TWO-WAY SATELLITE TIME TRANSFER USING INTELSAT 706 ON A REGULAR BASIS: STATUS AND DATA EVALUATION

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Abstract

TWSTT (Two-Way Satellite Time Transfer) observations in Europe and between Europe and the United States resumed on 20 January 1997, using the INTELSAT 706 satellite on a regular basis. Six European and two US stations observe regularly. Two other European stations are about to become operational. The paper first describes the activities of the CCTF (Consultative Committee for Time and Frequency) Working Group on TWSTT. The use of INTELSAT 706 satellite and status of participating stations is then discussed together with related data. Evaluation of the TWSTT data reported in this paper includes its comparison with GPS common-view time transfer data for selected continental and intercontinental links over a period of one-and-a-half years.

INTRODUCTION

TWSTT (Two-Way Satellite Time Transfer) observations in Europe and between Europe and the United States resumed on 20 January 1997 (MJD = 50468) using the INTELSAT 706 satellite on a regular basis. Three one-hour observation windows, on Monday, Wednesday and Friday, have been purchased from INTELSAT. Within these windows two-minute TWSTT measurements are performed between participating stations according to a schedule. Six

European and two US stations observe regularly. Two other European stations are about to become operational. No significant problems concerning the satellite have been encountered. An ITU standard format is used for the exchange of data. The exchange and storage of dataareeasy, as the files are small. Data are available within two days.

First, a résumé is given of the activities of the CCTF (Consultative Committee for Time and Frequency) Working Group on TWSTT. The use of INTELSAT 706 satellite is then described, as well as the status of participating stations and related data. Evaluation of the TWSTT data reported in this paper includes its comparison with GPS common-view time transfer data for selected continental and intercontinental links over a period of one-and-a-half years. The goal of this study is to compare the stability of GPS common-view and TWSTT techniques, not accuracy.

CCTF WORKING GROUP ON TWSTT

The 11th CCDS (now CCTF) meeting of 1989 issued a declaration 1989/1 encouraging the use of TWSTT and suggesting the creation by the BIPM of an *ad hoc* Working Group on TWSTT. The *ad hoc* Group met twice in 1989 and 1992. Following the decision of the 12th CCDS meeting in 1993, the *ad hoc* Group was converted into a permanent CCDS Working Group with the task of helping the BIPM to elaborate the TWSTT technique for its possible use in the construction of TAI [1]. Since 1993 there has usually been one annual meeting of the full WG and two technical annual meetings of the participating stations. The main achievements of the WG are: development of a standard format; organization of TWSTT time links (choice of modems, schedule of observations, duration of observation, data exchange, ...); negotiation of the best conditions for the use of INTELSAT satellite; and the evaluation of TWSTT links by comparison with other available time transfer techniques.

USE OF INTELSAT 706 ON A REGULAR BASIS

As mentioned in the introduction, the TWSTT system has access to three one-hour observation periods from INTELSAT. In each window, beginning at 14 h UTC, 30 minutes are dedicated to links within Europe, and another 30 minutes to links between the United States and Europe. Within each 30-minute window, sessions are scheduled to last for 2 minutes with a 1-minute break to switch the codes [2].

The participating stations, namely the DTAG, NIST, NPL, PTB, TUG, USNO, and VSL, continue to perform observations on a regular basis, and the data from the present project are currently under evaluation. At the OCA, TWSTT equipment is presently undergoing tests before going into regular operation.

Each session between stations A and B consists of two-minute periods during which second-to-second measurements are carried out simultaneously at both stations. The time transfer measurement for each station is then obtained from a quadratic fit over the 1-second measurement interval. A specific data format has been developed to allow the exchange of two-minute tracks between partner stations. A provisional description of this format is given in the Report of the 3rd Meeting of the CCTF Working Group on TWSTT, held in Braunschweig (Germany) on 28-29 September 1995 [3]. A draft revision of Recommendation ITU-R TF.1153, recommending the use of this format, is presently under study.

Table 1. Availability of TWSTT data.

Laboratory	Continuous observations since ...
TUG	20 January 1997
USNO	22 January 1997
VSL	22 January 1997
DTAG	7 February 1997
PTB	17 February 1997
NIST	21 February 1997
NPL	20 April 1998
OCA	Temporarily interrupted

It is of considerable interest to note that all TWSTT data files listed above use the ITU-R format. This greatly simplifies the computation of time links. It should be emphasized that TWSTT dataareavailable quickly, usually one or two days after a session and, in the case of TUG, one hour after.

COMPARISON OF GPS AND TWSTT MEASUREMENTS

The goal of this study is to compare the stability of GPS common-view and TWSTT techniques, not accuracy. However, some indications on the constant biases between these two techniques are provided. A detailed study of the accuracy of the two techniques is provided elsewhere in these Proceedings in "Calibration of Three European TWSTFT Stations Using A Portable Stations and Comparison of TWSTFT and GPS Common-View Measurement Result" by D. Kirchner et al.

Aside from other differences, the TWSTT and GPS common-view data differ in their density: TWSTT measurements are performed every two or three days during 120 s intervals; GPS measurements are performed every day and there are about thirty 780 s tracks per day, which corresponds to 23400 s GPS observations per day.

It will be shown that very short interval TWSTT data give comparable or sometimes better results when compared with GPS. For the needs of the present comparison a choice was made to smooth and interpolate GPS data to the midpoints of the TWSTT sessions. As a result we obtained differences between the two techniques at intervals of two or three days. This comparison was performed for two types of time link:

- short-distance time link, over 700 km, between the PTB and the TUG,
- long-distance time link, over 8000 km, between the PTB, and the NIST.

The Figure 1 shows the differences between UTC(TUG) and UTC(PTB) obtained by TWSTT and GPS common-view for a period of about fourteen months. One can observe an apparent agreement between the two methods with a shift of several nanoseconds. We observe also a large drift between the two time scales, which complicates somewhat the statistical analysis. Figure 2 indicates the differences between the two methods at the times of the TWSTT observations, as well as the outside temperature at the TUG. The scatter of the differences between the TWSTT and GPS data for this short-baseline is about 12 ns. These differences exhibit an apparent systematic variation correlated with the external temperature. The seasonal effect has always been attributed to the environmental sensitivity of the GPS time equipment [4]. The stronger seasonal effect in 1997 stems from a problem with the power supply to the GPS time receiver at the TUG, which has amplified the temperature dependence of TUG GPS equipment. One should note that clocks are not entirely removed in these differences because of the different nature of the TWSTT and GPS data already mentioned: for GPS we have over 20000 s of observations per day, while for TWSTT we have 120 s of observations every two or three days. Concerning the bias of several nanoseconds between the two methods it should be pointed out that a differential correction issued from a TWSTT equipment calibration was applied to the TWSTT data considered here, but GPS data were not corrected for calibration during this study. Once GPS calibration corrections provided by a series of GPS calibration trips [5] are applied, the observed shift between the two methods disappears (see D. Kirchner et al. in these Proceedings).

Figure 3 shows the time deviation of [*UTC(TUG) – UTC(PTB)*] for the TWSTT and GPS common-view data. We see the same behavior for the two methods. The small differences are not significant. In fact from the beginning we see the behavior of the two clocks used in the comparison. The plot is not a property of the time transfer measurement, but an indication of the performance of the two cesium clocks. A comparison involving two masers would produce a different curve.

The long-distance comparison over 8000 km was performed between UTC(PTB) and UTC(NIST) for a period of about fourteen months (see Figure 4). We also observe for this long-baseline an apparent agreement between the two methods with a shift of several nanoseconds. The scatter of the differences between the TWSTT and GPS data reported on Figure 5 is about 20 ns. If we remove two outliers, this scatter reduces to about 12 ns. No seasonal effect is noticeable. The bias of several nanoseconds observed between the two methods is due to the way in which the TWSTT data were calibrated. As no independent TWSTT calibration was available for this link, the TWSTT link was calibrated using a GPS link provided by the BIPM Circular T. All transatlantic GPS links in Circular T are corrected for precise satellite ephemerides and ionospheric measurements. No such corrections were applied to the GPS link computed for this study. The GPS link was computed with broadcast ephemerides and modelled ionospheric delay. This is because no reliable ionospheric measurements were available. Differences between the measured and modelled ionospheric delays for the period covered by this study are roughly equal to −10 ns. So the bias we observe here arises from the differences in the computation of GPS links, and not from the differences between the two methods. As was mentioned earlier, this study is not about the comparison of accuracy between TWSTT and GPS methods,but about their stability. To realize a comparison of the accuracy of the two methods an independent calibration of TWSTT and GPS equipment should be organized.

Figure 6 shows the time deviation of [*UTC(PTB) – UTC(NIST)*] for TWSTT and GPS common-view data. For averaging times up to 10 days, the TWSTT link seems to be more stable than the GPS link. This GPS behavior is probably linked to the poor quality of broadcast ephemerides and modelled ionospheric delay which were used for this study.

CONCLUSIONS

• The CCTF WG on TWSTT has been very active for the past five years and has successfully moved the TWSTT method to an operational phase.

• Presently there are six operational and two pre-operational TWSTT stations in Europe and two operational stations in the USA using the INTELSAT 706 satellite. Preparations are also under way to operate several other TWSTT stations in the Asia-Pacific region. They are using INTELSAT 702 and JCSAT-3 satellites. Future connection between Asia-Pacific and Europe-North America TWSTT networks is already under consideration (see M. Imae et al. in these Proceedings).

• The INTELSAT 706 satellite was used for the past twenty-two months on a commercial basis. For this period we observed smooth, uninterrupted, routine operations of a network of TWSTT stations.

• Comparison of the stability of TWSTT and GPS common-view methods during this study can be summarized roughly as follows:

- for the short-baseline comparison a seasonal effect correlated with outside temperature was observed; difference in the stability of the two methods could not be determined, as their performance from the beginning is covered by the noise of the two cesium clocks being compared;

- for the long-baseline comparison the TWSTT method is more stable than GPS for up to 10 days (GPS was not corrected for precise ephemerides and ionospheric measurements);

- the performance of TWSTT appears to be at least as good as the performance of GPS common view.

• The progress accomplished until now allows us already to look toward possible consideration of the TWSTT method for TAI needs.

REFERENCES

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[4] D. Kirchner et al.,"Comparison of GPS Common-View and Two-Way Satellite Time Transfer Over a Baseline of 800 km," *Metrologia* **30**, pp. 183-192, 1993.

[5] W. Lewandowski and H. Konate, " Differential Time Corrections for GPS Time Equipment Located at the OP, VSL, NPL, DTAG, PTB, TUG, IEN, USNO and NIST: 4th Evaluation," Rapport BIPM, 1998 (in preparation).

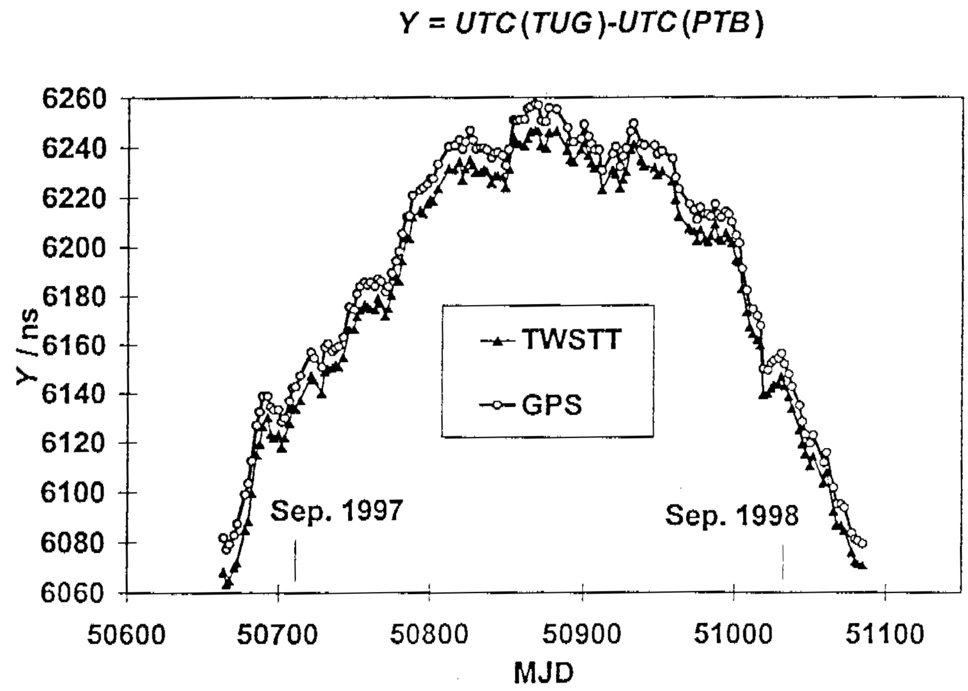

Figure 1. Differences between UTC(TUG) and UTC(PTB) obtained by TWSTT and GPS common-view for a period of about fourteen months (after slope removal).

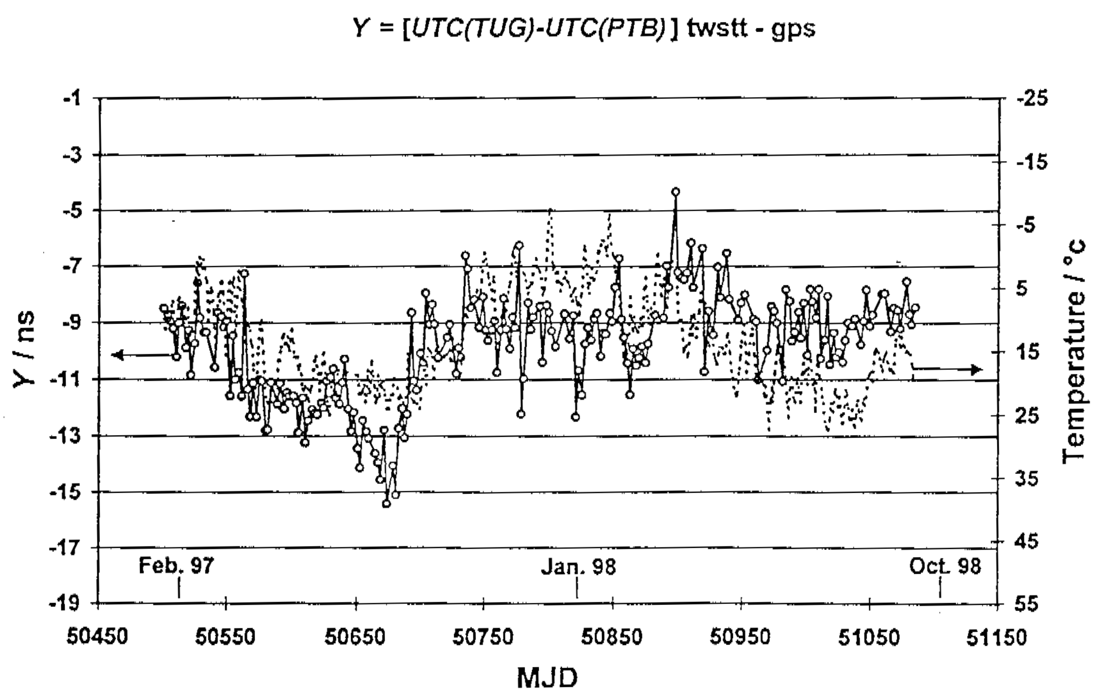

Figure 2. Differences between TWSTT and GPS common-view methods at the times of TWSTT observations, and the outside temperature at the TUG.

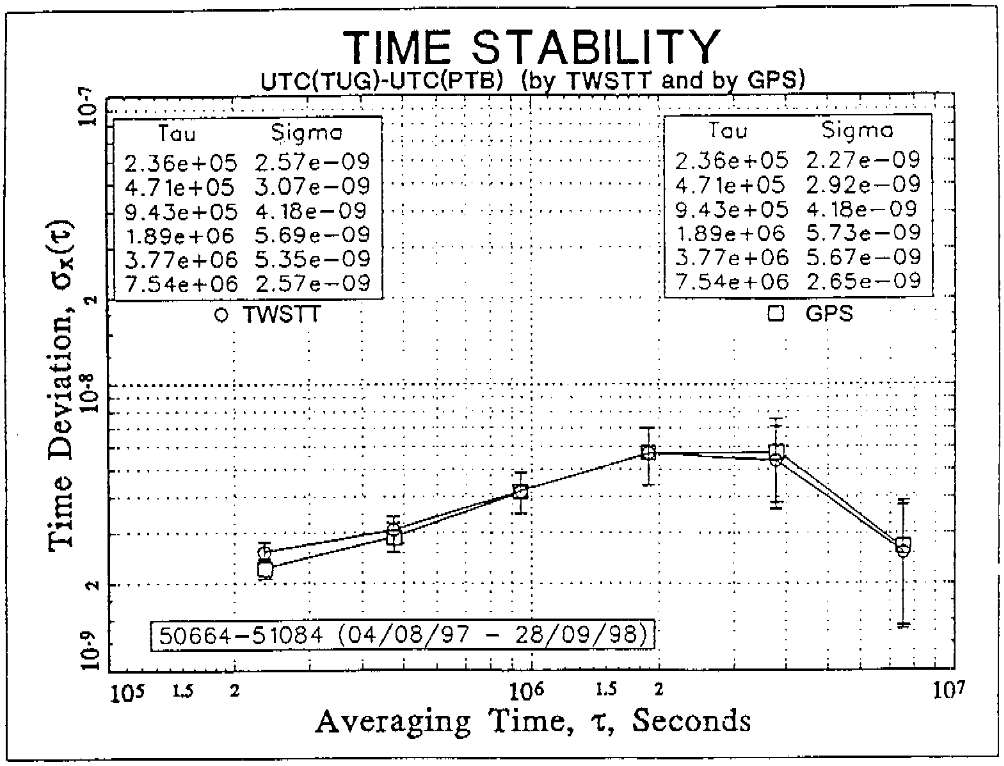

Figure 3. Time deviation of [*UTC(TUG) – UTC(PTB)*] for TWSTT and GPS common-view.

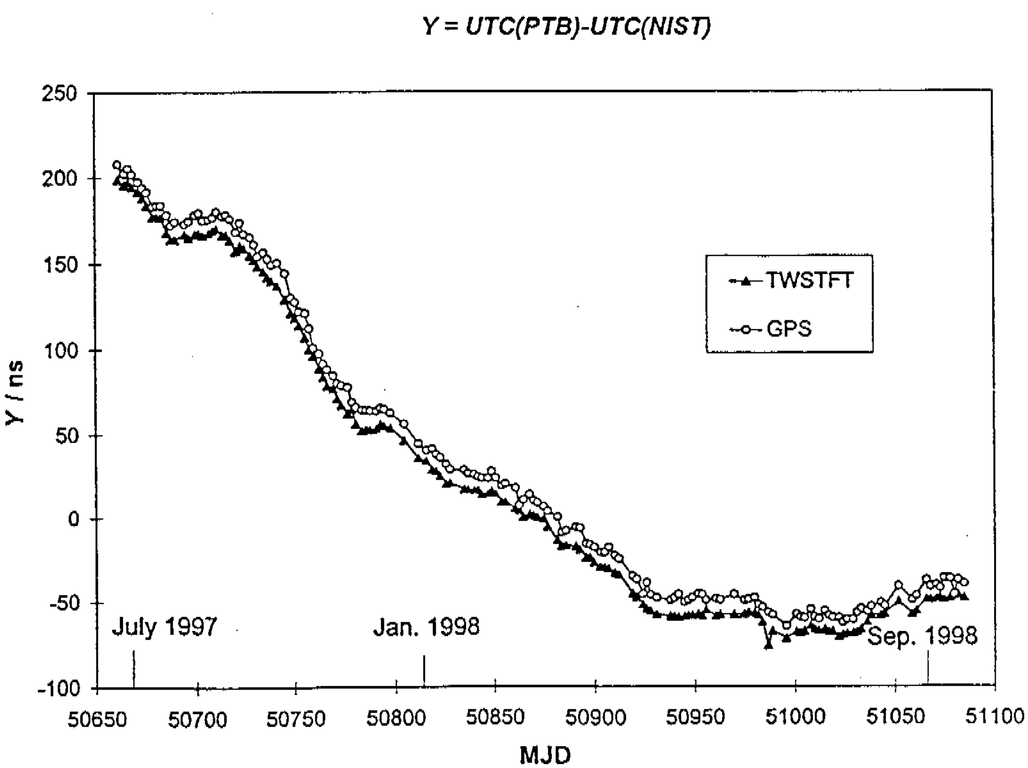

Figure 4. Differences between UTC(PTB) and UTC(NIST) obtained by TWSTT and GPS common-view for a period of about fourteen months.

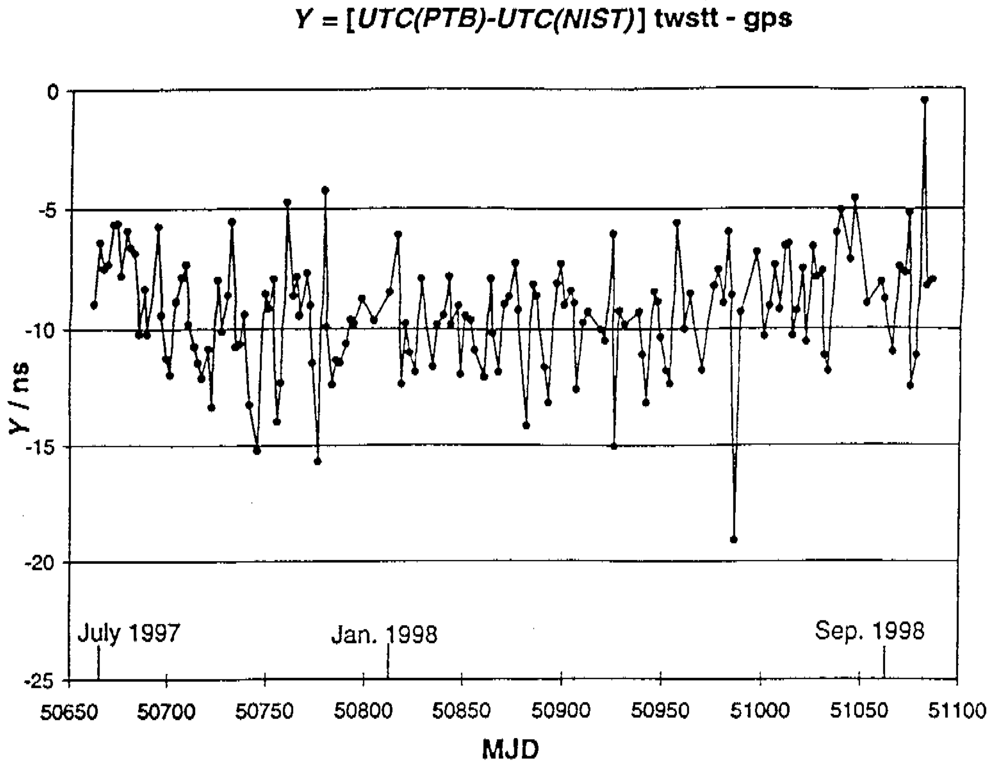

Figure 5. Differences between TWSTT and GPS common-view methods at the times of TWSTT observations.

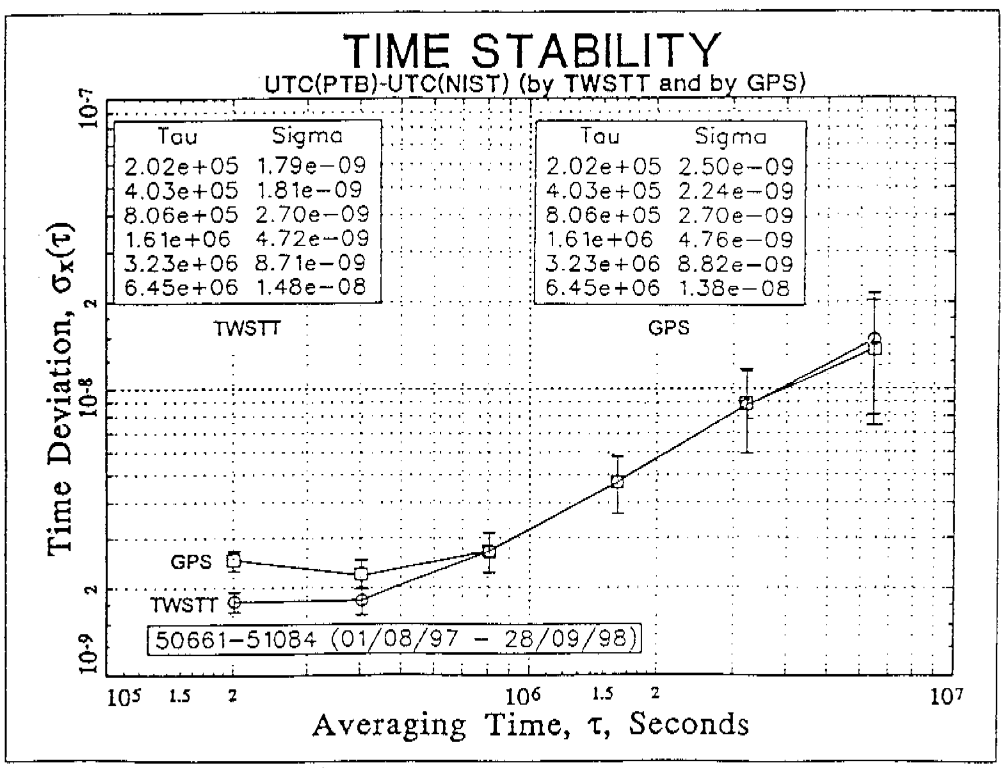

Figure 6. Time deviation of [*UTC(PTB) – UTC(NIST)*] for TWSTT and GPS common-view.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): I just wanted to point out that the two-way data that you are talking about is two-way as done in this experiment, which is three times a week. It is actually much more accurate than GPS as is proven at the AMC. The plots that Jim DeYoung showed of free-running time scales between the USNO at Washington and the USNO at the Alternate Master Clock show increased improvement out to well past a month. If you look at unsteered maser-only time scales, that improvement seems to go all the way out to many, many months. But, there is problems there due to the correlation between parabolas and drift, which Marc Weiss was talking about. Certainly, the two-way technique, if it is done repeatedly, like every hour, is even more stable.

JACQUES AZOUBIB (BIPM): I forgot to mention that the data here is not equally spaced. When I computed the time variation, I took an average. So the values of TVAR shown in my vugraphs are a bit biased.

JUDAH LEVINE (NIST): I noticed in the TUG-PTB data that you showed that there was a bias between the two-way data and the GPS data of about 10 or 11 nanoseconds. I was wondering how that is consistent with Dr. Kirchner's calibrations.

JACQUES AZOUBIB: With Dr. Kirchner?

JUDAH LEVINE: Dr. Kirchner reported on a number of calibrations in which you went around measuring the delays of the various stations. I was wondering how, if the delays are understood. You have a bias of about 10 nanoseconds.

JACQUES AZOUBIB: I do not understand your question. Here?

JUDAH LEVINE: No, no. The average of that curve is about 10 nanoseconds off of zero.

JACQUES AZOUBIB: No, I do not agree with you. Because one cannot average here because it is not white phase noise. It is only white noise to 40 days. So if you want to average, you have to average over 40 days, 40 days, 40 days,and 40 days.

JUDAH LEVINE: Every one of those points is more negative than minus seven nanoseconds except one. That curve does not have a mean of zero. Your whole curve is biased down by about 10 nanoseconds.

DIETER KIRCHNER (TUG): Yes, it is true.

JIM DeYOUNG (USNO): The obvious answer that the numbers which BIPM is using are not Dr. Kirchner's answers? So, there is obviously a great deal of improvement there.

JACQUES AZOUBIB: Yes, you are right. If you want, we can make Dr. Kirchner's values in agreement if we add 12 nanoseconds. Because while computing these values, we applied a time constant of 12 nanoseconds, and it was used in order to take GPS calibrations into account.

DIETER KIRCHNER: May I explain it briefly? It is a long story, and I avoided going into this story. BIPM applies corrections to the GPS data and then they calculate the Circular T. After doing the first

GPS calibration trip the next one and the next one showed that there is a bias in the Circular T data. There was a total difference between the Circular T data and the two-way data by about 20 nanoseconds. The correct number was 18.3 nanoseconds. After calibrating the two-way data, with location of the station, and the GPS data,with the results from the GPS receiver trips, the difference is about zero, as we have shown.

These 10 nanoseconds are coming from applying a wrong correction to the GPS data by BIPM. I always had some suspicion about this correction, and in my opinion when this correction was calculated, they simply used a wrong sign. Ten nanoseconds in one direction, in the wrong direction, you have a bias of 20 nanoseconds.

I did not want to explain all this. I can show you the different steps going from Circular T, GPS data, difference between Circular T GPS data, and two-way data, after applying the correction for the two-way data using the transportable station, you have about 20 nanoseconds. Then you apply to the original GPS data the correction found by the GPS receiver trips and you have no difference. You have the zero offset that you want to see. I agree with you here, you see, about the minus ten nanoseconds.

JUDAH LEVINE: And are you saying that the PTB NIST link has the same error in it? Because the number is about the same.

DIETER KIRCHNER: No.

JACQUES AZOUBIB: No, this is a special case for –

JUDAH LEVINE: Please put up the PTB NIST same plot? It also has a mean of about seven, eight, nine, or ten or some number like that. Is that a coincidence or is there another mistake?

JACQUES AZOUBIB: No, for this link, no time constant has been applied.

JUDAH LEVINE: But that number has a mean of about, I do not know, seven maybe, or eight or nine. It is not zero either.

WLODZIMIERZ LEWANDOWSKI (BIPM): I would like to clarify the difference in the delays. First, for the previous graph, we cannot call this a mistake. This is a practice – we are using all the corrections for GPS calibration. That does not mean it is always wrong. These values are changing with time, as shown during the Dr. Kirchner's talk. So Jacques Azoubib was using the current differential calibration for GPS. What he was showing, he was not applying the most recent calibrations. There is a separate talk on this issue. This explains why we have about 10 nanoseconds. It is because we are using several old years' GPS corrections.

This vugraph, this difference comes from something else because here, the two-way link is not calibrated. So just value does not matter, the difference – because there is no calibration for two-way. GPS is calibrated, but two-way link is not. Okay? GPS is calibrated at the level which we can do, several nanoseconds uncertainty. But we do not have a differential calibration for PTB NIST.

DIETER KIRCHNER: I am sorry, I have to make a correction. Also, the two-way link here is calibrated using the Circular T data. So, I think that all this stuff demonstrates that we have to be a bit cautious using the Circular T as an absolute difference between time scales. We already know from USNO that therewere similar problems, 29 nanoseconds or something like that.

WLODZIMIERZ LEWANDOWSKI: Yes, you are right. But what I wanted to say was that there is no independent calibration for two-way.

JUDAH LEVINE: I guess I am a little unclear, under these circumstances, of how we are going to combine GPS data and two-way data into TAI when the calibrations do not seem to agree, for whatever reason. I mean, I am not suggesting that one of them is right or one of them is wrong; but if one has these sorts of differences, then the difference between two laboratories calculated using one method and using another method, it is going to have a difference of something like 10 nanoseconds in it.

WLODZIMIERZ LEWANDOWSKI: I do not agree with this because of Dr. Kirchner's paper. He has shown an excellent argument between GPS calibration and two-way calibration. This is the story of all calibrations which were used from the past GPS calibration trips. But GPS delays are changing. Dr. Kirchner has shown that in fact we have to apply the seasonal GPS calibration results.

DIETER KIRCHNER: Really, it is simple to explain and there is no mystery about it. One has to distinguish between different data sets. So Laboratory "A" and Laboratory "B" are doing GPS measurements. These are the data which are coming out of the GPS receivers. These data are sent to BIPM. BIPM applies corrections to this data according to past GPS receiver trips and one should not use these old calibrations. One should simply use GPS data as relayed from the laboratories and apply the most recent corrections, and we try to do it.

DEMETRIOS MATSAKIS: Can I make a comment here? I had asked Claudine Thomas in June and received a very positive response from her about having the BIPM create a product which would be post-processed corrections for all of these things, which we could all refer to when we are comparing different time scales.

WLODZIMIERZ LEWANDOWSKI: Very quick comment. At the BIPM, because of the changes in the GPS delays, we have decided not to apply calibration results which give values of differential delays lower than 10 nanoseconds. Because we think it does not matter if we apply them because in several months there will be a several nanosecond offset from this value. So, the values of calibration lower than 10 nanoseconds are no longer applied to our GPS links.

GERARD PETIT (BIPM): The whole question of the delay was reviewed more than one year ago, but clearly, it should be reviewed again. It is a moving process and the uncertainties in calibrations are increasing, so we will review it again.

I would like to remind you that for the long-distance links that are used in TAI, GPS links, precise ephemeris on the ionosphere measurements are used for the situation of the GPS links in TAI, are not bad compared to what has been shown here where no corrections have been applied.

DIETER KIRCHNER: I know it is late, but on the other hand, this discussion is so important. I think it is possible to clear up these mistakes. Maybe we can find time in the afternoon to proceed with this discussion. There are action items and discussions right before the closing session. So, I think we should really proceed. I would be sorry if we would go from here without having explained these discrepancies.