and UTC(OP), the time scale provided by the the Paris Observatory. Because of a frequency step introduced in UTC(OP) during the above analysis period, a stable period prior to this step during July 1983 was analyzed. In figure 6, the measurement noise is limiting for sample times of one and two days but for sample times of from 4 to 32 days it appears that none of the above three scales has instabilities worse than about 1×10^{-14} for mod. $\sigma_y(\tau)$ and for the analysis period covered. Assuming flicker noise FM as the stability model and translating to $\sigma_y(\tau)$ increases the instability value by only a factor of about 1.2.

Recently some repair work was performed on the NBS prototype passive hydrogen maser (PHM4). Because of this repair work the maser was not included in the NBS computation of AT1. This provided an opportunity to use the maser as an independent local reference to measure the stability of AT1. Because of the maser's excellent white noise FM characteristics, its absence from the time scale computation increased the over-all white noise FM level of AT1 as compared to Figure 3. Even so, as shown in Figure 7, the long term stability of AT1 versus the passive maser is still very good -- of the order of 1×10^{-14} for sample times of one to four days. The stability of AT1 versus UTC(USNO MC) from Figure 5 is plotted for comparison -- it should be noted that this data is contaminated by measurement noise. A conservative conclusion from the data shown in Figure 7 is that the stability of AT1 is better than 2×10^{-14} for sample times in the range of one day to a month.

To test if the steering of UTC(NBS) was affecting the long term stability, UTC(NBS) was measured against UTC(USNO MC) via GPS in common-view and no significant change in the $\sigma_y(\tau)$ diagram resulted compared to that obtained in Figure 5. One can apparently also say that the time scales UTC(NBS) and/or UTC(USNO MC) have stabilities better than 2×10^{-14} for sample times from a few days to a month.

Conclusion

The new NBS time scale measurement system (1) coupled with the time scale algorithm research (13) has provided NBS with a solid foundation for developing the time scales UTC(NBS), TA(NBS), and AT1 as explained above. All three scales have frequency stabilities of the order of 1×10^{-14} for sample times from one day to a month. UTC(NBS) is synchronized to UTC, and TA(NBS) is syntonized to the NBS "best estimate" of the frequency given by the NBS primary frequency standards (currently NBS-6). AT1 provides state-of-the-art frequency stability for sample times of the order of one day and longer with the ability to include and to calibrate clocks of diverse as well as of state-of-the-art quality. As new and better clocks are added, AT1, UTC(NBS), and TA(NBS) will continue to improve in their frequency stabilities.

With the advent of GPS used in the common-view measurement mode, the full frequency stability and accuracy of the above time scales is available at a remote user's location for sample times of about 4 days and longer (14). This measurement is about a factor of 20 times better than using Loran-C. With this measurement technique, not only will the time difference UTC(USNO MC) - UTC(NBS) be known in near real time to an accuracy of about 10 ns (3), but also it is anticipated that UTC(NBS) will be able to maintain synchronization with UTC, which is calculated two months after the fact, with an accuracy of about 100 ns.

Acknowledgments

The authors are deeply appreciative for the helpful comments given in review by Dr. Karl Kessler and by Dr. Lindon Lewis.

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Table 1 is a list of changes in time scale frequencies of both TA(NBS) and UTC(NBS) as well as a list of the time and frequency differences between TA(NBS) and UTC(NBS) at the dates of leap seconds, and/or frequency or frequency drift changes.

TABLE 1

DATE	(MJD)	FREQUENCY CHANGES TA(NBS)	FREQUENCY CHANGES UTC(NBS)	TA(NBS) - UTC(NBS)	$y_{UTC(NBS)} - y_{TA(NBS)}$
1 Jan 80	44239			19.045 071 150 s	-0.36×10^{-13}
1 Apr 80	44330	$+1.0 \times 10^{-13}$/year	+50 ns/day	19.045 071 432 s	$+5.43 \times 10^{-13}$
1 July 80	44421	(Drift continued)	-35 ns/day	19.045 067 262 s	$+0.88 \times 10^{-13}$
1 July 81	44786		+ 4 ns/day	20.045 065 283 s	$+0.59 \times 10^{-13}$
1 July 82	45151	$+1.0 \times 10^{-13}$/year	- 3 ns/day	21.045 063 425 s	$+0.24 \times 10^{-13}$
1 Sept 82	45213	(Drift stopped)	-3.7 ns/day	21.045 063 341 s	-0.36×10^{-13}
1 Oct 82	45243			21.045 063 464 s	-0.45×10^{-13}
1 Nov 82	45274	$+1.0 \times 10^{-13}$/year	+1.4 ns/day	21.045 063 583 s	-0.34×10^{-13}
1 Dec 82	45304	(Drift continued)	+0.77 ns/day	21.045 063 671 s	-0.25×10^{-13}
1 Jan 83	45335	(Drift continued)	+1.49 ns/day	21.045 063 715 s	-0.08×10^{-13}
1 Feb 83	45366	(Drift continued)	+1.51 ns/day	21.045 063 716 s	$+0.11 \times 10^{-13}$
1 Mar 83	45394	(Drift continued)	+1.28 ns/day	21.045 063 656 s	$+0.30 \times 10^{-13}$
1 Apr 83	45424	(Drift continued)	+0.93 ns/day	21.045 063 565 s	$+0.21 \times 10^{-13}$
1 May 83	45455	(Drift continued)	-0.17 ns/day	21.045 063 547 s	$+0.08 \times 10^{-13}$
1 Jun 83	45486	(Drift continued)	-0.44 ns/day	21.045 063 522 s	-0.11×10^{-13}
1 July 83	45516	(Drift continued)	-0.94 ns/day	22.045 063 605 s	-0.37×10^{-13}
1 Aug 83	45547	(Drift continued)	-1.04 ns/day	22.045 063 721 s	-0.47×10^{-13}
1 Sept 83	45578	(Drift continued)	-1.20 ns/day	22.045 063 856 s	-0.62×10^{-13}
1 Oct 83	45608	(Drift continued)	0.00 ns/day	22.045 064 070 s	-0.72×10^{-13}

TABLE 2 Estimated values of σ_ε and σ_n and 95% confidence intervals.

Clock	Length of data (days)	σ_ε (ns) Lower Limit	σ_ε (ns) Est.	σ_ε (ns) Upper Limit	σ_n (ns) Lower Limit	σ_n (ns) Est.	σ_n (ns) Upper Limit
1316	364	3.81	4.14	4.53	0.53	0.80	1.23
167	361	12.58	13.52	14.67	0.57	1.11	2.07
137	358	10.41	11.31	12.27	1.76	2.49	3.56
61	67	5.48	6.77	8.43	1.53	2.80	4.83
352	354	8.12	8.85	9.74	2.42	3.32	4.41
323	255	2.06	2.37	2.74	0.63	0.94	1.34
1375	357	9.93	10.71	11.64	0.96	1.48	2.25
NBS4	66	0	0.88	1.86	0.72	1.34	2.16
113	354	8.73	9.48	10.38	2.49	3.18	4.11
8	360	7.98	8.65	9.49	2.11	2.76	3.66
601	298	1.89	2.13	2.41	0	0.06	0.52
PHM4	203	0	0.65	1.19	0.55	0.77	1.09

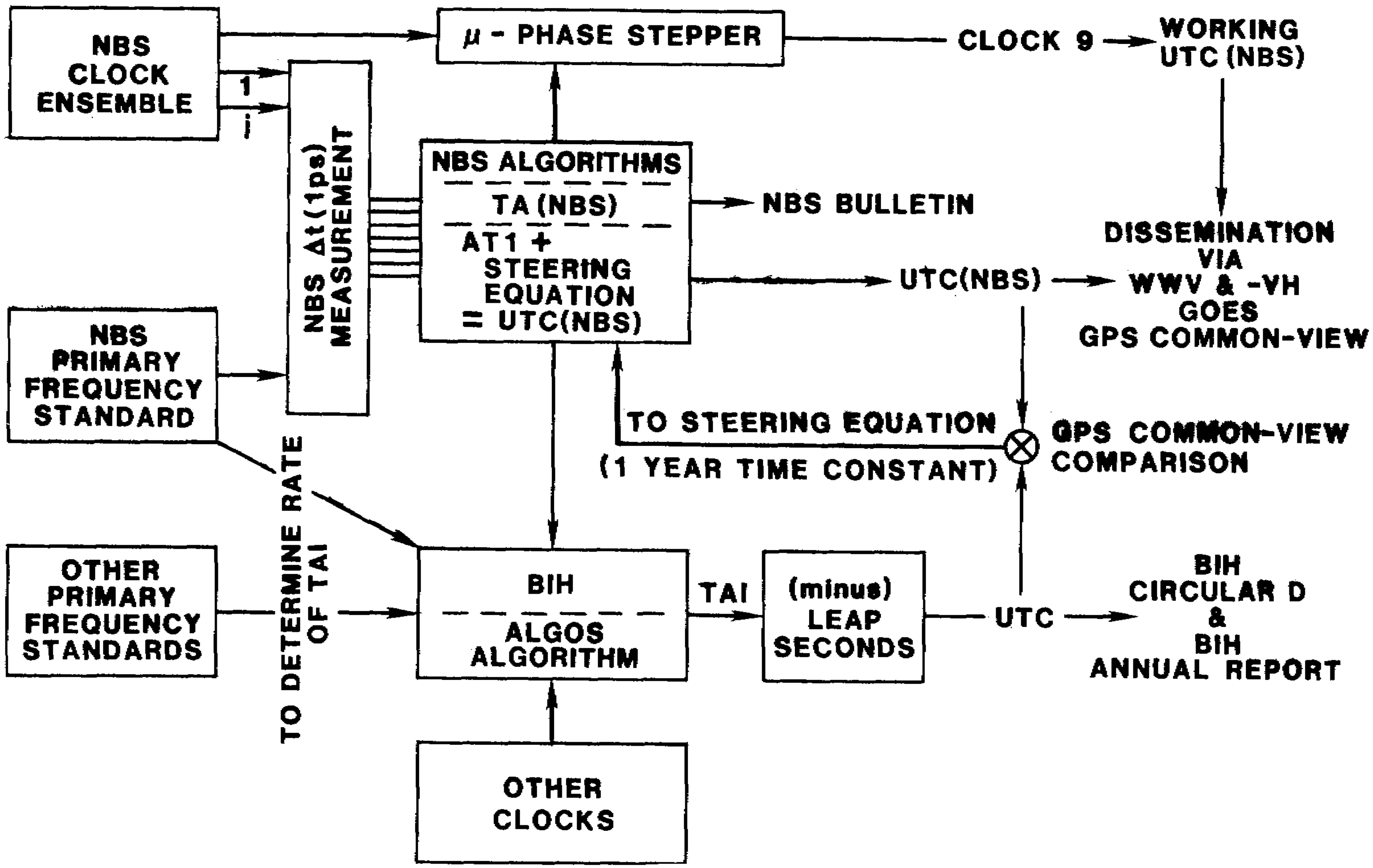

Figure 1. Conceptual block diagram illustrating how the International Time scales and the NBS Time scales are generated.

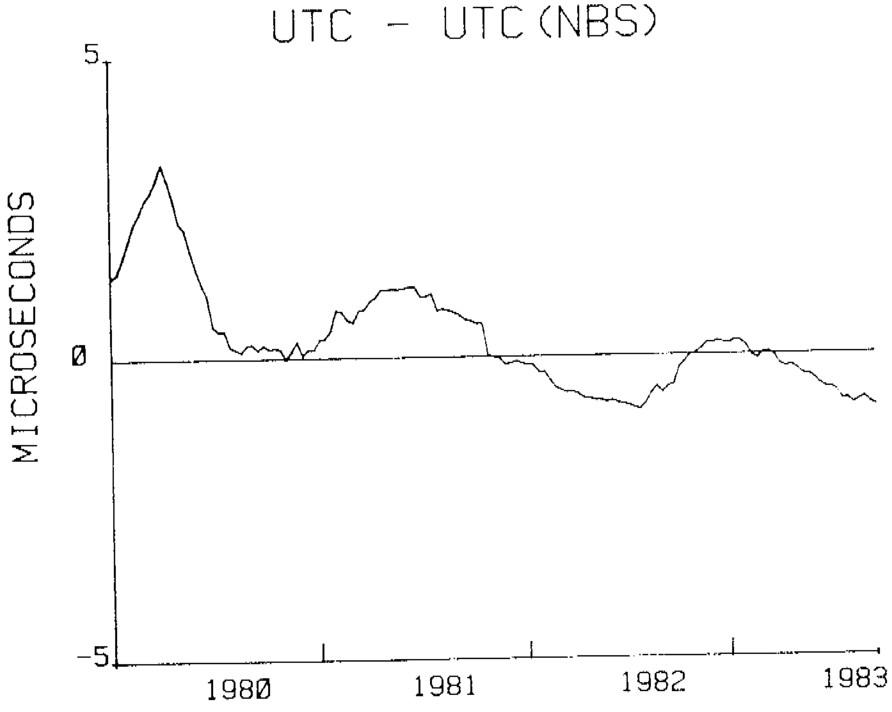

Figure 2. Universal Time Coordinated (UTC) minus UTC(NBS) via Loran-C.

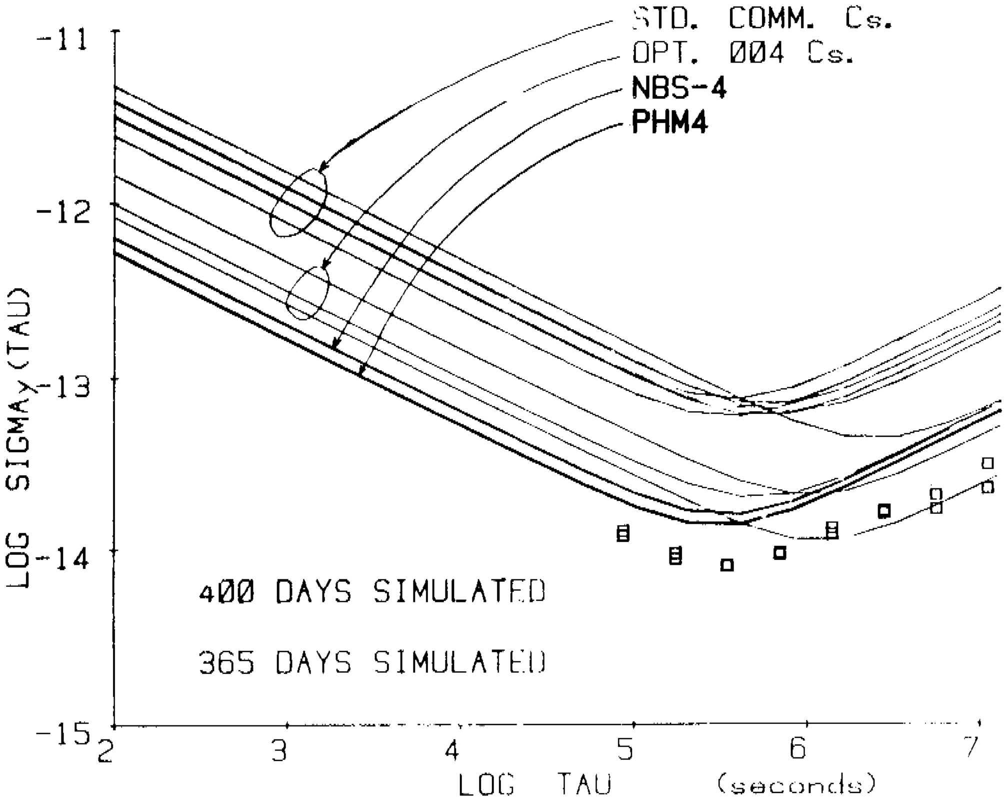

Figure 3. Frequency stability models of clocks in NBS ensemble. The squares are estimates of the stability of NBS.AT1 and UTC(NBS) via the NBS algorithm.

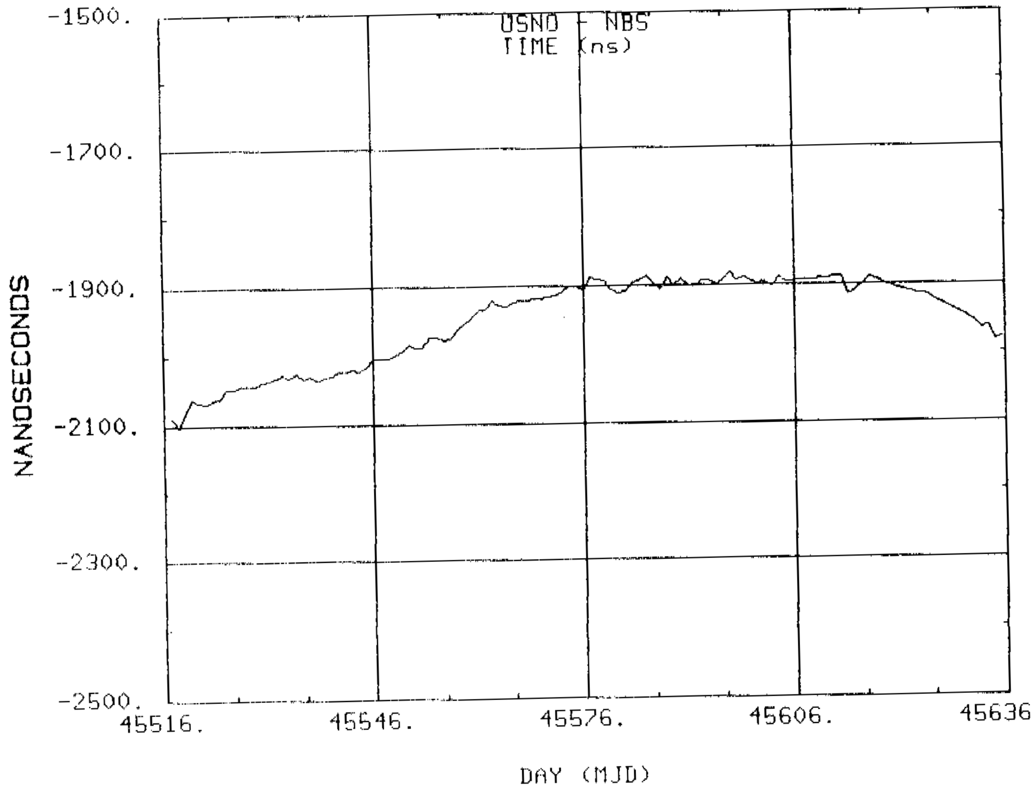

Figure 4. USNO master clock, UTC(USNO MC), minus UTC(NBS) via GPS in common-view (July through October 1983).

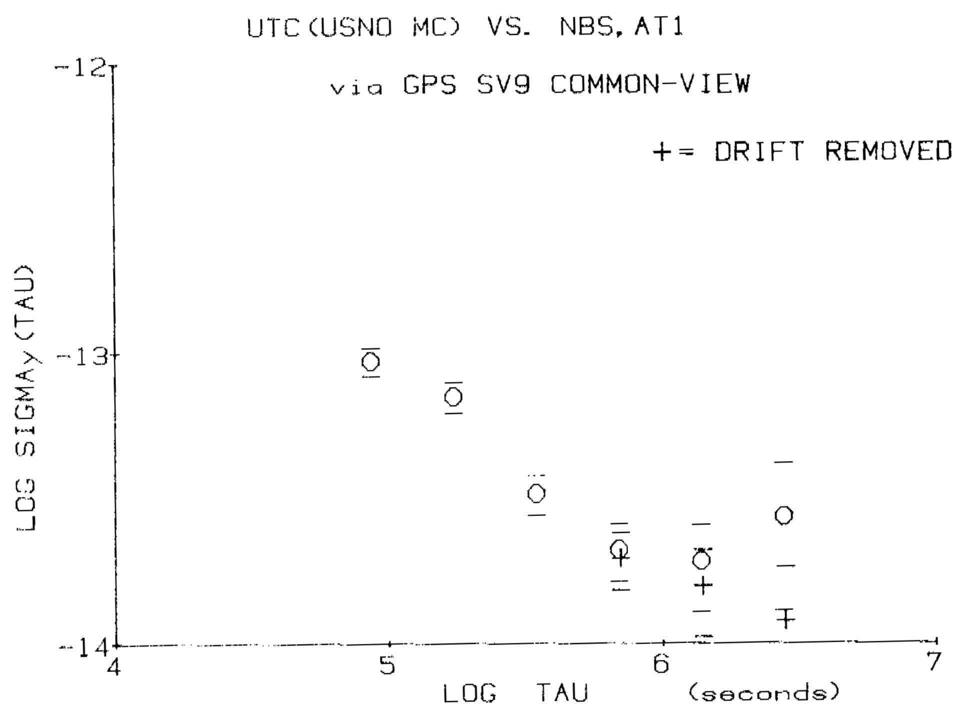

Figure 5. Frequency stability of UTC(USNO-MC) vs AT1 with and without an apparent frequency drift removed.

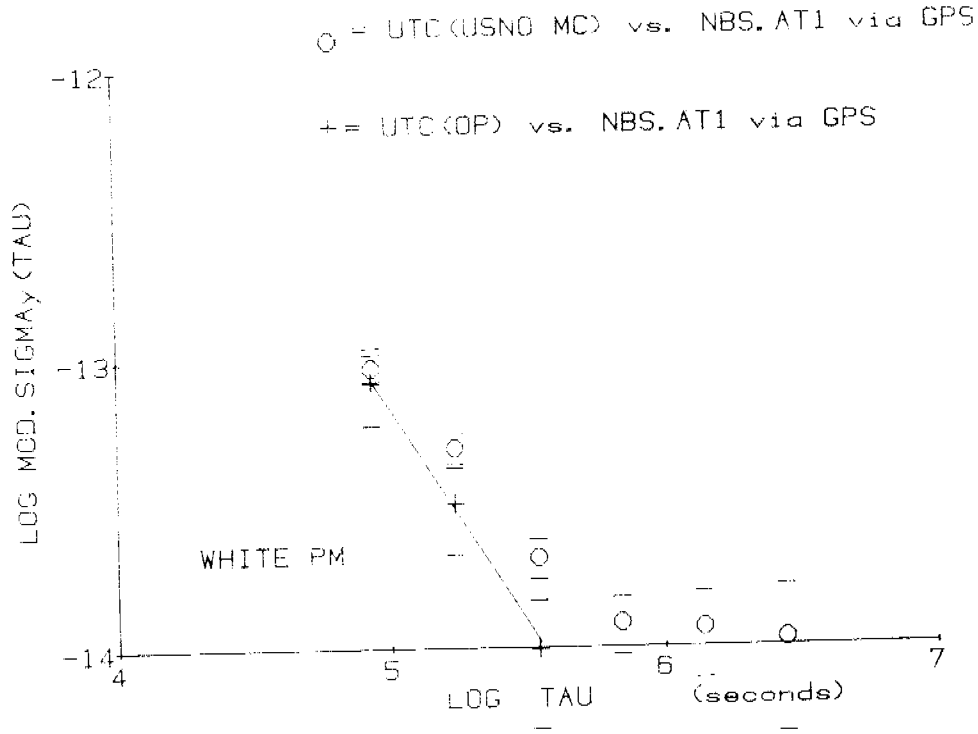

Figure 6. Frequency stability of NBS.AT1 vs. UTC(USNO-MC) and UTC(OP) via GPS in common-view using the modified $\sigma_y(\tau)$ analysis technique.

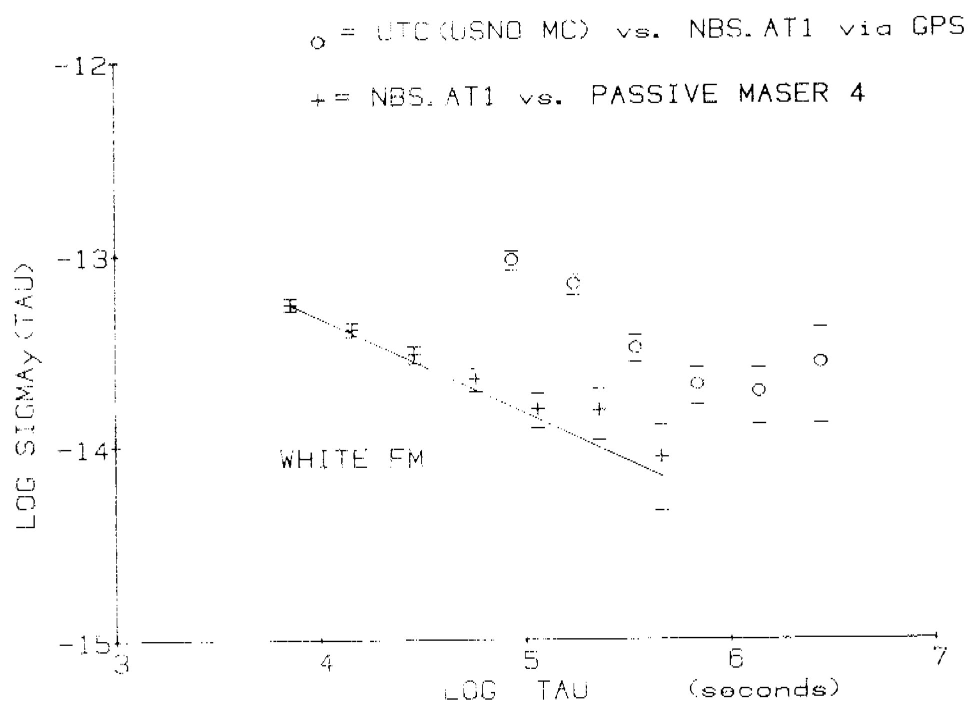

Figure 7. The frequency stability of NBS.AT1 vs. a passive hydrogen maser and vs. UTC(USNO-MC) via the GPS in common-view technique.

QUESTIONS AND ANSWERS

MR. WARD:

Sam Ward, Jet Propulsion Laboratory. When did you start using this smoother rate?

MR. ALLAN:

Basically, October of last year, all of this year. Roughly, about a year ago.

MR. WARD:

Well, as a matter of added infomation, we had been having a problem with hydrogen masers, and one of them in particular had been left open for an excessive period and it cooled down, and when it came back up it had a very high drift rate. Now, normally, this drift rate is around a few parts in 10^{15} per day; so we have been trying to use the G.P.S. to measure that drift rate. So you can see why we didn't like it being diddled.

MR. ALLAN:

That's right.

MR. WARD:

But we, indeed, found the rate, after about three months, had settled down to a rate that was approaching a part in 10^{14}; and before it was taken off the line last month, it had settled down to 3.5×10^{-15} per day.

MR. ALLAN:

In fact, J.P.L. was one of the driving forces why N.B.S. improved their performance.