Comparison of GPS Common-view and Two-way Satellite Time Transfer Over a Baseline of 800 km

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Abstract. For about one year the time scales UTC(OCA) and UTC(TUG) were compared by means of GPS common-view and two-way satellite time transfer. At the end of the experiment, both links were independently "calibrated" by measuring the differential delays of the GPS receivers and the satellite Earth stations by transportation of one GPS receiver and one satellite terminal to the other site. The results obtained by the two methods differ by about 3 ns, but reveal a seasonal variation of about 8 ns which, most likely, is mainly the result of temperature-dependent delays in the GPS receiving equipment used.

1. Introduction

The GPS common-view technique currently provides the best operational means for comparing remote time scales. For distances up to about 1 000 km, GPS common-view time transfer can be realized with a precision and accuracy of about 2 ns [1]. The voluntary degradation of the GPS signal known as Selective Availability (SA) can be overcome by strict procedural standardization and, if necessary, the use of post-processed ephemerides [2]. Of great importance for the achievable accuracy is knowledge of the receiver delays. The differential delay of the receivers can be measured by transporting the receivers to a common site.

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Two-way time transfer via communication satellites using spread-spectrum techniques is capable of 100 ps precision, but requires transmit and receive satellite terminals at both stations, which must work together in pairs [3]. Accuracies at nanosecond or even subnanosecond level are expected by using the same satellite transponder in both signal directions and by measurement of the differential delay of the stations using portable satellite terminals.

Through the cooperative efforts of several laboratories, both methods have been implemented at the Observatoire de la Côte d'Azur (OCA), Grasse, France, and the Technical University Graz (TUG), Austria, allowing comparison of the time scales UTC(OCA) and UTC(TUG) by these two techniques over a period of almost one year [4]. The experiment was concluded by an independent "calibration" (measurement of the differential delays) of the GPS receivers and the two-way stations by transportation of a GPS receiver of the Bureau International des Poids et Mesures (BIPM) to the sites involved and by transporting the OCA satellite terminal to the TUG.

2. Basics of Two-way Satellite Time Transfer

The two-way technique has been developed for point-to-point time transfer of the highest precision and accuracy. Both laboratories require receive and transmit stations in order to exchange timing information via communication satellites employing pseudo

noise (pn) coded signals and code division multiple access (CDMA). The measurement consists of simultaneous time interval measurements at both sites in which the one pulse-per-second (1 PPS) generated by the local clock starts both the local time interval counter and, transmitted via the satellite, stops the remote time interval counter. The time difference ΔT between the time scales T_1 and T_2 of the clocks at station 1 and station 2 is given by [3]

$$\Delta T = (\Delta T_1 - \Delta T_2)/2$$
$$+ [(\tau_1^U + \tau_2^D) - (\tau_2^U + \tau_1^D)]/2$$
$$+ (\tau_{12} - \tau_{21})/2$$
$$+ \Delta \tau_R$$
$$+ [(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})]/2, \qquad (1)$$

where

(a) The first term of the right side of (1) is given by the difference of the counter readings $(\Delta T_1 - \Delta T_2)/2$ of stations 1 and 2 which have to be exchanged to compute the clock differences.

(b) The second term $[(\tau_1^U + \tau_2^D) - (\tau_2^U + \tau_1^D)]/2$ contains the differences of the sums of the signal delays in the uplink and downlink (path delays) for both signal directions. (Under the assumption of path reciprocity this term cancels out. This assumption is likely to hold to better than 100 ps for simultaneous transmissions at Ku-band frequencies [5].)

(c) The third term $(\tau_{12} - \tau_{21})/2$ contains the difference of the transponder delays in the two directions and is zero when employing the same transponder in both signal directions.

(d) The fourth term $\Delta \tau_R$ is a correction for the path nonreciprocity caused by the Earth rotation (Sagnac effect). (It can be computed from the positions of the Earth stations and the satellite without requiring knowledge of these positions with high accuracy.)

(e) The last term $[(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})]/2$ represents the difference of the delay differences of the transmit and receive parts (station delays) of Earth stations 1 and 2. (The accuracy of the time comparison is determined mainly by knowledge of these station delay differences.)

The delay difference of the stations can be measured by using a third station as a transfer standard, or by co-location of the stations. For the latter case one obtains [6]

$$[(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})] = (\Delta T_2 - \Delta T_1), \qquad (2)$$

where the right side of (2) represents the difference of the counter readings obtained during co-location of the stations.

3. Experiment Configuration and Equipment

3.1 Time scales

Both time scales UTC(OCA) and UTC(TUG) were generated by a single atomic clock of "high performance" type until the sudden break-down (14 January 1991) of the TUG "high performance" clock and its replacement by a clock of "standard" type. After repair, the "high performance" clock was reconnected to the measurement system (17 January 1991). This provided a comparison with the other TUG clocks every hour, and at GPS measurement times, and a continuous phase recording with the "standard" clock which was then used to generate UTC(TUG). It was thus possible to replace the "standard" clock by the "high performance" clock in the computations of the two-way and GPS differences although the actual measurements were carried out with the "standard" clock.
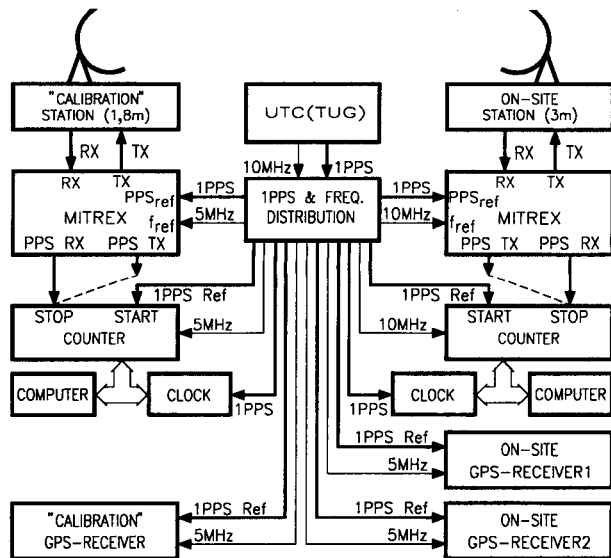
3.2 GPS receivers

The GPS receivers used at the OCA and at the TUG are from different manufacturers, but of NBS design. At the TUG a second GPS receiver of different design is operated in addition to allow the comparison of GPS receivers of different design. At the beginning of the experiment the software of the OCA receiver differed from that of the TUG receiver with respect to the interpretation of data from Block II satellites, but since 12 December 1990 the same software has been used. The portable receiver employed to measure the differential delay of the on-site receivers, which allowed an absolute comparison of UTC(OCA) and UTC(TUG) by means of GPS, is also of NBS design. For this comparison the delay, in both stations, between UTC(Lab) and the one pulse-per-second used as time reference (1 PPS Ref) for the portable receiver, had to be measured (see Figure 1).

3.3 Two-way stations and satellite

The satellite Earth stations used were the permanent station of the TUG at the Observatory Lustbühel Graz and a temporary station at the OCA of VSAT type [6]. This later served as the portable station for measurement of the delay difference of the stations necessary for the absolute two-way comparison of UTC(OCA) and UTC(TUG). The main characteristics of the stations are given in Table 1.

Initially the two-way measurements were carried out via the SMS (Satellite Multi-Service) transponder of the European communication satellite EUTELSAT I-F2 and since 16 October 1990 via the SMS transponder of EUTELSAT I-F4, which replaced

Figure 1. Schematic of the two-way setup at the TUG including the OCA two-way station ("calibration" station) and the BIPM GPS receiver ("calibration" GPS receiver).

Table 1. Main characteristics and positions of the TUG and OCA Earth stations.

	TUG	OCA
Antenna diameter	3 m	1,8 m
G/T	23 dB/K	21 dB/K
Max. EIRP	72 dBW	49 dBW
Receive frequency	10,95-12,75 GHz	12,5-12,75 GHz
Transmit frequency	14,0-14,5 GHz	14,0-14,5 GHz
Synthesizer step-size	100 Hz	1 MHz
Position	15° 30′ E	06° 55′ E
	47° 04′ N	43° 45′ N
	480 m MSL	1 260 m MSL

EUTELSAT I-F2, both at a nominal position of 7° E and working at Ku-band frequencies.

To obtain a nominal carrier-to-noise power density ratio (C/N_0) of 55 dBHz at both stations [3], according to EUTELSAT link budget calculations, the OCA transmitted with its maximum EIRP and the TUG with about 2 dB more than the OCA to compensate for the smaller G/T of the OCA station. A block diagram of the two-way setup at the TUG is given in Figure 1. This includes the transported OCA station, and thus shows the configuration used for the measurement of the differential delay of the Earth stations. Because of the allocated frequencies of 14 022, 0 MHz for transmission and 12 522, 0 MHz for reception (the latter resulting from the nominal satellite translation frequency of 1 500 MHz, which

turned out to be very stable), no problems were caused by the limited frequency agility of the VSAT [6, 7].

At both stations MITREX-modems [8, 9] of the original type were used. These modems require a 5 MHz or 10 MHz signal as a reference frequency to generate the 1 PPS signal which is modulated onto the pn-sequence (derived from the same reference frequency) for transmission. In contrast with the basic two-way procedure outlined in the previous section, where the 1 PPS generated by the station clock starts the local counter and is transmitted to the remote station, in the actual setup (see Figure 1) the local counter is started by a 1 PPS signal generated by the station clock (1 PPS Ref), but the transmitted pulse (PPS TX) is generated by the MITREX-modem. In each station, therefore, the delay between UTC (Lab) and the 1 PPS Ref and the delay between the 1 PPS Ref and the PPS TX have to be measured in addition to the actual time transfer measurements. During these measurements the counter is started by the 1 PPS Ref and is stopped by the received 1 PPS (PPS RX). Both stations used counters of a type which provides 20 ps resolution and has an internal jitter well below 50 ps.

4. Measurements

4.1 GPS time transfer

GPS time transfer measurements have been carried out for years at the OCA and the TUG using the European common-view schedules issued by the Bureau International des Poids et Mesures (BIPM). Thus at the beginning of the experiment schedule No. 15 was used. Due to the shift of the schedule by about four minutes per day the number of thirteen-minute tracks (32 over 24 hours) around the two-way time transfer measurements – performed at fixed times of the day – decreased. Therefore, starting with 19 December, a special schedule (48 tracks over 24 hours), including the European schedule No. 16, was introduced for the OCA and the TUG in order to optimize the number of tracks around the two-way measurements.

4.2 Two-way time transfer

Two-way time comparisons on a regular basis began on 22 June 1990 and lasted until 17 April 1991 with a gap from 11 October to 8 November resulting from a breakdown of the receive part of the OCA station. A schedule of three sessions per week (Monday, Wednesday and Friday), each lasting from 12:00 to 12:30 UTC, was used. Initially each session consisted of two measurement blocks each of four minutes duration and of 240 individual measurements 1 s

apart, starting at 12:15 and 12:20 UTC. From 30 July 1990 blocks of two minutes duration starting at the same times were used since earlier experiments showed two minutes of data to be sufficient to obtain good average values of the time transfer [10]. From 9 November 1990 a third two-minute block was performed starting at 12:27 UTC. To study the stability of the measurements over longer periods (see Section 6.4), additional data were recorded on 20, 22 and 24 August 1990 and on 27 and 29 March 1991. In these sessions only one block of data was taken, each lasting for about twenty minutes. Before and after the time transfer measurements, several measurements were carried out to determine the delays between the 1 PPS Ref and the PPS TX in each station.

4.3 Delays and differential delays

At the TUG, the delay between UTC(Lab) and the 1 PPS Ref for the GPS measurements, and the delay between UTC(Lab) and the 1 PPS Ref for the two-way measurements, were measured at the beginning of the experiment and during the MITREX and GPS delay comparisons. At the OCA, the final measurements of these delays were carried out after the experiment.

The delay comparisons between the GPS receivers operated at the OCA and the TUG ("calibration") by means of the transported receiver were carried out between 30 March and 20 May 1991. They began and ended with comparisons between this receiver and the on-site receiver of the Paris Observatory (OP), a receiver which is also of NBS design.

The measurement of the differential delay of the two-way stations ("calibration") was performed on 23 and 24 April 1991. One measurement block (12:25 to 12:28 UTC) was recorded on the first day. On the second day, three measurement blocks of four minutes duration were recorded, starting at 12:05, 12:10 and 12:15 UTC, with a fourth block of nineteen minutes duration beginning at 12:40 UTC.

5. Data Processing

5.1 GPS measurements

Nearly all GPS data were common-view data in the strict sense, but tracks with a maximum tolerance of four minutes were also employed. This was possible without degrading the measurement accuracy because, before 19 December 1990, no Block II satellites (SA turned on) were used (different receiver software at the OCA and the TUG, see Section 3.2) and subsequently SA was turned off. All time comparisons were referred to the mid-points of the tracks

and restricted to tracks with elevation angles greater than 10° and a standard deviation of less than 20 ns. Furthermore, all satellites reported as unusable by the US Naval Observatory (USNO) were discarded and all tracks between 5 August 7:22 and 10 August 8:06 were unusable as a result of a receiver problem. The average standard deviations of the thirteen-minute tracks for the OCA and the TUG were about 5 ns and 4 ns, respectively.

The results of the GPS receiver delay comparisons performed at the OP, the OCA and the TUG are given in Table 2 [11].

Table 2. Differential delay measurements obtained by GPS receiver transportation. The differential delay is defined as
$\{[UTC(Lab) - GPS\ time]_{Portable\ receiver}$
$- [UTC(Lab) - GPS\ time]_{Local\ receiver}\}$,
where Lab = OP, OCA or TUG. The values reported are the means of the given single tracks.

Laboratory	Date	Number of tracks	Differential delay/ns	
			Mean	Standard deviation
OP	30 March -7 April	292	-0,9	2,3
OCA	12 April -15 April	154	17,6	2,0
TUG	23 April -26 April	158	10,3	2,0
OCA	1 May -12 May	452	15,7	1,6
OP	17 May -20 May	147	-1,8	2,2

According to the values given in Table 2 (using the mean of the data obtained at the OCA) the difference [UTC(TUG) - UTC(OCA)] obtained from the uncorrected GPS data has to be corrected by -6,4 ns. The uncertainty estimated from the repeated comparisons at the OP and the OCA is 1,5 ns.

5.2 Two-way measurements

The first step in deriving the time difference [UTC(TUG) - UTC(OCA)] was to compute, for each measurement block, the expected value, referred to the mid-point of the block, of a linear regression through the second-to-second differences divided by two. The corresponding standard deviation was also computed. The process was repeated for each block. Figure 2 shows the standard deviations for all sessions including those performed at the TUG during measurement of the differential delay. The dashed vertical line indicates the change of clock at the TUG. The values, which are larger than the usual ones (on average 0,8 ns until February), are caused by outliers in the measurements of the OCA and/or the TUG. The observed standard deviations of about 0,8 ns are

186
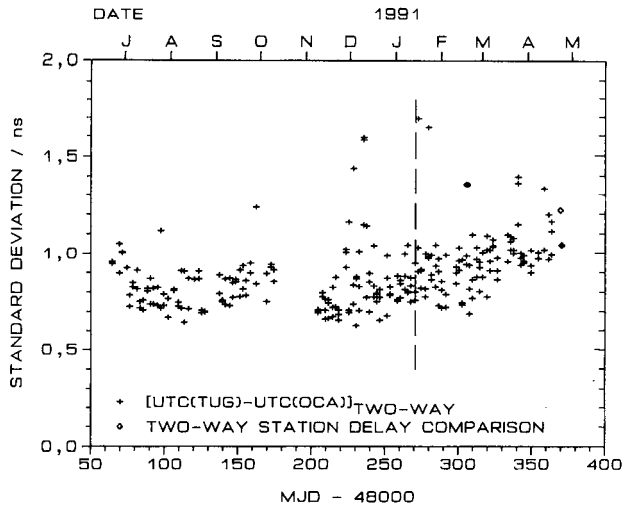
Figure 2. Standard deviations of the two-way measurements of [UTC(TUG) − UTC(OCA)] and of the two-way stations' delay comparisons (two-way "calibration").

in good agreement with the values one can expect for a C/N_0 of about 55 dBHz [8, 12]. The gradual increase of the standard deviations, beginning in February, is probably due to a degradation of the performance of the satellite link. The mid-point value of each measurement block was subsequently corrected by the differences (1 PPS Ref − PPS TX) measured at each station.

The result of the delay comparison of the two-way stations performed at the TUG is given in Table 3.

Table 3. Differential delay of the two-way stations obtained by station co-location at the TUG. The overall mean is − 81,3 ns.

| Date | Number of measurements | Differential delay/ns | |
		Mean	Standard deviation
23 April	128	− 81,37	1,2
24 April (Block 1-3)	720	− 81,04	1,0
24 April (Block 4)	1 140	− 81,41	1,0

To obtain [UTC(TUG) − UTC(OCA)] by the two-way method, the data, already corrected by (1 PPS Ref − PPS TX), have to be corrected further by the differential delay between the stations, − 81,3 ns, and by the difference (UTC(Lab) − 1 PPS Ref) of the two stations, 307,7 ns. Finally, the correction forthe Earth's rotation (Sagnac effect) amounting to − 22,2 ns has to be applied. This results in a total correction of 204,2 ns.

## 5.3 Comparison of GPS and two-way measurements

Using the data described above, Figure 3 shows the differences [UTC(TUG) − UTC(OCA)] obtained by GPS and two-way measurements. These differences
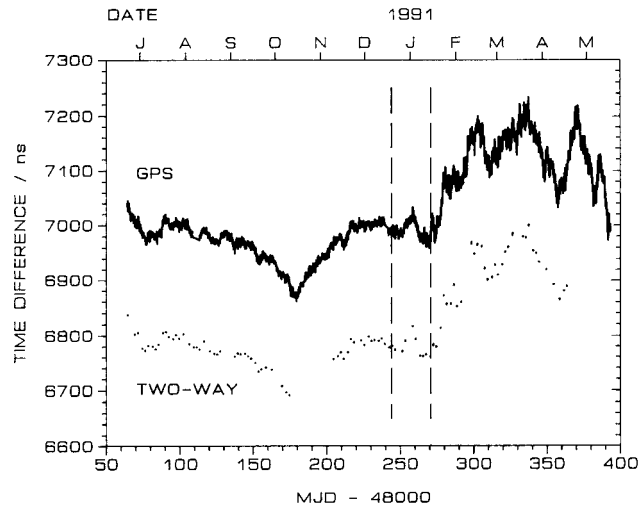

Figure 3. [UTC(TUG) − UTC(OCA)] computed from single GPS common-view tracks (GPS raw data) and from two-way measurement blocks (corrected for 1 PPS Ref − PPS TX) after removal of all time steps and the mean rate differences of UTC(TUG) and UTC(OCA).

are shown without corrections for the GPS and two-way differential delays, but all intentional time steps at the OCA and the TUG have been removed, as have the mean rate differences between UTC(OCA) and UTC(TUG) before and after the clock change at the TUG. The dashed vertical lines in this and following figures indicate the change of the GPS schedule and of the clock at the TUG.

Figure 4 shows [UTC(TUG) − UTC(OCA)] via GPS and via two-way measurements for a period of five days after applying all of the above corrections. Evidently for the computation of the difference between [UTC(TUG) − UTC(OCA)] obtained by two-way measurements and [UTC(TUG) − UTC(OCA)] obtained by GPS measurements, the GPS data have to be smoothed and interpolated to obtain GPS time-transfer results concurrent with the two-way measurements. The criterion for the processing of the GPS data is that the GPS measurement noise should be smoothed without smoothing the noise of the clocks. The appropriate smoothing periods were estimated to be about eight hours for the intervals in which the two "high performance" clocks were compared (before break-down of the "high performance" clock at TUG and after its repair) and about one hour for those in which the "high performance" clock was compared with the "standard" clock [13].
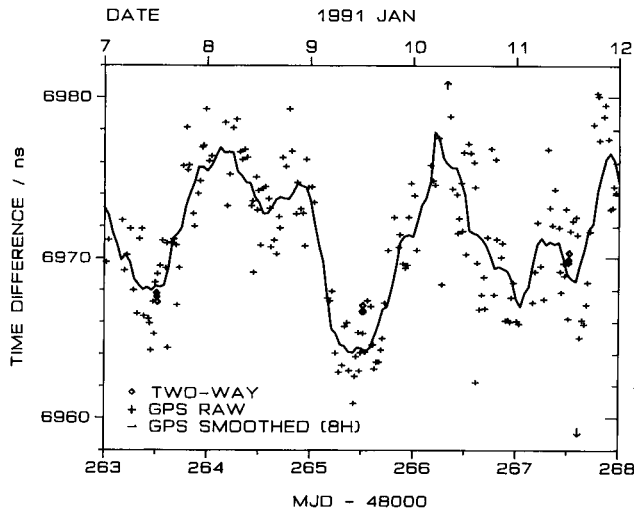
Figure 4. [UTC (TUG) − UTC (OCA)] computed from GPS common-view raw and smoothed data (eight hour mean) and from two-way data for a period of five days (all GPS and two-way corrections applied). The two arrows indicate three points outside the plotting area (MJD 48 266,31 : 6 983,0 ns; MJD 48 266,33: 6 990,2 ns; MJD 48 267,61: 6 954,7 ns).
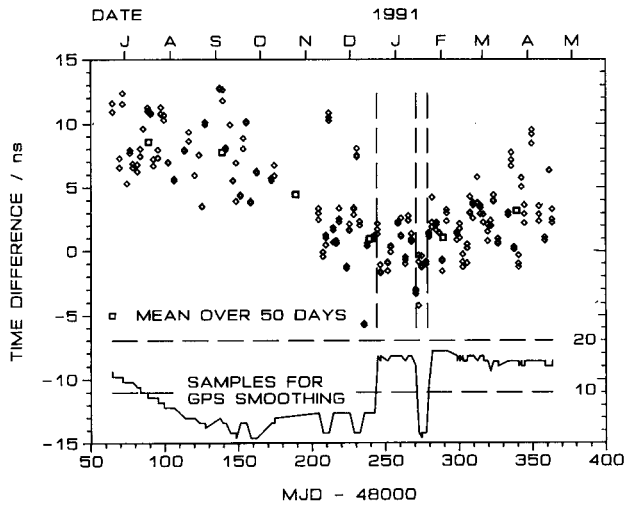
Figure 5. Difference between [UTC (TUG) − UTC (OCA)] obtained by two-way measurements and [UTC (TUG) − UTC (OCA)] obtained by GPS common-view measurements, and mean values of the differences for periods of fifty days, and number of GPS tracks per GPS smoothing period.

The GPS data were smoothed by computing the means for the estimated smoothing periods of eight hours and one hour around the two-way measurements, using those data from which the mean difference of the clock rates had already been removed. Results obtained for $\{[UTC(TUG) − UTC (OCA)]_{\text{TWO-WAY}} −$
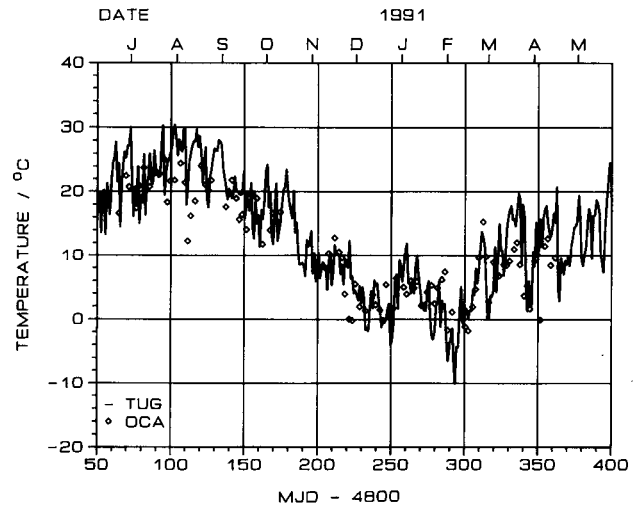
Figure 6. Outside temperatures at the TUG and at the OCA (12 UTC).

$[UTC (TUG) − UTC (OCA)]_{\text{GPS}}\}$ are given in Figure 5. The third vertical dashed line indicates the date from which the "high performance" clock at the TUG was again available for the computation of the two-way and GPS differences, but it should be remembered that the actual measurements were carried out with the "standard" clock. The efficiency of the chosen smoothing periods was confirmed by using other smoothing periods. These gave a larger scatter of the data, especially for longer smoothing times, when using the standard clock. The lower trace in this figure indicates the number of tracks per smoothing period, essentially depending on the GPS schedule used and the length of the smoothing period.

5.4 Related data

At the TUG, temperature, humidity and air pressure are recorded every hour and for all GPS measurements. The daily outside temperatures (12 UTC) at the TUG and at the OCA for the days of two-way measurements are shown in Figure 6. Also shown, Figure 7, is the differential delay of the two GPS receivers permanently operated at the TUG.

6. Analysis of Results

6.1 Estimation of accuracy

6.1.1 GPS measurements

Estimates of the accuracy of the time comparison obtained by GPS have been published [1]. For distances up to 1 000 km, station coordinates known to better than 30 cm and identical receiver software, one

MJD – 48000

DATE   1991
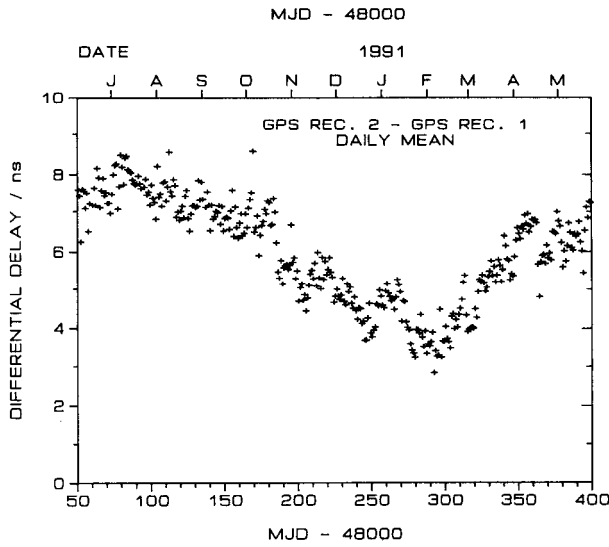
Figure 7. Differential delay (daily mean) of GPS receiver 2 and GPS receiver 1 at the TUG.

obtains about 9 ns for a single common-view track and about 3,1 ns when averaging ten common-view tracks (one day average). This assumes an uncertainty in the relative receiver delay of 1,5 ns, but does not consider contributions arising from the noise of the station clocks, the rise time of the reference pulses and possible instabilities of the delays of the receivers. The OCA-TUG baseline is about 800 km and the GPS antenna coordinates for both stations are known with an uncertainty of 10 cm in the ITRF88 [14].

6.1.2 Two-way measurements

An assessment of an error budget for the two-way time transfer between the OCA and the TUG is given in Table 4.

**Table 4.** Error budget for two-way time transfer between the OCA and the TUG.

	Error/ns
UTC(Lab) – 1 PPS Ref	0,5
Counter	0,5
MITREX modem	1,0
Earth station delay (relative)	1,2
Transponder delay (relative)	0,0
Satellite link (Ku-band)	0,1
Sagnac effect	0,1
Total	1,7

The first four contributions depend on equipment performance and can be reduced in future experiments by a factor of at least three. The contribution from the satellite transponder is zero because the same frequency band of one transponder is used for both

signal directions (see Section 2). Possible contributions due to coherence between signals are not considered [15].

6.2 Agreement of GPS and two-way measurements

The data presented in Figure 5 show the difference of [UTC(TUG) – UTC(OCA)] obtained by two-way measurements and [UTC(TUG) – UTC(OCA)] obtained by GPS measurements after independent "calibration" (measurement of the differential delays of the two-way and GPS equipment) of the two-way and GPS measurements at the end of the experiment. Because the differences exhibit an apparent systematic (seasonal) variation, the mean value and the standard deviation of the differences (3,6 ns and 3,9 ns, respectively) are not appropriate measures with which to describe the agreement of the two-way and GPS measurements at the time of the "calibration". The modified Allan variance Mod. $\sigma_y(\tau)$ [16] of the differences, Figure 8, shows that the differences exhibit
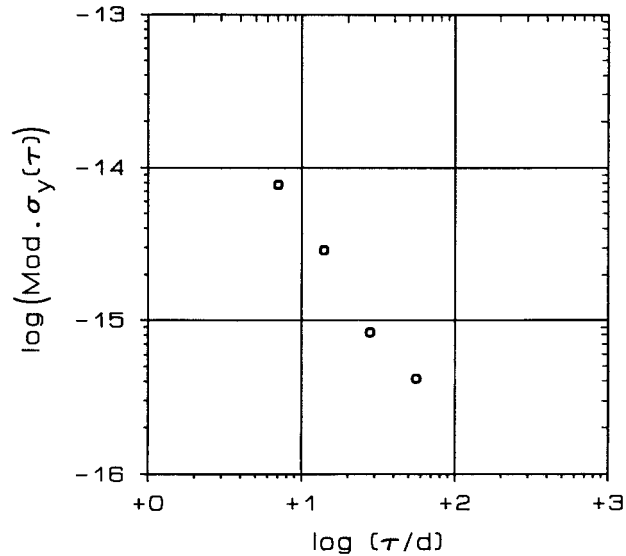
Figure 8. Modified Allan variance Mod. $\sigma_y(\tau)$ of the difference between [UTC(TUG) – UTC(OCA)] obtained by two-way and by GPS common-view time transfer as given in Figure 5.

white-noise PM up to an averaging time τ of about 56 days, so computation of mean values and corresponding standard deviations is justified for data intervals up to this value. The results for averaging periods of 50 days are given in Table 5 and plotted in Figure 5.

For the time of "calibration" the mean difference between the two-way and GPS measurements is 3,2 ns and the standard deviation is 2,6 ns. The maximum difference of the means is about 8 ns. The total estimated accuracy of the difference between two-way

Table 5. Mean values and standard deviations of the differences of [UTC(TUG) − UTC(OCA)] obtained by two-way measurements and [UTC(TUG) − UTC(OCA)] obtained by GPS measurements after independent "calibration" of both links.

Averaging period	Number of samples	Difference/ns	
		Mean	Standard deviation
48 064-48 113	35	8,6	2,1
48 114-48 163	31	7,7	2,9
48 164-48 213	15	4,4	3,9
48 214-48 263	54	0,9	2,6
48 264-48 313	57	1,0·	2,1
48 314-48 363	47	3,2	2,6

and GPS measurements, computed from the individual estimates given in Section 6.1, is 3,5 ns, 1 sigma, and all points are well within the 3-sigma limits.

6.3 Temperature-dependence

Comparison of Figure 5 with Figure 6 reveals an obvious correlation between the difference of [UTC(TUG) − UTC(OCA)] obtained by two-way measurements and [UTC(TUG) − UTC(OCA)] obtained by GPS measurements and the outside temperatures recorded at the TUG and the OCA. This strong correlation is demonstrated by Figure 9 where the differences shown in Figure 5 are plotted against
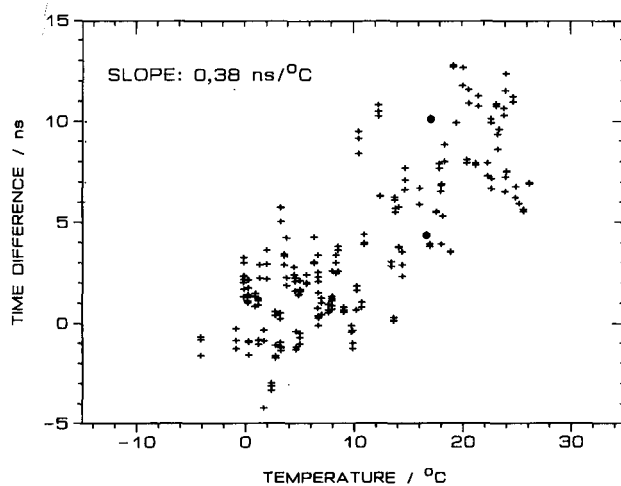

Figure 9. Difference between [UTC(TUG) − UTC(OCA)] obtained by two-way and GPS common-view time transfer (Figure 5) against the mean value of the outside temperature at the OCA and the TUG (Figure 6).

the mean of the OCA and TUG temperatures. Different reasons for this temperature-dependent behaviour are conceivable, but the main one is likely to be a difference in the temperature behaviour of the OCA and TUG GPS receiving equipment. This is

even more evident in Figure 7, which shows the variation of the differential delay of the two GPS receivers permanently operated at the TUG and correlates closely with the temperature variation of Figure 6. Using the alternate receiver for the time comparison between the TUG and the OCA would reduce the observed temperature dependence by about 20 %.

6.4 Stability

In addition to accuracy, stability is an important characteristic of a time and frequency transfer system. The measurement stability can be expressed by $\sigma_x(\tau)$ which is defined as $\mathrm{Mod}.\sigma_y(\tau)$ multiplied by $\tau/\sqrt{3}$ [16, 17]. In a $\sigma_x(\tau)$ versus τ diagram a $\tau^{-1/2}$ behaviour of the measurement noise denotes white-noise PM behaviour of the data and gives the region of τ where
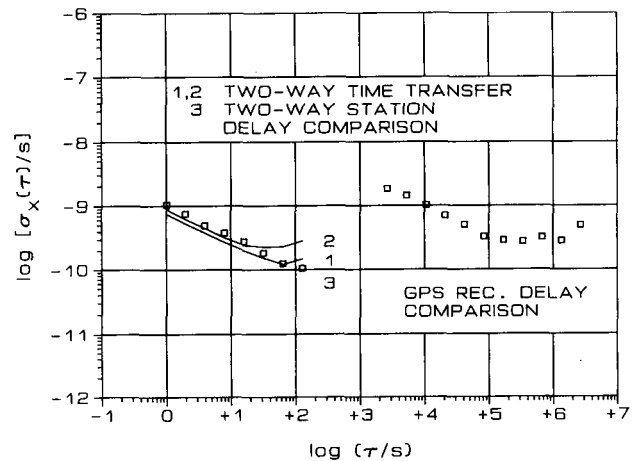
Figure 10. $\sigma_x(\tau)$ of two-way measurements of [UTC(TUG) − UTC(OCA)], and of the measurement of the differential delay of the two-way stations and of the measurements of the differential delay of the two GPS receivers operated at the TUG. The two-way time transfer measurements are the long measurement blocks at 24 August 1990 and 29 March 1991. This is before (1) and after (2) the clock change at the TUG. The two-way station delay comparison (3) is the long measurement block at 24 April 1991.

averaging is of benefit. Figure 10 shows (i) $\sigma_x(\tau)$ for two-way measurements of [UTC(TUG) − UTC(OCA)] (long measurement blocks before and after the clock change at the TUG: 24 August 1990 and 29 March 1991, respectively) and for the measurement of the differential delay of the two-way stations (24 April 1991, long measurement block); and (ii) $\sigma_x(\tau)$ for the measurements of the differential delay of the two GPS receivers operated at the TUG (see Sections 3.1, 3.2, 4.2 and 4.3).

The noise level of the two-way time transfer of about $8 \times 10^{-10}(\tau/s)^{-1/2}$ is given by the carrier-to-noise power density ratio of the satellite link (see Section 3.3 and 5.2), but for averaging times of minutes (depending on the type of clock used) the measurement noise is already dominated by the clock noise. For the measurement of the differential delay of the two-way stations no systematic deviation from the white-noise PM behaviour can be seen. On the assumption that the white-noise PM behaviour of the two-way measurement noise will continue for longer averaging times, an assumption which has to be verified by future experiments on the delay stability of two-way stations and of two-way satellite links, frequency comparisons of better than 1×10^{-15} could be carried out employing averaging times of about five hours. GPS receiver delay comparisons carried out by receiver co-location allow estimation of the best performance for GPS common-view time transfer between given pairs of receivers. Usually the measurement noise shows a systematic departure of white-noise PM behaviour for averaging times longer than one day, as can be seen in Figure 10 for the two receivers operated at the TUG.

7. Conclusion and Considerations for Future Experiments

This experiment allowed us to compare the accuracies of the two most accurate time transfer methods currently in operation and demonstrates the feasibility of comparing Earth station delays by means of a portable station.

At the time of "calibration", the mean value of the differences between two-way and GPS measurements was about 3 ns. Over the duration of the experiment a systematic variation of the difference, by about 8 ns, can be observed. This shows a strong correlation with the outside temperature at the OCA and the TUG. It is likely that the largest part of this variation is caused by a difference in the temperature behaviour of the delays of the GPS receiving equipment used at the OCA and the TUG.

To compare the two methods, the GPS measurements have to be smoothed and interpolated to obtain GPS data concurrent with that from the two-way measurements. In this procedure, the number of GPS measurements surrounding the two-way measurements, the level of GPS measurement noise and the stability of the local time scales are critical parameters, so the use of clocks with appropriate stability and of a well-balanced GPS tracking schedule is important. Furthermore, all equipment employed should be checked carefully in advance of the experiment to detect any systematic variations likely to affect the accuracy of the measurement. It should be possible to resolve the problem of temperature-dependence in the delays of the outdoor units (antenna, preamplifier/mixer, cable) of the GPS receivers by experiments in a temperature chamber using a GPS signal simulator. Similar tests could be carried out with two-way equipment [18]. GPS receiver delay comparisons by receiver transport should be repeated in the course of such an experiment to check the consistency of the measurements. In this connection, it would be helpful to operate more than one GPS receiver at each site. Delays in the two-way systems could thus be compared: this should be done by repeated Earth station co-location and the satellite terminals should preferably be adapted to detect delay variations by use of local means such as a satellite simulator. By appropriate selection of equipment and by careful operation, the first four contributions to the error budget of Table 4 could be reduced by a factor of at least three, leading to a two-way time transfer accuracy of about 0,5 ns. Similar accuracies are expected for GPS using geodetic receivers and ultra-precise ephemerides [1]. The stability data from the two-way satellite time transfer indicate the potential of this method to compare frequencies to better than 1×10^{-15} for averaging times of some hours.

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