Reliability of lakes monitoring by means of satellite based systems

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1. Introduction

The monitoring of lake surface and its water quality is a crucial issue for most national and international agencies since lakes are places that are of great importance from the point of view of tourism, leisure, sport and recreation. The monitoring of parameters that provide explicit evidence of the health state of a lake, affects significantly the economic stability of a country, at both national and local level, and thus the constant monitoring and evaluation of parameters that indicate the quality of the lake is an essential tool for making informed lake management decisions [1]. However, the use of ground monitoring stations based on wireless sensor networks requires high cost for design and management as well as long time for the acquisition of data useful to assess the health status of the entire surface of the lake [2]. As a consequence, these systems are prevalently used for monitoring only small fractions of a lake. In this context, it is clear that the use of parameters estimation methods based on satellite remote sensing systems represents a cost-effective tool to be integrated to ground-based monitoring programs and can facilitate the evaluation of metrics related to water quality [3], [4]. In fact, these instruments can provide values accurately measured on the entire surface of a lake, and gives spatially unbiased information on parameters of a targeted lake.

The integrated monitoring system should provide precise and accurate data that automatically compensate for undesired and unpredictable failures of the employed instrumentation. In particular, in this paper the effects of satellite mal-functioning, due to failure of on-board atomic clocks, on the positioning data given by the GNSS receiver are considered. In fact, atomic clocks are the key devices in the Global Navigation Satellite Systems that guarantee the timing synchronization among different satellites and that assure to GNSS users accurate timing and localizing information [5]. Phase and frequency stability of these devices need to be carefully monitored because an anomalous behavior could heavily affect the whole satellite integrity and could result in an anomalous service, i.e. in an estimate of the GNSS user position heavily biased by errors of thousands of meters. It follows that a prompt detection of clock anomalies by means of simple and reliable algorithms is of fundamental importance in order to guarantee an accurate GNSS service.

The scientific literature proposes many detection and identification techniques specifically dedicated to atomic clock anomalies. In particular, [6], [7], [8], [9] present methods based on the evaluation of the Dynamic Allan VARiance (DAVAR), [6], [8], [10] propose also the Generalized Likelihood Ratio Test (GLRT) to quickly detect both phase and frequency jumps [11], [12].

In this paper we analyze the clock-phase anomalies detector based on the GLRT, a method based on a threshold criterion, already introduced by some of the authors [6], [8], [10]. We propose an operative point of view for applying the algorithm to measured data in order to effectively and promptly detecting a phase jump or a phase variance change that could lead to an anomalous clock behavior. In particular, a practical criterion for choosing the threshold value, γ, to be used for guaranteeing a-priori the target False Alarm Probability (PFA) is explicitly

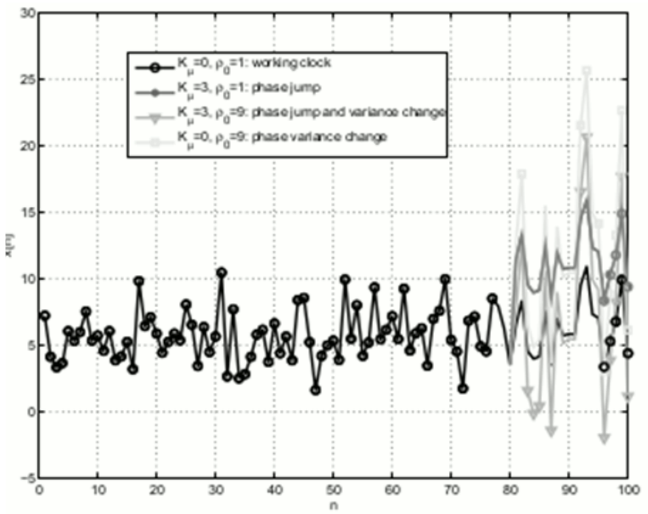

Figure 1: Behavior of samples acquired from a clock correctly working (black line with circles) and of faulty clocks. In particular, it is shown the behavior of a clock affected by a phase jump (gray line with diamonds), a change in the variance factor (grey line with triangles) and a change in both mean and variance value (gray line with circles)

given. The proposed methodology is validated by means of Monte-Carlo simulations.

2. Definition of Anomalous Clock Behavior

In this section is defined the correct model of the *n*-th measured atomic clock phase–deviation, $x[n]$, [13] and also the corresponding anomalies to be detected by means of the GLRT based algorithm.

When the clock works correctly, thus the n-th sample of the measured clock phase-deviation, represented in fig.1 with circled dots and a black line, can be modeled as a White Gaussian Noise (WGN) with statistical mean and variance respectively equal to μ_0 and σ_0^2,i.e. $x[n]\sim\mathcal{N}(\mu_0, \sigma_0^2)$. The anomalous behavior that could affect the position given by the GNSS receiver is the phase-deviation jump, indicated with K_μ, or the variance change, indicated with ρ_0. In the proposed model, the two anomalies could also arise together.

In order to detect an anomalous behavior, a number *N* of phase deviations values are acquired and processed by the GLRT detection algorithm for detecting if available phase data, supposed to be acquired by a working clock, have been affected by any of the considered anomalies from a data sample indicated by the index n_0. The possible anomalous behaviors considered in this paper are shown in Fig.1 with three grey lines that represent a clock that is subjected to one of the faulty behavior, as indicated by the corresponding label, when $K_\mu = 3$ and $\rho_0 = 9$.

The statistical model that describes the corresponding working or a faulty behavior in terms of hypothesis testing, is given in eq.(1). In particular, the null hypothesis, $\mathcal{H}_0$, is verified when all available phase deviations can be modeled as Gaussian random variable with the same mean, μ_0, and the same variance σ_0^2

The alternative hypothesis takes into account a faulty behavior from the sample numbered as n_0 up to the last sample indexed as $N-1$ which is represented

$$\begin{aligned}\mathcal{H}_0 &: x[n] = \mu_0 + \sigma_0 \cdot w[n], \quad n = 0, ..., N-1 \\ \mathcal{H}_1 &: x[n] = \begin{cases} \mu_0 + \sigma_0 \cdot w[n], & n = 0, ..., n_0 - 1 \\ \mu_1 + \sigma_1 \cdot w[n], & n = n_0, ..., N-1 \end{cases}\end{aligned} \quad (1)$$

by a phase deviation jump to the value μ_1 and/or by a change in the variance to the value . σ_1^2:

where $w[n]\sim\mathcal{N}(0,1)$. It follows that the alternative hypothesis describes the case that in the observation interval of length *N* a phase jump equal to $K_m \triangleq (\mu_1 - \mu_0)$ and/or a change in the variance value of a $\rho_0 \triangleq (\sigma_1^2 / \sigma_0^2)$occur from the sample index indicated with n_0.

It should be noticed that in the previous model the only parameter known a-priori is *N* , while the other parameters, μ_0, μ_1, σ_0^2, σ_1^2 and n_0, are unknown.

It has been shown that by assuming a deterministic model of the unknown parameters, thus the detector based on the optimal LRT criterion and that substitutes the unknown true values with the corresponding MLE estimates, is the Generalized LRT algorithm given by Nunzi et al. 2007 and Nunzi and Carbone 2008:

$$T(\mathbf{x};\hat{\boldsymbol{\theta}}) = \log(L_G(\mathbf{x})) = \frac{N}{2}\log\frac{\widehat{\sigma^2}_{0\_H_0}}{\widehat{\sigma^2}_{1\_H_1}} - \frac{\hat{n}_0}{2}\log\frac{\widehat{\sigma^2}_{0\_H_1}}{\widehat{\sigma^2}_{1\_H_1}} \quad (2)$$

where $\hat{\theta}=[\widehat{\mu_0}_{\_H0}, \widehat{\sigma_0^2}_{\_H0}, \widehat{\mu_0}_{\_H1}, \widehat{\sigma_0^2}_{\_H1}, \widehat{\mu_1}_{\_H1}, \widehat{\sigma_1^2}_{\_H1}, \widehat{n_0}]$ is the MLE estimates vector, which is explicitly given in Tab.1. In particular, $\widehat{\mu_0}_{\_H0}$ e $\widehat{\sigma_0^2}_{\_H0}$ are the MLE estimators of $\mu 0$ and σ_0^2, respectively, designed for data that satisfy the null hypothesis $\mathcal{H}_0$.

On the other hand, $\hat{\mu}_{0-H1}$, $\widehat{\sigma_0^2}_{-H1}$, $\widehat{\mu_1}_{\_H1}$, $\widehat{\sigma_1^2}_{\_H1}$ and $\widehat{\mu_0}$ represent the MLE estimators of μ_0, $\widehat{\sigma_0^2}$, μ_1, $\widehat{\sigma_1^2}$ and n_0, respectively, created for data that respect the model presented in $\mathcal{H}_1$.

3. The test setting

Table 1:

MLE estimators	
$\hat{\mu}_{0\_H_0} = \frac{1}{N}\sum_{n=0}^{N-1} x[n]$	$\widehat{\sigma^2}_{0\_H_0} = \frac{1}{N}\sum_{n=0}^{N-1}(x[n] - \hat{\mu}_{0\_H_0})^2$
$\hat{\mu}_{0\_H_1} = \frac{1}{N}\sum_{n=0}^{\hat{n}_0-1} x[n]$	$\widehat{\sigma^2}_{0\_H_1} = \frac{1}{\hat{n}_0}\sum_{n=0}^{\hat{n}_0-1}(x[n] - \hat{\mu}_{0\_H_1})^2$
$\hat{\mu}_{1\_H_1} = \frac{1}{N-\hat{n}_0}\sum_{n=\hat{n}_0}^{N-1} x[n]$	$\widehat{\sigma^2}_{1\_H_1} = \frac{1}{N-\hat{n}_0}\sum_{n=\hat{n}_0}^{N-1}(x[n] - \hat{\mu}_{1\_H_1})^2$
$\hat{n}_0 = \max\left\{p(\mathbf{x}; \left[\hat{\mu}_{1\_H_1}, \widehat{\sigma^2}_{1\_H_1}, n_0\right] H_1)\right\}$	

The LRT based test is executed as indicated below. Clock phase deviation data are acquired and organized as an *N* -length vector, ***x***, that is uploaded in the processing system. Maximum Likelihood Estimates (MLEs) of the mean and variance are evaluated under both working and non-working clock hypotheses.
The corresponding Generalized Likelihood Ratio, $GLRT(x,\hat{\theta})$, is calculated as indicated in [6], [10].The hypotheses test is performed by comparing the outcome with a given threshold γ, that is related to the target *PFA* test value, i.e.:

$$GLRT(x,\hat{\theta}) > \gamma \quad (3)$$

If (3) is true, data are assumed to be affected by an anomalous behavior, otherwise the clock is supposed to work properly. It has been shown by means of intensive simulations that the threshold γ is strictly related to the target

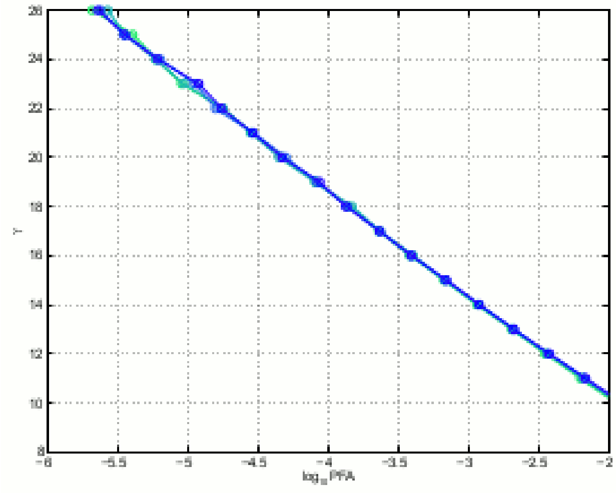

Figure 2: Monte Carlo simulations on 10^7 records of data obtained by setting the γ value from 10 to 25 with step 1 for 4 different values of N (25, 50, 75, 100) indicated with lines of different colors

PFA value of the test, which is defined as the probability of assessing as true the hypothesis that the clock is not working properly when the clock is working correctly, indeed [6], [10] i.e.

(4)

$$PFA \triangleq Pr\{GLRT(\mathbf{x}; \widehat{\theta}) > \gamma; \mathcal{H}_0\}.$$

The linear relationship between γ and $\log_{10}(PFA)$, shown in Fig. 2, has been evaluated by fitting for each N the simulated curves to the following function :

(5)

$$\gamma = \frac{(\log(PFA) - a_0)}{a_1}$$

thus obtaining the estimates of the a_0 and a_1 coefficients, parameterized with N , equal to:

(6)

$$\widehat{a}_1 = -0.536$$
$$\widehat{a}_0 = \frac{0.11N}{100} + \frac{76}{100}.$$

Fig. 3 shows the relative error between lines obtained with Monte Carlo simulations reported in Fig.2 and the corresponding fitted curves obtained by using linear model shown in (5) that uses estimates reported in (6). The relative error obtained by using (5) is smaller than 1% for *PFA* values between 0.05% and 1%, thus assessing the reliability of the given linear model.

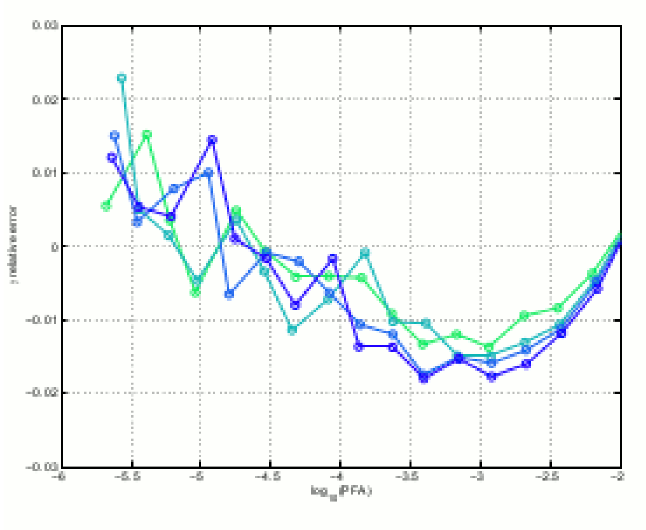

Figure 3: Relative error between lines obtained with Monte Carlo simulations reported in Fig.2 and the corresponding fitted lines obtained by using coefficients estimated with (6).

4. Conclusions

The use of the GNSS system for monitoring lakes water quality over larger areas is a relatively low-cost technique widely used for integrating information obtained locally from dedicated wireless sensor systems that acquire water parameters. However, the reliability and the accuracy of the used information strictly depend on the satellite integrity. In fact, an on-board failure of the atomic clock that coordinates timing between different satellites could heavily affect data measured by the GNSS receiver used for monitoring parameters on the lake surface. In this paper, an LRT-based algorithm for detecting quickly and reliably both clock phase jumps and clock phase variance changes has been analyzed. The detection procedure is described from a practical point of view and the criterion for setting a-priori the target *PFA* of the clock monitoring processing is given. In particular, the threshold value γ to be used in the decision process for evaluating if a fault has occurred, is linearly related to the logarithm of the *PFA* of the decision process by means of a simple relationship and the linear function is explicitly estimated and characterized in the paper.

References

[1] Combining lake and watershed characteristics with landsat {TM} data for remote estimation of regional lake clarity, Remote Sensing of Environment 123 (0) (2012) 109–115.
doi: http://dx.doi.org/10.1016/j.rse.2012.03.006.

[2] M. Femminella, R. Francescangeli, G. Reali, J. W. Lee, H. Schulzrinne, An enabling platform for au-

tonomic management of the future internet., IEEE Network 25 (6) (2011) 24–32.

URL:http://dblp.unitrier.de/db/journals/network/network25.html#FemminellaFRLS11

[3] Sols: A lake database to monitor in the near real time water level and storage variations from remote sensing data, Advances in Space Research 47 (9) (2011) 1497 – 1507. doi: http://dx.doi.org/10.1016/j.asr.2011.01.004

[4] Validation of satellite data for quality assurance in lake monitoring applications, Science of The Total Environment 268 (13) (2001) 3 – 18, lake water monitoring in. doi:http://dx.doi.org/10.1016/S0048-9697(00)00693-8

[5] S.-W. Lee, J. Kim, Y. J. Lee, Protecting signal integrity against atomic clock anomalies on board gnss sat IEEE T. Instrumentation and Measurement 60 (7) (2011) 2738–2745.

URL: http://dblp.unitrier.de/db/journals/tim/tim60.html#LeeKL11

[6] E. Nunzi, L. Galleani, P. Tavella, P. Carbone, Detection of anomalies in the behavior of atomic clocks, IEEE T. Instrumentation and Measurement 56 (2) (2007) 523–528.

[7] P. T. L. Galleani, The dynamic allan variance, IEEE Trans. ultrason. Ferroelectr. Freq. Control.

[8] E. Nunzi, P. Carbone, P. Tavella, Fault detection in atomic clock frequency standards affected by mean and variance changes and by an additive periodic component: the glrt approach, Instr. and Meas. Tech. Conf.

[9] P. T. L. Galleani, Detection and identification of atomic clock anomalies, Metrologia.

[10] E. Nunzi, P. Carbone, Monitoring signal integrity of atomic clocks by means of the glrt, Metrologia 45 (6) (2008) S103–S107.

[11] G.Baruffa, M. Femminella, F. Mariani, G. Reali, Protection ratio and antenna separation for dvb - t/lte coexistence issues., IEEE Communications Letters 17 (8) (2013) 1588–1591.

URL: http://dblp.unitrier.de/db/journals/icl/icl17.html#BaruffaFMR13

[12] M. Femminella, F. Giacinti, G. Reali, Enhancing java call control with media server control functionsarXiv:1307.8257.

[13] Ieee standard definitions of physical quantities for Fundamental frequency and time metrology, IEEE Standard 11392008.