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**ERRATA**



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# **ERRATA FOR THE 1994 PTTI PROCEEDINGS**

**DR. RICHARD L. SYDNOR**

**EDITORIAL COMMITTEE CHAIRMAN**

June 26, 1995

The enclosed paper superseded "ANTICIPATED UNCERTAINTY BUDGETS OF PRARETIME AND T2L2 TECHNIQUES AS APPLIED TO ExTRAS", pages 127 through 140. Several figures in this paper were omitted in the 1994 PTTI Proceedings.

# ANTICIPATED UNCERTAINTY BUDGETS OF PRARETIME AND T2L2 TECHNIQUES AS APPLIED TO ExTRAS

C. Thomas<sup>1</sup>, P. Wolf<sup>1,2</sup>, P. Uhrich<sup>3</sup>, W. Schäfer<sup>4</sup>  
H. Nau<sup>5</sup>, and C. Veillet<sup>6</sup>

<sup>1</sup>Bureau International des Poids et Mesures, Sèvres, France

<sup>2</sup>Queen Mary and Westfield College, London, United Kingdom

<sup>3</sup>Laboratoire Primaire du Temps et des Fréquences, Paris, France

<sup>4</sup>Institut für Navigation, Stuttgart, Germany

<sup>5</sup>Deutsche Forschungsanstalt für Luft und Raumfahrt e.V.,  
Oberpfaffenhofen, Germany

<sup>6</sup>Observatoire de la Côte d'Azur, Grasse, France

## Abstract

*The Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS, was conceived jointly by the European Space Agency, ESA, and the Russian Space Agency, RSA. It is also designated the 'Hydrogen-maser in Space/Meteor-3M project'. The launch of the satellite is scheduled for early 1997. The package, to be flown on board a Russian meteorological satellite includes ultra-stable frequency and time sources, namely two active and auto-tuned hydrogen masers. Communication between the on-board hydrogen masers and the ground station clocks is effected by means of a microwave link using the modified version for time transfer of the Precise Range And Range-rate Equipment, PRARETIME, technique, and an optical link which uses the Time Transfer by Laser Link, T2L2, method. Both the PRARETIME and T2L2 techniques operate in a two-directional mode, which makes it possible to carry out accurate transmissions without precise knowledge of the satellite and station positions.*

*Due to the exceptional quality of the on-board clocks and to the high performance of the communication techniques with the satellite, satellite clock monitoring and ground clocks synchronization are anticipated to be performed with uncertainties below 0.5 ns ( $1 \sigma$ ). Uncertainty budgets and related comments are presented.*

## INTRODUCTION

The Experiment on Timing Ranging and Atmospheric Sounding, ExTRAS, was conceived jointly by the European Space Agency, ESA, and the Russian Space Agency, RSA. It is also designated the "Hydrogen-Maser in Space/Meteor-3M project", and is scheduled for early 1997. The experiment calls for ultra-stable frequency and time sources, two active and auto-tuned hydrogen masers, to be flown on board a Russian meteorological satellite, Meteor-3M.

Communication between the on-board hydrogen masers and the ground stations is effected by a microwave link using the Precise Range And Range-Rate Equipment modified for time transfer, PRARETIME, technique, and an optical link which uses the Time Transfer by Laser Link, T2L2, method. The combination of ultra-stable time and frequency sources with precise and accurate tracking equipment should help to solve a number of scientific and applied problems in the fields of navigation, geodesy, geodynamics and Earth atmosphere physics. It should also allow timing measurements with accuracies never reached before.

## ON-BOARD HYDROGEN MASERS

Compared with other atomic frequency standards, passive hydrogen masers offer improved short-term stability<sup>[1]</sup>. They are generally used as short-term references in timing laboratories, but cannot serve as time-keepers because of the huge drift they generate over averaging times longer than several hours. However, recent developments of active hydrogen masers operating according to specific auto-tuning modes for the cavity reduce frequency drift while causing a negligible degradation of the short-term stability<sup>[2]</sup>. This type of hydrogen maser already contributes, on the ground, to short-term internal time comparisons and to long-term time keeping in national timing centres concerned with time metrology.

Rubidium and caesium clocks are currently used in navigation systems, for example in the Global Positioning System, GPS, where all Block II satellites are equipped with caesium standards. To date, no hydrogen maser has ever been flown with the exception of a hydrogen maser belonging to the Smithsonian Astrophysics Observatory which was sent into parabolic flight in 1976<sup>[3]</sup>. Space hydrogen masers are also planned as future on-board clocks for the Russian GLObal NAVigation Satellite System, GLONASS, in order to improve the short-term stability of the flying standards.

The active auto-tuned hydrogen masers scheduled for flight on Meteor-3M are a Russian-designed hydrogen maser, proposed by the Institute of Metrology for Time and Space, VNI-IFTRII, Mendeleev (Russia), and a Swiss Space Hydrogen Maser, SHM, proposed by the Observatoire de Neuchâtel, ON, Neuchâtel (Switzerland). These two units are of a weight ( $\leq 50$  kg), volume ( $\leq 0.1$  m<sup>3</sup>) and power consumption ( $\leq 60$  W) compatible with an on-board installation. In addition they will be compared continuously and are interchangeable. Their short-term stability is characterized by the Allan deviation given in Table 1.

Averaging time	Allan Deviation
$\tau/s$	$\sigma_y(\tau)$
1	$1.5 \times 10^{-13}$
10	$2.1 \times 10^{-14}$
100	$5.1 \times 10^{-15}$
1000	$2.1 \times 10^{-15}$
10000	$1.5 \times 10^{-15}$
100000	$\leq 1 \times 10^{-14}$

*Table 1: Allan deviation  $\sigma_y(\tau)$ , versus the averaging time  $\tau$ , of the Space Hydrogen Maser (SHM) developed by the Observatoire de Neuchâtel, ON, Neuchâtel (Switzerland), for flying on board Meteor-3M. Numbers are provided by Dr G. Busca, of the ON, in his proposal for ExTRAS (1993).*

The first consequence is that the comparison of ground clocks with the on-board hydrogen maser ensures access to a stable and slowly drifting time scale for synchronization of local

time scales used for real-time dating of events on the Earth. In a complementary process, the time scale to be delivered by the on-board clock can be closely steered in real-time on any reference time scale, such as a local representation of UTC, UTC(k), kept by laboratory k: for this purpose, it is sufficient to distribute, in the satellite message, a time correction between the on-board and ground time scales. The experiment ExTRAS thus serves all the functions of time dissemination.

The specifications of Table 1 have another impact on time metrology when flying such hydrogen masers on Meteor-3M. This is linked to particular features of the satellite orbit: its polar orbit and its altitude, of order 1000 km, lead to a period of revolution around the Earth of order  $T = 100$  min, and to possible observation of the satellite at least four times a day from any location on the Earth. The total error ( $1 \sigma$ ) accumulated by the on-board hydrogen maser during one revolution can be estimated as<sup>[4]</sup>:

$$\sigma \approx \sigma_y(\tau) \cdot T, \quad (1)$$

which leads to the value 12 ps. If two observations are distant by 3 hours, the error ( $1 \sigma$ ) accumulates to less than 50 ps.

It follows that comparisons between remote clocks on the Earth can be performed by differential observation of the time scale provided by the on-board hydrogen maser when it is visible from the stations. This is the clock transportation method, and there is no need to organize common views, as is done with GPS and GLONASS, the uncertainty caused by the on-board clock during its flight between the two stations being typically of order 50 ps.

To conclude, ExTRAS provides a means of time transfer based upon the transportation, via satellite, of an ultra-stable clock able to keep its time very precisely throughout the period of transportation. This time transfer method, the simplest imaginable, is thus of major interest to the timing community. Full advantage of the qualities of hydrogen masers on board Meteor-3M can be taken only if very accurate methods are used to ensure the connection between observing stations on the ground and the spacecraft. Specific features of two-direction links, such as via PRARETIME and T2L2 are discussed in the following sections.

## **PRARETIME: PRECISE RANGE AND RANGE-RATE EQUIPMENT, MODIFIED VERSION FOR TIME TRANSFER**

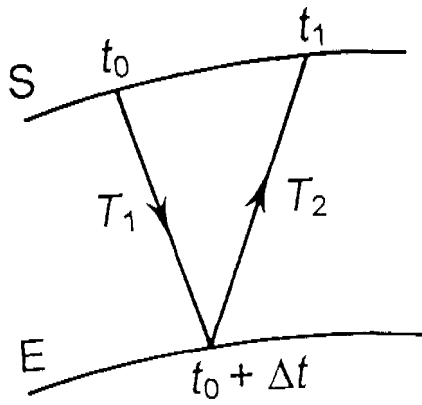
The Precise Range And Range-Rate Equipment, PRARE, is a high precision and fully automated facility for microwave link between clocks on board a satellite and ground stations. Its primary function consists of range and range-rate measurements, but a modified version of PRARE devoted to time transfer, PRARETIME, has also been developed. The modification concerns some hardware details and an additional time interval measurement at the ground station site. The PRARE equipment operates with a down-and-up link in the X-band (8489 GHz for down-link and 7225 GHz for up-link) between the ground and the satellite, together with a down-link in the S-band (2248 GHz)<sup>[5, 6, 7]</sup>. The PRARE X-band up-link exists only if the ground station is equipped with a ground transponder and its 60 cm parabolic dish. In this

case, the only one considered in this paper, the PRARE system operates in a two-way mode, which can be used for timing purposes such as:

- time comparisons between one ground clock and the on-board clock: this is known as satellite clock monitoring, and
- time comparisons between two ground clocks through transportation of the on-board clock: this is known as ground clock synchronization.

## Timing applications through ExTRAS via PRARETIME

### Satellite clock monitoring



A signal is emitted by the satellite S and retransmitted immediately by the Earth station E. The time interval  $t_{SE}$  between emission and reception on board the satellite,  $t_{SE} = t_1 - t_0$ , is recorded. The time difference between the clocks  $\Delta t$  is given by<sup>[8]</sup>:

$$\Delta t = t_{SE}/2 + \delta. \quad (2)$$

With  $T_1$  and  $T_2$  the individual transmission times for the down-link and the up-link, the time correction  $\delta$  is written as:

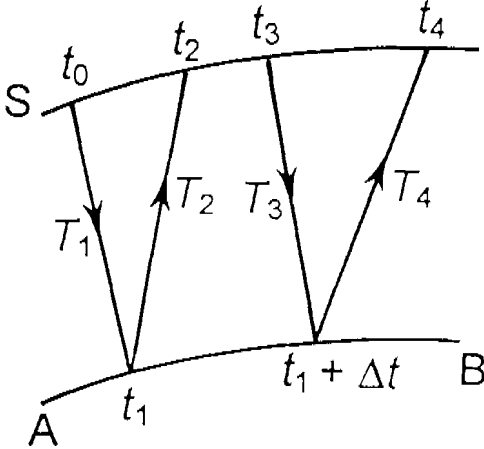
$$\delta = (T_1 - T_2)/2, \quad (3)$$

which may be expressed as<sup>[8]</sup>:

$$\delta = [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]/2 - \mathbf{v}_S(t_0) \cdot \mathbf{R}_{ES}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \quad (4)$$

where  $\delta_e$  and  $\delta_i$  are external (ionospheric and tropospheric) and internal (cables, ...etc) delays respectively, subscripts 'd' and 'u' refer to the down- and up-links,  $\mathbf{R}_{ES}(t_0)$  is the station to satellite vector at date  $t_0$ ,  $\mathbf{v}_S$  is the satellite velocity in a geocentric inertial frame and  $c$  is the speed of light in vacuum.

### Ground clock synchronization



The satellite S emits signals to each ground station A and B which are immediately re-transmitted to the satellite. Three time intervals are recorded by the satellite:

- $t_S = t_3 - t_0$ , the time elapsed between the emission of the two signals,
- $t_{SA} = t_2 - t_0$  and  $t_{SB} = t_4 - t_3$ , the times elapsed between the emission and reception on-board the satellite of the signals received in stations A and B.

The time difference between the ground clocks  $\Delta t$  is given by<sup>[8]</sup>:

$$\Delta t = (t_{SB} - t_{SA})/2 + t_S + \delta. \quad (5)$$

The time correction  $\delta$  is written as:

$$\delta = [(T_3 - T_4) - (T_1 - T_2)]/2, \quad (6)$$

where  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$  are the individual transmission times for the down-links and the up-links.

Using (4),  $\delta$  is expressed as:

$$\delta = [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]_B/2 - [\delta_{e,d} - \delta_{e,u} + \delta_{i,d} - \delta_{i,u}]_A/2 - \mathbf{v}_S(t_3) \cdot \mathbf{R}_{BS}(t_3)c^{-2} + \mathbf{v}_S(t_0) \cdot \mathbf{R}_{AS}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \quad (7)$$

in a notation following that of (4).

In (4) and (7) no range estimations are involved in terms of order  $c^{-1}$ , which is typical of a two-way method. Terms of order  $c^{-2}$  can amount to 300 ns and can be calculated at the picosecond level even with a poor knowledge of satellite ephemerides and velocity (accuracies of these quantities should be of order 12 m and 0.02 m/s respectively). Terms in  $c^{-3}$  contribute a few picoseconds.

It follows that the time comparison value between the ground clock and the on-board clock, or between the two ground clocks, can be deduced from measurements of time intervals on-board the satellite, and from the estimations of differential delays in the up- and down-paths. No accurate estimation of the range between the satellite and the station is needed.

It is important to note that tropospheric delays totally cancel in the up- and down-paths because the troposphere is a non-dispersive medium which yields the same delay for the PRARE up

and down carrier frequencies. In contrast, the ionosphere is a dispersive medium and the corresponding differential delays do not cancel in (4) and (7). The up- and down-links from the stations to the satellite do not necessarily pass through the same internal electronic circuits and cables, so internal differential delays remain in (4) and (7).

## Sources of uncertainties for timing applications through ExTRAS via PRARETIME

The uncertainties affecting timing observations come from the on-board hydrogen-maser, signal transmission through the atmosphere, and the equipment which is used to emit and transmit the signals. All the uncertainties given in the following are  $1 \sigma$  estimations: they are summarized in Table 2.

### Uncertainty due to the on-board hydrogen maser

The uncertainty brought by the on-board hydrogen maser is deduced from its stability. This is negligible for the quantities  $t_{SE}$ ,  $t_{SA}$ , and  $t_{SB}$  and thus has no impact on satellite clock monitoring. It must be taken into account, however, for the quantity  $t_S$  since this depends on the time duration which separates the observations of the satellite from the two stations being compared. A conservative estimate is of order 50 ps ( $1 \sigma$ ).

### Uncertainty on the atmospheric delay of the signal

The frequency separation between the S-band and X-band PRARE down-links makes it possible to measure the ionospheric delay of the signal. One expects a very low level of uncertainty, of order 20 ps ( $1 \sigma$ ), for the measurement of the difference between down and up ionospheric delays. For ground clock synchronization, this uncertainty appears twice (in quadratic).

### Uncertainty on the calibration of equipment

The on-board payload, the Earth stations, and the PRARETIME modems and counters must be very carefully calibrated before launch. One expects an uncertainty in the calibration of order 50 ps ( $1 \sigma$ ) for each of these elements. These uncertainties appear twice (in quadratic) for ground clock synchronization. However, the on-board payload is known to remain very stable between adjacent observations. It follows that the corresponding uncertainty partly disappears for ground clock synchronization. One estimates a total residual uncertainty of 20 ps ( $1 \sigma$ ) for this particular case.

The uncertainty associated with PRARETIME modems and counters arises from error sources such as instrumental delays (temperature, calibration of electronic components,  $C/N_0$  influence, ...etc), timer resolution, multipath transmission, and problems related to the antenna phase centre. It may not be possible to separate this uncertainty from those coming from the on-board payload and the Earth station calibrations.



## Uncertainty due to the links to local 1 pps signals

The PRARETIME technique only uses the high frequency (5 MHz) signals from the on-board and ground clocks. Time transfer, however, usually takes place between time scales which take the form of a series of local signals at 1 pulse per second, 1 pps. It is thus necessary to take into account uncertainties arising in the links to the local 1 pps signal. Passing from 5 MHz signals to 1 pps signals requires cables and electronic circuits for frequency division and pulse formation. It generates uncertainties which are generally estimated to be of order 300 ps ( $1 \sigma$ ). In the PRARETIME system, no 1 pps signal is physically available on board the satellite, so this class of uncertainty arises only in the timing circuitry of the ground stations.

## Anticipated uncertainty budgets for timing applications through ExTRAS via PRARETIME

The anticipated uncertainty budgets for satellite clock monitoring and ground clock synchronization are given in Table 2. Those parts of uncertainty arising from the method itself and from the links to the local 1 pps signal are shown separately. The uncertainty of the method itself amounts to 89 ps ( $1 \sigma$ ) for satellite clock monitoring, and 117 ps ( $1 \sigma$ ) for ground clock synchronization. The total uncertainties of 313 ps and 440 ps ( $1 \sigma$ ), largely dominated by uncertainties due to local links to the 1 pps signals in the ground stations, are well below 0.5 ns ( $1 \sigma$ ), which represents a major improvement for time metrology. In addition, the PRARETIME instrument makes it possible to disseminate any time scale maintained on the ground thanks to additional information contained in the S-band downward signal. The achievable uncertainty of this particular timing mode is to be further investigated.

## T2L2: TIME TRANSFER BY LASER LINK

The Time Transfer by Laser Link, T2L2, technique provides an optical time link between the on-board hydrogen masers and ground clocks. It may be seen as a continuation of the LASER Synchronization from Satellite Orbit (LASSO) technique, which was successfully carried out between the McDonald Observatory in Texas, USA, and the Observatoire de la Côte d'Azur, France, in 1992, through the geostationary satellite Meteosat-P2. Very few LASSO time comparison points were obtained during this experiment<sup>[9, 10]</sup>. They show a precision of order 200 ps, which is a major improvement over other methods, but, unfortunately no accuracy evaluation has been made so far now. The LASSO experiment also showed the possibility of monitoring the on-board clock with a precision of order 50 ps. This could serve time dissemination purposes, but again the corresponding uncertainty has not yet been evaluated.

The specific and principal difficulties of the LASSO experiment are:

- the rather poor stability of the oscillator on board Meteosat-P2. The consequence is that the stations to be synchronized must both shoot the laser onto the satellite within a time window equivalent of common-view conditions.
- the weather conditions must be excellent to avoid excessive light dissipation which prevents the ground observer from counting an adequate number of return photons.

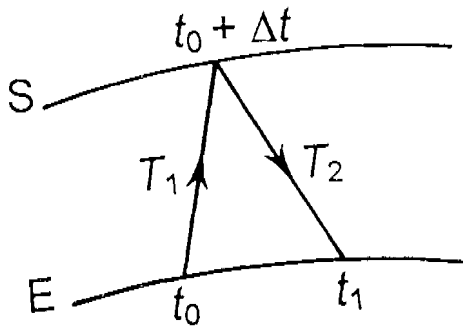
Problems with on-board oscillators should largely be resolved using T2L2, because ultra-stable sources are used. In addition, as the Meteor-3M satellite orbit is far lower altitude than that of the geostationary Meteosat-P2 satellite, the effects of weather conditions should be less severe.

The T2L2 equipment can easily be installed on board the satellite. The principal elements in this equipment are a light detector linked to an event timer, and an Optical Retroreflector Array (ORA). The Earth sites concerned with this experiment require to have at their disposal facilities for high-power pulsed-laser shooting, together with a telescope. Very few sites meet these requirements and it may be necessary to increase the number of laser stations to take full advantage of the ExTRAS experiment.

## Timing applications through ExTRAS via T2L2

The T2L2 time transfer system can serve satellite clock monitoring and remote ground clock synchronization according to schemes symmetrical to those already presented for the PRARETIME technique.

### Satellite clock monitoring



A signal is emitted by the Earth station E with  $T_1$  and is reflected immediately by the satellite S. The time interval  $t - ES$  between emission and reception at the station,  $t_{ES} = t_1 - t_0$ , is recorded. The time difference between the clocks  $\Delta t$  is given by<sup>[8]</sup>:

$$\Delta t = t_{ES}/2 + \delta. \quad (8)$$

$T_2$  the individual transmission times for the up-link and the down-link, the time correction  $\delta$  is written as:

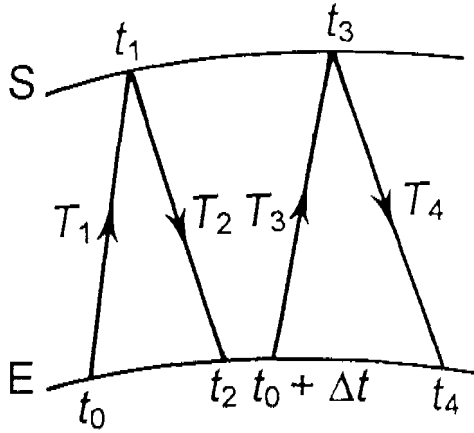
$$\delta = (T_1 - T_2)/2. \quad (9)$$

Using (4), this is expressed as:

$$\delta = [\delta_{i,u} - \delta_{i,d}]/2 + \mathbf{v}_E(t_0) \cdot \mathbf{R}_{ES}(t_0)c^{-2} + \mathbf{O}(c^{-3}), \quad (10)$$

with notations similar to that of (4).

## Ground clock synchronization



Laser pulses are emitted from the ground stations A and B, and reflected by the satellite S. Three time intervals are recorded:

- $t_S = t_3 - t_1$ , the time elapsed between the reflection of the two signals (recorded on the satellite),
- $t_{AS} = t_2 - t_0$  and  $t_{BS} = t_4 - t_0 - \Delta t$ , the times elapsed between the emission and reception (recorded in stations A and B).

The time difference between the ground clocks  $\Delta t$  is given by<sup>[8]</sup>:

$$\Delta t = (t_{AS} - t_{BS})/2 + t_S + \delta. \quad (11)$$

The time correction  $\delta$  is written as:

$$\delta = [(T_1 - T_2) - (T_3 - T_4)]/2, \quad (12)$$

where  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$  are the individual transmission times for the up-links and the down-links.

Using (10), this is expressed, with a notation similar to that of (4), as:

$$\delta = [\delta_{i,u} - \delta_{i,d}]_A / 2 - [\delta_{i,u} - \delta_{i,d}]_B / 2 + \mathbf{v}_A(t_0) \cdot \mathbf{R}_{AS}(t_0) c^{-2} - \mathbf{v}_B(t_0 + \Delta t) \cdot \mathbf{R}_{BS}(t_0 + \Delta t) c^{-2} + \mathbf{O}(c^{-3}). \quad (13)$$

In (10) and (13) no range estimations are involved in terms of order  $c^{-1}$ , which is again typical of a two-way method. Terms of order  $c^{-2}$  may amount to 20 ns and can be calculated at the picosecond level even with a poor knowledge of satellite-station ranges and station velocities in an inertial frame (accuracies in these quantities should be of order 100 m and 0.02 m/s respectively). Terms in  $c^{-3}$  contribute a few picoseconds.

It follows that the time comparison value between the ground clock and the on-board clock, or between the two ground clocks, can be deduced from measurements of time intervals on-board the satellite and in the ground stations, and from the estimations of differential delays in the up- and down-paths. No accurate estimation of the range between the satellite and the station is needed.

It is important to note that atmospheric delays totally cancel in (10) and (13) since the T2L2 up and down frequencies are equal. The up- and down-links from the stations to the satellite do not necessarily pass by the same internal electronic circuits and cables, so internal differential delays remain in (10) and (13).

## Sources of uncertainties for timing applications through ExTRAS via T2L2

The uncertainties affecting timing observations come from the on-board hydrogen-maser, and from the different equipment which is used for emitting and reflecting the optical pulses. Similar comments apply to the estimation of uncertainties as were given for PRARETIME, but two points should be noted:

- no uncertainties are to be taken into account for atmospheric delays, and
- only counters, and no modems, are used in the T2L2 technique, which reduces the corresponding uncertainty to 10 ps ( $1 \sigma$ ).

## Anticipated uncertainty budgets for timing applications through ExTRAS via T2L2

The anticipated uncertainty budgets are given in Table 3 for satellite clock monitoring and ground clock synchronization through ExTRAS via T2L2. Again, the parts of the uncertainty coming from the method itself and from the links to the local 1 pps signals are separated. One obtains an uncertainty for the method of 71 ps ( $1 \sigma$ ) for satellite clock monitoring, and 90 ps ( $1 \sigma$ ) for ground clock synchronization. The total uncertainties of 308 ps and 434 ps ( $1 \sigma$ ) are again largely dominated by terms arising from the local links to the 1 pps signals in the ground stations.

To conclude, the estimates of the T2L2 anticipated uncertainty budgets are very close to those obtained with PRARETIME: the main uncertainty is not due to the method itself, and the overall accuracy of time transfer is characterized by an uncertainty well below 0.5 ns ( $1 \sigma$ ). In terms of the method itself, T2L2 is slightly more accurate than PRARETIME and may be considered as the reference technique. In addition, studies about the calibration of the on-board payload are being carried out, which may show that the tentative estimate of the corresponding uncertainty, which is given in Table 3, is too pessimistic. Unfortunately, however, T2L2 depends on clear weather and on specific laser equipment of a kind not available in many time laboratories.

## CONCLUSIONS

The ExTRAS experiment could provide a time transfer method based on satellite transportation of ultra-stable hydrogen masers. Two-way connections with the satellite are ensured by two techniques, PRARETIME and T2L2, both potentially accurate at a level about 300 ps ( $1 \sigma$ ) and both able to provide satellite clock monitoring and ground clocks synchronization. This could represent a very interesting improvement in the accuracy of time transfer methods when compared to GPS common views, achieved with an uncertainty of order 2 ns ( $1 \sigma$ ) over short distances ( $\leq 1000$  km) and 5 ns ( $1 \sigma$ ) over long distances ( $\geq 5000$  km), and to Two-Way Satellite Time Transfer via geostationary satellite, for which the best accuracy achieved is at present 1.7 ns ( $1 \sigma$ ). This would be of major interest for time metrology, in particular for comparison of future clocks designed for frequency uncertainties of some parts in  $10^{16}$ .

## REFERENCES

- [1] VANIER J., and AUDOIN C., *The Quantum Physics of Atomic Frequency Standards*, Adam Hilger, 1989.
- [2] DEMIDOV N.A., EZHOV E.M., SAKHAROV B.A., ULJANOV B.A., BAUCH A., and FISHER B., *Proc. 6th EFTF*, p 409, 1992.
- [3] VESSOT R.F.C., MATTISON E.M., NYSTROM G.U., COYLE L.M., DECHER R., FELTHAM S.J., BUSCA G., STARKER S., and LESCHIUTTA S., *Proc. 6th EFTF*, p 19, 1992.
- [4] ALLAN D.W., *IEEE Trans. on Ultr. Ferr. and Freq. Cont.*, 34, 6, p 647, 1987
- [5] SCHÄFER W., and WILMES H., *Workshop on Advances in Satellite Radio Tracking*, 1986, Austin, Texas, USA.
- [6] SCHÄFER W., *Proc. 6th EFTF*, p 41, 1992.
- [7] HARTL P., SCHÄFER W., CONRAD M., REIGBER C., FLECHTNER F., HÄRTING A., and FÖRSTE C., *Workshop on Navigation Satellite Systems*, 1994, ESOC, Darmstadt, Germany, 1994.
- [8] PETIT G., and WOLF P., *Astronomy and Astrophysics*, 286, p 971, 1994.
- [9] GAIGNEBET J., HATAT J.L., MANGIN J.F., TORRE J.M., KLEPCZYNSKI W., MCCUBBIN L., WIAN T J., and RICKLEFS R., *Proc. 25th PTTI*, p 367,1993.
- [10] LEWANDOWSKI W., PETIT G., BAUMONT F., FRIDELANCE P., GAIGNEBET J., GRUDLER P., VEILLET C., WIAN T J., and KLEPCZYNSKI W.J, *Proc. 25th PTTI*, p 357,1993.

Table 2: Anticipated uncertainty budgets for satellite clock monitoring and ground clock synchronization through ExTRAS via PRARETIME. All uncertainties are in picoseconds and correspond to a 1 sigma statistical analysis. No uncertainties on time comparison arise from range estimation.

Uncertainty source	Satellite clock monitoring	Ground clocks synchronization
Range	0	0
Hydrogen maser	0	50
Atmospheric delay	20	$20\sqrt{2}$
On-board payload	50	20
Earth station	50	$50\sqrt{2}$
Modems & counters	50	$50\sqrt{2}$
Method accuracy	89	117
Ground link to 1 pps	300	$300\sqrt{2}$
Total accuracy	313	440

Table 3: Anticipated uncertainty budgets for satellite clock monitoring and ground clocks synchronization through ExTRAS via T2L2. All uncertainties are in picoseconds and correspond to a 1 sigma statistical analysis. No uncertainties on time comparison arise from range estimation and atmospheric delays.

Uncertainty source	Satellite clock monitoring	Ground clocks synchronization
Range	0	0
Hydrogen maser	0	50
Atmospheric delay	0	0
On-board payload	50	20
Earth station	50	$50\sqrt{2}$
Counters	10	$10\sqrt{2}$
Method accuracy	71	90
Ground link to 1 pps	300	$300\sqrt{2}$
Total accuracy	308	434

## QUESTIONS AND ANSWERS

**SIGFRIDO M. LESCHIUTTA:** I was saying that we shall aim to the 10 ps resolution. So, this experiment is aiming to 300 ps.

**CLAUDINE THOMAS (BIPM):** Maybe I must add that funding is not yet voted for this experiment. So, I'm not so sure it will happen, but let's hope.

# **ERRATA FOR THE 1994 PTTI PROCEEDINGS**

**DR. RICHARD L. SYDNOR**

**EDITORIAL COMMITTEE CHAIRMAN**

February 14, 1996

The enclosed papers supersedes those published in the 1994 PTTI Proceedings. Several figures were inadvertently omitted by the printing subcontractor. These papers are reprinted in this errata in the format intended by the respective authors.



# DoD PTTI Report

CAPTAIN RICHARD E. BLUMBERG  
Superintendent  
United States Naval Observatory  
Washington, DC

## Abstract

*The widespread application of Precise Time and Time Interval (PTTI) in modern electronic systems has been rapidly expanding. This growth reflects the importance of PTTI to many advanced systems. Precise time is closely related to precise distance measurements, the coordination of remote actions over extended periods of time, and the better utilization of the frequency spectrum. DoD Instruction 5000.2 emphasizes the need for a common time reference (The USNO Master Clock) for these systems of vital interest to our security. This report will present the results of the Annual PTTI Summary which describes the utilization of PTTI among the different components of the Department of Defense and highlight areas of primary interest and concerns.*

It's a pleasure to once again address you this morning. I'm still tickled over the award presentation earlier this morning. It's well deserved and always nice to get recognition from your peers. And I'm honored to have had the opportunity to present the award in their behalf.

What I would like to do is talk a little bit about major PTTI accomplishments in '94 (Figure 1), where we're headed, and where you can help us in terms of PTTI. Validation of requirements was a significant effort last year, particularly in this day and age of downsizing of resources. Everything is tied back to a requirement; and it's absolutely vital that every one of those requirements be stated and documented in order to go on from there. I'll talk a little bit about improvements to the Master Clock and then to two-way satellite time transfer. With regard to requirements (Figure 2), we took the 1990 survey as a baseline, and essentially re-validated that. In the re-validation process, we determined what the requirements really were for precise time and time interval and who our customers are out there — who uses it and of those who use it who don't recognize that they use it (which is a big problem in precise time). As Mr. McNeff stated, it's free, it's available anytime you want it; you just don't appreciate what's behind that timing signal. Our requirements have been validated by the Oceanographer of the Navy and have been submitted to the Office of the Secretary of Defense. So the requirements are, in fact, entered into the official DoD requirements process, covering not only Navy, but also the Air Force and Army requirements as well.

Improvements to the Master Clock (Figure 3): We are continuously improving the Master Clock. The big improvements for the previous year, a plus year, were replacing a number of the older 5061s with the newer HP 5071 cesium beam clocks. There are 10 hydrogen masers which have been incorporated into the time scale. The biggest comment I could say

on the Master Clock is that the effects of the improvements to the Master Clock can be seen by the contribution of the U.S. Naval Observatory (USNO) to the Bureau International des Poids et Mesures (BIPM), changing to 38 percent from last year's 20 percent. This significant improvement, is largely due to the better stability and, I should say, maybe the better reliability, of these clocks. We retain many of the 5061s, as they're still providing accurate, precise time, and we will continue to keep these clocks in the time scale as long as they continue to perform.

Keeping time is one thing, getting it out to the people who need it is another issue altogether. It doesn't do us any good to have the best time in Washington, D.C., if we can't disseminate it. We have made some significant improvements in the two-way satellite time transfer (Figure 4) this year. The technology transfer from the Naval Research Laboratory (NRL) of their modem to the commercial market was a big accomplishment. These modems are, in fact, operating much better than previously expected. Certainly the production models are really doing the job that they were designed to do.

We've been using the Defense Satellite Communication System (DSCS) for time transfer. It has been working exceptionally well. We have also been doing some experiments with commercial satellites as well. You will hear early in the program discussions of two of the calibration trips, one to Europe, between some of the laboratories in Europe, as well as a trip to the West Coast, using satellite two-way time transfer and an ensemble of clocks from the USNO.

Now, with regard to some of the newer issues in '94 (Figure 5), we are trying to tell our story to the people who need it. We did strengthen the master navigation plan. The reference for the wide-area augmentation system (WAAS) of the FAA will be UTC(USNO), the same reference that is used for the GPS system. So we will have again a single timing reference for both the FAA wide-area augmentation system and the GPS system, itself.

With regard to the GPS monitor station upgrade: By creating an independent clock ensemble at each of the GPS monitoring stations, we will allow the GPS operational community to detect immediately if they have a problem, because they will have the capability of an independent timing signal with which to compare the satellite performance with the monitor station timing signal. This program is underway. You will hear a little bit more about that later on, as well. Development of ultra-high precision timing reference stations at a number of special sites is also continuing worldwide.

Continuing on with accomplishments for '94 (Figure 6): The NATO standard agreement, STANAG 4430, on precise time and frequency interface for NATO was signed. It uses UTC(USNO), tied to the BIPM, as the standard for NATO operations. In support of DISA and the DSCS, as LORAN is shifting from U.S. control to European and Japanese control, USNO is helping to coordinate the timing signals for those systems at the local levels. Our role, particularly in the European area, is to provide some atomic clocks during that transition period, to ensure that timing — again, particularly in Europe — is maintained without interruption until alternate sources are provided. Some cesium clocks have been loaned to the Defense Satellite Communication System so that their timing could be maintained to a standard time. USNO has also transferred clocks to the Autodyn system for the same sort of function — to provide a standard to compare their time to ours.

One of the other items that I wish to stress is the fact that what has been accomplished has been done in the face of DoD downsizing. Our resources are really getting smaller. One of the keys to being able to accomplish those things that I showed for '94 have been the people who have been involved in the programs, and their efforts to get the job done, and to do it on a shoestring, so to speak. Keep in mind, as we will talk a little bit about these things later on in the conference, that we are facing downsizing reduction in the funds that not only buy hardware and improve the software, but also in the number of people who are able to perform these functions. And it's really vital that the folks in this room carry the message of PTTI.

Some of the functions and objectives of the PTTI manager are shown in Figures 7 and 8, respectively. This is a slide from last year, but I wanted to bring it back this year because it still applies. We need to ensure the uniformity of PTTI. We're doing that and working continuously to tell the story that all the communication and navigation systems need to be tied into one standard for time. I can't imagine a more chaotic situation than to have two timing standards and have them off by even a few nanoseconds. It would just create a nightmare. And again, most of you in here appreciate that. But we really need to get that message to the program managers and project managers, both in the commercial market as well as in the DoD, and ensure that they pay attention to the timing signals within their systems.

The requirements process which we went through last year did a good scrub on the requirements. But I'll guarantee you that there are many that have emerged since then that we are not aware of and have not begun to even look at in terms of their impact. The most stringent requirement that came out of that, potentially a future requirement at the 100 picosecond ("ps") level. If we're going to push to that level, certainly the Observatory needs to have a tenfold better capability, in-house, so that we can transfer time to that 100 ps level to those customers. We aren't there yet. We need to get there.

And that leads into the necessity for research. Such things as the mercury ion device — we have three of those that we are using and will add them into the time scale in the near future. It is still an R&D effort. We are still not certain exactly whether the mercury ion device is the device of the future or will allow us to approach that 100 ps level. But again, industry is looking in that direction, and I think we will push that technology edge here in the near future.

Adequate infrastructure support is really a problem in the downsizing world. As I alluded a little earlier, our dollars that were there two or three or four years ago are not there now. We continue to decrease and lose funding. We aren't seeing the impacts yet; the 5071s are brand new clocks, and there is very little maintenance required for them. But in the out years, I have concerns on the funding levels. Will we be able to maintain the infrastructure and the number of pieces necessary to keep the Master Clock ensemble accurate as well as reliable?

Concerning the utilization of PTTI resources: We work very closely with the GPS in two ways, operations and development. We need to continue similar cooperative efforts for PTTI resources in other areas such as fleet support and planning conferences. There is also a particular problem in the training area. The training in precise time and the ability to maintain equipment on site at the various stations is a concern. In all of our training courses, particularly in the DoD, the emphasis is to minimize the training pipeline and get people through as quickly as you can. Timing is certainly one of those things that is frequently overlooked. It's an

issue with which we continually do battle. We will continue to try to strengthen the training opportunities in PTTI.

That's a quick and dirty overview of the highlights for '94. The challenges for '95 are even more severe in terms of our resources. I'm happy to report that right now we're able to protect our people, who are our most valuable resource. Conversely, our people will then be challenged to continue to do more with less. We've heard it for years; it is a reality today. It certainly is a reality at the Observatory.

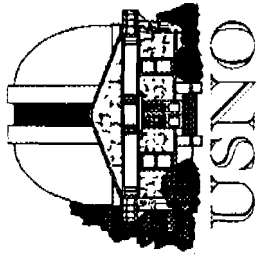
## QUESTIONS AND ANSWERS

**MR. KEATING:** This is not so much a question as a comment. I just want to reiterate Capt. Blumberg's comment about training, because I have actually listened to some conversations over a telephone to remote locations such as Hawaii and the Far East. And when you tell a person to move his clock ahead by two microseconds, 50 percent of the time the person on the other end causes actions which moves the clock in the exact opposite direction. And while that could be considered funny, when you're trying to maintain timing synchronization, that's a disaster. So I just want to emphasize that if you're a manager, don't downplay the need for training of your people.

**RAYMOND CLAFFIN (CLAFFIN ASSOCIATES):** Do you see in the new Congress any chance that this type of scientific military endeavor is going to receive any additional funding? Because, your needs really aren't as big as that of some of the other programs.

**CAPT. BLUMBERG:** That's one of our biggest problems, we are not as big as other programs and don't get the visibility that a lot of other programs do get. But I am a little optimistic that we will see the DoD budget grow in the future. How long it will take and at what point it does really benefit us is a real question mark. I mean, we have some serious problems across the board within DoD in terms of funding capabilities of getting our ships to sea, getting them properly manned, getting the personnel trained. And unfortunately, as I mentioned earlier, the timing is lost a lot of times in the hustle and bustle in trying to get things done. And so, again, it's our role in here as program managers, certainly my role, to promote timing with my resource sponsor and get him to promote within the Navy and the DoD to try to get the additional funding we need to get on with it.

So in answer to your question, I don't know specifically whether I can be optimistic or not. But I at least feel that we have an opportunity now to fight for a small share anyway.



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## **Major Accomplishments in 1994**

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- ★ **Validation of PTTI Requirements**
- ★ **Improved DoD Master Clock**
- ★ **Improvements to Two Way  
Satellite Time Transfer**



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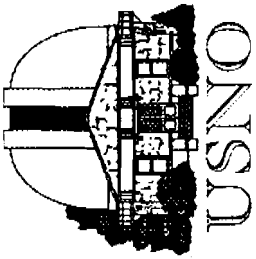
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# Validation of PTTI Requirements

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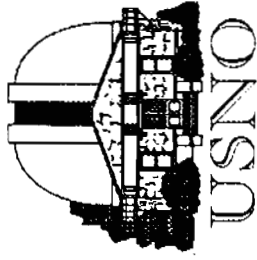
- ★ Original Survey made 1990
- ★ Contacted past respondents
- ★ PTTI Requirements Validated by OP096



# Improved DoD Master Clock System

- ★ Replaced inventory of aging HP5061 clocks
- ★ Added HP5071
- ★ As of May 1994, 78 Clocks in Time Scale
  - 44 HP5071
  - 24 HP 5061
  - 10 Hydrogen Masers
- ★ Increased USNO contribution to BIPM





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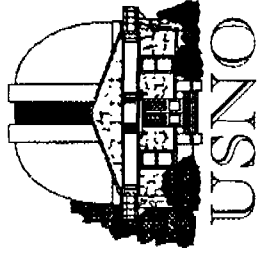
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## **New Initiatives in 1994**

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- ★ **Strengthen PTTI Input to Master Navigation Plan (MNP)**
- ★ **Reference for WAAS of FAA**
- ★ **GPS Monitor Station Upgrade**
- ★ **Development of UHPTRS**



## Other Accomplishments

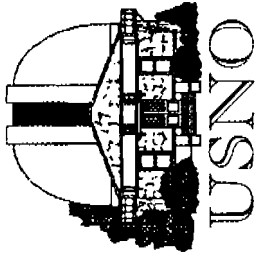
### ★ STANAG 4430

→ Precise Time & Frequency Interface for NATO

### ★ Support to DISA/DSCS

→ Clock Loans

### ★ Transfer of clocks to Autodin



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## Other Accomplishments

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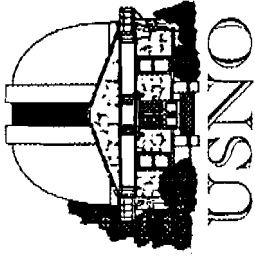
★ **STANAG 4430**

→ Precise Time & Frequency Interface for NATO

★ **Support to DISA/DSCS**

→ Clock Loans

★ **Transfer of clocks to Autodin**



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## Functions of PTTI Manager

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- ★ Insure uniformity of PTTI operations
- ★ Derive & Maintain Standards of PTTI
- ★ Prepare Annual Summary of PTTI Requirements
- ★ Coordinate/Monitor DoD PTTI Research Programs



## Objectives for PTTI Managers

- ★ Encourage adequate infrastructure support
- ★ Assist with negotiation of MoA and ISA to utilize PTTI resources effectively
- ★ Support DoD PTTI Planning Conferences
- ★ Promote DoD-wide PTTI Training opportunities

# Navy PTTI Report

CDR. JIM BURTON  
United States Navy

## Abstract

*The U.S. Naval Observatory is charged under Department of Defense (DoD) instruction 5000.2 with the responsibility for maintaining the timing standard in support of all DoD operations. Accomplishment of this task involves generating a time reference and then disseminating the Precise Time and Time Interval (PTTI) information to users within, as well as outside, DoD. A major effort has been undertaken by Navy scientists in recent years to upgrade and improve these services. Understanding the characteristics of atomic clocks, such as hydrogen masers, cesium beam frequency standards, and stored ion devices, is a prerequisite for modelling their performance and developing the most stable time reference possible. Algorithms for optimum clock ensembling and precision clock steering must be developed to ensure the stability of the time reference. Implementing new methods for time transfer, such as two-way satellite time transfer and laser ranging, will lead to improved accuracies to less than one nanosecond. In addition, the determination of astronomical time based on the Earth's rotation and definition of parameters for the position of the poles, enable the correction of the dynamical reference frame of Earth-orbiting satellites to an inertial reference frame, which is needed to improve the precision of satellite orbits. Current and planned initiatives in PTTI within the Navy, such as those listed above, are described.*

It is a great pleasure to address you this morning. I'm Jim Burton. I'm the GPS Action Officer for N6 and I am the U.S. representative to a NATO subcommittee on navigation. Ron Beard is also a member of this NATO subgroup. Today, I will talk very briefly about Navy-funded initiatives concerning work in PTTI (Figure 1).

There are three major achievements which I will address today:

- a) the GPS monitor station upgrade;
- b) the technology transfer of the modem that NRL developed; and
- c) the USNO Time Service Substation being rebuilt in Florida.

First, the GPS monitor station upgrades (Figure 2). When the upgrades are completed, each monitor station will be an ensemble of three cesium clocks, one of which will be a standard that's connected to the USNO through a two-way time transfer. As we collect the data from this ensemble and compare it to the existing operations, it will enable us to better model the clock rate errors and separate the clock and ephemeris errors a little bit better than is being done right now. This is all part of Navy initiatives to improve the accuracy of GPS and the integrity as well.

With the third clock that we'll be installing in each of the monitor stations, we'll have the capability to work independently of the two clocks that are currently operating within the monitor station. But even if it's operating independently, it will enable us to gather the data and do the diagnostics to better model the system for accuracy improvements in the future.

Secondly, NRL developed a pseudorandom noise time transfer modem (Figure 3) for the basic requirement of providing a communications capability besides just passing time pulses back and forth through the modem. It also gets a U.S. vendor into the market, so we are not relying on vendors from Germany; now we have Allen Osborne and Associates as the American vendor.

Finally, concerning the restoration of the USNO Time Service Substation (Figure 4) which was destroyed in Hurricane Andrew, a couple of years back, it is basically restored. It is going through the final stages of testing before it's back on line as a fully certified backup.

Since I'm here to replace Dave Markham, who was not supposed to be here, I will be happy to answer any questions -- or at least point them in the right direction.

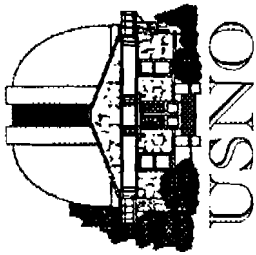
**DAVE MARKHAM:** Let me elaborate on Cdr. Burton's last comment. Those of you who didn't hear the story yet, I was supposed to be in Bahrain today. But unfortunately through a "snafu," as we say in the Navy, my orders and tickets were withdrawn and I'm here instead. He was gracious enough to stand in for me and give the presentation that I was supposed to give. So I thank him and I appreciate your support, Jim.



## Major Achievements

- ★ GPS Monitor Station Upgrade funded
- ★ Technology Transfer of NRL developed modem to Allen Osborne Assoc., Inc.
- ★ NOTSS restored to back-up status after Hurricane Andrew





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# GPS Monitor Station Upgrade

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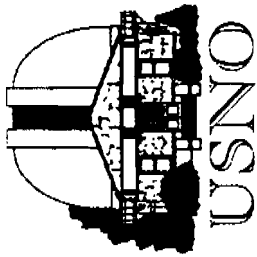
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- ★ Ensemble of 3 Cesium Clocks
- ★ Independent Time Transfer  
via TWSTT
- ★ Diagnostics



# Technology Transfer of NRL Developed Modem

- ★ NRL developed PRN Time Transfer Modem
- ★ Communications Capability
- ★ Transferred to Allen Osborne Associates, Inc..



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# NOTSS Restoration

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- ★ Buildings rebuilt
- ★ New Antenna under construction
- ★ Clock System being upgraded
- ★ Back-up Status being tested

# FINE TUNING GPS CLOCK ESTIMATION IN THE MCS

Capt Steven T. Hutsell, USAF  
2d Space Operations Squadron  
300 O'Malley Avenue Suite 41  
Falcon AFB CO 80912-3041

## Abstract

*With the completion of a 24 operational satellite constellation, GPS is fast approaching the critical milestone, Full Operational Capability (FOC). Although GPS is well capable of providing the timing accuracy and stability figures required by system specifications, the GPS community will continue to strive for further improvements in performance.*

*The GPS Master Control Station (MCS) recently demonstrated that timing improvements are always possible, provided we don't sacrifice system integrity in the process. The most recent improvements have concentrated on a re-evaluation of the MCS Kalman Filter's Continuous Time Update Process Noises, also known as  $qs$ . Rubidium (Rb)  $qs$  received notable (and well needed) attention in early 1994. In late 1994, the MCS completely re-assessed the  $qs$  for all individual GPS frequency standards.*

*By tuning MCS clock estimation on a satellite-by-satellite basis, we've safely optimized the utility of the GPS Composite Clock, and hence, Kalman Filter state estimation, providing a small improvement to user accuracy.*

## INTRODUCTION

Though well capable of meeting and/or exceeding customer expectations, the GPS Master Control Station (MCS) will continuously search for safe and efficient methods for improving GPS timing accuracy and stability performance. The most recent improvements have focused on fine tuning the Continuous Time Update Process Noises (a.k.a.  $qs$ ) for all GPS satellite frequency standards.

Process noises are nothing new to the timing community. Many time scale algorithms update these parameters dynamically for their respective systems. As in many Kalman Filters, the Defense Mapping Agency (DMA) periodically reviews their  $q$  values for their OMNIS computation program. OMNIS, like the MCS Kalman Filter, estimates the ephemeris, solar, and clock states for 25 GPS satellites [3]. However, up until 6 Oct 94, the timing community had never undertaken the task of re- $q$ ing an entire operational GPS constellation in the MCS Kalman Filter.

Thanks to the generous input from several outside agencies, we now employ process noise values that are unique to the individual characteristics of the 25 operating frequency standards on orbit. Perhaps more importantly, we now also have the precise data, know-how, tools, and procedures to safely and efficiently review and update our  $q$  values on a periodic basis.

## RUBIDIUM CLOCK ESTIMATION

Each GPS satellite uses one of two different types of atomic clocks to provide a stable output frequency, to, in turn, generate accurate navigation signals. The majority of Block II/IIA GPS satellites currently use one of two available Cesium (Cs) frequency standards. Orbiting Cs clocks demonstrate reliable performance, with one-day stabilities ranging between 0.8 E-13 to 2.0 E-13 [13,14,15]. The drift rate term for a Cs frequency standard is typically on the order of 1 E-20 s/s<sup>2</sup> or less. Such a small drift rate term, an order of magnitude smaller than our time steering magnitude, has negligible effects on GPS timing (hundredths of a nanosecond over one day). Because of its relatively insignificant effect on frequency estimation, the MCS currently fixes the drift rate estimate to zero for all Cs frequency standards (on-orbit and ground based).

Two Rubidium (Rb) clocks also reside on each Block II/IIA satellite. Rb clocks *do* exhibit a significant aging characteristic, typically on the order of 1 E-18 s/s<sup>2</sup>. However, if a Filter properly corrects for drift rate, the typical one-day frequency stability of a Rb clock *state* is significantly better than that of a Cs (0.6 E-13 versus 1.0 E-13) [13,14,15]. Unfortunately, in the past, our Kalman Filter had difficulty estimating drift rate. As a result, Rb clock estimates have had somewhat large variances, causing, in turn, increased difficulty in estimating frequency. Although a Rb clock itself is usually more stable than a Cs at one day, the stabilities of the MCS's Kalman Filter Rb clock *states* have, in the past, been *worse* than those for Cs clocks.

This Filter instability has impeded the MCS from incorporating their inherently better stability into GPS time calculations. Consequently, the timing community has been uneasy about using Rb clocks in GPS. Of the first 24 operational satellites, we initialized only *three* with Rubidium clocks.

Despite this reluctant attitude towards using Rubidium clocks, many have realized that as Cesium clocks reach their respective ends of operational life, we will have *no choice* but to use more Rubidium clocks. In any case, it seemed counterintuitive that GPS was not making the most use of our most stable clocks. In early 1994, the 2 SOPS Navigation Analysis Section began tackling this long-standing concern. Because the problem resided in estimation, as opposed to physical clock performance, the Kalman Filter really only needed a fine tuning.

### Deriving New Rubidium Clock $q_s$

The MCS Kalman Filter performs recursive time and measurement updates of the state residuals and covariances. In pure prediction, the clock state covariances are functions of the system  $q_s$  [18]:

$$P = \begin{bmatrix} q_1 t + q_2 t^3 / 3 + q_3 t^5 / 20 & q_2 t^2 / 2 + q_3 t^4 / 8 & q_3 t^3 / 6 \\ q_2 t^2 / 2 + q_3 t^4 / 8 & q_2 t + q_3 t^3 / 3 & q_3 t^2 / 2 \\ q_3 t^3 / 6 & q_3 t^2 / 2 & q_3 t \end{bmatrix} \quad (1)$$

The Naval Research Laboratory (NRL) produced a report for 2 SOPS (ALL-5, 27 Jan 94), on SVN25. The report included a series of drift rate plots for the Rb clock that was active from Mar 1992 until Dec 1993. NRL plotted 5, 10, 20, and 30-day averaged values for drift rate [11]. In analyzing the 30-day average plot, we noticed that the drift rate changed significantly more during the first 90 days than during the remaining operational time [figure 1]:

From the above P matrix, in pure Filter prediction, the system variance for drift rate is the scalar time product of  $q_3$ :

$$C_3 = q_3(\tau) \tag{2}$$

Using the above equation, along with the NRL data, we derived new  $q$  values, both from the 90-day initialization period, and from the remaining period, and we compared these to the old system  $q$  values:

$q$ Value	OLD	INITIAL	NEW NORMAL
<b>Drift Rate (<math>q_3</math>)</b>	9.00 E-42 s <sup>2</sup> /s <sup>5</sup>	1.35 E-43 s <sup>2</sup> /s <sup>5</sup>	6.66 E-45 s <sup>2</sup> /s <sup>5</sup>

We also looked at calculating a new drift (frequency)  $q$  value. The old Rb  $q$  value for drift, 4.44 E-32 s<sup>2</sup>/s<sup>3</sup>, was the same as that for Cs. We chose  $q_2 = 2.22$  E-32 s<sup>2</sup>/s<sup>3</sup> [4]. Again, to be conservative, and to allow the Filter to handle any possible instability resulting from clock "warm-up", we set the initialization  $q_2$  value to 3.33 E-32 s<sup>2</sup>/s<sup>3</sup>. We kept the phase (bias)  $q$  unchanged. Below is a comparison of the old set and the two new sets of process noise values for Rubidiums:

$q$ Value	OLD	INITIAL	NEW NORMAL
<b>Bias (<math>q_1</math>)</b>	1.11 E-22 s <sup>2</sup> /s	1.11 E-22 s <sup>2</sup> /s	1.11 E-22 s <sup>2</sup> /s
<b>Drift (<math>q_2</math>)</b>	4.44 E-32 s <sup>2</sup> /s <sup>3</sup>	3.33 E-32 s <sup>2</sup> /s <sup>3</sup>	2.22 E-32 s <sup>2</sup> /s <sup>3</sup>
<b>Drift Rate (<math>q_3</math>)</b>	9.00 E-42 s <sup>2</sup> /s <sup>5</sup>	1.35 E-43 s <sup>2</sup> /s <sup>5</sup>	6.66 E-45 s <sup>2</sup> /s <sup>5</sup>

Of course, one might question using 30-day averaged drift rate values for deriving  $q_3$ --could the drift rate change by an unacceptable amount during those 30 days, thus undermining the premise of these calculations? Well, in the past, NRL has been able to apply as much as a 150 day flat-average aging correction to their Allan Deviation plots--plots showing one-day stability figures similar to SVN25's [10]. The implication is, if the Filter has a good drift rate term, that value can essentially be fixed for, in some cases, up to 150 days, without significantly degrading the one-day accuracy of the other clock states. Certainly, assuming drift rate consistency over 30 days, let alone 150, was safe for deriving the above  $q$  values for the MCS Kalman Filter.

## SVN9 End Of Life Testing

50th Space Wing approved a 1 SOPS and 2 SOPS joint effort to conduct End Of Life testing on SVN9 during March and April 1994 [19]. As part of the plan, Rockwell suggested dedicating 7-8 days for testing Rubidium clock drift rate estimation. We used the "New Normal"  $q$  values, and monitored the resulting system performance.

The test, which lasted 8.7 days, produced very encouraging results [19]. At the end of the test, with tighter process noise values, the Kalman Filter converged on a drift rate value of -2.38 E-18 s/s<sup>2</sup>, with an associated standard deviation of 1.99 E-19 s/s<sup>2</sup> (compared to a typical standard deviation of 1.0 E-18 s/s<sup>2</sup>, using the old  $q$  values). Using an off-line tool, Rockwell derived post-processed values for comparison. Using a simple slope of their  $A_1$  (frequency) estimates over 7 days, Rockwell's drift rate estimate was -2.44 E-18 s/s<sup>2</sup>, well within one sigma of the Filter's estimate. The National Institute of Standards and Technology (NIST) Report on SVN9 End of Life Testing pointed to a value of -2.32 E-18 s/s<sup>2</sup> [8], also well within one sigma of the Filter estimate. These comparisons indicated that the Filter had performed as

designed--to converge on a more accurate drift rate estimate, with a correspondingly representative error estimate (standard deviation) [figure 2].

By, in effect, "clamping" on the Filter estimate, one must question whether this covariance tightening is too restrictive, limiting the Filter's capability to respond to normal clock movement. We used two MCS parameters to test this capability.

a. The first parameter was the Measurement Residual Statistical Consistency Test (MRSCT). Essentially, the MRSCT decides whether or not to accept Pseudoranges (PRs). Over 8.7 days, the Filter accepted each and every smoothed PR for SVN9. The average PR residual (PRR) was no higher than that of a typical healthy, operational vehicle, or SVN9's prior to the test.

b. The second parameter was the Estimated Range Deviation (ERD). The ERD gives a good indication of the range error a user is experiencing, based on the current navigation upload residing in the vehicle. Over the 8.7 days, we uploaded SVN9 only once per day, and the ERD RMS never once exceeded 3.1 meters--well within our ERD criteria of 10 meters. Correspondingly, the one-day User Range Accuracy (URA) dropped from 5.0 to 3.8 meters, and the four-day URA dropped from 33.0 to 13.0 meters. In hindsight, we could have even set SVN9 healthy during the test, and netted a small improvement to global coverage and accuracy [figure 2].

In short, results from the SVN9 drift rate test indicated that Filter estimation worked quite better with the reduced process noise ( $q$ ) values.

## **Real World Implementation Of The New Rubidium $qs$**

On 18 Mar 94, we began applying these results towards real-world SVN10 and SVN24 clock estimation. Since, at that time, SVN24's Rb was less than three months old, and since SVN10 is a Block I, always susceptible to the effects of eclipse seasons, we selected the "Initialization"  $qs$  instead of the "New Normal"  $qs$ .

For SVN10, during the three months prior to the test, ERDs exceeded 5.0 meters on 19 separate days. During the three months after the new  $qs$  were installed, SVN10 ERDs didn't once exceed 4.8 meters. In addition, our Smoothed Measurement Residual (SMRES) tool showed that SVN10 residuals from the DMA monitor stations, since 18 Mar 94, have been consistent with those prior to 18 Mar 94, as well as those for our other satellites. Similarly, between these two time periods, SVN10's time transfer error dropped from 14.6 to 9.9 nanoseconds (RMS), according to United States Naval Observatory (USNO) data [5]. These data points, from independent agencies, further show a significant improvement in satellite accuracy.

Similar to SVN10's, the ERDs for SVN24 decreased after 18 Mar 94. Additionally, after installing the "New Normal"  $qs$  on 24 Apr 94, from that time to the present, the Filter has easily and consistently accepted SVN24 PRs. Likewise, SVN24 residuals from DMA, since 24 Apr 94, have been as good or better than those prior to 24 Apr 94, and better than those of the other 23 operational satellites. In terms of upload accuracy, SVN24's ERDs routinely exceeded 4.0 meters prior to 24 Apr 94. Since 24 Apr 94, SVN24's ERDs have rarely exceeded 3.5 meters, and have typically stayed under 2.5 meters. SVN24, now, is one of our two most accurate satellites. To complete the usefulness of this improvement, on 28 Apr 94, we included SVN24 into the GPS composite clock, allowing it to better stabilize GPS time.

For the time being, after the 2 SOPS has initialized a Rubidium clock for 7-14 days, we'll probably install the "Initialization"  $qs$  for 90 days. At the three month point, assuming nominal clock performance, we'll likely install the "New Normal"  $qs$ . Also, at three months, we will aggressively consider including that satellite into the GPS composite clock--a Block II/IIA Rubidium clock estimate, now properly corrected for drift rate, now has a *better* one-day frequency stability than those of each of the on-orbit Cesiums. The GPS community, as a whole, can now at least tame a long existing ambivalence we've had about using Rubidium clocks in operational satellites. A Rubidium clock, now properly tuned in the Kalman Filter, significantly improves GPS timing and positioning accuracies. Currently, five GPS satellites use Rubidium clocks. One, in particular, SVN36, is arguably now our *most accurate* satellite.

## CESIUM CLOCK ESTIMATION

Having resolved perhaps the most significant recent problem with GPS clock estimation through improved Rubidium  $qs$ , we decided to expand this opportunity for improvement to the remainder of all on-orbit GPS frequency standards: Cesium (Cs) clocks. As demonstrated earlier, deriving clock  $qs$  involves two main steps: 1) obtaining data that can accurately describe the behavior of the clocks involved, and 2) mathematically translating this behavior into the  $qs$  themselves.

DMA has already been doing exactly this. A snapshot of some recently-derived DMA  $qs$  shows values that are, for the most part, unique to the individual clocks [3]. DMA's  $qs$  vary significantly between satellites. In contrast, prior to 6 Oct 94, the MCS  $qs$  were *equal* for most GPS Cs clocks. Also noteworthy is that the MCS's  $q_1$  value was less than *each* of DMA's equivalent  $q_1$  values [3]:

	MCS $q$ Values	DMA $q$ Values	
		Smallest	Largest
Bias ( $q_1$ )	1.11 E-22 $s^2/s$	4.25 E-22 $s^2/s$	4.35 E-21 $s^2/s$
Drift ( $q_2$ )	4.44 E-32 $s^2/s^3$	7.35 E-33 $s^2/s^3$	5.16 E-32 $s^2/s^3$

This comparison raised two questions: 1) Would uniquely tuning the  $qs$  provide a significant improvement to GPS performance? 2) Does a legitimate reason exist for deliberately having lower  $q_1$  terms in the MCS Kalman Filter? The remainder of this paper answers the first question. The second question, however, is more philosophical.

MCS software experts will argue that a fundamental difference in purpose between the respective Kalman Filters at the MCS and at DMA constitutes a legitimate reason for using different  $q_1$  terms. Since the MCS Kalman Filter is designed, in part, to provide accurate 24 hour predictions for navigation uploads, one could argue that we might want to deliberately keep our  $q_1$  low to reduce the gain, and hence, prevent a situation whereby a noisy Kalman update could skew a 24-hour navigation upload prediction. Timing experts, however, will argue that tinkering with this parameter can be dangerous, since doing so can impose a configuration inconsistent with the basic intended design of a Kalman Filter. Both sides have very legitimate arguments.

## Deriving New Cesium Clock $qs$

Analysts at NRL provide timely, accurate, and understandable reports on GPS clock performance. In particular, we now greatly utilize their Allan Deviation [ $\sigma(\tau)$ ] plots, created from DMA precise ephemeris



data. The following equation relates the Allan Variance  $[\sigma^2(\tau)]$  to Kalman Filter  $qs$ . This equation assumes independence between each sample frequency pair [2].

$$\sigma^2(\tau) = q_1(\tau^{-1}) + q_2(\tau)/3 + q_3(\tau^3)/20 \quad (3)$$

In order to relate current clock performance (via the Allan Deviation) to the system  $qs$ , we try not to use data more than 90 days old. Unfortunately, by only using 90 days of data, we experience the tradeoff of degraded confidence intervals for  $\tau > 20$  days. For Cesium clocks, this is a non-concern, since we currently fix the drift rate and  $q_3$  values to zero. For Rubidium clocks, however, the degraded confidence intervals, combined with the difficulty of correcting for drift rate without violating the sample frequency pair independence assumption, makes calculating the last term dangerous. As demonstrated earlier in this paper, we now have very suitable  $q_3$  values for Rubidium clocks. Thus, for  $\tau < 20$  days, we can substitute these into the Allan Variance equation, and simply solve for  $q_1$  and  $q_2$ . Then, we can compare our theoretical values to empirical values, using NRL Allan Deviation plots (with flat aging corrections applied for Rubidium clocks) [12].

One other concern relates to measurement noise. The data from NRL, and hence from DMA, has a fairly certain amount of measurement noise. The MCS's parameter for measurement noise, which we'll call  $q_0$ , accounts for some of the GPS monitor station (MS) receiver noise, some of the satellite clock's white and flicker phase noise, MS location errors, and general modeling errors. DMA has a similar parameter designed to account for measurement noise, currently set to  $(45 \text{ cm})^2 \cong 0.20 \text{ m}^2$ . For years, the MCS set this parameter at  $1.0 \text{ m}^2$ . Thanks to recently refined MS location coordinates from DMA [6], the MCS was recently able to reduce  $q_0$  to  $(0.86\text{m})^2 \cong 0.74 \text{ m}^2$ . We derived this value using 500 Pseudorange Residual values from a widely distributed assortment of times and satellite-MS combinations. Our new value of  $0.74 \text{ m}^2$ , not surprisingly, is not a dramatic reduction from  $1.0 \text{ m}^2$ , but nonetheless is consistent with our expectation of improvement from the new coordinates:

$$\sqrt{(1.00^2 - 0.86^2)} = .51 \text{ (meters)} \quad (4)$$

One might suggest using DMA's lower value. However, since our parameter accounts for more than just pure white measurement "noise", our parameter is higher for a legitimate reason. Although not purely white phase noise in nature, noise associated with measurements can tend to misrepresent the stability of the estimated clock states. We can roughly express the instability resulting from this representation error as [1]:

$$\sigma_r^2(\tau) = 3q_0(\tau^{-2}) \quad (5)$$

By assuming independence between this representation error and the other noise processes on a given clock, the equation for the Allan Variance of the measured clock adds an additional term [7]:

$$\sigma_m^2(\tau) = 3q_0(\tau^{-2}) + q_1(\tau^{-1}) + q_2(\tau)/3 + q_3(\tau^3)/20 \quad (6)$$

We created a Basic program to plot the theoretical  $\sigma(\tau)$  values, using the above equation, for  $\tau = 0.1$  to 100 days. Using recent precise ephemeris  $\sigma(\tau)$  plots from NRL [12], along with the Basic program, we derived new  $q$  values for all satellites [figure 3]. Note that the Rubidium  $qs$  remained *unchanged*. The Rb  $qs$  we derived earlier this year are, and have been, consistent with true clock performance. Nonetheless, Figure 4 shows how the theoretical Allan Deviation *does* change significantly for, in particular, SVN21 and SVN23, by using the newer  $qs$ .

The current MS bias and drift  $q_s$ ,  $1.11 \text{ E-22 s}^2/\text{s}$  and  $4.44 \text{ E-32 s}^2/\text{s}^3$ , respectively, are *not* representative of true MS clock performance. However, the MCS uses three separate mini-Kalman Filters, a.k.a. "partitions" to individually estimate MS clock states. Since a *partition reconciliation* algorithm keeps these states fairly consistent [1,4], over time, the MCS estimation structure effectively triples the weighting of the long term effects of MS clocks. With this current  $q_2$  value for MSs, this "triple weighting" produces, in a roundabout fashion, the *effect* of using a  $q_2$  roughly the same as the smallest satellite  $q_2$ . We may tweak this parameter in the future, but, for the time being, this effect produces a fairly accurate result [16].

We also began using a newer set of  $q_s$  during Cesium clock initialization. Below is a comparison of the old  $q_s$ , and new initialization  $q_s$  we've derived:

Old $q_1$ E-22 $\text{s}^2/\text{s}$	Old $q_2$ E-32 $\text{s}^2/\text{s}^3$	Old $q_3$ E-45 $\text{s}^2/\text{s}^5$	New $q_1$ E-22 $\text{s}^2/\text{s}$	New $q_2$ E-32 $\text{s}^2/\text{s}^3$	New $q_3$ E-45 $\text{s}^2/\text{s}^5$
1.11	4.44	0	4.44	3.33	0

### Testing The New Cesium $q$ Values

We safely tested the validity of these changes on 3 Oct 94, using a Test & Training simulator in the MCS. The results were impressive.

a. As expected, the state covariances converged to steady state values more truly representative of the unique short- and long-term variances of the individual clocks. Also as expected, none of these new steady state covariances differed drastically from the typical older values. The implication of these small, but significant changes is that the Filter safely re-weighted clock state estimation based on true frequency standard performance, as opposed to assumed performance equality (equal  $q_s$ ):

Value	OLD VARIANCES (All Cs)	NEW VARIANCES (Minimum)	(Maximum)
<b>Bias</b>	$1.25 \text{ E-17 s}^2$	$1.07 \text{ E-17 s}^2$	$1.83 \text{ E-17 s}^2$
<b>Drift</b>	$3.20 \text{ E-27 s}^2/\text{s}^2$	$1.38 \text{ E-27 s}^2/\text{s}^2$	$4.38 \text{ E-27 s}^2/\text{s}^2$

b. As expected, the current state residuals experienced small (not trivial, not severe) changes, indicating that the Filter more responsibly distributed error to the appropriate states.

c. The MCS Pseudorange Residuals (PRRs) dropped from 1.61 m (RMS) to 0.87 m (RMS), after the Filter reprocessed the same raw data with the new set of  $q_s$ . This more dramatically indicates that the Filter more responsibly distributed error to the appropriate states, so well that Filter predictions can now have less systematic error, and hence, less error when compared to smoothed measurements.

d. The consistency of MS clock states across the Kalman Filter partitions experienced a small, but not trivial improvement (A 3.8 % reduction in Bias divergence error, and 21.6 % reduction in Drift divergence error). Again, by more responsibly appropriating error to the respective clock states, short-term MS clock state instability across the partitions dropped.

## Real-World Implementation Of The New Cesium $q_s$

By installing these new  $q_s$  on 6 Oct 94, we safely improved a) Kalman Filter clock estimation, b) navigation error representation, and c) the stability of the GPS composite clock.

The stability of GPS time, defined by the GPS composite clock, intuitively, should have improved simply as a result of the improved weighting, again, by uniquely tuning the  $q_s$  based on true clock performance. When we used equal  $q_s$ , the Allan Variance,  $\sigma_{\Delta}^2(\tau)$ , of the implicit ensemble of  $N$  equally weighted clocks (for  $\tau = 1$  day) was approximately [4]:

$$\sigma_{\Delta}^2(\tau) \cong 1/(N^2) \sum_{i=1}^N \sigma_{y_i}^2(\tau) \quad (7)$$

Using the one-day Allan Deviation figures from NRL Quarterly Report 94-3 [15], the one-day stability of this implicit ensemble was approximately  $1.55 \text{ E-14}$ .

By using clock-unique  $q_s$ , the Allan Deviation of the now finely tuned implicit ensemble (for  $\tau = 1$  day) is approximately [1,4]:

$$\sigma_{\Delta}^2(\tau) \cong \left[ \sum_{i=1}^N (\sigma_{y_i}^2(\tau))^{-1} \right]^{-1} \quad (8)$$

Incorporating the same one-day NRL Allan Deviation figures into the above equation, the one-day stability of the implicit ensemble dropped to approximately  $1.22 \text{ E-14}$ . Similarly, the *observed* Allan Deviation of GPS time, derived from USNO-smoothed measurements [5,9], also dropped, not only for  $\tau = 1$  day, but for  $1 \leq \tau \leq 10$  days [figure 5].

Important to note is a large improvement in extended (14 day) navigation performance. By utilizing more representative (lower)  $q_2$  values, the 14-day URA predictions have dropped to lower, more representative values for most satellites. Figure 6 shows a comparison of the typical 14-day URA values before and after 6 Oct 94, for all Block IIA satellites in estimating partitions. Though not an absolute indication of extended navigation accuracy, by uniquely tuning the  $q_s$ , these URA values now, at least, have more validity than before. The 14-day URA values for all healthy GPS satellites, since 6 Oct 94, have been well below the NAVSTAR GPS System Operational Requirements Document (SORD) User Range Error (URE) specification of 200 meters [17].

## CONCLUSION

This fine tuning reinforces how deriving and installing clock-unique MCS Kalman Filter process noise values can safely and significantly improve GPS timing performance. We will continue to update these parameters on a regular basis. In the near future, we plan to review these values every three months, and as needed (after a clock swap or a dramatic change in clock performance).

Loral Federal Systems Division received a tasking to more comprehensively review these and other data base parameters in 1995. We expect the results from their analysis to be more precise than the above results, due to the extensive background of the team of experts that will tackle this project.

Nonetheless, this successful attempt at fine tuning the MCS  $qs$  helps pave a path for future MCS data base analyses, and hence for future refinements to GPS timing performance.

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## REFERENCES

- [1] Brown, Kenneth R., *The Theory of the GPS Composite Clock*, Proceedings of ION GPS-91, 11-13 Sep 91
- [2] Chaffee, James W., *Relating the Allan Variance to the Diffusion Coefficients of a Linear Stochastic Differential Equation Model for Precision Oscillators*, from the IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. UFFC-34, No. 6, November 1987
- [3] Hermann, Bruce R., *Allan Variance Model Parameters Determined From OMNIS Satellite Clock Files*, 23 Mar 94
- [4] Hutsell, Steven T., Capt, USAF, *Recent MCS Improvements to GPS Timing*, Proceedings of ION GPS-94, 20-23 Sep 94
- [5] ICD-GPS-202, 21 Nov 84

- [6] Malys, Stephen, and Slater, James, Defense Mapping Agency, *Maintenance and Enhancement of the World Geodetic System 1984*, Proceedings of PAWG '94, 3-4 Aug 94
- [7] Maybeck, Peter S., *Stochastic Models, Estimation and Control, Volume 1*, 1979
- [8] NIST Report on End of Life Testing, 25 Apr 94
- [9] NIST Technical Note 1337, Mar 90
- [10] NRL Analysis Update, SVN25, 15 Oct 92
- [11] NRL Analysis Update, 25-6, 17 May 94
- [12] NRL Analysis Update All-9, 17 Aug 94
- [13] NRL Quarterly Report No. 94-1, 15 Jan 94
- [14] NRL Quarterly Report No. 94-2, 15 Apr 94
- [15] NRL Quarterly Report No. 94-3, 15 Jul 94
- [16] NRL Technical Update No. 1, 5 Oct 94
- [17] NAVSTAR GPS System Operational Requirements Document (SORD), 22 Jan 90
- [18] Taylor, John V., IV, Rockwell International, *Estimation of Clock Drift Rate States on GPS SVs Using Rb Frequency Standards* MFR, 31 Jan 94
- [19] 1 SOPS/2 SOPS/Rockwell SVN9 End of Life Test Results, Mar-Apr 94

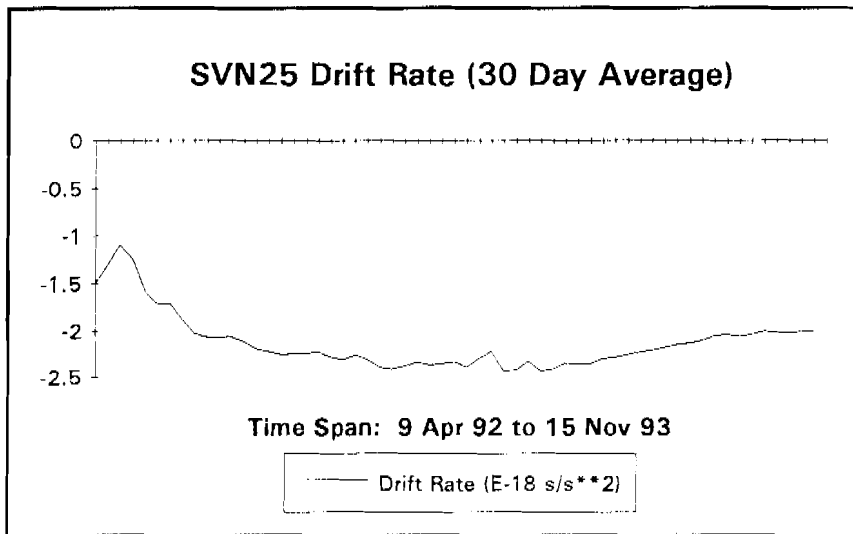


Figure 1

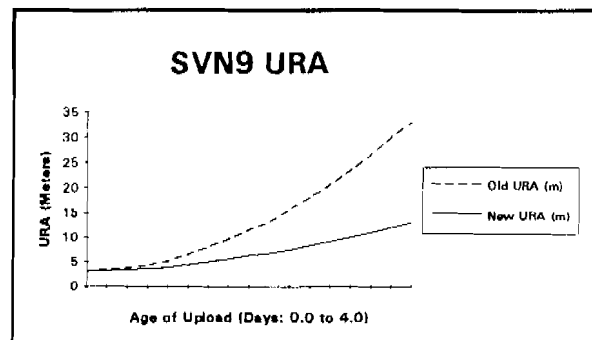
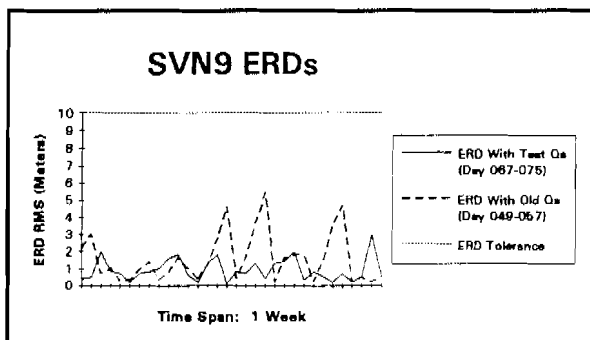
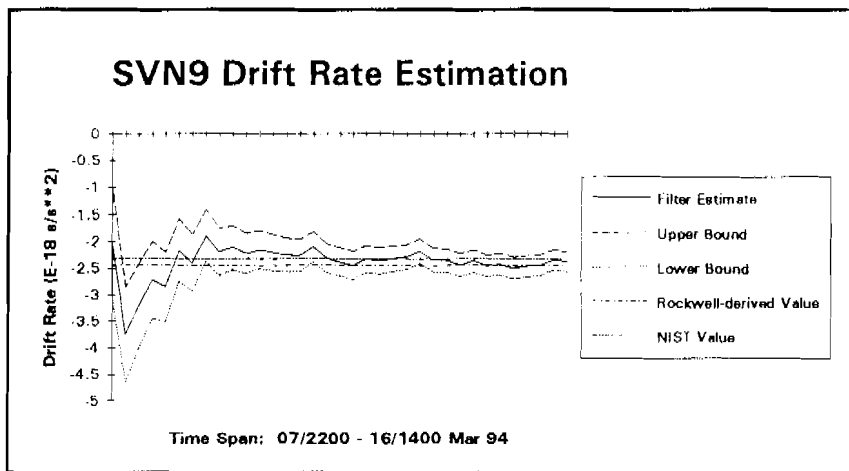


Figure 2

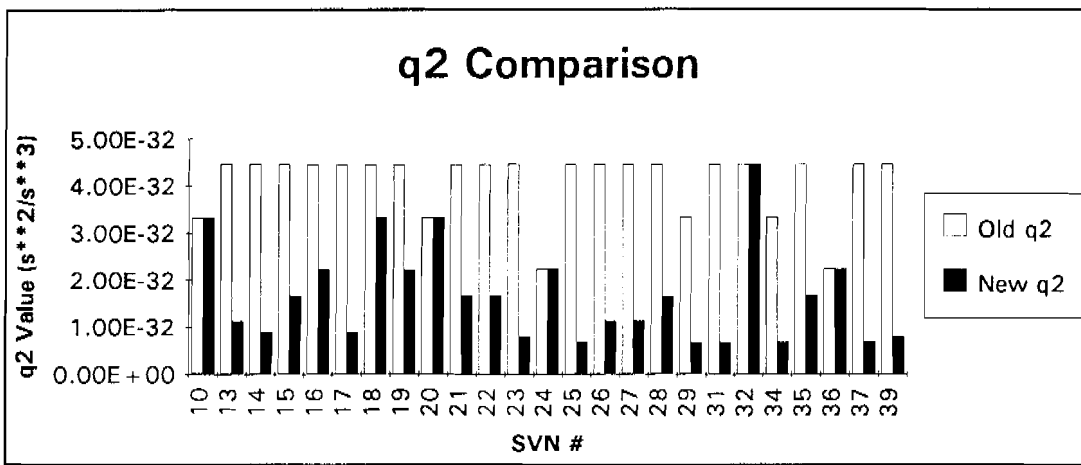
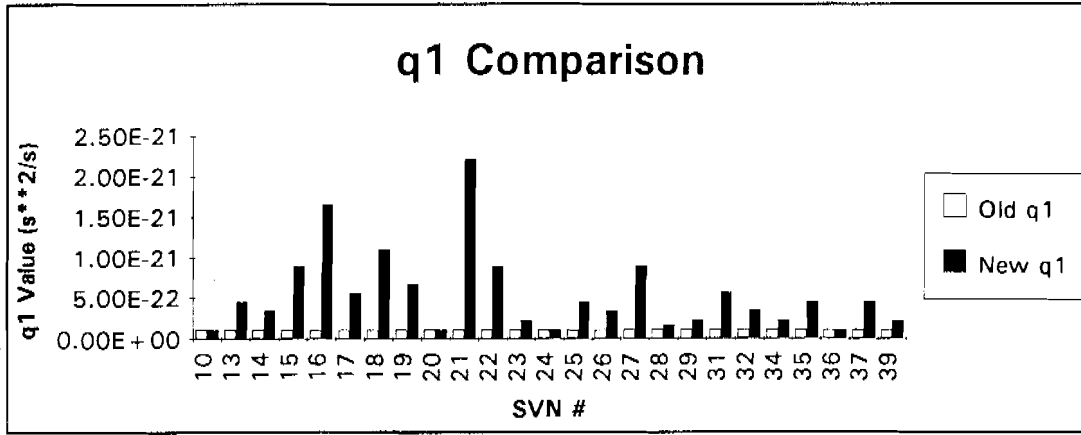


Figure 3

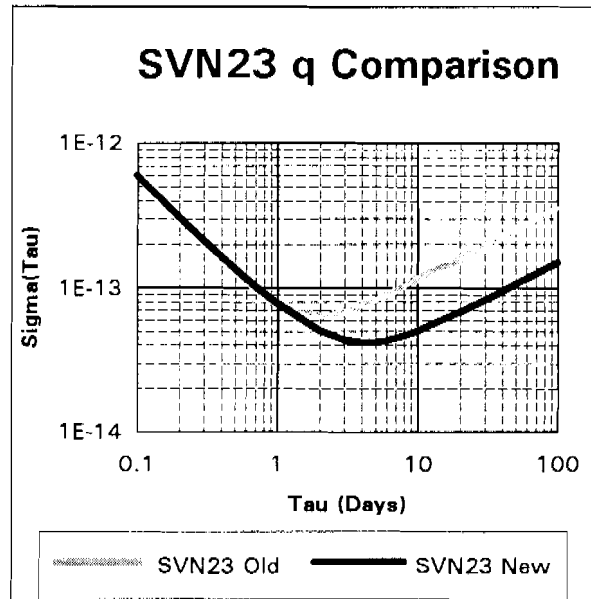
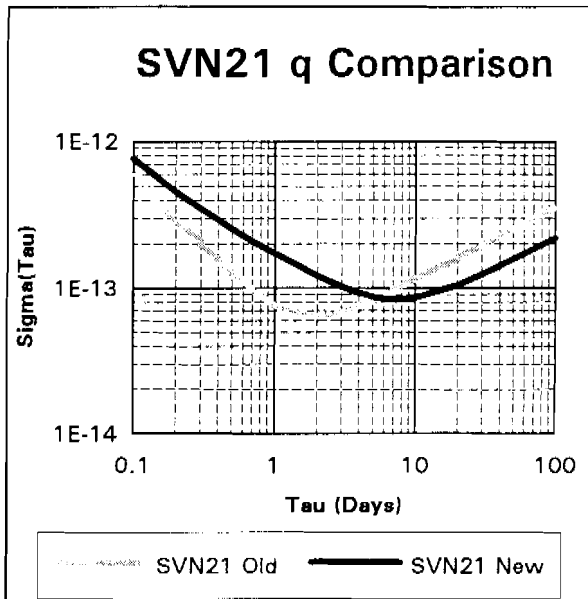


Figure 4

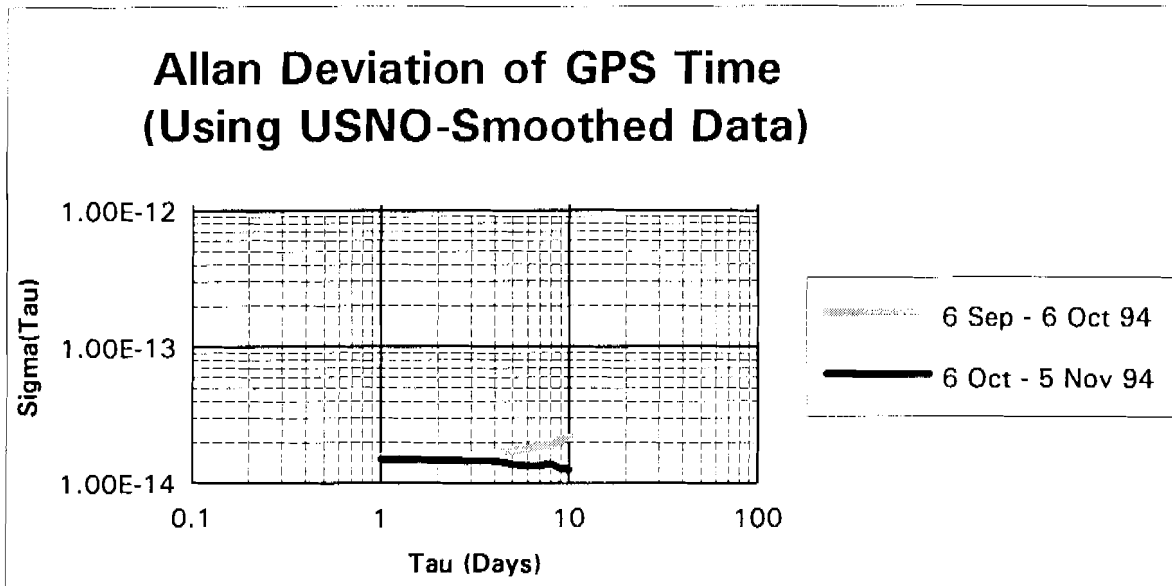


Figure 5

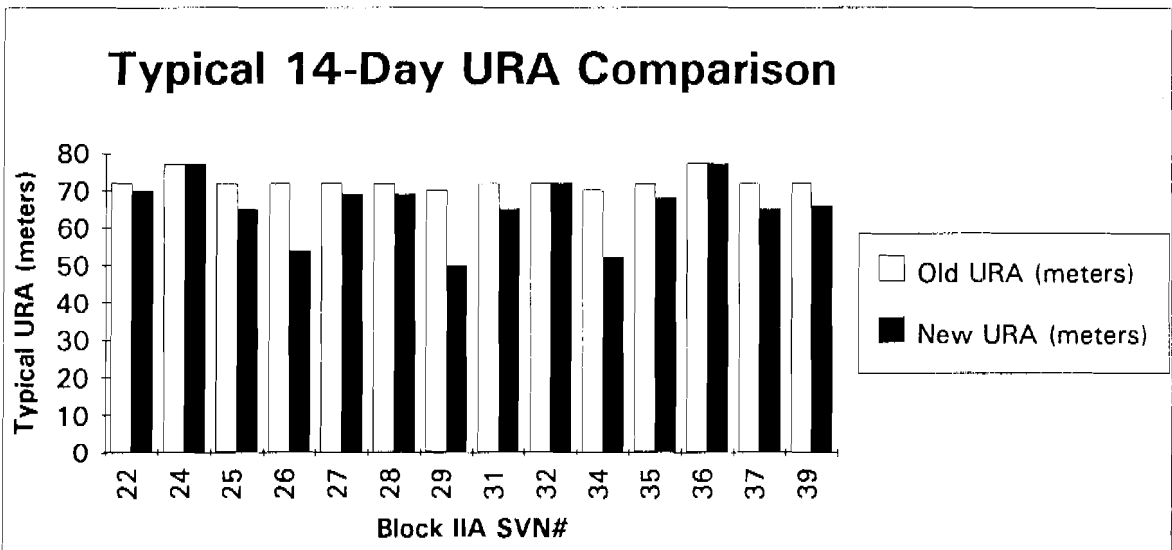


Figure 6



# TIME ACTIVITIES AT THE BIPM

Claudine Thomas  
Bureau International des Poids et Mesures  
Pavillon de Breteuil  
32312 Sèvres Cedex  
France

## Abstract

*The generation and dissemination of International Atomic Time, TAI, and of Coordinated Universal Time, UTC, are explicitly mentioned in the list of the principal tasks of the BIPM, recalled in the Comptes Rendus of the 18th Conférence Générale des Poids et Mesures, in 1987. These tasks are fulfilled by the BIPM Time Section thanks to international cooperation with national timing centers, which maintain, under metrological conditions, the clocks used to generate TAI. Besides the current work of data collection and processing, research activities are carried out in order to adapt the computation of TAI to the most recent improvements occurring in the time and frequency domains. Studies concerning the application of general relativity and pulsar timing to time metrology are also actively pursued. This paper summarizes the work done in all these fields and outlines future projects.*

## INTRODUCTION

The Comité International des Poids et Mesures, CIPM, discussed the role of the Bureau International des Poids et Mesures, BIPM, in the 1980s and its conclusions were made known in the Convocation to the 18th Conférence Générale des Poids et Mesures [1], in the following terms:

*“The purpose of the BIPM is to provide the physical basis necessary to ensure worldwide uniformity of measurements. Therefore, its principal tasks are:*

- *to establish and disseminate the International Atomic Time, and, in collaboration with the appropriate astronomical organizations, Coordinated Universal Time;*
- *to furnish whatever help is possible in the organization of [those] international comparisons which, although not carried out at the BIPM, are carried out under the auspices of a Comité Consultatif;*
- *to ensure that the results of international comparisons are properly documented and, if not published elsewhere, are published directly by the BIPM... ”*

The definition of TAI was approved by the Comité International des Poids et Mesures in 1970, and recognized by the Conférence Générale des Poids et Mesures, CGPM, in 1971. It reads as follows:

*International Atomic time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of Units.*

In 1988, responsibility for TAI was transferred to the Time Section of the BIPM, according to one of the explicit missions recalled above.

From its definition, TAI is the result of a collective effort. It calls for the maintenance of atomic clocks in national timing laboratories, and for international comparisons between these clocks. One has thus established an exchange in which: \* timing centres produce time transfer and clock data and send it to the BIPM, \* the Time Section of the BIPM produces TAI, distributes it as time corrections to national time scales, and then publishes international time comparisons.

*The efficiency of this organization and the quality of its results rely upon the care and the rigor of the work effected in the contributing laboratories and at the BIPM, and upon a continuous, positive, and fruitful dialogue between both parties.*

The Time Section of the BIPM is helped in its work in two ways:

- The Comité Consultatif pour la Définition de la Seconde, CCDS, creates working groups on specific topics such as Improvement of TAI, GPS Standardization, and Two-Way Satellite Time Transfer. The membership of these groups includes experts and members of the staff of the Time Section. Recommendations are issued and proposed for adoption to the CCDS, and then the CIPM and the CGPM, after extended discussions. This procedure makes it possible for the Time Section to keep itself informed about new techniques or studies. The Recommendations which are passed also give a formal guide to its work.
- The Time Section of the BIPM has at its disposal a time laboratory including two caesium clocks and several GPS time receivers. Most of this equipment is on loan from private companies or from national timing centres. Data taken at the BIPM are not introduced in the TAI computation, but are simply analyzed for specific studies. This work provides a background of practical experience which sensitizes the Section to the problems of gathering data and allows it to make better use of that reported from outside.

The organization of the work at the Time Section is described in Fig. 1. The main objectives are perfectly clear and concern, as already stated, the generation and dissemination of TAI and UTC. However, they can easily be extended to the production of good realizations of the Terrestrial Time, TT, as defined by the International Astronomical Union, IAU, in 1992

[2]. These objectives imply that current activities centre on the regular production of TAI and on clock comparisons. More fundamental investigations are also carried out about time scale algorithms, time transfer methods, pulsar timing, and general relativity. This is described in the following sections.

## GENERATION OF TAI AND UTC

As is well known, TAI is obtained through the computation of a weighted average of clock readings [3]. The main algorithm, optimized for long-term stability, treats as a whole blocks of data collected over a two-month period, and produces in deferred-time a free time scale, EAL. External to this main algorithm, accuracy is ensured by frequency steering corrections, which are applied to EAL to obtain TAI, after comparison with the best primary frequency standards.

The 230 contributing clocks are kept in 46 national time centers spread world-wide. At present, all but four of these laboratories are compared using the Global Positioning System, GPS. Rough data are sent to the BIPM and treated according to strict common views in order to overcome Selective Availability effects [4, 5]. The general organization of the international GPS network used by the BIPM is shown in Fig. 2. It comprises:

- two long distance lines, linking three nodes: the NIST (USA), the OP (France), and the CRL (Japan), where GPS antenna coordinates are known accurately, and where ionospheric measurements are available. In addition, GPS data are corrected in post-processing with precise satellite ephemerides available from the International Geodynamics Service, IGS. For these two long-distance links (*ge* 6000 km) clock comparison noise is smoothed out for averaging times of order three days, and the overall accuracy is of order 6 ns to 8 ns ( $1 \sigma$ )<sup>[6]</sup>.
- local stars on a continental scale. Ionospheric measurements and precise satellite ephemerides are not used for these short-distance links (*le* 1000 km), but accurate GPS antenna coordinates help to improve the accuracy obtained. Typically, clock comparison noise is smoothed out for averaging times of order 12 hours to 24 hours, and the overall accuracy is of order 2 ns ( $1 \sigma$ )<sup>[6]</sup>.

The reference time scales TAI and UTC have been regularly computed and published in the monthly *Circular T* since the 1st January 1988, the date of official transfer of this responsibility from the old BIH to the BIPM. Annual reports are also produced by the BIPM Time Section, and have been available, in the form of computer-readable files, in the BIPM INTERNET anonymous FTP since 5 April 1994.

For years, the TAI scale interval has been regularly compared with the best realizations of the SI second provided by the primary frequency standards maintained at the PTB (Germany), PTB CS1 and CS2, which operate continuously as clocks. Their stated accuracies are respectively  $3 \times 10^{-14}$  and  $1.5 \times 10^{-14}$  ( $1 \sigma$ ). Recently, two newly designed caesium frequency standards, using optical production and detection of atoms have been evaluated:

- NIST 7, developed at the NIST (Boulder, Colorado, USA) reaches an accuracy of  $1 \times 10^{-14}$ [7].
- JPO (Jet à Pompage Optique), developed at the LPTF (Paris, France) attained an accuracy of  $1.1 \times 10^{-13}$  when evaluated for the first time in May 1993[8].

The deviation of the TAI scale interval, to the SI second as realized by PTB CS1, PTB CS2, and NIST 7, is shown in Fig. 3 for the last three years. The JPO is not included because its uncertainty is much larger than that of other primary frequency standards. On average, this deviation is estimated to be of order  $0.2 \times 10^{-14}$ , with an uncertainty of  $11 \times 10^{-14}$  ( $1 \sigma$ ) for the two-month interval July–August 1994. Since April 1993, the TAI frequency has remained constant with respect to the best primary standards, so no frequency-steering corrections have been applied.

## ALGORITHMS FOR TIME SCALES

The quality of the timing data used for TAI computation is rapidly evolving thanks to the wide use of GPS time transfer, and to the extensive replacement of older designs of commercial clocks by the new HP 5071A clocks and active auto-tuned hydrogen-masers. White measurement noise of distant time comparisons is thus smoothed out by averaging data on periods shorter than 10 days. In addition, the use of very stable clocks leads to a large improvement in the stability of TAI and UTC. By application of the N-cornered hat technique to the data obtained in 1993 and at the beginning of 1994, for the comparisons between TAI and the best independent time scales of the world (maintained at the NIST, the VNIIFTRII, the USNO and the PTB), one obtains the following estimates of stability (expressed in terms of Allan standard deviation and shown in Fig. 4):

$$\begin{aligned} \sigma_y TAI (\tau = 10\text{days}) &= 3.9 \times 10^{-15}, \\ \sigma_y TAI (\tau = 20\text{days}) &= 3.2 \times 10^{-15}, \\ \sigma_y TAI (\tau = 40\text{days}) &= 3.5 \times 10^{-15}, \\ \sigma_y TAI (\tau = 80\text{days}) &= 4.9 \times 10^{-15}. \end{aligned}$$

The stability of TAI and UTC lies thus below  $5 \times 10^{-15}$ . It also appears that the basic interval of computation, at present 60 days, can be reduced. This, if done, will help to shorten the delay of access to TAI. We are thus testing a new version of the algorithm ALGOS for the definitive computation of TAI each month, using real data from the beginning of 1992. Results are encouraging and it has been decided that the CCDS working group on Improvements to TAI should meet in March 1995 to discuss this new algorithm.

An interesting point is that the same stability study carried out using EAL instead of TAI gives the following results:

$$\begin{aligned} \sigma_y EAL(\tau = 10\text{days}) &= 3.9x10^{-15}, \\ \sigma_y EAL(\tau = 20\text{days}) &= 3.2x10^{-15}, \\ \sigma_y EAL(\tau = 40\text{days}) &= 3.1x10^{-15}, \\ \sigma_y EAL(\tau = 80\text{days}) &= 4.0x10^{-15}. \end{aligned}$$

A degradation of the stability of TAI, for averaging times ranging from 40 days to 80 days, is apparent when compared with the stability values obtained for EAL. This is probably due to the single frequency steering correction of  $5 \times 10^{-15}$  carried out in April 1993. Clearly the amplitude of this frequency step was too large, given the size of EAL fluctuations. It follows that steering corrections should be small (probably of order 1 to  $2 \times 10^{-15}$ ), and are useful only for modification of the TAI frequency in the very long term.

Given the high stability of recently designed commercial clocks and hydrogen-masers, it appears that it is now time to consider fundamental modification of the TAI algorithm. The next meeting of the CCDS working group on Improvement to TAI, scheduled for March 1995, is a good opportunity to discuss this topic. We are therefore studying, on real data, the following points:

- computation of TAI every 30 days instead of 60 days,
- introduction of a frequency drift evaluation in the frequency prediction of hydrogen-masers,
- change of the upper limit of weights,
- change of the weight determination procedure, which is at present based on the observation of systematic frequency changes with annual signature, a phenomenon which tends to disappear,
- danger of excessive dependence on a single clock type (HP 5071A),
- advantages of changing the basic measurement cycle from 10 days to 1 day,
- advantages of increasing or decreasing the number of participating clocks.

These studies have been partly reported<sup>9, 10</sup>, and it is already expected that the shortening of the period of definitive computation and a better use of hydrogen masers will be recommended by the working group.

## TIME LINKS

The BIPM Time section is interested in any time comparison method which has the potential for nanosecond accuracy. We are thus involved in the development of GLONASS, LASSO, two-way time transfer via geostationary satellites, and ExTRAS (Experiment on Timing, Ranging and Atmospheric Soundings, also named "hydrogen maser in space"), although GPS strict common-views remain the time transfer means used for current TAI computation.

## Global Positioning System, GPS

Among its current activities, the BIPM issues, twice a year, GPS international common-view schedules, produces international GPS comparison values, and also publishes an evaluation of the daily time differences between UTC and GPS time. These differences were obtained by treatment of data from Block I satellites only. Since April 1994, only one Block I satellite has

been observable, and daily values have been obtained by smoothing data taken from the Block II satellites viewed at angles of elevation greater than 30°. The results are less precise than before (daily standard deviations of order 12 ns, against 3 ns) because Selective Availability is currently implemented. Although we have shown that precise restitution of GPS time is possible using multi-channel P-code GPS time receivers<sup>[11]</sup>, this method cannot be used because reliable and regular data from such a receiver is not yet available.

An important part of our current work is to check the differential delays between GPS receivers which operate on a regular basis in collaborating timing centres, by transporting a portable GPS time receiver from one site to the other. Exercises in differential calibration of GPS receivers carried out in 1994 concerned the links between the OP ( France) and the NPL (United-Kingdom)<sup>[12]</sup>, the NIST (USA)<sup>[13]</sup>, the USNO (USA)<sup>[14]</sup>, and a European round-trip OP to OP successively through the OCA (France), the TUG (Austria), the FTZ (Germany), the PTB (Germany), the VSL (The Netherlands), and the NPL (United Kingdom)<sup>[15]</sup>.

Since 1983, several differential calibrations have been performed between the NIST and the OP. The results are shown in Table 1.

Date $t$	$\delta$ /ns	$\sigma$ /ns
July 1983	0.0	2.0
January 1985	-7.0	13.0
September 1986	+0.7	2.0
October 1986	-1.4	2.0
January 1988	-3.8	?
April 1988	+0.6	?
March 1994	+1.4	2.0

*Table 1. Results of 7 exercises in the differential calibration of the GPS time equipment in operation at the NIST and at the OP. The quantity  $\delta$  is the time correction to be added to the values  $UTC(NIST)(t) - UTC(OP)(t)$ , obtained at date  $t$  from raw GPS data, in order to ensure the best accuracy of the time link. The quantity  $\sigma$  is the estimated uncertainty ( $1 \sigma$ ) in the value  $\delta$ .*

In 1983 the internal delay of the OP GPS time receiver was determined at the NIST, before shipping to the OP, so that the time comparison values between  $UTC(NIST)$  and  $UTC(OP)$  could be obtained from GPS data without any systematic correction. This accuracy is maintained by applying time corrections  $\delta$  which compensate for variations with time in the internal delays of the two pieces of GPS equipment. The values of  $\delta$  remain inferior to their stated uncertainty ( $1 \sigma$ ) even after 10 years of continuous operation, which indicates the excellent long-term stability of the equipment.

For several years, GPS accuracy has also been studied by testing the closure condition through a combination of three links, OP-NIST, NIST-CRL and CRL-OP, using precise GPS satellite ephemerides and ionospheric delays measured at the three sites<sup>[6]</sup>. As shown in Fig. 5, the closure condition presents a residual bias of a few nanoseconds on daily averages which can

be determined with a precision of less than 2 ns. With the passage of time, the IGS precise satellite ephemerides continue to improve, which results in a corresponding improvement in the determination of the deviation from the closure. The residual bias now probably originates from errors in station coordinates and errors in ionospheric measurements. Results from codeless dual-frequency ionospheric measurement systems are sensitive to multipath effects which induce biases in particular directions<sup>[16]</sup>: these biases are not averaged when testing the closure condition if the observations selected are directed towards the East and West. Work is under way to evaluate these biases.

Within the group on GPS Time Transfer Standards, GGTTS, the BIPM has made a considerable effort to formulate technical directives for the standardization of GPS time-receiver software, together with a new format for GPS data files<sup>[17, 18]</sup>. The implementation of such directives and of the new data format should help to provide sub-nanosecond accuracy for GPS common-view time transfer. Practical development of the standardized software is in hand at the NIST and it is intended that it will be available for world-wide use from beginning of 1995<sup>[19]</sup>.

Another issue is the estimation of the tropospheric delay. At present, GPS time-receivers use simple models of the troposphere which, as was believed until recently, should provide an estimation of tropospheric delay with an uncertainty of 1 ns to 2 ns. Recent comparisons of these models with a semi-empirical model based on weather measurements show, however, differences of several nanoseconds for hot and humid regions of the world<sup>[20]</sup>. Further investigations of the tropospheric delay will continue at the BIPM.

## **GLOBAL NAVIGATION SATELLITE SYSTEM, GLONASS**

Values of comparison between UTC and GLONASS time, provided from observations of GLONASS satellites by Prof. P. Daly, University of Leeds, are currently published in the *BIPM Circular T*. The BIPM intends to issue an experimental international GLONASS common-view schedule in 1995, and to test it through an experiment with the RIRT, Russia. For this purpose, the BIPM will receive a GLONASS time receiver on loan from Russia.

## **TWO-WAY SATELLITE TIME TRANSFER, TWSTT**

Two-way time transfer through a geostationary satellite is potentially more accurate than one-way methods such as those using GPS or GLONASS, essentially because there is no need to evaluate the range between ground station and satellite. No two-way time transfer experiment has been conducted at the BIPM, which does not possess the necessary heavy equipment, however, the BIPM does chair the CCDS working group on Two-Way Satellite Time Transfer, which meets every year, and was involved in the comparison between the two-way technique and the GPS common-view method which used the link between the TUG (Austria) and the OCA (France)<sup>[21]</sup>. The BIPM was also involved in the field-trial which was organized in 1994. This is an international two-way time transfer experiment through the INTELSAT V-A(F13) satellite at 307°E, which involves both European and North-American laboratories. This began in January 1994 and should last one year. During the summer of 1994, the Earth stations involved have been calibrated using a portable station. At the same time, the GPS equipment in these laboratories was differentially calibrated using a portable GPS time receiver provided

by the BIPM. These calibration exercises should allow previous estimates of the accuracy, of order 2 ns (1  $\sigma$ ), of the two-way technique to be verified<sup>[15]</sup>.

### **LASer Synchronization from Satellite Orbits, LASSO**

The BIPM has been involved in an experiment to compare time transfer by LASSO with GPS common-view time transfer between Texas and France<sup>[22]</sup>. The results of the calibration of laser equipment at the two sites should be available at the end of 1994 and will allow, for the first time, an estimation of the accuracy of the LASSO technique, which is expected to be of order 1 ns (1  $\sigma$ ).

### **Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS**

The Experiment on Timing Ranging and Atmospheric Soundings, ExTRAS, calls for two active and auto-tuned hydrogen masers to be flown on board a Russian meteorological satellite Meteor-3M, planned for launch at the beginning of 1997. Communication between the on-board clocks and ground stations is effected by means of a microwave link using the PRARE technique, Precise Range And Range-rate Equipment, and an optical link operating using the T2L2 method, Time Transfer by Laser Link. The PRARE and T2L2 techniques are upgraded versions of the usual two-way and LASSO methods. Associated with the excellent short-term stability of the on-board hydrogen masers, these should make it possible to solve a number of scientific and applied problems in the fields of time, navigation, geodesy, geodynamics and Earth-atmosphere physics. The impact of ExTRAS in the time domain, has been studied<sup>[23]</sup> in terms of anticipated uncertainty budgets: the potential accuracy of this experiment is characterized by uncertainties below 500 ps (1  $\sigma$ ) for satellite clock monitoring and ground clock synchronization.

## **APPLICATION OF GENERAL RELATIVITY TO TIME METROLOGY**

An investigation of the application of the theory of relativity to time transfer has been completed<sup>[24]</sup>. Explicit formulae have been developed, which make it possible to compute, to picosecond accuracy, all terms describing the coordinate time interval between two clocks situated in the vicinity of the Earth, and linked through *i*) a one-way technique (GPS), *ii*) a two-way method via a geostationary satellite (TWSTT), or *iii*) a two-way optical signal (LASSO).

Current work centers on the application of the theory of relativity to the frequency syntonization of a clock with respect to the Geocentric Coordinate Time (TCG) at an accuracy level of  $10^{-18}$ . For Earth-bound clocks, this is limited to some parts in  $10^{17}$  due to poor knowledge of some geophysical factors (essentially the potential on the geoid). However, for clocks on terrestrial satellites, all terms can be calculated with  $10^{-18}$  accuracy. The results of this work will allow the establishment of a complete relativistic framework for the realization of TCG at a stability of  $10^{-18}$  and picosecond TCG datation accuracy. This should be sufficient to accommodate all expected developments in clock technology and time transfer methods for some years to come.



The work of the CCDS working group on the Application of General Relativity to Metrology was supported by numerous discussions with Prof. B. Guinot, Chairman of the working-group, and participation in the preparation of a text to be used as part of the final report of this group.

## **PULSARS**

Millisecond pulsars can be used as stable clocks to realize a time scale by means of a stability algorithm. Work has been carried out with a view to understanding how such a pulsar time scale could be realized and how it could be used for monitoring very-long instabilities of atomic time. An important feature of this work is that a pulsar time scale could allow the transfer of the accuracy of the atomic second from one epoch to another, thus overcoming some of the consequences of failures in atomic standards<sup>[25]</sup>.

## **CONCLUSIONS**

The Time Section of the BIPM produces time scales which are used as the ultimate references in the most demanding scientific applications. They serve also synchronization of national time scales and local representations of the Coordinated Universal Time, upon which rely all time signals used in current life. This work is thus in complete accordance with the fundamental missions of the BIPM.

Timing data used to generate the International Atomic Time comes from national metrological institutes where timing equipment is maintained and operated in the best conditions. An international collaboration is thus necessary and requests from the contributing laboratories to follow guides given by the BIPM. In return, the BIPM has the duty to process data in the best way in order to deliver the best reference time scales. For this purpose, it is necessary for the BIPM to examine in detail timing techniques and basic theories, to propose alternative solutions for timing algorithms, and to follow advice and comments expressed inside the CCDS working groups.

## References

- [1.] *"BIPM Comptes Rendus 18e Conférence Générale des Poids et Mesures, BIPM Publications, 1987, p 23.*
- [2.] *IAU, Information Bulletin 67, 1992, p 7.*
- [3.] *TAVELLA P. and THOMAS C., "Comparative Study of Time Scale Algorithms," Metrologia, 1991, 28, 57-63.*
- [4.] *ALLAN D.W. and WEISS M.A., "Accurate time and frequency transfer during common-view of a GPS satellite," Proc. 34th Ann. Symp. on Freq. Control, 1980, p 334.*
- [5.] *ALLAN D.W., GRANVEAUD M., KLEPCZYNSKI W.J., and LEWANDOWSKI W., "GPS Time Transfer with Implementation of Selective Availability," Proc. 22nd PTTI, 1990, 145-156.*
- [6.] *LEWANDOWSKI W., PETIT G., and THOMAS C., "Precision and Accuracy of GPS Time Transfer," IEEE Trans. Inst. Meas., 42, 1993, 474-479.*
- [7.] *LEE W.D., SHIRLEY J.H., LOWE J.P., and DRULLINGER R.E., "The accuracy Evaluation of NIST-7," IEEE Trans. Instr. Meas., 1995, accepted.*
- [8.] *ROVERA D., DE CLERCQ E., and CLAIRON A., "An Analysis of the Major Frequency Shifts in the LPTF Optically Pumped Primary Frequency Standard," IEEE Trans. Utl. Fer. and Freq. Cont., 41, 1994, p 245.*
- [9.] *THOMAS C. and ALLAN D.W., "A real-time prediction of UTC," Proc. 25th PTTI meeting, 1993, 217-229.*
- [10.] *AZOUBIB J. and THOMAS C., "The Use of Hydrogen Masers in TAI Computation," Proc. 9th EFTF, 1995, accepted.*
- [11.] *THOMAS C., "The use of the AOA TTR-4P GPS receiver in operation at the BIPM for real-time restitution of GPS time," Proc. 25th PTTI, 1993, 183-194.*
- [12.] *THOMAS C. and MOUSSAY P., "Determination of differential time correction between GPS time receivers located at the Observatoire de Paris, Paris, France, and the National Physical Laboratory, Teddington, United Kingdom," Rapport BIPM-94/2, 1994; 12 pages.*
- [13.] *THOMAS C., MOUSSAY P., "Determination of differential time correction between GPS time receivers located at the Observatoire de Paris, Paris, France, and the National Institute of Standards and Technology, Boulder, Colorado, USA," Rapport BIPM-94/3, 1994, 12 pages.*
- [14.] *LEWANDOWSKI W., "Determination of the differential time correction between GPS time equipment located at the Observatoire de Paris, Paris, France, and the United States Naval Observatory, Washington D.C., USA," Rapport BIPM-94/11, 1994, 14 pages.*

- [15.] KLEPCZYNSKI W.J, DAVIS J.A., KIRCHNER D., DE JONG G., BAUMONT F., HETZEL P., SOERING A., HACKMAN C., GRANVEAUD M., and LEWANDOWSKI W., "Comparison of Two-Way Satellite Time Transfer with GPS Common-View Time Transfer during the Intelsat Field Trial," *Proc. 9th EFTF, 1995*, accepted.
- [16.] THOMAS C., PETIT G., and MOUSSAY P., "Comparison between different dual-frequency GPS receivers measuring ionospheric delay for time and frequency applications," *Proc. 8th EFTF, 1994*, 1012-1028.
- [17.] ALLAN D.W. and THOMAS C, "Technical Directives for Standardization of GPS Time Receiver Software," *Metrologia*, 1994, 31, 69-79.
- [18.] THE GROUP ON GPS TIME TRANSFER STANDARDS, "Technical Directives for Standardization of GPS Time Receiver Software," *Rapport BIPM-93/6, 1993*, 32 pages.
- [19.] WEISS M.A. and THOMAS C., "Implementation and Release of a Standard Format for GPS Common View data," *Proc. 26th PTTI, 1994*, accepted.
- [20.] LEWANDOWSKI W., GRUDLER P., and BAUMONT F., "Study of tropospheric correction for GPS common-view time transfer between the BIPM and the OCA," *Proc. 8th EFTF, 1994*, 981-997.
- [21.] KIRCHNER D., RESSLER H., GRUDLER P., BAUMONT F., LEWANDOWSKI W., HANSON W., KLEPCZYNSKI W., and UHRICH P., "Comparison of GPS and Two-Way Satellite Time Transfer Over A Baseline of 800 km," *Metrologia*, 1993, 30, 183-192.
- [22.] LEWANDOWSKI W., PETIT G., BAUMONT F., FRIDELANCE P., GAIGNEBET J., GRUDLER P., VEILLET C., WIANT J., KLEPCZYNSKI W.J, "Comparison of LASSO and GPS time transfers," *Proc. 25th PTTI, 1993*, 357-365.
- [23.] THOMAS C., WOLF P., UHRICH P., SCHAEFER W., NAU H., and VEILLET C., "Anticipated Uncertainty Budgets of PRARE and T2L2 Techniques as Applied to ExTRAS," *Proc. 26th PTTI, 1994*, accepted.
- [24.] PETIT G., WOLF P., "Relativistic theory for picosecond time transfer in the vicinity of the Earth," *Astronomy and Astrophysics*, 1994, 286, 971-977.
- [25.] PETIT G., TAVELLA P., and THOMAS C., "How can Millisecond Pulsars improve the Long-Term -Stability of Atomic Time Scales?," *Proc. 6th EFTF, 1992*, 57-60.

Acronyms of the laboratories quoted in the text

CRL	Communications Research Laboratory, Tokyo, Japan
FTZ	Forschungs – und Technologiezentrum, Darmstadt, Germany
LPTF	Laboratoire primaire du Temps et des Fréquences, Paris, France
NIST	National Institute of Standards and Technology, Boulder, CO, USA
NPL	National Physical Laboratory, Teddington, United Kingdom
OCA	Observatoire de la Côte d’Azur, Grasse, France
OP	Observatoire de Paris, Paris, France
PTB	Physikalisch–Technische Bundesanstalt, Braunschweig, Germany
RIRT	Russian Institute of Radionavigation and Time, St. Petersburg, Russia, Austria
TUG	Technische Universität, Graz, Austria
USNO	U.S. Naval Observatory, Washington D.C., USA
VSL	Van Swinden Laboratorium, Delft, The Netherlands

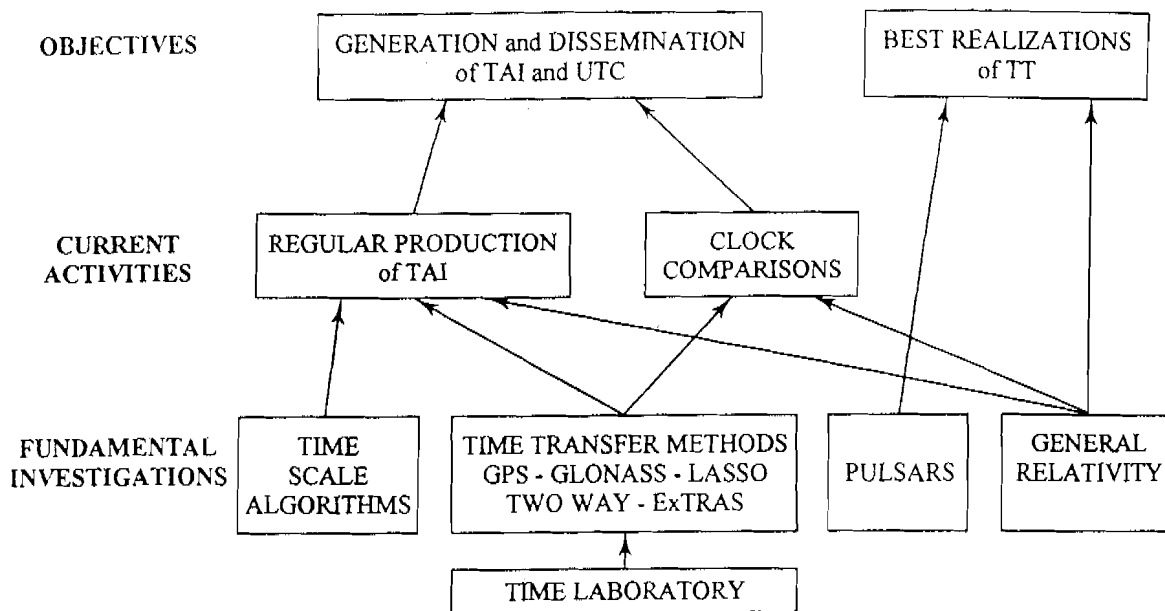


Figure 1. Organization of the work of the Time Section of the BIPM

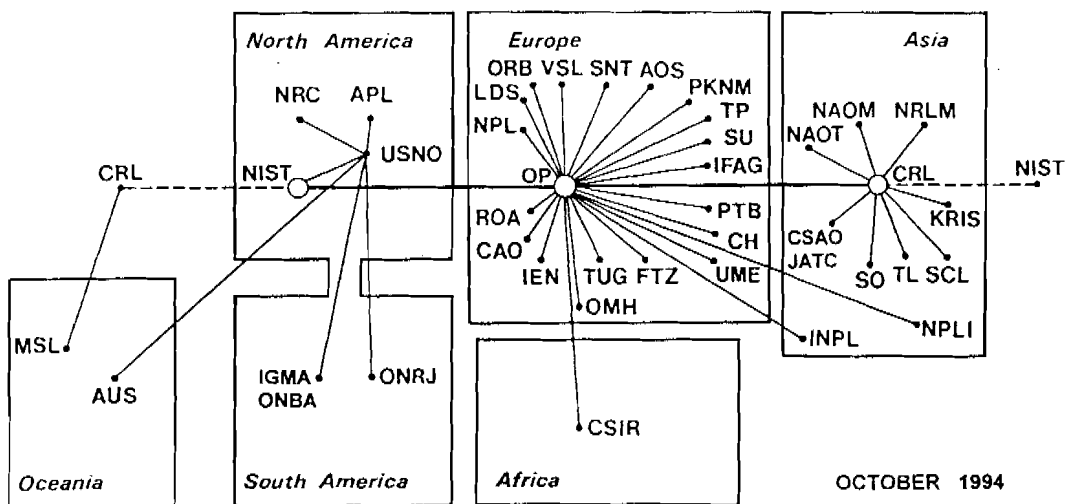
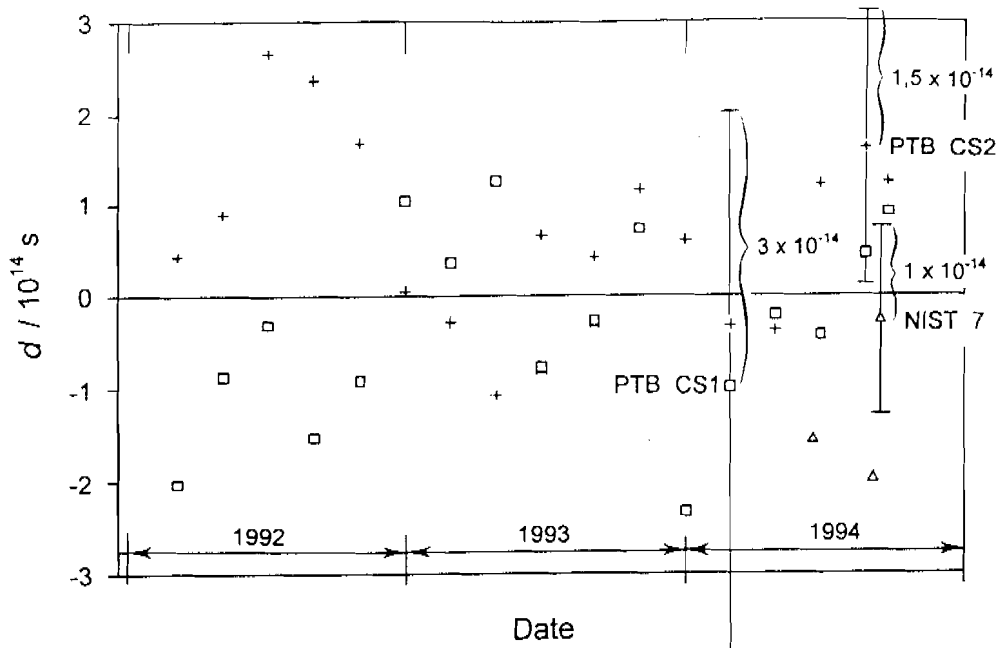
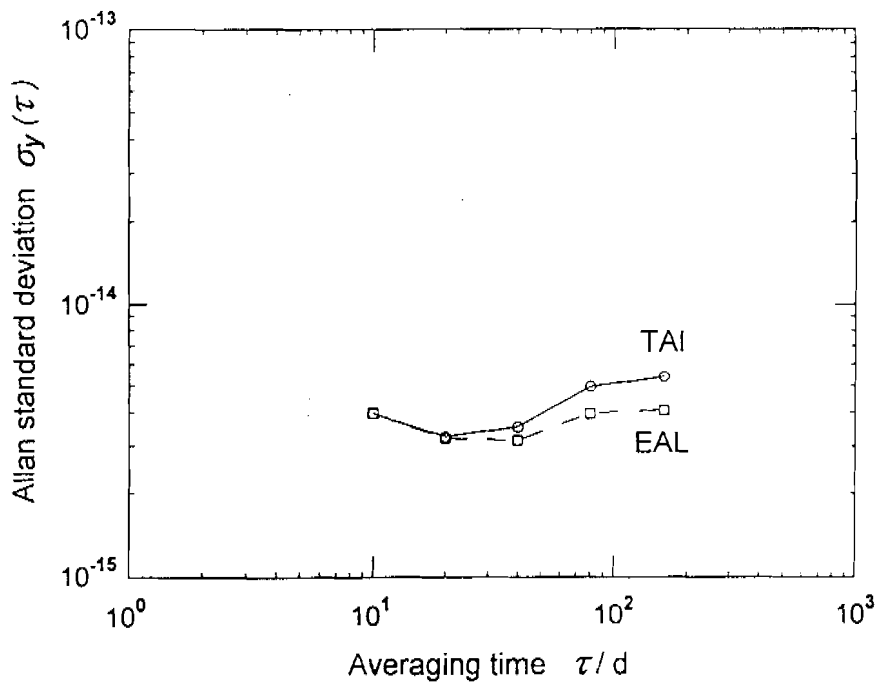


Figure 2. Organization of the international GPS time link network used for TAI computation (October 1994). Acronyms can be found in Table 3 of the Annual Report of the BIPM Time Section, Volume 6, 1994.



**Figure 3.** Deviation  $d$  of the TAI scale interval from the SI second on the rotating geoid, as provided by the primary frequency standards PTB CS1, PTB CS2, and NIST 7 (error bars correspond to the published uncertainty  $1 \sigma$ ). Recall that the frequency of NIST 7 is corrected for the black body radiation shift while those of PTB CS1 & 2 are not.



**Figure 4.** Stability of TAI and EAL. Allan standard deviations obtained by application of the N-cornered hat technique to data obtained in 1993 and at the beginning of 1994, for the comparisons between TAI and the time scales maintained at the NIST, the VNIIFTRI, the USNO and the PTB.

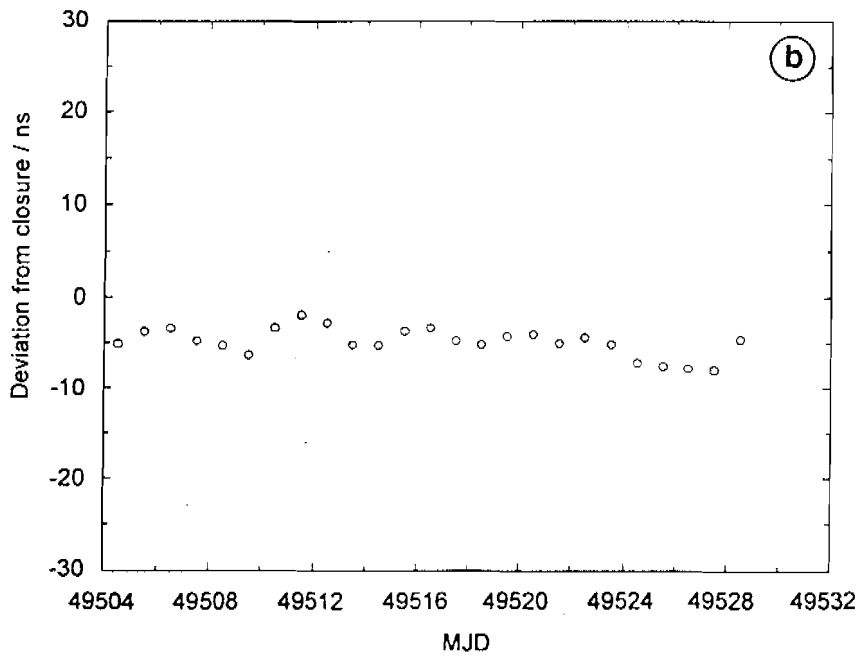
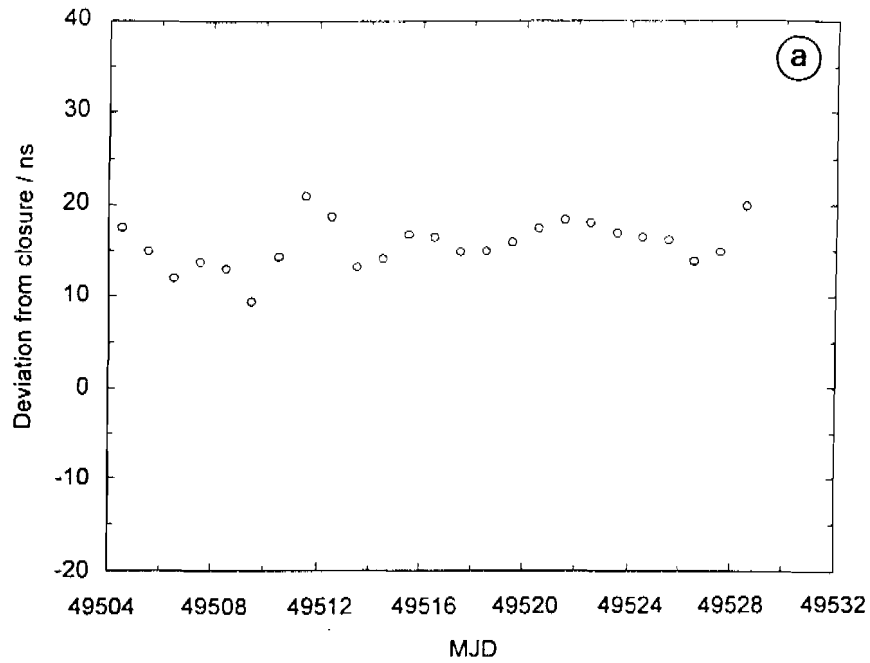


Figure 5. Deviation from the closure around the world obtained from GPS common-views between the OP and the CRL, the CRL and the NIST, and the NIST and the OP. The sum of these three links is computed: in Fig. 5.a. with raw GPS data and amounts to  $(15,7 \pm 2,6)$  ns, and in Fig. 5.b. with GPS data corrected for measured ionospheric delays and post-processed precise satellite ephemerides, and amounts to  $(-4,8 \pm 1,6)$  ns.

# THE EFFECTS OF CLOCK ERRORS ON TIMESCALE STABILITY

Lee A. Breakiron  
Directorate of Time  
U.S. Naval Observatory  
Washington, DC 20392

## Abstract

*The weighting scheme for the cesium clocks and hydrogen masers constituting the USNO timing ensemble is reexamined from an empirical standpoint of maximizing both frequency accuracy and timescale uniformity. The utility of a sliding-weight relation between the masers and the cesiums is reaffirmed, but improvement is found if one incorporates inverse Allan variances for sampling times of 12 and 6 hours for the cesiums and masers, respectively, with some dependence on clock model.*

## INTRODUCTION

Maximum timescale stability and efficient use of resources require the proper relative weighting of data from atomic clocks. This paper represents a continuation in our quest for an optimal weighting scheme as the U.S. Naval Observatory (USNO) clock ensemble has changed, first with the addition of hydrogen masers to our cesium-beam frequency standards and then with the introduction of the new-model HP5071A cesium standards, which are phasing out our HP5061 standards. The previous study of our weights was based on data from HP5061 cesiums and a few masers<sup>[1]</sup>. The lower noise of the HP5071A cesiums justifies a reexamination of our weighting procedures.

Since timescale algorithms are generally designed to optimize frequency stability, clocks are commonly weighted according to their individual frequency stabilities, as measured by inverse Allan variances  $1/\sigma_y^2$ . A previous study, however, found no significant improvement in our timescale if inverse Allan variances were used rather than equal weights, so the latter have been retained<sup>[2]</sup>. The performance of each USNO clock is closely monitored and any change in its rate precipitates total deweighting until its behavior is again satisfactory and its rate accurately redetermined. The deweighting is done automatically in the computation of the near-real-time mean timescale (done every hourly measurement) toward which the Master Clocks are steered; deweighting is done manually during the repeated postprocessing which ultimately results in the final timescale.

The incorporation of hydrogen masers, with their different noise characteristics, requires special treatment of their data. Some labs use a Kalman filter to handle data from such a heterogenous



ensemble<sup>[3]</sup>. We have obtained good results from a sliding-weight relation between the masers and the cesiums that mirrors their respective class average sigma-tau plots, with the sampling time  $\tau$  replaced by the time prior to the latest measurement<sup>[1]</sup>. This results in a time dependence of the weights, requiring recomputation of the entire timescale every hourly time step. The masers dominate the clock weights in the recent past, but are entirely phased out over a 75-day period, so only the last 75 days actually need to be recomputed. This zeroing of the maser weights prevents any drift of the timescale due to the masers, since even though the frequency drifts of all clocks are determined and removed from the data, some errors in these drift corrections might otherwise accumulate.

Still, as data collect, reconsideration of the sliding-weight relation might be worthwhile, as might that of assuming equal weights for the masers among themselves. Also, fitting average sigma-tau plots to a class of clocks is not a straightforward, and may be a questionable, procedure, so the approach taken here is to select clocks of homogeneous type for generation of test timescales whose sigma-tau plots may then be meaningfully compared.

## THE HP5071A CESIUMS

The new-model HP5071A commercial cesium frequency standards exhibit a significant reduction in noise level over the older HP5061 models and other cesiums due to improvements in electronics and careful allowance for environmental effects<sup>[4]</sup>. USNO currently has 50 HP5071A cesiums in 13 vaults or environmental chambers available for timescale data acquisition. In fact, they have been used in the timescale computation since February 1992. A preliminary scheme weighted an HP5071A cesium equal to 1.5 times that of an HP5061 cesium.

In order to further investigate their weights, twelve of the best HP5071A cesiums were selected which displayed constant rate and negligible drift over an interval of 200 days (MJD 49137–49337, when the reference maser changed rate). Fig. 1 is a sigma-tau plot for the twelve HP5071A cesiums relative to the Sigma-Tau maser NAV5 (in all such plots, a frequency offset has been removed). Approximating their weights with inverse Allan variances at a sampling time of 30 days (around the minimum), we find that the weights range over a factor of 3.1.

However, how valid are Allan-variance-based weights for these clocks, and what sampling time should be used? Though the theoretical answer to the latter for our algorithm is one hour, the true answers to both questions are affected by noise and systematics. In particular, the noise of our time-interval-counter measurement system is significant at one hour. A proper gauge of a clock's contribution to a timescale is:

$$\frac{1}{\sigma_{c,i}^2(\tau)} = \frac{1}{\sigma_{t,si}^2(\tau)} - \frac{1}{\sigma_{t,so}^2(\tau)} \quad (1)$$

where  $\sigma_{c,i}^2(\tau)$  is the reduction in variance contributed by clock  $i$ ,  $\sigma_{t,si}^2(\tau)$  is the Allan variance of the timescale computed including clock  $i$ , and  $\sigma_{t,so}^2(\tau)$  is the Allan variance of the timescale computed without clock  $i$ .

This assumes that the clocks involved are not significantly correlated. This has been found to

be the case for USNO clocks when the clocks are not disturbed by environmental and human influences<sup>[2,5]</sup>, which are minimized by the environmental control and maintenance procedures at USNO; data affected by such disturbances have been rejected from this study, as they are from the computation of UTC (USNO). While correlations may seem to be significant when clock frequency variations are intercompared<sup>[5]</sup>, unpublished USNO results indicate that few of these cannot be explained by the use of a common reference, as has been found by others<sup>[6]</sup>.

The intention was to use these clocks to generate test timescales, and twelve clocks were thought to be sufficient to produce a stable timescale, while still being few enough for such a timescale to show a measurable effect if one of the clocks was omitted. Test timescales were generated for all twelve clocks and every subset of eleven clocks, using equal weights; the clock contributions were then calculated via Eq. (1). An indication of the best Allan variance to weight by would be that which best predicts a clock's contribution to such a timescale. Unfortunately, a scatter plot showed only that an Allan variance for a sampling time of a few hours was better for weighting than one for a few days.

To better quantify this, a relative error parameter  $\phi$  was defined such that:

$$\phi_i^2(\tau) = \frac{|\sigma_{c,i}^2(\tau) - \sigma_{y,i}^2(\tau)|}{\sigma_{c,i}^2(\tau)} \quad (2)$$

where  $\sigma_{y,i}^2(\tau)$  is the Allan variance of clock  $i$ . Values of  $\log \phi$  are plotted vs.  $\log \tau$  for all the cesiums in Fig. 2. Some points are missing because  $\phi$  was not available when the computed clock contribution was negative, as it occasionally was, due to noise. Averages were not very stable, but the median minimum relative error occurred for a sampling time of 12 hours.

As a check, test timescales were generated for the same interval and clocks, weighting the clocks by inverse Allan variances over a range of sampling times from 1 hour to 30 days. The resulting sigma-tau plots are given in Fig. 3. There is little difference between most of them, but the worst are the long sampling times, as one would expect. The best sampling time was around 12 hours. Variances computed for  $\tau = 12$  hours would also reflect well the effects of any diurnal environmental perturbations. At  $\tau = 12$  hours,  $\sigma_{c,i}^2(\tau)$  varied over a factor of 2.8 and  $\sigma_{y,i}^2(\tau)$  varied over a factor of 2.0. Consequently, inverse 12-hour Allan variances will be our choice for weighting the HP5071A cesiums.

## THE HP5061 CESIUMS

At present, 14 HP5061A cesiums and two HP5061B cesiums in four vaults or environmental chambers are available for timescale data acquisition. The sigma-tau plots for ten HP5061A cesiums are given in Fig. 4 for from 80 to 169 days of data. A similar analysis was attempted of the clock contributions as was done for the HP5071A cesiums. Also, each HP5061A clock was substituted for a member of the HP5071A ensemble, and timescales were generated and analyzed for each. In both cases, the HP5061A data were too noisy to reach reliable conclusions.

Comparing the average 12-hour Allan deviations in Fig. 4 with those in Fig. 1 gives:

$$\langle \sigma_{5071} / \sigma_{5061} \rangle = 0.795$$

Comparing the median 12-hour Allan deviations gives:

$$\langle \sigma_{5071} / \sigma_{5061} \rangle = 0.785$$

Consequently, we will adopt a weight ratio of:

$$w_{5061} / w_{5071} = \sigma_{5071}^2 / \sigma_{5061}^2 = 0.62$$

for any HP5061 cesium relative to a typical HP5071A cesium.

As a check on whether equal weights should be retained for the HP5061A clocks, test timescales were generated for 104 days of data (MJD 49233–49337), weighting by inverse Allan variances for a range of sampling times. The results are presented in Fig. 5. While inverse 1-hour Allan variances make slightly better weights than those for somewhat longer sampling times, equal weights yielded significantly better stabilities than did any of the Allan-variance-based weights.

## THE MASERS

USNO currently has three SAO masers and ten Sigma-Tau masers in seven vaults or environmental chambers available for timescale data acquisition. During a 222-day interval (MJD 49404–49626) of constant drift and variance, four SAO masers (one has since left) and five Sigma-Tau masers were selected for analysis. Some rate corrections and occasional outlier rejections were required, but this is done routinely by the timescale algorithm. Some of these masers were steered in frequency, so their data were mathematically dестeered.

An n-cornered-hat analysis was performed to obtain their absolute Allan deviations, which are plotted in Figs. 6 (for the SAO masers) and 7 (for the Sigma-Tau masers). (The analytical method, which produces identical results as the method commonly in use<sup>[7]</sup>, is described in the Appendix and is due, as far as we know, to Winkler<sup>[8]</sup>.) The curves for the Sigma-Tau masers differ systematically from those of most of the SAO masers, as might be expected, since the former are auto-tuned. The average  $\tau$  of minimum variance is 0.8 days for the SAO masers and 5.9 days for the Sigma-Tau masers. Approximating their weights with inverse Allan variances at the average  $\tau$  of their minimum variances, we find that the weights range over a factor of 166 for the SAO masers and 14 for the Sigma-Tau masers. This indicates that the weights of the two types of masers should be derived separately and that an upper limit on the weight of a clock will be necessary (more on this later).

Meaningful computations of clock contributions, then, will require unequal weighting. In order to determine the  $\tau$  of the Allan variances for such weights, test timescales were generated for the above interval and masers relative to the masers MC #1 and MC #2, weighting by

inverse Allan variances over a range of sampling times. A three-cornered-hat analysis was then done between each timescale relative to Master Clock (MC) #1, each timescale relative to MC #2, and the difference MC #1 - MC #2 in order to determine the absolute Allan variances of each timescale. The sigma-tau curves of these timescales are displayed in Fig. 8. At smaller sampling times (where the stability of the masers is of most interest to us), 6-hour Allan-variance-based weights are best.

On that basis, 6-hour Allan-variance-weighted timescales were generated for all nine masers and for every subset of eight. Clock contributions were next computed as they were for the cesiums. The corresponding values of relative error  $\phi$  are plotted in Figs. 9 (for the SAO masers) and 10 (for the Sigma-Tau masers). Again, some of the points are missing due to noise. The situation is less clear than for the HP5071A cesiums, but the sampling time of the median minimum relative error is also 6 hours. Hence, we will adopt 6-hour Allan-variance-based weights for the masers.

## THE MASERS RELATIVE TO THE CESIUMS

The rationale behind the sliding-weight scheme relating the masers to the cesiums is that: (1) it combines the short-term stability of the masers with the long-term stability of the cesiums; and (2) it retains the systematic frequency accuracy of the cesiums as an anchor to the final timescale, while maximizing the relative frequency stability of the timescale in the recent past, where it is used to steer the Master Clocks. A Kalman-filter-based timescale algorithm can provide (1), but not (2). As noted above, the method requires recomputation of the timescale every time step, with the consequences that: (1) our timescale only becomes final 75 days in the past; and (2) UTC (USNO) at any given time may change by a few nanoseconds during those 75 days. The latter is logical because, as data accumulate, clock rates and drifts become more accurately determined, improving one's knowledge of the timescale at any point in the past.

As mentioned, HP5071A cesiums have been used in the timescale computation since February 1992. A preliminary scheme weighted the HP5071A cesiums and the hydrogen masers as follows:

$$w_{5071}(t) = 1/[\text{antilog}(0.130x^2 - 0.137x - 13.959)]^2 \quad (3)$$

$$w_{hm}(t) = 1/[\text{antilog}(0.309z^2 - 0.037z - 14.239)]^2 \quad (4)$$

where  $x = \log t - 5.9$ ,  $z = \log t - 5.2$ , and  $t$  is the time difference in seconds prior to the most recent measurement. At  $t = 0$ , the weight was arbitrarily set equal to  $t = 3600$  (not  $t = -1$ , as misstated in [1], p. 299).

In order to redetermine these relations using sigma-tau plots of timescales rather than those of clocks, test timescales were generated for: (1) the four SAO masers; (2) the five Sigma-Tau masers; and (3) five of the above HP5071A cesiums, all for the above 222-day interval. The masers were weighted by inverse 6-hour Allan variances and the cesiums by inverse 12-hour Allan variances. An upper limit of 33% of the total weight was placed on the individual

clock weights. Sigma-tau plots were computed for all three timescales. The ratio of the corresponding Allan variances for each maser timescale and the cesium timescale were taken and fitted with a second-order curve, as shown in Figs. 11 (for the SAO masers) and 12 (for the Sigma-Tau masers). The equations of these fits are:

$$w_{SAO/5071}(t) = [6.1 \pm 0.9](\log t)^2 - [79 \pm 9](\log t) + [257 \pm 22] \quad (5)$$

$$w_{ST/5071}(t) = [5.5 \pm 1.4](\log t)^2 - [76 \pm 14](\log t) + [261 \pm 34] \quad (6)$$

where  $t$ , the time in seconds prior to the latest measurement, has been substituted for  $\tau$ . The weights at  $t = 0$  are arbitrarily set equal to those at  $t = 3600$ . These relations reach minima at  $\log t = 6.5$  and  $6.9$ , respectively, at which point they can be ramped down to zero by  $t = 75$  days.

As a final test of the new weights, these sliding-weight relations, 6-hour maser weights, and 12-hour cesium weights were used for the same nine masers and nine of the HP5071A cesiums to generate timescales for the above 222-day interval. A single sigma-tau plot cannot properly characterize such a timescale because of the change in short-term stability relative to long-term stability with time. Since the cesiums dominate after 15 days in the past and it has been shown that the new weights provide some improvement over the old, the remaining question is whether the stability in the last 15 days has been enhanced. Accordingly, the interval was divided into fourteen 15-day segments and timescales were generated for each segment, with  $t$  reckoned from the end of each segment. The Allan variances of these timescales were then averaged and are presented in Fig. 13, where for comparison there have also been plotted the corresponding averages if one used the old weights<sup>[1]</sup> and the new weights but with no sliding relation. As can be seen, the new weights are a significant improvement on the short term over both the old and to not using the sliding relation at all.

## SUMMARY

The proper choice of timescale algorithm and clock weighting scheme depends on the purpose to which the resulting timescale is to be put. One objective of the USNO timescale is systematic frequency accuracy of the final timescale coupled with optimal relative stability in the recent past for the purpose of steering the Master Clocks. Compromise between these two aims is avoided by use of the sliding-weight relations between the masers and the HP5071A cesiums given in Eqs. (5) and (6). Adoption of inverse 6-hour Allan-variance weights for the masers and similar 12-hour weights for the cesiums will further improve UTC (USNO) by introducing responsiveness of the timescale to the performance of individual clocks beyond that already provided by careful monitoring and deweighting.

The new weights for an HP5071A clock  $i$  (of  $n$  such clocks) and an HP5061 clock  $j$  are, respectively:

$$w_{5071,i}(t) = \left[ \frac{\frac{1}{\sigma_{12,i}^2}}{\sum_{i=1}^n \frac{1}{\sigma_{12,i}^2}} \right] D_i(t) \quad (7)$$

and

$$w_{5061,j} = 0.62 \langle w_{5071} \rangle D_j(t) \quad (8)$$

where  $\sigma_{12}^2$  is the Allan variance for  $\tau = 12$  hours;  $D_i$  and  $D_j$  are deweighting factors in case of changes in performance, an uncertain rate, or an upper limit on the weight; and  $\langle \rangle$  denotes an average over all clocks. The new weight for a maser  $k$  (of a total of  $m$  such) is:

$$w_{hm,k}(t) = \left[ \frac{\sigma_{6,k}^2}{\sum_{k=1}^m \sigma_{6,k}^2} \right] D_k(t) w_{hm/5071}(t) \quad (9)$$

where  $\sigma_6^2$  is the Allan variance for  $\tau = 6$  hours,  $D_k$  is a deweighting factor, and  $w_{hm/5071}$  is given by Eq. (5) or (6). A upper limit on the weight prevents one or more superior clocks from dominating the timescale, which might lead to jolts of the timescale in the case of clock failure. The imposition of such a limit detracts from optimality, but is a requirement for reliability, which is another objective of the USNO timescale.

If the weights were based on stability relative to the mean timescale, a correction factor would have to be added to Eqs. (7), (8), and (9) for the so-called clock-ensemble effect, which would otherwise bias the timescale toward the best-performing clocks<sup>[9]</sup>. One may also question variances based on reference to a timescale whose own stability changes with time. Both problems may be avoided by referring the clocks to an unweighted, unsteered (or desteered) maser, rather than to the mean timescale.

Whether the adoption of gradual (robust), rather than instantaneous, deweighting would be a significant improvement remains to be tested; our large number of clocks has not made this a priority. Our short-term measurement noise should be appreciably reduced when our experimental Erbttec, or its successor the Steintech, system is reliable and capacious enough to be implemented, at which time the above weighting scheme will need to be reexamined. Further automation of the postprocessing procedure and more statistically rigorous treatment of rate and drift determination and rate and drift change detection are planned.

## REFERENCES

- [1] Breakiron, L. A., "Timescale algorithms combining cesium clocks and hydrogen masers," Proceedings of the 23rd Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1991, Pasadena, California, pp. 297-305.
- [2] Breakiron, L. A., "The effects of data processing and environmental conditions on the accuracy of the USNO timescale," Proceedings of the 20th Annual Precise Time and

Time Interval (PTTI) Applications and Planning Meeting, 29 November–1 December 1988, Tysons Corner/Vienna, Virginia, pp. 221–236.

- [3] Jacques, C., Boulanger, J.-S., Douglas, R. J., Morris, D., Cundy, S., and Lam, L. F., “*Time scale algorithms for an inhomogeneous group of atomic clocks*,” Proceedings of the 24th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 1–3 December 1992, McLean, Virginia, pp. 399–412.
- [4] Kusters, J. A., “*A new cesium beam frequency standard performance data*,” Proceedings of the 1992 IEEE Frequency Control Symposium, 27–29 May 1992, Hershey, Pennsylvania, pp. 143–150.
- [5] Breakiron, L. A., “*The effects of ambient conditions on cesium clock rates*,” Proceedings of the 19th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 1–3 December 1987, Redondo Beach, California, pp. 175–184.
- [6] Tavella, P. and Thomas, C., “*Report on correlations in frequency changes among clocks contributing to TAI*,” BIPM Report 91/4, 1991.
- [7] Allan, D. W., “*Time and frequency (time-domain) characterization, estimation, and prediction of precision clocks and oscillators*,” IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. UFFC-34, 1987, pp. 647–654 = NIST Technical Note 1337, pp. TN121–TN128.
- [8] Winkler, G. M. R., 1994, private communication.
- [9] Tavella, P., Azoubib, J., and Thomas, C., “*Study of the clock-ensemble correlation in ALGOS using real data*,” Proceedings of the 5th European Frequency and Time Forum, 12–14 March 1991, Besancon, France, pp. 435–441.

## APPENDIX

An n-cornered-hat analysis for the individual variances of a set of uncorrelated clocks may be performed by writing the variance of the difference between the measurements of clocks i and j as the sum of their individual variances:

$$\sigma_i^2 + \sigma_j^2 = \sigma_{ij}^2$$

for all possible pairs of n clocks and then solving these as a system of n (n - 1)/2 simultaneous linear equations. The matrix equation could be expressed as:

$$\mathbf{M} \mathbf{X} = \mathbf{Y}$$

where, for four clocks:

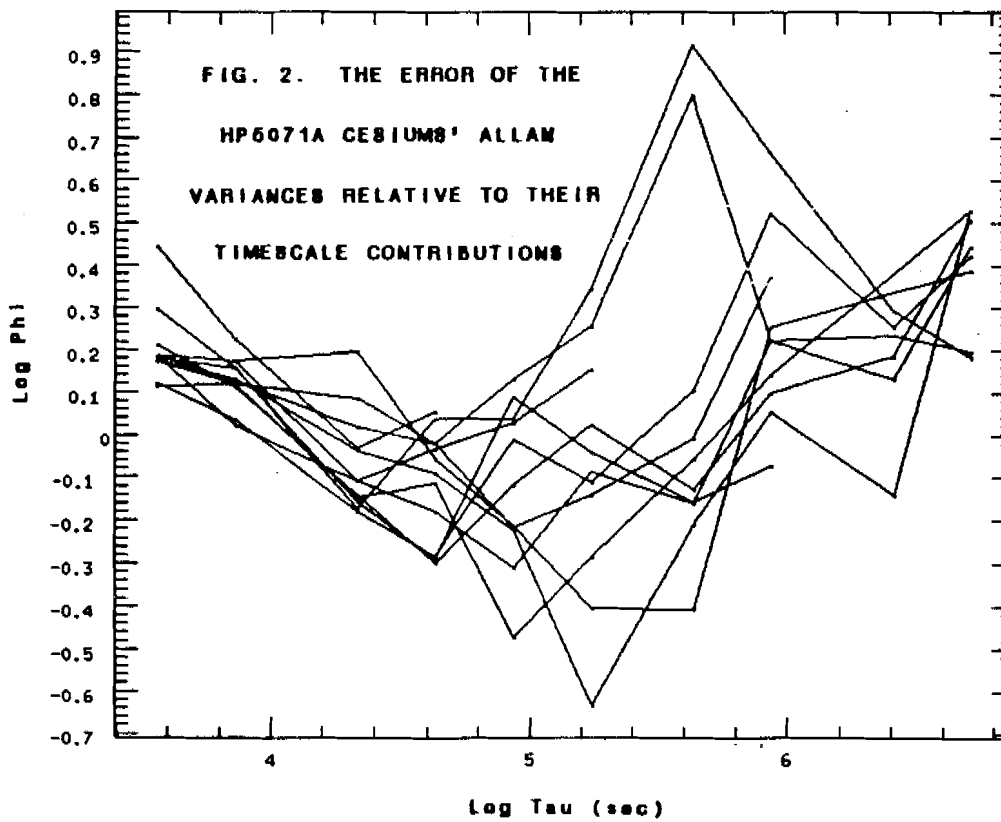
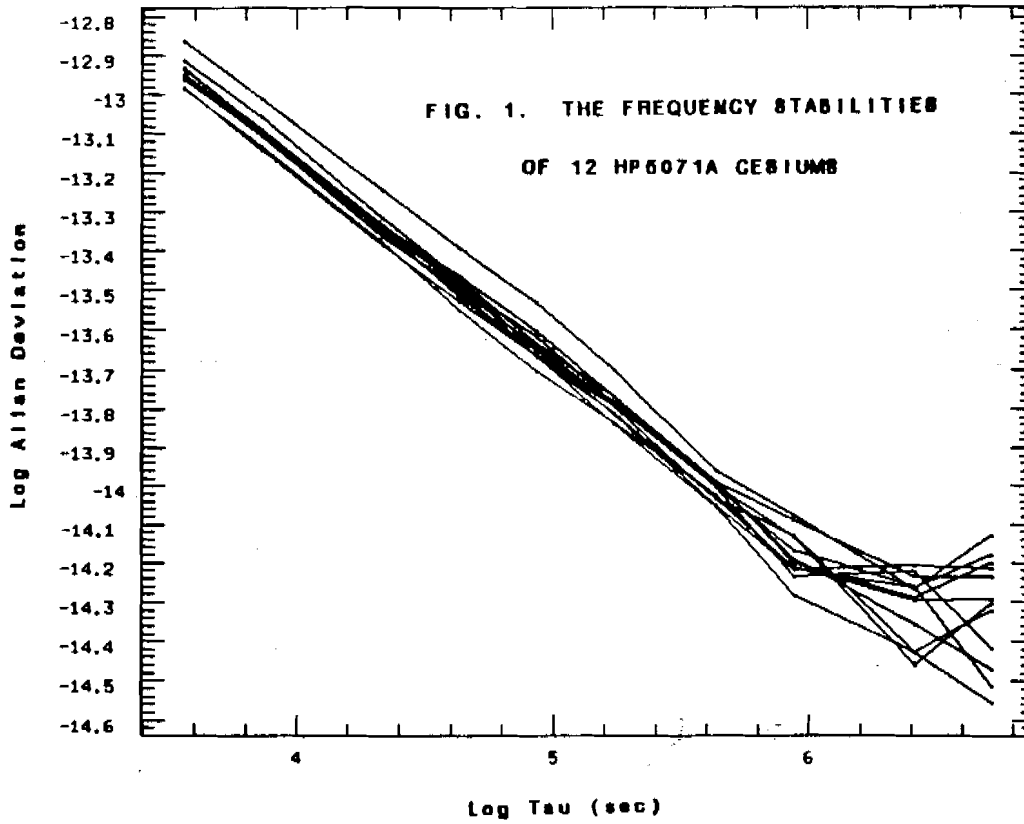
$$\mathbf{M} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \\ \sigma_4^2 \end{bmatrix} \quad \mathbf{Y} = \begin{bmatrix} \sigma_{12}^2 \\ \sigma_{13}^2 \\ \sigma_{14}^2 \\ \sigma_{23}^2 \\ \sigma_{24}^2 \\ \sigma_{34}^2 \end{bmatrix}$$

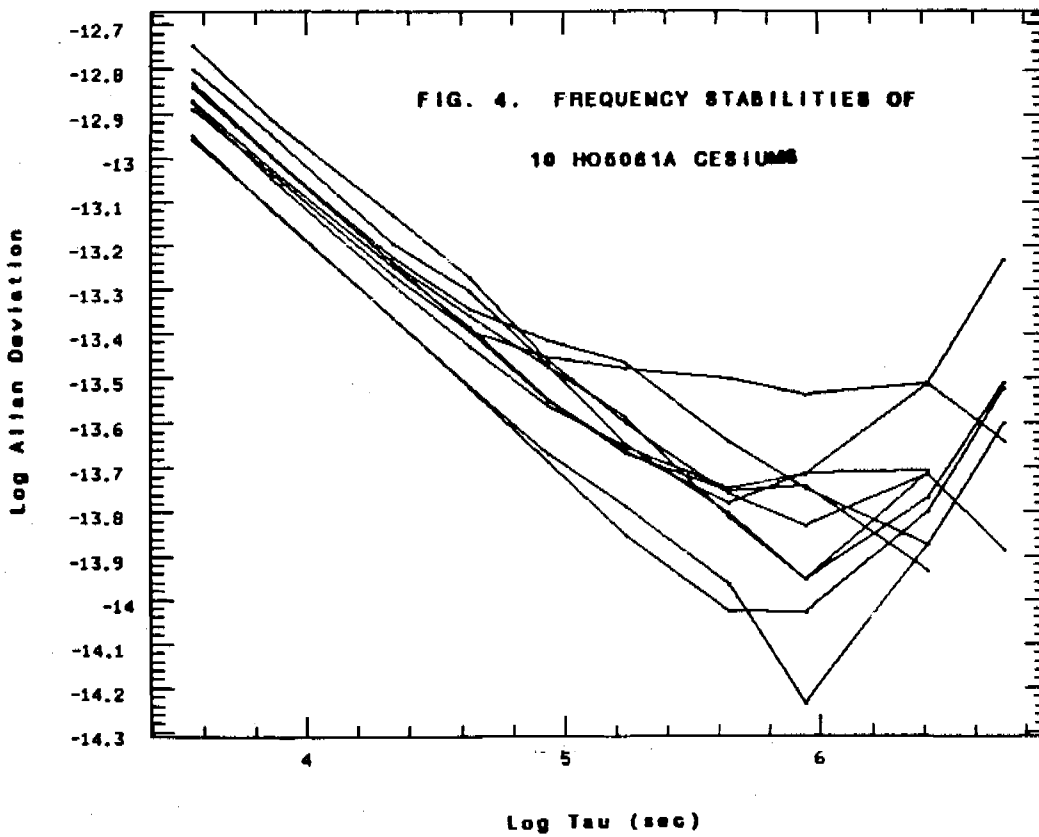
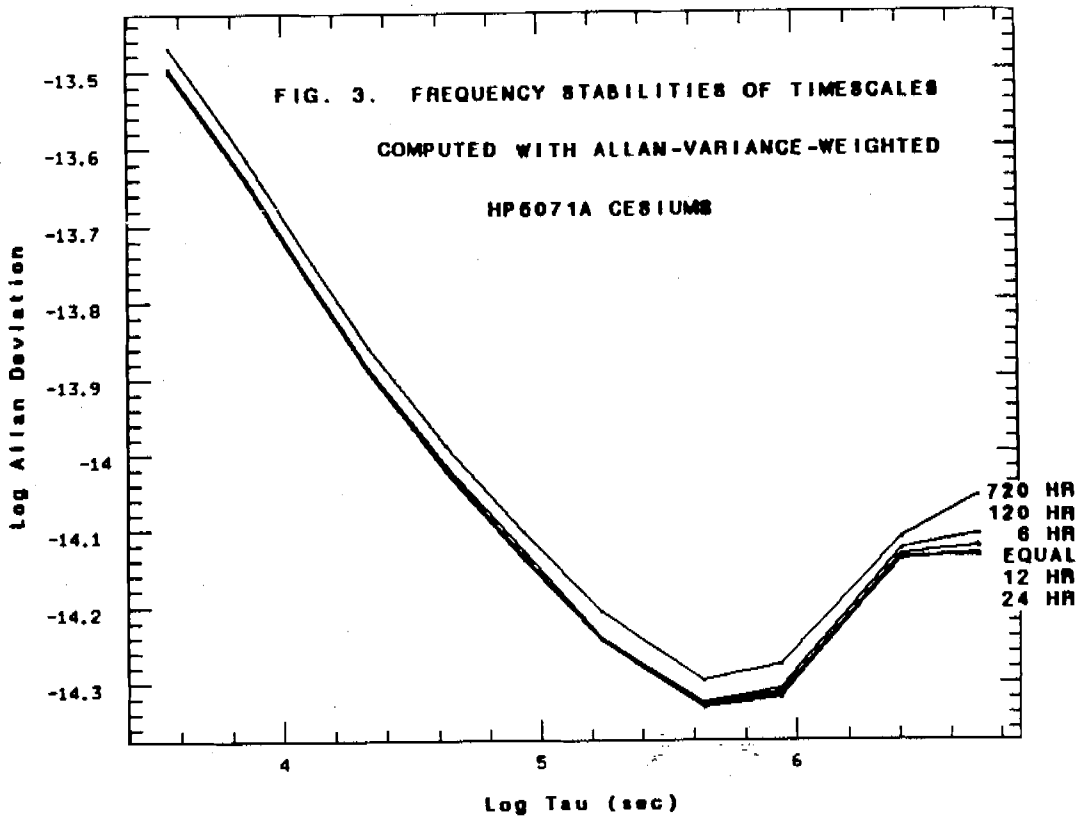
X may then be solved for by multiplying both sides by the Penrose pseudo-inverse of M, which here is:

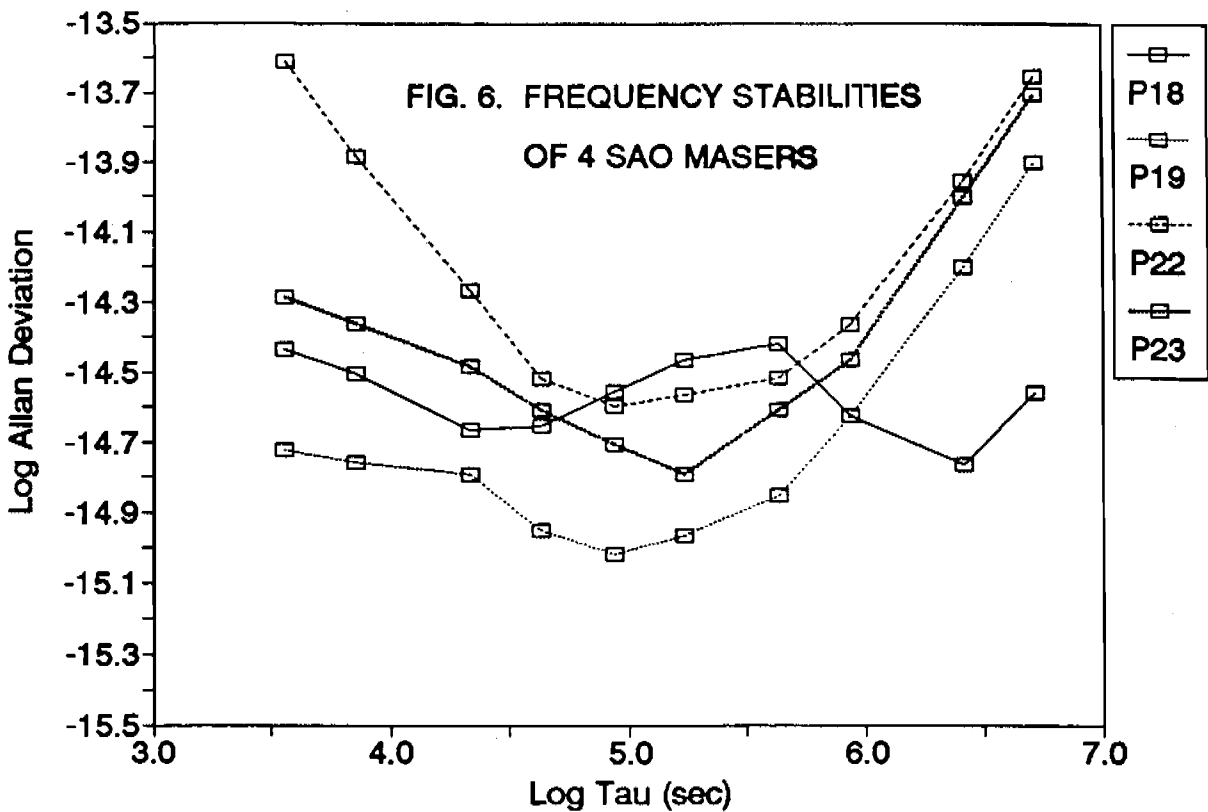
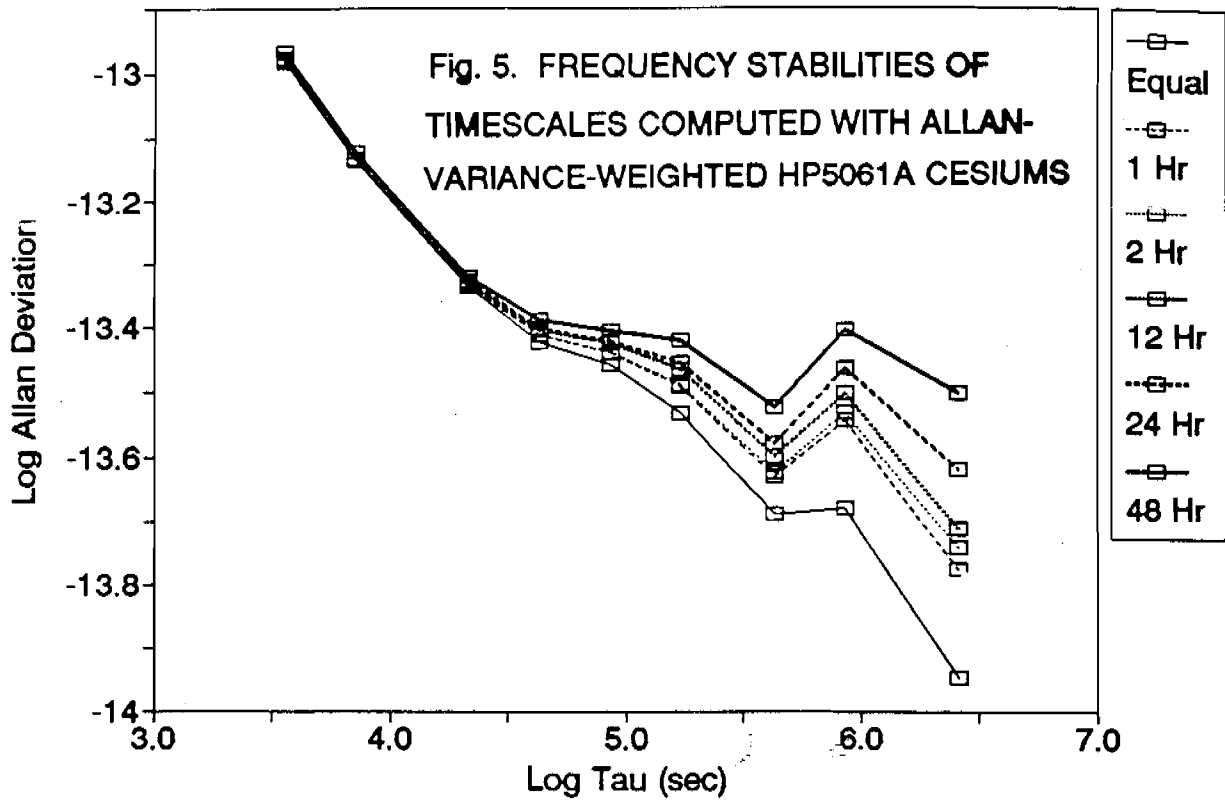
$$\mathbf{M}^{-1} = \begin{bmatrix} 0.3\bar{3} & 0.3\bar{3} & 0.3\bar{3} & -0.1\bar{6} & -0.1\bar{6} & -0.1\bar{6} \\ 0.3\bar{3} & -0.1\bar{6} & -0.1\bar{6} & 0.3\bar{3} & 0.3\bar{3} & -0.1\bar{6} \\ -0.1\bar{6} & 0.3\bar{3} & -0.1\bar{6} & 0.3\bar{3} & -0.1\bar{6} & 0.3\bar{3} \\ -0.1\bar{6} & -0.1\bar{6} & 0.3\bar{3} & -0.1\bar{6} & 0.3\bar{3} & 0.3\bar{3} \end{bmatrix}$$

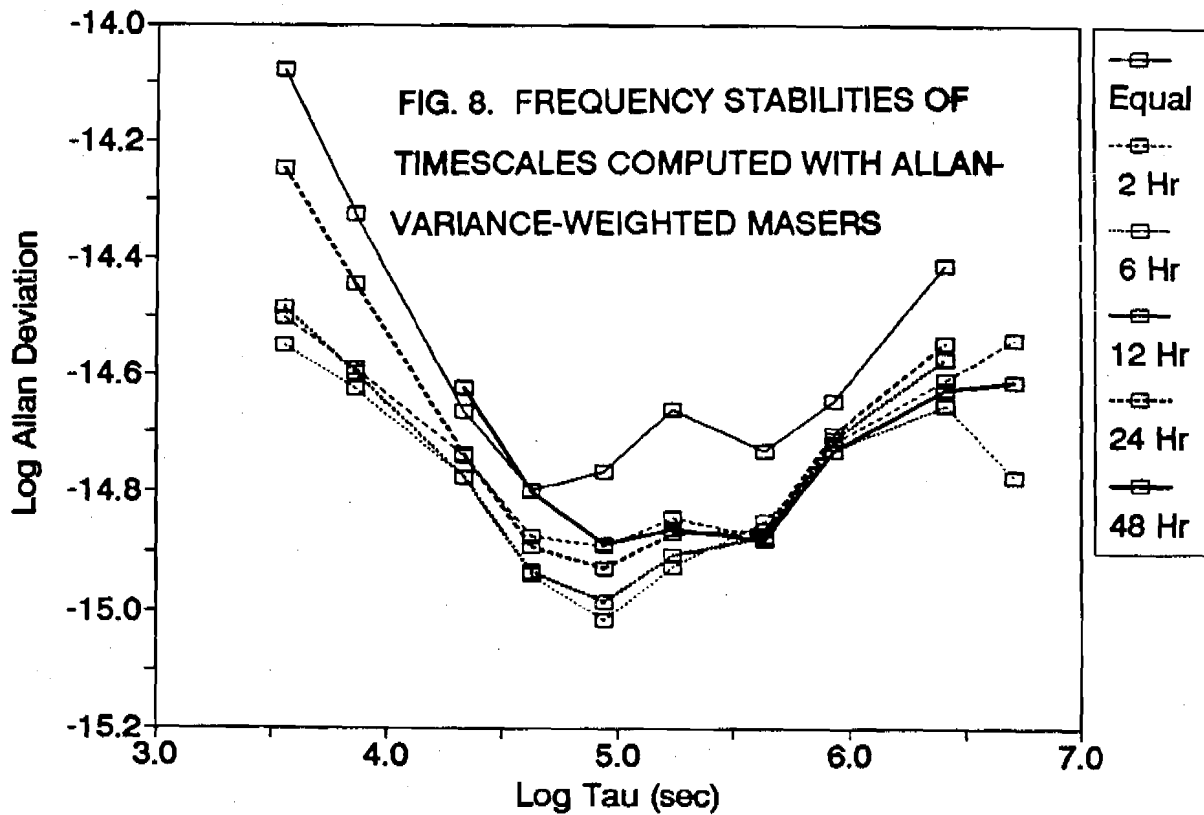
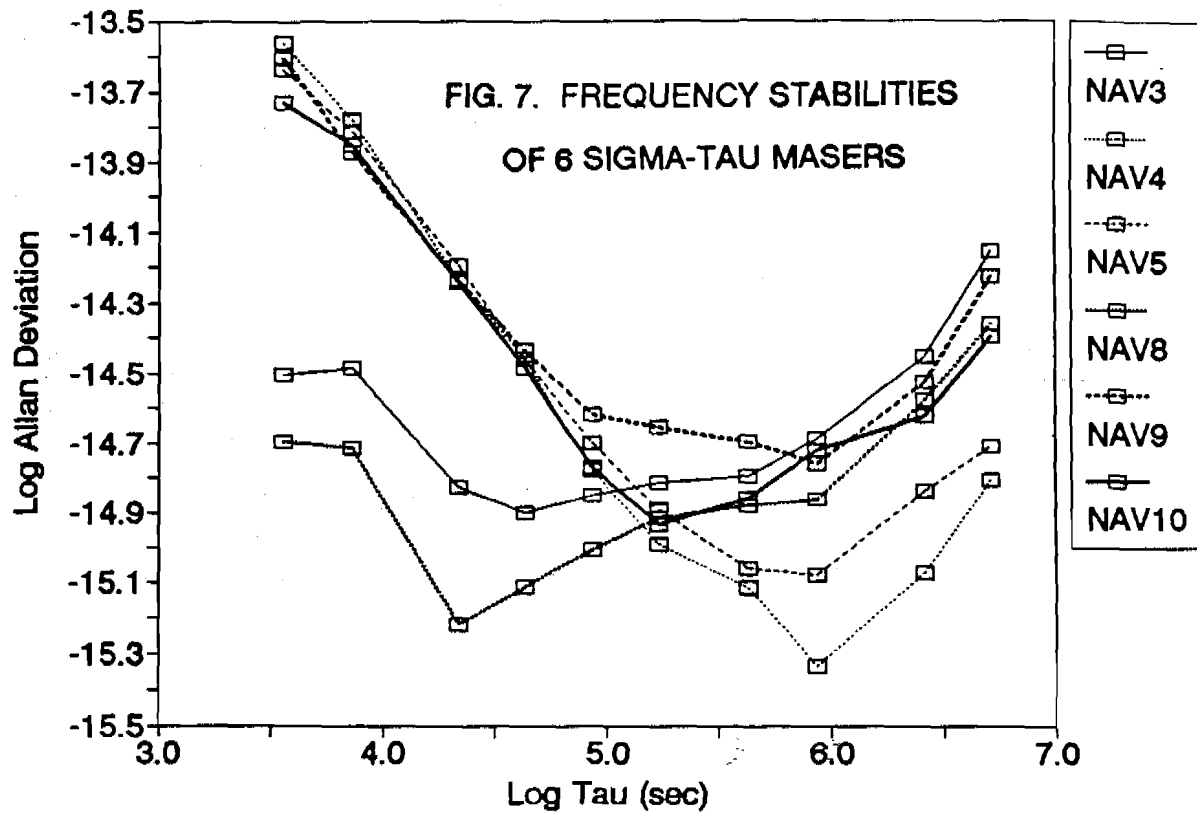
As with the standard n-cornered-hat method, the analysis fails if any of the variances solved for comes out negative. This generally occurs when the clocks are significantly intercorrelated, causing the variances to be underestimated.

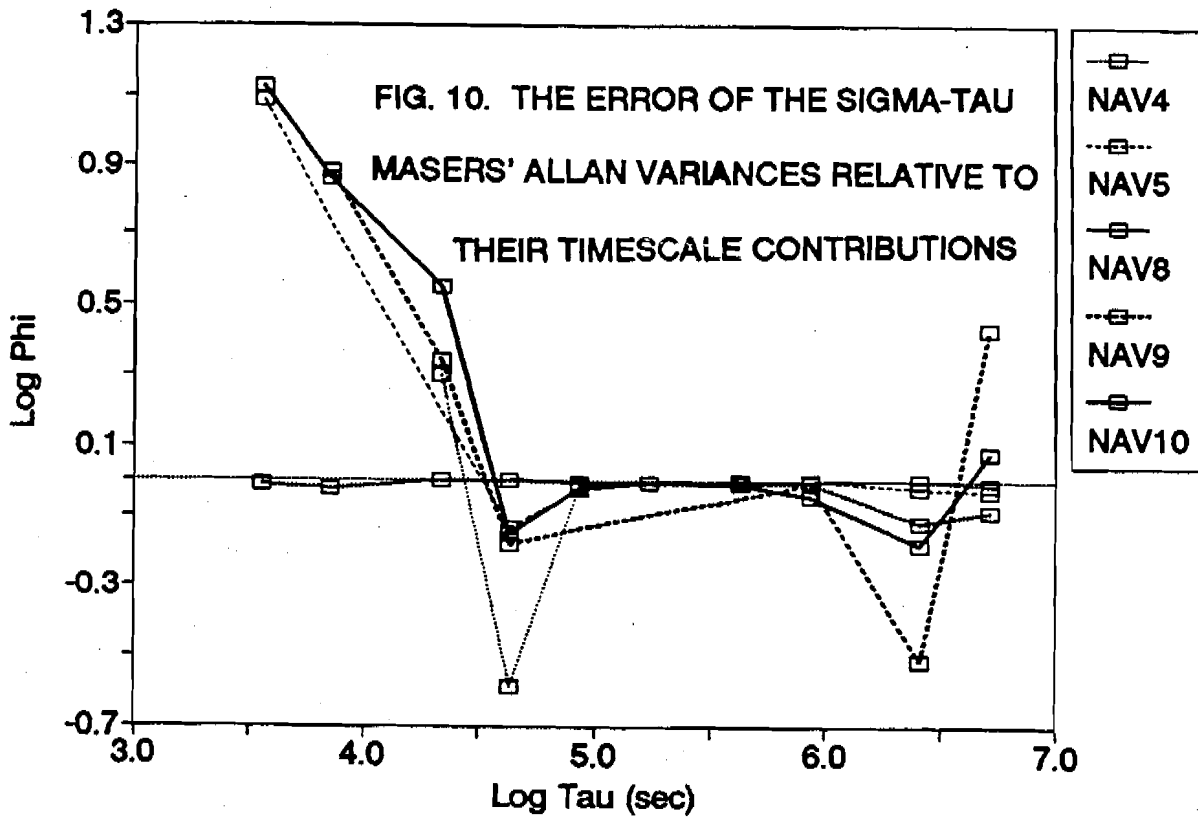
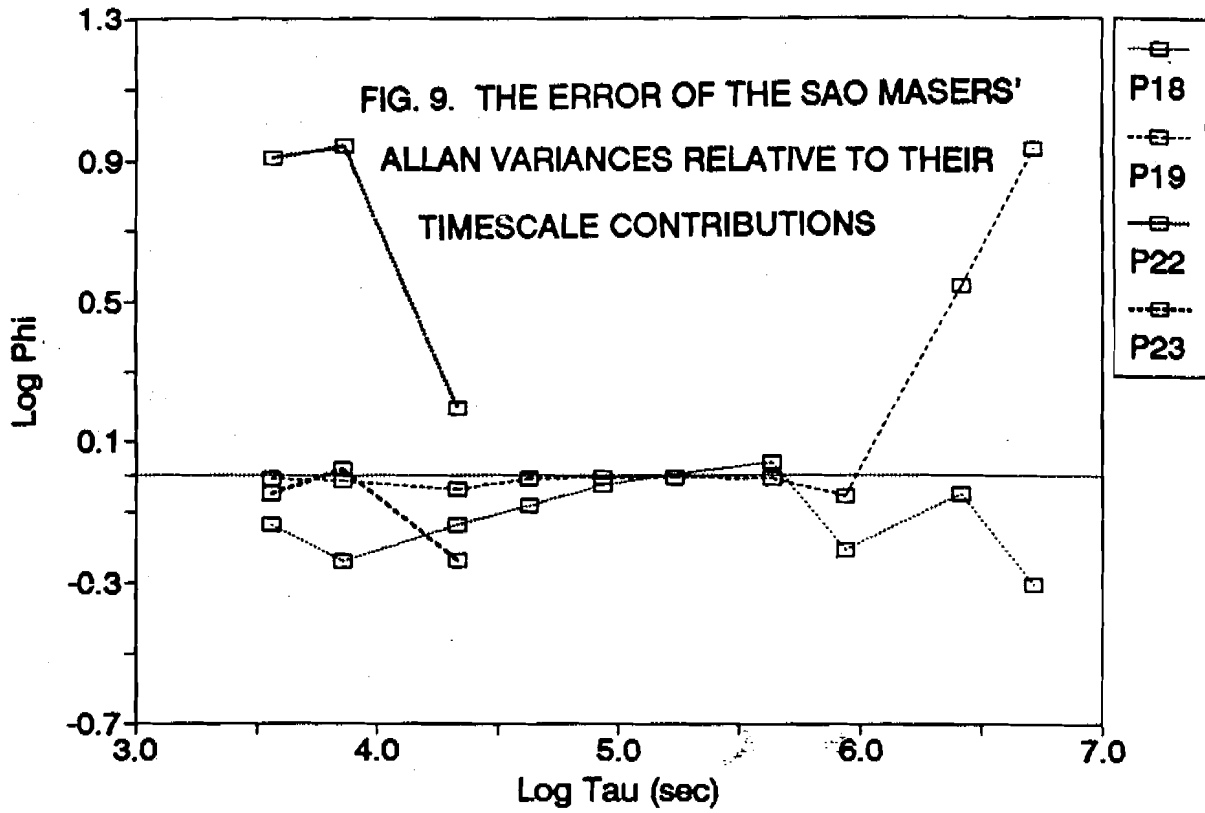


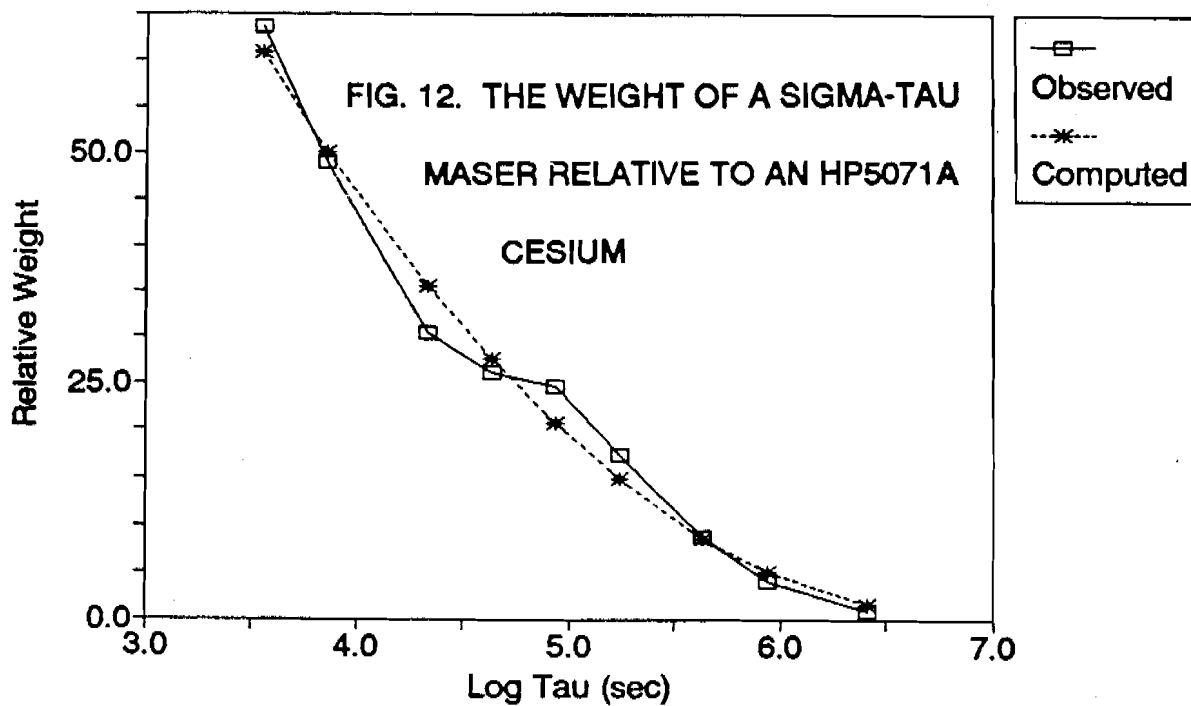
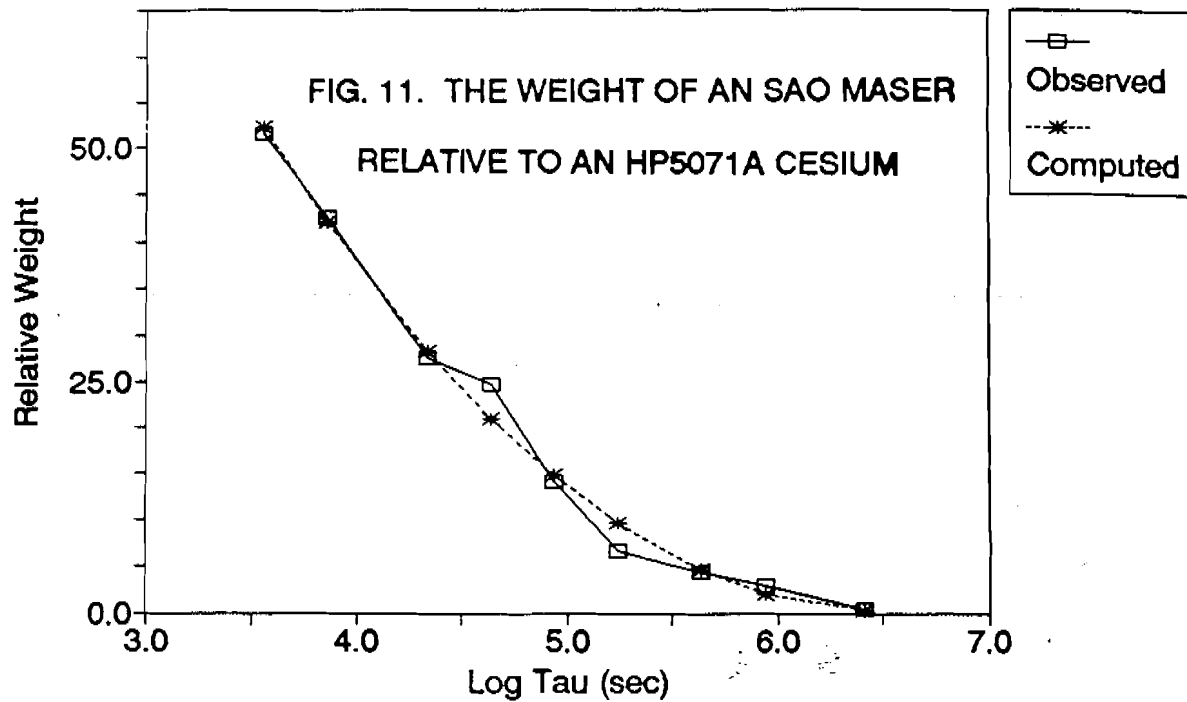












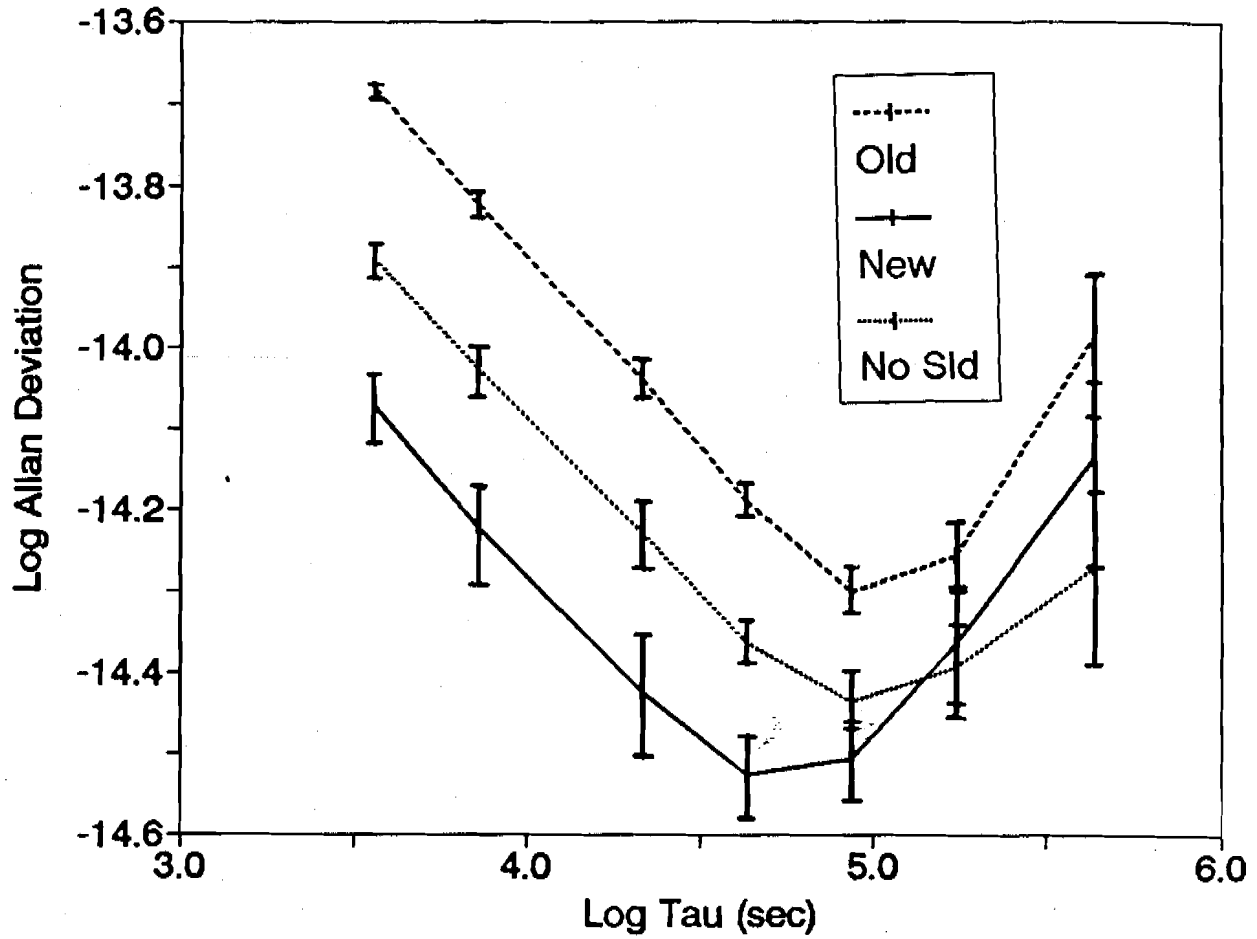


FIG. 13. FREQUENCY STABILITIES OF  
TIMESCALES COMPUTED WITH THE OLD  
WEIGHTS, THE NEW WEIGHTS, AND THE NEW  
WEIGHTS BUT WITHOUT THE SLIDING  
RELATION