Improved GPS-Based Time Link Calibration Involving ROA and PTB

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***Abstract*—The calibration of time transfer links is mandatory in the context of international collaboration for the realization of International Atomic Time.**

In this paper, we present the results of the calibration of the GPS time transfer link between the Real Instituto y Observatorio de la Armada (ROA) and the Physikalisch-Technische Bundesanstalt (PTB) by means of a traveling geodetic-type GPS receiver and an evaluation of the achieved type A and B uncertainty. The time transfer results were achieved by using CA, P3, and also carrier phase PPP comparison techniques. We finally use these results to re-calibrate the two-way satellite time and frequency transfer (TWSTFT) link between ROA and PTB, using one month of data.

We show that a TWSTFT link can be calibrated by means of GPS time comparisons with an uncertainty below 2 ns, and that potentially even sub-nanosecond uncertainty can be achieved. This is a novel and cost-effective approach compared with the more common calibration using a traveling TWSTFT station.

I. Introduction

GPS time and frequency transfer is among the most useful tools for comparison of remote clocks and represents the basis for the contributions of timing laboratories to the realization of International Atomic Time (TAI) [1]. It is one of the most accurate techniques in this field; in the case of precise point positioning (PPP), it is at the same level of performance as the state-of-art technique, two-way satellite time and frequency transfer (TWSTFT) [2]. However, to provide accurate time transfer by means of a GPS link, it is necessary to carry out calibrations periodically to verify the long-term stability of the equipment.

Generally there are 2 types of calibration procedures: absolute and differential ones. The absolute procedure is carried out by GPS signal simulators [3], [4], and although some new developments have been introduced during the last decade, it still is complex and not widely used. The differential procedure was used, e.g., in 2004, when a TTR6-AOA GPS receiver from ROA was circulated in a calibration campaign between selected European laboratories that contribute with their data to the computation of TAI. After visiting 3 European sites, the receiver came back to ROA, where an unexpected delay change of more than 6 ns was detected in the closure measurement, indicating the well-known limitations of the equipment that was used [5].

For the purpose of link calibrations, the Bureau International des Poids et Mesures (BIPM) has performed several differential calibrations for geodetic GPS receivers contributing to TAI [6], the complete history of which is now available on the BIPM's web pages [7]. ROA has resumed its previous activities and took an initiative to improve the calibration accuracy of its time transfer link to PTB, which is presently the pivot laboratory in Europe for TAI realization. In this paper, we report on the results of a calibration trip performed in October 2008 with a focus on the uncertainty budget evaluation. It is a revised version of [8], which was presented at the EFTF–IFCS 2009 Joint Conference in Besançon, France.

II. The Traveling GPS Receiver

The traveling receiver (TR) comprises of a receiver of type DICOM GTR50 intended for time and frequency transfer, its NovAtel antenna, of type GPS-702-GG, with pinwheel technology for multipath rejection and stable phase center, and 48 m low loss, easy to handle H155 antenna cable, nearly as flexible as the RG-58 standard.

The TR is basically a Linux PC in a 19¨ chassis together with a GPS board (Javad GGD-112T) and a time interval counter. The Javad GPS board supports both code and phase measurements on both GPS frequencies L1 and L2. Its internal quartz oscillator is the reference for pseudo-range measurements and the source of a one pulse per second (PPS) output synchronized to GPS time. The difference between this PPS and the PPS input reference is measured with the time interval counter, which together with the receiver circuits, and the GPS board, are located in a thermostated box (based on thermoelectric Peltier modules) to minimize the impact of their delay temperature sensitivity.

All components of this setup were transported in a single box, which weighs less than 20 kg.

III. Calibration Trip Results

To accomplish the GPS calibration in the differential mode, we started the common clock measurement at ROA

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TABLE I. Mean ± SD Values of the Two CCD Measurements Recorded at ROA.

CCD	P1 (ns)	P2 (ns)	P3 (ns)	CA (ns)	PPP (ns)	Number of Data P3/PPP
TR-ROAG (before the trip)	1.03 ± 0.27	1.04 ± 0.34	1.03 ± 0.95	−3.01 ± 0.25	1.29 ± 0.12	400/1150
TR-ROAG (after the trip)	0.91 ± 0.37	0.96 ± 0.27	1.04 ± 0.98	−3.09 ± 0.28	1.25 ± 0.15	525/1560
Closure measurements	0.12	0.08	−0.01	0.08	0.04	

on October 1, 2008. The GPS units involved in the calibration were disposed in a common clock set-up, with UTC(ROA) as reference, physically realized by one high-performance cesium frequency standard (type 5071A). This time reference is also connected to the TWSTFT station of ROA.

The TR was shipped to PTB on October 7, 2008, arriving 3 days later. Here UTC(PTB) served as the time reference, which is derived from the primary clock CS2 steered toward UTC. The TR was operated for 11 days. Finally, the equipment was shipped back to ROA, to carry out the closure measurements with the initial set-up. These measurement results are very important to validate the results and because of their impact in the uncertainty budget based on the differences obtained. Table I shows these results stated as mean value ± standard deviation (SD) of individual values with respect to the mean value over several days. For coarse acquisition (CA), P1, P2, and P3 data, individual values are CGGTTS common-view (CV) data, averaged at each standard epoch. PPP data are 5-min averages.

The final link calibration value is calculated by the simple difference of common clock difference (CCD) results obtained in both laboratories (Lab1-TR and Lab2-TR). It is assumed that this calibration value remains valid until any change or event happens in any of the 2 installations and it can thus be taken into account in calculation of the time scale differences between ROA and PTB.

The CCD computation for the C/A code data is illustrated in a detailed example in Fig. 1. The individual CV results are averaged at each standard epoch. In a second step, a 3-sigma filter is applied. The averaged and filtered data show a standard deviation of 0.18 ns. P3 data are summarized in Fig. 2 and in summary, Table II lists all results determined with CV CA, P1, P2 and P3 [9] techniques. The latter has been used by BIPM since 2003 to compute time links after applying different corrections (precise IGS ephemerides, where IGS stands for International GNSS Service [10] clocks and solid Earth tides). The P3 software was developed to provide CGGTTS files from code pseudo-ranges collected with geodetic receivers and filed initially in the RINEX format. The software should follow the Consultative Committee for Time and Frequency (CCTF) approved procedures. The differential satellite orbit, troposphere, geodetic, and ionosphere corrections should be negligible because of the quasi-zero baselines at both sites, and neglecting such corrections in the software procedures does cause no harm.

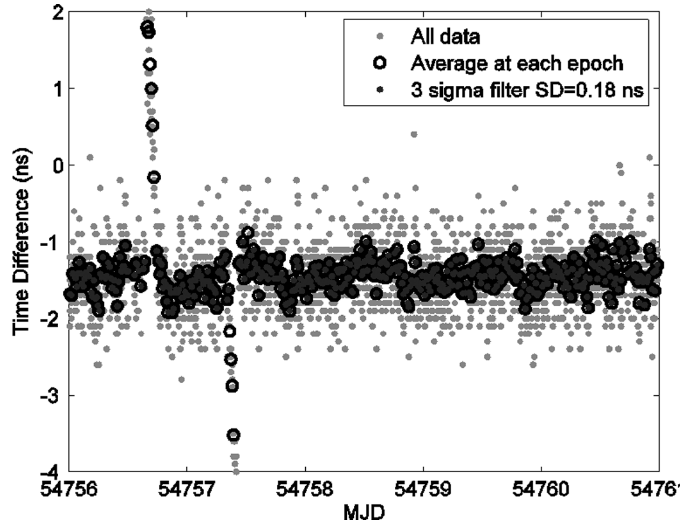

Fig. 1. Common-view CCGGTTS CA code data showing the difference of TR-PTB07 receivers.

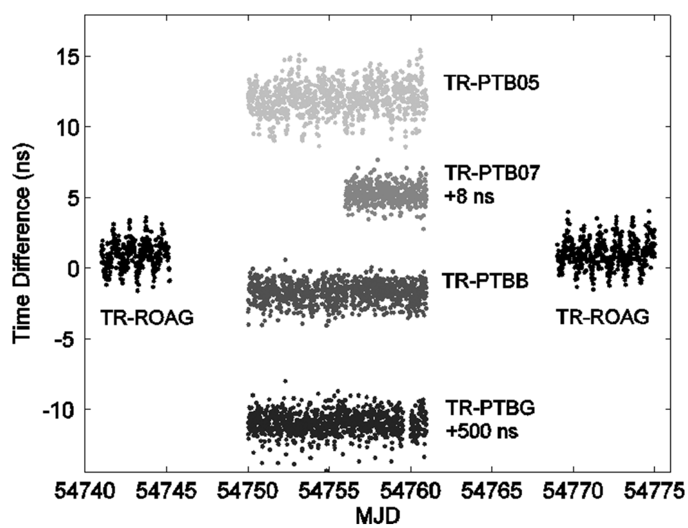

Fig. 2. P3 Common clock difference of GPS receivers participating in the calibration.

We used the so-called Pascale Defraigne program [9] and also a ROA-authored MATLAB version, in which the CCD is obtained by simple differences of pseudo-ranges, only corrected for the geometric effect of receivers' and satellites' positions. The difference between the results obtained with the ROA P3 MATLAB routine using every 30-s datum and the strict CGGTTS rules—for each scheduled track, it uses twenty-six 30-s data points which

TABLE II. Mean ± SD Values of the CCD Recorded at PTB.

CCD	P1 (ns)	P2 (ns)	P3 (ns)	CA (ns)	PPP (ns)	Number of Data P3/PPP
TR – PTBB	−1.05 ± 0.27	−0.62 ± 0.28	−1.70 ± 0.71		−1.62 ± 0.13	966/3020
TR – PTBG	−544.05 ± 0.27	−565.45 ± 0.25	−510.93 ± 0.72		−510.72 ± 0.11	990/3100
PTBB – PTBG	−542.98 ± 0.24	−564.84 ± 0.26	−509.19 ± 0.64		−509.10 ± 0.11	930/3170
TR – PTB05			12.04 ± 1.08	−2.11 ± 0.79		960/ —
TR – PTB07 (Only 5 d)	−2.46 ± 0.21	−2.27 ± 0.24	−2.74 ± 0.66	−1.46 ± 0.18	−2.60 ± 0.05	438/1420

The receiver types are: ROAG, TR, and PTB07 (GTR50) using different antennae from the same manufacturer, PTBB and PTBG (ASHTECH Z-XII3T), PTB05 (AOS TTS-3).

are within the 13-min tracks—was smaller than 0.2 ns in all cases.

The CCD has also been established with the PPP technique. In this technique, the RINEX files from each station are processed using dual-frequency phase and code measurements together with IGS precise ephemerides and space clocks, solving the local position, troposphere, and the clocks differences with respect to a reference time scale. Finally, the time link between the 2 stations can be obtained by the simple difference of clock results from each station.

For this purpose, we have used 2 different PPP software packages. First, we used GIPSY 5.0 [11] provided by the Jet Propulsion Laboratory, California Institute of Technology, released summer 2008, which includes new models for the troposphere mapping function, Earth orientation models, and the capability to model second-order ionosphere effects. Then we used the NRCan 1087 software [12], provided by the Geodetic Survey Division (GSD) of Natural Resources, Canada, which uses updated models for station displacements and troposphere mapping functions. In both analyses, we have tried to use the same correction models and the same IGS absolute antenna phase center offsets (atx file). The latter also implied modifying the header of GTR50 RINEX files with the proper antenna type (NOV702GG for TR and ROAG), as it is automatically read from here by the NRCan software. Fig. 3 shows the results of the 2 receivers PTBB and PTBG compared with TR, obtained with both software packages processing each day separately. The largest difference observed is below 300 ps, and the final mean values over 11 days are very close to zero.

The PPP clock solution is obtained with the combined code/carrier phase data analysis: for each day the evolution obtained from carrier phases has to be determined using the code information. This is the reason why CCD of P3 and PPP must be very close (see Table II). Whether the small (~0.2 ns) and reproducible CCD offset TR-ROAG is a real effect remains to be studied.

IV. Uncertainty Evaluation

The overall uncertainty of the calibration value is estimated from the following expression:

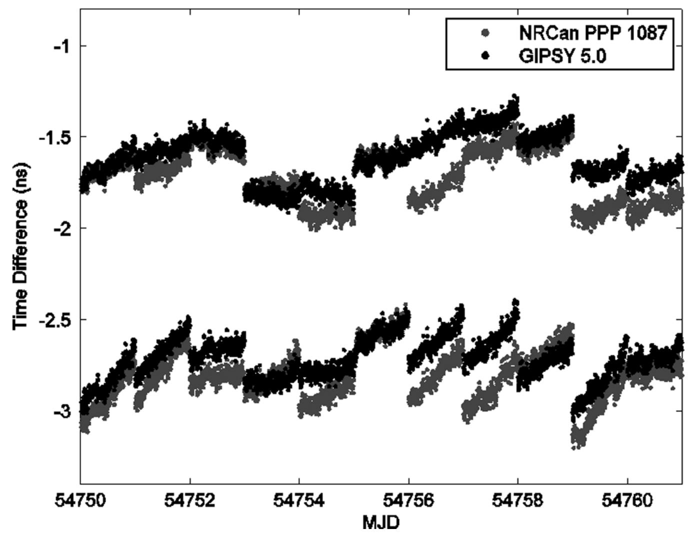

Fig. 3. CCD of TR-PTBB (upper) and TR-PTBG+508 ns (lower) obtained by NRCan and GIPSY.

$$U = \sqrt{u_{A,1}^2 + u_{A,2}^2 + u_{B,1}^2 + u_{B,2}^2 + u_{B,3}^2 + u_{B,4}^2 + u_{B,5}^2},$$

where $u_{A,1}$ reflects the statistical uncertainty of the determination of the CCD at ROA, and $u_{A,2}$ reflects the statistical uncertainty of the CCD measurements at PTB. In order not to underestimate the resulting uncertainty, we have directly used the SD of Tables I and II. For $u_{A,1}$ we have used the higher of the 2 values before and after the trip. It would probably be allowed to estimate both based on the standard deviation of the mean (SDOM), because the CCD measurements are independent and random, with predominant white phase noise as can be inferred from the dominant slope −3/2 in the log-log plot of the Modified Allan Deviation versus τ, see Fig. 4. The diurnal variations in the TR-ROAG data, the origin of which is presently unknown, motivated us to use the SD values in a conservative approach.

The systematic uncertainties $u_{B,1}$ and $u_{B,2}$ represent the uncertainty of the 1PPS delay from the local UTC, connected to each pair of receivers at ROA and PTB, respectively, and are based on the specifications of the uncalibrated time interval counter (TIC) in use (0.5 ns), the jitter of a TIC measurement (0.05 ns) and an estimation of the instability of the local distribution equipment (0.1 ns).

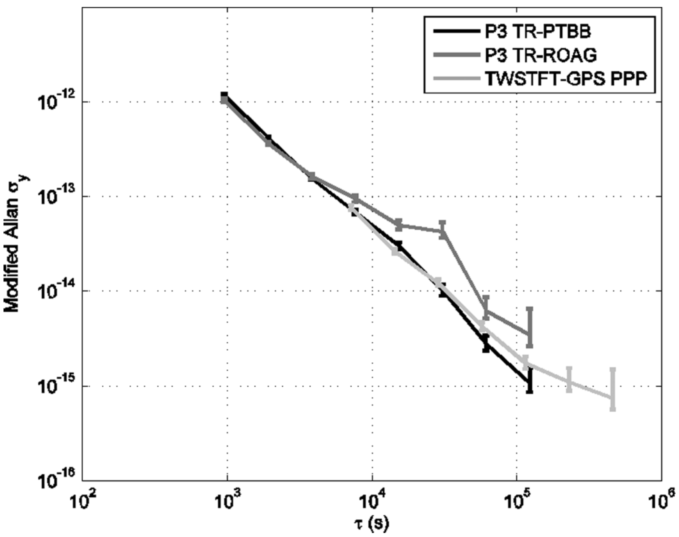

Fig. 4. Frequency instability diagrams in terms of modified Allan deviation.

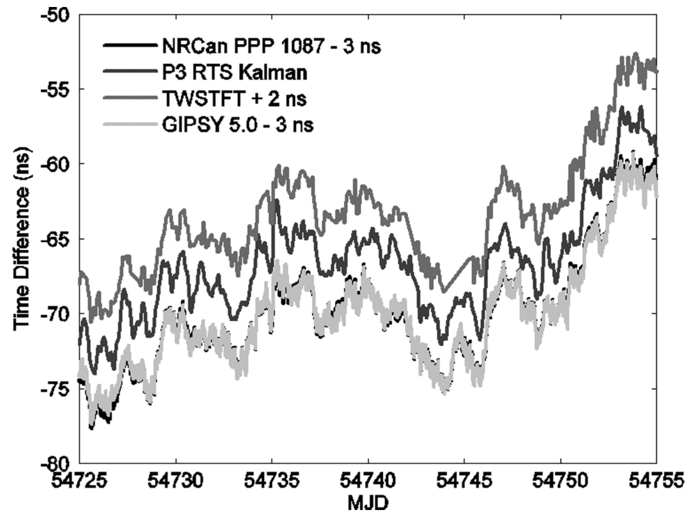

Fig. 5. ROA-PTB results from TWSTFT, P3, and PPP. The 2 PPP solutions (NRCan and GIPSY) are almost indistinguishable.

We point out that in the case of the ASHTECH receivers, the internal reference is derived from an externally provided 20-MHz signal, and the measurement of the offset between the internal reference and the 1PPS signal input makes use of an oscilloscope [13]. Because of a calibration in the differential mode, we do not have to take into account these measurements in the uncertainty budget.

In $u_{B,3}$ we have included the instability of the receivers and antennae. Environmental effects like humidity and especially temperature have been demonstrated to have a significant impact. Linear temperature coefficients of 0.04 ns/°C have been reported [14] in case of CV and P3 analysis. We account 0.4 ns for this contribution. The second contribution is the stability of the receivers during the whole trip. This is commonly estimated from the difference of the CCD measurements before and after the trip. We observed, fortunately, differences of only 0.01 ns and 0.04 ns for the P3 and PPP analysis, respectively.

In $u_{B,4}$ we account for signal propagation effects, which mostly cancel in the chosen quasi-zero baseline configuration. Only multipath errors might cause a small contribution to the uncertainty (0.3 ns) [15].

Finally, $u_{B,5}$ represents the uncertainty of the ambiguity estimation [16] in the PPP processing which we conservatively estimate to be 0.8 ns.

The uncertainty estimation results are summarized in Table III. The overall values were in the range from 1.2 to 1.5 ns. When the uncertainty of the ambiguity estimation can be reduced significantly, subnanosecond accuracy would become possible. These values are substantially lower than the type-B uncertainty attributed to GPS links in the BIPM Circular T. Here 5 ns are stated for "classical" relative calibrations, and 3 ns for GPS links calibrated using a portable TWSTFT station [17]. We understand that BIPM uses uncertainties that are somewhat higher than their statistical analysis usually calls for, and this is to take into account the observed long-term variation of calibration results involving L1 CA code single-channel receivers in the past.

V. TWSTFT Link Calibration

In the next step, we use the GPS time transfer results to re-calibrate the TWSTFT link between ROA and PTB using a 30-d data set partly overlapping with the calibration trip schedule. Thus we do not need to take into account the potential long-term instability of GPS equipment.

Links connecting European sites have usually been calibrated with a portable TWSTFT station with associated lower uncertainty. The differential calibration through GPS link is, however, unavoidable for most intercontinental links, like the ones established between NICT, NIST, and PTB [18], [19].

We have initially derived the differences between the GPS and TWSTFT links, shown in Fig. 5, using the P3 technique with ROAG and PTBB receivers, applying a Rauch-Tung-Striebel (RTS) algorithm in the implemented Kalman filter to smooth the noisy data [20]. Then we have used the NRCan software to process a 30-d batch of RINEX files in the backward smoothed mode. Finally,

TABLE III. Uncertainty Values (in ns) Estimated for GPS Link Calibration, Involving ROAG, PTBB, and TR Receivers.

Method	U	$u_{A,1}$	$u_{A,2}$	$u_{B,1}$	$u_{B,2}$	$u_{B,3}$	$u_{B,4}$	$u_{B,5}$
P3	1.5	0.98	0.71	0.51	0.51	0.4	0.3	—
PPP	1.2	0.15	0.13	0.51	0.51	0.4	0.3	0.8

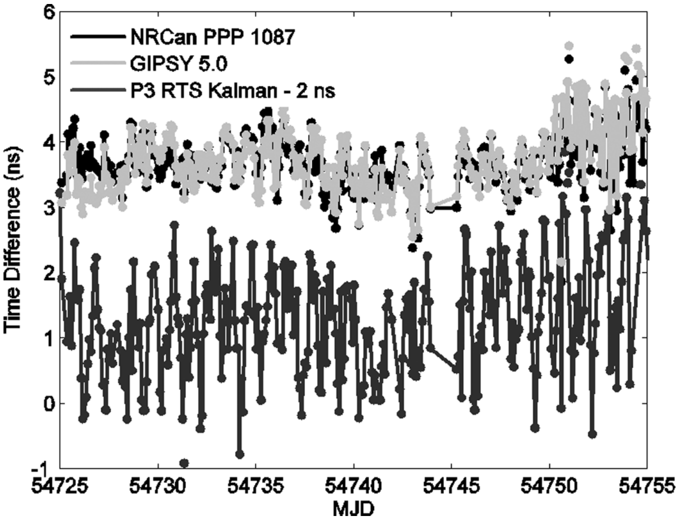

Fig. 6. TWSTFT-GPS differences of ROA-PTB link.

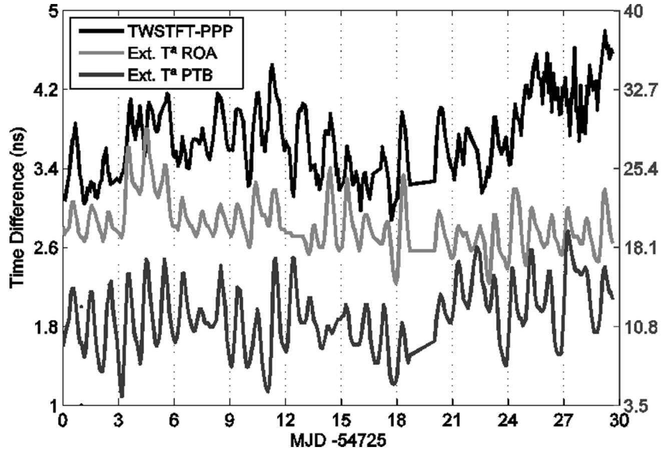

Fig. 7. ROA-PTB links differences conveniently smoothed to highlight their relation with external temperature at ROA and PTB.

we also used the GIPSY software, which has provided a close solution to NRCan in the daily processing mode. Each data point in Fig. 6 is the result of the exact difference of a TWSTFT value and the interpolation of the 2 adjacent PPP values (computed every 5 min) or P3 values (computed about every 16 min). Because of a malfunction of the TIC involved at ROA, a deterioration of the TWSTFT data occurred after MJD 54 750 (see Fig. 6). Therefore, the period we evaluated is from MJD 54 725 to 54 750.

The resulting values ± SD are:

$$\text{TWSTFT-P3} = (3.17 \pm 0.74)\ \text{ns},$$
$$\text{TWSTFT-GIPSY} = (3.60 \pm 0.37)\ \text{ns},$$
$$\text{TWSTFT-NRCan} = (3.63 \pm 0.32)\ \text{ns}.$$

We must not forget to apply the GPS link correction for the 2 participating GPS receivers, to be derived from Table I and II, respectively: P3 (1.04 ns + 1.70 ns = 2.7 ns), GIPSY and NRCan (1.27 ns + 1.62 ns = 2.89 ns). As the final result, the ROA-PTB TWSTFT link would need to be corrected by less than 1 ns. Beyond these results, the more important aspect is the uncertainty involved in this calculation, which is estimated from the following expression:

$$U = \sqrt{u_{A,3}^2 + u_{B,6}^2 + u_{B,7}^2},$$

where $u_{A,3}$ reflects the statistical uncertainty of TWSTFT-GPS differences, estimated by the SD value and following a similar reasoning as stated for GPS link type-A uncertainty.

In $u_{B,6}$, we have estimated the additional overall instability of the involved equipment for the calibration of the TWSTFT link: distribution of local UTC signals, the TWSTFT station components' instabilities, and environmental effects. We can see in Fig. 7 the fluctuations of the differences between TWSTFT and PPP of the ROA-PTB link, together with the external temperature at ROA and PTB. It might be that the diurnal part of these variations is due to thermal effects in the TWSTFT system. The GPS equipment could produce this effect by itself, but the phase data inserted in the PPP processing would reduce such influences considerably. Nevertheless both systems' noise contributions should be more closely studied based on long-term link comparison data.

TABLE IV. Range of Uncertainty Values (in ns) Estimated for the TWSTFT Link Calibration Using a GPS Link in Differential Mode.

Method	U	$u_{A,3}$	$u_{B,6}$	$u_{B,7}$
P3	1.7	0.74	0.3	1.5
PPP	1.3	0.37	0.3	1.2

In $u_{B,7}$, we have included the calculated uncertainty of the GPS link, and the final uncertainty for the GPS-calibrated TWSTFT link is summarized in Table IV.

VI. Conclusion

In this paper, we have summarized the GPS calibration trip experience between ROA and PTB, using a portable GTR50 receiver. The uncertainty estimate is very promising because it indicates the possibility of 1-ns accuracy calibration of GPS links. This definitely needs to be confirmed by future calibrations. Calibration trips of the same kind between PTB on one side and METAS (Bern, Switzerland), INRiM (Torino, Italy), and ROA have been scheduled. The results will hopefully reveal the suitability of the involved equipment as well as the validity of the uncertainty estimates made here.

We have found a very good agreement between TWSTFT and PPP, with similar short-term variations which are substantially below that attainable for smoothed P3 solutions.

The conventional TWSTFT link calibrations [18] have a considerably lower uncertainty than those hitherto made using GPS equipment, which has been demonstrated by the repeated calibration of European TWSTFT links. The good results found in this GPS-based calibration, however, have made the estimation of TWSTFT link delays feasible with an uncertainty lower than 2 ns. It seems reasonable to accept this result immediately for the TWSTFT link between ROA and PTB instead of the traditional 5-ns uncertainty, because it relies on GPS closure measurements made in rapid sequence during the routine TWSTFT analysis overlapped with the GPS calibration period. The use of the PPP processing and analysis makes the 1-ns level for link calibrations relying on GPS data feasible. We plan to repeat such a calibration exercise to confirm the validity of the present results.

It will be worthwhile to demonstrate in the future a TWSTFT calibration using a portable TWSTFT station and to perform, at the same time, a GPS calibration as reported here. This could demonstrate that a TWSTFT link can be calibrated with a slightly higher uncertainty than shown in [18], but with a significantly lower cost for the participating stations when relying on GPS equipment alone.

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Captain Palacio has served on the Scientific Committee of the European Frequency and Time Forum (EFTF) since 2001. He is member of the Consejo Superior de Metrología de España.

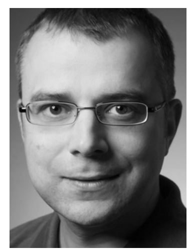
Francisco Javier Galindo was born in Melilla, Spain, in 1963. He entered the Naval Academy in 1982, becoming Lieutenant Junior Grade on July 16th 1987. As a naval officer, he has served aboard the frigate *Numancia* as Weapon Officer. He has held the rank of Commander since July 2007.

After studying the Course of Advanced Studies and the Master in Astronomy, Geodesy, and Geophysics at the Royal Institute and Observatory of the Navy (ROA), he received his Diploma degree in physics from the Complutense University in 1993, and his Ph.D. degree in Physical Sciences from the University of Cadiz in 2004. He joined the ROA Time Department in July 1995 as head of the Time Service. Since then, he has been always involved in time and frequency metrology, focused mainly on the operation of atomic clocks and the realization and maintenance of the Spanish timescales, but also on the time comparison techniques.

Since February 2002, Dr. Galindo has been the responsible person for the metrological area of time and frequency of the Spanish Defense Ministry. He is also a member of the sub-group of the CCTF Working Group on International Atomic Time: Algorithms.

Thorsten Feldmann was born in Duisburg, Germany, in 1977. He received his diploma degree in physics from the University Duisburg-Essen in 2005. Since 2007, he has been a Ph.D. student in the time and frequency dissemination working group at the Physikalisch-Technische Bundesanstalt (PTB), where he is engaged in the construction of a highly precise mobile frequency reference, based on a passive hydrogen maser, that can be compared to PTB´s primary frequency standards using the GPS carrier-phase technology. Especially, he is interested in improvements of GNSS software packages as well as hardware solutions.

Andreas Bauch was born in Wiesbaden, Germany, on January 17, 1957. He received his Diploma degree in Physics and his Dr.Rer.Nat. degree in 1982 and 1986, respectively, both from Johannes-Gutenberg Universität, Mainz, Germany. He joined the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany, as a Ph.D. student in 1983, being initially engaged in studies on frequency shifting effects in cesium atomic clocks. Since then, he has always been involved in time and frequency metrology, focused at first on the development and operation of atomic clocks, later more and more on time comparison techniques (GPS CV, TWSTFT). He became the responsible for PTB' s Time Unit Laboratory in 1991.Today, he is Head of PTB's Time Dissemination Working Group, and as such is the management responsible for the operation of PTB's time dissemination services. He has served as delegate to the Comité Consultatif du Temps et Fréquences (CCTF), to Study Group 7 of the International Telecommunication Union. Since June 2009, he has chaired the EURAMET Technical Committee for Time and Frequency. He has authored and co-authored more than 90 papers in refereed journals and conference proceedings. He has been strongly involved in the development of the timing system of the European satellite navigation system Galileo.



Dirk Piester was born in Salzgitter, Germany, in 1969. He received his Diploma degree in physics and Dr.-Ing. degree from the Technical University Braunschweig in 1999 and 2002, respectively. In A. Schlachetzki's group his work was focused on the design and characterization of semiconductor nanostructures for novel laser applications. Before he began his study of physics, he worked as a technician for electronics at the Siemens AG.

Since 2002, he has been with the time dissemination group of the Physikalisch-Technische Bundesanstalt (PTB) where he is in charge of PTB's time dissemination services, among them, the low-frequency transmitter DCF77. His main research interest is the comparison of remote atomic clocks and time scales. He presently focuses on improvements of time and frequency transfer technologies and calibration techniques via telecommunication and navigation satellites. In 2007, he joined the National Institute of Information and Communications Technology (NICT) in Tokyo, where he worked for two months as a postdoctoral fellow of the Japan Society for the Promotion of Science (JSPS).

Dr. Piester has served on the Scientific Committee of the European Frequency and Time Forum (EFTF) since 2006 and as Vice-Chair for the Consultive Committee for Time and Frequency (CCTF) Working Group on Two-Way Satellite Time and Frequency Transfer (TWSTFT) since 2007. He is a member of the Deutsche Physikalische Gesellschaft and the German Alumni Association JSPS-Club.