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IMPROVEMENT OF SIGNAL SYNCHRONIZATION IN GPS SOFTWARE RECEIVER

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Abstract:

In GPS receivers, navigation bit allocation is performed throughout the process of signal tracking and detection. In the process of signal tracking, the locally generated signal must be synchronized with the received signal. The Costas phase-locked loop (PLL) behavior, which is often used for signal synchronization, is characterized by dominant tracking error sources. The resulting phase tracking errors are significant in the presence of weak signals, i.e. signals with the low signal-to-noise ratio (SNR). In order to improve the signal synchronization and enable signal tracking by the receiver, we here proposed the usage of a non-data-aided (NDA) phase estimator. Based on the practical processing of the GPS signals, it is shown that the applied NDA algorithm is more resistant to sudden changes in frequency (phase) of the input signal than the previously considered phase discriminator in the Costas PLL. Also, we have shown that the solution analyzed here exhibits more stable operation in signal tracking for a low SNR.

Key words: *global positioning system, phase estimation, receiver, signal processing, software.*

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Introduction

The usage of the Global Positioning System (GPS) is considered in many different applications and under various operating conditions, where necessary, the presence of the continuous GPS information.

However, the operation of a GPS receiver under harsh environmental conditions is limited by a complex nature of radio signal propagation (Djogatovic, Stanojevic, 2012, pp.650-671), which comprises multipath propagation, shadowing and interference. Also, when indoor reception is considered, GPS signals are always subject to the effects of multipath propagation, fading, dominant non-line-of-sight signals, absent line-of-sight signals and other issues, which cause GPS receiver's performance degradation (Sathyamoorthy, et al., 2012, pp.338-347). However, GPS receivers are expected to enable GPS signals detection under all working conditions, especially in cases when it is integrated within multisensor platforms (Sokolović, et al., 2013, pp.451-455).

One of the problems regarding weak signal reception by the GPS receiver is the signal tracking performance. In this paper, the coarse/acquisition (C/A) code on the GPS L1 frequency (1575.42 MHz) is observed and the tracking of weak signals by the GPS receiver is analyzed.

In order to perform our analysis, we have developed a software GPS receiver model in the MATLAB environment.

A typical GPS receiver channel, as shown in Figure 1, has two modes of operation: acquisition and tracking (Borre, et al., 2007). The acquisition and/or tracking of GPS signals with a low SNR, presents a difficult task (Kaplan, 1996), (Psiaki, 2001, pp.2838-2850). During the acquisition, the receiver estimates the code phase and the carrier Doppler shift of the received signal (Sun, et al., 2008, pp.1-6). The special block processing algorithms designed for the acquisition in software GPS receivers are already known (Tsui, 2005), (Sokolovic, Popovic, 2009, pp.604-607), (Sokolovic, 2011, pp.81-95).

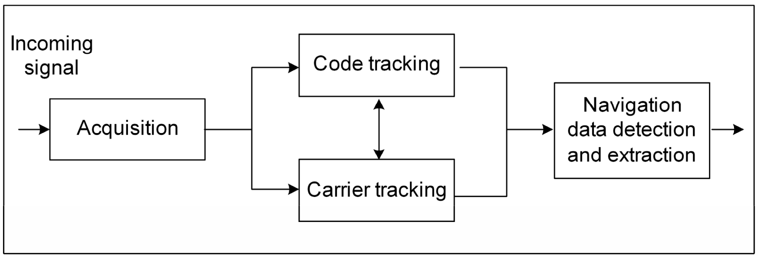

Figure 1 – The block diagram of one GPS receiver channel
Slika 1 – Blok-dijagram jednog kanala GPS prijemnika
Рис. 1 – Блок диаграмм одного канала GPS приемника.

The acquisition parameters are further refined during the tracking operation mode. After the tracking is performed, the navigation data can be properly detected and extracted, and based on these data pseudo-ranges are computed (Borre, et al., 2007).Thus, the main purpose of tracking is to enable the proper estimation of the C/A code phase and carrier frequency and to keep a track of these quantities while the received signal properties change over time.

The code tracking is usually implemented in the form of a delay-locked loop (DLL). In this paper, we have observed and analyzed the carrier tracking implemented in the form of carrier phase tracking. The GPS receiver continuously executes the tracking process in order to provide a synchronization of the received and the locally generated signal. If an interruption in the signal tracking occurs, the receiver must start a new acquisition process, and only after that can return into the tracking mode. Since the Costas PLL is found to be insensitive to the phase transitions, which occur due to the navigation bits transitions (Borre, et al., 2007), it is one of the reasons that this type of PLLs is used in the GPS receivers. The major application constraint regarding the Costas PLL usage is its relatively small loop bandwidth that suggests a small pull-in and locking frequency range. When the maximum possible frequency deviation is just a small fraction of the received signal bandwidth, the Costas PLL is an effective solution.

The dominant tracking error sources of PLLs are: thermal noise, oscillator phase noise and dynamic stress error (Sokolovic, 2011, pp.81-95). Increasing a pre-detection integration time can resultin a decrease of the thermal noise error (Kazemi, et al., 2008). Unfortunately, since the digital tracking loops are normally used in GPS receivers, when the pre-detection integration time increases, the receiver dynamics uncertainty in the integration time also increases which leads to an unacceptably high phase error. Such a phase error can further result in losing signal tracking and/or in the incorrect detection of navigation bits (especially for the tracking of weak signals).

In order to improve signal synchronization and thus enable a more successful signal tracking of weak signals, we here propose an additional measure, which is embedded in our model of the software GPS receiver. We applied a well-known non-data-aided (NDA) method (Irsigler, et al., 2004, pp.119-139). In fact, we integrated the NDA method as a phase estimation algorithm in the GPS receiver tracking mode, as a part of carrier tracking, instead of the usual phase discriminator within the Costas PLL. By observing the reception of weak GPS signals (with a low SNR) with such a developed receiver, we have shown that the carrier tracking solution proposed here improves the detection of weak signals when compared to the previously considered Costas PLL based solution.

Signal tracking

In Figure 2, a typical design of the Costas PLL is shown (Tsui, 2005). The observed input signal is mixed with locally generated signals obtained by using the output of the voltage controlled oscillator (VCO). The resulting complex signals represent the in-phase (I) and the quadrature (Q) signal components. The control signal for the VCO is generated with a phase discriminator by using the I and Q signal components (Kaplan, 1996). The main purpose of the applied Costas PLL is to direct all of the signal energy into the I (in-phase) arm (Borre, et al., 2007).

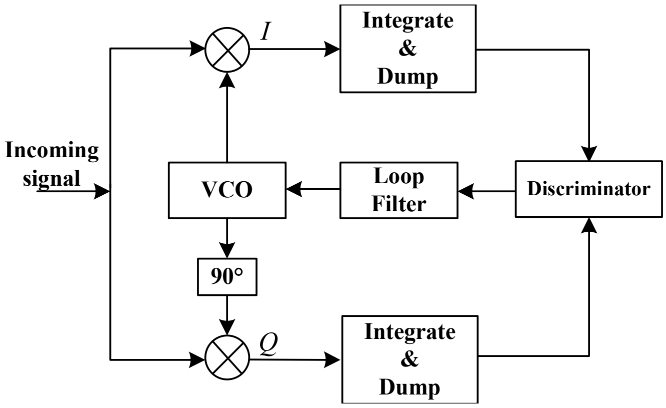

Figure 2 – The block diagram of the Costas PLL
Slika 2 – Blok-dijagram Costasove PLL
Рис. 2 – Блок диаграмм Costas PLL.

The phase error of the locally generated signal for the k-$_{th}$ satellite, ϕ_k, e.g. the carrier phase difference between the received signal and the locally generated replica for the observed satellite, can be found (Borre, et al., 2007), as:

$$I^k = \frac{1}{2} D^k(n)\cos(\phi), \quad Q^k = \frac{1}{2} D^k(n)\sin(\phi), \tag{1}$$

$$\phi^k = \arctan\left(\frac{Q^k}{I^k}\right), \tag{2}$$

where $D^k(n)$ are the navigation data (n indicates a discrete-time received signal). From Eqn. (2), it is obvious that when the correlation in the in-phase arm is maximal, the phase error tends to be zero and vice versa.

The Costas PLLs are very sensitive to the dynamic stress which may arise due to the receiver dynamic or due to the interference signals. The dynamic stress can trigger the loss of the lock in the PLL, which then causes the receiver to return into the acquisition operation mode, and afterwards to repeat the PLL closure process.

It should be noticed that updating the data regarding a position and the speed of the GPS receiver is a relatively slow process.In that sense, an additional repetition of the signal acquisition, caused with the loss of the lock inside the PLL, represents a further waste of time for the information updating process. Therefore, in this paper, we have proposed the application of an NDA phase estimator that is less sensitive to the dynamic stress in order to avoid a frequent need for re-acquisition while receiving weak GPS signals.

Non-Data-Aided algorithm

The fundamental frequency estimation can be achieved without using any prior information, i.e. with the NDA approach. In this section, we will define an automatic phase control algorithm (or tracking algorithm) for the software GPS receiver which involves the use of phase estimation. The automatic phase control (APC), or the carrier phase estimation/tracking, can be considered in the form of the general structure given in Figure 3.

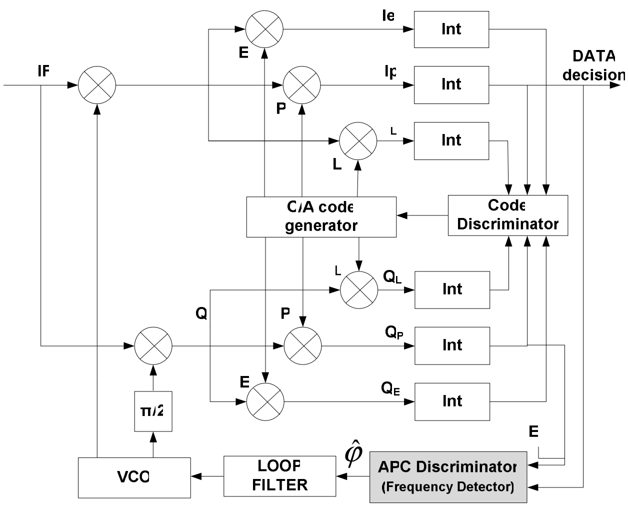

Figure 3 – General configuration used for signal tracking in the GPS software receiver, with the integrated DLL and PLL
Slika 3 – Opšta konfiguracija za praćenje signala u softverskom GPS prijemniku, sa integrisanom DLL i PLL
Рис. 3 – Принципиальная схема отслеживания сигнала в программируемом GPS приемнике, с интегрированными DLL и PLL

In Figure 2, the signal tracking and the navigation bits detection processes are presented. The code tracking is implemented by using the DLL, while the synchronization of the carrier signal is realized by using the PLL with the NDA phase discriminator (shown in Figure 3 as the gray block).

A synchronization algorithm based on the maximum-likelihood criterion should select a set of synchronization parameter values (*φ,ε*), that maximizes the likelihood function $p(r_f / \varphi, \varepsilon)$, where (*φ,ε*) represent real phase and timing offsets, respectively, and $(\hat{\varphi}, \hat{\varepsilon})$ are their estimated values.

The data dependency is removed through averaging. To achieve the data independency of an M-ary phase-shift keying (MPSK) signal at the matched filter output detected navigation bits, z_n (*ε*), are taken to the M_{th} power (Meyr, et al.,1998) as,

$$z_n^M(\hat{\varepsilon}) = [a_n e^{j\varphi_0} + m_n]^M = a_n e^{jM\varphi_0} + m_n^{'}, \tag{3}$$

where a_n is a symbol value at the time *nT* at the output of the detector, $m_n^{'}$ is the white Gaussian noise with the flat power spectral density N_0 and the covariance σ^2. Since $a^M = (e^{jM\pi l/M})^M = 1$ the data independency is achieved, and thus we obtain, (Meyr, et al.,1998),

$$z_n^M(\hat{\varepsilon}) = e^{jM\varphi_0} + m_n^{'}, \tag{4}$$

For the known timing and the independent data symbols, when the NDA method is used to process the binary phase-shift keying signals, by using M = 2 and $a_n^{(0)} = 1, a_n^{(1)} = -1$, we obtain the likelihood function as,

$$L(\varphi, \hat{\varepsilon}) = \frac{1}{2}\prod_{n=0}^{N-1}\cosh\left(\frac{2}{\sigma_n^2}\mathrm{Re}\left[z_n(\hat{\varepsilon})e^{-j\varphi}\right]\right), \tag{5}$$

where cosh() is the hyperbolical cosine. By taking the logarithm and differentiating Eqn. (5), with the respect to φ, a phase error signal is obtained as, (Meyr, et al.,1998),

$$\frac{\partial}{\partial\varphi}L_1(\varphi, \hat{\varepsilon}) = \frac{2}{\sigma_n^2}I_m\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right]\tanh\left(\frac{2}{\sigma_n^2}\mathrm{Re}\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right]\right). \tag{6}$$

It is necessary to observe the cases with the high and low SNR. For the high SNR $\sigma_n^2 \to 0$, thus the approximation $\tanh(x) \approx sign(x)$ is valid, and we obtain the error signal, (Meyr, et al.,1998),

$$x_n^{(1)} = I_m\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right]sign\left(\frac{2}{\sigma_n^2}\mathrm{Re}\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right]\right), \quad (7)$$

and also,

$$a_n = sign\left(\frac{2}{\sigma_n^2}\mathrm{Re}\left[z_n(\varepsilon)e^{-j\varphi}\right]\right). \quad (8)$$

This leads to the conclusion that the estimation performance is the same as in the classic PLL, (Meyr, et al.,1998). As the case of main interest in this work is the low SNR, *i.e.* when $\sigma_n^2 >> 1$ and the approximation $\tanh(x) \approx x$ is valid, the error signal becomes (Meyr, et al.,1998),

$$x_n^{(2)} = I_m\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right]\mathrm{Re}\left[z_n(\hat{\varepsilon})e^{-j\hat{\varphi}}\right] \quad (9)$$

Based on Eqn. (9), the error signal is equal to zero when

$$\hat{\varphi} = \frac{1}{2}\arg z_n(\hat{\varepsilon}) + k\pi. \quad (10)$$

Based on the above equations, the phase error estimation and correction is performed. The APC block observes the signal samples through the window length of 20 samples and estimates a signal phase error and corrects it in a feed-forward loop. The correction of a phase slip, in the case when the difference between a current phase estimate and a previous one becomes larger than the slip phase, π is added or subtracted from the current phase in order to move it near the previous phase error (we assume that the phase offset can not change rapidly and that any rapid change of the phase estimate is caused by a phase slip). Bearing in mind that within a single bit of data, there are 20 samples with an identical phase (Borre, et al., 2007), and the phase correction for $\pm \pi$ is required after every 20 samples.

A compensation for the frequency offset is performed by the frequency integrator block, which corrects a frequency error in a feed-back loop (a PLL shown in Figure 3). The frequency integrator operates as a proportional integral frequency regulator and uses the phase estimator output as the error signal. The proportional-integral frequency regulator loop performs symbol by symbol phase estimation and correction.

Experiment results

In our analysis, we used the front-end module SE4110 for data collection that consists of an antenna, filter, amplifier, mixer, and analog-to-digital converter. A data set collected by using this discrete component front-end design represents the primary reference set (SiGe Semiconductor SE4110L Datasheet, 2006).

The testing was executed for a large number of recorded signals, but in this paper only the results for a typical case of the weak signal tracking with the occurrence of dynamic stress, shown in Figure 4, are described. In Figure 4, the change in the frequency of the input signal is shown. At a given time (360ms) a disturbance of the input signal occurs. Such frequency disorder is caused by the disturbances (or the receiver motion). This signal was analyzed for the cases when the Costas PLL and the NDA phase estimators are used.

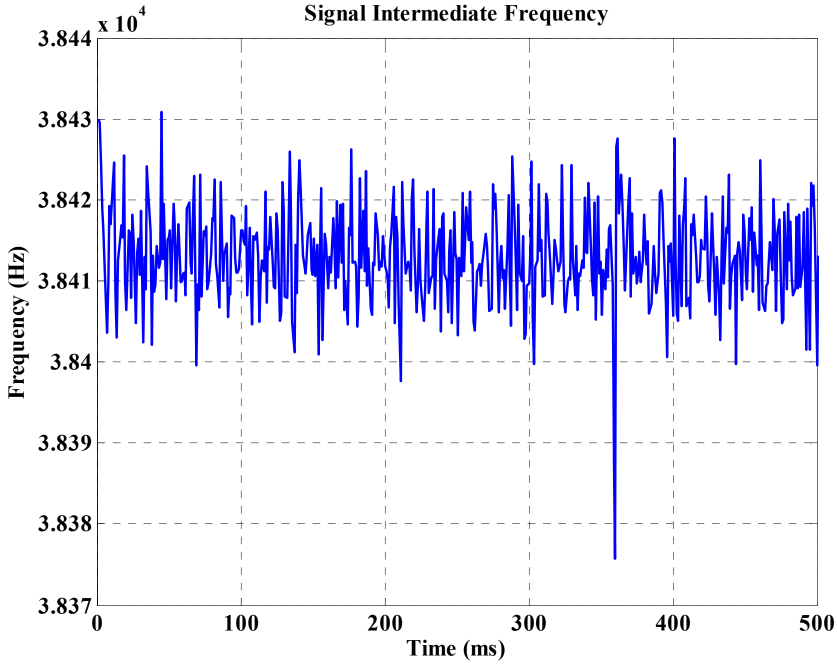

Figure 4 – Change of the frequency of a typical input signal with the frequency disorder that occurs at one point (at 360ms)

Slika 4 – Promena frekvencije tipičnog ulaznog signala sa frekventnim poremećajem koji se javlja u jednom trenutku (na 360 ms)

Рис. 4 – Изменение частоты типичного входного сигнала с частотным изменением, проявляющимся одномоментно (на 360ms)

If we consider the response of the phase discriminator in the Costas PLL, we can see that, at the same time when the frequency disorder occurs (at 360ms), a sudden jump of phase arises at the output of the phase discriminator, as shown in Figure 5.

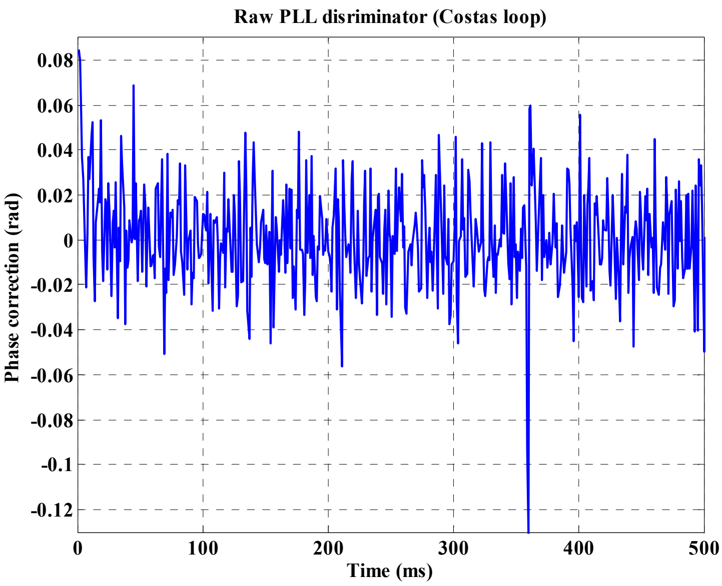

Figure 5 – Signal at the output of the phase discriminator for the Costas PLL
Slika 5 – Signal na izlazu faznog diskriminatora za Costasovu PLL
Рис. 5 – Сигнал на выходе фазового дискриминатора Costas PLL

This phase disorder at the exit of the phase discriminator causes an error in the navigation bits detection. The figure also shows that the phase of the detected signal varies in a wide range of phases as a consequence of the rapid Costas PLL response.

When the NDA phase estimator instead of the Costas PLL is used to process the same signal as in the previous case, the signal at the discriminator output is shown in Figure 6. This signal is used to correct the VCO operation, and when compared to the one obtained by using the Costas PLL, it generates a lower error signal amplitude. We can see that the signal changes over time when using the NDA phase estimator are slower and more resistant to the frequency offset than when compared to the case when the Costas PLL is used. The NDA phase estimator generates the error signal without the rapid changes, which in turn enable less sudden correction of the VCO operation. In the analyzed reference case, the NDA phase estimator has proven to be more resistant to the sudden changes in the input signal frequency.

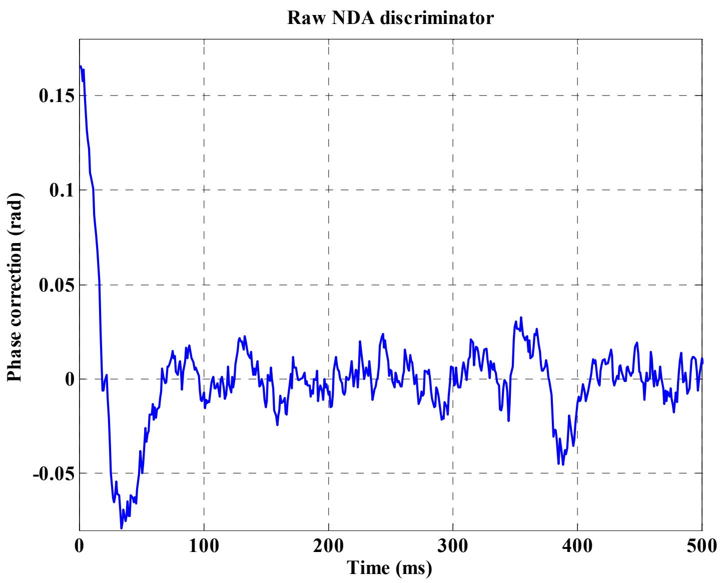

Figure 6 – Signal at the output of the phase discriminator for the NDA algorithm
Slika 6 – Signal na izlazu faznog diskriminatora za NDA algoritam
Рис.6 – Сигнал на выходе фазового дискриминатора для алгоритма NDA

In the case of the Costas PLL, a dynamic disorder occurring at 360ms time instance disrupts signal tracking; while in the case of the NDA phase estimator, the same dynamic disorder does not disrupt signal tracking. Such a behavior clearly indicates an advantage of the NDA based solution when compared to the Costas PLL based solution.

Furthermore, the error signal amplitude for the NDA phase estimator is much smaller than the one obtained for the Costas PLL. If we observe the same time point when the frequency disorder occurs (360ms), we thus obtain more than twice lower error signal amplitude.

The advantage of the NDA phase estimator in comparison to the Costas PLL estimator is also obvious at the DLL output (shown in Figure 3 at the point E). The signals that represent the noise at the DLL output in the case of the Costas PLL or the NDA phase estimator are shown in Figure 7.

The first (upper) signal represents the output of the DLL in the case when the Costas PLL is used, and the second (lower) signal represents the output of the DLL in the case when the NDA phase estimator is used. The signal amplitude obtained with the NDA phase estimator is more than twice lower than the one obtained with the Costas PLL. These results shown in Figure 7 indicate that when the Costas PLL is used, a lot of energy goes into the noise.

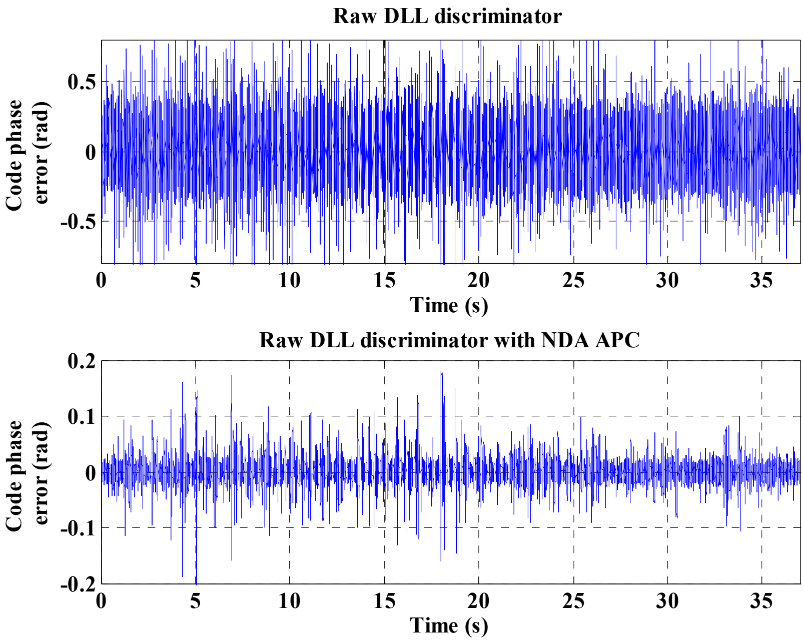

Figure 7 – Signals at the output of the discriminator (DLL) in the case of the Costas PLL (upper) and the NDA phase estimator (lower)
Slika 7 – Signal na izlazu diskriminatora (DLL) za slučaj Costasove PLL (gore) i NDA fazni estimator (dole)
Рис. 7 – Сигнал на выходе дискриминатора (DLL) для случая Costas PLL (вверху) и NDA оценки фазы (внизу)

Conclusion

In this paper, the accuracy and reliability of the proposed NDA phase estimator was analyzed for the weak GPS signal scenario, and compared to those achieved with the widely used Costas PLL estimator. Based on a practical processing of the referent GPS signals, it is shown that the NDA phase estimator is more resistant to sudden changes in the frequency (phase) of the input signal in respect to the traditional Costas PLL solution. In the case of a high SNR, the proposed NDA phase estimator behaves similarly to the Costas PLL estimator, while in the case of a low SNR, the solution proposed here exhibits a stable signal tracking operation. The analysis presented here leads to the conclusion that the proposed NDA solution achieves good results in the case of the weak GPS signal reception, and also when the GPS receiver is used in a very dynamic working environment.

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УЛУЧШЕНИЕ СИНХРОНИЗАЦИИ СИГНАЛА В ПРОГРАММИРУЕМОМ GPS ПРИЕМНИКЕ

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ОБЛАСТЬ: телекоммуникации
ТИП СТАТЬИ: оригинальная научная статья
ЯЗЫК СТАТЬИ: английский

Резюме:

В GPS приемнике, распознавание навигационных битов реализовано путем отслеживания и определения и обнаружения сигнала. В процессе отслеживания сигнала, локально генерируемый сигнал должен быть синхронизирован с входящим сигналом. Характеристикой фазового контура Costas, который традиционно используется для синхронизации сигналов, является подверженность влиянию источников погрешностей. Ошибки в результатах по отслеживанию фазы существенны при слабом входном сигнале, например, для сигналов с малым отношением сигнал-помехи. Для улучшения синхронизации отслеживаемого сигнала со стороны приемника, мы рекомендуем использовать non-data-aided (NDA) фазовый компаратор.. Основываясь на практической обработке GPS сигналов, можно сделать вывод, что применение алгоритма NDA обеспечивает большую устойчивость к внезапным изменениям в частоте входного сигнала по сравнению с применяемыми в настоящее время фазовыми дискриминаторми с фазовым контуром Costas. Кроме того, на основании проведенного анализа было показано, что предложенное решение позволяет обеспечить стабильность работы, особенно для сигналов с низким отношением сигнал-помехи.

Ключевые слова: *система глобального позиционирования, компарация фаз, приемник, обработка сигнала, программное обеспечение.*

POBOLJŠANJE SINHRONIZACIJE SIGNALA U SOFTVERSKOM GPS PRIJEMNIKU

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OBLAST: telekomunikacije
VRSTA ČLANKA: originalni naučni članak
JEZIK ČLANKA: engleski

Sažetak:

Prepoznavanje navigaocionih bita u GPS prijemniku realizuje se kroz procese praćenja i detekcije signala. U procesu praćenja signala lokalno generisani signal mora biti sinhronizovan sa primljenim signalom. Karakteristika Costasove fazne petlje, koja se najčešće koristi za sinhronizaciju signala, jeste podložnost uticaju izvora grešaka. Rezultantne greške praćenja faze značajne su u prisustvu slabog ulaznog signala, kao, na primer, kod signala sa malim odnosom signal–šum. Radi poboljšanja sinhronizacije omogućavanja praćenja signala koji emituje strane prijemnika, predlažemo upotrebu non-data-aided (NDA) fazni estimator. Na osnovu praktične obrade GPS signala pokazano je da primena NDA algoritma omogućava veću otpornost na iznenadne promene frekvencije ulaznog signala u odnosu na do sada primenjivani fazni diskriminator u Costasovoj faznoj petlji praćenja. Na osnovu izvršene analize pokazano je, takođe, da predloženo rešenje omogućava stabilan rad, naročito kod signala sa malim odnosom signal–šum.

Ključne reči: *sistem globalnog pozicioniranja, estimacija faze, prijemnik, obrada signala, softver.*

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