Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

FIRST RESULTS OF REAL-TIME TIME AND FREQUENCY TRANSFER USING GPS CODE AND CARRIER PHASE OBSERVATIONS

P. Jarlemark, K. Jaldehag, C. Rieck, and J. Johansson
SP Swedish National Testing and Research Institute, Box 857, S-501 15, BORÅS, Sweden

Abstract - **We have used code and carrier phase data from the Global Positioning System (GPS) satellites to estimate time differences between atomic clocks in near (< 10 s) real-time. For some sites we have used data transmitted via Internet connections and TCP/IP, while for other sites data were collected in deferred time, but processed by a Kalman filter-based software as if they were available in real time. Satellite orbit and clock data of different quality have been used. The real-time estimates of time differences of the station clocks have been compared to those estimated from regular postprocessing using accurate satellite orbits and clocks from the International GPS Service (IGS). First results show that the standard deviation of the differences between the real-time carrier phase-based and the postprocessing estimates of the clock time differences can be less than 100 ps for baselines of about 1000 km.**
***Keywords* - Atomic clocks, GPS, Kalman filter, Time, Real-Time**

I. INTRODUCTION

The Global Positioning System (GPS) is today used extensively for comparing atomic frequency standards and clocks located in different timing facilities around the world. The well-established common-view method [1], which is based on code data, is suitable for comparing clocks for averaging times of about 24 hours and above. Carrier phase-based methods and equipment, on the other hand, have potential for being useful for averaging times down to a few hours [2]. The dominating methodology has been to process the collected data in a post-processing mode. This implies the availability of accurate satellite orbits and clocks, and the possibility to have good control of bad data. In this study, we evaluate near (< 10 s) real-time processing of GPS code and carrier phase-data for estimates of time and frequency differences of atomic clocks.

Real-time access to time and/or frequency differences is for instance necessary in hyperbolical bearing applications working with the Time Difference Of Arrival (TDOA) technique, but could also be useful for communication network synchronization. Remote clock steering of calibration laboratories and time metrology are other applications.

Section II describes the real-time Kalman filter methodology we have used. Section III presents the different GPS data sets, stations, and satellite orbits data that are used in this study. The first results of comparisons to postprocessing clock difference estimates are given in Section IV.

The results are presented with an arbitrary offset removed as no intention was made to use calibrated receiver chains. Thus, only the precision of the method for time transfer is evaluated. Real-time access to data was only available from two of the stations evaluated in the study, SP and ONSA (see Table I). For the other receivers involved, data was collected in deferred time, but treated as if it was available in real time.

II. ESTIMATION METHODS

Three different estimation methods have been studied. All methods are based on a Kalman filter that models the station clock and the tropospheric signal delay as Random Walk processes. Clock jumps are handled using preliminary estimates before data enters the Kalman filter in a manner described in [3]. Station coordinates are not estimated from the real time data. They are presumed to be well known within a few centimeters.

A. Network solution

Method A is based on a network solution of the carrier-phase ionospheric free L3 observable. In addition to station clocks and tropospheric delay the Kalman filter also estimates corrections to the *a priori* satellite orbits and clocks as well as phase ambiguity parameters (not fixed to integers) [3]. Broadcast ephemerides are used as *a priori* orbits.

The Swedish permanent GPS network, SWEPOS, is the main source of data for this method (see Fig. 1). The network currently consists of about 25 stations, all equipped with geodetic quality GPS receivers connected to external atomic frequency standards of different kind. Data from these stations are available in real time (< 10 s) via the SWEPOS operational center using TCP/IP connections. The method is in principle useful also for a global network with real time access to observational data.

B. Single baseline solution

In this method data from pairs of stations are used to estimate the clock difference between the stations. In contrast to Method A, only satellite observations that are common to both stations are used. The difference between the two observations for each satellite enters the Kalman filter. It is therefore a sort of common-view method. The method uses predicted satellite orbits or ephemerides that are available in real time. In difference to Method A, no further estimates of satellite orbits or clocks are done. A Kalman filter estimates in real time phase ambiguity parameters (not fixed to integers), tropospheric signal delays, and station clock differences between the stations.

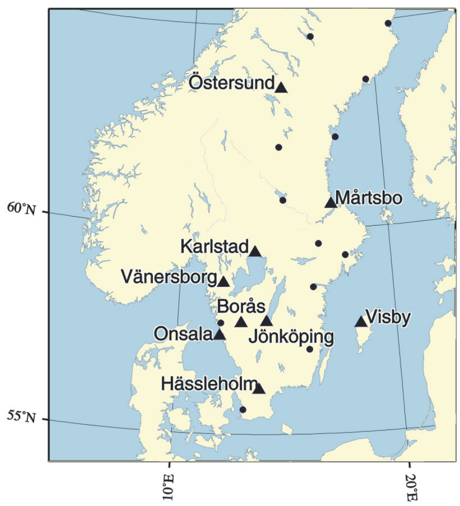

Fig. 1. Part of the Swedish permanent GNSS receiver network (SWEPOS) that has been used in Method A.

We have evaluated the use of the carrier-phase ionospheric free L3, the code single frequency P1, and the code ionospheric free P3 observables. We have evaluated the use of both "ultra rapid" orbit predictions (IGU) from the IGS (International GPS Service) [4] and broadcast ephemerides. The IGU satellite coordinates are accurate in the order of some ten centimeters, while those derived from broadcast ephemerides are accurate in the order of 10 m.

C. Point positioning solution

Method B is useful only when a certain number of common satellite observations are available for the Kalman filter. For intercontinental baselines (for example between Europe and North America) the number of single differences might be too small. A third method was therefore studied that are based on Precise Point Positioning (PPP) solutions [5].

In Method C, each station is processed independently of the other(s). It differs from Method A in the respect that no corrections to the *a priori* satellite orbits and clocks are estimated. Accurate *a priori* values are therefore required to be available in real time. Station clocks are independently estimated relative to the satellite clocks. The station clock differences are then obtained by subtracting these estimates from each other.

III. CLOCK DIFFERENCE SOLUTIONS

Data from the GPS stations listed in Table I have been used in the study. Data from stations other than SP was retrieved from the IGS. For the three methods A, B, and C as described above, Table II shows the different solutions, in total 15 runs, that have been evaluated. Solution #1 is based on data from June 6-7, 2001. Solutions #2 to #15 are based on data from one single day, February 11, 2003. The reference clock, to which all station clocks are related, is a cesium beam atomic clock located at SP.

The estimates of the time differences obtained from the real-time solutions described in Table II are compared to those obtained from post-processing analysis using the GIPSY/OASIS software package [6], which is thus used as a reference method in this study. In order to achieve the best post-processing solution possible the final accurate satellite orbit and clock estimates from the IGS have been used.

TABLE I
STATIONS USED IN THE STUDY

Station	Location	Baseline length to SP	Receiver type	Clock type
SP	SP Swedish National Testing and Research Institute, Borås, Sweden	NA	Ashtech Z12	Cesium
ONSA	Onsala Space Observatory, Onsala, Sweden	68 km	Ashtech Z12	H-maser
NPLD	National Physical Laboratory, Teddington, UK	1101 km	Ashtech Z12T	H-maser
PTBB	Physikalisch-Technische Bundesanstalt,Braunschweig, Germany	623 km	Ashtech Z12T	H-maser
AMC2	U.S. Naval Observatory, Alternate Master Clock, Colorado, USA	7351 km	Ashtech Z12T	H-maser

IV. RESULTS

A significant source of error in all three real-time methods is the errors in the satellite positions. The resulting error in the calculated signal path will propagate differently into the parameters estimated if the geometry of observation differs between the stations. This effect results in a baseline length dependence of the clock difference. This is illustrated for Method B in Fig. 2 (short baseline, small error) and Fig. 3 (longer baseline and larger errors). The quality of the satellite orbit data used play, of course, also a significant role. This is shown in Fig. 4, where one curve show the results using the low quality broadcast data, while the other use IGU data. In Method C also errors in the *a priori* satellite clock estimates propagate differently into the different estimated parameters. This is not the case for Method B, where satellite clock errors are cancelled thanks to the differencing of observables before entering the Kalman filter.

The results of the 15 different solutions are presented in the last column of Table II as the standard deviation (STD) of the difference between the real-time and the postprocessed (GIPSY/OASIS) estimates.

TABLE II

CHARACTERISTICS OF THE DIFFERENT SOLUTIONS OF THIS STUDY

#	Method (see text)	Station	Observable	Orbit	STD[a] (ps)
1	A	ONSA	Carrier phase L3	Broadcast	58
2	B	ONSA	Code P1	IGU	348
3	B	ONSA	Code P3	IGU	646
4	B	ONSA	Carrier phase L3	Broadcast	30
5	B	ONSA	Carrier phase L3	IGU	17
6	B	NPLD	Code P1	IGU	2404
7	B	NPLD	Code P3	IGU	567
8	B	NPLD	Carrier phase L3	Broadcast	255
9	B	NPLD	Carrier phase L3	IGU	51
10	B	PTBB	Carrier phase L3	Broadcast	105
11	B	PTBB	Carrier phase L3	IGU	38
12	C	ONSA	Carrier phase L3	IGU	450
13	C	NPLD	Carrier phase L3	IGU	433
14	C	PTBB	Carrier phase L3	IGU	561
15	C	AMC2	Carrier phase L3	IGU	925

[a]standard deviation of the difference between the real time and the postprocessed (GIPSY/OASIS) estimates.

We can summarize the preliminary findings as follows:

- The single difference solution in Method B gives fairly similar result as the network solution used in Method A. For the short baseline between SP and ONSA, the STDs of solutions #1 and #4, both using broadcast ephemerides, are in the order of some tens of picoseconds.
- The results based on carrier-phase data and Method B are depicted in Fig. 4 as a function of baseline length. For a baseline of the order of 1000 km (NPLD in this case), the STD for the solution using broadcast ephemerides is less than 300 ps and using the IGU rapid orbits less than 50 ps.
- For code data used with Method B there is a trade-off between the effects of increased measurement noise for P3 and the effects of ionospheric differences remaining in P1 for longer baselines (see solutions #2, 3, 6 and 7 in Table II).
- The results obtained using Method C are depicted in Fig. 5 as a function of baseline length. They are all several times worse than what is obtained using Method B.

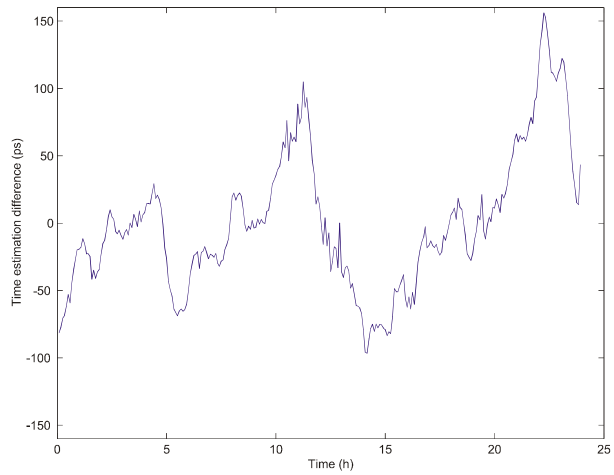

Fig. 3. Difference between the real-time Method B and the postprocessed (GIPSY/OASIS) time difference estimates for SP-NPLD. (See Table II #9)

V. CONCLUSION

The method based on single differences, Method B, seems to be very promising for continental baselines. The results

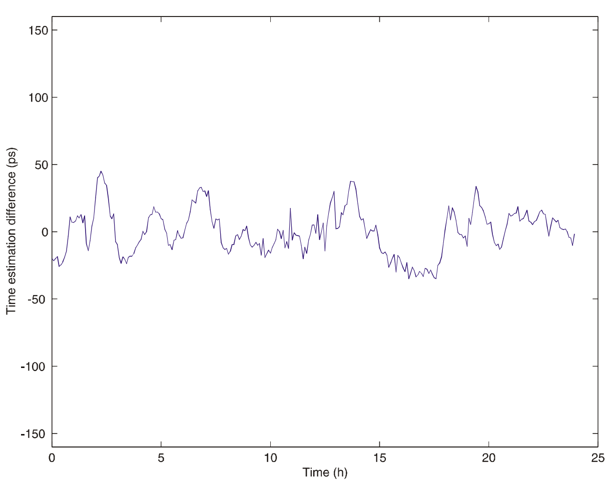

Fig. 2. Difference between the real-time Method B and the postprocessed (GIPSY/OASIS) time difference estimates for SP-ONSA. (See Table II #5)

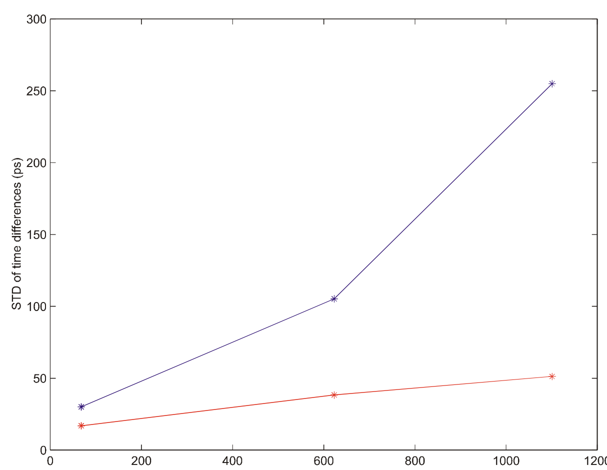

Fig. 4. Difference between the real-time Method B and the postprocessed (GIPSY/OASIS) time difference estimates as a function of baseline length. Top curve: using broadcast ephemerides, Table II #4, 8, and 10, Bottom curve: using IGU data, Table II #5, 9, and 11.

presented show a potential of obtaining a precision of time differences of the order of less than 100 ps using predicted IGS orbits and less than 500 ps using broadcast ephemerides. Studies using more stations, including intercontinental baselines, and longer time series are required for more certain conclusions.

Methods A and C do not require observations common to the two stations of interest. The methods are therefore useful also for the longest baselines. The results are, however, sensitive to the quality of the estimates or predictions of the satellite clocks.

ACKNOWLEDGMENTS

The work is partly supported by the Swedish Foundation for Knowledge and Competence Development, KKS, under contract 2001/0334.

REFERENCES

[1] D. W. Allan and M. A. Weiss, ‘‘Accurate Time and Frequency Transfer during Common-View of a GPS satellite”, Proc. of the 34th Annual Symposium on Frequency Control, pp. 334-346, 1980.

[2] K. M. Larsen and J. Levine, “Carrier Phase Time Transfer”, IEEE Trans. on Ultrasonics, Ferroelectronics, and Freq. Control, 46(4), pp. 1001-1012, 1999.

[3] P. O. J. Jarlemark, J. M. Johansson, B. Stoew, and G. Elgered, “Real Time GPS Data Processing for Regional Atmospheric Delay Derivation, Geophysical Research Letters, 29(16), 2002.

[4] http://igscb.jpl.nasa.gov/

[5] J. F. Zumberge, M. B. Heflin, D. C. Jeffereson, M. M. Watkins, and F. H. Webb, “Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks, J. Geophysical Research, 102, pp. 5005-5017, 1997.

[6] F. H. Webb and J. F. Zumberge, “An Introduction to the GIPSY/OASIS-II, JPL Publ. D-11088, Jet Propulsion Laboratory, Pasadena, Calif., 1993.

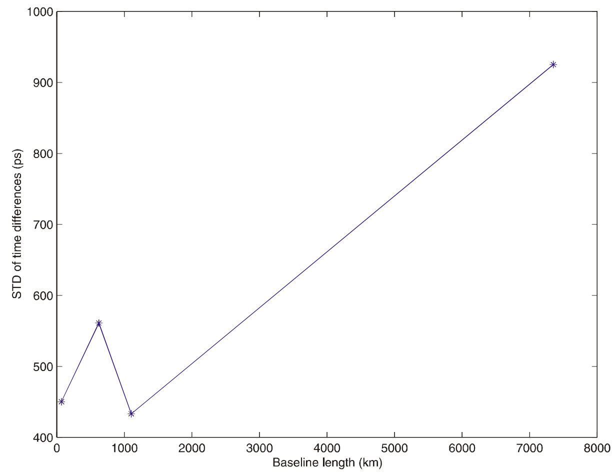

Fig. 5. Difference between the real-time Method C and the postprocessed (GIPSY/OASIS) time difference estimates as a function of baseline length. See Table II #12, 13, 14, and 15.