Recent Time and Frequency Transfer Activities at the Observatoire de Paris

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Abstract- **Important investigations in the time and frequency transfer have been done during the last four years at the Observatoire de Paris (OP). The goal was twofold: improvement of the GPS comparison technique by the use of dual frequency GPS multi-channel receivers in common-views (GPS P3) and the development of a full two-way satellite time and frequency transfer (TWSTFT) station in the Ku-Band.**

The advantage of the GPS P3 technique is the compensation of the ionospheric delays. The GPS P-Code is transmitted simultaneously on both carriers L1 and L2, and the dual-frequency multi-channel GPS receiver Ashtech Z12-T allows for the so-called P1 and P2 measurements. A simple linear combination gives the ionosphere free P3 measurements. The software developed by the Observatoire Royal de Belgique [1] builds from the geodetic RINEX files such P3 data in the CGGTTS format, and the Common-View method is applied. Due to the availability of several simultaneous Common-Views, a selection can be made which improves the short term frequency stability of the results. A typical result on European baselines gives an Allan Time Deviation $\sigma_x(\tau)$ below 200 ps over an analysis period lower than 1 d between H-Masers.

The TWSTFT technique, a direct comparison between ground clocks through a communication satellite, is a well-known technique independent from GPS. In this field, OP developed a full Ku-band two-way station with a dual offset antenna, active up/down-converters and a SATRE modem. The station, calibrated in relative mode in 2004, is officially used for TAI since January 2005. A complete uncertainty budget on the two-way measurement has been evaluated giving a combined uncertainty of only 1 ns. Moreover, the realization of a satellite simulator based on an original design [2] is in progress. Such a simulator will permit mainly an absolute difference delay calibration of a two-way station. During the Primary Frequency Standard comparison done in 2004 over 27-days measurement period, it was observed that H-Masers can be reached at only 0,6 d, with a $\sigma_x(\tau)$ = 80 ps on the OP-PTB two-way link.

I. INTRODUCTION

This paper presents the recent time and frequency transfer activities at Observatoire de Paris (OP), based on two complementary techniques: the so-called GPS P3 Common-Views, and the Two-way satellite time and frequency transfer (TWSTFT) technique. Chapter II presents the GPS P3 technique as implemented in OP. The advantage of this technique is the compensation of the ionosphere delays. The GPS P-Code being transmitted simultaneously on both carriers L1 and L2, the dual-frequency multi-channel GPS receiver Ashtech Z12-T [3] allows for the so-called P1 and P2 measurements. A simple linear combination gives the ionosphere free P3 measurements at the cost of a small increase of the noise compared to a single P1 measurement. The software developed by the Observatoire Royal de Belgique [1] builds from the RINEX files such P3 data in the TAI required CGGTTS format [4], and the Common-View method is applied for time and frequency transfer. Due to the available number of simultaneous Common-Views, a selection can be made which improves the short term frequency stability of the results, an important issue for Primary Frequency Standards (PFS) comparison.

Chapter III presents the recent TWSTFT activities. The TWSTFT technique, a direct comparison between ground clocks through a communication satellite, is a well-known technique independent from GPS. In this field, OP has developed a full Ku-band two-way station with a dual offset antenna, active up/down-converters, and a SATRE modem. The station, calibrated in relative mode in 2004, is officially used for TAI since January 2005. A complete uncertainty budget on the TWSTFT measurements is evaluated giving a combined uncertainty of only 1 ns, and the realization of a satellite simulator based on an original design [2] being in progress. Such a simulator will permit mainly an absolute difference delay calibration of a two-way station. Chapter IV shows a direct comparison between the stability of different techniques in the frame of the PFS comparison campaign between five European and American laboratories in October–November 2004.

II. TIME AND FREQUENCY TRANSFER USING THE GPS P3 COMMON-VIEW TECHNIQUE

A. Implementation of the GPS P3 Technique at OP

An Ashtech Z12-T, a specific design of a well known multi-channel GPS geodetic receiver [3], has been implemented at OP since 1997. Following extensive tests of temperature dependency of the equipment [5], it was decided to connect this receiver to a Temperature stabilized antenna (TSA) with an RF cable exhibiting a low sensitivity to temperature fluctuations, the receiver itself being in a temperature controlled area. The software developed by P.

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Defraigne from Observatoire Royal de Belgique [1] allowing the computation of result files in the required TAI CGGTTS format [4], was implemented in 2001. Since July 2002, OP is formally contributing to the so-called TAI-P3 network organised by the BIPM Time Section, forwarding the OP CGGTTS multi-channel files on a monthly basis, for GPS P3 Common-Views. This process is the current back-up link for the TAI computation including OP clocks. Moreover, this OP implementation forms the core equipment of the registered station of the International GPS service (IGS) called OPMT, which is also registered in the French "Réseau GPS permanent" (RGP). One of the advantages for time metrology laboratories is the computation of the antenna phase centre coordinates by the IGS at the cm level. For the TSA at OP, the latest results are:

X = 4 202 777,3831 m
Y = 171 367,9881 m
Z = 4 778 660,1844 m

The delays of the ensemble formed by the Z12-T, the TSA, and the RF cable was differentially calibrated by the BIPM Z12-T travelling receiver, which has been calibrated in an absolute sense [6]. Three differential calibration campaigns have been undertaken by the BIPM: one in March 2001, one in February 2003 and one in June 2004. The differences between the results of these calibrations do not exceed 3 ns, the difference between 2003 and 2004 being mostly due to a mix-up in one cable delay measurement at OP which was not done simultaneously, allowing for an uncertainty budget evaluation of 1,5 ns (1 σ) for this technique. A second Ashtech Z12-T has been implemented in 2003 in OP, connected to the same TSA. There is currently a project of absolute calibration of OP equipment with the French Space Agency CNES where GPS signal generators are available.

Because UTC(OP) is currently based on a Caesium standard [7], and because beside the contribution to the TAI the main objective of this implementation was the PFS comparison, it was decided to connect to the Z12-T the 1 pps and 10 MHz signals from the H-Maser which is used as local oscillator for the PFS of OP. A separate file transmitted also to the BIPM contains hourly differences between the chosen H-Maser and UTC(OP) for the TAI computation. This will not be required any more when the new UTC(OP) based on an H-Maser and a Caesium ensemble will be operational [7], provided the same H-Maser will be chosen for the UTC(OP) generation and as the PFS local oscillator.

On the Fig. 1 can be seen the TSA on the roof of B building in OP. The location in the city centre means there is an important building mask in the West South-West direction (not appearing in the picture).

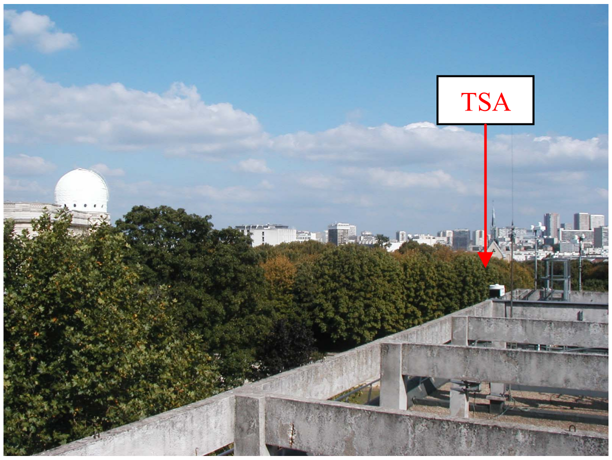

Figure 1. The small black and white box is the TSA of the OPMT IGS station on the roof of the B building in OP, looking from West to East.

B. *Typical Results on a European Baseline.*

The multi-channel GPS P3 Common-View method is also based on a computation of the mean of simultaneous Common-Views for each epoch of the regular BIPM schedule. Over short baselines as between European laboratories, this leads to an average of around 7 simultaneous Common-Views at each epoch. Fig. 2 shows typical results on the link between NPL and OP, with H-Masers directly connected to the Z12-T in both sides: UTC(NPL) and H-Maser 816(OP).

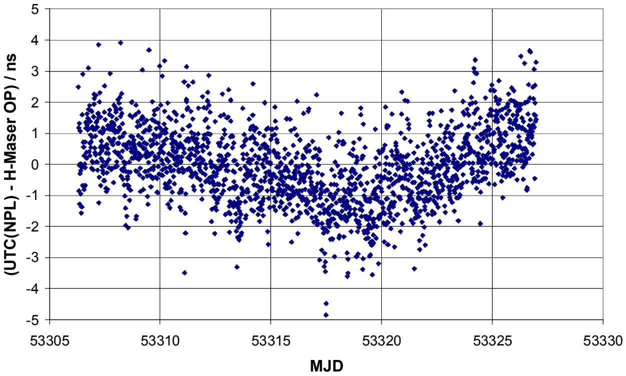

Figure 2. Residuals to a second-order polynomial fit of UTC(NPL) – H-Maser 816(OP) by satellite averaged GPS P3 Common-Views from October 28 to November 16, 2004.

Moreover, the technique is sensitive to unexpected events present in the data. As an example, Fig. 3 shows what happened during the night of 27 to 28 October 2004 (MJD 53305-53306). From an analysis of different GPS P3 and TWSTFT links during that period of time, it was rapidly obvious that this was related to something in the OP location. An internal inquiry showed that the event was due neither to the H-Maser, nor to the distribution amplifier of the H-Maser signal. But as a direct comparison between the two Z12-T connected to the same H-Maser at that time did not show any jump. So the best explanation to date is a short time failure of the temperature control of the common TSA, which would explain why the ensemble went back to the continuity of the time differences afterwards.

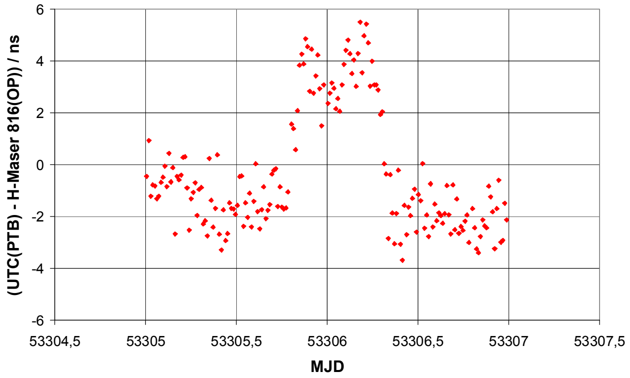

Figure 3. Unexpected event in the OP location during the night of 27-28 October 2004 as seen by comparison between UTC(PTB) and H-Maser 816(OP).

C. *Improvement of the Short-Term Stability by Selection among the Simultaneously Tracked Satellites*

During the PFS comparison campaign of October-November 2004, the GPS P3 computations were made by the BIPM [8], by using some of the IGS products as precise ephemeris of the GPS satellites or troposphere maps. This is not yet implemented in OP, and this is why we have tried, instead of computing a simple mean of the simultaneous Common-Views, to implement a filtering process. Different attempts have led to a very simple 3-sigma filtering. For each epoch, the Common-View average is computed along with the standard deviation of each individual tracks. The difference between each individual Common-View and the mean is computed, the largest being compared to the ± 3-sigma limit, and the corresponding satellite rejected when outside. This process is repeated three times maximum, considering that there should remain at least four simultaneous Common-Views. The results show a noticeable improvement of the short term stability of the Common-View averages, even at the cost of slightly lowering the average number of simultaneous Common-Views.

This is illustrated on the link OP-NPL and OP-PTB in the Fig. 4 to 7. Fig. 4 is made from the satellite averaged GPS P3 Common-Views between OP and NPL from October 28 to November 16, 2004. H-Masers were directly connected to the Z12-T receivers on both sides: UTC(NPL) and H-Maser 816 at OP. There is an average of 7,57 simultaneous Common-Views over the period. The 3-sigma filtering process leads to an average of 6,77 simultaneous Common-Views, but one can see on Fig. 4 that the short term time stability is improved (red squares) compared to the simple mean computation (blue circles). The stability of the H-Maser comparison is largely improved around an averaging period of one day, where $\sigma_x(\tau = 1\ \mathrm{d}) < 200$ ps. The lowest stability is given by $\sigma_x(\tau = 82\ 000\ \mathrm{s}) = 194$ ps. Fig. 5 is a TDEV obtained from residuals to a quadratic fit in the satellite averaged GPS P3 Common-View. It shows that the gain on the short term data is not modified by a drift computation.

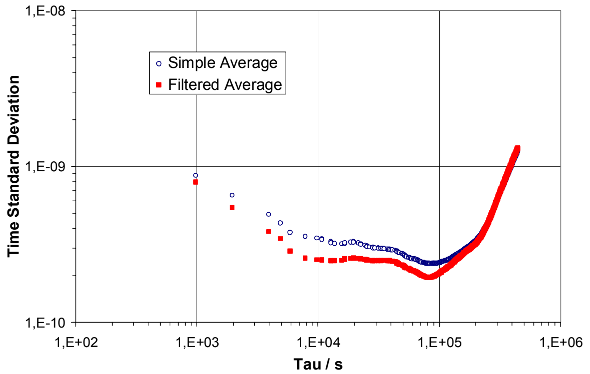

Figure 4. Time Standard Deviation of UTC(NPL) – H-Maser 816(OP) by satellite averaged GPS P3 Common-Views from October 28 to November 16 2004, either by simple average of the simultaneous Common-Views (blue circles), or by the 3-sigma filtering process (red squares). No quadratic fit removed in the original data.

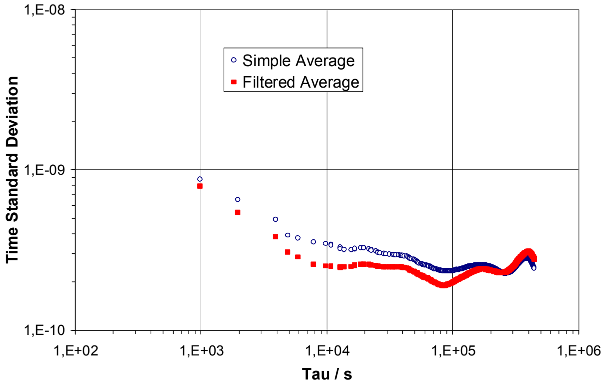

Figure 5. Same as above but with a quadratic fit removed from the original data.

Fig. 6 is made from the satellite averaged GPS P3 Common-Views between OP and PTB from October 28 to November 16, 2004. Originally, UTC(PTB), which is not an H-Maser was connected. It was nevertheless possible to connect the data to the H-Maser H4 of PTB with the appropriate hourly measurements kindly provided [9]. There were 7,1 original simultaneous Common-Views over the period, and 6,4 after the 3-sigma filtering process. Here again, even if not as large as for the OP-NPL link, the stability is improved, and $\sigma_x(\tau) < 200$ ps for an averaging period of about 25 000 s. The lowest stability is given by $\sigma_x(\tau = 36\ 000\ \mathrm{s}) = 170$ ps. Fig. 7 is a TDEV obtained from residuals to a quadratic fit in the satellite averaged GPS P3 Common-View. It shows that there is a small improvement after a one day averaging period, to the cost of a small loss for shorter term averaging periods.

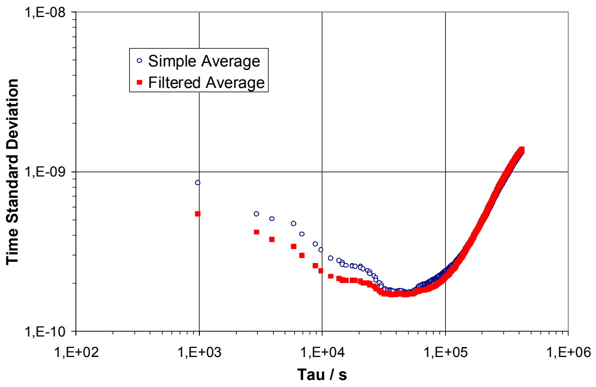

Figure 6. Time Standard Deviation of H-Maser H4(PTB) – H-Maser 816(OP) by satellite averaged GPS P3 Common-Views from October 28 to November 16 2004, either by simple average of the simultaneous Common-Views (blue circles), or by the 3-sigma filtering process (red squares). No quadratic fit removed in the original data.

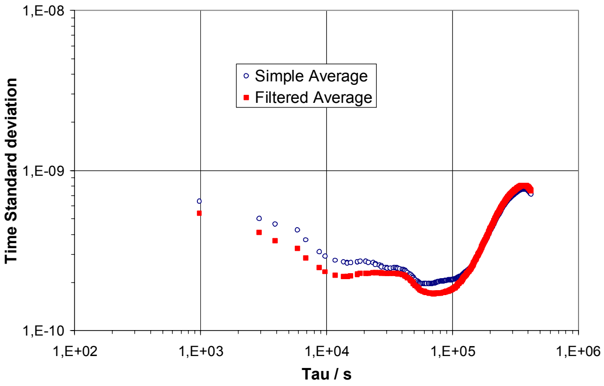

Figure 7. Same as above, but with quadratic fit removed in the original data.

In all the last four figures, the diurnal term can be clearly seen as a bump around an averaging period of half a day. A future development in OP would be the use of IGS products for the computation of satellite averaged GPS P3 Common-Views, which is mandatory for long distance links [10].

III. TIME AND FREQUENCY TRANSFER USING THE TWSTFT TECHNIQUE

Two-Way Satellite Time and Frequency Transfer (TWSTFT) is one of the leading techniques for remote frequency standards and time scales comparison, using microwave links between ground clocks and geostationary satellites. The TWSTFT data are used by the Bureau International des Poids et Mesures (BIPM) in order to determine the different links between Coordinated Universal Time UTC*(k)* scales realized in the different national metrology institutes *k*, permitting to make the International Atomic Time (TAI), as it is published monthly by the BIPM Circular T [11]. OP developed in 2003 a full automated Ku-band two-way earth station for INTELSAT satellite communications [12], based on a 2,4 m Gregorian dual offset antenna, active up/down-converters with 125 kHz steps, different microwave components (cables, waveguides, couplers, attenuators, splitters), and a SATRE modem allowing 2,5 MChips pseudo-noise codes for its Tx/Rx modules with an in-built Time Interval Counter (TIC). A spectrum analyzer and an external TIC are also connected to the station for additional precise measurements.

A. Calibration of the OP Earth Station using a Portable Station

A few years ago, most of the TWSTFT time links have been calibrated using GPS common-view measurement results, which limit the attainable uncertainty to several nanoseconds. Consequently, the CCTF Working Group on TWSTFT stimulated to perform calibrations of TWSTFT links using a portable station on a regular process, based on what was done in the past [13]. OP and three additional institutes (PTB, NPL and VSL) agreed to have the differential delays of their Ku-band TWSTFT systems determined by using a portable station assembled by TUG, through INTELSAT 903 @325,5 °E during an intensified schedule from 5 to 16 July 2004 [14]. Figure 8 shows the portable station in co-location at OP on 9 of July. There were normal weather conditions during the whole trip, which had no noticeable impact on the results of the campaign. A half hour time-table was arranged between OP, all other sites and the portable station, which was repeated seven times to a total schedule lasting four hours from 10:00 UTC to 14:00 UTC. Additional measurements before and after the schedule were recorded at all sites between the portable station and the local station.

Figure 8. The TUG portable station collocated with OP earth station at OP site on 9 July 2004.

The calibration results related to OP, including Sagnac corrections, are given in Table 1, with a standard deviation less than 0,7 ns and a total estimated uncertainty down to 0,9 ns. A test for closing errors showed no significant deterioration of the accuracy of the calibration. Since January 2005, OP station is officially used on the main link with PTB in the contribution to TAI.

TABLE I. CALIBRATION CONSTANTS RELATED TO OP

TWSTFT Link Related To OP	Calibration Constant (ns)
PTB-OP	-6982,77
NPL-OP	-7832,05
VSL-OP	-7029,06

B. Evaluation of Uncertainty Budget on the Ku-Band TWSTFT Link

A complete evaluation of both statistical uncertainty U_A and systematic uncertainty U_B [15] on the TWSTFT Ku-band link, based on the differentiation of the time equation, was calculated at OP. The main uncertainty contributions come from the calibration of stations, the link between clocks and stations and the two-way time interval measurements. Typical values of $U_A = 0{,}53$ ns and $U_B = 0{,}96$ ns were found, giving a combined uncertainty $U = 1{,}10$ ns (k=1) calculated on the two-way two-minute measurement data. Clock differences between OP and PTB over the year 2004 were calculated including uncertainties, using both Ku band TWSTFT and GPS Single Frequency Common View techniques [16]. The results are reported in Fig. 9.

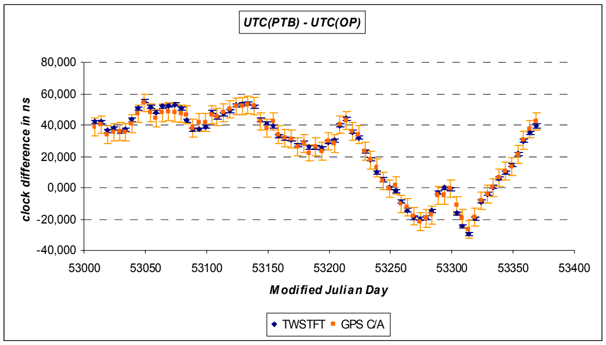

Figure 9. UTC(PTB)-UTC(OP) over the year 2004 using TWSTFT and GPS C/A.

A good agreement was observed between the two techniques, giving a mean value of 0,32 ns ± 6 ns on the difference between the two techniques, widely dominated by the GPS (combined uncertainty of 5,6 ns). It indicates that no important effect was forgotten in the evaluation of the uncertainty budget on the two-way time transfer link. The very promising result (accuracy of 1,1 ns) obtained shows that the nanosecond accuracy level can be reached with this time transfer link. This work will be achieved in considering additional contributions of uncertainties due mainly to high frequency reflections effects in cables and a possible variation of internal delays of the stations during the calibration campaign. Moreover, calibration results were assumed to be constant values over one year. In reality, some effects like temperature, humidity and pressure can affect differential delay stations in time and the monitoring of these internal delays will be carried out at OP using a satellite simulator actually in development, in order to take into account systematic effects in the uncertainty budget as seasonal variation.

C. Calibration corrections due to the change of satellite

Considering the TWSTFT technique is using communications satellite, some corrections were necessary to the calibration links when the satellite used to link two Earth stations changed. This can be done either in modelling the clocks behaviour or by two-way technique (different satellite, different RF band) or by GPS technique. The last one was used on the link PTB-OP and the correction to be applied was calculated and reported as it is shown in figure 10. In order to reach this result (step of 21,9 ns ± 0,5 ns), an intensified schedule of 12 sessions per day before and after the satellite change was followed by the stations and the PTB-OP link was bridged by the GPS Carrier Phase (GPS CP) data collected every 5 minutes, processed and provided gratefully by AIUB in Switzerland.

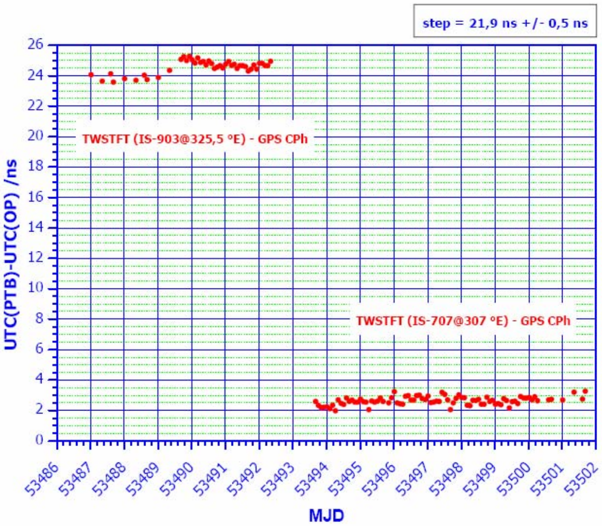

Figure 10. Plots of the difference TWSTFT minus GPS CP data before and after the change of INTELSAT satellite.

The fluctuations are found within 2 ns (before) and 1,5 ns (after). The step was calculated as the difference between the two averaged values, before and after the satellite change. The value obtained in Fig. 10 is consistent with the evaluation made by the BIPM using data bridged by GPS P3 with 21,8 ns ± 0,7 ns.

D. Progress work on the realization of the OP TWSTFT Satellite Simulator

OP is developing an original and rigorous calibration method, based on the satellite simulator equipment and coupled with a faster and accurate measurement process [2]. The main design of the simulator is given in Fig. 11. The measurement of the delay difference between transmission and reception paths inside the TWSTFT station is done in only two successive measurements. It takes into account the whole internal delays of the station. The calibration device is placed in a temperature controlled box (Fig. 12), containing a double-balanced microwave mixer, two RF and IF filters, different programmable switches (assembled in a metallic box showed in Fig. 13, and a microwave local oscillator driven by UTC(OP). An orthogonal IEC-R120 conical waveguide horn supported by a non-magnetic structure is used, with two flexible waveguides, two coaxial to waveguide adaptors, coaxial cables and connectors.

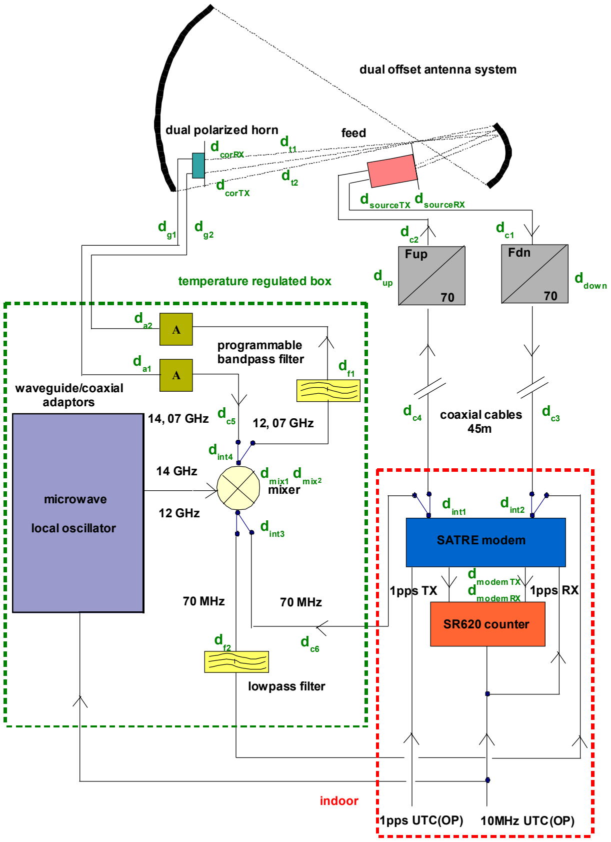

Figure 11. Main design of the OP TWSTFT satellite simulator.

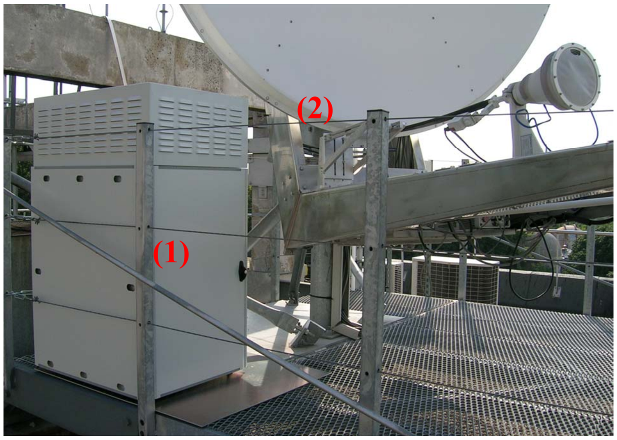

Figure 12. Temperature controlled box (1) and non-magnetic metallic support (2) of the dual polarized horn, installed nearby the OP station.

This work will be completed by a full characterization of the microwave part of the satellite simulator using a Vector Network Analyzer (VNA) in the time domain. The validation of the system will be done by including the calibration process into the TWSTFT measurement.

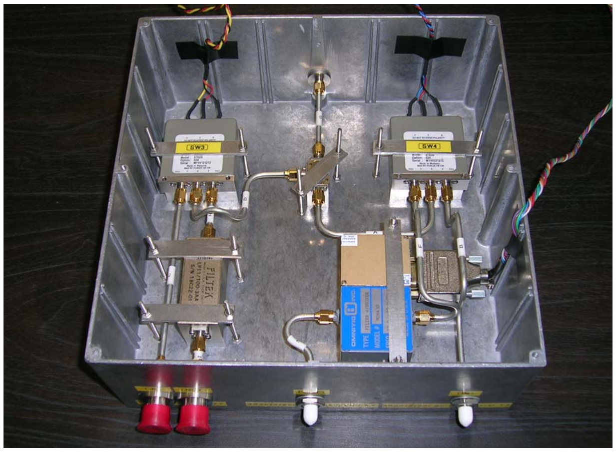

Figure 13. Microwave components assembly of the OP satellite simulator.

IV. COMPARISON BETWEEN TWSTFT AND GPS TECHNIQUES

In October-November 2004, an intensive comparison campaign of PFS maintained in five national institutes was achieved. Three different time and frequency transfer techniques were involved [8]: TWSTFT in Ku band, GPS P3 and GPS Carrier Phase (GPS CP).

TWSTFT measurements were performed in an intensified schedule of 12 equally spaced measurements per day. The active hydrogen masers (H-masers), used as fly-wheel oscillators for the fountain frequency standards, were connected to all the TWSTFT equipments.

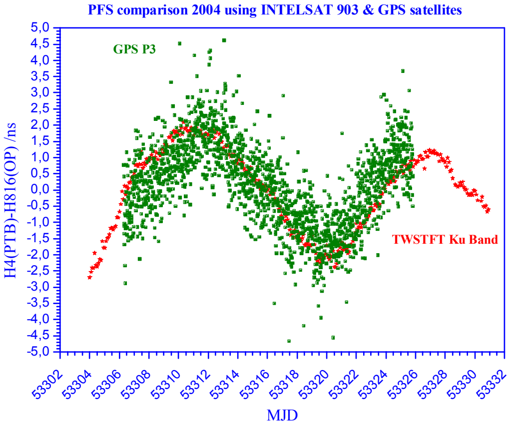

Figure 14. Time interval fluctuations obtained by TWSTFT and GPS P3 over a period of 27 d and 19 d respectively.

We report here only results on the OP-PTB link. The fluctuations observed over a 27 d period of analysis for the TWSTFT and 19 d for the GPS P3, are within 4,5 ns and 9 ns respectively (Fig. 14). The systematic behavior of the measurements is coming from two frequency changes of the H-Maser in OP, as checked by the PFS of the laboratory. The related data processed for the time stability are reported in Fig. 15. It is clearly shown that hydrogen masers are reached at 0,6 d by TWSTFT with $\sigma_x(\tau) = 80$ ps, and at about 2 d by GPS P3.

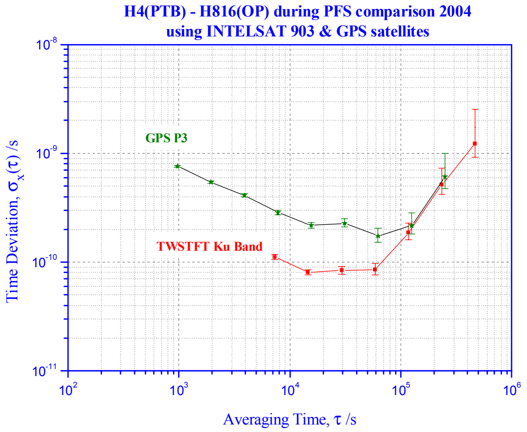

Figure 15. Time stability comparison on the PTB-OP link between TWSTFT and GPS P3 techniques.

While for the stability analysis of the double difference TWSTFT – GPS CP, it was shown that frequency comparisons with a statistical uncertainty of close to 1 part in 10^{-15} at averaging times of about 1 day can be done with the TWSTFT technique [8].

V. CONCLUSION

Important investigations in the time and frequency transfer have been done during the last four years at OP. The use of dual frequency GPS multi-channel receivers in common-views (GPS P3) including a temperature stabilized antenna and the development of a full automated two-way satellite time and frequency transfer (TWSTFT) station in the Ku-Band having 2,4 m Gregorian dual offset antenna have really improved time and frequency transfer. From our computations, we can say that satellite averaged GPS P3 Common-views is a method which stability is less than 200 ps for a 1 d averaging period over European baselines, even without using any IGS product. The next step is to incorporate IGS products, especially for long distance links. The uncertainty evaluation of the differential calibration of the equipment is currently 1,5 ns (k = 1).

Concerning the TWSTFT technique recently implemented at OP, excellent results have been obtained, reaching a time stability of 80 ps on 0,6 d. This technique allows to within easy reach the noise of H-masers at a very short analysis period. Moreover, the time measurement accuracy has been evaluated at 1 ns level on a calibrated two-way link. The next step will be the implementation of the satellite simulator in the TWSTFT measurement sessions. The direct comparison between TWSTFT and GPS P3 on the same links gives confidence into the presented results. These developments contribute to TAI with accurate time transfer methods, and compare PFS using very stable frequency transfer methods. It is also important that different techniques not too far from the point of view of accuracy and stability be used on the same link, in order to get some crosscheck on all such studies. Future developments are expected with the start of the European Galileo project.

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