GPS carrier phase and precise point positioning time scale comparisons using different software packages

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Abstract—**Precise point positioning (PPP) software combines dual frequency code and phase GPS observation data with precise information about the satellite clocks and orbits provided by the International GNSS Service (IGS). It is also a very interesting method for time metrology. Error sources like tropospherical path delay and site displacements have to be modeled or estimated, while the error induced by the first order ionosphere terms can be canceled due to the usage of both GPS frequencies. In case of long baselines the atmospherical effects dominate. Here the physical correction models become important.**

In this work we compare several precise point positioning (PPP) software packages and study not only the clock solution but also other estimated parameters like positions and zenith tropospheric zenith path delays in order to find the software that is most suitable for time transfer. Especially the repeatability of the position could be a good indicator for quality. We use Dicom GTR50 time and frequency transfer receivers connected to local time scale realizations on baselines with different lengths.

I. Introduction

Using the Global Positioning System (GPS) for international time scale comparisons is a well-established method. It is possible not only to use the code broadcasted by the satellites, but also to track the carrier phase (GPSCP) of both frequencies L1 = 1575,42 MHz and L2 = 1227,6 MHz [1]. Thus it becomes possible to compare frequencies with similar accuracy as with two-way satellite time and frequency transfer (TWSTFT) [2].

The concept of precise point positioning (PPP) was originally developed for geodetic needs in order to estimate a position at the centimetre level. Generally speaking, PPP is an all-in-view process. That means, that an individual solution is calculated for each station separately using all visible satellites. This way the receiver clock offset is related to a paper time scale, the IGS time, which is calculated using precise information about the satellite clock offsets and the satellite positions. The GPS observation equations [1] for code and phase

$$\begin{aligned} \ell_P &= \rho + c(dT - dt) + \varepsilon_P \\ \ell_\phi &= \rho + c(dt - dT) + \varepsilon_\phi + \lambda N \\ &\text{with } \rho = \sqrt{(X-x)^2 + (Y-y)^2 + (Z-z)^2} \end{aligned} \quad (1)$$

have to be solved for the position (x, y, z) and the receiver clock offset dt and the unknown phase ambiguity N. The Satellite position (X, Y, Z) and the satellite clock offsets dT are taken from the IGS data [3]. The error contributions $\varepsilon_{P,\phi}$ arise from atmospherical and environmental effects. The ionospheric signal path delay depends on the frequency. Thus it can be cancelled in first order by using the ionosphere-free linear combination of the L1 and L2 frequencies,

$$\ell_P = 2.546\, P_1 + 1.546\, P_2 \text{ and } \ell_\phi = 2.546\, \lambda_1\phi_1 - 1.546\, \lambda_2\phi_2, \quad (2)$$

where P_1 and P_2 are the code based pseudorange measurements on L1 and L2 in metres and ϕ_1 and ϕ_2 are the carrier phase measurements in cycles of the carrier wave. In contrast, the effect due to the troposphere has to be modelled or estimated. For highest accuracy estimation of troposphere parameters is a must. Site displacements can be modelled, for example, coefficients for a correction of the ocean loading can be included in the solution.

In zero and short baseline setups the errors are similar for all receivers. Remaining differences between the solutions of different software packages are probably caused by slightly different data screening and the estimation algorithm [4]. In a long baseline setup external effects dominate, especially the tropospheric delays.

In this analysis, we want to find the software package that is most suitable for time transfer, in order to perform carrier

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phase time transfer as an independent method to TWSTFT and to study its performance with respect to future applications, like comparisons of fountain clocks and optical frequency standards. Due to the noise of the clocks connected to the receivers, this performance can not be tested only by the time transfer results. Therefore, we also compare the position estimates and the estimates for the troposphere zenith path delay. These parameters are directly related to the clock solution by the observation equations (1). Especially the repeatability of the position estimates shows if the algorithm works stable.

II. SOFTWARE AND EXPERIMENTAL SETUP

For our analysis we have used data of three Dicom GTR50 time and frequency receivers at PTB, NICT and ROA. The 1 PPS inputs of these receivers have been connected to the local UTC realizations (Table 1). The initial position is the position that is known before the analysis and stored in the receivers.

TABLE 1. Initial positions of the stations and timescale input

Station	***Initial position***	***1 PPS input***
PTB	+3844056.75 m +709664.09 m +5023131.73 m	UTC(PTB): Steered primary standard CS2
NICT	-3942087.86 m +3368252.55 m +3702001.32 m	UTC(NICT): Active H-Maser steered by clock ensemble
ROA	+5105511.68 m -555187.02 m +3769791.71 m	UTC(ROA): Steered Cs 5071 A

We used five different software packages along with IGS final orbits and clocks and ocean loading coefficient from the GOT002 model [5]. The packages require different input data. For instance, the NRCan-PPP software uses Chebychev Polynomials for the interpolation of the satellite orbits [13]. This interpolation method is more stable around the boundary points than others, so that only the IGS orbit file of the processed day (pd) is needed.

TABLE 2. Available software packages

Software	***Algorithm***	***File input***
Atomium [6] (PPP mode)	Least square estimation	pd RINEX , -1d, pd, +1d orbit, clock and earth rotation IGS data
NRCan PPP[7] (static mode)	Kalman-Filter	pd RINEX, pd clock and orbit, no earth rotation
GIPSY 5.0 [8]	Kalman-Filter	pd RINEX, -1d, pd, +1d orbit, clock and earth rotation
Bernese GPS Software 5.0 [9]	Least square estimation	pd RINEX, -1d, pd, +1d orbit, clock and earth rotation
NICT C4 [2]	Least square estimation	-6h, pd, +6h RINEX, -1d, pd, +1d orbit and clock, -2d, -1d, pd, +1d, +2d earth rotation

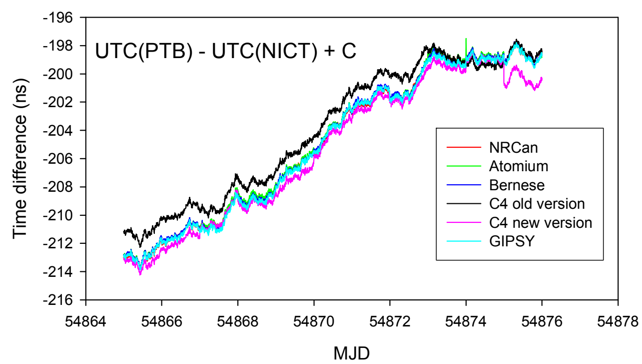
Furthermore the data are processed directly in the earth centered, earth fixed coordinate system (ECEF), so that there is no need for earth rotation parameters.

The C4 software uses an overlapping process, so that also RINEX data of 6 hours of the day before (-6h) and 6 hours of the day after (+6h) the processed day are needed. This software is currently available in two versions: An older version with some bugs related to outlier rejection and correlation avoidance between parameters, and a new optimized version, but C4 is still in an experimental status.

For timing applications the NRCan software and the C4 software have a special relevance, because they allow for processing of longer periods than one day without the day boundary phase jumps, that occur if every daily solution is processed independently. For reasons of comparability, we did not use this features for this analysis.

III. TIME SCALE COMPARISON

We have made two time scale comparisons, one for the intercontinental baseline PTB-NICT (8333 km) and the other for the European baseline PTB-ROA (2182 km) with all available software packages. To avoid inconsistencies due to data gaps and receiver problems, we have selected a period for data computation where all three receivers were operating normally.



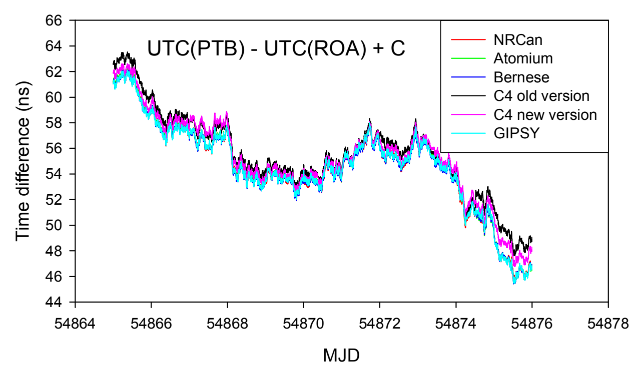


Figure 1. Time scale comparison: The GTR50 receivers were not calibrated. C denotes an additional calibration constant that depends on the cable delays. One outlier at the beginning of MJD 54870, induced by the IGS products and present in all solutions, has been removed

We see a maximum divergence of about 2 ns between any of the solutions. In this picture we can hardly distinguish between the packages of the NRCan, Atomium, Bernese and GIPSY software. The high divergence of the C4 old version solution gives a first indication that it has some shortcoming.

To cancel the clock noise, we decided to use the NRCan solution as common reference and compare all other solutions to it.

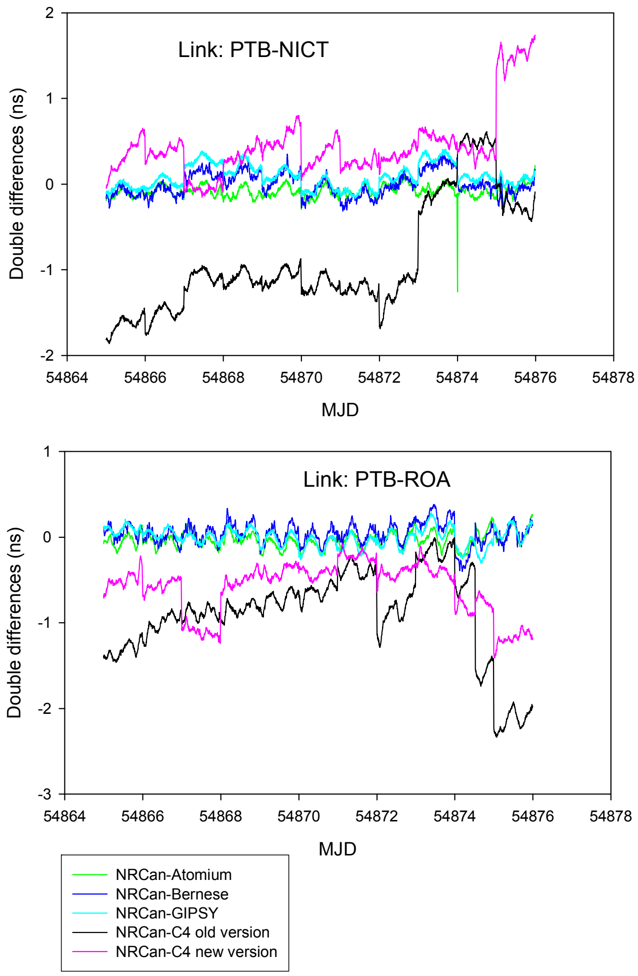


Figure 2. Double differences NRCan-other software solutions

We see a good agreement of Atomium, Bernese and GIPSY solution with NRCan of less than +/-350 ps The ambiguitiy solutions are similar in this four packages, in consequence no significant jumps occur.

The C4 old version solution shows mostly an agreement of about 2 ns with NRCan and the C4 new version of about 1 ns. Clearly, the ambiguities are solved differently.

Besides the evaluation of the agreement of the GPS solutions with each other, the study of systematic deviations with respect to other techniques or a available ground truth is important. However, TWSTFT is not very helpful for this purpose, because of the noise of the TWSTFT observations we do not get more information than from Figure 1, as shown in Figure 3 exemplarily for the link PTB-ROA.

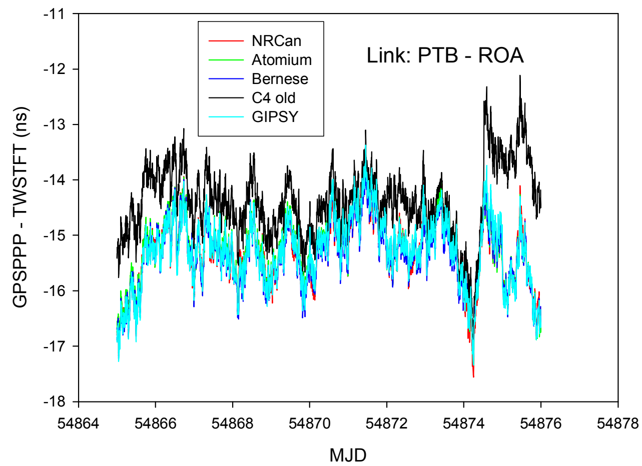


Figure 3. Comparison of GPS PPP with TWSTFT, exemplarily for the link PTB-ROA. Here only the C4 old version solution is plotted.

IV. Position Estimates

Another way to assess the reliability of the PPP clock solution is the comparison of the position estimates, because position and clock offset have to be solved simultaneously. A good indicator for the quality of the software is the repeatability of the position estimates, because the positions are fixed and no significant movement happens within 10 days.

To separate effects related to the vertical and the horizontal position, the position estimates have to be known in an ellipsoidal coordinate system. Unfortunately some packages output the results only in Cartesian coordinates. To compare all software on the same level, all coordinates have to be converted afterwards.

Due to the fact, that the earth is not a perfect sphere, the transformation from (x, y, z) to ellipsoidal coordinates (h, λ, φ), where the altitude h is orthogonal to the surface of the earth ellipsoid, is given by [10]

$$
\begin{aligned}
&\tan\varphi = z/\sqrt{x^2+y^2}\left(1-e^2\frac{N}{N+h}\right)^{-1}\\
&\tan\lambda = y/x\\
&h = \sqrt{x^2+y^2}/\cos\varphi - N\\
&\text{with} \qquad (3)\\
&h:\text{altitude},\ \lambda:\text{longitude},\ \varphi:\text{latitude}\\
&N = a/\sqrt{1-e^2\sin^2\varphi}\\
&a:\text{semimajor axis},\ e:\text{eccentricity}
\end{aligned}
$$

This formula has to be solved by iteration, because latitude and height are not independent from each other. This is the correct point of view in the context of geodesy, but in the framework of this study we use an easier coordinate system.

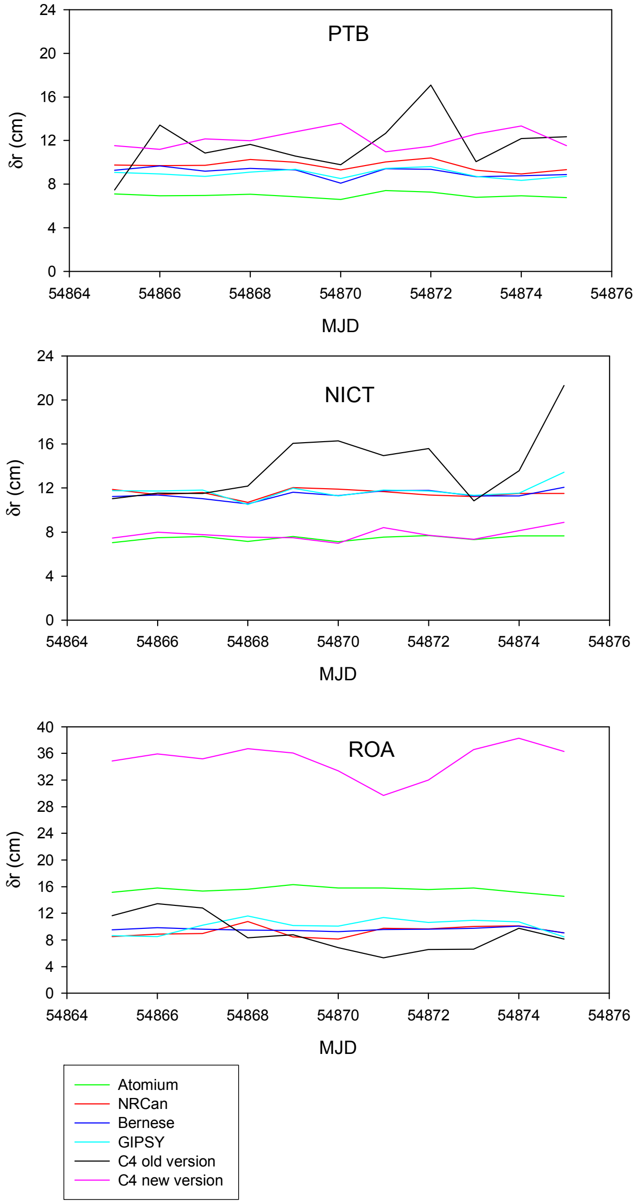


Figure 4. Divergence of the estimated position with respect to the initial position. The output of all packages is a daily position estimate

We use the conversion to spherical coordinates

$$r = \sqrt{x^2 + y^2 + z^2}\,,\ \tan\lambda = y/x,\ \tan\phi = z/\sqrt{x^2 + y^2}\,, \qquad (4)$$

where the radius r is nearly orthogonal to the orbit of a satellite that crosses the zenith. ϕ represents the geocentric latitude and is related to the geodetic latitude by

$$\tan\phi = \{1 - e^2[N/(N+h)]\}\tan\varphi. \qquad (5)$$

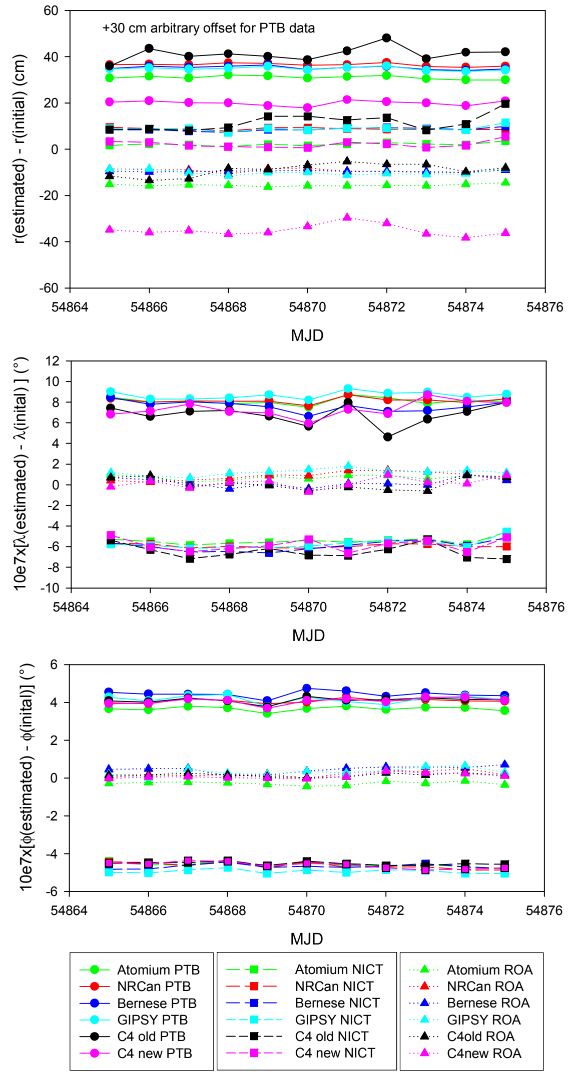


Figure 5. Divergence of the estimated position with respect to the initial position in geocentric coordinates. Dots represents the result for the station PTB, squares for NICT, triangles for ROA. 10e-7° equals 1.1 cm

In this coordinates each of the three components is independent from each other.

For visualization and simplification, we calculate the differences of the estimated values with respect to the initial position.

In a first step (Fig. 4), we calculate the distance between the estimated position vector and the initial position vector:

$$\delta r = \left|\vec{r}(\text{estimated}) - \vec{r}(\text{inital})\right|. \qquad (6)$$

If the initial positions would be known to be true, it would be an estimation for the absolute positioning error of the software. Unfortunately the 3 GTR50s are not IGS stations, so that the initial positions cannot be taken from the IGS data, and the positions might have changed over the years. Since in reality we do not know the true position, the expression can just serve as a relative error estimation, i.e. it can show if a software gives repeatable results.

The position estimates for the C4 old version software show a very unstable characteristic for all the 3 stations (Fig. 4). This affects the clock offset in a similar way. The NRCan, GIPSY and Bernese solutions are in close agreement. Thus we can assume that the initial positions have drifted away over the years.

The Atomium and the C4 new version solution diverge from the other solutions by 1 to 2 cm, except for the station ROA the divergence goes up to 20 cm. This effect is currently not understood and should be examined separately in order to apply further improvements to the C4 software.

In order to distinguish between vertical and horizontal position errors we also computed the spherical coordinates of the three stations (Fig. 5). Most of the position variations of the solutions, especially of the C4 solutions, show up in the height estimate, while latitude and longitude differ only by 6 cm for all software packages (using an average earth radius of 6378 km, 10e-7° equals just 1.1 cm).

V. TROPOSPHERE ZENITH PATH DELAY ESTIMATES

The signal delay induced by the troposphere is in the order of more than 2 meters. It has to be modelled and estimated [10], [11] and the models depend on the coordinates of station. It is one of the most important error source for time scale comparisons over long baselines. A wrong estimation leads directly to an offset of the clock estimation. The common way to model the troposphere is to use one model for the dry part, an other one for the wet part of the troposphere zenith path delay (zpd) [12]. The estimation strategies are different in the software concepts (Table 3). The Kalman-Filter based software estimates a new value as often as a clock offset is estimated. In the Bernese solution a zpd was estimated every 30 min and in the Atomium and C4 solutions every 2 h.

TABLE 3. Zenith path delay estimation in different software concepts

Software	***zpd output***
Atomium (PPP mode)	every 2h wet part estimation, dry part extracted by Saastamoinen model
NRCan PPP	every 5 minutes, modified Hopfiel model
GIPSY 5.0	Every 5 minutes
Bernese	Every 30 minutes
NICT C4	every 2h wet part estimation, dry part extracted by Saastamoinen model from initial position

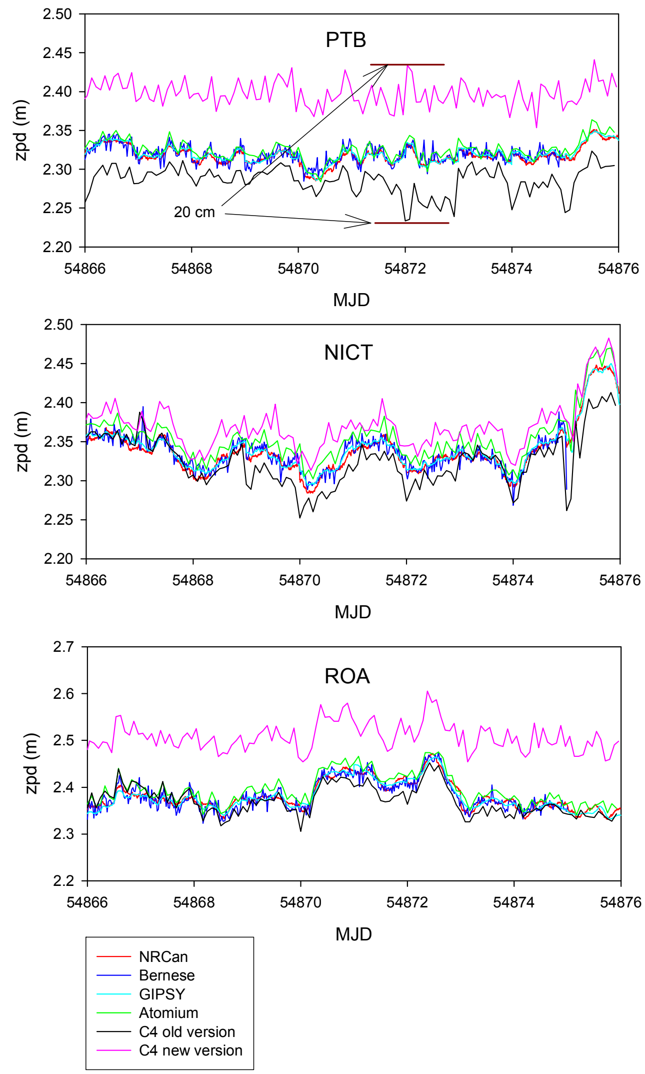


Figure 5. Zenith path delay estimates

The estimated corrections are applied to the solution algorithm by mapping functions.

Since the correct value for the zpd is unknown we just can estimate a relative uncertainty from the divergence of the different estimates, as done before for the position.

The zpd estimates are in close agreement for all stations and for all software concepts, except C4 (Figure 5). Excluding C4 the divergence between the solutions is less than 5 cm.

VI. SUMMARY AND OUTLOOK

We have compared five PPP software packages to asses their quality, using data of three identical receivers at PTB, NICT and ROA. We have shown that it is impossible to assess the quality of the PPP solution using the time transfer results alone, because it is not determinable, which solution reflects the reality best. We are just able to see a trend: The solutions of NRCan, Bernese and GIPSY show the best agreement. This leads to the conclusion, that all three software packages provide similar and repeatable results.

Since the receiver clock, the station height, and the tropospheric zenith delays are mathematically highly correlated in the GPS analysis and thus difficult to separate, it is worth to compare not only the clock solution but also to analyze the agreement of the estimated coordinates and zenith path delays. The positions of time and frequency receivers are fixed, so an ideal software should always give the same position estimates within a threshold determined by the quality of the observation data. If the initial position would be known perfectly, we would be able to select the best software.

Nevertheless, we can now definitely see, that the C4 old version software is of limitations. The highest instability contributions come from the estimation of the vertical component.

The other software packages show good agreement, except the C4 new version position estimates for the station ROA and the zpd estimates for all stations. Optimizing C4 would be desirable, because to our knowledge only the C4 software and the NRCan software have implementations to process long periods of continuous observation data without resetting the ambiguities. Using only NRCan for time transfer one should be aware that the Kalman Filter can cause problems if there are gaps in the data [4].

We can conclude that the two Kalman-Filter based software packages and the Bernese seem to output the best results for high quality data input. These three packages were originally developed and optimized for positioning, not for time transfer.

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DISCLAIMER

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