SATMIX TIME-SCALE COMPARISONS USING A SINGLE-CHANNEL FAST-SEQUENCING GPS RECEIVER WITH CARRIER-PHASE SMOOTHING

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Abstract

Two single-channel fast-sequencing GPS receivers (of type K+K GPS5) tracking the GPS signals of all satellites in view and using carrier-phase smoothing have been studied in time-scale comparisons between the Physikalisch-Technische Bundesanstalt (PTB) and the Technical University Graz (TUG). The receiver output signal is a 1PPS pulse which is the physical representation of UTC(USNO) obtained as the average from the individual satellites (SATMIX). At PTB and TUG, the 1PPS is measured with respect to UTC(PTB) and UTC(TUG), respectively. After exchange of data, the time-scale differences UTC(PTB) – UTC(TUG) are calculated and compared with those obtained by the GPS common-view (CV) and TWSTT methods. These comparisons show that the daily mean values of UTC(PTB) – UTC(TUG) found with the SATMIX technique are by only a factor of 2 more noisy (about 4 ns) than those obtained with the CV and TWSTT methods (about 2 ns). Measurement results over about 1 year are presented. It appears that the SATMIX technique is an useful alternative method for time comparisons. An advanced version (K+K GPS5-2K) based on the same principle as the K+K GPS5 is under development. The expected features of the advanced receiver are described briefly.

1 INTRODUCTION

For time-scale comparisons between timekeeping institutes the so-called common-view (CV) method receiving the signals of GPS satellites is the most widely used time-transfer technique. Application of the CV method [1] allows the influence of the "selective availability" (SA) to be reduced to a great extent. CV time comparisons require, however, that receivers of the same design and the same evaluation procedures are used by the stations taking part in the comparison. A fixed tracking schedule must be strictly observed, i.e. the time differences between the local time scales and the GPS system time received must be determined for the same observation time to ensure that, after exchange of the CV data, these data can be assigned exactly to the second. Only then the errors caused by the SA are eliminated when the differences are formed.

Another approach is aimed at restoring, by suitable reception methods, the quality of the GPS signals, which has been deteriorated as a result of the SA. One suitable method consists in averaging the GPS signals of as many satellites as possible. As the intentionally introduced deviations of the received GPS system time from its nominal value are different for each satellite, but limited in their extent and not correlated among each other, the true GPS system time can be better approximated when the time information received from all satellites in view is averaged. A multi-channel receiver or a so-called SATMIX single-channel fast-sequencing receiver – as described in the following section – can be used for this purpose. If a reference time scale of high stability is available at the place of reception, the variations of the SATMIX-GPS signals received, which have been measured in relation to this scale, can be further reduced by additional averaging over long measuring times. Time-scale comparisons carried out in accordance with this principle by the Physikalisch-Technische Bundesanstalt (PTB) and Technical University Graz (TUG) will be described in the following.

2 SINGLE-CHANNEL FAST-SEQUENCING GPS RECEIVER WITH CARRIER PHASE SMOOTHING AND SATMIX AVERAGING

The characteristics of the low-cost GPS receiver (of type K+K GPS5, manufacturer: K+K Messtechnik GmbH) used for the time-scale comparisons have been described in detail by Kramer and Klische [2]. The receiver, which works in time-multiplex operation, is a single-channel fast-sequencing receiver which combines C/A code evaluation and carrier phase smoothing. No attempt is made to resolve for the carrier cycle ambiguity as is done in geodetic P-code receivers. Integration of a quasi-noise-free rate obtained by carrier smoothing gives the time with an offset, which then is determined by C/A code cross-correlation. Figure 1 illustrates the advantages of the combination of C/A synchronization and carrier-phase smoothing. The triangular envelope represents the cross-correlation function CCF for the C/A code and the fast oscillation indicates the carrier of 1.5742 GHz. Corresponding to a clock rate of 1.023 Mbit/s the chip length of approx. 1 μs for the C/A code covers 1540 carrier oscillations, only 15 of which are displayed. From this follows that the sensitivity of the carrier-phase measurement is about 10,000 times higher than that of the C/A code evaluation. Whereas the typical timing noise over a measuring time of one second is approx. 10 ns in the C/A code measurement, it amounts to only approx. 1 ps in carrier-phase measurement. As a result of the low timing noise achieved by carrier-phase smoothing, a dwell time of only 100 ms is sufficient for the observation of each satellite. In time multiplex operation the K+K GPS5 can, therefore, evaluate in fast sequences the signals of all satellites in view and obtain superior time information from its single-channel multiplex signal than a multi-channel receiver without carrier-phase smoothing.
Receiving the signals from all satellites available, the K+K GPS5 determines the "SATMIX" mean value of the GPS system time T(GPS) and applies the correction for the value of the respective time difference between T(GPS) and the Coordinated Universal Time of the US Naval Observatory, UTC(USNO), transmitted in the GPS data stream. At its outputs the receiver provides a 1PPS signal (1 pulse per second), which approximately represents UTC(USNO), as well as a phase-coherent 10 MHz signal. SATMIX averaging considerably reduces the influence of the SA. As the phase-time variations caused by the SA are of a random nature, the variations are reduced by SATMIX averaging in accordance with the square root of the number of satellites observed. For about 8 satellites which are normally in view, the variations due to SA become smaller by about a factor of 3 compared with the phase-time variations of the signal received from an individual satellite. Figure 2 illustrates how the phase-time variations are reduced by SATMIX averaging from typically 85 ns when only one satellite is received, to approx. 30 ns when the signals of all satellites in view are evaluated.

3 MEASURING ARRANGEMENT FOR THE TIME SCALE COMPARISONS

Figure 3 shows the block diagram of the measuring arrangement used for the time-scale comparisons UTC(PTB) – UTC(TUG) carried out between PTB and TUG (distance about 700 km) using the SATMIX method. Both institutes used a time-interval counter to determine the time differences between the seconds pulses of the time scales UTC(PTB) and UTC(TUG) and the seconds pulses generated by the K+K GPS5 receivers and referred to as 1PPS(SATMIX). The time-interval counters used were directly incorporated into the PCs as plug-in cards and, every second, furnished measurement values with a resolution of 0.1 ns, which were stored on the PCs' hard disk. After that, hourly and daily mean values were calculated from the measurement values obtained every second (referred to as M(PTB) and M(TUG)). In a next step, the hourly and daily mean values were exchanged via Internet, and the respective time scale difference DT(SATMIX) was determined:

$$\begin{aligned} &\mathrm{UTC(PTB)} - \mathrm{1PPS(SATMIX)} = \mathrm{M(PTB)} \\ &\underline{-[\mathrm{UTC(TUG)} - \mathrm{1PPS(SATMIX)}] = -\mathrm{M(TUG)}} \\ &\mathrm{UTC(PTB)} - \mathrm{UTC(TUG)} = \mathrm{M(PTB)} - \mathrm{M(TUG)} = \mathrm{DT(SATMIX)} \end{aligned}$$

4 MEASUREMENT RESULTS

Figure 4 shows the daily mean values of the time differences UTC(PTB) - 1PPS(SATMIX) measured at the PTB. The respective hourly mean values and the seconds values have not been presented, as their pattern is the same, only subject to a greater scatter of approx. ±30 ns for the second values and of approx. ± 15 ns for the hourly mean values. Instead, the relative frequency instability of the 1PPS(SATMIX) output signal has been plotted in Figures 5 and 6 versus the averaging time τ, expressed by the modified Allan standard deviation Mod $\sigma_y(\tau)$ [3]. Figure 5 shows Mod $\sigma_y(\tau)$ for τ up to approx. 10^4 s, determined from a data set of time differences UTC(PTB) – 1PPS(SATMIX) measured every second over a period of 1 day. Figure 6 shows the respective instability values for τ up to approx. 10^6 s, calculated from a data set of the hourly mean values of UTC(PTB) – 1PPS(SATMIX) over a period of 96 days. The slope of Mod $\sigma_y(\tau)$ shown in Figures 5 and 6 reflects the type of the phase noise of the 1PPS(SATMIX) output signal. As Mod $\sigma_y(\tau)$ is approximately proportional to $\tau^{-3/2}$ for averaging times τ >200 s, the phase fluctuations behave as white phase noise.

As, due to small frequency differences between the local atomic clocks, the time-scale differences slowly change with time, the measured time-scale differences determined by the SATMIX method do not explain whether the measured time-scale changes have to be contributed to different clock frequencies or to the SATMIX time-transfer technique. To illustrate the capability of the SATMIX method,the results of the SATMIX time-scale comparisons are, therefore, compared with the measurement results obtained by two other time-transfer techniques which are also applied in regular time-scale comparisons between PTB and TUG. These two methods are the common-view (CV) time-transfer method mentioned in the introduction, which also uses the signals of the GPS satellites, and the two-way time transfer via the Intelsat 307°E satellite, also referred to as Two-Way Satellite Time Transfer (TWSTT) [4]. Figures 7 to 9 show the differences between the measurement results obtained by the different time-comparison methods. Figure 7 shows the differences between the time-scale comparisons found by the CV and SATMIX methods, Figure 8 those between the TWSTT and SATMIX methods, and Figure 9 those between TWSTT and CV methods. The time-scale differences denoted as DT(SATMIX) and DT(CV) are daily mean values. DT(TWSTT) is the time-scale difference determined three times a week,in the afternoon (measuring time 2 minutes) via Intelsat satellite 307°E. As can be seen from Figures 7 to 9, over a time of approx. one year, significant systematic receiver delay changes did not occur either in the

SATMIX-receivers or in the CV and TWSTT equipment. The scatter of the measurement results obtained by the SATMIX method is, however, greater by a factor of 2 compared with the two more accurate time-transfer methods.

5 RECEIVER K+K GPS5-2K, AN ADVANCED VERSION OF THE K+K GPS5

Encouraged by the promising results from testing the receiver K+K GPS5, the PTB has ordered three receivers of the advanced version K+K GPS5-2K. The advanced version is based on the same principles as described in Chapter 2, but will have additional features: a second channel will continuously provide all data transmitted in the GPS data stream. The first channel can therefore remain in the fast sequencing mode and has not to be interrupted for the data readout. Further on a time-interval counter will be incorporated in the K+K GPS5-2K, which allows the receiver to measure the respective time difference between an external 1PPS reference pulse of the local clock and the 1PPS(SATMIX) generated from the signals of all satellites in view. Once per second the new receiver will furnish on a RS232-serial interface all data necessary for different evaluation methods: the time difference between the external reference pulse and 1PPS(SATMIX); the offsets between the 1PPS(SATMIX) and the GPS time as received from all satellites in view individually; the ephemerides of all satellites observed; additional data as azimuth, elevation, satellite clock data, tropospheric and ionospheric correction, GPS and UTC time, difference UTC(USNO) - GPS system time, etc. Along with the advanced receiver K+K Messtechnik GmbH supplies a QBASIC software which allows an external PC to convert the data read via the serial port to the GGTTS format of the BIPM [5]or any other format to be developed in the future.
Two prototypes of the advanced version will be delivered at the beginning of the year 2000, the third one in spring 2000. In a first step the PTB will operate two receivers in co-location to study their delay instabilities. If these tests are successful the PTB will offer the third receiver as a loan to any timekeeping laboratory which is interested in time comparisons with the PTB using the new receiver. It is to be hoped – but it can not be promised now – that K+K Messtechnik GmbH in cooperation with the PTB will succeed in developing a reliable and stable receiver for timekeeping purposes.

6 CONCLUSIONS

Application of the SATMIX method in the K+K GPS5 receiver considerably reduces the influence of the SA. As can be seen from the instability curves found, the phase-time variations of the receiver's output signal 1PPS(SATMIX) behave like white phase noise for measurement times greater than 200 s. If an atomic clock of high stability is available, these phase-time variations can, therefore, be further reduced by averaging the measured time differences between the time scales to be compared and the 1PPS(SATMIX) signals over prolonged measuring times. Compared with the CV method, the SATMIX method has the great advantage that no "tracking schedules" have to be observed and that the evaluation procedures do not have to be exactly harmonized. For the time–scale comparison it is sufficient to exchange only a single daily mean value. With 4 ns, the standard deviation of a single daily mean value from the long-term mean is, however, larger by a factor of 2 than the standard deviation achievable by the more sophisticated CV or TWSTT method. On the other hand a scatter of 4 ns is still of the same order of magnitude as the delay changes observed in some CV receivers currently on the market. In summary, it can be said that the SATMIX method using the K+K GPS5 receiver is an appropriate alternative for time comparisons.
Based on the receiver K+K GPS5 an advanced version K+K GPS5-2K is under development. If the advanced version meets the specifications expected, it can be used as a stand-alone receiver like the K+K GPS5, but can also be operated in the common-view mode.

7 REFERENCES

[1] W. Lewandowski and C. Thomas, "GPS Time Transfer," Proc. IEEE, Vol.79, pp. 991-1000, 1991.
[2] G. Kramer and W. Klische, "The GPS Carrier as a Practical Frequency Reference," Proc. 11th European Frequency and Time Forum, pp. 331-335, 1997.
[3] E.S. Ferre-Pikal et al., "Revision of IEEE STD 1139-1988, Standard definitions of physical quantities for fundamental frequency and time metrology," Proc. 51st FCS, pp. 338-357, 1997.
[4] D. Kirchner, "Two-Way Satellite Time and Frequency Transfer (TWSTFT): Principle, Implementation, and Current Performance," The Review of Radio Science 1996-1999, p. 27-44, 1999.
[5] D.W. Allan and C. Thomas, "Technical Directives for Standardization of GPS Time Receiver Software," Metrologia 31, pp. 67-79, 1994.

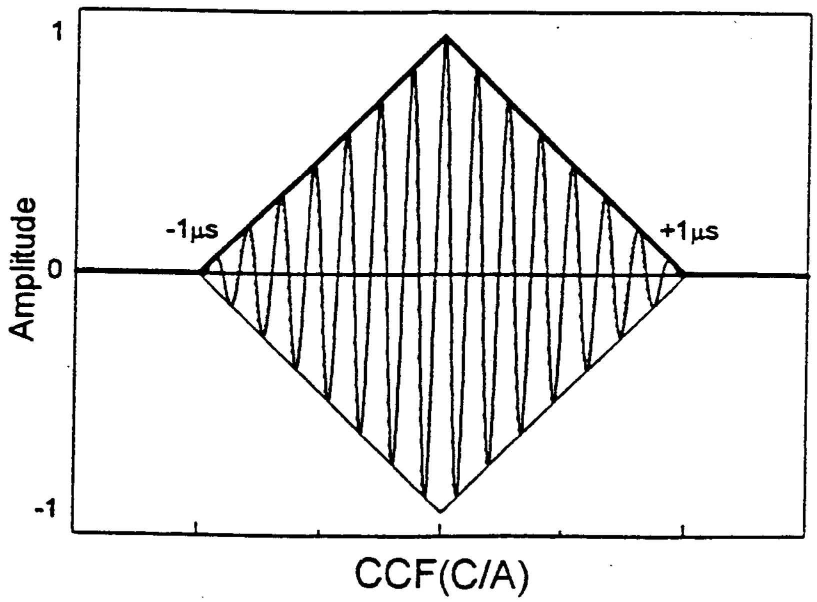

Figure 1: Cross-correlation function CCF(C/A) for C/A code synchronization. The indicated carrier oscillations illustrate the advantages of carrier-phase smoothing because of the steep slope of the carrier zero-crossings compared with the CCF(C/A).

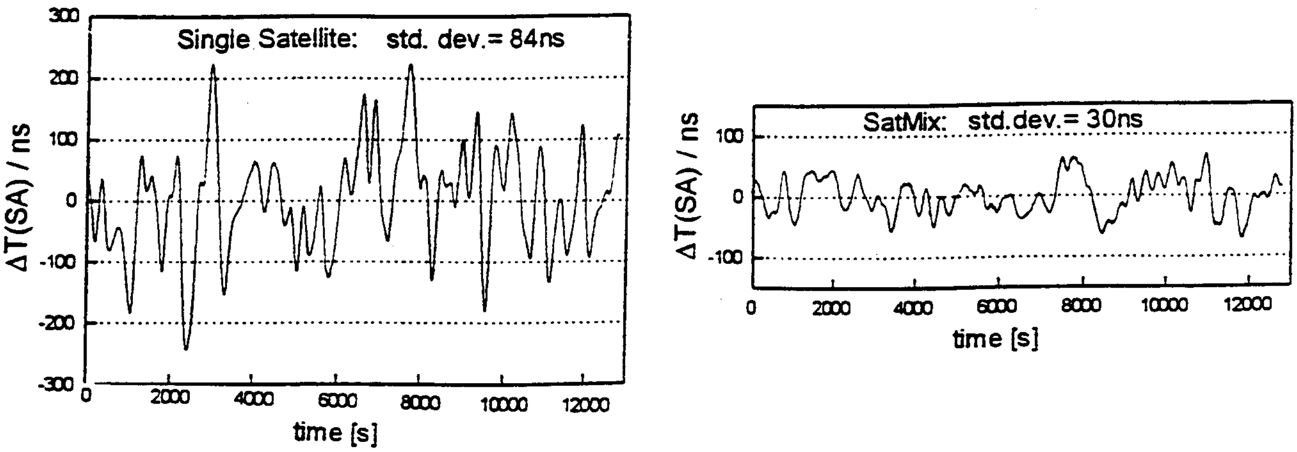

Figure 2: Phase time variations ΔT(SA) of the receiver output signal caused by the "Selective Availability." On the left: reception of a single satellite only. On the right: Multiplex reception and SATMIX averaging of all satellites in view.

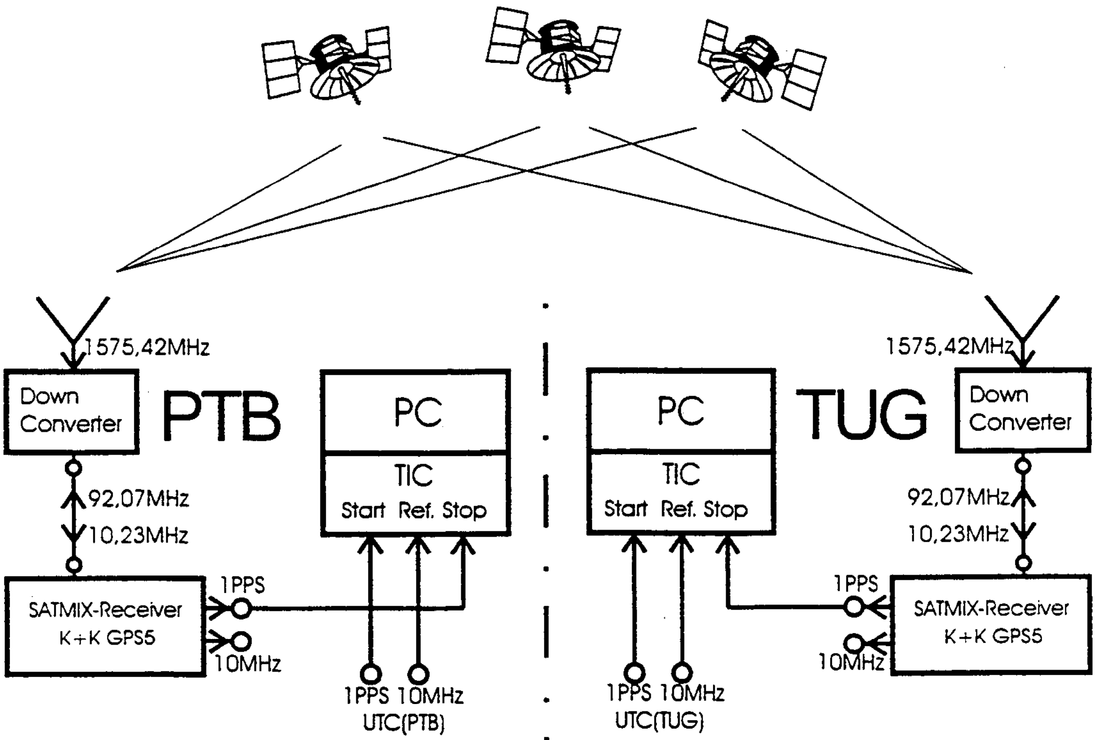

Figure 3: Block diagram of the setup for SATMIX time scale comparisons UTC(PTB)-UTC(TUG).

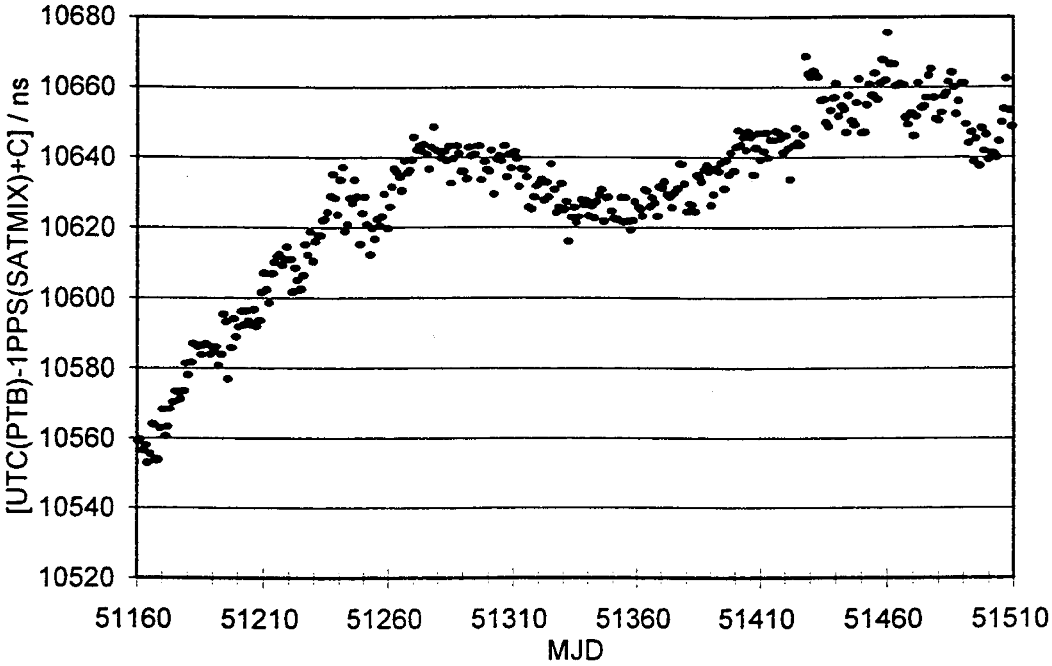

Figure 4: Daily mean values of the time differences UTC(PTB) - 1PPS(SATMIX) measured at the PTB in Braunschweig. MJD: Modified Julian Date, MJD 51160: December 13, 1998.

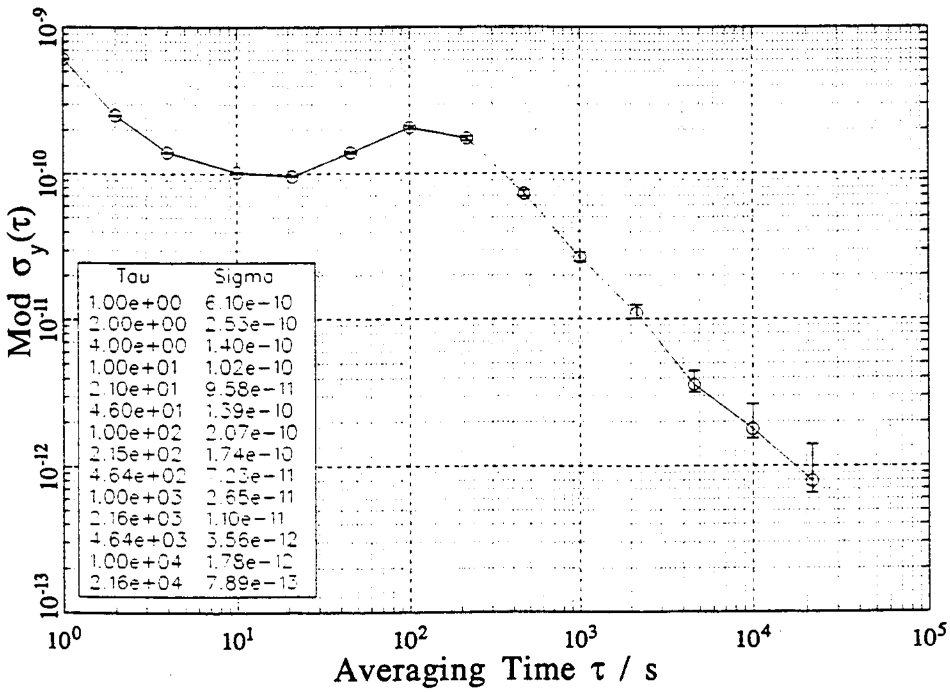

Figure 5: Relative frequency instability of the 1PPS(SATMIX) output signal, expressed by the modified Allan standard deviation Mod $\sigma_y(\tau)$, determined from the time differences UTC(PTB)-1PPS(SATMIX) measured every second.

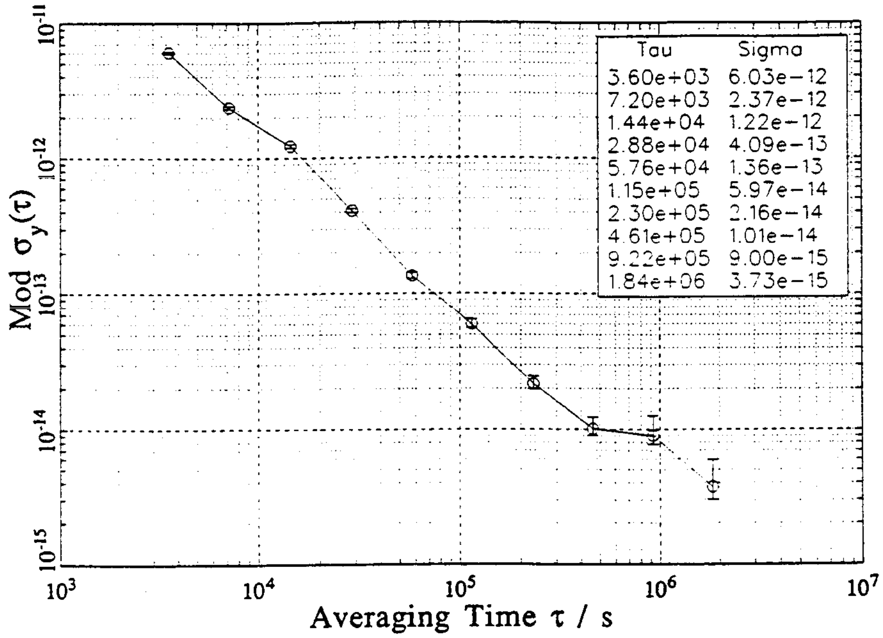

Figure 6: Relative frequency instability of the 1PPS(SATMIX) output signal, expressed by the modified Allan standard deviation Mod $\sigma_y(\tau)$, calculated from the hourly mean values of the time differences UTC(PTB) - 1PPS(SATMIX).

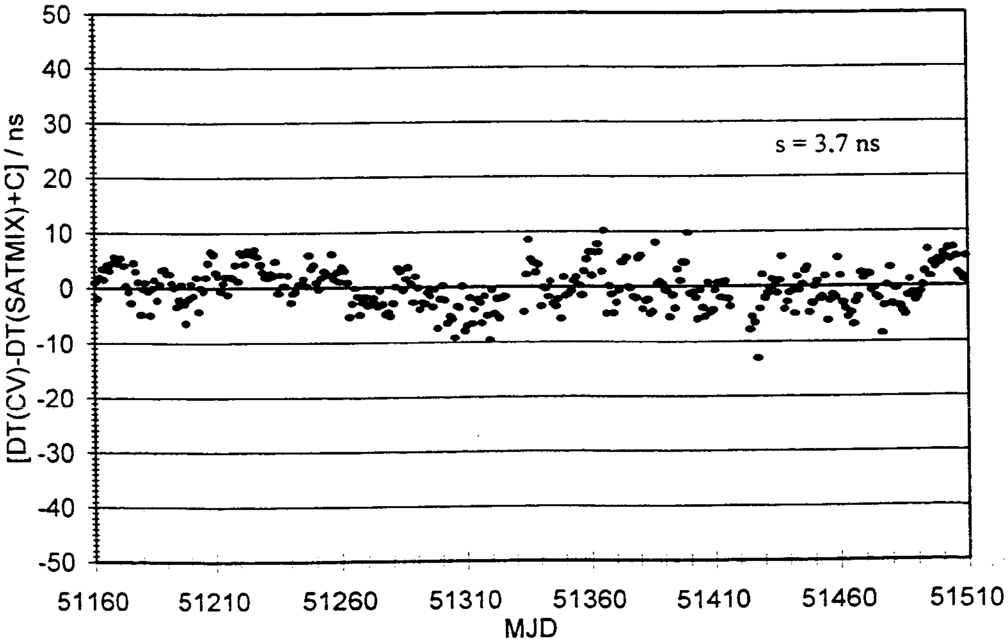

Figure 7: Difference between the measurement results of two time comparison methods (CV method and SATMIX method). s: standard deviation. C: constant.
MJD: Modified Julian Date. MJD 51160: December 13, 1998
DT(CV) UTC(PTB)-UTC(TUG): determined by the CV method
DT(SATMIX) UTC(PTB)-UTC(TUG): determined by the SATMIX method.

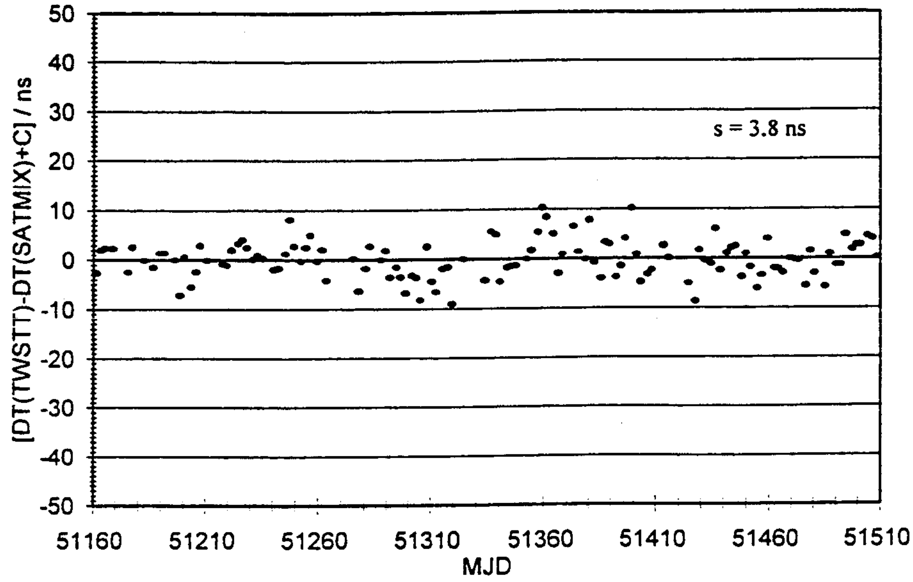

Figure 8: Difference between the measurement results of two time comparison methods (TWSTT method and SATMIX method). s: standard deviation. C: constant. MJD: Modified Julian Date, MJD 51160: December 13, 1998.
DT(TWSTT) = UTC(PTB).- UTC(TUG): determined by the TWSTT method
DT(SATMIX) = UTC(PTB) - UTC(TUG): determined by the SATMIX method.

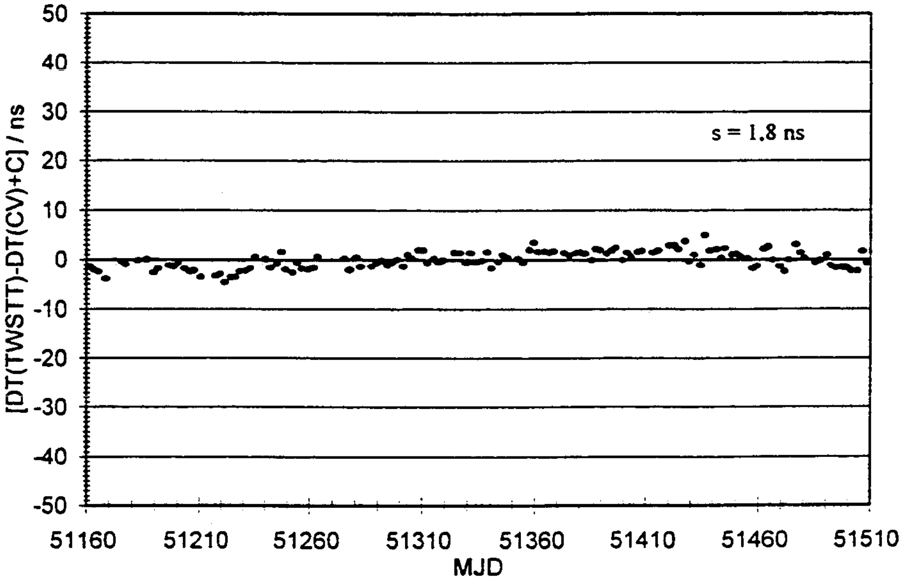

Figure 9: Difference between the measurement results of two time comparison methods (TWSTT method and CV method). s: standard deviation. C: constant. MJD: Modified Julian Date, MJD 51160: December 13, 1998.
DT(TWSTT) = UTC(PTB) - UTC(TUG): determined by the TWSTT method
DT(CV) = UTC(PTB) - UTC(TUG) determined by the CV method.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): It looks like you're coming up with a nice product. Will your stability studies include temperature and humidity variations? And can you give a brief rundown of the differences between your system and that done by Jerzy Nawrocki?

PETER HETZEL (PTB): I don't know about the other system.

MATSAKIS: Okay, just talk about yours.

HETZEL: Temperature tests are a little bit difficult, but we study it in a cool location with two antenna poles close together. This is how we want to start.