AN EFFICIENT DUAL AND TRIPLE FREQUENCY PREPROCESSING METHOD FOR GALILEO AND GPS SIGNALS

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ABSTRACT

Data preprocessing is a mandatory stage for most of GNSS applications. In the frame of space weather and precise point positioning applications, the Geomatics Unit of the University of Liège has purchased two Septentrio PolaRx3eG receivers which allow tracking GPS L1/L5 and Galileo E1/E5a signals.

In order to fully exploit these new data, we developed a preprocessing method extending existing techniques. Our preprocessing method consists of three consecutive steps. The first step is devoted to the compensation of receiver clock slips affecting code pseudorange and carrier-phase measurements. The second step covers cycle slips detection and the third step assesses data quality in terms of noise essentially affecting code pseudorange measurements.

This preprocessing method was initially developed for GPS L1/L5 and Galileo E1/E5a dual frequency data but finally enhanced to also preprocess triple frequency data from first operational Galileo satellites as soon as data are available. The developed method already showed promising results.

1. INTRODUCTION

High precision GNSS applications require advanced solutions for data preprocessing. The goal of the GNSS data preprocessing stage is to prepare raw data to subsequent specific treatments.

In November 2009, the Geomatics Unit of the University of Liège purchased two Septentrio PolaRx3eG receivers which allow tracking Galileo E1/E5a and GPS L1/L5 signals. These receivers were installed in the Geophysical Centre of Dourbes in Belgium (50.0915°N – 4.5912° E). This observation site was initially chosen because of its quiet electromagnetic environment. Receivers installation integrate in the Space Weather And Navigation Systems project (SWANS) funded by the European Space Agency (ESA) and driven by the University of Liège (ULg) and the Royal Meteorological Institute (RMI) of Belgium in collaboration.

In order to fully exploit these new data, an efficient dual frequency preprocessing method for Galileo and GPS signals was required. Considering applications such as Precise Point Positioning (PPP) and Space Weather (SW), the developed preprocessing method had to meet some important criteria.

Firstly, the method had to efficiently work in standalone mode, using only raw measurements included in RINEX observation files without using any data from many other receivers or satellites ephemeris. This first property is involved by PPP applications. By this way, the preprocessing method can easily be applied to data from other stations. Secondly, regarding space weather research, the preprocessing method should be efficient regardless atmospheric activity, in particular ionospheric activity. We called this second property “atmosphere-free”. In addition, real-time property constituted a worthwhile aspect of the developed method. Finally, we also extended the capabilities of the method with the goal to treat triple frequency data. This last improvement added to the standalone property makes the developed method very flexible to other data from a great number of stations and receivers.

Aiming at reaching these objectives, we developed a preprocessing method which consists in three important stages described respectively in the three next sections of this paper.

The first section is dedicated to clock slips compensation. In order to monitor its internal clock bias, the receiver imposes jumps on its internal clock. This technique keeps the absolute value of the receiver clock error due to the clock drift in a specific range but generates undesirable discontinuities in raw observables. The second section covers cycle slips detection. Cycle slip detection is an already well documented and studied topic but the current evolution of GNSS, especially new signals availability, is likely to improve the efficiency of cycle slips detection techniques. Finally, the third section is devoted to data quality assessment. Inspired by an existing technique, the last stage of our preprocessing method was conceived in order to obtain information about the data quality. Initially, we focused our study on noise affecting code pseudorange measurements.

2. CLOCK SLIPS COMPENSATION

The first step of the preprocessing method presented in this paper is devoted to receiver clock slips compensation. This phenomenon is poorly documented in specific literature; however it can produce undesirable effects in the data processing stage [1]. In order to tackle these effects, we developed an original standalone methodology to compensate receiver clock slips. This section is composed of three distinct parts. The first subsection considers the receiver clock role in the global context of satellite positioning. The second subsection shows how some GNSS receivers manufacturers, in particular Septentrio, are managing the inevitable drift of GNSS receiver clocks and what are the effects on raw measurements. Finally, the third section provides our efficient and stand-alone solution to compensate receiver clock slips.

2.1. GNSS clock synchronisation

Satellite positioning is based on measurements of signals propagation time between GNSS satellites and GNSS receivers. Each satellite and each receiver is equipped with an internal clock. Satellite and receiver internal clocks are never perfectly synchronized with the global GNSS time scale causing errors in computed position. They are continuously and unavoidably drifting relative to the global GNSS time scale.

In the frame of a classical standalone positioning problem, satellites and receivers clock errors are handled differently. The first is generally modelled from parameters included in the navigation message. The second is classically considered to be an additional unknown of the problem as well as the unknown position coordinates of the receiver [2].

Most of GNSS receivers are designed to keep the absolute value of the bias between the receiver time scale and the global GNSS time scale in a specific range. The clock drift rate of a GNSS receiver depends essentially on the quality of the internal clock.

2.2. Receiver clock drift management

Septentrio PolaRx3eG receivers keep their internal time scale close to the GNSS time scale by continuously monitoring the receiver clock error value. At each observation epoch, a position computation is performed allowing to determinate the receiver clock error value. Each time the receiver clock error exceeds a fixed threshold by an absolute value, a clock jump is imposed on the internal clock (Fig. 1) [3].

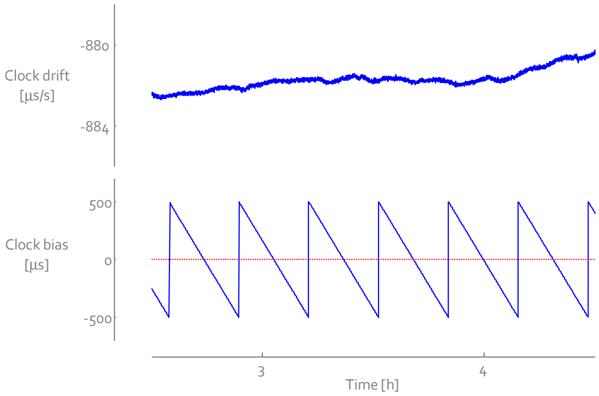

Figure 1. Receiver clock is unavoidably drifting relative to global GNSS time scale. Septentrio PolaRx3eG receivers handle their internal clock drift by imposing clock jumps when the internal clock bias exceeds a fixed threshold [3].

Since the receiver clock error is one of the unknowns to be determined in the position computation, a clock jump on the internal clock does not produce any effects on the positioning solution. On the other hand, this operation causes undesirable effects on raw observable data (code pseudorange and carrier-phase measurements), generating typical discontinuities (slips) in raw measurements time series (Fig. 2).

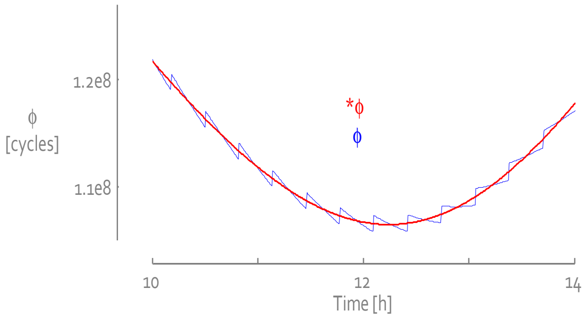

Figure 2. Clock jumps imposed on the internal clock do not affect positioning solution but produce undesirable discontinuities in raw measurement time series (code pseudorange and carrier-phase measurements) (blue curve). The preprocessing method provideq a technique to compensate receiver internal clock slips in raw measurements (red curve).

Scientific GNSS applications preferentially use raw observables rather than the computed position values and require a rigorous clock slips compensation method.

2.3. Receiver clock slips compensation solution

For dealing with receiver clock slips effects on raw observables, we first built dual, triple and between satellite differences combinations from our two Septentrio PolaRx3eG receivers data. While all these three types of combination allow to get rid of the receiver clock error, residual clock slips of the two receivers are always visible in these receiver clock error free combinations (Fig. 3).

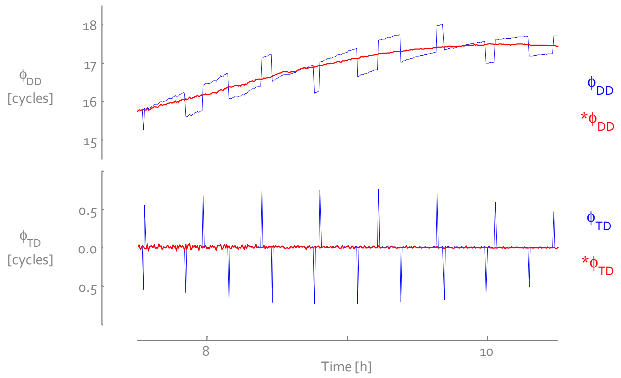

Figure 3. Discontinuities in raw measurements time series due to the imposition of clock jumps on the receiver internal clock are always visible in receiver clock free linear combinations such as double and triple difference combinations (blue curves). The preprocessing method provides a technique to compensate receiver internal clock slips in raw measurements (red curves).

This residual phenomenon is a direct consequence of the imposition of a clock jump on the receiver internal clock between two measurements epochs: the duration of the epoch affected by the clock jump is slightly different (considered in the global GNSS time scale) causing a relative small discontinuity in raw observable time series. In receiver clock error free combinations, the residual discontinuity is directly related to the differential distance traveled by satellites involved in combinations during the target epoch. Such persistent residual discontinuities in linear combinations time series are a real problem, e.g. when applying a cycle slip detection method.

Then, we designed a receiver clock slip compensation method based on Doppler measurements and receiver clock error values, available in RINEX observation files. This method is composed of two fundamental steps (Fig. 4). The first step consists in applying a correction to raw observable measurement to deduce the measurement that would have been achieved at the GNSS time specified, if the two time scales were perfectly synchronized. This operation is based on a back linear interpolation using the Doppler measurement as an estimation of the observable time variation rate. The compensation of the observable measurement error due to receiver clock drift is the object of the second step.

Eq. 1 and Eq. 2 provide a mathematical formulation of the clock compensation technique in the case of carrier-phase and code pseudorange measurement respectively, where ϕ and $^*\phi$ are the raw and compensated carrier-phase measurement in cycles respectively, P and $^*P$ are the raw and compensated code pseudorange measurements in meters respectively, dt is the receiver clock bias in seconds, D is the Doppler measurement in cycles per second and f and λ are the signal frequency in Hertz and signal wavelength in meters respectively.

$$^*\phi(t_j) \approx \phi(t_j + dt) + D\,dt + f\,dt \qquad (1)$$

$$^*P(t_j) \approx P(t_j + dt) + \lambda\,D\,dt + \lambda\,f\,dt \qquad (2)$$

We validated the clock slips compensation method designed on a large data set from Septentrio PolaRx3eG receivers. The validation was achieved on raw code pseudorange and carrier-phase measurements (Fig. 2) and results were also observed on dual, triple and between satellite differences combinations (Fig. 3).

The clock slips compensation technique is characterized by standalone property since it uses only information from a single RINEX observation file (considering receiver clock error value included in RINEX observation file).

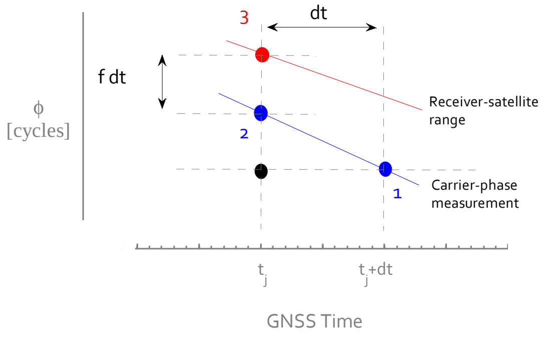

Figure 4. Clock jumps in raw observables can be compensated by a two-steps methodology. The first step applies a correction to deduce the measurement that would have been achieved without time scale desynchronization (point 1 to point 2). The second step compensates the error measurements due to receiver clock bias (point 2 to point 3).

3. CYCLE SLIPS DETECTION

High-precision GNSS application such as space weather, precise point or real time kinematic positioning require a rigorous treatment of cycle slips. Extending existing techniques, we developed an original cycle slips detection method for dual and triple-frequency

GPS and Galileo data, which presents standalone and real-time properties.

The first subsection below presents the definition, origin and consequences of cycle slips. It also provides a brief review of the main principles of existing cycle slips detection methods. The second subsection is devoted to the development of the new methodology, highlighting technical operation, main characteristics, benefits and drawback of the method. The effectiveness of the developed technique is validated on real data in the third subsection.

3.1. Definition

A GNSS receiver achieves carrier-phase measurements on satellite signals by observing the fractional part of the beat phase. When a receiver starts to track the signal from a satellite, an integer cycle counter is initialized to an unknown integer value: the integer phase ambiguity. This counter is thereafter incremented according to the fractional phase evolution due to relative satellite-receiver motion.

Under some circumstances, the receiver can lose phase lock of the satellite signal generating a sudden jump by an integer number of cycles in the carrier-phase measurement time series. This phenomenon is called a cycle slip and means that the value of the initial integer phase ambiguity has changed. Typically, a cycle slip can be due to a material obstruction of the signal, a low signal strength or a failure in the receiver software [2].

In the frame of high precision application, cycle slips have to be detected because they indicate a change in the value of the initial integer phase ambiguity. Cycle slips detection is an old problem in GNSS positioning and numerous methods have been developed in the past [4].

Almost all cycle slips detection methods present common principles. They consist of a semi or fully automatic detection process of discontinuities, launched on a low time variation quantity (called “testing quantity”) built from undifferenced raw observables measurements.

Testing quantity

The role of a testing quantity is to obtain a low time variation combination from raw undifferenced observables in which a cycle slip, a change of the initial phase ambiguity value, will be more easily detectable. Testing quantities can combine code pseudorange, carrier-phase and Doppler measurements from many frequencies, receivers and satellites into an undifferenced or differenced linear combination. Testing quantities are characterized by different properties such as geometry-free, ionosphere-free, low noise and multipath effects properties and each testing quantity has unavoidably benefits and drawbacks according to environmental conditions and available observations.

Cycle slips detection process

Once the testing quantity is produced, the cycle slip detection process can be launched. Main detection methods have been classified in many distinct groups but all have the same objective: the detection of discontinuities in testing quantities time series [4]. Some methods are based on high order time differencing or low degree polynomial fitting applied to time series. These methods require setting a priori specific tolerance values to which differences between successive testing quantities values are compared.

Other methods consist of filtering testing quantities values. The main benefit of this type of methods is that they use statistical information from the data themselves. Filtering techniques use the well-known Kalman filter or other filters such as running average filters [5].

Considering our research topics, space weather and precise point positioning, we need a cycle slip detection method with testing quantities specific properties. Regarding space weather, our method must absolutely not confuse cycle slips and atmospheric variations due to high ionospheric or tropospheric activity. For this reason, in addition to being geometry-free, the chosen testing quantity has to be ionosphere-free. Moreover, precise point positioning applications require a cycle slips detection method with real-time and standalone properties. Our method should be capable of operating on the basis of only one RINEX observation file, i.e. using only classical undifferenced observables and without knowing the position of the receiver and satellites.

Regardless of the choice of the testing quantity, running average filtering methods seemed to be best suited to our needs. They are effective, they don’t require initial parameterization since they use statistical information from target data and their implementation is quiet simple. But running average filters have problems when applied in cycle slips detection due to the inertia of the statistical parameters.

On the basis of these considerations and our objectives, we extended existing techniques to obtain a new cycle slip detection method that has proved effective on dual and triple frequency GPS and Galileo data.

3.2. Development

The first step in the development of the cycle slip detection method consisted of choosing a testing quantity. From raw code pseudorange and carrier-phase measurements, we chose two testing quantities: the widelane-narrowlane (WLNL) code-phase combination and the geometry-free ionosphere-free (GFIF) triple frequency phase combinations adapted to dual and triple frequency data respectively [4] [6].

Observables

The observation equations, forming the mathematical model, for raw code pseudorange and carrier-phase observables are represented by Eq. 3 and Eq. 4 respectively. Φ_i and P_i are the measured carrier-phase and code pseudorange (in distance units) respectively, G is the geometric term (i.e. a function of the geometric range ρ from receiver to the satellite tracked, the vacuum speed of light c, the tropospheric delay T and the receiver and satellite clock bias δt_r and δt^s respectively), I_i is the ionospheric delay, M is the multipath delay, ξ is the hardware, ε is the random errors, λ_i the carrier wavelength and N_i the initial integer phase ambiguity. Subscripts Φ_i and P_i indicate the term dependency on carrier-phase or code pseudorange observable and the subscript i highlights the term dependency on the frequency following RINEX 3.0 conventions ($i = 1, 2, 5, 6, 7, 8$) [7].

$$P_i = G + I_i + M_{P_i} + \xi_{P_i} + \varepsilon_{P_i} \quad (3)$$

$$\Phi_i = G - I_i + M_{\Phi_i} + \xi_{\Phi_i} + \varepsilon_{\Phi_i} + \lambda_i N_i \quad (4)$$

$$G = \rho + c\,(\delta t_r - \delta t^s) + T \quad (5)$$

Dual frequency testing quantity: WLNL code-phase

The first objective of our preprocessing method was to treat GPS L1/L5 and Galileo E1/E5a data recorded by our two Septentrio PolaRx3eG receivers. The dual frequency testing quantity implemented in our method is the widelane-narrowlane code-phase combinations. Eqs. 6-10 provide the mathematical formulations related to this combination in the case of GPS L1/L5 or Galileo E1/E5a signals. Carrier-phase random errors and multipath effects are very small compared with code pseudorange random errors and multipath effects, and so have been neglected in Eq. 9.

In Eqs. 6-10, w_{ij} is the WLNL code-phase combination on i and j signals, WL and NL are the widelane and narrowlane combination in distance units respectively, f_i is the i signal frequency in Hertz and K_{ij} is the multiplication factor depending on implied frequencies i and j.

$$WL_{\varphi_{15}} = \Phi_1 - \Phi_5 \quad (6)$$

$$NL_{P_{15}} = K_{15}\left[P_1 + P_5\right] \quad (7)$$

$$K_{15} = \frac{f_1 - f_5}{f_1 + f_5} \quad (8)$$

$$w_{15} = WL_{\varphi_{15}} - NL_{P_{15}} \quad (9)$$

$$w_{15} = N_1 - N_5 - K_{15}\left(M_{P_1} + \varepsilon_{P_1} + M_{P_5} + \varepsilon_{P_5}\right) \quad (10)$$

The main drawback of this combination for cycle slips detection is its high noise level due to the integration of code pseudorange measurements into the combination. Therefore, small cycle slips cannot be detected using this testing quantity. On the other hand, this combination is geometry-free, ionosphere-free and standalone (Eq. 10).

Triple frequency testing quantity: GFIF phase

The second testing quantity built in order to treat triple frequency data is the geometry-free ionosphere-free triple frequency phase combination, represented by Eqs. 11-13.

$$s_{ijk} = a_i\,\lambda_i\,\varphi_i + a_j\,\lambda_j\,\varphi_j + a_k\,\lambda_k\,\varphi_k \quad (11)$$

$$\begin{aligned} a_i &= \lambda_k^2 - \lambda_j^2 \\ a_j &= \lambda_i^2 - \lambda_k^2 \\ a_k &= \lambda_j^2 - \lambda_i^2 \end{aligned} \quad (12)$$

$$s_{ijk} = \sum_{l=i,j,k} a_l \lambda_l N_l + a_l (M_{\Phi_l} + \varepsilon_{\Phi_l}) \quad (13)$$

In Eq. 13, s_{ijk} is the geometry-free ionosphere-free triple frequency phase combination in distance units for i, j and k signals [6]. This combination is a simple linear combination of three carrier-phase measurements on three distinct signals with three coefficients a_i, a_j and a_k. By allocating specific values to the three coefficients (Eq. 12), this testing quantity is characterized by several important benefits: it is geometry-free, ionosphere-free, standalone and slightly noisy because it only includes carrier-phase measurements (Eq. 11). Inversely, the combination does not significantly vary for some specific combinations of simultaneous cycle slip on each frequency [8].

Detection method

The two testing quantities selected for dual and triple frequency cycle slips detection similarly behave when a cycle slips occur: the combination is affected by a shift in average. This common characteristic allows to initiate a similar discontinuity detection method on the two testing quantities, making the implementation and process of the method more simple and more efficient.

Running average filtering technique is especially suited to needs of our preprocessing method. To detect cycle slips at the current epoch, this technique consist of computing mean and standard deviation of the testing quantity from the beginning of the satellite visibility period to the tested epoch (not included). From the mean and standard deviation computed, the technique builds a confidence interval and detects a cycle slip if the current value of the testing quantity is out of it [4].

Drawbacks of running average filtering are due to the great inertia of statistical parameters: mean and standard deviation. At the beginning of a satellite visibility period, high noise and multipath level due to low satellite elevation involves a very large confidence interval. Inversely, at the end of a visibility period, the confidence interval does not follow data variability because of the great amount of data used to compute statistical parameters: the confidence interval is too close. On the other hand, this method uses only statistical information from data themselves and does not require any initial parameterization.

With the goal to get rid of specific running average filtering problems and to keep main benefits, this technique has been extended following rigorous statistical concepts.

The developed method relies on a moving average filter. Unlike a running average filter, the moving average filter computes statistical parameters from a fixed-size moving convolution window, filtering testing quantity values. By this way, statistical parameters are always computed from a same number of values. The only parameter to initialize is the size of the convolution window which depends on data variability. The moving average filter is formulated in Eqs. 14-15, where α_t and β_t are the moving mean and standard deviation parameters respectively, γ is the convolution window size and v_t is the value of the testing quantity at the epoch t.

$$\alpha_t = \frac{\sum_{i=1}^{\gamma} v_{t-i}}{\gamma} \tag{14}$$

$$\beta_t = \sqrt{\frac{\sum_{i=1}^{\gamma} (v_{t-i} - \alpha_t)^2}{\gamma - 1}} \tag{15}$$

Then, for in-depth development, the method is developed based on a classical statistical problem: from a sample extracted from a global population, the membership of a new individual is tested. Two types of events can be detected by the filtering technique: outliers (isolated peaks) and cycle slips (average shifts) (Fig. 5). When the detection process detects an outlier value, this value is not considered as being part of the population and the value is not included in statistical parameter computation. If the detection process detects a cycle slip, the moving mean parameter is shifted but the moving standard deviation is not reinitialized because cycle slips affect only the position parameter (moving mean) and not the dispersion parameter (moving standard deviation).

As outputs, the cycle slips detection method assigns a flag value to epochs affected by cycle slips or outliers and generates a final report.

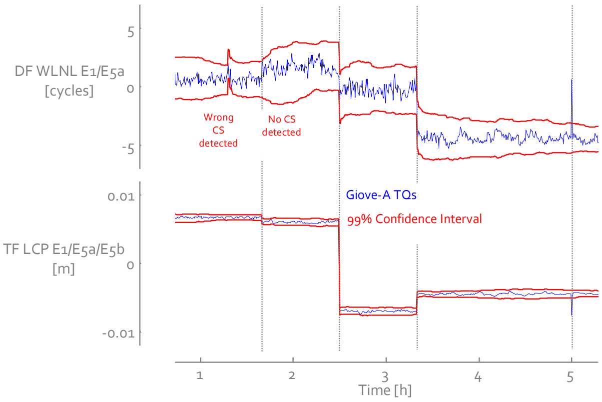

Figure 5. Availability of triple frequency data allow to build low noise testing quantity including only carrier-phase measurements and making cycle slips detection more efficient than dual frequency data. In this figure, cycle slips and outliers were manually inserted on E1 signal from Giove-A (ESA data from GKOU station - 18th January 2008) in order to compare dual and triple frequency cycle slips detection method. High noise level of the dual frequency testing quantity involves the detection of a wrong cycle slip and an undetected cycle slip between 1 and 2 o'clock AM.

3.3. Validation

In order to validate the developed method, fictive cycle slips were manually inserted in real data. By this way, we could validate the method in a great number of situations, e.g. with small and great cycle slips, with consecutive cycle slips and outliers, with cycle slips at the beginning, at the end and in the middle of satellite visibility period and with cycle slips on each frequency tested.

The cycle slips detection method was first sucessfully validated on dual frequency data from Septentrio PolaRx3eG receivers (GPS L1/L5 and Galileo E1/E5a signals). The moving average filtering allows the detection process to follow data variability. This improvement makes the method efficient especially at the beginning and at the end of a satellite visibility period. As expected, the detection process cannot detect small cycle slips because of the high noise and multipath level affecting the dual frequency testing quantity (Fig. 5).

Triple frequency cycle slips detection method was also validated on ESA Galileo triple frequency data (Fig. 5). The low noise level of the triple frequency testing quantity allows the detection of smallest cycle slips on each of the three frequencies implied in the cycle slips detection process.

In first conclusion, the detection process itself seems very efficient on all data preprocessed. In particular, problems in dual frequency cycle slips detection process are essentially due to testing quantity properties. With the future availability of triple frequency GNSS data from many satellites (GPS and Galileo), we think the effectiveness of cycle slips detection methods will increase.

4. DATA QUALITY ASSESSMENT

Data quality assessment consists in assessing the measurement noise and the multipath level which characterize raw measurements made by a receiver on GNSS satellite signals. In order to assess the quality of data recorded by our Septentrio PolaRx3eG receivers, we were inspired by a technique developed by the University of Delft. This technique is based on a geometry-free model (a linear combination of code pseudorange and carrier-phase measurements). Using polynomial fitting and time differencing on undifferenced, single and double differenced (Zero-Baseline (ZB) and Short-Baseline (SB)) single frequency measurements, it is possible to separate the different contributions to the measurement noise of code pseudorange and carrier-phase measurements for each signal and for each satellite [9].

Aiming at keeping standalone property of our preprocessing methodology, we only partially implemented the data quality assessment technique developed at the University of Delft. First, we built code-minus-phase linear combination in order to obtain a geometry-free model. Then, two approaches were exploited: the first consists in computing the standard deviation of polynomial fitting residuals while the second computes standard deviation after time differencing of the initial geometry-free model. The mean standard deviation is then estimated following method described in [9].

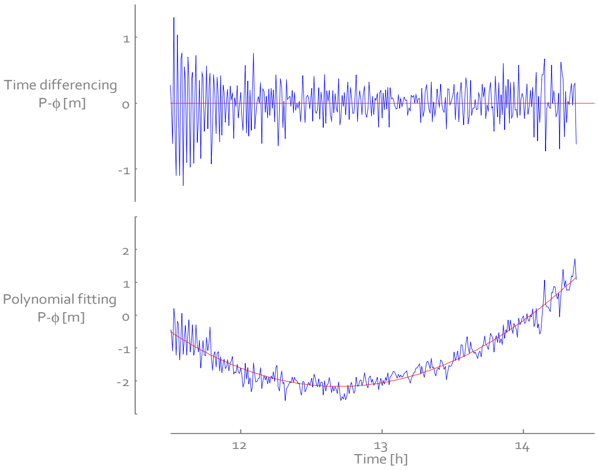

Figure 6. Noise level affecting code pseudorange measurements can be estimated by computing standard deviation of polynomial fitting and time differencing residuals based on a geometry-free model built from raw code pseudorange and carrier-phase measurements.

Currently, the final output of the preprocessing method regarding data quality assessment is a daily report including noise measurements values affecting code pseudorange measurements from all tracked satellites.

5. CONCLUSIONS

We presented in this paper the first version of a preprocessing method. This method was initially developed to treat GPS L1/L5 and Galileo E1/E5a data from Septentrio PolaRx3eG receivers but was finally enhanced to also be operational for triple frequency data from many other stations.

The first part of the method was conceived to compensate clock slips in raw observables due to the receiver handling of the internal clock drift. Based only on information from receiver RINEX observation file, the clock slips compensation technique provided conclusive results on all data recorded by our two Septentrio PolaRx3eG receivers.

The second part of the method, consisting in a cycle slip detection technique, meets also the standalone criteria. Extending some existing techniques, we developed a cycle slips detection method based on rigorous statistical concepts and first results of this method obtained on dual and triple frequency data were promising. In particular, the availability of triple frequency GNSS data makes possible the formation of low noisy testing quantity improving the sensitivity of cycle slips detection process.

Finally, the third part of the method was dedicated to data quality assessment. This methodology is inspired of a powerful procedure developed at the University of Delft [9] and could be strongly improved in the future.

REFERENCES

1. Misra, P. & Enge, P. (2006). *Global Positioning System: Signals, Measurements, and Performance*, 2nd ed., Ganga-Jamuna Press, Lincoln (USA), pp. 148-151.

2. Hofmann-Wellenhof, B., Lichtenegger, H. & Wasle, E. (2008). *GNSS Global Navigation Satellite Systems*, Springer-Verlag Wien, NewYork (USA), pp. 3-6.

3. Septentrio Satellite Navigation (2009). *Firmware User Manuel*, pp. 29-30.

4. Bisnath, S. B. (2000). *Efficient, automated cycle-slip correction of dual-frequency kinematic GPS data*. In Proc. ION GPS 2000, Salt Lake City (USA), pp. 145-154

5. Blewitt, G. (1990). *An automated editing algorithm for GPS data*. Geophysical Research Letters (**17**-3), pp. 199-202

6 Simsky, A. (2006). *Three's the charm – triple frequency combinations in future GNSS*. Inside GNSS (**5**), pp. 38-41. Tiberius C.

7 Werner, G. & Estey, L. (2007). *RINEX The Receiver Independent Exchange Format Version 3.00*.

8 Dai, Z., Knedlik S. & Loffeld, O. (2009). *Instantaneous Triple-Frequency GPS Cycle-Slip Detection and Repair*. International Journal of Navigation and Observation (**2009**), 15p.

9 de Bakker, P. F., van der Marel, H. & Tiberius C. (2009). *Geometry-free undifferenced, single and double differenced analysis of single frequency GPS, EGNOS and GIOVE-A/B measurements*. GPS Solution (**13**), pp. 305-314.

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