Rapport BIPM-94/3

BUREAU INTERNATIONAL DES POIDS ET MESURES

DETERMINATION OF THE DIFFERENTIAL TIME CORRECTION BETWEEN THE GPS TIME RECEIVERS LOCATED AT THE PARIS OBSERVATORY, PARIS, FRANCE, AND THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, BOULDER, COLORADO, USA

by

C. Thomas and P. Moussay

April 1994, corrected July 1994

Pavillon de Breteuil, F-92312 SEVRES Cedex

23 mars 1994.

Correction du retard interne du récepteur GPS de référence de l'Observatoire de Paris.

Le LPTF (Observatoire de Paris, Bureau National de Métrologie) possède 4 récepteurs GPS utilisés comme suit:

- Un récepteur de référence pour les comparaisons horaires par GPS, de type NBS et dénommé NBS51, sur lequel sont programmées les poursuites du programme international de poursuites édité par le BIPM.
- Un autre récepteur de type NBS, doublure du récepteur de référence, programmé sur les mêmes poursuites en parallèle du NBS51, et comparé en permanence au NBS51, dénommé VSL15.
- Un récepteur de type NBS, dénommé TTR06, affecté aux étalonnages des liaisons horaires françaises.
- Un récepteur de type SERCEL NRT2, dénommé NRT28, utilisé à des fins expérimentales (CE-GPS, ...).

Au cours du mois de juillet 1993, un glissement a été observé sur les différences entre les récepteurs VSL15 et NBS51. Des comparaisons aux autres récepteurs du laboratoire, ou à d'autres récepteurs français par l'intermédiaire du TTR06, ont confirmé l'amplitude et le signe de ce glissement, attribué avec certitude à une variation inexpliquée du retard interne du NBS51, dont la valeur numérique était jusque-là de + 50 ns.

En conséquence, il a été décidé de corriger le retard interne du NBS51 par une valeur déterminée comme l'écart entre la moyenne des différences [UTC(OP)-GPS(VSL15)] - [UTC(OP)-GPS(NBS51)] sur le mois de juin 1993, et la moyenne analogue sur le mois d'août 1993:

MOY_{juin}([UTC(OP)-GPS(VSL15)] - [UTC(OP)-GPS(NBS51)]) = - 0.51 ns, σ = 0.34 ns
$MOY_{août}$([UTC(OP)-GPS(VSL15)] - [UTC(OP)-GPS(NBS51)]) = - 4.70 ns, σ = 0.34 ns

La valeur numérique choisie est donc:

Correction retard NBS51 = + 4.2 ns, incertitude = 0.4 ns (1σ)

Le nouveau retard programmé sur le NBS51 est de + 54 ns.

Cette correction est intervenue le 23 mars 1994 à 0 h UT.

LPTF
OBSERVATOIRE DE PARIS, 61 AVENUE DE L'OBSERVATOIRE, F-75014 PARIS
Tél. (33) 1-40 51 22 21 Télécopie (33) 1-43 25 55 42 Télex 270776.OBS
Span OPDAF1::LPTFOP Earn/Bitnet LPTFOP@FRIAP51

ABSTRACT

The method of clock comparison using GPS satellites in common view can now reach an accuracy of a few nanoseconds. However errors of calibration of the internal delays of GPS time receivers can limit this accuracy. The best method of removing calibration errors is the comparison of remote receivers by transfer of a portable receiver from one location to another.

We report here the conditions of such an exercise organized under the auspices of the NIST and the BIPM. It consists of the comparison of the internal delays of the GPS time receivers located at the Paris Observatory (OP), Paris, France, and the National Institute of Standards and Technology (NIST), Boulder, Colorado, USA. This was effected in two steps:

1. A GPS time receiver was compared with the NIST primary GPS time receiver in December 1993, in order to determine its internal delay. It was then shipped to the BIPM where it began its operation in January 1994.
2. A differential calibration between this receiver and the OP primary GPS time receiver was carried out, from mid-February till mid-March 1994, by means of a portable GPS time receiver.

From December 1993 till mid-March 1994, the differential correction to be added to the GPS comparison of the time scales kept by the OP and the NIST, was 2,6 ns with an uncertainty of 1,5 ns (1σ). On 23 March 1994 at 0h UTC, a correction of 4 ns was physically applied to the internal delay of the primary GPS time receiver in operation at the OP. Since then, the differential correction has thus been -1,4 ns with the same uncertainty. In both cases, the offset is small and of the same order of magnitude as its estimated uncertainty. In consequence, it is the view of the BIPM that it should not be taken into account.

RESUME

La méthode de comparaison des horloges utilisant les satellites du GPS observés en vues simultanées peut, à ce jour, atteindre une exactitude de l'ordre de quelques nanosecondes. Cependant le mauvais étalonnage des retards internes des récepteurs du temps du GPS constitue l'un des facteurs limitant cette exactitude. La méthode qui permet le mieux d'éliminer les erreurs d'étalonnage consiste à comparer des récepteurs distants par transport d'un récepteur portable.

Nous explicitons ici les conditions d'une telle campagne d'étalonnage organisée sous les auspices du NIST et du BIPM. Il s'agit de la comparaison des retards internes des récepteurs situés à l'Observatoire de Paris (OP), Paris, France, et au National Institute of Standards and Technology (NIST), Boulder, Colorado, Etats-Unis d'Amérique. Ceci a été effectué en deux étapes:

1. Afin d'en déterminer le retard interne, un récepteur du temps du GPS avait été comparé au récepteur primaire du NIST en décembre 1993. Il a été ensuite envoyé au BIPM où il a été mis en fonctionnement dès janvier 1994.
2. Un étalonnage différentiel a été effectué entre ce récepteur et le récepteur primaire de l'OP, de la mi-février à la mi-mars 1994, par transport d'un récepteur portable.

Pour la période allant de décembre 1993 à la mi-mars 1994, la correction différentielle à ajouter aux valeurs de comparaison des échelles de temps maintenues par l'OP et le NIST, se montait à 2,6 ns et était caractérisée par une incertitude de 1,5 ns (1σ). Le 23 mars 1994 à 0h UTC, un décalage de 4 ns a été physiquement appliqué au retard interne du récepteur primaire du temps du GPS de l'OP. Depuis cette date, la correction différentielle se monte donc à -1,4 ns et reste caractérisée par la même incertitude. Dans les deux cas, cette correction différentielle est petite et du même ordre de grandeur que son incertitude estimée. En conséquence, le BIPM adopte la position qui consiste à ne pas en tenir compte.

INTRODUCTION

The method of time transfer between remote locations using GPS satellites in common view is widely used by the time laboratories participating in the establishment of the International Atomic Time TAI under the coordination of the Bureau International des Poids et Mesures [1]. The accuracy of GPS time transfer can now reach the level of a few nanoseconds [2].

Errors of calibration of the instrumental delays of GPS time receivers is one of the limiting factors to this accuracy. The best method of removing calibration errors is the comparison of remote receivers by transfer of a portable receiver from one location to another [3, 4, 5]. Recently the BIPM has carried out differential calibrations on the occasions of comparisons of the GPS common-view method with other time transfer methods such as LASSO and two-way [6, 7], and also on the occasion of visits to outside laboratories [8, 9, 10].

We report here the results of a calibration exercise organized under the auspices of the NIST and the BIPM. Comparison of the receivers located at the Paris Observatory (OP), Paris, France, and the National Institute of Standards and Technology (NIST), Boulder, Colorado, USA, was effected in two steps.

1. In January 1994, the NIST shipped to France a GPS time receiver, its antenna and its calibrated antenna cable, on temporary loan to the BIPM. Before shipment, this equipment was compared to the NIST primary GPS time receiver in December 1993. The purpose of this comparison was to determine the internal delay of the receiver, which could ensure the best coherence of results obtained through this receiver and the NIST primary receiver. This led to the value 53 ns with an estimated uncertainty of 1 ns (1σ) [11]. Since 19 January 1994, this GPS receiving equipment has been operated at the BIPM, with the predetermined internal delay of 53 ns.

2. A differential calibration between this receiver, on loan at the BIPM from the NIST, and the OP primary GPS time receiver was carried out, from mid-February till mid-March 1994, by the means of a portable GPS time receiver belonging to the BIPM.

Usually differential calibration exercises are carried out without any determination of internal delays [8, 9, 10]. That is to say, comparisons with a portable receiver are performed on two different sites, and only a differential correction is determined. In addition, a round trip is usually organized, the portable receiver coming back to the first site after visiting the second site. It allows the monitoring of any systematic biases due to shipment. For the present exercise it was not possible to operate the usual method, but, even if the procedure is not the best one, it is important to report its results.

Indeed, only very few differential calibrations of the OP and NIST receivers have taken place in the past. One of them was carried out in 1986 and led to published results [3]. The observed offset was of order 1 ns and it was agreed that no correction should be added to the GPS comparison of the time scales maintained by the two laboratories. Since then, these two GPS time receivers have been usually regarded as local primary receivers, acting as references for other comparisons. It has thus become essential to compare them at every opportunity.

EQUIPMENT

In comparisons of GPS receivers, as well as in current GPS time comparisons, the receiver software, the adopted reference frames and the constants should be identical. Differences have already been found in the software of receivers of different types, but, fortunately for the present exercise, all the receivers involved are of the so-called 'NBS design'. They are single channel, C/A code receivers. Although constructed at different times, the essential features of these receivers are identical and the constants used were updated as appropriate.

When the local time reference produces a pulse of poor shape, differences of trigger level between the receivers can produce a significant differential delay. Here this problem does not appear, reference pulses at the OP, the NIST and the BIPM, having a short rise-time (3-4 ns) and all receivers using a single trigger level (0,5 V).

The principal characteristics of the receivers are listed below:

Receiver at NIST:	Maker	- Allen Osborne Associates,
REC(NIST)	Type	- NBS/TTR5,
	Serial Number	- S/N010.
Receiver at OP:	Maker	- Allen Osborne Associates,
REC(OP)	Type	- NBS/TTR5,
	Serial Number	- S/N051.
Receiver at BIPM:	Maker	- Allen Osborne Associates,
REC(BIPM)	Type	- NBS/TTR5,
	Serial Number	- S/N051∗.
Portable receiver:	Maker	- Allen Osborne Associates,
BIPM3	Type	- NBS/TTR6,
	Serial Number	- S/N0277.

Two NBS/TTR5 GPS time receivers have the same serial number: S/N051. They are in operation at the OP and the BIPM. The BIPM unit is identified by the addition of a star.

CONDITIONS OF COMPARISON

Since 19 January 1994 the NBS-design GPS time receiver S/N051* has been in continuous operation at the BIPM. The antenna and cables shipped with the receiver are used and the internal delay is fixed to the value 53 ns, predetermined at NIST with an uncertainty of 1 ns (1σ).

The portable equipment, which consists of the BIPM3 receiver, its antenna and a calibrated antenna cable, was carried from the BIPM to the OP for differential calibration between the OP primary receiver and the GPS time receiver S/N051*. The OP and the BIPM supply:

a) a 5 MHz reference signal,

b) a series of 1 s pulses from the local reference, UTC(OP) or the BIPM Local Clock, via a cable of known delay.

In each laboratory the portable receiver is connected to the same clock as the local receiver, and the antenna of the portable receiver is placed close by (less than 2 meters away). The differential coordinates of the antenna phase centres at each site are known with uncertainties of a few centimetres.

In this exercise the receivers were programmed with the BIPM Common-View International Schedule No 22 including 48 tracks for the Paris area.

Only strict common-views (0 s common-view tolerance and 780 s exact duration of the tracks) are used in order to remove the effects of Selective Availability, currently implemented on Block II satellites.

The comparison at short distances allows the cancellation of time transfer errors arising from satellite ephemerides and imperfect modelling of the ionosphere. In addition, no errors should arise from errors in the relative coordinates. As all the receivers involved are of the same type, all software anomalies are also cancelled.

RESULTS

The processing of the comparison data obtained in laboratory k, consists first of the computation, for each track i, of the time differences:

$$dt_{k,i} = [\mathrm{UTC}(k) - \mathrm{GPS\ time}]_{\mathrm{BIPM3},i} - [\mathrm{UTC}(k) - \mathrm{GPS\ time}]_{\mathrm{REC}(k),i}.$$

Then the noise exhibited by the time series dt_k is analysed for each laboratory by the use of the modified Allan variance.

Here, for the comparisons at the OP and at the BIPM the time series dt_k exhibit white phase noise for an averaging time of one day. This is illustrated in Figures 1 and 2.

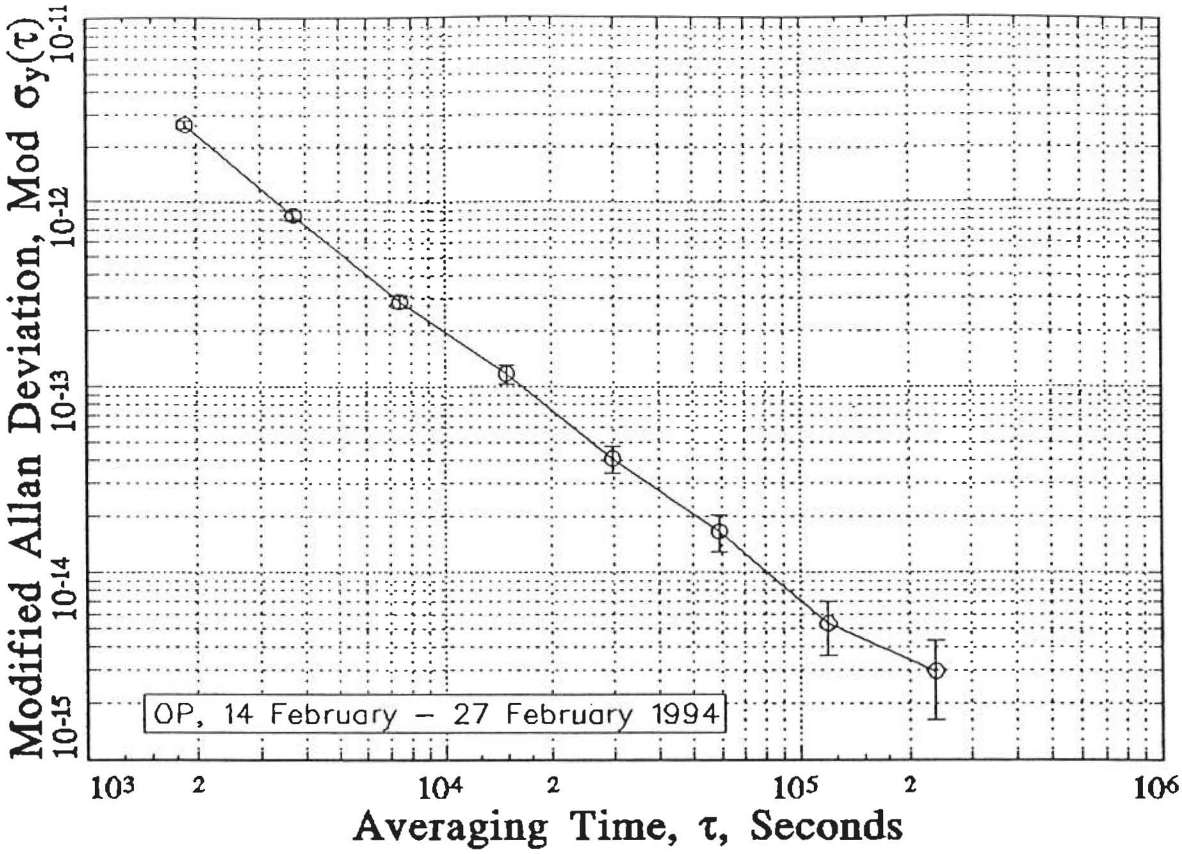

Figure 1. Square root of the modified Allan variance of the time series dt_{OP} for the period 14 February - 27 February 1994.

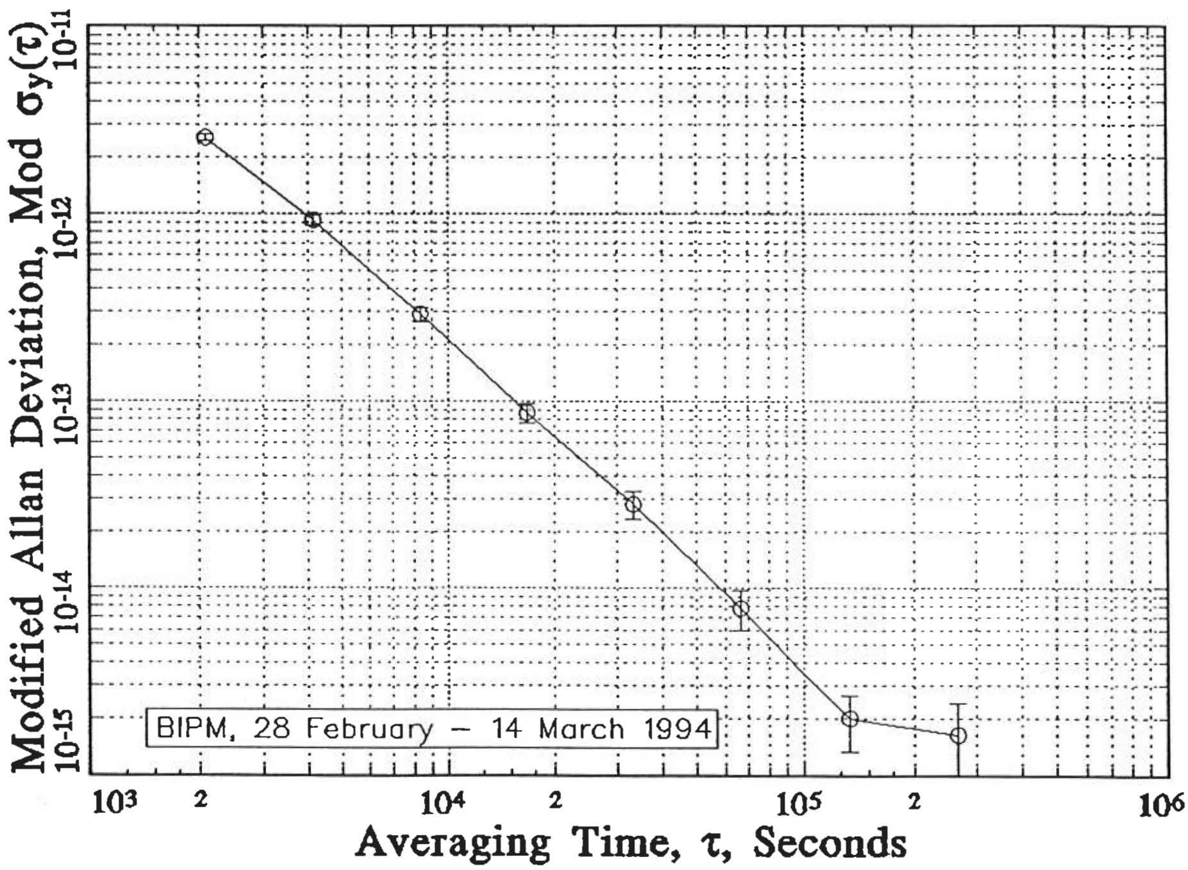

Figure 2. Square root of the modified Allan variance of the time series dt_{BIPM} for the period 28 February - 14 March 1994.

This justifies computation of an averaged value for one-day intervals and of the standard deviation of the mean as an expression of confidence on the obtained averaged value.

The daily results of the comparisons are then as follows:

Lab	Date 1994	Number of individual common views	Mean offset /ns	Standard deviation of individual common views /ns	Standard deviation of the mean /ns
OP	Feb 14	22	-7,97	2,34	0,50
	Feb 15	43	-7,48	2,42	0,37
	Feb 16	46	-7,89	2,66	0,39
	Feb 17	44	-7,76	2,37	0,36
	Feb 18	44	-7,68	2,00	0,30
	Feb 19	46	-7,30	2,09	0,31
	Feb 20	46	-7,65	2,16	0,32
	Feb 21	45	-8,66	2,52	0,38
	Feb 22	45	-7,76	2,34	0,35
	Feb 23	48	-8,01	2,41	0,35
	Feb 24	43	-8,10	1,93	0,29
	Feb 25	48	-7,03	2,47	0,36
	Feb 26	47	-7,55	2,58	0,38
	Feb 27	44	-7,58	2,49	0,38
BIPM	Feb 28	20	-5,80	2,00	0,45
	Mar 01	40	-5,30	3,43	0,54
	Mar 02	39	-5,58	2,65	0,42
	Mar 03	42	-5,70	3,19	0,49
	Mar 04	39	-4,99	1,87	0,30
	Mar 05	40	-5,18	2,15	0,34
	Mar 06	40	-4,71	1,95	0,31
	Mar 07	38	-4,03	1,74	0,28
	Mar 08	39	-4,42	2,10	0,34
	Mar 09	42	-5,23	3,06	0,47
	Mar 10	38	-4,97	1,91	0,31
	Mar 11	38	-4,86	1,81	0,29
	Mar 12	40	-5,16	2,47	0,39
	Mar 13	38	-5,07	2,54	0,41
	Mar 14	14	-5,88	2,40	0,64

The following table gives averaged offsets taken over the total number of common views for each period of comparison and corresponding mean residuals, chosen as estimates of the uncertainties (1σ). These estimates are conservative and take into account eventual systematic effects which can perturb the hardware of the GPS time receivers involved.

Lab	Period 1994	Total number of common views	Mean offset /ns	Estimated uncertainty /ns
OP	14 Feb - 27 Feb	611	-7,7	0,4
BIPM	28 Feb - 14 Mar	547	-5,1	0,5

The internal delay of the BIPM receiver has been calibrated by comparison at NIST with an uncertainty of 1 ns (1σ). The differential time correction to be added to the GPS comparisons of the time scales kept by the OP and the BIPM can thus be transferred to the GPS comparisons of the time scales kept by the OP and the NIST. It amounts to:

$UTC(k_1) - UTC(k_2)$	Differential correction /ns	Estimated uncertainty /ns
UTC(OP) - UTC(NIST)	-2,6	1,5 (1σ)

CONCLUSIONS

A differential calibration exercise between the GPS time receivers located at the Paris Observatory (OP), Paris, France, and the National Institute of Standards and Technology (NIST), Boulder, Colorado, USA, was performed in two steps, via the BIPM, from December 1993 till mid-March 1994. For this period, the differential time correction which would be normally added to the comparisons of the time scales kept by the OP and the NIST, was-2,6 ns with an estimated uncertainty of 1,5 ns (1σ).

On 23 March 1994 at 0h UTC, the internal delay of the primary GPS receiver NBS/TTR5 S/N051, in operation at OP, has been physically modified by 4 ns (see enclosed letter):

- * till 23 March 1994, 0h UTC, the internal delay value entered in the receiver was 50 ns,
- * since 23 March 1994, 0h UTC, the new value entered in the receiver has been 54 ns.

As a result of this change in internal delay, since 23 March 0h UTC, the differential time correction has been reduced to +1,4 ns with the same uncertainty. In both cases, the differential correction is small and of the same order of magnitude as its uncertainty. In consequence, it is the view of the BIPM that no differential correction should be applied when GPS time comparisons are made between the OP and the NIST, and that the values of the internal delays presently introduced in the GPS time receivers should be kept without modification.

ACKNOWLEDGEMENTS

We wish to express our gratitude to our colleagues from the OP and the NIST for their full collaboration without which this work could not have been accomplished.

REFERENCES

1. LEWANDOWSKI W. and THOMAS C., GPS Time Transfer, *Proc of the IEEE, Special Issue on Time and Frequency*, 1991, 991-1000.

2. LEWANDOWSKI W., PETIT G. and THOMAS C., Precision and Accuracy of GPS Time Transfer, *IEEE Transactions on Instrumentation and Measurement*, **42**, 2, 1993, 474-479.

3. LEWANDOWSKI W., WEISS M.A. and DAVIS D., A Calibration of GPS Equipment at Time and Frequency Standards Laboratories in the USA and Europe, *Metrologia*, **24**, 1987, 181-186.

4. BUISSON J.A., OAKS O.J. and LISTER M.J., Remote Calibration and Time Synchronization (R-CATS) Between Major European Time Observatories and the US Naval Observatory Using GPS, *Proc. 17th PTTI*, 1985, 201-222.

5. WEISS M.A. and DAVIS D., A Calibration of GPS Equipment in Japan, *Proc. 20th PTTI*, 1988, 101-106.

6. KIRCHNER D., RESSLER H., GRUDLER P., BAUMONT F., VEILLET C., 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*, **30**, 1993, 183-192.

7. BAUMONT F., GRUDLER P., VEILLET C., WIANT J., LEWANDOWSKI W. and PETIT G., Preliminary report on the comparison of LASSO and GPS time transfers, *Proc. 7th EFTF*, 1993, 641-643.

8. LEWANDOWSKI W., THOMAS C. and IMAE M., Determination of differential time corrections between GPS time receivers located at the Observatoire de Paris and the Communications Research Laboratory of Tokyo, *Rapport BIPM-93/4*, 1993, 12 pages.

9. THOMAS C. and MOUSSAY P., Determination of differential time corrections between GPS time receivers located at the Paris Observatory and the Standards and Calibration Laboratory, Hong Kong, *Rapport BIPM-93/5*, 1993, 12 pages.

10. THOMAS C. and MOUSSAY P., Determination of differential time corrections between GPS time receivers located at the Paris Observatory, Paris, France, and the National Physical Laboratory, Teddington, United Kingdom, *Rapport BIPM-94/2*, 1994, 14 pages.

11. WEISS M.A., NIST, Boulder, CO, USA, personal communication.