Continuous Real-Time GPS Carrier Phase Based Frequency Transfer on Medium

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We have studied a continuous real-time frequency transfer method on the SP-PTB baseline by using GPS carrier phase observations from geodetic GNSS receivers SP01 and PTBB, and post-processed two time periods in 2004 and 2007 with a continuous working filter under real-time conditions using integer phase ambiguity fixing. The results are a continuous time series of the relative time difference of the receiver clocks UTC(SP) and UTC(PTB), which was compared to results from TWSTFT between the two laboratories. We found that as long as the filter parameter modeling is well tuned and the necessary real-time orbit predictions are within a typical accuracy of a few 100 mm, the use of ambiguity resolution offers a correct estimation of the phase relations of the common phase measurements on this baseline. However, if errors in the orbit predictions are in the order of a few meters, which is generally difficult to detect in real-time, then a wrong resolution of the phase ambiguities can occur and thus create wrong phase and frequency estimates. Within the investigated time periods we have detected erroneous IGS orbit predictions in the order of 10m, which caused a wrong estimation of phase relations. The paper quantifies the quality of current IGS orbit predictions and the impact of orbit errors on the ambiguity resolution for medium baselines. Continuous real-time frequency estimations are useful for system critical oscillator monitoring as for example in real-time interferometry applications, or as input for the calculation of real-time time scales.

I. INTRODUCTION

An earlier work [1] describes the algorithm of a real-time GPS carrier phase filter for clock comparisons based on common satellite observations and floating phases. [2] extends this work with a phase ambiguity fixing algorithm that solves frequency offset problems caused by errors in the estimated baseline vector. The method works well for short baselines, for example ONSA-SP01 (68km). However, clock difference estimates for longer baselines, such as PTBB-SP01 (623km), that are important from a metrological point of view, seem to suffer from range errors caused by inaccurate orbit parameters. Robust real-time processing of GNSS data for time and frequency depends on the quality of the orbit information available in real time. The two products that are commonly available are shown in Table I.

TABLE I. TYPICAL ACCURACY OF REAL-TIME GPS ORBITS PRODUCTS.

Product	Accuracy POS	Accuracy CLK	Availability
Broadcast Ephemerides	~1.6m	~7ns	Receiver
IGS Ultra Rapid Predicted	~0.1m	~5ns	Network, 900s (0.25d)

Broadcast orbits are only usable for short baselines and are not considered here [3].

Figure 1 illustrates the advantages of the usage of integer phase ambiguities in GPS processing for time and frequency. New observations are synchronized with established ones, continuously carrying the right phase relations in the real-time process. The difference between the use of fixed and floating ambiguities can be illustrated with an analogy to classical drivetrain technology. While a float solution acts like a belt-driven transmission with slippage between the pulleys, can a fixed ambiguity solution be described with the characteristics of a locked pinion gear. In both cases the wheels represent the differenced observations, whereas the individual shaft torques are caused by modeling errors of troposphere and range. Like two engaged cog-wheels only allow backlash movement between each other does the ambiguity fixing method only allow small distortions in the modeling of range and atmosphere.

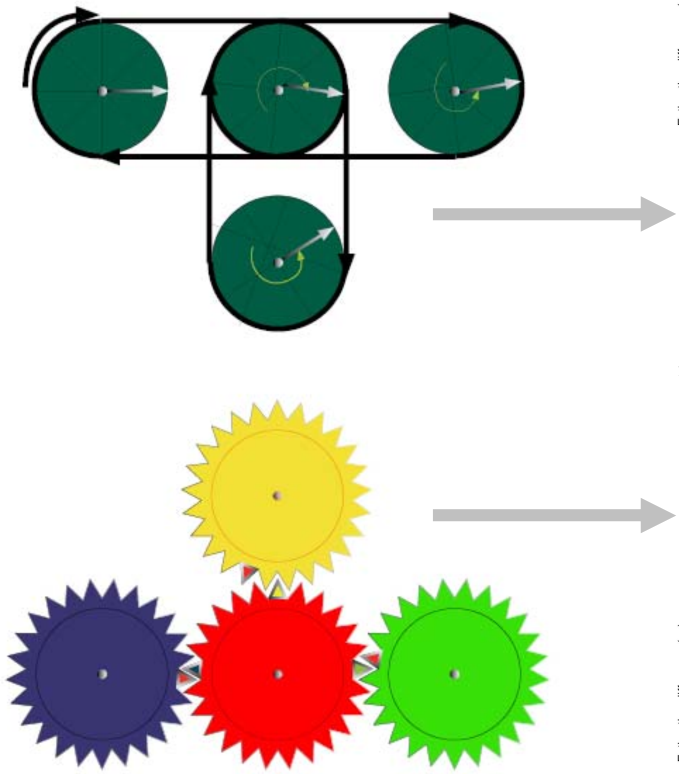

Figure 1. Analogy of carrier phase processing with classical mechanics. Float solution can be compared with belt drives depicted in the top, whereas ambiguity fixing has properties that resembels interlocking pion gears as shown in the bottom.

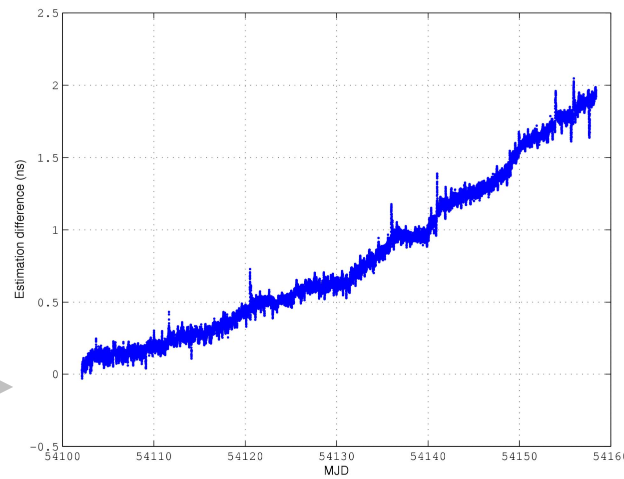

Figure 2. Difference between the reference solution and a solution based on constant float phase ambiguities for the PTBB-SP01 baseline for the first two months of 2007. The frequency offset seen in the graph is caused by an error in the assumed baseline length corresponding to about 1.6mm east component offset.

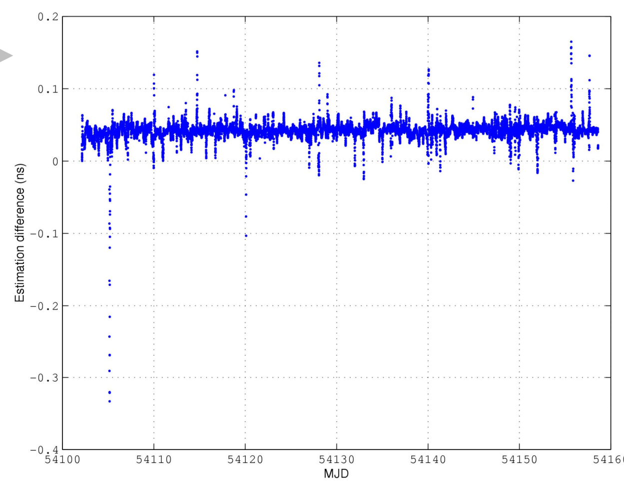

Figure 3. Difference between the reference solution and a solution based on fixed integer phase ambiguities for the PTBB-SP01 baseline for the first two months of 2007.

II. RESULTS

Figures 2 and 3 show results from the PTBB-SP01 baseline (623km) using float phase ambiguities and integer phase ambiguities, respectively, under real-time conditions. In both cases the graphs represent differences to a reference solution using fixed ambiguities and final IGS orbits. The results from the float solution confirm previous results on that baseline, which can mainly be explained by errors in the assumed baseline length. An error of 1.6mm in the east component has caused a frequency offset between the solutions of about 36ps/day (ca $4.2e^{-16}$). The solution based on fixed integer ambiguities shows as expected no frequency deviation from the solution using final orbits. This means that both runs were estimating the same integer relation between the carrier frequencies despite the different orbit information available.

A comparison of the real-time integer phase ambiguity solution with independent TWSTFT measurements can be seen in Figure 4. The graph shows an insignificant frequency offset between the methods. The size and characteristic of the residuals can be caused by variable equipment delays and environmental factors, such as temperature. These results can be seen as a proof of the technique being able to work well in real time for such baseline lengths. The dependence on the baseline orientation has not been studied here.

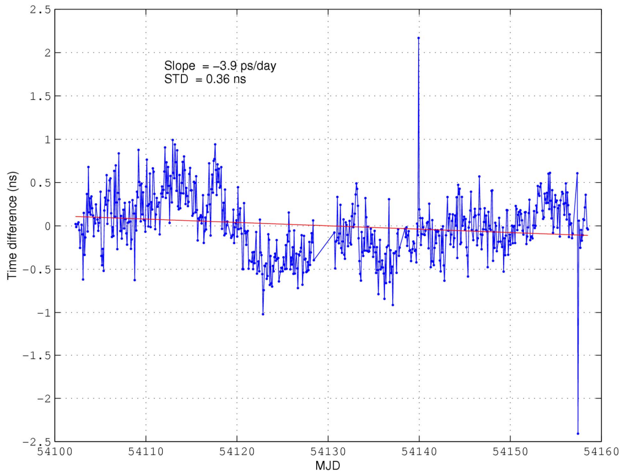

Figure 4. Difference between the real time GPS solution based on fixed integer phase ambiguities and measurements taken by TWSTFT of the PTBB-SP01 baseline for the first two months of 2007. The frequency offset seen in the graph is insignificant and variations are mainly for example due to environmental parameters such as temperature.

III. PROBLEM DISCUSSION

The few cases of orbit predictions that are outside of the typical uncertainties, which in 2007 are given by the IGS with 0.1m, cause problems during filtering. Figure 5 shows the principle of mapping orbit errors to projection errors. This mapping is dependent on the orientation of baseline and orbit error vectors. Two extreme cases can be pointed out:

- vectors that are in line (e.g. low elevation on short baselines) cause no projection error (ε1),
- vectors that are parallel in orientation but orthogonal in position (e.g. high elevation on short baselines) result in maximal errors (ε2).

The sum of projection error and the error due to atmospheric modeling restrict the possibility of finding the right integer ambiguity combination and may result in distinct clock difference offsets reflecting the choice of integers. As Table I shows are the nearest phase combinations that produce the same ionospheric residual as the true combination caused by errors of around 50mm, this defines the general limitation of the method. We can assume that about 10mm can arise from errors in the atmospheric modeling above 30 degrees elevation and the rest can be divided between projection errors and the allowed span of ionospheric residuals (5-12mm). Prediction errors of less the 30mm can be seen as save in order to still robustly find the right cycle relation.

TABLE II.
OFFSET OF INTEGER PHASE AMBIGUITIES ON THE TWO CARRIERS CAUSE DISTINCT TIME OFFSETS IN THE SOLUTION

N_{L1}	N_{L2}	Offset Length [m]	Offset Time [ps]
$^{+/-}3$	$^{+/-}4$	$^{-/+}0.0566$	$^{-/+}188.88$
$^{+/-}4$	$^{+/-}5$	$^{+/-}0.0503$	$^{+/-}167.89$
$^{+/-}1$	$^{+/-}1$	$^{+/-}0.1070$	$^{+/-}356.76$
$^{+/-}7$	$^{+/-}9$	$^{-/+}0.0063$	$^{-/+}$ 20.99

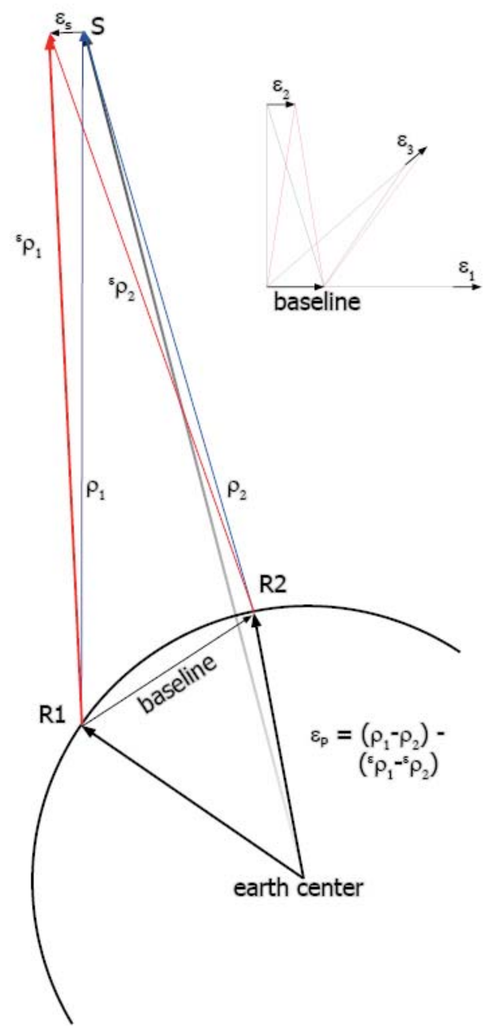

Figure 5. Projection of errors in the orbit information is dependent on the length and orientation of baseline and orbit error vectors.

Figure 6 shows results from the PTBB-SP01 baseline from a period in 2004 where on several occasions the integers were badly chosen. Figures 7 and 8 show how the projection error and the orbit error develop for PRN29 under the time the filter uses a wrong set of ambiguities. If the projection error gets bigger than the value defining the residual range the right cycle relation is lost. But if the error approaches one of the offsets given in the table above it is likely to choose a wrong combination. Range errors due to inaccurate orbit information usually develop smoothly and are thus very difficult to detect in real time. Figure 9 shows all relevant projection errors for

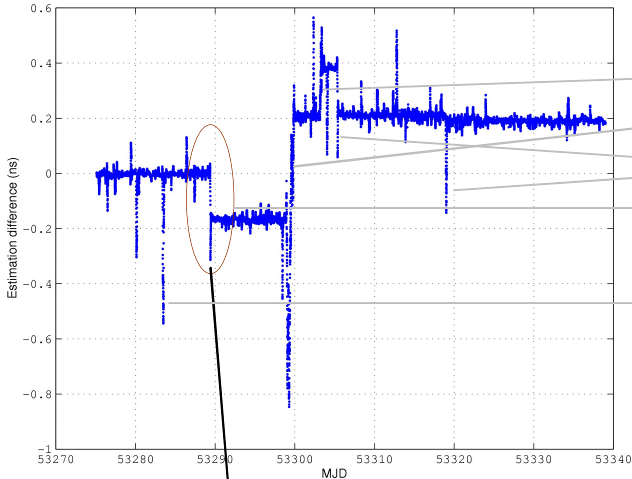

Figure 6. Difference between the reference solution and a real-time solution based on an integer phase ambiguities for the PTBB-SP01 baseline for the days 271-334 in 2004.

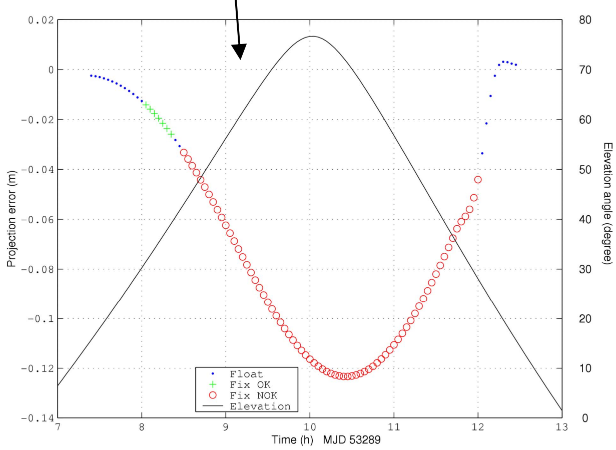

Figure 7. PRN29: Development of the projection error due to errors in the orbit information (igs-igup) for one satellite pass. The satellite carries the wrong integer relation to new satellites and causes a phase glitch.

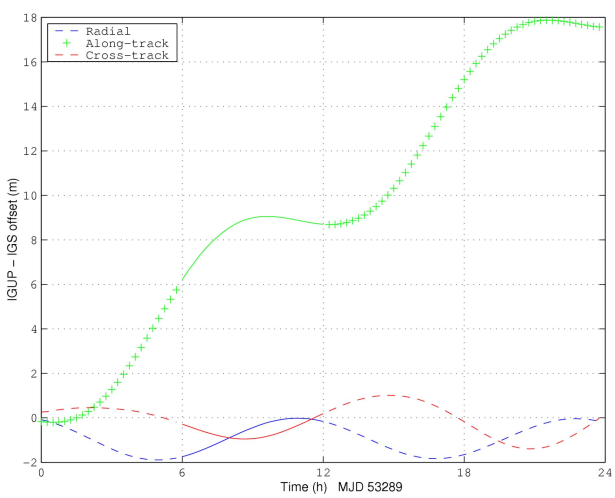

Figure 8. PRN29: IGS-IGUP difference for day 285:2004. The projection error in Figure 7 was caused by large orbit errors. Changes in the along track component are apparently difficult to predict.

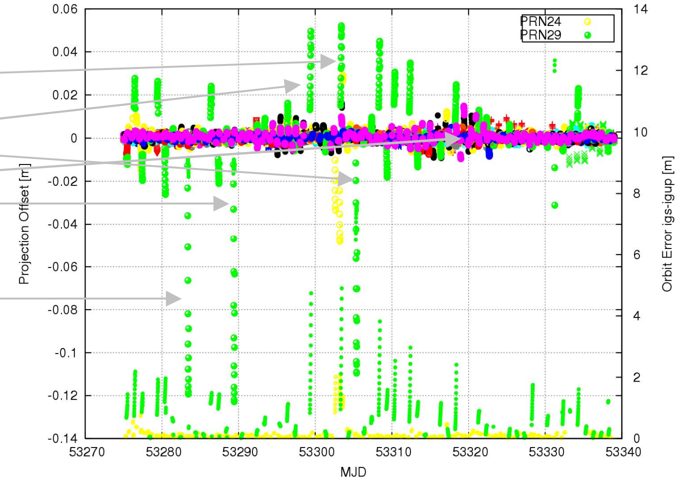

Figure 9. Projection errors for PTBB-SP01 in 2004 of Figure 6. A 30mm error can be seen as a limit for not selecting the wrong pair of ambiguity integers. The bottom of the graphs (small symbols) indicate the orbit info error of the two satellites that violate that limit.

the 2004 time period defining the jumps in Figure 6. The size of the jumps corresponds to the combination of integers that that were used to fix the observations. Table II indicates that the quality of IGS orbit predictions has improved during the last few years. The table arbitrarily color codes the quality for indication of the changes over the years. However, satellites, like PRN29, that always are difficult to predict should be presently avoided during real-time processing.

IV. CONCLUSION

By comparing results from real-time processed GPS data with results from TWSTFT from the same baseline, we have proven that fixing integer ambiguities on double differences does not introduce frequency offsets. Baselines of about 600km can be difficult if the used real-time orbits are erroneous above one meter. Real-time estimates of station clock differences are valuable for use with distributed real-time timescales.

ACKNOWLEDGMENT

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[2] Rieck et al. “The Use of Ambiguity Resolution For Continuous Real-Time Frequency Transfer by Filtering GNSS Carrier Phase Observations”, EFTF 2006

[3] GPS-LAB http://gge.unb.ca/gauss/htdocs/grads/orbit/

[4] IGS http://igscb.jpl.nasa.gov/components/prods.html

TABLE III. IGS-IGUP, ORBITS OUTSIDE THE TYPICAL UNCERTAINTY GIVEN BY THE IGS IN 2007 GIVEN IN %. COLOR INDEX INDICATES OVERALL QUALITY OF THE ORBIT PREDICTIONS :RED >WHITE >GREEEN: 3σ (5%,0.5%), 5σ (1%,0.05%)

σ=0.1m	2003		2004		2005		2006		2007 (Jan-Mar)	
PRN	3σ	5σ	3σ	5σ	3σ	5σ	3σ	5σ	3σ	5σ
01	12.99	5.384	2.498	0.400	0.506	0.012	0.298	0.014	0.338	0.000
02	22.11	10.79	2.405	0.502	0.030	0.000	0.000	0.000	0.086	0.038
03	12.10	4.947	1.701	0.163	1.413	0.118	1.475	0.181	3.339	0.704
04	16.12	5.287	3.119	0.679	1.021	0.106	0.883	0.089	0.000	0.000
05	10.52	3.529	2.111	0.431	0.835	0.086	1.157	0.429	0.583	0.019
06	13.61	3.950	2.244	0.293	0.881	0.092	1.530	0.314	1.978	0.315
07	11.24	3.800	3.584	1.082	1.777	0.579	0.952	0.159	2.500	0.412
08	12.06	3.442	2.996	0.645	1.381	0.089	0.683	0.078	1.511	0.572
09	10.07	3.152	3.456	0.745	2.506	0.360	0.942	0.130	0.760	0.009
10	11.03	4.007	1.160	0.104	0.372	0.017	0.455	0.072	0.891	0.661
11	8.304	0.577	0.374	0.020	0.161	0.060	0.017	0.000	0.385	0.197
12							2.054	0.187	0.028	0.000
13	4.568	0.526	0.146	0.000	0.311	0.000	0.331	0.098	0.000	0.000
14	4.883	0.364	0.285	0.035	0.127	0.000	0.217	0.031	0.319	0.000
15	32.63	15.74	4.632	2.082	1.759	0.337	2.628	0.523	1.139	0.000
16	9.005	2.186	0.558	0.121	0.155	0.000	0.098	0.000	0.000	0.000
17	27.55	15.99	4.047	0.754	3.270	0.698	0.175	0.017	0.133	0.000
18	7.495	0.717	0.537	0.023	0.190	0.000	0.235	0.000	0.133	0.076
19			3.933	0.580	0.117	0.000	0.101	0.000	0.869	0.397
20	6.299	0.738	0.348	0.032	0.009	0.000	0.158	0.000	0.000	0.000
21	9.023	2.169	0.619	0.057	0.029	0.000	0.343	0.043	0.000	0.000
22	18.97	6.494	1.651	0.260	0.143	0.000	0.066	0.000	0.000	0.000
23	35.82	19.93	6.252	2.523	0.192	0.111	0.398	0.135	0.038	0.000
24	23.89	13.01	14.01	7.709	1.688	0.356	1.130	0.118	0.108	0.00
25	6.325	1.422	1.762	0.357	0.355	0.046	1.367	0.292	0.238	0.200
26	10.39	2.781	1.498	0.060	0.617	0.000	0.758	0.072	1.386	0.716
27	12.24	4.470	2.604	0.344	0.842	0.000	0.449	0.000	0.141	0.000
28	9.666	1.476	0.356	0.055	0.100	0.000	0.143	0.000	0.445	0.218
29	37.72	22.31	28.25	17.63	23.99	13.69	22.79	11.67	20.09	9.536
30	10.73	4.369	2.685	0.574	0.750	0.020	0.763	0.158	0.282	0.000
31	10.05	2.011	1.802	0.396	1.694	0.431	3.170	1.522	0.000	0.000
All	13.79	5.351	3.252	1.223	1.482	0.542	1.287	0.447	1.161	0.432