Automated quasi-realtime prediction of GNSS clock corrections



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Abstract

For positioning and time transfer applications with GNSS knowledge about satellite specific orbits and clock-corrections is required. The ACs (Analysis Centers) of the IGS (International GNSS Service) provide satellite ephemeris as well as clock corrections to GPST (GPS-Time) in sp3-format for free via internet with a latency of about one day. These orbit and clock information result from a least squares adjustment of the parameters based on observations from the IGS reference station network.

The accurate and reliable prediction of satellite clocks and orbits is an indispensable condition of all GNSS based positioning applications in real-time. While the orbits are output to an integration of the well-known force field the clock corrections to GPST (GPS-Time) have to be extrapolated by means of an experienced prediction model. The model used for predicting GPS and GLONASS satellite clocks within program GNSS-VC (GNSS-Vienna Clocks) contains basically the coefficients of a quadratic polynomial as well as an amplitude and a phase shift of an once per revolution periodic term. These parameters were initially determined in a least squares adjustment based on the observed part of the IGS Ultra-Rapid clock solutions. Since October 2006 the program GNSS-VC is operated in a fully automated mode.

To get rid of the 3 hours delay of the IGS Ultra-Rapid-solution we developed a KF (Kalman-Filter) approach which allows to issue clock predictions in near real-time. This is important, because the accuracy especially of predicted clock-corrections decreases rapidly with time. Parameters in the KF are again the 3 coefficients of a quadratic polynomial. After an initial pre-determination of the parameters the KF continuously updates the model using real-time clock corrections calculated from a one-minute data stream based on observations of the RT-IGS network (Real-Time IGS; more than 50 almost globally distributed stations). These once-per-minute clock correction data are output of the program RTR-Control [5]. Clock predictions are calculated every 15 minutes for the upcoming 6 hours period.

We present comparisons of our clock predictions with the Ultra-Rapid and the Rapid solutions of the IGS and with solutions of individual ACs of the IGS. The results of GNSS-VC can be obtained from the institutes webpage [10].

Kurzfassung

Für Positionierungs- und Zeitübertragungsaufgaben mittels GNSS benötigt der Nutzer Informationen über die Satellitenbahndaten und -uhren. Die Analysis Centers (ACs) des IGS (International GNSS Service) stellen die Bahnkoordinaten sowie die Abweichungen der GPS und GLONASS Satellitenuhren zu GPST (GPS-Time) im sp3-Format zur Verfügung. Diese Dateien sind jeweils am folgenden Tag über einen freien ftp-Server erhältlich. Die Bahn- und Uhrinformationen sind das Ergebnis einer Parameterschätzung (vermittelnder Ausgleich nach der Methode der kleinsten Quadrate) auf Basis der Beobachtungsdaten des IGS-Stationsnetzes.

Für Echtzeit- oder beinahe Echtzeit-Anwendungen ist es notwendig, die Satellitenbahnen und -uhren für einen begrenzten Zeitraum vorauszurechnen. An der TU-Wien wurde das Programm GNSS-VC (GNSS-Vienna Clocks) entwickelt, welches seit Oktober 2006 mittels eines eigenen Prädiktionsmodells Satellitenuhrkorrekturdaten über einen Zeitraum von 12 Stunden prädiziert. Modellparameter sind die Koeffizienten eines quadratischen Polynoms sowie die Amplitude und die Phasenverschiebung einer zusätzlichen Sinusschwingung mit der Periodendauer eines Satellitenumlaufs. Als Eingangsgrößen dienen die Ultra-Rapid Produkte des IGS, welche dem Nutzer mit einer Verzögerung von ca. 3 Stunden auf der Homepage des IGS [11] zur Verfügung stehen. Die mittels GNSS-VC prädizierten Uhrkorrekturen unterliegen deshalb ebenfalls einer entsprechenden Verspätung.

Um die Uhrkorrekturdaten auch in quasi-Echtzeit, also ohne die oben beschriebene Verzögerung, vorhersagen zu können, wurde im Anschluss ein Prädiktionsalgorithmus auf Basis eines KF (Kalman-Filters) entwickelt. Dies ist insofern wichtig, als prädizierte Uhrkorrekturen mit fortschreitender Zeit deutlich an Genauigkeit verlieren. Nach der Bestimmung von Startwerten für die Modellparameter (Koeffizienten eines quadratischen Polynoms) werden diese mit Hilfe des KFs in regelmäßigen Intervallen aktualisiert. Als Eingangsgrößen werden dafür Echtzeit-Uhrkorrekturen des Programms RTR-Control herangezogen [5]. Dieses errechnet Uhrkorrekturdaten im Minutentakt, basierend auf einer Lösung des globalen RT-IGS Stationsnetzes (Real-Time IGS Network), welches zur Zeit mehr als 50 Stationen umfasst. Die über den KF berechneten Uhrdaten werden jeweils alle 15 Minuten für die folgenden 6 Stunden ermittelt. Ihre Genauigkeit liegt dabei im 2-Nanosekunden-Bereich, was einem radialen Distanzfehler von ca. 60 cm entspricht.

1. Introduction

Precise point determination by means of GPS relies to a considerable extent on the quality of available satellite orbits and clock offsets with respect to GPST. GPST itself differs from the International Coordinated Time (UTC) by an amount of up to 40 ns (nanoseconds), ignoring leap-second differences. For many geodetic applications using differencing schemes the broadcast ephemeris, currently issued with an accuracy of about ±2 m and a clock rms (root mean square) of ±3-5 ns, are sufficient. To achieve highest precision, especially over baseline lengths larger than 20 km, the user is well-advised to take advantage of precise ephemeris provided by the IGS [11]. Moreover, when analysing pseudorange and phase data, these products allow users to determine consistent coordinates and clock values even for an isolated GPS receiver with an internal accuracy of a few centimetres (PPP, precise point positioning) [8].

The IGS provides so-called "IGS Final Orbits" of all GPS satellites on a weekly basis since the end of 1993. Compared to broadcast orbit information these ephemeris are more accurate by a factor of about 100, i.e. a few centimetres with a satellite clock rms of less than ±0.1 ns. They are available for post processing applications with a delay of 13 days (counted from the last day of the week which is contained in the orbit-file). IGS combined clocks are based on a linear alignment to GPST separately for each day. So while the internal stability of ±0.1 ns is quite good, the day-to-day stability of this reference is poor. Besides, the IGS also provides so-called "Rapid" solutions (IGR) with a slightly lower quality which are available at 17.00 UTC the following day. IGS Final and Rapid solutions are available from the IGS website at [11] free of charge.

It is worth mentioning that a joint project of the IGS and the BIPM (Bureau International des Poids et Mesures) aims to develop and demonstrate the operational capabilities of satellite navigation systems for time transfer [1, 9]. In this context concepts to steer the IGS time scale to UTC were investigated [7]. This will allow for a general dissemination of accurate and easily accessible UTC in the near future.

Moreover, since November 2000, the IGS distributes "Ultra-Rapid" products (IGU) comprising precise GPS satellite orbits and satellite clocks for real-time or near real-time applications. This solution, issued 4 times daily, contains both an observed and a predicted part. Both cover a period of 24 hours. While the orbits of the predicted part are output to an integration of the well-known force field the clocks have to be extrapolated by means of a sophisticated prediction model.

Nevertheless, for real-time applications which require high accuracy the situation should be further improved. Broadcast orbits and clocks are, e. g. for PPP, to imprecise, while the problem with the Ultra-Rapid products is their latency of 3 hours. A real-time prediction of satellite orbits and clocks without any latency and with a high accuracy is at the moment still not available. For this reason we developed the program GNSS-VC (see chapter 2) which has been enhanced recently by a KF-approach (see chapter 3).

2. GNSS-VC – basic principle

In the past years we developed at the IGG (Institute of Geodesy and Geophysics, Research Unit Advanced Geodesy, TU-Vienna) a program to predict GNSS satellite clock corrections. The basic version of GNSS-VC determines the parameters of a prediction model which reads:

$$p(t) = a \cdot t^2 + b \cdot t + c + A_0 \cdot \sin(\omega \cdot t + \phi) \quad (1)$$

with: a, b, c ... polynomial coefficients
A_0 ... amplitude
ω ... frequency
ϕ ... phase shift

The nature of the model results from the assumption that the satellites oscillator operates on a slightly shifted and drifting frequency with respect to (w.r.t.) the nominal frequency. Clock observations (phase-observations of this oscillator) are obtained by integration of this deviating satellite frequency and their description therefore yields in a quadratic polynomial. Most satellite clocks satisfy this model very well (see figure 1a).

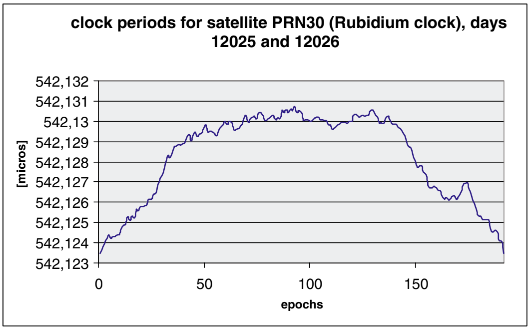

Figure 1a: IGU clock corrections of PRN30 (Rb), GPS week 1202, days 5, 6

Moreover we add a cyclic term to our primary model because of a periodic effect (w.r.t. the satellites revolution time) which basically concerns satellites working on Cesium (Cs) clocks. We assume that the periodic effect of the satellite clock data relate to temperature variations. The Cesium clocks also show a slightly worse stability over time than Rubidium (Rb) clocks, displayed in figure 1b by means of the Allan-variance [1].

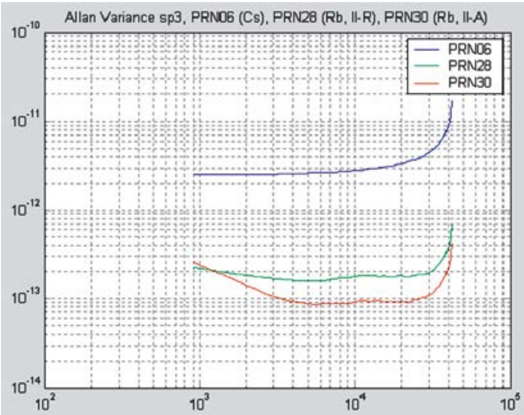

Figure 1b: Allan-variance for different clock types, x-axis in seconds

If the Allan Variance is displayed with respect to time in a logarithmic scale on both axis, one can identify the noise characteristic of the signal. The value of parameter α in table 1 allows to distinguish between different kinds of noise. α is parameter of a model Sy(f) describing the power spectral density of time or frequency fluctuations. For frequency analysis this model reads as

$$S_y(f) = \sum_{\alpha=-2}^{2} h_\alpha f^\alpha \qquad (2)$$

is a constant depending on the source data and usually ranges between -2 and $+2$. Figure 1c shows the different model slopes of the Allan Variance representing various noise characteristics of a signal. p denotes the slope of the straight line.

α	Noise
2	White phase noise
1	Flicker phase noise
0	White frequency noise
-1	Flicker frequency noise
-2	Random walk frequency noise

Table 1: Allan-variance – noise characteristics

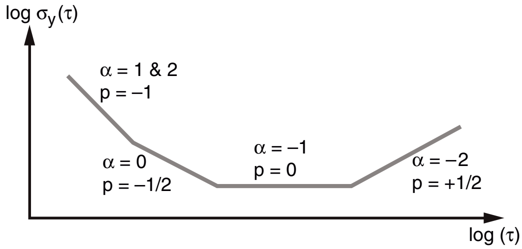

Figure 1c: Allan-variance – noise characteristics

Because we used in figure 1b 24 hours of clock observations with a temporal resolution of 900 s the variance graphs of PRN06 and PRN28 mainly cover the flicker noise part while the more stable clock of PRN30 shows white frequency noise up to 4000 s. The extreme steep gradient of the graphs at the longest interval around 40000 s are artefacts of the computation model used.

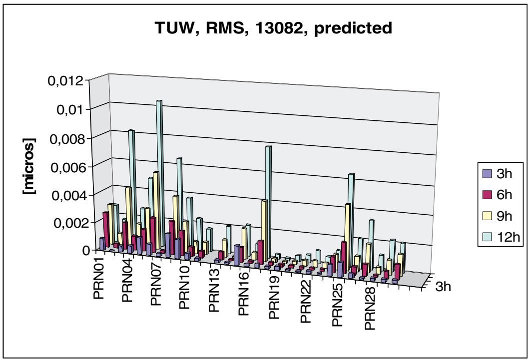

Figure 1d: rms of TUW clock predictions w.r.t. IGR, GPS week1308, day 2

In order to explore reliable model parameters, valid over a span of about 12 hours, we use the available observed part of the IGS Ultra-Rapid solutions of the past 48 hours. A least squares adjustment determines the coefficients of the prediction model presented by equation (1).

To evaluate of the quality of our results we calculated the rms w.r.t. to the IGS Rapid clock corrections (see figure 1d) for different prediction time spans. Every interval starts at 00:00:00, lasting for 3, 6, 9, and 12 hours.

For more detailed information about the algorithm used in GNSS-VC as well as comparisons of the results (w.r.t. the IGS Rapid solution and the ACs Ultra-Rapid solutions) we refer to [2] and to various posters of the authors at the institutes homepage [10].

3. Kalman-filtering

Because of the latency of the Ultra-Rapid solutions (3 hours) as well as the necessary computation time the delay of our predicted clock corrections is about 3 hours and 15 minutes. To get rid of this time delay we developed an algorithm based on a KF [3], using input-data with a time resolution of one minute. These data results from the program RTR-Control, which uses the observations of the RT-IGS station network to calculate real-time clock corrections every 15 seconds. Afterwards the clock corrections are combined in one smoothed solution per minute. The resulting data can be retrieved by registered users from [12], where the clock correction table is actualized every minute. These data also serve as input for the KF-algorithm in GNSS-VC.

To set up reliable initial values of our parameters we use 10 consecutive epochs of the one-minute-data of RTR-Control. We determine an offset and the linear coefficient of our parameter vector. The offset might be the last input-value of the initial values (representing the first prediction epoch), the linear coefficient corresponds to the slope of a straight line through the first to the last data-point. The initial value of the quadratic coefficient of the polynomial is zero. Currently we do not evaluate the coefficients of the periodic term given in equation (1). Moreover with the small amount of input data of 10 clock corrections in the first test version it does not make sense to evaluate an amplitude and a phase shift. Thus the KF approach does not distinguish any more between different clock types (Cesium or Rubidium) because the parameter vector is used for predictions over not more than 6 hours while the cyclic term has a period of about 12 hours (revolution period).

After the initial process we update the parameter vector every minute. If there appears a gap in the data the new parameters are predicted as long as the gap does not exceed a limited time window, which at the moment is set to 10 minutes. These results will be published via internet (see chapter 5). Every 15 minutes the new parameters are used for predicting clock corrections over an interval of 6 hours. Within this time span the rms of the predictions w.r.t to the IGS Rapid solutions remains at the two-nanoseconds-level (or below) for most of the satellites.

The results are also stored in a format similar to the sp3-format with a time interval between consecutive epochs of 15 minutes. The reason is just convenience for comparisons with the IGS products. Of course in the future the time resolution of the predicted clock corrections can vary depending on the application.

4. Comparisons

To get information about the quality of our predictions we computed the rms w.r.t. the IGS Rapid solution by means of:

$$rms_i = \sqrt{\left(\sum(\Delta IGR_i)^2\right)/n} \quad (3)$$

with: ΔIGR_i difference between the IGS Rapid solutions and TUW
i satellite
n number of epochs

The rms contains the whole prediction time span over 6 hours. As in former studies, e.g. [2], we take into account an offset between the two data sets as well as a linear drift in time. The following figures 2a-c show the improvement of the KF predictions at the begin of a test-day in GPS-week 1401.

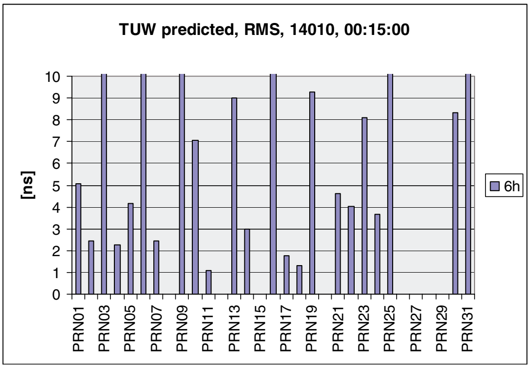

Figure 2a: *rms w.r.t. IGR for week 1401, day 1, prediction time 00:15:00*

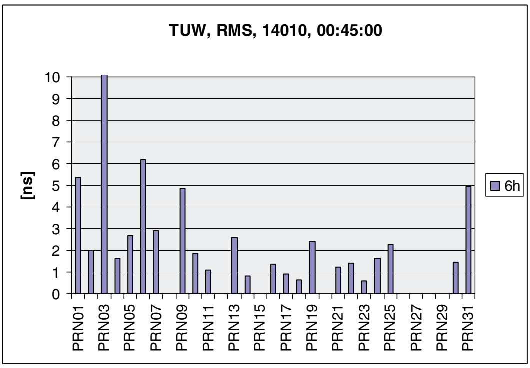

Figure 2b: *rms w.r.t. IGR for week 1401, day 1, prediction time 00:45:00*

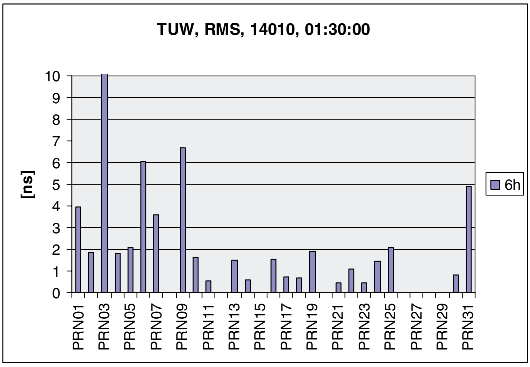

Figure 2c: rms w.r.t. IGR for week 1401, day 1, prediction time 01:30:00

It is obvious that the quality of the predicted clock corrections increases over the time (for an easy comparison the y-axis of all diagrams is scaled to 10 ns). For the first prediction epoch (figure 2a) the model-parameters are, w.r.t. the input data of this day, calculated from the ten initial values as described above and corrected for just one epoch with the KF. Afterwards the predicted clock corrections improve very fast and already after 1.5 hours (figure 4.b) the rms-values for more than half of the given satellites come close to the expected 2 ns-level. After this time span the KF delivers stable output data. Of course it is also possible, that the rms of a satellite gets worse for shorter time spans. This happens if the input data worsens or clock corrections lack for a couple of epochs in the input file. For small gaps the prediction parameters are not corrected for the new epoch but just calculated with the prediction-rules defined in the transition-matrix of the KF. Therefore the predicted clock corrections get continuously worse until at a certain time the predictions are stopped (currently after 10 minutes). Whether satellites are missing or not solely depends on the input data of RTR-Control.

5. Further work

In the near future we will improve the current test-version of GNSS-VC to provide reliable clock predictions via the "IGU – Real Time Monitoring"-homepage [12] of the IGS-RT working group. Because the IGS-RT network (figure 3) is currently still to sparse to track all satellites by enough stations at any time there remain gaps in the observations. Therefore it is necessary to consider reasonable intervals to start and stop the clock correction predictions of single satellites.

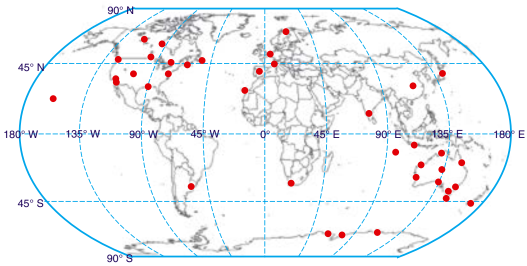

Figure 3: IGS-RT network, spring 2007

According to figures 2a-c it does not make sense to start with the predictions just a couple of minutes after the first parameter vector has been calculated in the KF. A good starting interval might be about 1.5 hours following the fact that the rms gets stable after about this time span. Secondly, there is no reasonable breakpoint for the case of gaps in the input data at the moment. Currently this parameter is set to 10 minutes, but it has to be checked whether it is possible to expand this limit. One might consider a threshold for the rms (e.g. ±10 ns, comparable with a radial distance error of ca. ±3 m), so that satellites beyond this value will not be available in the output files. Therefore the predicted clock data will have to be compared to the IGS Ultra-Rapid clock corrections right after their predetermination.

6. Summary

As shown above it is possible to compute GNSS clock correction data in quasi real-time for a limited time span (about 6 hours) with a simple prediction model in form of a quadratic polynomial based on a KF. The rms remains in most cases below ±2 ns for the 6 hours prediction interval. For the future (July 2007) we plan to provide our clock products via the institutes webpage. The advantage of this new clock solutions is that it is computed in almost real-time whereas the former predicted clock corrections as well as the IGS- and the ACs Ultra-Rapid solutions are released with a delay of about 3 hours.

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