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Method and system for disciplining a local reference oscillator by GPS 1PPS signal

Abstract. *This article presents an algorithm and system for synchronizing a local OCXO reference generator to an one-pulse-per-second (1PPS) GPS clock reference signal. The generator system flowchart and the structure of the program performing the synchronization process are discussed. Appropriate measurement system, which allows assessment of obtained results, is also presented and measurement results are shown.*

Streszczenie. *W artykule przedstawiono algorytm dyscyplinujący lokalny generator wzorcowy OCXO względem sygnału sekundowego 1PPS systemu nawigacyjnego GPS. Omówiono metodę i układ do synchronizacji generatora oraz odpowiedni układ pomiarowy do kontroli procesu tej synchronizacji. Zaprezentowano uzyskane wyniki pomiarów. (**Metoda i układ do dyscyplinowania lokalnego generatora wzorcowego względem sygnału 1PPS systemu GPS**).*

Keywords: comparison of reference frequencies, GPS Disciplined Oscillator, 1 PPS signal, GPS.
Słowa kluczowe: porównywanie częstotliwości wzorcowych, generator dyscyplinowany GPS, sygnał 1 PPS, GPS.

Introduction

The GPS receiver provides an one-pulse-per-second (1 PPS) signal with a very specific period equal to 1 second. Even though it is very precise, this signal is relatively limited due to accidental signal edge position changes caused mainly by the influence of the Earth's atmosphere on the propagation of satellite signals. On the other hand, an OCXO quartz oscillator with temperature stabilization is characterized by high precision due to its high short-term stability but much lower accuracy due to lower long-term stability. Therefore, synchronizing a local OCXO reference generator to a 1 PPS GPS signal is a simple and efficient way to obtain the reference frequency signal with high accuracy and precision [1, 2, 3]. It requires applying an appropriate method for measuring very small differences in frequency between two impulse signals [4, 5] as well as an appropriate algorithm for retuning a local OCXO generator and synchronizing its output signal to a 1 PPS GPS receiver signal [2, 3].

Measurement of small differences in frequency of reference signals

Fig. 1 shows time waveforms explaining the basis for measuring the small difference Δf_{gen} between the frequency f_{gen} of the local reference generator and the frequency f_{ref} of the reference GPS receiver signal [4, 5]. The reference signal with a stable, known frequency f_{ref} and the period T_{ref} has the phase $\varphi_{ref}(t)$ ramping linearly over time with a speed of the 2π radians per one period:

(1) $$\varphi_{ref}(t) = 2\pi \frac{t}{T_{ref}},$$

where: φ_{ref} – phase of the reference signal, T_{ref} – period of the reference signal, t – time.

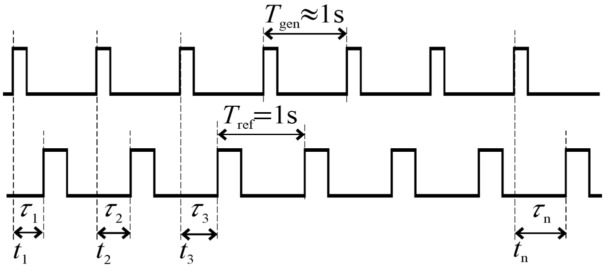


Fig.1. Basis for measuring the small frequency differences

Local reference generator signal of the similar frequency $f_{gen} \approx f_{ref}$ and the period T_{gen} is shifted in the phase with respect to the reference signal by the so-called phase time τ, and its phase $\varphi_{gen}(t)$ equals:

(2) $$\varphi_{gen}(t) = \varphi_{ref}(t) + 2\pi \frac{\tau}{T_{ref}} = \frac{2\pi}{T_{ref}}(t+\tau).$$

Therefore, the frequency f_{gen} of the local generator signal may be determined by calculating the derivative of its phase function $\varphi_{gen}(t)$ with respect to time:

(3) $$f_{gen} = \frac{1}{2\pi}\frac{d\varphi_{gen}}{dt} = \frac{1}{2\pi}\frac{d}{dt}\left(\varphi_{ref}(t) + 2\pi\frac{\tau}{T_{ref}}\right) = = \frac{1}{T_{ref}}\left(1 + \frac{d\tau}{dt}\right).$$

If the phase time $\tau = const.$, its derivative with respect to time equals zero; therefore, in this case, the generator frequency f_{gen} exactly equals the reference frequency: $f_{gen} = f_{ref}$. However, if the phase time τ is not constant, then the difference Δf_{gen} between the local generator frequency f_{gen} and the reference f_{ref} equals:

(4) $$\Delta f_{gen} = f_{gen} - f_{ref} = \frac{1}{T_{ref}}\frac{d\tau}{dt},$$

and the relative frequency error δf_{gen} equals:

(5) $$\delta f_{gen} = \frac{f_{gen} - f_{ref}}{f_{ref}} = \frac{d\tau}{dt}.$$

If the frequency f_{gen} is constant and phase times τ_1, τ_2, ... τ_n are measured at subsequent moments t_1, t_2, ... t_n, the derivative (5) can be determined as a difference quotient:

(6) $$\delta f_{gen} = \frac{\Delta\tau}{\Delta t} = \frac{\tau_n - \tau_1}{t_n - t_1},$$

where δf_{gen} is the relative frequency deviation with respect to the reference f_{ref}.

The main source of uncertainty $u(\delta f_{gen})$ is the uncertainty $u(\Delta\tau)$ of the phase time measurement τ:

(7) $$u(\delta f_{gen}) \cong \frac{u(\Delta\tau)}{\Delta t}.$$

The phase time measurement uncertainty $u(\Delta\tau)$ is caused by a quantization error during digital measurement of the phase time τ and the uncertainty of positions of the GPS receiver reference signal edges. For example, if the uncertainty $u(\Delta\tau)$=100 ns, then in order to obtain the uncertainty $u(\delta f_{gen})$ at a level of 10^{-9} Hz/Hz, the required measurement time $\Delta\tau$=100 s [4]. This time must be extended in order to obtain subsequent, more accurate synchronization of a local generator to a 1 PPS signal.

System and algorithm for synchronizing a local generator to the GPS signal

The flowchart of the implemented system for synchronizing the local OCXO generator to the 1 PPS signal is shown in Fig. 2. The GPS receiver with an active antenna provides the reference 1 PPS signal and sentences in National Marine Electronics Association (NMEA) format, which contain information on proper reception of signals from a sufficient number of satellites. The Recommended Minimum Specific Data (RMC) message is used to this end. The OCXO generator provides a 5MHz signal, which is divided by frequency dividers (FD) to generate a 1 Hz signal. The time interval counter (TIC) measures intervals τ between subsequent rising edges of 1 PPS GPS and 1 PPS OCXO signals (Fig.1). TIC measurement results and NMEA sentences of the GPS receiver are fed to the microcontroller μC, which executes the synchronization algorithm and controls the OCXO generator using a Digital-to-Analog Converter (DAC) and synchronizes it to a 1 PPS GPS signal.

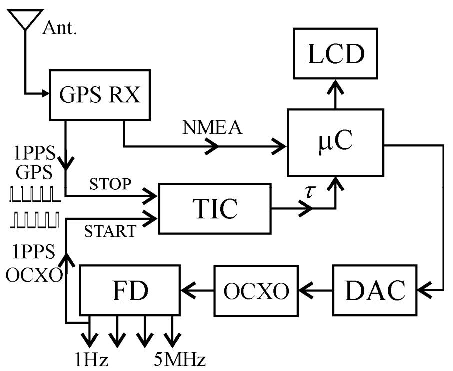


Fig.2. The flowchart of the OCXO generator synchronized to the 1 PPS GPS signal

The flowchart of the algorithm for synchronizing an OCXO generator is shown in Fig. 3. Upon connecting the power supply, a RMC frame is read in a loop until the receiver properly synchronizes with a sufficient number of GPS satellites. From this moment on, the TIC begins measuring time intervals τ and the microcontroller μC calculates the detuning of the OCXO generator as a slope $\delta f_{gen}=a$ of linear regression line:

(8) $$\tau = at + b\ ,$$

where a is the slope and b is the intercept of the fitting line obtained by the Least-Squares Regression from set of n values of phase times τ_1, τ_2, ... τ_n measured at subsequent moments t_1, t_2, ... t_n.

Then jitter $\Delta\tau_i$ is calculated as a difference between each measured phase time τ_i, and regression line:

(9) $$\Delta\tau_i = \tau_i - (at_i + b)\ .$$

Finally the standard deviation of jitter σ_τ is calculated:

(10) $$\sigma_\tau = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\overline{\Delta\tau_i} - \Delta\tau_i)^2}\ .$$

While the thermostat warms up, the standard deviation σ_τ is high (of the order of 10 μs) and decreases to less than 1 μs upon OCXO reaching stable temperature. The synchronization process can only begin upon reaching stable temperature in the thermostat of the OCXO generator, therefore, the standard deviation σ_τ is calculated for subsequent intervals τ, taking current detuning δf_{gen} into account. Then the microcontroller μC, based on the determined detuning δf_{gen}, adjusts the OCXO generator frequency by using a DAC. Along with reaching continuously lower values of the detuning δf_{gen}, the measurement time Δt is prolonged from its initial value of 100 s to as high as 10000 s, which allows the detuning δf_{gen} to reach the level of 10^{-11} Hz/Hz.

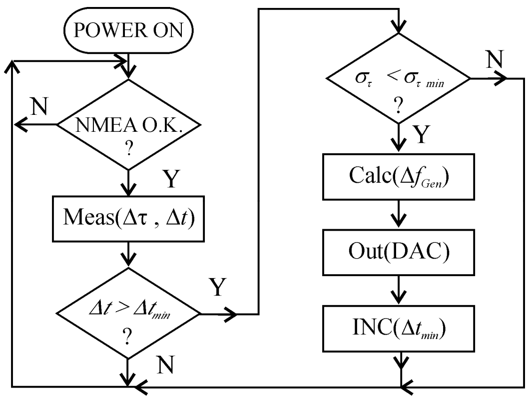


Fig.3. The synchronization algorithm for disciplining OCXO by the 1 PPS GPS signal

Measurement system for controlling the operation of the reference generator

For the purpose of experimental assessment of operation of the implemented generator system, the measurement system shown in Fig. 4 was assembled using the studied OCXO disciplined by GPS (GPSDO), a second GPS receiver with 1 PPS output, a HP53131A digital timer counter connected via the RS232 interface to a PC computer using the LabVIEW software.

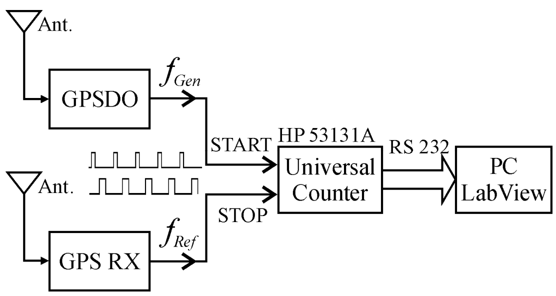


Fig.4. The flowchart of the measurement system for controlling the operation of the reference generator

Front panel of the application written in the LabVIEW environment for controlling the operation of the reference generator is shown in Fig. 5. On the panel it can be seen and analyzed all of the measured and calculated values: time chart of the phase times τ_1, τ_2, ... τ_n, linear regression line (8), jitter $\Delta\tau_i$ (9), standard deviation of jitter σ_τ (10), histogram of jitter and the relative frequency error δf_{gen} of the examined OCXO.

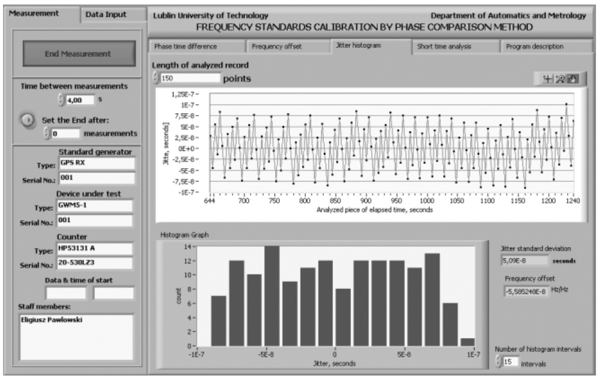


Fig.5. Front Panel of the LabVIEW measurement application for controlling the operation of the reference generator

Diagram of this LabVIEW application is shown in Fig. 6. It calculates the detuning offset δf_{gen} (5) of the studied OCXO generator in real-time with respect to the 1 PPS GPS signal using the method of least squares [6] as the slope of the linear regression [5]. Additionally, the standard deviation σ_τ is calculated (10) based on measurement point deviations (9) with respect to the previously determined linear regression (8).

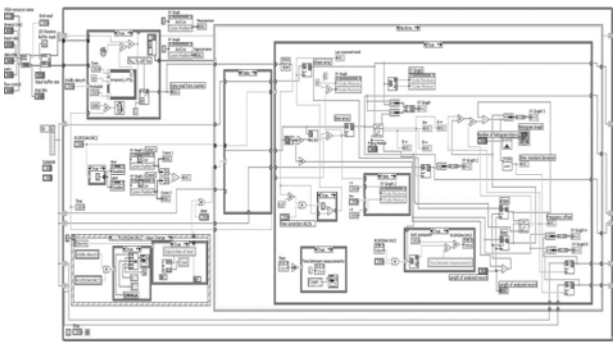


Fig.6. Diagram of the LabVIEW measurement application for controlling the operation of the reference generator

Fig. 7 shows an example time chart of the phase times τ_1, τ_2, ... τ_n measured at subsequent moments t_1, t_2, ... t_n, immediately after switching device on. As we can see, at the beginning of the warm-up process, the changes of the phase times τ are very large. Then, after about 1000 seconds, the changes decreased considerably.

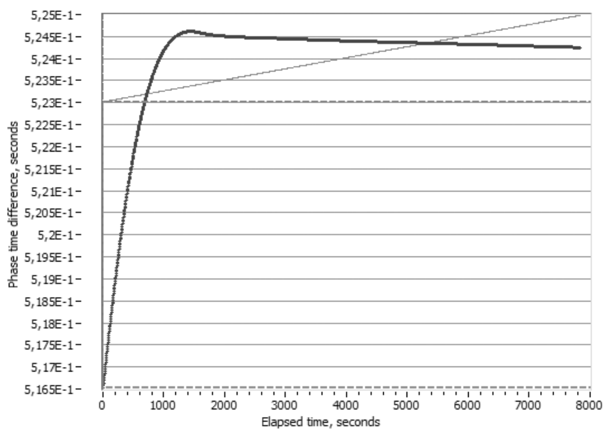
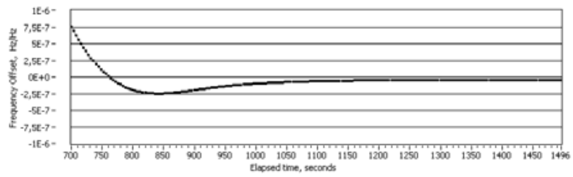


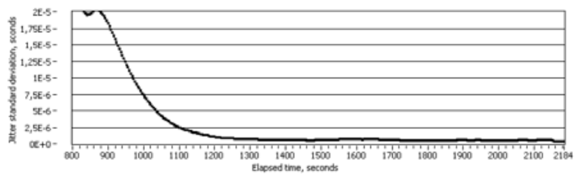
Fig.7. Phase time changes during the warm-up process of an OCXO thermostat after switching device on

Fig. 8 shows example detuning measurement results δf_{gen} of the studied generator and the standard deviation σ_τ during the same warm-up process of the thermostat of an OCXO generator upon connecting the power supply. In the preliminary stage of the generator's operation, its detuning offset is high up to $7.5{\cdot}10^{-7}$ Hz/Hz and changes quickly along with the temperature of the thermostat (Fig. 8a); at the same time, the value of the standard deviation σ_τ is also high up to $2{\cdot}10^{-5}$ seconds (Fig. 8b) and the jitter histogram is very wide and asymmetrical (Fig. 8c).

a)



b)



c)

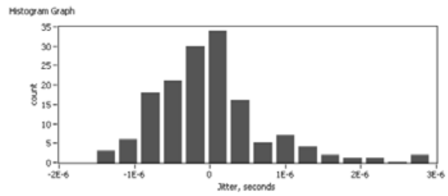
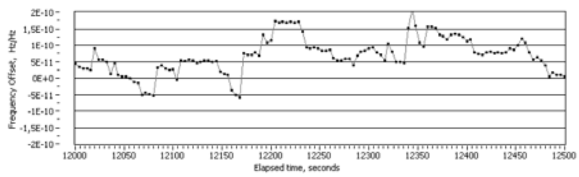


Fig.8. The warm-up process of an OCXO thermostat: a) detuning measurement offset δf_{gen} in Hz/Hz, b) the jitter standard deviation σ_τ in seconds, c) the asymmetrical shape histogram of the jitter

Fig.9 shows measurement results after the temperature stabilizes and the generator is going to start synchronize to the 1 PPS GPS signal, using the presented algorithm with short averaging time equal to 500 seconds.

a)



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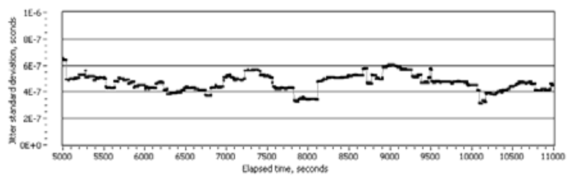

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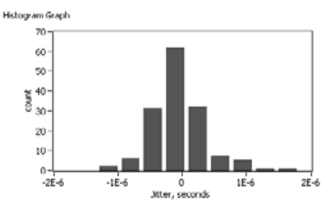


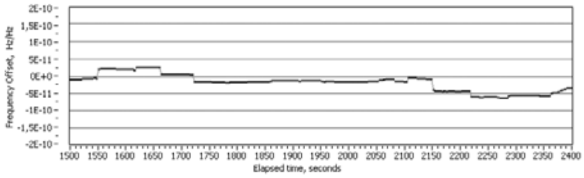
Fig.9. Measurement results obtained after the temperature stabilized and the generator is going to start synchronize to the 1 PPS GPS signal with short averaging time equal to 500 seconds: a) detuning measurement offset δf_{gen} in Hz/Hz, b) the jitter standard deviation σ_τ in seconds, c) the symmetrical shape histogram of the jitter

As we can see, upon reaching a stable temperature, the standard deviation σ_τ decreases significantly to a value less than 1μs (Fig.9b), the histogram goes to the shape of the symmetrical distribution (Fig.9c), while the synchronization algorithm adjusts the generator to the reference frequency with the error $\delta f_{gen} < 2\cdot10^{-10}$ Hz/Hz (Fig.9a).

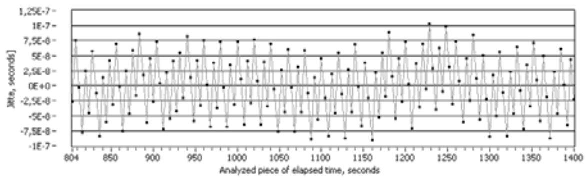
In order to obtain more accurate synchronization, in the next steps, the averaging time is extended step by step up to 10000 seconds. Fig.10 shows an example measurement results after the final synchronization process with averaging time equal to 5000 seconds.

Finally, the synchronization algorithm adjusts the OCXO generator to the 1 PPS GPS reference frequency signal with the error $\delta f_{gen} < 5\cdot10^{-11}$ Hz/Hz (Fig.10a), the jitter has a sawtooth shape with an amplitude of less than 100 ns (Fig.10b), while the histogram goes to the shape of the uniform distribution (Fig.10c).

a)



b)



c)

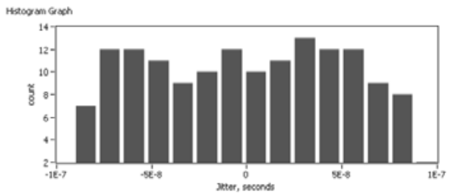


Fig.10. Measurement results obtained after the temperature stabilization and the generator is synchronized to the 1 PPS GPS signal with long averaging time equal to 5000 seconds: a) detuning measurement offset δf_{gen} in Hz/Hz, b) the sawtooth shape jitter in seconds, c) the uniform distribution shape histogram of the jitter

Conclusion

The system and algorithm for synchronizing an OCXO generator to a 1 PPS GPS signal as well as the measurement system allowing continuous control of the generator's operation and on-going assessment of its metrological parameters was presented. The system uses the1 PPS GPS signal as a reference frequency. The GPS receiver and OCXO generator are software controlled and requires no operator attention. Measurements are made using a time interval counter HP53131A. Designed application in LabVIEW environment completely automates the measurement process and presents the measurement data in a clear digital and graphic, easy-to-understand format. While measurements are being made, a full-colour time charts and bar graphs display the performance of disciplined OCXO generator. These charts and bar graphs are updated every time the measurement is performed. It lets you see at a glance how well OCXO is performing. All data recorded by the system is stored on a solid state disk. At any time, you can retrieve and analyze past data recorded by the system. The obtained measurement results confirm the possibility of synchronizing a local OCXO generator using the presented method to a 1 PPS GPS signal with the error δf_{gen} not worse than $5\cdot10^{-11}$ Hz/Hz.

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