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A New Algorithm of Compensation of the Time Interval Error GPS-Based Measurements

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Abstract: In this paper we present a new algorithm of compensation of the time interval error (TIE) applying an unbiased *p*-step predictive finite impulse response (FIR) filter at the signal of the receiver Global Positioning System (GPS)-based measurements. The practical use of the system GPS involves various inherent problems of the signal. Two of the most important problems are the TIE and the instantaneous loss of the signal of the GPS by a small interval of time, called "holdover". The error holdover is a problem that at present does not possess solution and the systems that present this type of error produce lines of erroneous synchronization in the signal of the GPS. Basic holdover algorithms are discussed along with their most critical properties. Efficiency of the predictive filter in holdover is demonstrated in applications to GPS-based measurements of the TIE. *Copyright © 2010 IFSA.*

Keywords: GPS-based measurements, Time interval error, Holdover, Unbiased predictive FIR filter

1. Introduction

The problem of accuracy of wirelessly disciplined local clocks and oscillators arises whenever a synchronizing signal is temporary not available. The relevant operation mode is termed “holdover” and technical solutions for holdover are often crucial for both ground and space applications. Holdover can also be implied for available, but “bad” synchronizing signals.

In different applications, it is required to obtain normal functioning in holdover during all time. In deep space, oscillators and clocks typically operate without synchronizing signals meaning that normal functioning is required for years and decades of years [1]. The holdover time differs for different clocks being specified via the allowed fractional frequency departure that, for instance, in digital communication network nodes should not be greater than 1×10^{-11} [2].

In a short term (days and months), the holdover problem may be solved by predicting current errors via the nearest past history. On a long time base (months and years), internal resources may be exploited if additional resonances of the oscillator resonant system are observable. In applications to the oven controlled crystal oscillators (OCXOs), the long-term holdover approach was developed in [3] as the modulational method. The method employs a high aging correlation of the fundamental and harmonic frequencies of crystal resonators [4] to form a synchronizing signal. Its application to an OCXO with the AT-cut quartz crystal resonator has demonstrated an extremely small long-term frequency drift of about -3×10^{-10} /year [5].

Based upon prediction, the clock or oscillator holdover technology prolongs continued functioning time after loss of a synchronizing signal. For the clock to operate in holdover, prediction is provided of the time error at a current discrete time n by processing the nearest available past measurements. A control loop is then organized such that the synchronizing signal is produced by prediction. Based upon, different approaches can be used. One may employ extrapolation methods or prolong an interpolating function (Lagrange and Newton methods, splines, etc.) [6] and regression curve from the past to n that have been applied to clocks by many authors [7-13]. Setting aside these methods, the 1-step toward predictive FIR filters were derived by Heinonen and Neuvo in [14] employing the Lagrange multipliers. It was also stated in [7] that linear predictors are optimal or close to optimal for the prediction of clock instabilities.

Representation of the clock model in state space allows solving the problem from the standpoint of system theory using the Kalman filter. Suitable for holdover, the predictive Kalman filtering algorithms are used in many works as [15], [16] owing to a strong advantage: the current clock state is predicted via its past state. A disadvantage is that the Kalman filter needs the covariance of commonly unknown for users the clock noise. Moreover, Kalman claims the model to be known and all noises white Gaussian. Otherwise, under the model temporary uncertainty and non Gaussian noises, the Kalman filter may produce biased and noisy estimates [17]. The errors can be reduced using finite impulse response (FIR) filters having inherent bounded input/bounded output (BIBO) stability and better robustness against temporary model uncertainties and round-off errors. By FIR filters, measurement on a horizon of N past points is processed to estimate the state at n. Extensive investigations of optimal FIR filtering of state space models have been provided by Kwon et. al. [18-20] resulting in the theory of receding horizon control [21]. Of importance is that gains of the unbiased FIR filters do not depend on noise properties [14] and past system states [19, 22] that makes such filters simple for applications. An unbiased predictive FIR filter was proposed by [24] of a class of discrete time state space models associated with holdover problems in remote wireless clock synchronization, such as the Global Positioning System (GPS)-based.

In this paper, we present a new algorithm of compensation of the time interval error (TIE) applying the unbiased p-step predictive finite impulse response (FIR) filter at the signal of the receiver Global Positioning System (GPS)-based measurements.

2. Clock Time Model and Problem Formulation

The discrete time-invariant model of a local clock can be represented in state space at a current time point n with the state and observation equations, respectively, as follows

$$\lambda_n = A\lambda_{n-1} + w_n, \tag{1}$$

$$\xi_n = C\lambda_n + v_n, \tag{2}$$

where $K \times 1$ is the vector of the clock states x_{kn}, $k \in [1, K]$, is

$$\lambda_n = [x_{1n} x_{2n} \dots x_{Kn}]^T, \tag{3}$$

in which x_{1n} is the time interval error (TIE), x_{2n} is the fractional frequency offset, x_{3n} is the fractional frequency drift rate, etc. The $K \times K$ transition matrix

$$A = \begin{bmatrix} 1 & \tau & \frac{\tau^2}{2} & \dots & \frac{\tau^{K-1}}{(K-1)!} \\ 0 & 1 & \tau & \dots & \frac{\tau^{K-2}}{(K-2)!} \\ 0 & 0 & 1 & \dots & \frac{\tau^{K-3}}{(K-3)!} \\ \vdots & \vdots & & \ddots & \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix} \tag{4}$$

projects a nearest past clock state λ_{n-1} to the current state λ_n, where τ is a sampling time identical to 1s in GPS-based clock synchronization using the one pulse per second (1PPS) signal. For the measurement ξ_n of the clock first state x_{1n} used in synchronization, the $1 \times K$ measurement matrix is

$$C = [1 \quad 0 \quad \dots \quad 0]. \tag{5}$$

The $K \times 1$ clock noise vector

$$w_n = [w_{1n} w_{2n} \dots w_{Kn}]^T \tag{6}$$

contains zero-mean components with known covariance. In GPS-based synchronization, via 1PPS signals, the TIE excursions are compensated on a horizon of *N* points in the presence of the zero-mean measurement noise v_n that commonly dominates.

Let us now suppose that the 1PPS-based measurement ξ_n (2) has been provided from some far past point up to *n*-1. At *n*, measurement is not available or wrong (inapplicable). The problem formulates as follows. We would like to derive an unbiased *p*-step predictive FIR filter of the clock first state x_1 at *n* by processing the data taken from the time interval $[n - N + 1 - p, n - p]$, $p > 0$, of the past history (see Fig. 1). In such a formulation, the problem seems to be most general for holdover. We also would like to test the filter by simulation and GPS-based sawtooth and sawtooth-less measurements of the TIE of a crystal clock.

3. An Unbiased *p*-step Predictive FIR Filter

Below, following the diagram shown in Fig. 1, we derive a real time unbiased FIR estimator intended for *p*-step predictive filtering of the clock state x_{1n}.

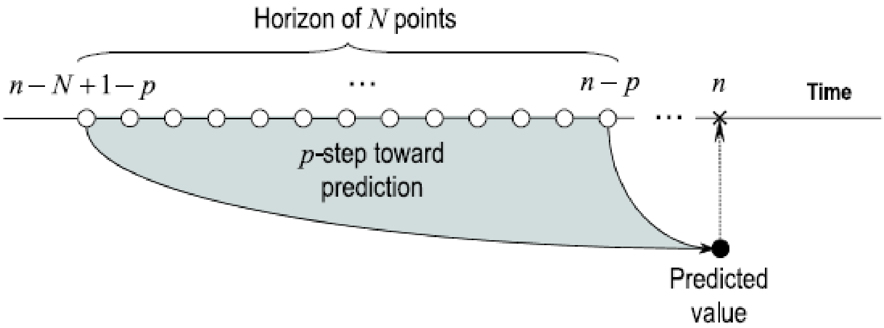


Fig. 1. The p-step toward predictive FIR filtering problem for holdover.

3.1. General Relations

To find the estimate, we start at $n-N+1-p$ and represent (1) and (2), neglecting w_n, as

$$\lambda_n = A^{N-1+p}\lambda_{n-N+1-p}, \tag{7}$$

$$\xi_n = C\lambda_n + v_n, \tag{8}$$

where

$$A^i = \begin{bmatrix} 1 & \tau i & \frac{\tau^2 i^2}{2} & \dots & \frac{(\tau i)^{K-1}}{(K-1)!} \\ 0 & 1 & \tau i & \dots & \frac{(\tau i)^{K-2}}{(K-2)!} \\ 0 & 0 & 1 & & \frac{(\tau i)^{K-3}}{(K-3)!} \\ \vdots & \vdots & & \ddots & \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix}. \tag{9}$$

Now, the noiseless state model (7) projects ahead from $n-N+1-p$ to n with the degree Taylor polynomial such that the first state (TIE) is represented with

$$\begin{aligned} x_{1n} &= \sum_{q=0}^{K-1} \bar{x}_{1+q} \frac{\tau^q (N-1+p)^q}{q!} \\ &= \bar{x}_1 + \bar{x}_2 \tau(N-1+p) + \bar{x}_3 \frac{\tau^2 (N-1+p)^2}{2} + \dots + \bar{x}_K \frac{[\tau(N-1+p)]^{K-1}}{(K-1)!}, \end{aligned} \tag{10}$$

where $\bar{x}_k \underline{\underline{\Delta}} x_{k(n-N+1-p)}, k \in [1, K]$, is the clock k-state at $n-N+1-p$.

To provide the p-step toward predictive estimate $\bar{x}_{1n} \underline{\underline{\Delta}} \bar{x}_{1n|n-p;N}$ of x_{1n} via (7) and (8) utilizing N points starting at $n-N+1-p$, the discrete-time convolution operator can be applied to (8),

$$\tilde{x}_{1n} = \sum_{i=p}^{N-1+p} h_{li}\xi_{n-i} = W_l^T \Xi, \tag{11}$$

where $l \geq 0$ is the degree of thee FIR filter polynomial gain h_{li}. The l-degree $N \times 1$ gain matrix and

$N \times 1$ matrix of measurements are given with, respectively,

$$W_l = \left[h_{lp} h_{l(p+1)} \ldots h_{l(p+N-1)}\right]^T, \tag{12}$$

$$\Xi = \left[\xi_{n-p} \xi_{n-p-1} \ldots \xi_{n-p-N+1}\right]^T. \tag{13}$$

It is known that unbiasedness in the FIR estimate is guaranteed if h_{li}, existing from p to $N-1+p$, obeys several fundamental properties. Modified for (11), these properties, namely

$$\sum_{i=p}^{N-1+p} h_{li}(N,p) = 1, \tag{14}$$

$$\sum_{i=p}^{N-1+p} h_{li}(N,p) i^u = 0, \; u \in [1,l], \tag{15}$$

assure that the prediction error is zero in the absence of noise when $K \le l+1$.

3.2. Generic Coefficients for Polynomial Gains

To specify W_l, it needs examining the mean square error (MSE) of the predicted estimate (11),

$$J = E\left\{\left(x_{1n} - \tilde{x}_{1n}\right)^2\right\} \tag{16a}$$

$$= E\left\{\left(x_{1n} - W_l^T \Xi\right)^2\right\} \tag{16b}$$

$$= E\left\{\left(x_{1n} - W_l^T \mathrm{X} - W_l^T v\right)^2\right\}, \tag{16c}$$

where

$$\mathrm{X} = \left[x_{1(n-p)} x_{1(n-p-1)} \ldots x_{1(n-p-N+1)}\right]^T, \tag{17}$$

$$v = \left[v_{1(n-p)} v_{1(n-p-1)} \ldots v_{1(n-p-N+1)}\right]^T. \tag{18}$$

By the commutativity property $W_l^T v = v^T W_l$ and zero-mean noise, $E\{v_n\} = 0$, we have

$$J = \left(x_{1n} - W_l^T \mathrm{X}\right)^2 + W_l^T R W_l, \tag{19}$$

where the $N \times N$ covariance matrix R has a generic component $R_{ij} = E\{v_i v_j\}, i, j \in [n-p, n-p-N+1]$. as can be seen, the first term in (19) represents the square bias and the second one the variance, both in the p-step toward prediction of the clock 1-state. It also follows that, in order for the prediction to be unbiased at any point, the following equality must be satisfied, namely

$$x_{1n} = W_l^T \mathrm{X}. \tag{20}$$

To solve (20) for W_l, the well known from the Kalman-Bucy filter theory condition may be applied, namely: the order of the optimal filter is the same as that of the system. That means that for x_{1n} represented with (10) and the $(K-1)$-degree polynomial, of the same degree $l=K-1$ a polynomial must be used to describe the gain

$$h_{li} = \sum_{j=0}^{l} a_{jl} i^j , \tag{21}$$

where a_{jl} are still unknown coefficients. Now, following [22] substituting (10) with $K=l+1$, (12) with (21), and (18) to (20) yields the generic coefficient

$$a_{jl} = (-1)^j \frac{M_{(j+1)1}}{|D|}, \tag{22}$$

calculated via the determinant $|D|$ and minor $M_{(j+1)1}$ of the $(l+1)\times(l+1)$ quadratic symmetric matrix

$$D = \begin{bmatrix} d_0 & d_1 & \dots & d_l \\ d_1 & d_2 & \dots & d_{l+1} \\ \vdots & \vdots & \ddots & \\ d_l & d_{l+1} & \dots & d_{2l} \end{bmatrix}, \tag{23}$$

which component $d_r, r \in [0,2l]$, is defined with the Bernoulli polynomials $B_n(x)$ [23] as

$$d_r(N,p) = \sum_{i=p}^{N-1+p} i^r = \frac{1}{r+1}\left[B_{r+1}(N+p) - B_{r+1}(p)\right]. \tag{24}$$

Determined h_{li}, the unbiased *p*-step predictive FIR filtering of the clock 1-state is provided at *n* (Fig. 1) by (11).

3.3. Noise Power Gain

The estimate variance σ_n^2 is evaluated by the term $W_l^T R W_l$ in (20). With large N, the noise induced by the GPS timing receiver becomes delta-correlated [22]. If also its variance σ_{vn}^2 is supposed to be constant over the horizon, then *R* becomes diagonal with equal components σ_{vn}^2 and we have $\sigma_n^2 = g_l \sigma_{vn}^2$, where

$$g_l(N,p) = W_l^T W_l \tag{25}$$

is the noise power gain (NG) [14]. For (15) and (21), the NG is defined to be

$$g_k = \sum_{i=p}^{N-1+p} h_{li}^2 \tag{26a}$$

$$= \sum_{j=0}^{l} a_{jl} \sum_{i=p}^{N-1+p} h_{li} i^j = a_{0l}\,, \tag{26b}$$

meaning that the coefficient a_{0l} in (21) is responsible for noise in the unbiased estimate. As it will be shown below, a_{0l} becomes zero when N tends toward infinity.

4. A *p*-step Predictive Filter with a Ramp Gain Function

Because of a lesser divergency with large *p*, linear predictors are often optimal or close to optimal in the sense of the minimum mean square error (MSE) in the predicted value. For linear prediction, $l = 1$, the filter gains is ramp,

$$h_l(i, N, p) = a_{01}(N, p) + a_{11}(N, p)i\,, \tag{27}$$

having the coefficients produced by (21)-(24) to be

$$a_{01} = \frac{2(2N-1)(N-1) + 12p(N-1+p)}{N(N^2-1)}\,, \tag{28}$$

$$a_{11} = -\frac{6(N-1+2p)}{N(N^2-1)}\,. \tag{29}$$

For small $p \in [0,3]$, (27) yields

$$h_{1i}(N,0) = \frac{2(2N-1) - 6i}{N(N+1)}\,, \tag{30}$$

$$h_{1i}(N,1) = \frac{2(2N+1) - 6i}{N(N-1)}\,, \tag{31}$$

$$h_{1i}(N,2) = 2\frac{2N^2 + 9N + 13 - 3(N+3)i}{N(N^2-1)}\,, \tag{32}$$

$$h_{1i}(N,3) = 2\frac{2N^2 + 15N + 37 - 3(N+5)i}{N(N^2-1)}\,. \tag{33}$$

If $p = 0$, (27) degenerates to the gain (not predictive) earlier derived in [25] using linear regression and thereafter in [22] via the state space model. For (26b) and (28), the NG is defined to be

$$g_1(N, p) = \frac{2(2N-1)(N-1) + 12p(N-1+p)}{N(N^2-1)}\,, \tag{34}$$

and its particular values are provided by (30)-(33) if to set $i = 0$. Fig. 2 illustrates (34), manifesting that prediction is achieved at increase of noise.

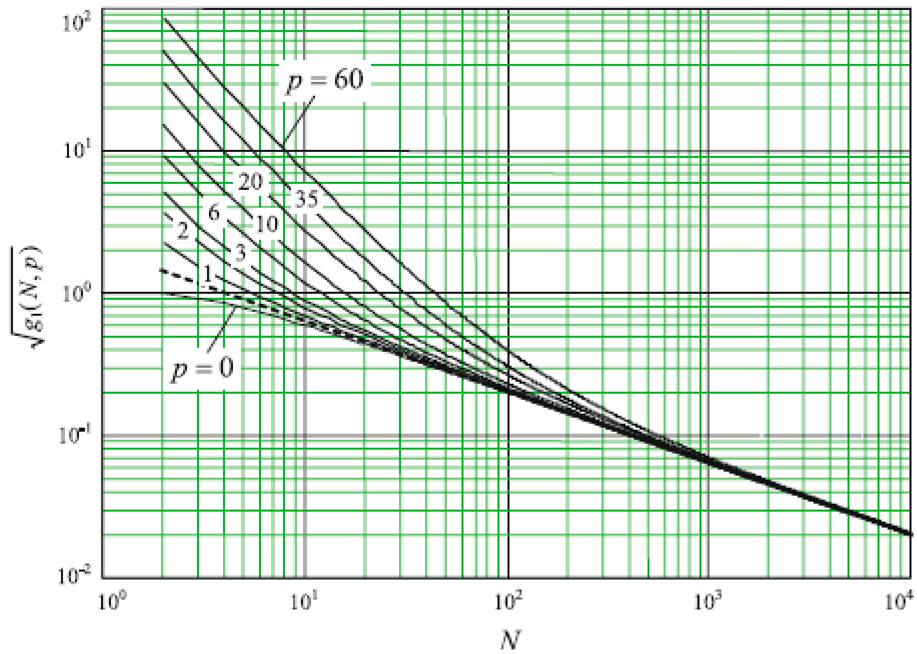


Fig. 2. NG of the 1-degree (*ramp*) unbiased *p*-step predictive FIR filter. The case of $p = 0$ corresponds to filtering without prediction. An asymptotic line (*dashed*) corresponds to $N >> 1$.

Indeed, when $2 \le N \le N_b$, where N_b is determined by solving $g_1(N_b, p) = 1$, the filter becomes inefficient, because noise is gained when NG exceeds unity. Clock synchronization, however, is commonly provided with large horizons. In this case, when $N >> N_b > 2$, the NG does not depend on *p* and fits the asymptotic function

$$g_1\big|_{N>>1} \cong \frac{4}{N} \tag{35}$$

shown as a dashed line in Fig. 2. Moreover, when $N >>> 1$ and (35), an unbiased predictive FIR filtering estimate becomes optimal in the sense of the zero bias and zero noise.

5. A *p*-step predictive Filter with a Quadratic Gain Function

For $l = 2$ and arbitrary step *p*, (21)-(24) yield a quadratic gain function

$$h_2(i, N, p) = a_{02}(N, p) + a_{12}(N, p)i + a_{22}(N, p)i^2\,, \tag{36}$$

having the coefficients

$$a_{02} = \frac{\begin{aligned}&3[3N^4 - 12N^3 + 17N^2 - 12N + 4\\ &+ 12(N-1)(2N^2 - 5N + 2)p\\ &+ 12(7N^2 - 15N + 7)p^2\\ &+ 120(N-1)p^3 + 60p^4]\end{aligned}}{N(N^4 - 5N^2 + 4)}\,, \tag{37}$$

$$a_{12} = \frac{\begin{array}{l} -18[2N^3 - 7N^2 + 7N - 2 \\ +2(7N^2 - 15N + 7)p \\ +30(N-1)p^2 + 20p^3] \end{array}}{N(N^4 - 5N^2 + 4)}, \tag{38}$$

$$a_{22} = 30\frac{N^2 - 3N + 2 + 6(N-1)p + 6p^2}{N(N^4 - 5N^2 + 4)}. \tag{39}$$

Fig. 3 sketches $g_2(N, p) = a_{02}(N, p)$ for different p and instantly indicates that (37), first, becomes inefficient with much smaller p than in (28) and, second, a singularity occurs at $N = 2$ causing instability with $N < 3$.

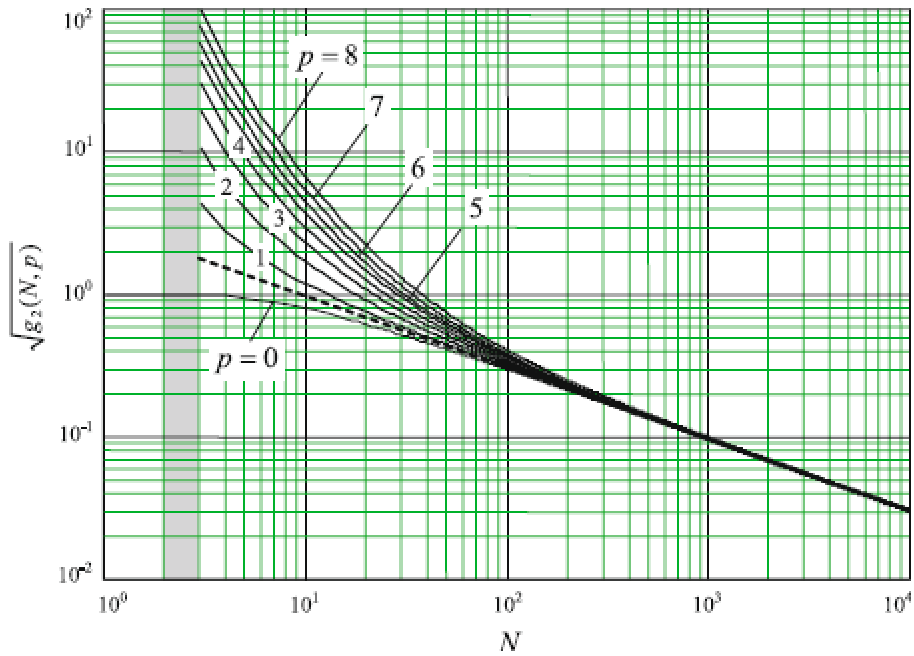


Fig. 3. NG of the 2-degree (*quadratic*) unbiased *p*-step predictive FIR filter. The case of $p = 0$ corresponds to filtering without prediction. An asymptotic line (*dashed*) corresponds to $N >> 1$. The range of instability is *shadowed*.

6. Holdover Algorithms

Based upon the proposed filter, the holdover algorithm can be designed following one of the diagrams shown in Fig. 4. Here the measurement (input) is depicted with "$\circ$", predicted estimate (output) with "$\bullet$", and unavailable or excluded "bad" measurement by "$\times$". It is implied that every measured point (from 1 to 9) represents the last point of the averaging horizon of *N* points shown in Fig. 1. From each of these points the filter is able to produce the *p*-step toward predictive estimate. For example, the point 1 (see Fig. 4a) representing a horizon of *N* neighboring past points, produces the estimate at 2a associated with the measurement at 2.

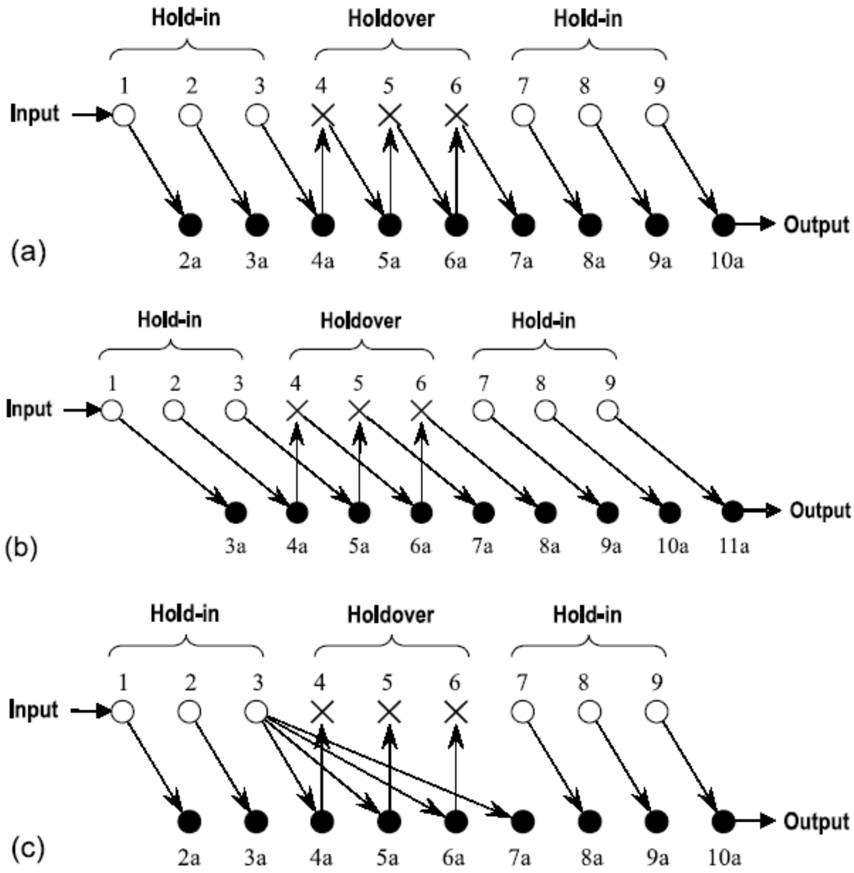


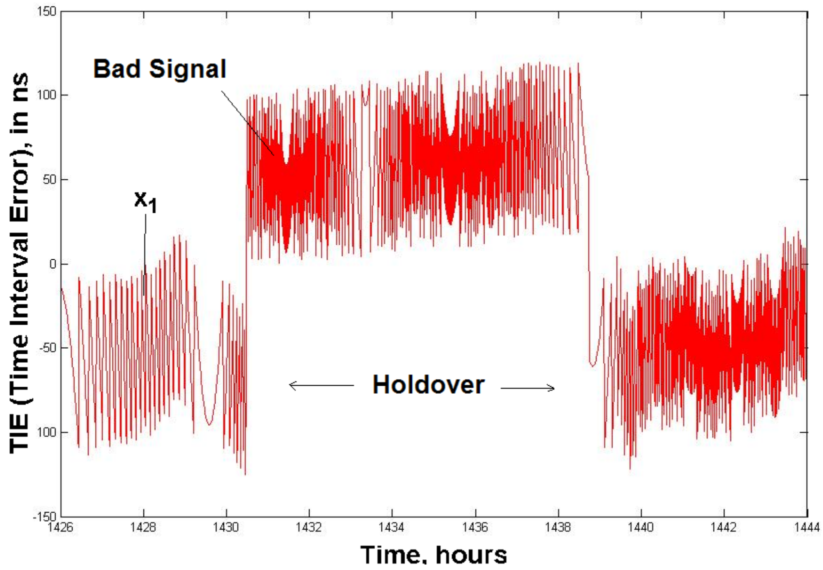
Fig. 4. Holdover algorithms with predictive filtering: (a) fixed-step ($p = 1$), (b) fixed-step ($p = 2$), and (c) variable-step.

The algorithm can be organized either with the fixed step (see Fig. 4a and 4b) or variable step (see Fig. 4c). In the fixed-step case of $p = 1$ (see Fig. 4a), the algorithm operates in "Hold-in" (from 1 to 3) producing the estimates (form 2a to 4a). At 4, the measurement is not available. Therefore, a predicted value (4a) is used instead and the filter produces the next estimate at 5a. Such a "Holdover" procedure is applied from 4 to 6. The filter then returns to "Hold-in". In a like manner, the algorithm is organized for the case shown in Fig. 4b and one can easily figure out how to design the fixed-step algorithm for arbitrary $p > 0$. In the variable-step case illustrated in Fig. 4c, the point 3 covers all the holdover range, producing individual estimates for the points 4a-7a. Here, predicted values are not involved in holdover and used in the subsequent hold-in range.

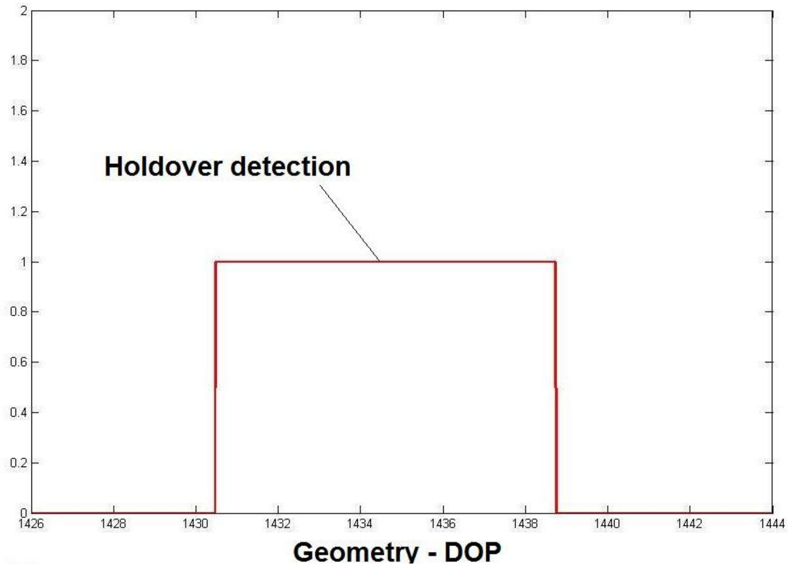
7. Design of the New Algorithm of Compensation of the TIE

In the Fig. 5, is the signal of the GPS that present holdover, loss of the signal in an interval of time. This problem occurs always in a time from 20 to 30 minutes in the morning. To apply our filter is necessary to have an indicator (flag), which is going to say us in which moment itself active and defuses the holdover. These indicators are obtained of the Geometry DOP (Dilution of Presicion) of the signal of the TIE. The problem holdover depends of the Geometry DOP of the satellites in the moment of the calculation of the position (see Fig. 5). This means that is not the same thing that 4 satellites be much separated (better precision) to that be more next (smaller precision).

With this algorithm we applied the unbiased predictive FIR filter at the signal of the TIE. When the indicator detects holdover, itself active the filter with prediction ($p = 1$) and predicts the future signal, until the indicator to stops detecting presence of holdover then is defused the filter without prediction ($p = 0$) and continuous the filter.



(a)



(b)

Fig. 5. (a) Show the signal of the TIE where is present the holdover during an interval of time, (b) represent the holdover detection how an indicator or flag, this is obtained of the Geometry DOP.

8. Results

The fixed-step, $(p = 1)$, holdover algorithm has been applied to GPS-based measurements of the TIE. The fixed-step algorithm is applied with $l = 1$ and $N = 2500$ (see Fig. 6). In the Fig. 7 is presented the FIR filtering with $l = 2$ and $N = 7000$. We use how reference the measurement of the atomic clock Rubidium (Rb).

The Fig. 7 assures of high efficiency of the solution. In fact, in the initial hold-in range, the values produced with $p = 0$ and $p = 1$ are indistinct. In the holdover range, the predicted estimate $(p = 1)$ still does not get out of the actual linear behavior and keeps tracing it in the subsequent hold-in range. In turn, the filter $(p = 0)$ exhibits inherent transients both within and beyond the holdover range.

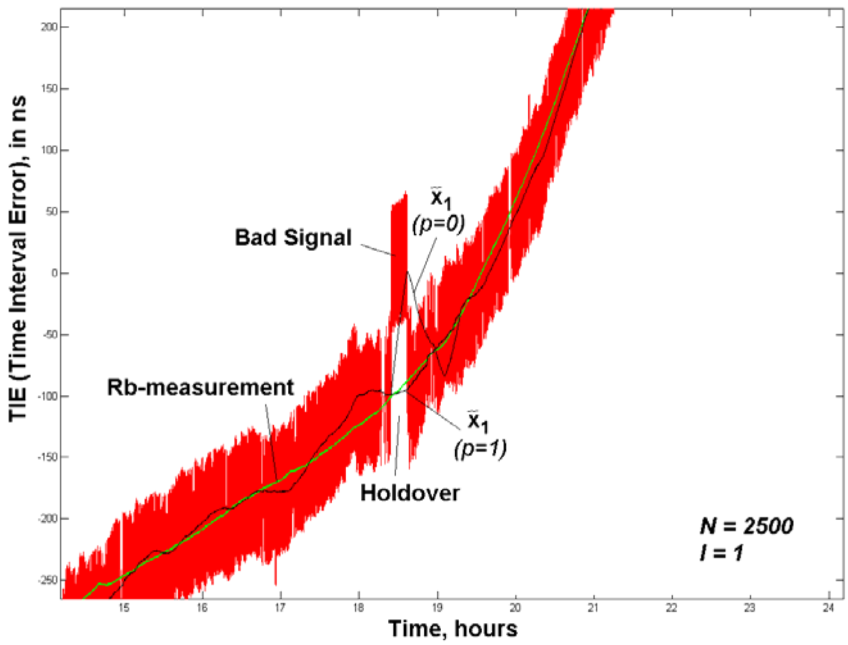


Fig. 6. Applications of the unbiased $(l = 1)$, 1-step $(p = 1)$ predictive FIR filtering estimate $\tilde{x}_1$ of the TIE with different measurement noises, by $N = 2500$. The estimate $\tilde{x}_1$ $(p = 0)$ is provided with the 1-degree unbiased FIR filter. To demonstrate holdover, "bad" points are excluded from the data.

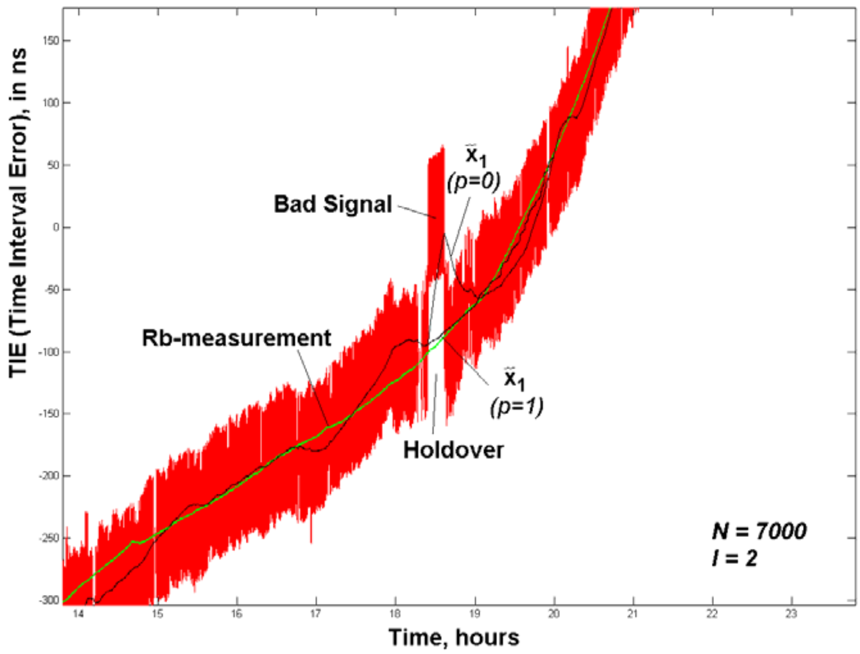


Fig. 7. Applications of the unbiased $(l = 2)$, 1-step $(p = 1)$ predictive FIR filtering estimate $\tilde{x}_1$ of the TIE with different measurement noises, by $N = 7000$. The estimate $\tilde{x}_1$ $(p = 0)$ is provided with the 2-degree unbiased FIR filter. To demonstrate holdover, "bad" points are excluded from the data.

9. Conclusion

In this paper we proposed a new algorithm of compensation of the TIE GPS-based measurement applying an unbiased predictive FIR filter. Unique coefficients were derived for a two-parameter family of the *l*-degree polynomial filter gain functions. The cases of linear and quadratic predictive filtering, they have been investigated in detail as near optimal, GPS-based measurements of the TIE. Based upon, the fixed-step $(p = 1)$ holdover algorithms has been worked out and examined.

It was shown that the filter of degree $l = 2$ is a lot better than the filter of degree $l = 1$, due to that the estimation of the unbiased predictive FIR filter comes be optimum in the sense that the noise and the bias are almost zero. The filter of degree $l = 2$ was more than sufficient, for which was not necessary to utilize a filter of greater degree to 2.

The new algorithm depends of the geometry of the satellites in the moment of the calculated of the position, due that the geometry relates with the DOP. With this we find an indicator for the algorithm, when the DOP is 1, we detect holdover and the predictive filter it active, and when is 0 does not occur anything, the predictive filter is defused.

With the new algorithm we reach the accuracy of the atomic clock of Rubidium and the possibility to reach that of an atomic clock of Cesium. We can rival an atomic clock using a receiver GPS, doing that the companies of communication have savings and they can apply it to the synchronization of their teams.

Acknowledgements

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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