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Report of the TAIP3 experiment
1. Comparison of time links with different techniques
2. Calibration of time links
3. Introduction of time links into TAI computation

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The TAIP3 pilot experiment was proposed in April 2002 to laboratories participating to TAI. The goal is to study time links computed with GPS P3 data obtained from geodetic-type dual-frequency receivers (Petit et al. 2002). Starting June 2003, some such time links were first introduced in the TAI computation. This memorandum presents the findings of the pilot experiment and draws some conclusions for the future use of these links in TAI.

In section 1, the results of the comparison of such P3 time links with other techniques used for TAI, GPS C/A and Two Way Time Transfer (TW) are presented. This allows to evaluate the long term stability of P3 time links and also that of the other techniques. In section 2, the results of the calibration exercises of P3 equipment carried out since 2001 are presented, and the results for some calibrated links are compared to those from other techniques. In section 3, some conclusions are drawn for the present and future use of such links in the TAI computation.

1. Comparison of P3 links with other techniques

In the following, we report results for all P3 links which can be compared to the TW technique, plus some links for which the only comparison is C/A single channel. See Table 1 for a list of equipment and Table 2 for a list of the computed links.

Laboratory	GPS P3 equipment	TW equipment	GPS C/A equipment
METAS (CH)	GeTT (Ashtech)		AOA TTR5A (SC)
IEN	Ashtech Z12T	MITREX 2500A	3S Nav. GNSS-300T (MC)
BNM/SYRTE (OP)	Ashtech Z12T	TimeTech/SATRE	NBS TTR5 (SC)
PTB	Ashtech Z12T	TimeTech/SATRE	AOA TTR5 (SC) AOS SRC TTS-2 (MC)
USNO	Ashtech Z12T	MITREX 2500	AOS SRC TTS-2 (MC)
CRL	Ashtech Z12T	AOA/Atlantis	3S Nav. R-100 (MC) EURO-80 (MC) AOA TTR6 (SC)
NMIJ	Ashtech Z12T	AOA/Atlantis	AOA TTR6 (SC)
TL	Ashtech Z12T	AOA/Atlantis	AOA (SC)

Table 1: List of laboratories considered in this study and their equipment (SC = Single Channel, MC = Multi Channel). Sources: Header of data files; BIPM TWSTFT report.

Link	Distance	Techniques
CH-PTB	650 km	P3, C/A SC
IEN-PTB	800 km	P3, TW, C/A SC-MC
OP-PTB	700 km	P3, TW, C/A SC
CRL-PTB	8300 km	P3, C/A SC-MC
USNO-PTB	6300 km	P3, TW, C/A MC
NMIJ-CRL	70 km	P3, TW, C/A SC
TL-CRL	2100 km	P3, TW, C/A SC

Table 2: List of the links which results are reported in this memorandum.

All GPS data presented in this section were corrected using GPS precise ephemerides from the IGS using the standard TAI procedure. In addition the C/A data were corrected using ionosphere maps from the IGS using the standard TAI procedure. Strict common-view measurements were differenced and a Vondrak smoothing was applied following the standard TAI procedure. Note that the Vondrak parameter was set to 100000 for the P3 data (which means that the smoothing is equivalent to a low pass filter with a cut-off period of about 0.6 day), and set to 1000 for the C/A date (cut-off period of about 1.3 day). This difference is to account for the lower noise of the P3 data.

In this report all results are differences between two time series of measurements of the same quantity, i.e. all should be constant with time. To evaluate a "long term instability", we therefore compute the standard deviation of a time series over a long interval, which typically includes several tens of points over several months. These raw link comparisons are reported in section 1.1 below. In some cases three nearly continuous series are available for the three techniques so that some information may be inferred on the performance of each technique, see section 1.2.

1.1. Comparisons of P3 links with TW(Ku) and GPS C/A links

The following links for which both P3 and TW(Ku) are available have been computed: IEN-PTB, USNO-PTB, OP-PTB, NMIJ-CRL, TL-CRL. The difference [P3-TW] is plotted in the Figures. For the Europe-America links, TW data are 3 points per week until about MJD 52800, then 1 point per day until about MJD 53030, then 4 points per day. For the Asia-Pacific links, 2 sessions per week are conducted, each providing 2 or 3 measurements separated by a few minutes (i.e. that can be considered as simultaneous for our purpose).

For IEN-PTB (Figure 1a) over several months, the RMS of the difference is between 1.0 ns and 1.2 ns. Note that the 2-month gap around MJD 52640, as well as smaller ones, are due to missing TW data, while a 15-day gap around MJD 52580 is due to P3. The two discontinuities between different intervals are due to undocumented changes in the P3 set-up. A third discontinuity occurred on MJD 52898 due to the TW link but was short enough to be bridged with negligible uncertainty using P3 data (D. Piester, PTB, pers. comm.).

For USNO-PTB (Figure 2a), the RMS of the difference over 17 months is 0.8 ns. However there are two distinct intervals in this comparison due to a change in the TW set-up, and the corresponding discontinuity has been bridged using P3 data (D. Piester, PTB, pers. comm.), but the uncertainty of this procedure depends on the stability of the P3 link. Note also that the 3-month gap is due to the interruption of P3 data transmission at USNO and that this data could be recovered.

For OP-PTB (Figure 3a), the RMS over one month is 1.2 ns and is likely dominated by short-term noise in the TW data (see section 1.2).

For the Asian-Pacific TW links, the RMS of the difference is 1.2 ns for NMIJ-CRL over 15 months (Figure 4b) and between 1.1 and 1.3 ns for CRL-TL over several months (Figure 5b). Note that the TW data used for NMIJ-CRL in Figure 4b has been edited for more than 10 outliers. These are when some of the 2-3 nearly simultaneous measurements differ by one to several ns, which indicates a problem, but the TW data themselves do not allow to determine which measurements are wrong. Outliers are identified by comparison of the TW link with the P3 or C/A link over extended period. Note also that the gap in theses links around MJD 52920 are due to change in the P3 set-up during calibration at CRL.

These comparisons indicate that, for a given link computed over several months, the standard deviation of the differenced data [P3-TW] is typically 1 ns, and slightly better in the best case (USNO-PTB).

For some links for which TW is not available, the comparison with GPS C/A, computed at the standard TAI dates, is presented: For CRL-PTB the RMS of the difference over 18 months is 1.7 ns(Figure 6) and for CH-PTB the RMS of the difference over 10 months is 1.9 ns (Figure 7). For the links with TW, the GPS C/A link has also been computed at the dates of the TW measurements over the longest and most recent continuous interval. For these comparisons, the RMS of the differenced data [P3-C/A] is typically at or below 2 ns, e.g. 1.5 ns for IEN-PTB over 5 months (Figure 1b), 1.1 ns for USNO-PTB over 5 months (Figure 2b), 1.6 ns for OP-PTB over 1 month (Figure 3b), 0.8 ns for NMIJ-CRL over 3 months (Figure 4a), 2.0 ns for TL-CRL over 4 months (Figure 5a).

It seems that all [P3-C/A] comparisons display some small long-term variations, at the level of a few ns, except in the very short link NMIJ-CRL (70 km, Figure 4a). These long-term variations, rather than short term noise, seem to set the level of the RMS of the difference [P3-C/A] and are attributable to C/A (see below).

1.2. Three-corner hat analysis of P3, TW and C/A time links

For five links, the three techniques P3, C/A and TW are available so that some information may be obtained on each technique. When data are in sufficient number and approximately regularly spaced (IEN-PTB and USNO-PTB), it is possible to compute an estimate of the variance of each technique from the observed variances of the differences, assuming no correlation between the different techniques.

For IEN-PTB (Figure 1b) and USNO-PTB (Figure 2b), the individual variances of each technique can be computed by 3-corner hat from 1-day measurements taken over 5 months (also including up to 4 points a day over the last month). The time deviations computed with this procedure are presented in Figures 8.a for IEN-PTB and 8.b for USNO-PTB. The values for P3 (blue squares in the Figures) are below 0.6 ns for all averaging times between 1 and 30 days. For TW, the long-term results are similar but significant short-term (1-day) noise seems to be present for IEN-PTB. For C/A, the values are at or slightly above 1 ns (note that the 1-day values are artificially lower because of the Vondrak filtering).

For OP-PTB (Figure 3a), only one month is available with up to 4 points a day. It may readily be seen that the TW link has a large (several ns peak to peak) diurnal signature, which is observed in the differences with both GPS techniques while no signature is observable between P3 and C/A. The 3-corner hat analysis does not provide reliable results.

For NMIJ-CRL (Figure 4a) and TL-CRL (Figure 5a), the TW data should be pre-processed (i.e. the 2-3 nearly simultaneous measurements should be averaged in some way) before a 3-corner hat analysis can be performed. This has not been done yet. Note that for NMIJ-CRL, Figure 4a indicates that the observed instabilities originate from the TW data.

1.3. Discussion on the instability of P3 and other links

From the previous two sections, we may draw some general lines of evidence:

- The long-term comparisons of P3 and TW values computed over several months show typical RMS values of 1 ns (values ranging from 0.8 ns to 1.3 ns).
- When 3-corner hat analysis is possible, it indicates that the stability of the P3 technique is well below 1 ns for all averaging times between 1 and 30 days.
- When dense TW measurements are available, in some cases they indicate that significant (1 ns or larger) short term, mostly diurnal, noise is present in the TW data. Some TW outliers are also evidenced by comparison to the P3 link.
- As already indicated by previous studies [Petit et al. 2002], there is no evidence of significant (1 ns) short term, notably diurnal, noise in the P3 data.
- When long-term comparisons are performed between GPS C/A and either P3 or TW, they generally indicate significant long-term variations (up to a few ns). These are therefore attributed to the C/A technique.

We thus conclude that the stability (one standard deviation) of the comparison [P3-TW] is typically 1 ns and that there is no evidence that the P3 share of it should be larger than the statistical part of 0.7 ns at any averaging time between 0.5 day and at least one month. Similar conclusion apply for some TW links (USNO-PTB in this study), but there is evidence of short term variations in several TW links (IEN-PTB, OP-PTB) and of other instabilities in other TW links (NMIJ-CRL). The long term stability of C/A links is more typically of order 2 ns (one standard deviation).

2. Calibration of P3 time links

In 2001, calibration of P3 equipment has been started using a travelling receiver from the BIPM that has been previously absolutely calibrated [Petit et al. 2001]. Each visited system is differentially calibrated against the travelling system and all links between two calibrated systems may thus be considered as calibrated. The list of the calibration experiments concerning the receivers participating in the TAIP3 experiment, and their result are given in Table 3.

The uncertainty in the differential calibration of a P3 link has been stated at 3 ns [Petit 2002]. Nevertheless discrete variations of up to a few ns in the (P1-P2) delay have sometimes been observed for some receivers and have been associated with changes in the "environment" e.g. change in connections. These discrete events are detectable in the comparisons between techniques and do not affect the comparisons presented here. However we cannot exclude that such events occur between calibrations or even that the results of a calibration exercise depend on the precise set-up of the travelling receiver. Until further information, we shall use a conservative value of 5 ns for the uncertainty in the differential calibration of a P3 link.

Laboratory	Sys. ID/IGS	Date of calib.	Lab. Report	Ref. receiver	**XR1+XS1**	**XR2+XS2**
BIPM	BIPC	May 2000		Absolute	**305.6 ns**	**321.9 ns**
METAS	WAB1 (Gett)	Feb. 2001	e-mail	BIPC	**Ref +1.5 ns**	**Ref +0.3 ns**
BNM-SYRTE	OPMT	Feb. 2003	e-mail	BIPC	**Ref +10.9 ns**	**Ref +6.2 ns**
ORB	BRUS	July 2003	e-mail	BIPC	**Ref -2.1 ns**	**Ref -9.1 ns**
	ZTBR	July 2003	e-mail	BIPC	**Ref -9.6 ns**	**Ref -9.6 ns**
IEN	IENG	Oct. 2001	Nov. 2001	BIPC	**Ref +2.1ns**	**Ref -4.5 ns**
TL	TWTF	Dec.01-Jan.02	Jan. 2002	BIPC	**Ref +1.9 ns**	**Ref -4.2 ns**
CRL	KGN0	Oct. 2003	24 Oct. 2003	BIPC	**Ref + 2.9 ns**	**Ref -4.9 ns**
NMIJ	NMIJ	Apr. 2002	19 Apr. 2002	BIPC	**Ref +4.6 ns**	**Ref +0.1 ns**
IFAG	BKG/WTZA	June 2003	16 June 2003	BIPC	**Ref - 12.8 ns**	**Ref - 14.7 ns**
PTB	PTBB	May-June 2003	26 June 2003	BIPC	**Ref - 0.6 ns**	**Ref - 2.6 ns**
USNO	USN1	Dec. 2002	pers. comm.	BIPC	**Ref - 305.7 ns**	**Ref - 318.9 ns**
DLR	OBET+TSA	April 2003	8 May 2003	BIPC	**Ref + 307.5 ns**	**Ref + 301.9 ns**
NRC	NR1C	Nov.-Dec. 2003	7 Jan. 2004	BIPC	**Ref + 5.9 ns**	**Ref + 2.5 ns**

Table 3: Calibration results for receivers participating to the TAIP3 experiment.

All P3 equipment considered in this study have been differentially calibrated. However the results for the CRL receiver are still under review and have been included here for completeness only. Therefore, out of the P3 links considered in this study, three can be compared with other independently calibrated techniques and the results are in Table 4.

Link	Date of P3 calibration	Type and date of compared calibration	Difference P3 - other	Comments
OP-PTB	02/2003-06/2003	C/A 06/2003, 08/2003	0-4 ns	several ns variations
USNO-PTB	12/2002-06/2003	TW 06/2002, 01/2003	7 ns	1-ns stability
CRL-PTB	10/2003-06/2003	C/A 11/2003	-19 ns	Uncertain P3 set-up
CH-PTB	02/2001-06/2003	C/A (OP-CH)12/2003	4-8 ns	several ns variations

Table 4: Comparison of calibrated P3 links with other calibrated techniques.

For OP-PTB (Figure 3b), the P3 and C/A links are calibrated and the average difference is of order 2.5 ns, while the stated uncertainty of a C/A differential calibration is 5 ns [see Lewandowski and Tisserand 2003]. Long-term variations at the level of a few ns over several months are apparent and attributable to C/A. For USNO-PTB (Figure 2a) a TW calibration was available until reconfiguration of the TW link around MJD 52880. The average difference between P3 and TW is of order 7 ns, with no significant long-term variations, while the uncertainty of the TW calibration is estimated to be 1 ns [D. Matsakis, USNO, pers. comm.]. For CH-PTB (Figure 7), the C/A receivers have been calibrated in two different calibration trips, therefore the uncertainty of the C/A calibration is somewhat larger than the standard 5 ns value. In addition long-term variations at the level of a few ns over several months are apparent.

We conclude that all comparisons of calibrations by different techniques are consistent within their combined uncertainties (with USNO-PTB P3-TW marginally significantly different).

3. Introduction of time links into TAI computation

A few P3 time links have already been introduced into TAI computation: DLR-PTB, IFAG-PTB, ORB-PTB in July 2003. In addition, all other P3 time links are computed as backup links and have occasionally been used. In addition, the P3 link CH-PTB has now been shown to agree with the C/A link within the uncertainty of calibration (see section 2, it turns out that the C/A link as presently used in TAI is in error by more than 30 ns. The P3 link should replace the C/A link as soon as possible.

Through a study of several time links with different techniques, we show that the time instability of GPS P3 time links is below 1.0 ns (one standard deviation) for averaging times up to one month. This performance is maintained at longer averaging times because the long comparisons with TW(Ku) links all show a standard deviation of about 1 ns. This performance is typically at least twice better than GPS C/A links and probably about equivalent to that of the TW(Ku) links. In addition several TW links presently used in the TAI computation display various forms of short-term instabilities, such as diurnal variations or outliers. It is therefore expected that improvement would result from complementing these links by the use of P3 links.

Acknowledgements

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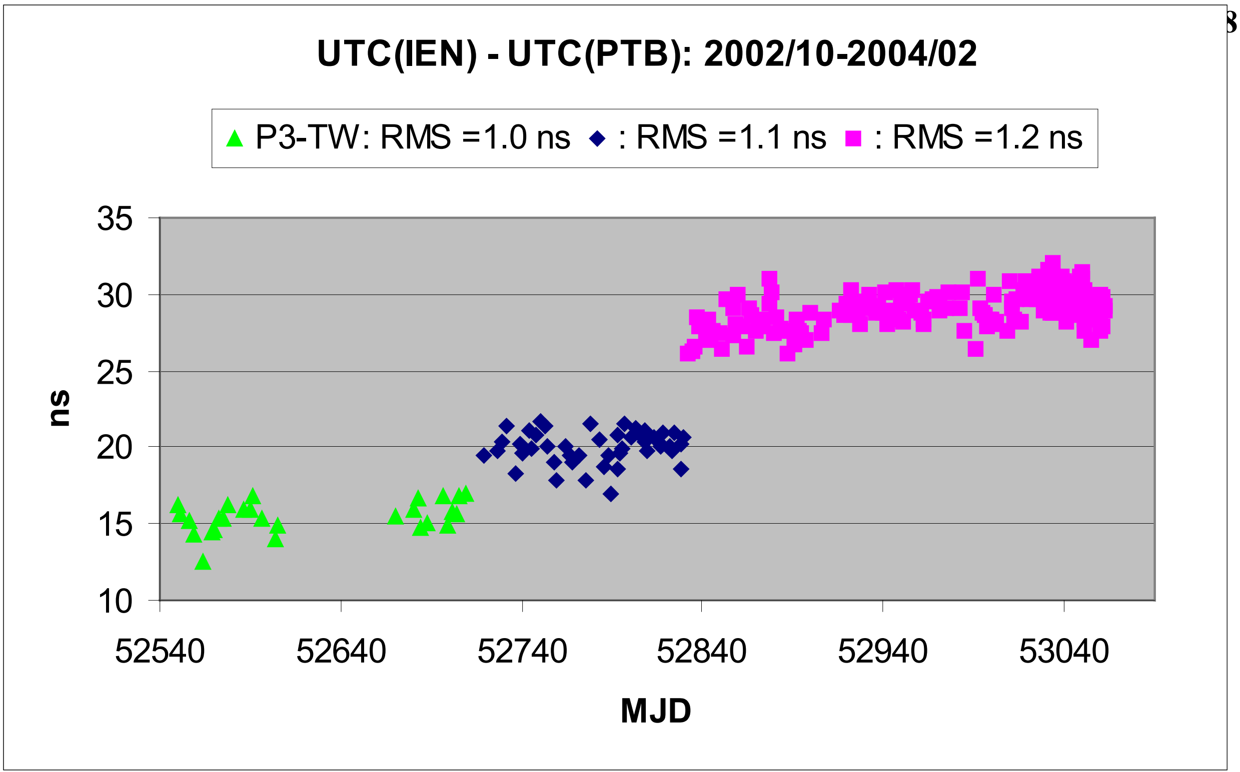

Figure 1a: Comparison of P3 and TW for IEN-PTB over 17 months

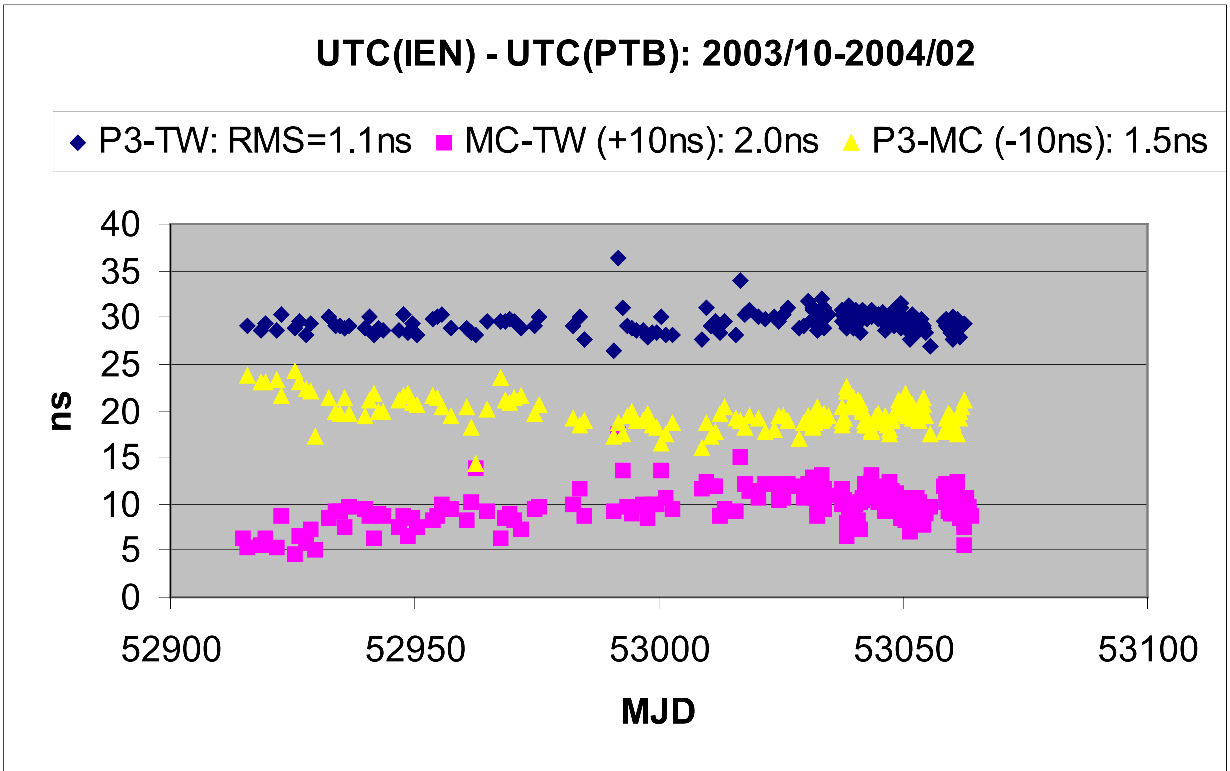

Figure 1b: Comparison of P3, C/A MC and TW for IEN-PTB over 5 months

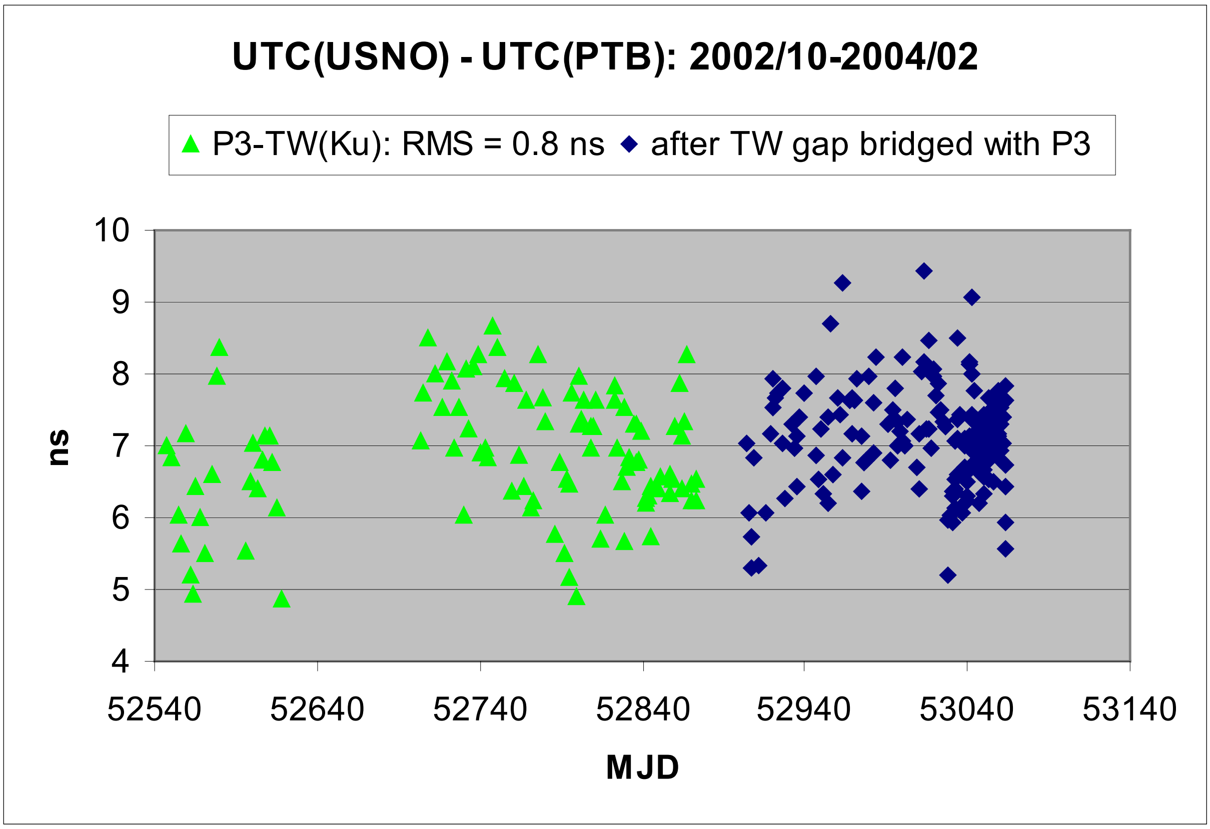

Figure 2a: Comparison of P3 and TW for USNO-PTB over 17 months

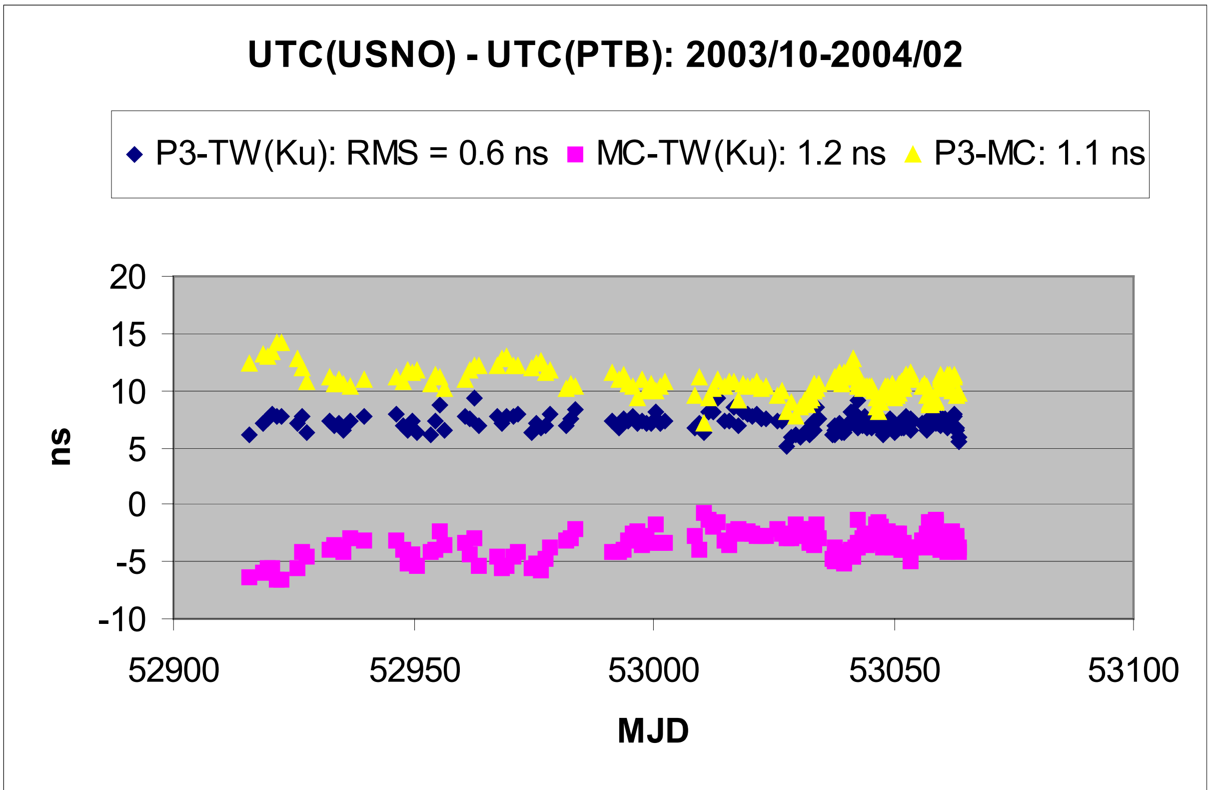

Figure 2b: Comparison of P3, C/A MC and TW for USNO-PTB over 5 months

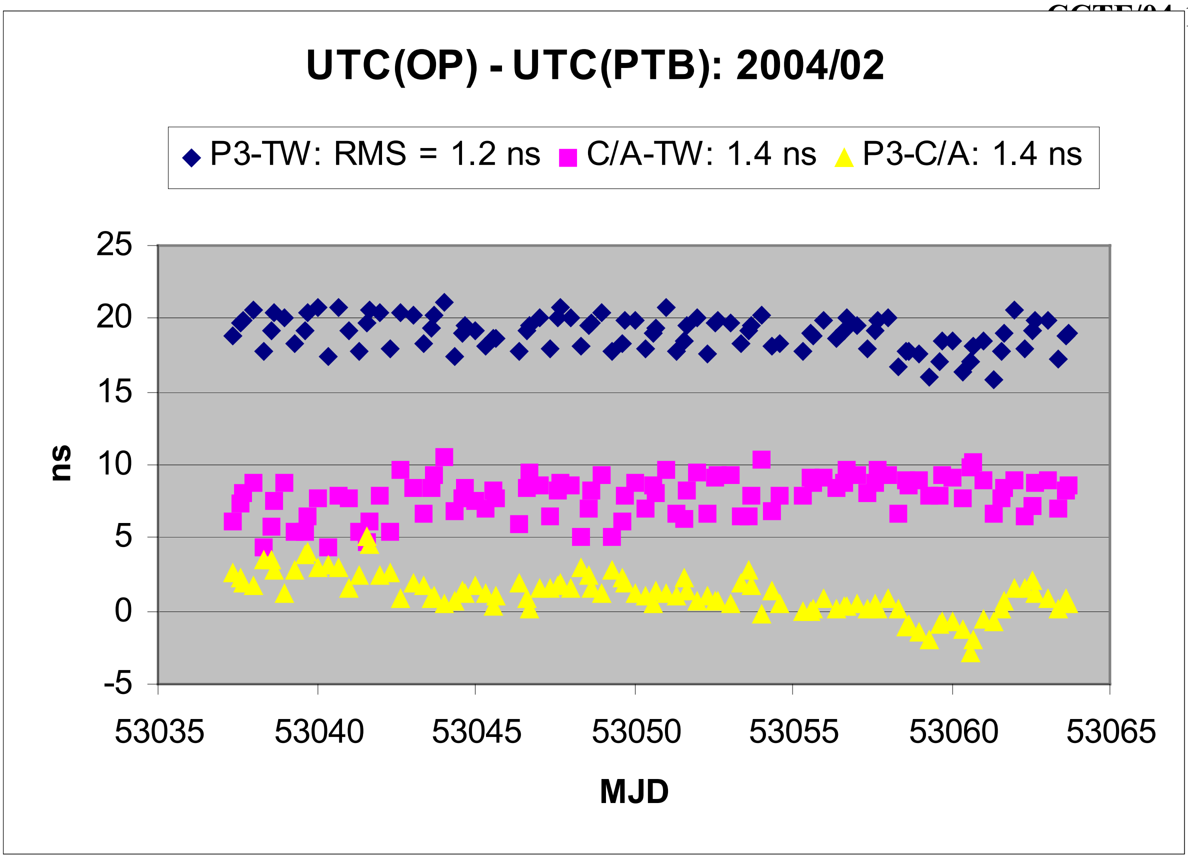

Figure 3a: Comparison of P3, C/A SC and TW (arbitrary offset) for OP-PTB over 1 month

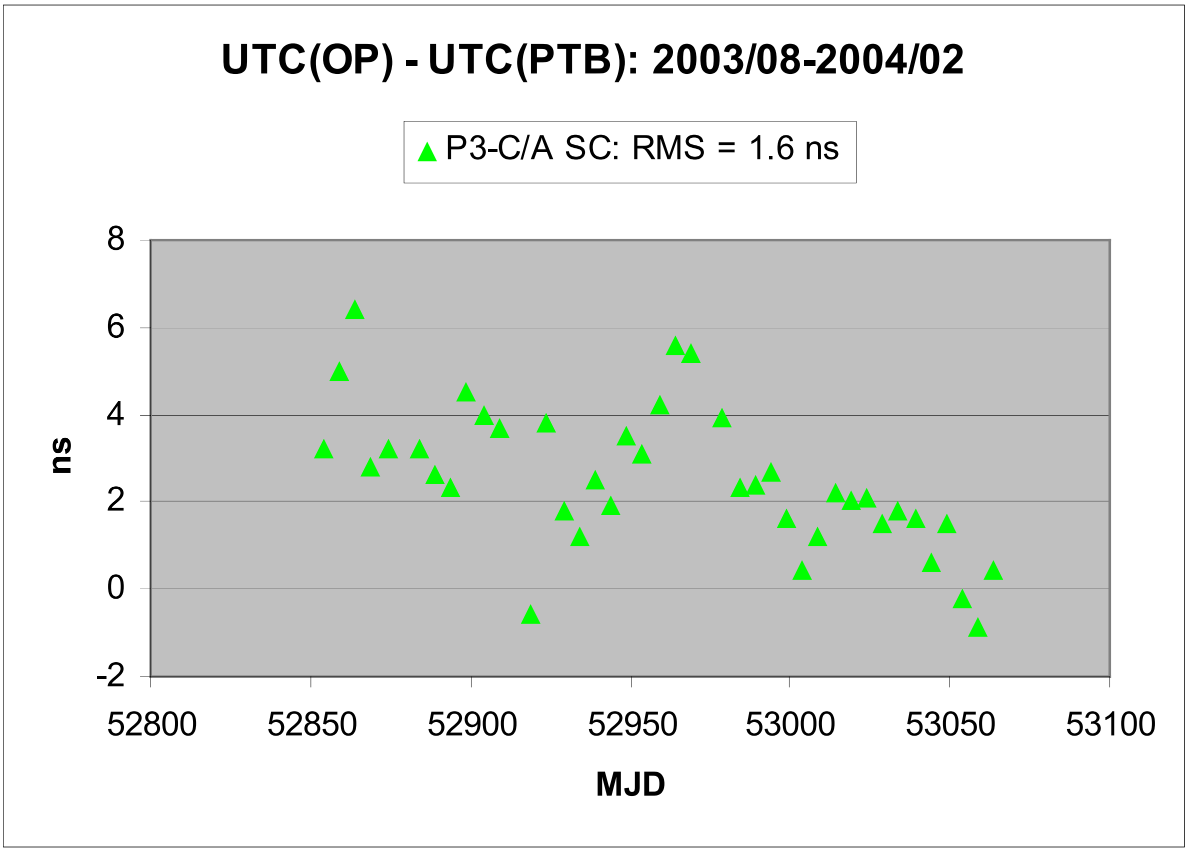

Figure 3b: Comparison of P3 and C/A SC for OP-PTB over 7 months

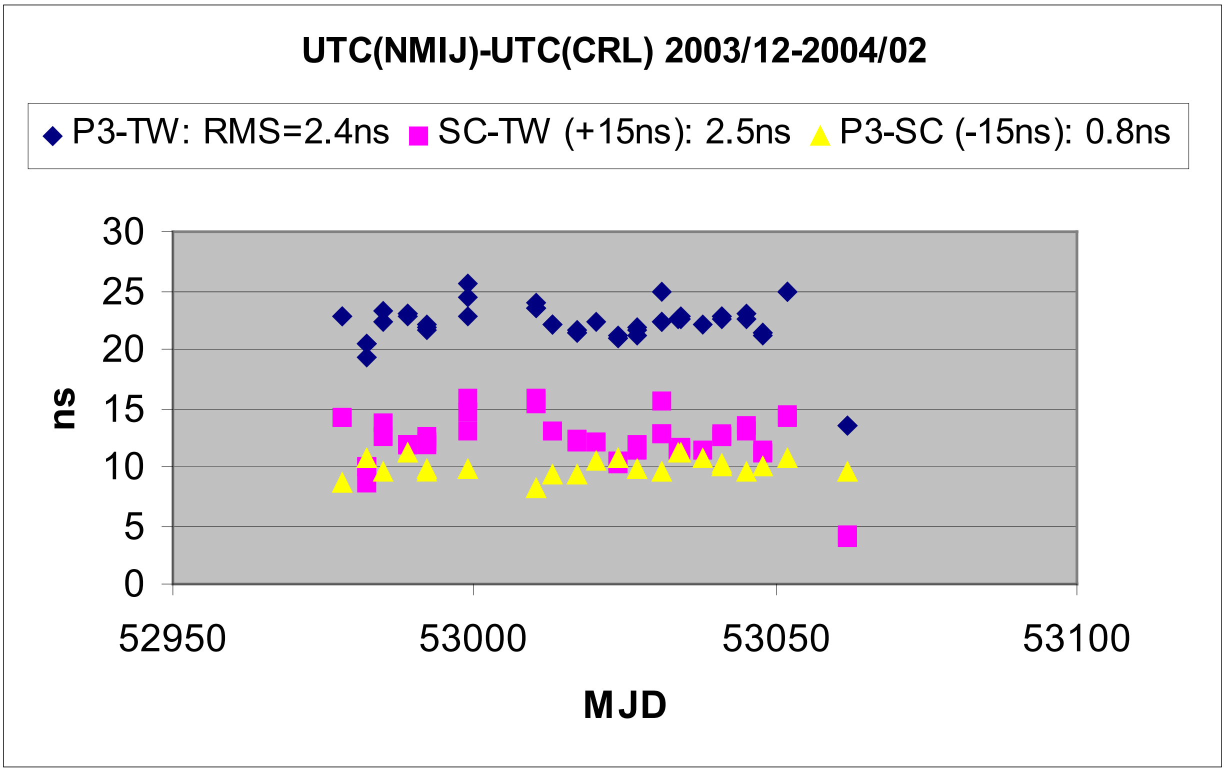

Figure 4a: Comparison of P3, C/A SC and TW for NMIJ-CRL over 3 months

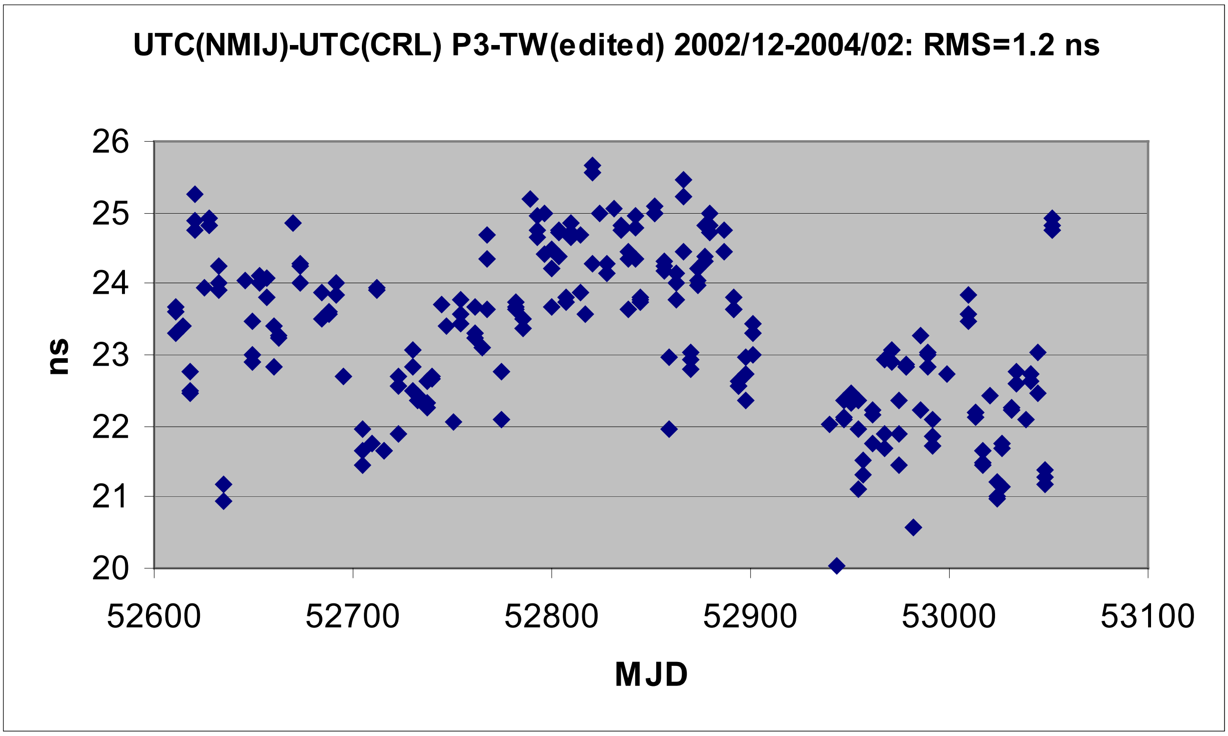

Figure 4b: Comparison of P3 and TW for NMIJ-CRL over 15 months after edition of outliers

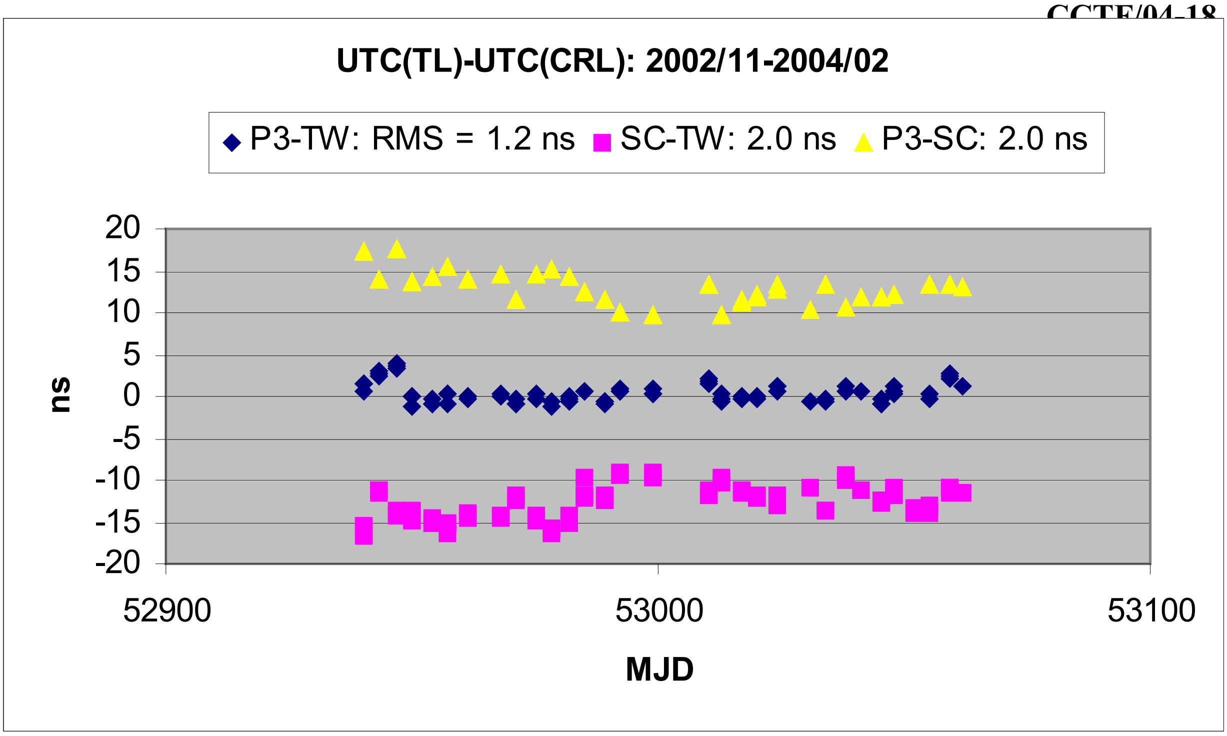

Figure 5a: Comparison of P3, C/A SC and TW for TL-CRL over 4 months

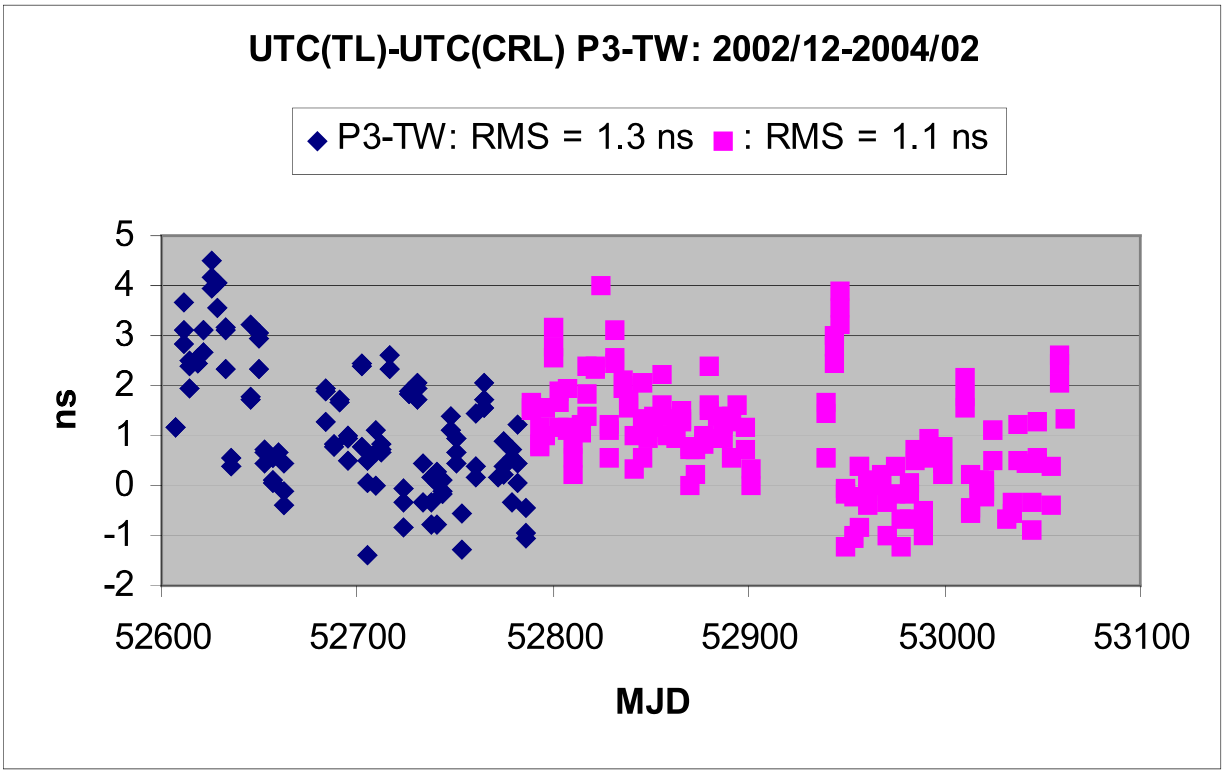

Figure 5b: Comparison of P3 and TW(Ku) for TL-CRL over 15 months

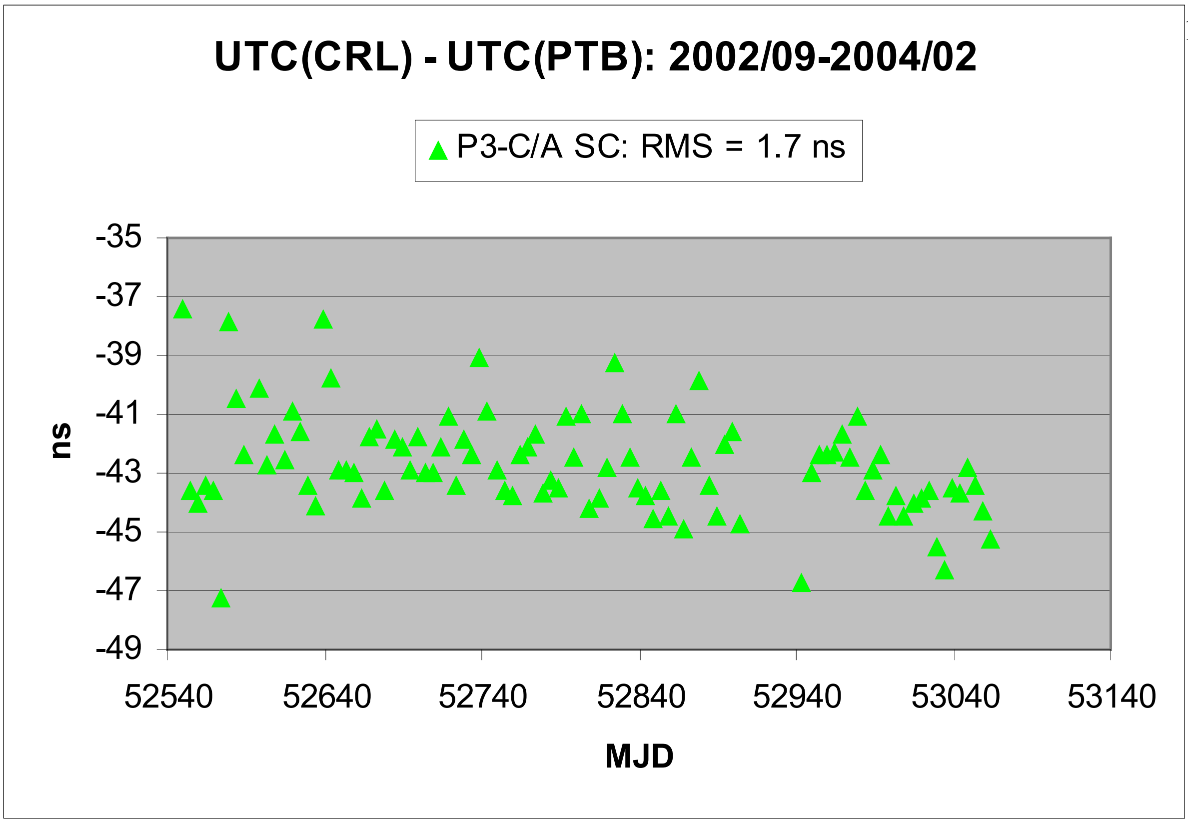

Figure 6: Comparison of P3 and C/A SC for CRL-PTB over 18 months

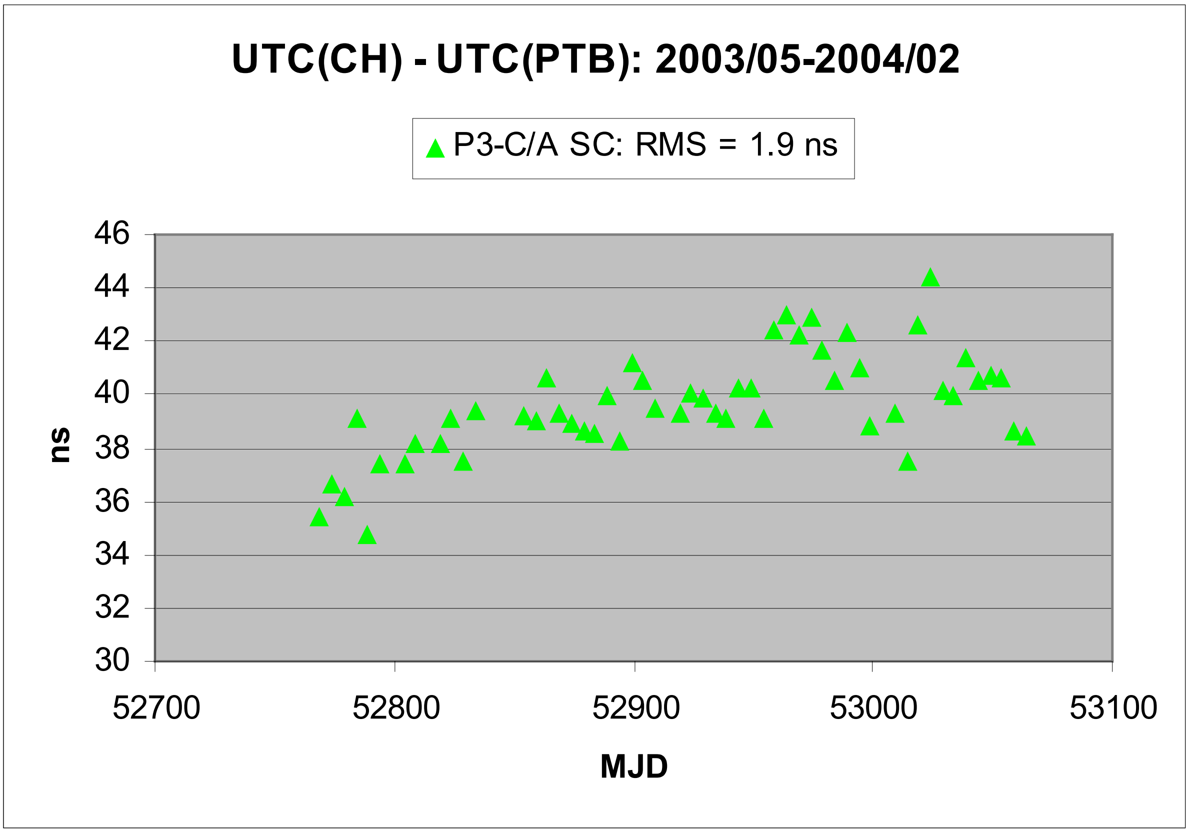

Figure 7: Comparison of P3 and C/A SC for CH-PTB over 10 months

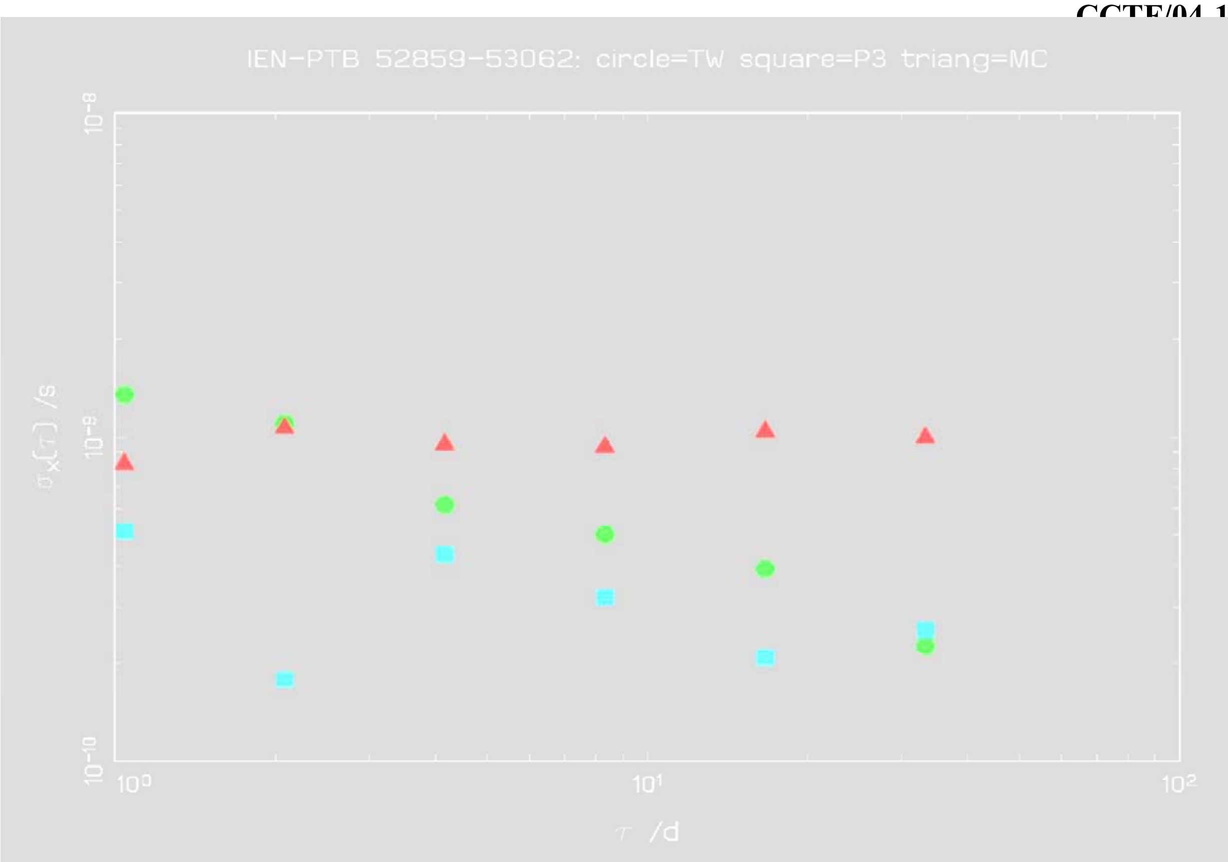

Figure 8a: Time deviations from three-corner hat analysis for IEN-PTB over 7 months

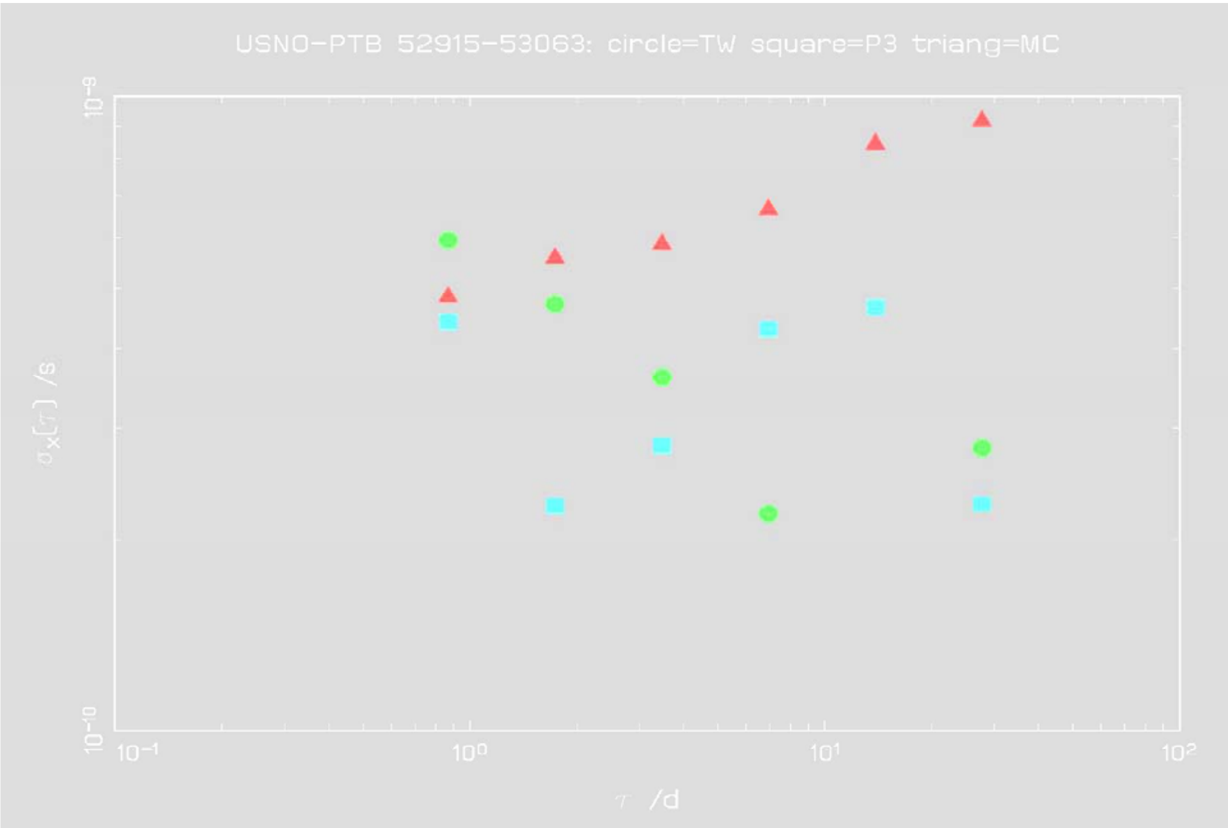

Figure 8b: Time deviations from three-corner hat analysis for USNO-PTB over 5 months