GPS CARRIER-PHASE TIME AND FREQUENCY TRANSFER WITH DIFFERENT VERSIONS OF PRECISE POINT POSITIONING SOFTWARE

T. Feldmann, D. Piester, A. Bauch
Physikalisch-Technische Bundesanstalt (PTB)
Braunschweig, Germany
E-mail: ***thorsten.feldmann@ptb.de***

T. Gotoh
National Institute of Information and Communications Technology (NICT)
Tokyo, Japan

Abstract

The GPS carrier-phase technique (GPSCP) allows one to compare the frequencies of remote clocks with similar accuracy as with two-way satellite time and frequency transfer. Thus, GPSCP enables a relatively cheap and easy method to compare a remote frequency source at any site with the primary frequency standards at PTB. For this reason, a Dicom GTR50 time and frequency transfer receiver has been combined with a transportable passive hydrogen maser. This mobile unit can be placed at institutes or companies that are interested in a highly accurate frequency link to PTB.

In this contribution, we focus on the software aspects, because the accuracy of GPSCP time and frequency transfer depends both on the performance of the receivers and the quality of the used precise point positioning (PPP) software. We use the NRCan-PPP software and the Concerto software package developed at NICT, which are based on different numerical models. These two packages were chosen because they allow processing of longer data than provided in one daily measurement data file.

Even in case of a quasi-zero-baseline and common-clock configuration, the solutions of the both software concepts for comparison of two receivers show sometimes small divergences. Thus, this is definitely induced by the software due to the different filter and processing methods. In the case of clock comparisons, the solutions can differ from each other up to 1 nanosecond in 1 day, depending on the starting point and the length of the processed epoch. We demonstrate that processing over long epochs strongly reduces this error. Therefore, we propose the new approach of continuous processing without resetting the ambiguities every 24 h as the best way to obtain proper results. With the Concerto software, the process can continue without limitation.

Finally, we show that using GPSCP frequencies can be compared with an uncertainty of 10^{-15} ***at averaging times of*** 10^4 ***seconds.***

INTRODUCTION

GPS carrier-phase time and frequency transfer (GPSCP) with the precise point positioning method (PPP) requires that the phase measurement data from the receivers are combined with precise information about the satellites ephemeredes and clocks provided by the International GNSS Service (IGS) **[1]**. Frequency comparisons with similar accuracy, as with two-way satellite frequency time transfer, are possible, if the receivers used are appropriate for this task. Unfortunately, the initial phase is unknown and has to be estimated by a code analysis.

As processing software we use the NRCan-PPP software and the Concerto software package developed at NICT, which are based on different numerical models. Even in case of a quasi-zero-baseline and common-clock configuration, the solutions of the both software concepts for comparison of two receivers sometimes show small divergences. Thus, this is definitely induced by the software and we can consider it as a first estimation of the limitations on accuracy in GPSCP frequency transfer.

Almost all comparisons described in this paper have been done with Dicom GTR50 time and frequency transfer receivers. The receiver is based on the Javad GGD 112-T board. As illustrated in Figure 1, the internal oscillator is synchronized to GPS time and the 1 PPS GPS signal is compared to an external 1 PPS clock signal with a time-interval counter card. The GPS measurement data and the time difference data are finally combined by the receiver software.

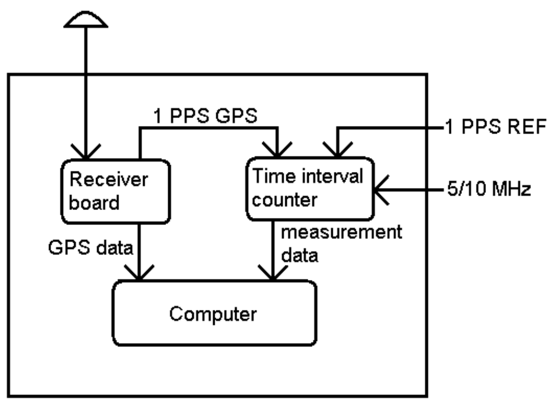

Figure 1. The Dicom GTR50 receiver and its mode of operation.

In this setup, the precision of the results is limited by the performance of the time-interval counter whose phase noise level is about 50 ps, as indicated in the specifications. Both receiver board and time-interval counter are located in a closed box together with a thermal element that stabilizes the temperature at 45°C ± 0.1°C. Thus, the performance of the GTR50 is always stable in environments with temperature from 0°C to 50°C (specifications).

SOFTWARE

In this study, we use two different software concepts, the NRCan-PPP software **[2]** and the Concerto software package developed at NICT (NICT C4) **[3]**. The NRCan-PPP software was originally designed for geodetic needs. Therefore, it uses a Kalman filter, because this is the way to enable dynamic processing (receiver antenna in motion). The NICT C4 software is specially constructed for time and frequency transfer and uses a simpler least-squares estimation algorithm.

Both software concepts enable processing without resetting the ambiguity every time a new file with measurement date is used as input. This means that daily phase jumps, causing the so-called day boundary problem, do not necessarily occur **[4]**. In NRCan-PPP, the phase jumps are removed by adopting the final normal equation of the Kalman filter of the previous day to the actual processed day. The C4 software uses the ambiguity stacking method in an iterative process.

The solution of the NRCan-PPP shows transient oscillations in the beginning due to the Kalman filter. For this reason, there is also the option of using a backward smoothed solution.

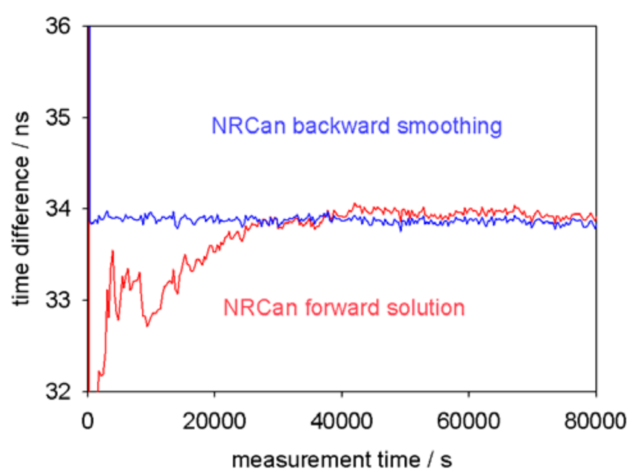

Figure 2. One-day comparison of two GTR50 receivers in common-clock quasi-zero-baseline setup with NRCan-PPP. The forward solution shows transient oscillations due to the Kalman filter.

As shown in Figure 2, the forward solution and the backward smoothing do not converge until half a day. Because of that, the forward solution is just useful if the processing time is longer than 1 day and the first days can be neglected.

COMMON-CLOCK QUASI- ZERO-BASELINE EXPERIMENTS

In Figure 3, the relative frequency instability of the comparison of two receivers in a common-clock quasi-zero-baseline setup (the antenna positions differ only by a few meters) is shown.

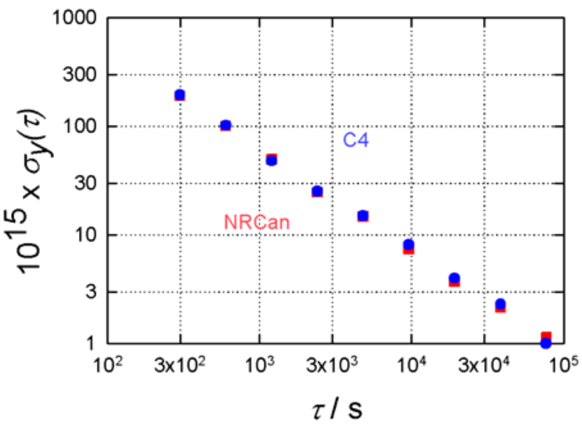

Figure 3. Relative frequency instability of comparison of two receivers obtained with NICT C4 (blue dots) and NRCan-PPP (red squares) results.

Because the 30-second measurement data are taken from a longer period ranging from MJD 54713 to 54732 and the first day is neglected, the NRCan-PPP backward and forward solution gives exactly the same result and can, thus, not be discriminated in Figure 3. Interpolations for IGS clock products have not been used and we have a processing result every 5 minutes. From the Allan deviation comparison between the NRCan-PPP and the C4 solution, it is not determinable which software concept is better and should be preferred. For this reason, further examinations are needed. But the results demonstrate that it is possible to compare frequencies with an uncertainty level of 10^{-15} at an averaging time of about 1 day with both software concepts and GTR50 receivers.

The solution provided by the two software concepts show sometimes a small divergence. In Figure 4, a cutout from a longer data batch is plotted. This divergence is typical; a difference larger than 400 ps has not been observed in different proper data records from different receivers. Normally, this divergence will increase after 3 months of continuous processing, because then the result of the NRCan-PPP software start diverging noticeably, as specified by the developer. Unfortunately, there are not yet such long data records with continuous phase measurements and without any gap available. If there is one small gap in the data, both software concepts restart the processing, reset the ambiguities, and the Kalman filter in NRCan-PPP produces again the transient solutions.

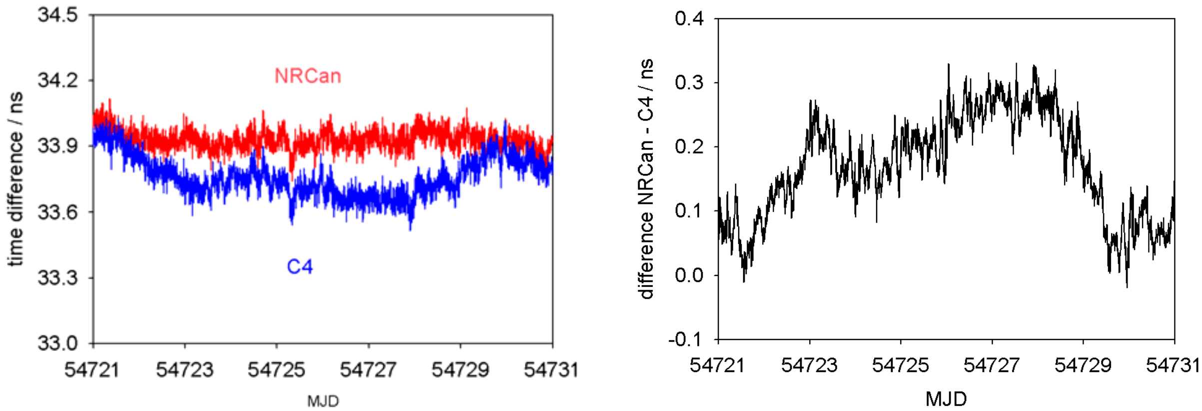

Figure 4. Cutout from a longer period with a typical divergence between C4 and NRCan-PPP common-clock zero-baseline solution.

In a zero- and quasi-zero-baseline setup, the maximum difference (~ 0.3 ns) between the two solutions is induced by the different numerical methods used to solve the observation equations. This conclusion is, of course, only valid in case of a longer data batch without gaps and in a zero-baseline setup. The difference between the two software solutions can, thus, also be used to locate defects in measurement data by noting if the difference grows up significantly.

CLOCK COMPARISON, DISCONTINUOUS MEASUREMENT DATA AND PHASE DRIFT

If clocks are compared with GPSCP over long baselines effects induced by troposphere and ionosphere make an impact (Figure 5).

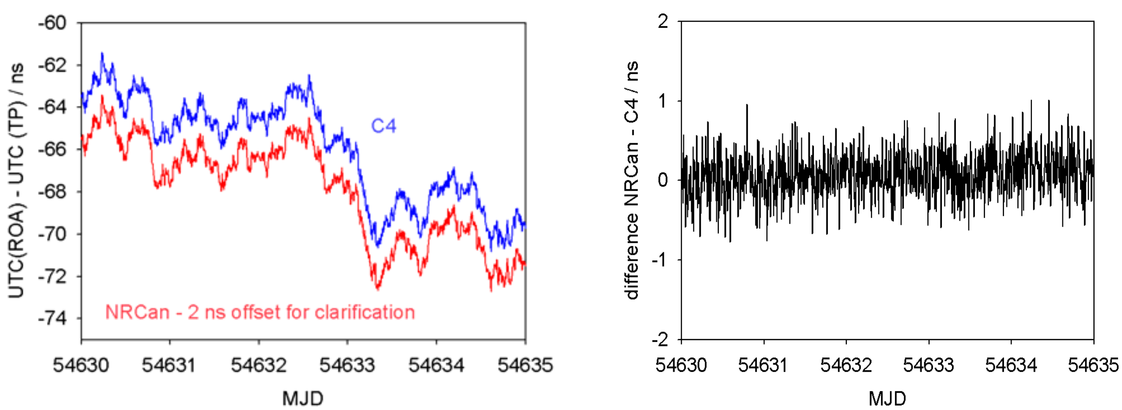

Figure 5. Takeout from a longer GPSCP measurement ranging from MJD 54584 to 54648 between ROA and UFE. The results are on a 5 min basis. These data are by courtesy of ROA and UFE.

To find the software properties in this case, we have compared the timescales UTC (ROA) and UTC (TP) (TP denotes Tempus Pragense) of the Spanish Royal Navy Observatory (ROA) and the Czech Institute of Photonics and Electronics (UFE), respectively. On both sites, GTR50s are connected to the local realizations of UTC derived from commercial cesium clocks. The standard deviation of the differences between NRCan-PPP and C4 results is 0.275 ns.

Above we have used the forward solution of the NRCan-PPP software. We have observed an additional error when we have made tests with the backward smoothing solutions. Depending on the starting point, the results can diverge from each other. In Figure 6, a Septentrio PolaRx receiver was compared to a GTR50 in a common-clock experiment.

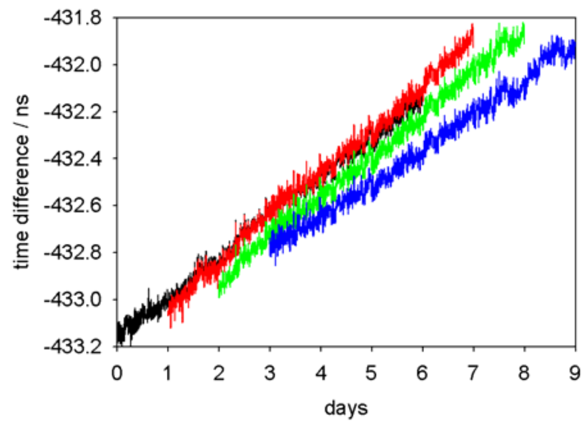

Figure 6. The NRCan-PPP backward 6-day smoothed solutions starting 1 day displaced from each. Outliers have been removed

The clock signals were provided by different pulse and frequency amplifiers and the cables were a few tens of meters long. So an erroneous drift might have been apparently induced, but the figure shows impressively that the slope of the solutions depends on the starting point. It is not determinable which solution represents the real slope for a given day. Comparing the red and blue plotted data for the days 3 to 7, the relative frequency differences differ from 1.6×10^{-15} for the blue data and 1×10^{-15} in 4 days for the red ones.

Until now we have used continuous measurement data; that means we have a code and phase measurement from both receivers every 30 seconds over the complete processed period. Gaps in the measurement data make for disrupting the processing and the ambiguities are reset. It is a well-known fact that this causes phase jumps of up to 1 ns in the results **[4]**. Furthermore, it is an interesting question how the different numerical concepts are responsive to corrupted measurement data.

To find this out, we have processed a 25-day data batch from a common-clock experiment with two GTR50s. Due to experiments with the receivers and the receiver software, the measurement was interrupted every 2 hours on average during the first 7 days.

As expected, the NRCan-PPP Kalman filter has to engage very often and this makes the solution very noisy. Surprisingly, the Kalman filter does not engage correctly in the period with continuous measurement data and produces an oscillation on a larger scale. In the backward smoothed solution, the noise is carried forward to the time interval with continuous measurement. However, if the starting point is located in the time interval with good measurement data, it equals the C4 solution up to 300 ps (Figure 4). In contradiction, the C4 software is much more resistant against corrupted measurement data.

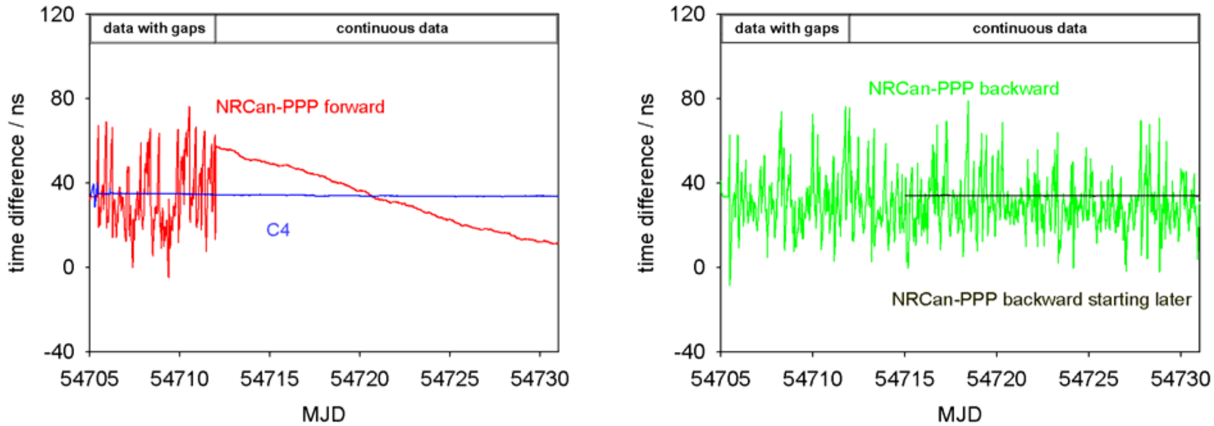

Figure 7. A 25-day data batch with corrupted measurements in the first 7 days processed with C4 and the two NRCan-PPP options.

As a result of the examinations shown in Figure 5, 6 and 7, we propose for processing over time intervals as long as possible with C4 software if GPSCP will be used for time transfer. The NRCan-PPP forward solution can thereby additionally be used to identify gaps in the measurement data by taking the difference to the C4 result.

PROJECT: HIGHLY PRECISE MOBILE FREQUENCY REFERENCE

Due to the temperature-stabilized measurement unit inside the GTR50, it is a well-suited receiver for mobile applications, because it works reliably under unknown environmental conditions. The core of the highly precise mobile frequency reference is a passive hydrogen maser in a special mount that protects it against mechanical shocks.

The first test with this device has been done at the Institute of Quantum Optics (IQO) of the Leibniz-University in Hannover (Figure 8). The GPS receiver is placed on top of the passive H-maser (Vremya VCH-1006) mounted together with a computer that monitors the operational parameters of the H-maser. Additional devices like the uninterruptible power supply unit (UPS) and direct current power supply (DCPS) are visible in the picture. The receiver can be controlled via Internet from PTB. Outdoor installation only consists of the small and easy to install NovAtel GPS 702 antenna.

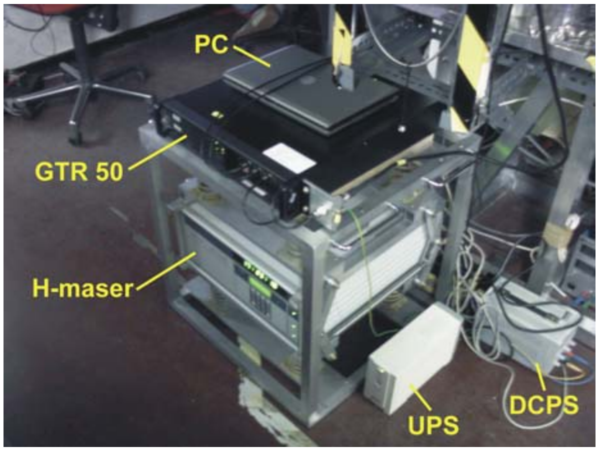

Figure 8. The mobile frequency reference at the Institute for Quantum Optics of Leibniz University, Hannover.

It is planned to transmit a frequency via an optical fiber from PTB to this institute **[5]**, so that the passive maser can be compared to an active maser in PTB with GPSCP as well as with the optical fiber to verify the GPS results. The distance between PTB and IQO is about 60 km.

The relative frequency instability plot (Figure 9) demonstrates that the passive maser can be compared to the primary frequency standards in PTB at averaging times larger than 10^4 seconds.

The GPS measurements where processed with NICT C4 software. Up to 10^4 seconds averaging time, the results are in agreement with those obtained for quasi-zero-baseline, shown in Figure 3. The local measurements at PTB where done with a high-resolution frequency comparator.

More experiments with institutes that are farther away from PTB are planned to see if there is a significant influence of the ionosphere and troposphere. Furthermore, it is interesting to do these tests with institutes that are equipped with two-way satellite time and frequency transfer devices to enable fundamental studies on absolute calibration of GPSCP.

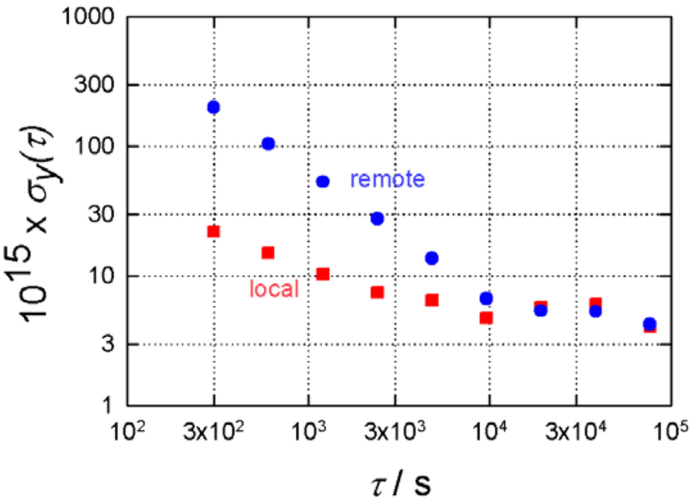

Figure 9. Relative frequency instability of comparison of the mobile maser to an active maser in PTB (red squares) and with GPSCP between PTB and Hannover.

OUTLOOK

We have demonstrated that frequency comparison using two GTR50s and C4 or NRCan-PPP software is possible with an uncertainty level of 10^{-15} at an averaging time of 10^5 seconds. As mentioned above, this receiver uses a time-interval counter (Figure 1), which is the limiting factor. To show that GPSCP has the capability to provide results better by about one order of magnitude, two geodetic receivers (Javad Legacy) based on another mode of operation were compared in a common-clock zero-baseline experiment, utilizing an antenna splitter.

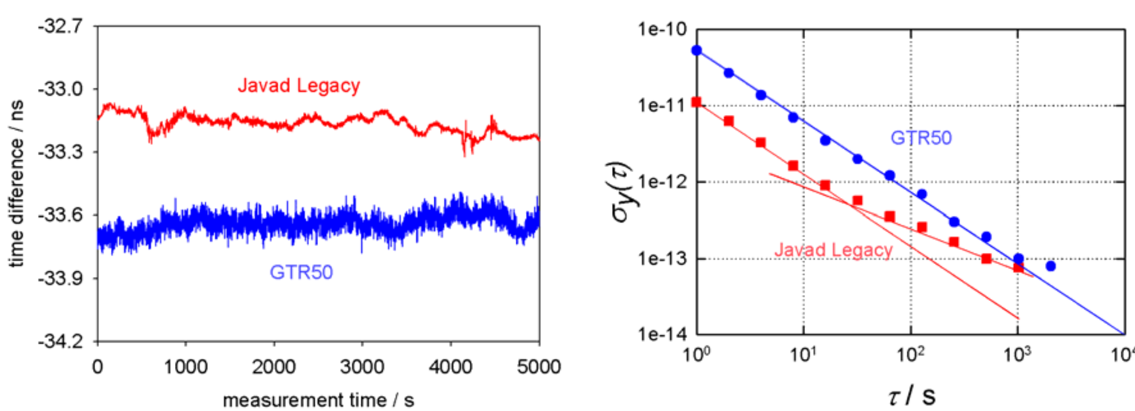

Figure 10. Zero-baseline common-clock experiment with two Javad Legacy receivers and two GTR50. The offset of the Javad Legacy phase data is arbitrarily chosen. This Javad Legacy data were provided by the Institute of Geodesy (IFE) of Leibniz University, Hannover.

Here, we used second-by-second measurement data and the NRCan-PPP backward-smoothed solution (having made sure that the measurements are not corrupted). The Javad Legacy receiver is designed for geodetic usage and not for time and frequency transfer. For this reason, there is no connection for a 1 PPS signal and no possibility for calibration. Instead of using a time-interval counter card, the internal GPS oscillator can be locked to an external 10-MHz frequency. At an averaging time of 10 seconds, the result is dominated by white phase noise, similar to the GTR50 result, but about one order of magnitude less noisy. Then the receiver performance is dominated by random walk noise, probably due to the slow interconnection of external frequency and internal crystal oscillator. Moreover, the Javad Legacy is not temperature-stabilized as is the GTR50.

From this result, we assume that it is possible to achieve an uncertainty level of 10^{-15} in 10^4 seconds, if it is possible to build a receiver that operates as stably as the GTR50, but without the 1 PPS measurement limitation. We propose a configuration in which a receiver uses a high-resolution frequency comparator in combination with a time-interval counter. Thus, the performance of the counter will no longer limit the GPS results, but delay calibration would remain possible.

We also demonstrated that time transfer using GPSCP is possible with an accuracy of about 300 ps, if long continuous measurement data batches are used. Unfortunately, sometimes it is unavoidable to interrupt a measurement, for example if the receiver software is updated. Hence, a new preprocessing algorithm to interpolate gaps in the phase measurement data is needed. Then both C4 and NRCan-PPP software can be considered as equivalent.

Further detailed comparisons including other parameters like positions and zenith troposphere delays for each solution and examinations concerning the influence of the physical corrections (satellite orbit, earth rotation model, earth displacement, ocean loading) are in progress. In this work, we have neglected this matter, because, except in the comparison of UTC (TP) and UTC (ROA), we basically studied effects on a quasi-zero baseline, a zero-baseline, and a short baseline.

ACKNOWLEDGMENTS

We would like to thank H. Esteban from ROA, P. Panek from UFE, and U. Weinbach from IFE for allowing us to use their measurement data. Special thanks go to P. Panek and A. Kuna from UFE for collaboration in case of initial problems with the GTR50s and for continuously updating the firmware.

DISCLAIMER

The institutes involved do not endorse any commercial product identified in the text for the purpose of scientific clarity nor do they permit any use of this document for marketing or advertisement.

REFERENCES

[1] K. Larson and J. Levine, 1998, *"Time Transfer using the Phase of the GPS Carrier,"* **IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control**, **UFFC-45,** 539-540.

[2] J. Kouba and P. Héroux, 2001, "*Precise Point Positioning using IGS Orbit and Clock Products,*" **GPS Solutions, 5** (2), 12-28.

[3] T. Gotoh, M. Fujieda, and J. Amagai, 2007, *"Comparison study of GPS carrier phase and two-way satellite time and frequency transfer,"* in Proceedings of TimeNav'07, the 2007 IEEE International Frequency Control Symposium Joint with the 21st European Frequency and Time Forum, 29 May-1 June 2007, Geneva, Switzerland (IEEE Publication 07CH37839), pp.1188-1193.

[4] R. Dach, U.Hugentobler, T. Schildknecht, L.-G. Bernier, and G. Dudle, 2005, "*Precise continuous time and frequency transfer using GPS carrier phase,"* in Proceedings of the 2005 IEEE International Frequency and Control Symposium and Exposition, 29-31 August 2005, Vancouver, Canada (IEEE Publication 05CH37664), pp. 329-336

[5] G. Grosche, B. Lipphardt, H. Schnatz, G. Santarelli, P. Lemonde, S. Bize, M. Lours, F. Narbonneau, A. Clairon, O. Lopez, A. Amy-Klein, and C. Chardonnet, 2007, "*Transmission of an Optical Carrier Frequency over a Telecommunication Fiber Link,"* in Proceedings of the Conference on Lasers and Electro-Optics, 6-11 May 2007, Baltimore, Maryland, USA (IEEE Publication), pp. 1-2.