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Real-Time Receiver Clock Jump Detection for Code Absolute Positioning with Kalman Filter

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Abstract In global navigation satellite systems (GNSS) navigation the receiver and satellite clocks play a key role. The receivers are usually equipped with inaccurate quartz clocks, which experiment large drift relative to system time and consequently offset growing very fast; receiver manufactures bound the magnitude of the receiver clock offset to prevent it becomes too large and the actual bounding procedures vary from one manufacturer to another. The most common approach consists of introducing discrete jumps when the offset exceeds a threshold (usually 1 ms). This method is common in low-cost GNSS receivers and influences several applications as differential positioning, cycle-slip detection, precise point positioning technique, absolute positioning with Kalman filter. In this work some techniques to detect and account for millisecond clock jump, suitable for code positioning of a single receiver with Kalman filter, are proposed. Two deterministic algorithms to detect receiver clock jumps are shown: in measurement and parameter domain. The technique in measurement domain uses current pseudorange measurements compared with pseudorange and Doppler measurements at previous epoch; the technique in parameter domain compares current and previous least squares estimations of receiver clock bias, considering the clock drift. Two different approaches are described to account for the clock jumps, once detected, a deterministic one, consisting of fixing the pseudorange discontinuities, and a statistic one, consisting of suitably varying the Kalman filter settings. A static GNSS data set is processed with and without the proposed algorithms to demonstrate their efficiency.

Keywords GNSS · Clock jump · Kalman filter · Absolute positioning with pseudorange

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1 Introduction

Global navigation satellite systems (GNSS) are worldwide, all-weather navigation systems able to provide three-dimensional position, velocity and time synchronization to coordinated universal time (UTC) scale [1,2]. GNSS currently full operational are the US GPS and the Russian GLONASS, while the European Galileo and the Chinese BeiDou are in development phase [3]. GNSS operational principle is trilateration, based on distance measurements between the satellites and users/receivers. The satellite–receiver distance is derived by measuring the propagation time that a signal takes to travel from the satellite to the receiver. The propagation time is defined as the difference between the reception time (measured with the receiver clock) and the transmission time (measured with the satellite clock). Receiver and satellite clocks are not synchronized with the system time. The satellites are equipped with atomic clocks whose offset and drift with respect to the reference time scale are estimated by the system ground segment and are broadcast to the user in the navigation message. The receivers are usually equipped with inaccurate and inexpensive quartz clocks which experiment large drift relative to system time and consequently offset growing very fast; these two parameters are estimated along with receiver position and velocity respectively [4]. To limit the magnitude of the receiver clock offset, several receivers introduce discrete jumps when the offset exceeds a threshold (usually 1 ms). The most obvious consequence of the receiver clock jump is that the time tag of the estimated receiver position can be shifted up to 1 ms, with negligible effects for several applications (for a user travelling at 100 km/h an error of <3 cm is obtained). The techniques involving the use of two or more receivers, as differential and relative positioning, require the synchronization of the devices and are affected by the clock jump, as described by Kim and Lee [6,7]. In case of carrier phase use, the clock jumps must be eliminated to simplify the cycle-slip detection and correction [8,9]. In the precise point positioning technique, failure to properly detect and correct for receiver clock jump can yield large errors in solution [10,11]. When Kalman Filter (KF) is used for absolute positioning with pseudorange measurements, clock jumps must be detected and properly accounted for, before using measurements in the filter; if otherwise the jumps are ignored, the measurements will be affected by a common error of about 300 km bringing to large position errors [5].

The objective of this work is to propose algorithms to detect and account for receiver clock jumps in case of KF absolute positioning with only code; the algorithms require only pseudorange at two consecutive epochs and Doppler measurements at the first epoch (used to “predict” the behavior of the pseudorange or to compute the receiver clock drift).

The authors consider this particular aspect not documented in literature, although post-processing techniques [12] or algorithms involving combination of carrier phase and pseudorange [6,10,11] have been introduced.

2 Kalman Filter and its Application for Absolute Positioning with Pseudorange Measurements

The Kalman filter is a technique commonly used in navigation, it is a recursive algorithm consisting of prediction and update steps, related to the process and the measurement model respectively, to obtain an optimal state vector estimate in a minimum variance sense [13,14].

The prediction step is used to predict the state and its covariance matrix from the current to the next epoch and consists of the following equations:

$$\underline{\hat{x}}_{k+1}^{-} = \Phi_k \underline{\hat{x}}_k^{+} \tag{1}$$

$$P_{k+1}^{-} = \Phi_k P_k^{+} \Phi_k^T + Q_k \tag{2}$$

where the superscript "−" indicates a predicted (or a priori) quantity (i.e. before the measurement update) and the superscript "+" indicates a corrected (or a posteriori) quantity (i.e. after the measurement update), Φ is the transition matrix, P is the covariance matrix of the state and Q is the covariance matrix of the process noise.

The update step is used to correct the predicted state and the covariance matrix with the measurements, as shown below:

$$\underline{\hat{x}}_{k+1}^{+} = \underline{\hat{x}}_{k+1}^{-} + K_{k+1} \underline{\upsilon}_{k+1} \tag{3}$$

$$P_{k+1}^{+} = (I - K_{k+1} H_{k+1}) P_{k+1}^{-} \tag{4}$$

where K is the Kalman gain matrix and $\underline{\upsilon}$ is the innovation vector respectively defined as

$$K_{k+1} = P_{k+1}^{-} H_{k+1}^T (H_{k+1} P_{k+1}^{-} H_{k+1}^T + R_{k+1})^{-1} \tag{5}$$

$$\underline{\upsilon}_{k+1} = \underline{z}_{k+1} - H_{k+1} \underline{\hat{x}}_{k+1}^{-} \tag{6}$$

The innovation vector is an indication of the amount of information introduced in the system by the current measurements. The Kalman gain matrix is a weighting factor, indicating how much the new information, contained in the innovation vector, influences the final state vector estimate.

The positioning with the pseudorange observable (or code) is the basic GNSS mode and it requires simply the measurements and the broadcast ephemerides to obtain the user position [2]. The least squares (LS) adjustment is the estimation technique usually adopted for it and is a snapshot technique, i.e. only the current measurements are used; past measurements can be considered using the KF, to improve the state estimation [2].

The pseudorange equation is:

$$\rho = d + c\delta t + \varepsilon \tag{7}$$

where ρ is the pseudorange measurement, d is the receiver–satellite distance, $c\delta t$ is the receiver clock offset, ε contains the residual measure errors after atmospheric and satellite clock corrections.

The measurement model consists of equations as (7), linearized for the unknowns, and assumes the following expression:

$$\underline{\Delta\rho} = H \cdot \underline{\Delta x} + \underline{\varepsilon} \tag{8}$$

where $\underline{\Delta\rho}$ is the difference between actual and predicted measurements, $\underline{\Delta x}$ is the state vector, consisting of the receiver position and clock errors used to correct previous state, and $\underline{\varepsilon}$ is the residual error vector.

The process model must be selected according to the user dynamics so that KF has an improvement relative to least squares; for a stationary user at an unknown location the position states are usually modeled as random walk or Gauss-Markov processes (P model). For user with low or high dynamics respectively velocity or acceleration states are modeled as random walk processes (PV or PVA models) as described by Parkinson and Spilker [15].

3 Receiver Clock Jump

GNSS receiver manufactures bound the magnitude of the receiver clock offset to prevent it becomes too large [5]; although the actual bounding procedures vary from one manufacturer to another, they can be classified in two different categories: “continuous clock steering” and “discrete clock jumping”.

In the first case, the receiver continuously steers the oscillator, driving the drift approximately to zero and the offset to a constant within the level of noise; this method has usually negligible effects on widespread GNSS applications and is common in high-grade receivers [6].

On the contrary in the last one the receiver clock is adjusted by introducing discrete jumps when the offset exceeds a threshold; this method is common in low-cost GNSS receivers and influences several applications as differential positioning, cycle-slip detection, PPP technique, absolute positioning with KF. These jumps usually occur when the clock offset exceeds 1 ms in magnitude and therefore are called millisecond jumps; in some receivers the jumps are larger than one ms (such as 5 or 10) but in this work only the most common case of ms jump is considered.

In particular the millisecond jump strongly influences the absolute positioning with KF and code measurements; in fact, when a discrete clock jump occurs, the innovation vector contains a common bias of about 300 km (1 ms expressed in distance units) which is distributed on the state components according to the Kalman gain matrix. This bias, if unaccounted, yields a large position error, hence a method for detection and compensation of the jumps must be adopted prior to enter the measurement in the filter.

4 Clock Jump Detection in Measurement and Parameter Domain

The receiver clock jump issue, in case of absolute positioning with code measurements and Kalman filter processing, can be treated in measurement or parameter domain.

In measurements domain the relationship between pseudorange observations at two consecutive epochs has to be considered:

$$\rho(t+\Delta t) \cong \rho(t)\dot{\rho}(t)\cdot\Delta t - c\cdot\Delta + \epsilon \tag{9}$$

where Δt is the time-difference between the observations, $\dot{\rho}$ is the pseudorange rate, Δ is the discrete jump (non-zero when a clock jump occurs) and ϵ contains the residual errors of higher order.

To perform a jump detection, a decision variable is compared with a threshold; the variable is defined as:

$$S_m = |\rho(t+\Delta t) - \rho(t) - \dot{\rho}\cdot\Delta t| = |\Delta\rho - \dot{\rho}(t)\cdot\Delta t| \tag{10}$$

and represents the difference between the pseudoranges at current and previous epochs, corrected with the evolution of the measurements indicated by the term $[\dot{\rho}(t)\cdot\Delta t]$. The pseudorange rate can be obtained multiplying the Doppler measurement with the wavelength (rigorously this is the derivative of the carrier phase). The variable S_m will indicate at each epoch the variation in the pseudorange not accounted by the evolution term $[\dot{\rho}(t)\cdot\Delta t]$, and will be about 300 km in case of millisecond jump and few meters otherwise.

The threshold T_m is set as

$$T_m = c\cdot 10^{-3} - 3\cdot\sigma_m \tag{11}$$

where c is the speed of light, σ_m is the pseudorange uncertainty (after atmospheric and satellite clock corrections) which in open-sky environment is about 5 m [2].

At each epoch, for each visible satellite a decision variable, as defined in (10), is computed and compared with the threshold; because the receiver clock jump, if present, equally affects all the measurements, only if all the variables exceed the threshold a jump is detected.

A similar decision variable is defined in [6,11], where the evolution term is replaced with the difference between carrier phase (in distance units), i.e. $\lambda \cdot \varphi$, at current and previous epochs

$$|[\rho(t+\Delta t)-\rho(t)]-[\lambda \cdot \varphi(t+\Delta t)-\lambda \cdot \varphi(t)]| = |\Delta\rho - \lambda \cdot \Delta\varphi|$$

The two decision variables, although mathematically identical, because $[\lambda \cdot \varphi(t+\Delta t)-\lambda \cdot \varphi(t)] = [\dot{\rho}(t) \cdot \Delta t]$, are practically different; indeed in several receivers, carrier phase is affected by clock jump as pseudorange, hence the variable $|\Delta\rho - \lambda \cdot \Delta\varphi|$ is not able to detect a jump on the pseudorange, while $|\Delta\rho - \dot{\rho}(t) \cdot \Delta t|$ is always able to do it and so is suitable for the considered application.

The proposed clock jump detection method in measurement domain can be implemented in real-time.

In parameter domain a decision variable to detect millisecond receiver jumps can be defined as

$$S_p = |c\delta t(t+\Delta t) - c\delta t(t) - c\dot{\delta t}(t) \cdot \Delta t| = |\Delta(c\delta t) - c\dot{\delta t}(t) \cdot \Delta t| \tag{12}$$

where the receiver clock bias $c\delta t$ is estimated with LS method as fourth unknown in the pseudorange positioning and the receiver clock drift $c\dot{\delta t}(t)$ is estimated, together with velocity, using Doppler measurements and LS method [2].

To perform a jump detection, the decision variable S_p has to be compared with a threshold

$$T_p = c \cdot 10^{-3} - 3 \cdot \sigma_{c\delta t} \tag{13}$$

where $\sigma_{c\delta t}$ is the standard deviation of clock bias at current epoch, obtained from the variance-covariance matrix of the positioning state.

The proposed clock jump detection method in parameter domain is not a good choice for real-time applications, because requires the LS pre-processing of the pseudorange measurements at current epoch before applying the KF for the solution.

5 Clock Jump Compensation

Once a jump is detected, it must be taken into account to avoid a large error in the solution. In this work the value of the jump is considered known and equal to 1 ms; anyway the clock jump value can be recovered from receiver characteristics or can be simply computed by using the methods described in [11].

A deterministic approach for clock jump compensation consists of fixing the pseudorange discontinuities; to this purpose a correction of $c \times 10^{-3}$ is applied to the current and future pseudorange sets. After the correction, the pseudoranges and the clock offset become continuous as shown in Figs. 1 and 2, where the measurements and the offset are plotted with and without clock jump compensation procedure.

An alternative approach, more empirical than the previous one, consists of increasing the process noise of the clock bias when a jump is detected. The reason undergoing this empirical method can be explained considering that a jump on the receiver clock is essentially an unmodeled error for the process model; increasing the clock bias noise in the process model,

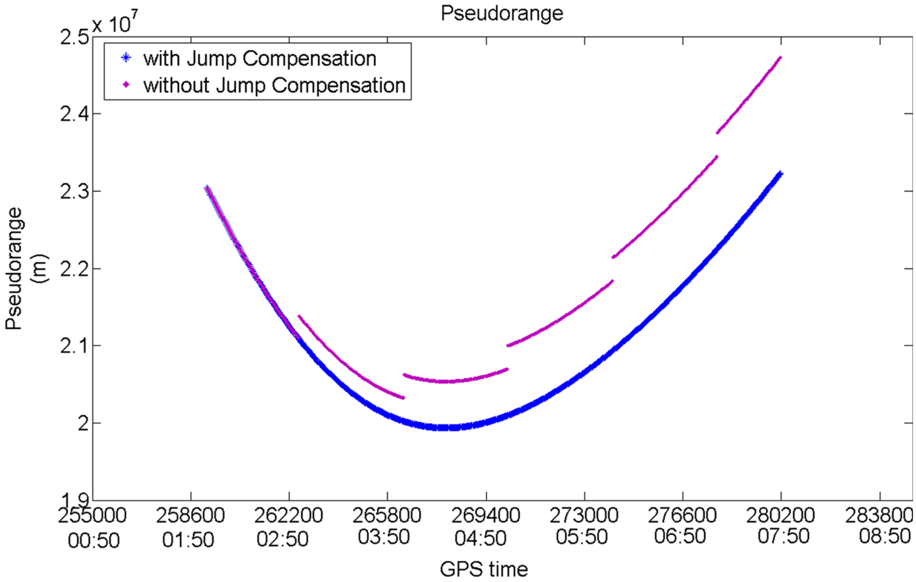


Fig. 1 GPS pseudorange with and without receiver clock compensation (Naples Station, PRN 32, Day 142 2013)

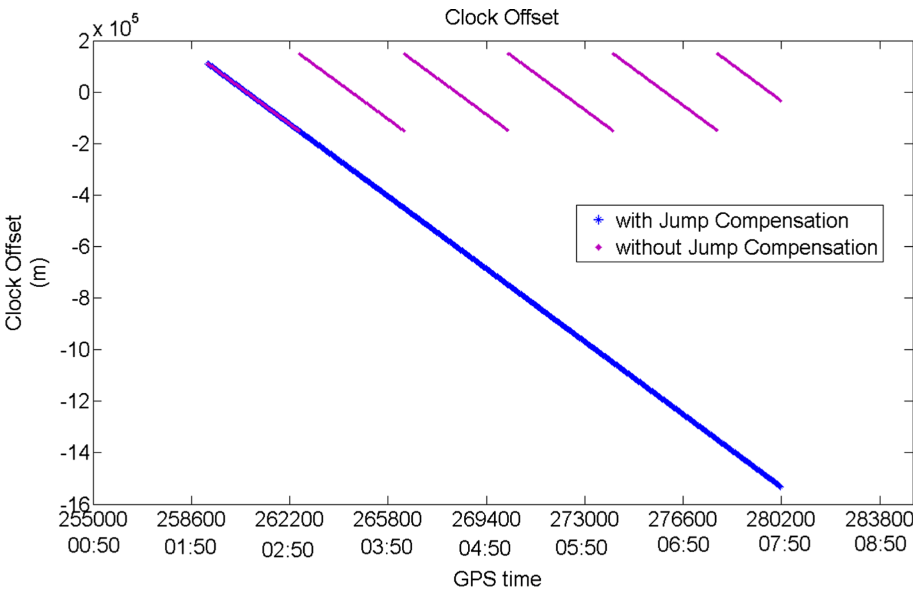


Fig. 2 Receiver clock offset with and without compensation (Naples Station, Day 142 2013)

corrects the problem, making the jump occurrence not un-modeled. This approach does not require the exact knowledge of the clock jump, but only its order of magnitude.

The efficiency of the two methods proposed is verified for a static test in the next section.

6 Test

To demonstrate the influence of the receiver clock jump on GNSS absolute positioning with pseudorange measurements and KF, one day of data is processed with the aforesaid technique with and without the application of the jump compensation procedures. The data have been download from the GNSS permanent station of Naples, belonging to the Campania Regional GNSS Network (http://gps.sit.regione.campania.it/), they refer to 22th May 2013 and their observation interval is 30 s. The equipment of the station includes a receiver Topcon Net—G3 and an antenna Topcon CR-G3.

The software adopted belongs to a tool implemented at the PArthenope Navigation Group of Parthenope University of Naples (http://pang.uniparthenope.it).

In this work only the GPS data are processed, but the results can be extended to other GNSS systems.

The session is static, hence a P model approach is adopted to define the process model of the KF. The covariance matrix of the process noise Q is set in order to consider that the receiver position is constant (small uncertainty on the coordinates) and that clock offset is uncertain because of clock drift and 30 s observation interval; the adopted Q matrix is detailed below (with values in meters squared):

$$Q = \begin{bmatrix} 0.3 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 \\ 0 & 0 & 0.3 & 0 \\ 0 & 0 & 0 & 5000 \end{bmatrix}$$

The measurement covariance matrix is diagonal (i.e. the measurement errors are considered uncorrelated) and is related to both satellite elevation and URA parameter as described in [16].

The clock jump detection methods, in measurement and parameter domain, work properly for the considered data, identifying all the jumps occurred during the session.

In figures 3 and 4 respectively the horizontal position and the altitude obtained with and without the clock jump compensation are shown.

In Fig. 3 it can be noticed that the horizontal position uncompensated for the jump largely coincides with the compensated solutions, except for few points which show errors few meters larger; the jump uncompensated altitude experiments errors several meters larger relative to the compensated solutions (Fig. 4). The compensated solutions are very similar, as it can be noticed in Figs. 3 and 4, where the magenta and the green lines are almost coincident.

For a more quantitative analysis, the horizontal and vertical errors are shown in Fig. 5, compared with the clock offset behavior. The Fig. 5 clearly demonstrates that the uncompensated receiver clock jumps yield errors in both horizontal and vertical components, with the last especially influenced owing to the strict correlation between altitude and clock state [15]. Moreover it must be noticed that the two compensated solutions are very similar, but their estimated clock bias are different: in jump compensation with discontinuity fixing the clock bias has a linear behavior, while in case of process noise increasing the clock bias maintains the typical saw-tooth form.

In Table 1 the performance of the considered configurations are shown in terms of RMS and maximum errors. The RMS of clock jump uncompensated and compensated cases are close because the solutions are practically identical except for the epochs when the clock jumps occur; on the other hand the maximum errors are very different, with the maximum vertical error of uncompensated configurations about 3 times its homologous of compensated case.

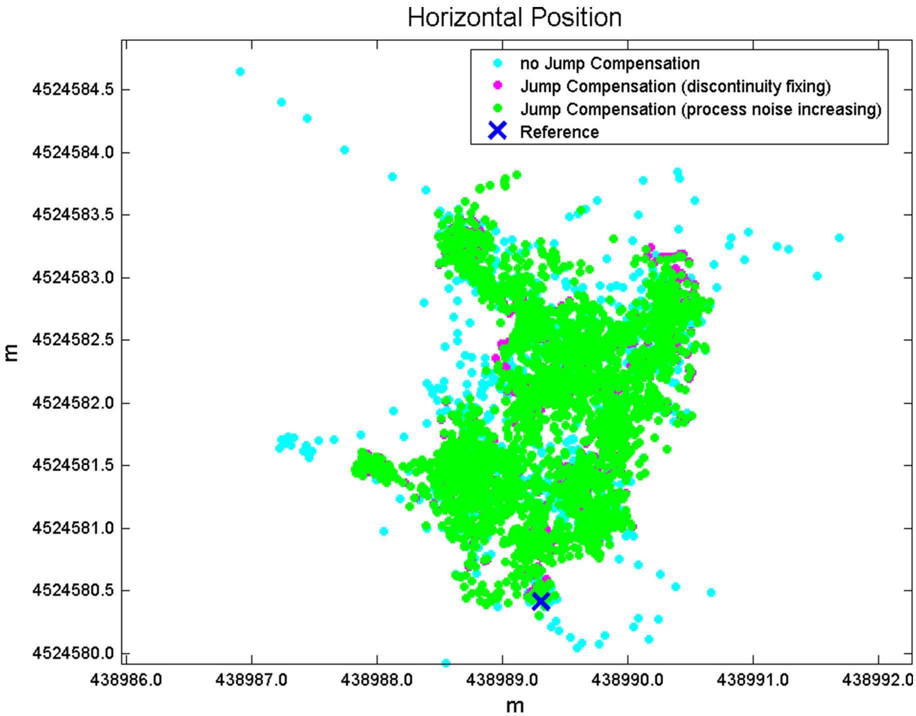


Fig. 3 *Horizontal position* with and without compensation (Naples Station, Day 142 2013)

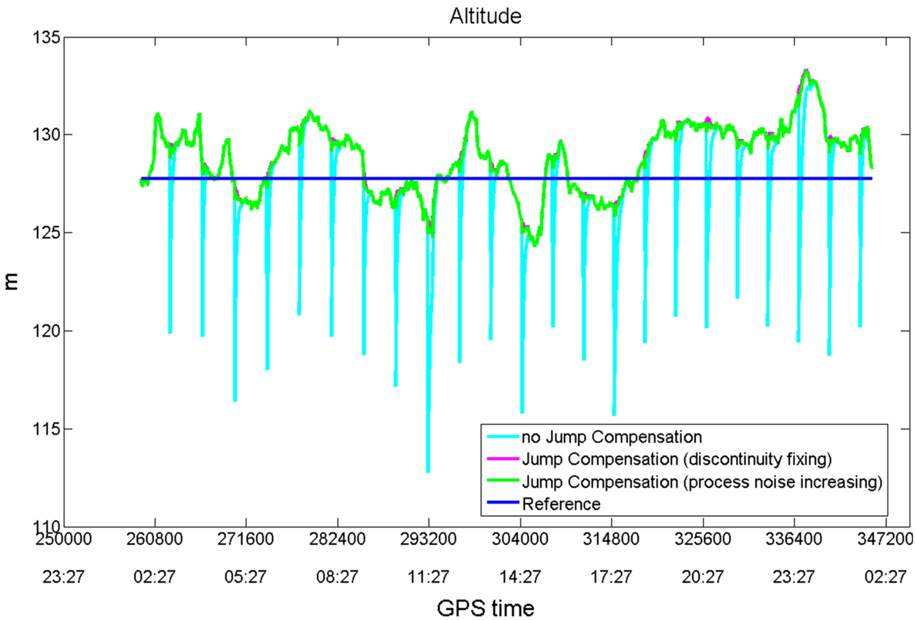


Fig. 4 *Vertical position* with and without compensation (Naples Station, Day 142 2013)

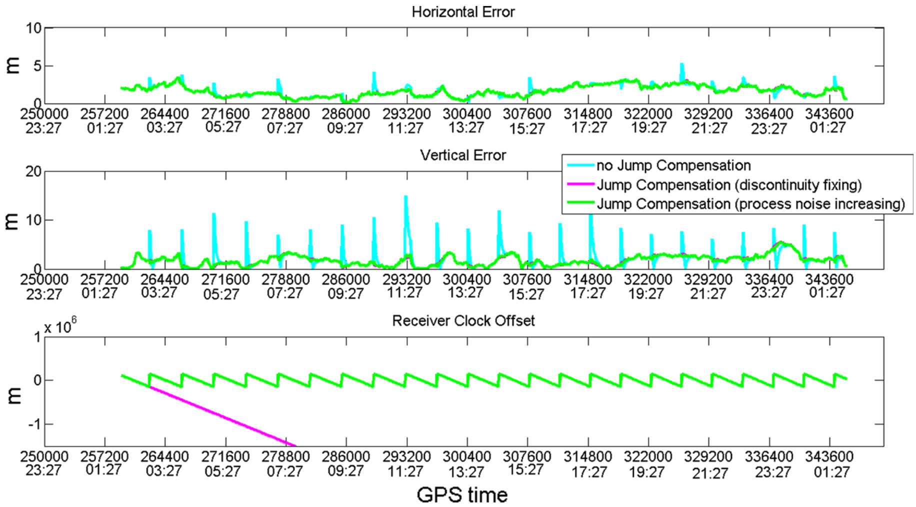


Fig. 5 *Horizontal and vertical errors* with and without compensation (Naples Station, Day 142 2013)

Table 1 RMS and maximum horizontal and vertical errors with and without compensation (Naples Station, Day 142 2013)

	RMS (m)		Max (m)	
	H	V	H	V
Clock jump uncompensated	1,80	2,49	5,27	15,01
Clock jump compensated "discontinuity fixing"	1,75	2,01	3,42	5,58
Clock jump compensated "process noise increasing"	1,75	2,00	3,42	5,51

7 Conclusions

In this paper the influence of the receiver clock jump on the absolute positioning with Kalman filter and code measurements is analyzed; a GPS static data set of 24 h, with observation interval of 30 s, is processed.

It is shown that if the problem is ignored, large errors are observed on horizontal and above all on vertical solution when the jumps occur. The altitude is the most influenced component owing to its strict correlation with the clock offset state.

Two detection methods of clock jumps are proposed, in measurement and parameter domain. In measurement domain, the jump detection is based on the analysis of the current pseudorange measurements compared with pseudorange and Doppler measurements at previous epoch. In parameter domain, the detection is based on the comparison between consecutive clock biases (estimated with LS), considering the estimated clock drift. The test carried out demonstrates that both methods are effective, detecting all the jump when occur.

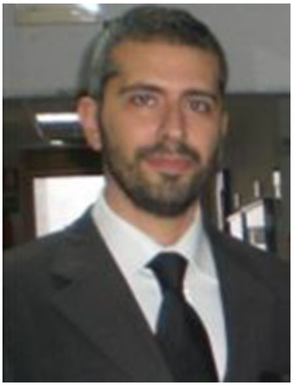
To account for the jumps, two methods are proposed. In the first every time a jump is detected, the current (and future) pseudorange measurements are corrected for the jump amount in meters, making the observable behavior continuous. In the last the process noise of the clock bias is increased when a jump is detected.

The test carried out demonstrates that both methods are effective and yield very similar results; in fact the compensated solutions shows an almost halved maximum horizontal error and vertical one reduced to 1/3.

The method is tested for GPS data only, but it can be applied to each GNSS system. Only the single frequency case has been analyzed, but the proposed methods can be applied to double-frequency case too.

References

1. Hoffmann-Wellenhof, B., Lichtenegger, H., & Collins, J. (1992). *Global positioning system: Theory and practice*. Wien: Springer.
2. Kaplan, E. D., & Hegarty, J. (2006). *Understanding GPS: Principles and applications* (2nd ed.). London: Artech House.
3. Angrisano, A., Gaglione, S., Gioia, C., Borio, D., & Fortuny-Guasch, J. (2013). Testing the test satellites: The Galileo IOV measurement accuracy. In *International conference on localization and GNSS, ICL-GNSS 2013*.
4. Angrisano, A., Gaglione, S., & Gioia, C. (2013). Performance assessment of GPS/GLONASS single point positioning in an urban environment. *Acta Geodaetica et Geophysica*, *48*(2), 149–161.
5. Petovello, M. (2011). GNSS solutions: Clock offsets in GNSS receivers. *Inside GNSS* 23–25.
6. Kim, H. S., & Lee, H. K. (2012). Elimination of clock jump effects in low-quality differential GPS measurements. *Journal of Electrical Engineering & Technology*, *7*(4), 626–635.
7. Kim, H. S., & Lee H. K. (2009). Compensation of time alignment error in heterogeneous GPS receivers. In *Proceedings of the 13th IAIN world congress, 27–30 Oct, Stockholm, Sweden*.
8. Kim, D., & Langley, R. B. (2001). Instantaneous real-time cycle-slip correction of dual-frequency GPS data. In *Proceedings of the international symposium on kinematic systems in geodesy, geomatics and navigation, Banff, Alberta, Canada, 5–8 June 2001*, pp. 255–264.
9. Kim, D., & Langley, R. B. (2002). Instantaneous real time cycle-slip correction for quality control of GPS carrier-phase measurements. *Journal Of the Institute of Navigation*, *49*(4), 205–222.
10. Guo, F., & Zhang, X. H. (2012). Real-time clock jump detection and repair for precise point positioning. In *Proceedings of the ION GNSS 2012* (pp. 17–21). Nashville, USA.
11. Guo, F., & Zhang, X. (2013). Real-time clock jump compensation for precise point positioning. *GPS Solutions*. doi:10.1007/s10291-012-0307-3.
12. Lonchay, M., Bidaine, B., & Warnant, R. (2011). An efficient dual and triple frequency preprocessing method for GALILEO and GPS signals. In *Proceedings of the 3rd international colloquium scientific and fundamentals aspects of the GALILEO programme, Copenhagen, Denmark, 31 Augs–2 Sept*.
13. Bar-shalom, Y., Li, X., & Kirubarajan, T. (2001). *Estimation with applications to tracking and navigation*. New York: Willey.
14. Kalman, R. E. (1960). A new approach to linear filtering and prediction problems. Trans. ASME J. Basic Engr. pp. 35–45.
15. Parkinson, B., & Spilker, J. J. (1996). *Global positioning system: Theory and applications* (Vol. 1–2). Washington, DC: American Institute of Aeronautics and Astronautics.
16. Angrisano, A., Gaglione, S., & Gioia (2012). RAIM algorithms for aided GNSS in urban scenario. In *Proceedings of the ubiquitous positioning indoor navigation and location based service, Helsinki, Finland, October 2012*.



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Salvatore Troisi graduated in January 1984 with honors and praise in Nautical Sciences at the Faculty of Nautical Sciences of the Naval University in Naples, with an experimental thesis in Nautical Astronomy on the use of optical amplification of light. Since'87 he is researcher for the group 135 (first discipline Complements Topography) at the Faculty of Nautical Sciences of the Naval University of Naples. Since November 1998 to September 2007 he served as associate professor of SSD ICAR 06 at the Faculty of Nautical Sciences of the Naval University of Naples. Since October 2007 he is full professor SSD ICAR06 at the Faculty of Science and Technology of the Parthenope University of Naples.