STABILITY OF GEODETIC GPS TIME LINKS AND THEIR COMPARISON TO TWO-WAY TIME TRANSFER

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Abstract

We quantify and analyze the time differences between simultaneous results for several pairs of TAI laboratories using the Two-Way satellite Time Transfer (TWTT) and different techniques using geodetic GPS methods. These include the combined clock products from the International GPS Service (IGS) and dual-frequency P3 common-view time transfers. Usable results are available for a few baselines over several months. The IGS and P3 results derive from the same GPS receivers, but P3 uses only the code measurements, while the IGS geodetic clocks use code plus phase and much more comprehensive modeling of the signal propagation. In addition, we compare these results to those obtained with C/A code GPS time receivers in classical common-view mode. All comparisons show levels of short-term noise and longer-term systematic effects well below 1 ns, with the exception of those involving the C/A code time receivers and a specific TWTT link. From the different comparisons and their interpretation, we infer the level of short-term noise and longer-term systematic effects for all techniques.

1. INTRODUCTION

In recent years, most time links used for International Atomic Time TAI have been based on C/A code, single-frequency, GPS receivers and on Ku-band Two-Way time transfer using geostationary satellites (denoted TW hereafter in this paper). Since 2003, GPS P3 code measurements obtained with calibrated dual- frequency receivers of the type Ashtech Z12-T have been introduced in TAI computation. Such geodetic-type receivers may also provide time links using more elaborated geodetic processing techniques. In this paper, we estimate the stability level that may be achieved by such geodetic techniques and by the TW technique. In Section 2, we briefly describe these two time transfer techniques, emphasizing their performance and factors that may limit it. In Section 3, we estimate the short-term stability of these techniques from direct measurements and, in Section 4, we infer the longer-term stability from the comparison of all techniques operated simultaneously. Section 5 recalls how the geodetic GPS techniques are used in TAI and discusses future prospects.

2. TIME TRANSFER TECHNIQUES

We briefly describe the time transfer techniques that will be considered in this paper and that presently provide the best performances: Two-Way time transfer by geostationary satellite and geodetic GPS techniques. We consider the characteristics of these techniques with respect to the achieved stability: measurement noise, factors that affect the short-term (here defined as < 5 days) and long-term (here defined as 5 days or more) stability. Our goal is to characterize the techniques at the 0.1 ns uncertainty level, so that any effect smaller than this value is considered negligible.

2.1. TWO-WAY TIME TRANSFER BY GEOSTATIONARY SATELLITE

In the Two-Way time transfer technique **[1]**, two stations simultaneously transmit a signal to a geostationary satellite. A transponder on board the satellite retransmits the signals for reception by the stations. In current systems, a pseudo-random code stamped by the local clock is modulated at a few Mbps. Transmissions are done in the Ku band (11-14 GHz) using commercial communications satellites. The statistical uncertainty of one 2-minute measurement is typically a few hundred ps or below. The reciprocity of the paths helps to cancel or greatly decrease a number of unknown propagation delays. Data used in this paper are transmitted to the BIPM for TAI computation and pertain to two networks:

> In the Europe-America TW (EU) network, four measurements are performed each day (~0h, 8h, 14h, 16h UTC) for selected links and, sometimes, measurements are done every hour or every 2 hours for limited periods. TW (EU) concerns the following TAI laboratories: USNO-NIST-PTB-IEN-NPL-ROA-SYRTE (OP)-VSL. The data typically have few outliers and the density of the data may allow, in some cases, one to perform an outlier detection based only on statistics.
>
> In the Asia-Pacific TW (AP) network, two sessions are organized each week, with each session generally containing two or three measurements between NICT (Japan) and each of the other participating laboratories (NMIJ-TL-NTSC-AUS). The number of outliers is slightly larger than in the EU network but, in general, there is not enough redundancy in the data to set up an outlier detection scheme based on statistics.

Because the very short-term noise (seconds to minutes) is characterized as white measurement noise, averaging of about 1000 s would easily provide measurement noise at or below the 0.1 ns level. However, such an amount of data is generally never available continuously, so that the stability is dominated by the longer-term behavior and is subject to possible systematic effects from, e.g., environmental effects on non-reciprocal parts of the propagation path. Additional effects may occur when separate transponders are used to transmit the two signals through the satellite, resulting in additional non-canceling delay instabilities. Some studies have found instabilities at a level of a few hundred ps **[2]**.

2.2. GEODETIC GPS TECHNIQUES

In GPS techniques, stations receive signals from a number of satellites. A pseudo-random code stamped by the satellite clock is compared to a locally generated code stamped by the local clock. Codes are modulated at a 1 Mbps (C/A transmitted at 1.5 GHz) or 10 Mbps (P1/P2 transmitted at 1.5/1.2 GHz). In addition, the phase of the transmitted signals can also be measured (to within an unknown number of cycles). Geodetic GPS techniques are defined as those using receivers that provide code and phase measurements on both frequencies, commonly reported in Rinex files (see the Web site of the International GPS Service, IGS, at *http://igscb.jpl.nasa.gov/*). Classical GPS time transfer, involving only C/A code measurements reported in CGGTTS files **[3]**, is only mentioned in the following sections as a comparison. We distinguish three techniques to compute geodetic GPS time links, depending on the computation procedure used. They are denoted P3, IGS, and PPP.

In the P3 technique, the code observables are extracted from the Rinex files and transformed to the CGGTTS data used in time transfer **[4]** using locally recorded broadcast GPS parameters. The files are gathered by the BIPM and used to compute time links after applying different corrections (precise IGS ephemeredes and clocks, solid Earth tides). This technique has been used since 2002 at the BIPM, starting with the pilot experiment TAIP3 and continuing in an operational mode since July 2003. Such data are currently provided by the following TAI laboratories: DLR, IEN, IFAG, METAS, NICT, NMIJ, NPL, NRC, NTSC, OP, ORB, PTB, SP, TL, USNO.

In the IGS "network" technique, e.g. used by the IGS, data from a global network of stations are processed simultaneously to determine all possible parameters (notably satellite ephemeredes, station positions, and tropospheric delays), providing also the differences between a reference time and all clocks **[5]**. The time link between any pair of stations can then be obtained by simple difference. Such dataares currently available from the IGS for the following TAI laboratories: DLR, IEN, NICT, OP, ORB, PTB, TL, USNO.

In the Precise Point Positioning technique (PPP), Rinex data from each station are individually processed using global parameters provided by the IGS, solving only for the local parameters such as station position, tropospheric delay, and the clock differences to the time reference used by the IGS. The time link between two stations can then be obtained by simple difference between the clock results obtained for each station. This computation can be performed for any of the stations for which Rinex data are available from the IGS, e.g. for all the TAI laboratories mentioned in the preceding paragraph.

For the purpose of this paper, we consider that PPP and IGS would provide equivalent results; thus, we here consider only IGS and ignore PPP. A detailed comparison all geodetic GPS techniques, with a particular emphasis on the PPP technique, is studied in **[6]**. The measurement noise in geodetic techniques is usually that of the phase measurements, i.e. is negligible in front of systematic effects (see below). However, the P3 technique is based on code only and needs about 1000 s averaging to reach 1 ns uncertainty and a few hours to reach 0.1 ns. By using the IGS products and dual-frequency phase and code measurements, all systematic effects (e.g., geometry, ionosphere, troposphere, multipath) should be limited to the 0.1 ns level, with the exception of those linked to environmental effects on the hardware. In the P3 technique, based on code only and not presently subject to a complete modeling like the IGS one, systematic effects (notably from troposphere and multipath) can be present at the level of several hundred ps.

3. MEASURED STABILITY OF TW AND GPS GEODETIC TIME LINKS

3.1 SHORT-TERM STABILITY BY COMPARISON OF H-MASERS

We estimate the short-term stability by computing the Modified Allan deviation (fractional frequency stability) or the Time deviation (time stability) from the time link data points. By using a link where the two clocks are very stable, we can estimate the stability of the time transfer methods for the longest averaging time. For this purpose, the link USNO-NPL (5700 km) is well suited, because the two clocks are well-maintained active hydrogen masers and because the TW and geodetic GPS techniques are available and well maintained. Figure 1 is an example of fractional frequency stability obtained for this link for the three techniques P3, IGS and TW using about 2 months of continuous data in 2004 (note that the period used for the IGS solution is slightly different). Note that the P3 link (Figure 1, top right) shows a significant diurnal effect that is not present in the IGS link and, thus, must be related to code multipath or to insufficient modeling in the P3 processing. The diurnal effect is not visible either in the link where the P3 is estimated at the dates of the TW points (Figure 1, top left), which is probably due to the insufficient sampling (three points per day on average). The stability level of the clocks seems to be reached for an averaging duration of 2-3 days, so that a reliable estimation of the performance of the time transfer techniques may be obtained only for an averaging time up to 1-2 days.

3.2 THREE-DAY STABILITY BY COMPARISON OF CS FOUNTAINS

In October-November 2004, a common experiment was designed by several laboratories operating Cs fountains in order to operate the fountains over the same time interval to best intercompare them. The equipment at all participating laboratories includes geodetic GPS and Two-Way time transfer. Here, we use the estimated stability of two Cs fountains SYRTE-FO2 **[7]** and PTB-CSF1 **[8]** to estimate the performance of the time transfer techniques by computing direct time links between the two fountains with both techniques. The stability of operational Cs fountains for an averaging time of a few days, needed for this study, is in the low 10^{-16}, as indicated in the laboratory reports published in the Annual Report of the BIPM Time section **[9]**. For example, for a 3-day averaging time, the stability of PTB-CSF1 (as it was operated in 2003) is 4×10^{-16} and that of SYRTE-FO2 is 2×10^{-16}, so that the contribution of the fountains to the observed stability of the time link data is below 5×10^{-16}. Over a 14-day interval (MJD 53304 to 53317), the two fountains were continuously operated (accounting for short dead-time periods by using the local H-maser), the GPS receivers were in normal operation and the Two-Way equipment was operated with a special schedule of one session every 2 hours. The measured stabilities of the two links are presented in Figure 2. We see that both techniques reach a stability of order 1×10^{-15} with 3-day averaging for TW and with about 4-day averaging for P3. It is expected that the IGS results are at least as good as the P3 ones.

3.3 SUMMARY OF MEASURED STABILITIES

The results of the stability analysis are summarized in Table 1. We can note that, in the present standard configurations (i.e. data as received by the BIPM for the computations of TAI for P3 and TW, and as received by the IGS), the P3, IGS, and TW techniques are about equivalent for averaging times above 2-3 days, at a level below 2×10^{-15} in fractional frequency. As shown in Figure 2, this level is conservative and it can be considered that a stability of order 1×10^{-15} is achieved by TW (when operating with 12 sessions per day) for a 3-day averaging and by P3 for a 4-day averaging time, with the IGS performance at least as good as P3. Below 1 day, the IGS technique has a clear advantage and the TW technique is slightly more stable than the P3 technique. Note also that only the TW technique is capable of obtaining a very significant improvement for the short-term stability by providing denser data (e.g. 24 points a day or even more). On the other hand, a modest improvement can be expected from geodetic GPS, mostly from the future increase in the number of GNSS satellites available or in the number of usable signals (code/frequency).

Table 1. Fractional frequency stability (modified Allan deviation) obtained for four time transfer techniques, as measured on the link USNO-NPL in 2004 (data of Figure 1, not shown for C/A). NA = not available.

Tau	C/A	P3	IGS/PPP	TW (EU)
1000 s	several 10^{-12}	$1\cdot10^{-12}$	several 10^{-14}	NA
10000 s	several 10^{-13}	$< 10^{-13}$	$1\cdot10^{-14}$	NA/several 10^{-14}
1 day	$> 10^{-14}$	$< 10^{-14}$	several 10^{-15}	several 10^{-15}
5 days	several 10^{-15}	$< 2\cdot10^{-15}$	$< 2\cdot10^{-15}$	$< 2\cdot10^{-15}$

4. LONG-TERM STABILITY FROM COMPARISON OF DIFFERENT TIME TRANSFER TECHNIQUES

In this section, we use four different time transfer techniques (IGS, P3, TW, and C/A) to compute the same link at the same dates (based on the measurement dates of TW, the less dense technique), continuously for a long period. Because the hardware for TW, C/A, and (IGS/P3) are completely independent, we infer that the systematic effects for the three sets are independent and we, therefore, attribute a level of noise due to systematic effects based on the level of noise in the mutual differences. The IGS and P3 techniques use the same hardware and the differences between them are expected to originate in incomplete modeling (e.g. troposphere) and in code multipath, both affecting P3. We expect these effects to be a few hundred ps (see Section 2.2).

Based on the data received at the BIPM for TAI computation on the one hand and on the data provided by the IGS clock products Web site on the other hand, we can identify four baselines (NPL-PTB, NPL-USNO, USNO-PTB, TL-NICT) for which we can expect to have the four different techniques available. However, due to missing data and several other events (e.g. change of TW transponder, receiver failure, etc.), it proves to be difficult to obtain continuous comparisons of four techniques over several months. The results presented here are based on the links NPL-PTB (750 km) over 6 months and on TL-NICT (2100 km) over 8 months.

Figure 3 shows the results for NPL-PTB and Figure 4 those for TL-NICT. We can draw the following conclusions:

1. IGS and P3 indeed differ by a few hundred ps with no sign of long-term systematics.
2. IGS and TW (EU) differ by much less than 1 ns. Other similar comparisons (not shown here) suggest a level of 0.7 ns; thus, we assume, as a first guess, that a level of instability of 0.5 ns is attributable to each of the techniques.
3. P3 and TW (EU) differ by less than 1 ns, as has already been shown **[10]**, but they differ more than IGS and TW (EU). This is consistent with the conclusions 1 and 2 and would yield, as a first guess, a level of instability of about 0.7 ns for the P3 technique.
4. IGS – TW (AP) and P3 - TW (AP) are significantly worse than the same comparisons with TW (EU), as already shown **[10]**. Because IGS links should be of similar quality, this is attributed to TW (AP) and yields a level of instability of about 1.3 ns to the TW (AP) technique.
5. C/A is significantly worse than other techniques at a level of instability between 1.2 ns and 2 ns. This value may indeed depend on the distance and on the precise link considered, because one dominant systematic effect in the C/A technique is the ionosphere map used to correct the single frequency measurements.

Based on these conclusions, we obtain the estimation of long-term (5-30 days) time stability listed in Table 2. Other values in Table 2 are obtained from those in Table 1. Note that these tables aim only at providing approximate estimations, so that no rigorous correspondence should be expected between the numbers in the two tables.

Table 2. Time stability obtained for four time transfer techniques. The first three lines are obtained from Table 1; the results in the last line are discussed in the text. NA = not available.

Tau	C/A	P3	IGS/PPP	TW (EU)	TW (AP)
1000 s	several ns	1 ns	tens of ps	NA	NA
10000 s	several ns	< 0.7 ns	100 ps	NA/hundreds ps	NA
1 day	> 1 ns	< 0.7 ns	hundreds ps	hundreds ps	NA
5-30 days	1.2-2 ns	0.7 ns	0.5 ns	0.5 ns	1.3 ns

5. USE OF GEODETIC GPS TIME LINKS IN TAI

Use of the P3 technique started in April 2002 with the start of the TAIP3 pilot experiment **[11]**. After an initial experimental phase, several P3 links have been introduced in the TAI computation since June 2003 (DLR-PTB, IFAG-PTB, ORB-PTB, CH-PTB, NICT-PTB) and other links have occasionally been used (USBO-PTB). At present, 15 laboratories provide P3 data, and all links are regularly computed either for official use (see above) or as a backup. In some cases, the P3 links are more stable than links presently used for TAI, e.g. the case of TW (AP) as shown in this paper, and may provide some improvement in the future.

As noted above, the time stabilities of the P3 and IGS techniques are equivalent for an averaging time of a few days and above. Because the interval of reporting in TAI is 5 days and because TAI is mainly concerned in long-term stability (typically 30 days and above), it has been considered sufficient to use the simpler P3 technique for TAI. Nevertheless, some extra instability (at a level of a few hundred ps) results from this choice, because each 5-day point is computed from the averaging of a few hours of P3 data and because some systematic effects remain in the P3 data (troposphere, multipath). Therefore, use of the PPP technique in the future is envisioned. In the mean time, use of the All-in-view processing technique **[12]** is expected to improve all GPS time links, particularly at long distance.

Time links used for TAI should be calibrated and a significant effort has been started in 2002 to differentially calibrate all geodetic receivers used for time transfer. The uncertainty of a differentially calibrated geodetic time link is estimated to be 3 ns, but assessing this value by comparison to other independently calibrated techniques is a long process, which is under way.

6. CONCLUSIONS

Geodetic GPS techniques are a promising tool for time transfer. Processing techniques (IGS and PPP) taking full advantage of such receivers should provide the best results in terms of stability at all averaging times, but the simpler P3 technique, which is actually used in TAI, has a similar stability for averaging times above a few days. Compared to TW, geodetic GPS techniques seem to provide a long-term instability similar to TW (EU) and are a better alternative than TW (AP), in the present use of these techniques. TW techniques could gain very significantly in short-term stability by conducting denser, or continuous, measurements. But, as shown in this paper, the estimation of the long-term stability of all techniques, which is essential for TAI, is still under investigation.

7. ACKNOWLEDGMENTS

Many thanks are due to J. Ray (NGS), who has brought a wealth of information during a stay at the BIPM in 2003-2004, and to K. Senior (NRL) for his work on the IGS clock products. The time laboratories that provide data in the frame of their participation to TAI are gratefully acknowledged, especially the BNM-SYRTE and the PTB, which provided the Cs fountain data.

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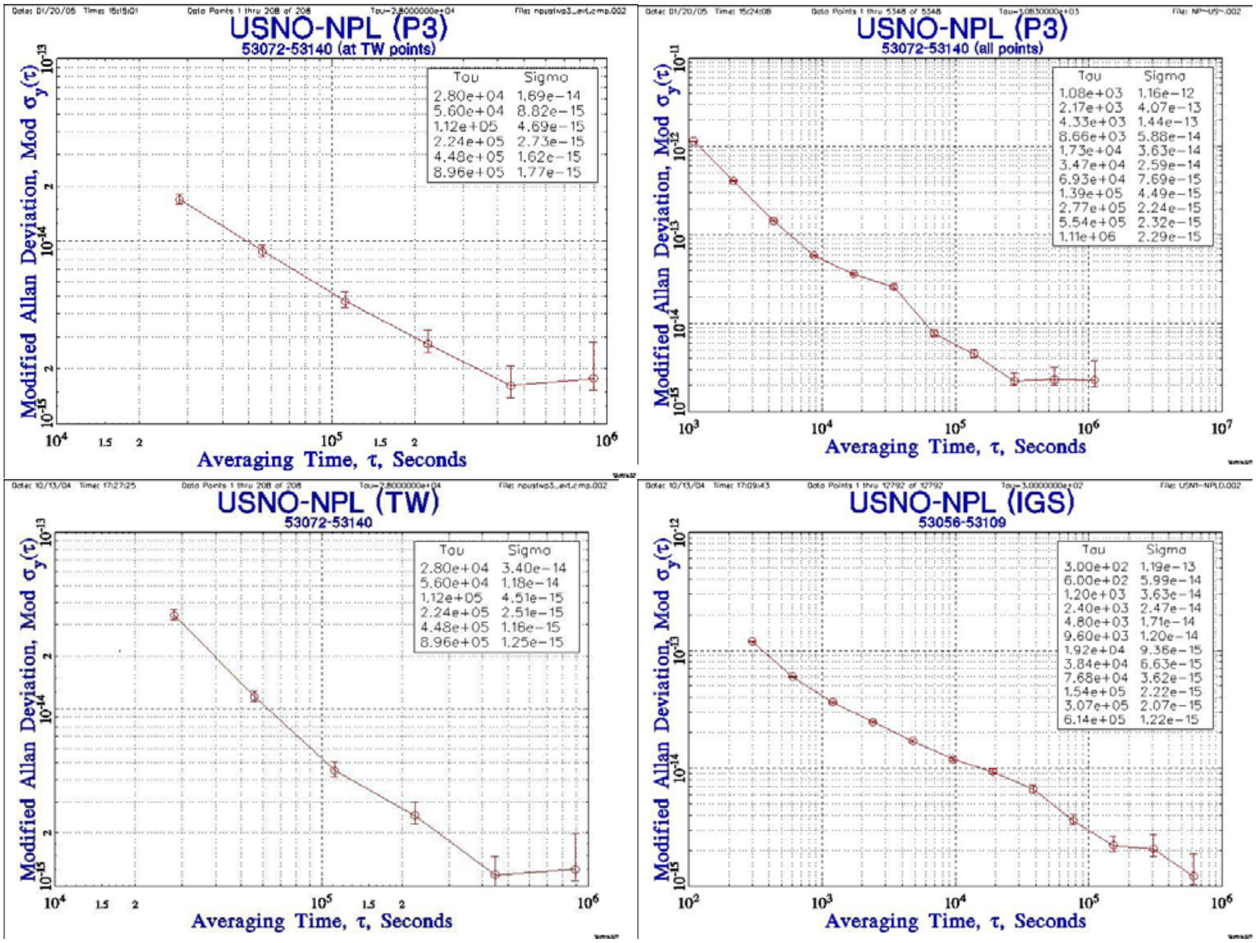

Figure 1. Modified Allan deviation for the link USNO-NPL computed with three techniques: P3 (top two plots), TW (bottom left), and IGS (bottom right).

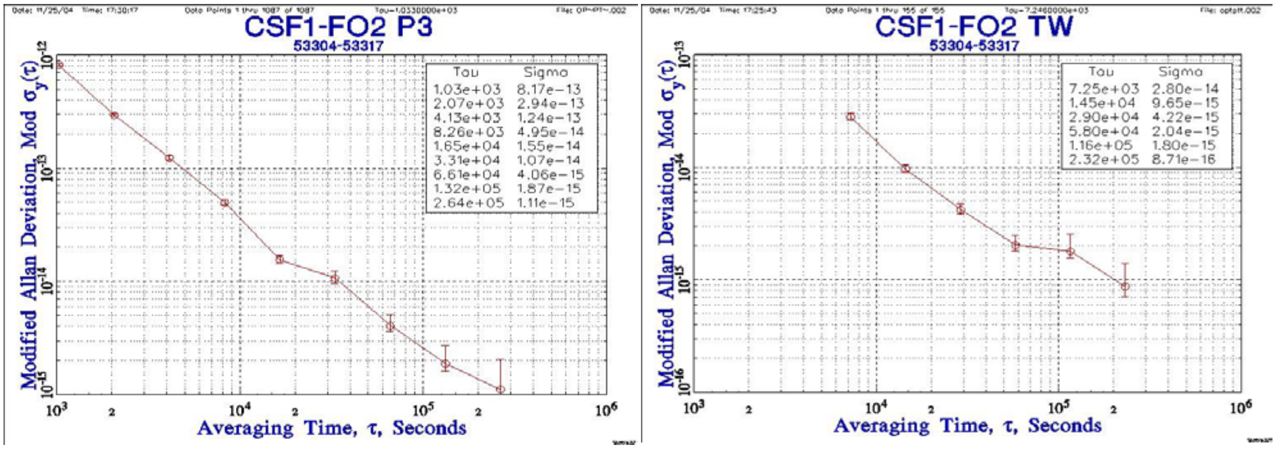

Figure 2. Modified Allan deviation for the link between Cs fountains at BNM-SYRTE and PTB, computed with two techniques: P3 (left) and TW (right).

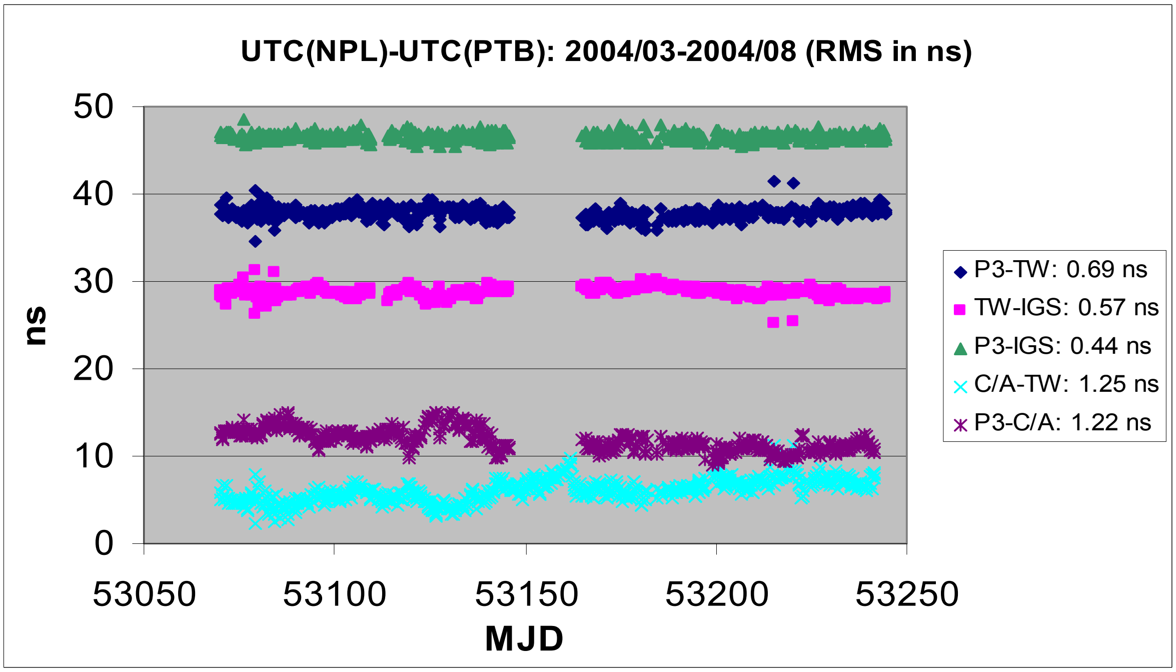

Figure 3. Five mutual comparisons of four different techniques for the link NPL-PTB (750 km) over 6 months; see text for details.

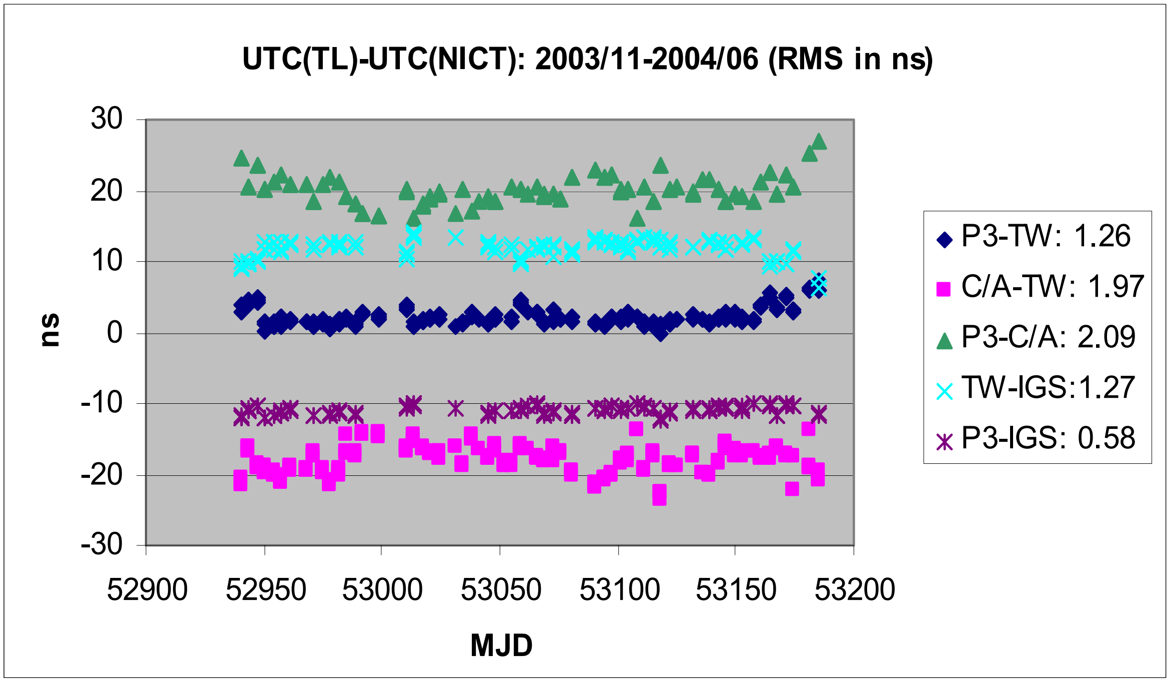

Figure 4. Five mutual comparisons of four different techniques for the link TL-NICT (2100 km) over 8 months; see text for details.

QUESTIONS AND ANSWERS

MARC WEISS (National Institute of Standards and Technology): I wonder if you have looked at the problem of impedance matching between the receivers and cables and antennas and antenna cables.

FELICITAS ARIAS: You want to know if they watched that problem?

WEISS: Have you looked at that issue?

ARIAS: No.

WEISS: Because, we have seen that that can cause, in the code, large deviations of many nanoseconds over time. Perhaps with carrier phase techniques, it is not quite as big an issue. But still, you use the code …

ARIAS: No, I have no information about that. So I suppose that they have not checked that.