GPS SYNCHRONIZED QUARTZ FREQUENCY SOURCE OF 10^{-11} ACCURACY

Aleksander Lisowiec

Tele and Radio Research Institute, Ratuszowa 11, 03-450 Warsaw, Poland
alisow@itr.org.pl

Abstract Discontinuance of S.A. effect in GPS system increased the potential accuracy of time and frequency sources synchronized by GPS signal. It became possible for a frequency source with quartz oscillator to have instantaneous frequency inaccuracy not worse than $1 \cdot 10^{-11}$. In the paper the design and measurement results of the GPS synchronized frequency source with battery backup of quartz oscillator power supply has been presented. This source has frequency accuracy presented above and can replace rubidium sources in many applications.

GPS, frequency standard

1. INTRODUCTION

Intentional degradation of GPS signal to civil users, the S.A. effect, which had been operational till 4 of May, 2000, manifested itself as a 100 ns RMS jitter of 1 pps signal at the output of GPS receivers around mean value. Time constant needed to filter out this jitter was hard to evaluate but, according to some sources [Ref. 1], was equal even to 3 days. Synchronization of quartz oscillator in a loop with so large time constant was not very practical, because aging and ambient temperature sensitivity of highest stability quartz oscillators led to frequency fluctuations of the order of 10^{-10}. Discontinuation of S.A. has led to about 5-fold decrease in RMS jitter of 1 pps pulse and much shorter time constant needed to filter it out. There appeared the possibility to construct GPS synchronized frequency source with quartz oscillator as a local frequency source with frequency instability not worse than 10^{-11}. Such source would have several advantages over rubidium sources, namely lower price, lower power consumption and longer, up to 20 years life-span. Lower power consumption makes possible emergency battery backup of local quartz oscillator supply so that the accurate frequency could be almost instantaneously reproduced after power supply return.

2. DESIGN METHODOLOGY

2.1. Analysis of the main factors determining the accuracy of the source

2.1.1 Requirements on the local quartz oscillator

Frequency accuracy of synchronized frequency source depends mainly on the stability of the local quartz oscillator and synchronization algorithm. In the case of frequency sources with improved parameters, especially of relative frequency inaccuracy not worse than 10^{-11}, what is equally important is proper choice of digital to analog converter generating the control voltage applied to VCXO.

The starting point for determining the specifications that must be met by internal VCXO are short term parameters of output signal and the time constant of synchronization loop. The time constant T can be determined as larger of two values T_1 and T_2.

T_1 results from the minimum time interval over which it is possible to measure relative frequency deviation of internal quartz oscillator relative to 1 pps pulse with specified accuracy. With 10^{-8} relative accuracy over measurement interval equal to 1 s, T_1 should equal 2000 s to attain measurement accuracy of $5 \cdot 10^{-12}$.

The value of T_2 can be determined from time period necessary to average the 1 pp jitter to the level of $5 \cdot 10^{-12}$ relative inaccuracy. The 1 pps RMS jitter without S.A., reported by some sources [Ref. 2], is equal to 19 ns. T_2 is calculated from

$$T_2 = \frac{2 \cdot 1.9 \cdot 10^{-8}[s]}{5 \cdot 10^{-12}} = 7600[s] \qquad (1)$$

The minimum value of loop constant, T, is thus equal to 7600 [s].

The control loop is able to react to the frequency change of internal oscillator after time period not shorter than loop time constant. Over this time period the relative change in the internal oscillator frequency due to all external influences should not be greater than 10^{-11}. Assuming that over 10^4 s time period the source can be subjected to temperature changes equal to 5° C (operation in a non air-conditioned laboratory room), the temperature coefficient of internal quartz oscillator should be lower than $2 \cdot 10^{-12}$/°C and recommended $1 \cdot 10^{-12}$/°C.

The maximum aging coefficient of quartz oscillator is

$$\frac{5 \cdot 10^{-12}}{\frac{7600}{86400}} \cong 5.7 \cdot 10^{-11} / 24h \qquad (2)$$

and recommended $3 \cdot 10^{-11}$/24h.

Also the frequency changes caused by air pressure and humidity fluctuations not greater than $5 \cdot 10^{-12}$ are desired.

Quartz oscillators with parameters specified above, namely aging coefficient $3 \cdot 10^{-11}$/24h, temperature coefficient $1 \cdot 10^{-12}$/°C and air tight enclosures belong to highest stability quartz oscillator and are manufactured by a number of companies.

2.1.2 Requirements on control voltage circuitry

The control voltage circuitry of internal quartz oscillator must provide:

- sufficiently fine tuning step, in the case of the source with 10^{-11} maximal frequency instability this tuning step should be equal to $10^{-11}/4$;
- tuning range necessary to compensate the aging of the quartz oscillator over the life-span of the source;
- lack of sensitivity to temperature changes.

The specifications of digital to analog converter, which is the main part of the tuning circuit, have to be chosen according to the above requirements. The choice of DAC reduces to specification of the resolution and then to selection from DAC's available on the market of the cheapest one that fulfils the requirements of output voltage stability.

The resolution of the DAC is determined from:

- aging coefficient of quartz oscillator, denoted by *a* and equal to $4 \cdot 10^{-11}$/24h;

- minimum (relative) tuning step, denoted by df_s and equal to $2.5 \cdot 10^{-12}$;
- estimated life-span of the source - t_s, in this case assumed equal to 20 years.

In the first step the total relative change in quartz oscillator frequency, Δf_{total}, due to aging is calculated as

$$\Delta f_{total} = 4 \cdot 10^{-11} \cdot 365 \cdot 20 = 2.92 \cdot 10^{-7} \quad (3)$$

Dividing Δf_{total} by minimal tuning step df_s, the number of tuning levels n is obtained as

$$n = \frac{\Delta f_{total}}{df_s} = 116800 \quad (4)$$

Logarithm of n to the base 2 gives the number n_{DAC} of bits of DAC minus 1, as the sign of aging coefficient a is not a priori known:

$$\log_2(n) = \log_2(116800) = 16.83\,, \quad (5)$$

so the number of bits of DAC is 18.

Stability of the DAC internal reference voltage is not very important as very high stability reference voltage usually can be obtained from quartz oscillator. The most important parameter of DAC is differential nonlinearity, which should not be greater than 1 LSB.

Digital to analog converters meeting above requirements are not very abundant but there are a few on the market and the one selected for our source was AD 760 as it was one of the cheapest.

2.2 Battery backup of internal oscillator power supply

One of disadvantages of GPS synchronized quartz frequency source is long time necessary to achieve by the source the specified parameters in the case when the synchronization process starts with cold oscillator. Best high stability quartz oscillators need hours to return to the aging level prior to power cut-off, when the interruption in power supply lasted longer than a few hours. During time interval when the aging rate is high, the control loop works with short time constant so the instantaneous frequency accuracy is not very high due to insufficient filtration of 1 pps jitter.

In the new frequency source a battery backup of power supply has been employed. In the case of main power supply cut-off the quartz oscillator is powered by a battery placed inside the source enclosure. The battery also powers the microprocessor unit. After main supply return the microprocessor unit restores the control voltage to the value prior to power failure so a very accurate frequency is obtained almost instantaneously. Limiting power backup only to quartz oscillator and microprocessor unit enables ten hours of keeping the quartz oscillator in warmed-up state.

3. MEASUREMENT RESULTS

3.1 Short term frequency stability of the source

The following short term parameters of the output frequency signal of the source have been measured.

Allan variance

Operation mode	f [MHz]	Averaging time [s]		
		0.001	0.01	0.1
free running	5	$4.0 \cdot 10^{-10}$	$8.7 \cdot 10^{-11}$	$3.5 \cdot 10^{-12}$
	10	$9.5 \cdot 10^{-11}$	$1.7 \cdot 10^{-11}$	$1.5 \cdot 10^{-12}$
locked-in	5	$1.8 \cdot 10^{-9}$	$6.0 \cdot 10^{-11}$	$1.3 \cdot 10^{-11}$
	10	$1.2 \cdot 10^{-10}$	$3.7 \cdot 10^{-11}$	$1.2 \cdot 10^{-12}$

Allan variance (continued)

Operation mode	f [MHz]	Averaging time [s]		
		1	10	100
free running	5	$1.7 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$	$2.3 \cdot 10^{-12}$
	10	$6.7 \cdot 10^{-13}$	$1.1 \cdot 10^{-12}$	
locked-in	5	$2.0 \cdot 10^{-12}$	$7.0 \cdot 10^{-13}$	
	10	$8.1 \cdot 10^{-13}$	$7.6 \cdot 10^{-13}$	$1.1 \cdot 10^{-12}$

SSB Phase noise

Operation mode	f [MHz]	Offset from the carrier [Hz]				
		1	10	100	1k	10k
free running	5	-92	-127	-147	-149	-149
	10	-105	-129	-142	-145	-148
locked-in	5		-135	-145	-148	-148
	10		-138	-140	-146	-146

Harmonics suppression

f [MHz]	Harmonic number			
	2	3	4	5
5	-38	-66	-74	-
10	-36	-48	-63	

3.2 Long term frequency stability of the source

The long term frequency stability of the source has been measured in a measurement setup presented in fig.1.

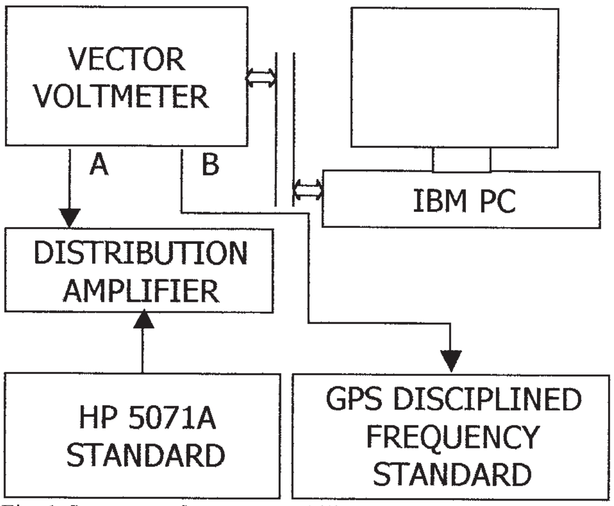

Fig. 1. Long term frequency stability measurement setup

In the measurement system the phase difference between 10 MHz signal from cesium HP 5071A frequency standard and 10 MHz signal from GPS source has been measured every second by vector voltmeter, averaged over 10 seconds intervals and saved to a file on hard disc of the computer.

3.2.1 Locked-in mode

Measurement results of the source working in the locked-in mode over a period of 2 and half days are presented in fig. 2. The measured phase difference was approximated by Bezier curve which can be barely seen in fig. 2 but has been shown on a stretched time period of 10000 seconds in fig. 4.

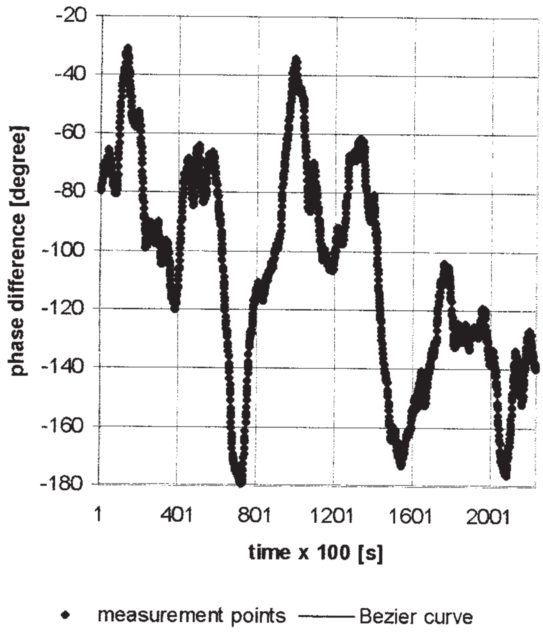

Fig. 2. Phase time error of the GPS source relative to HP 5071A in locked-in mode.

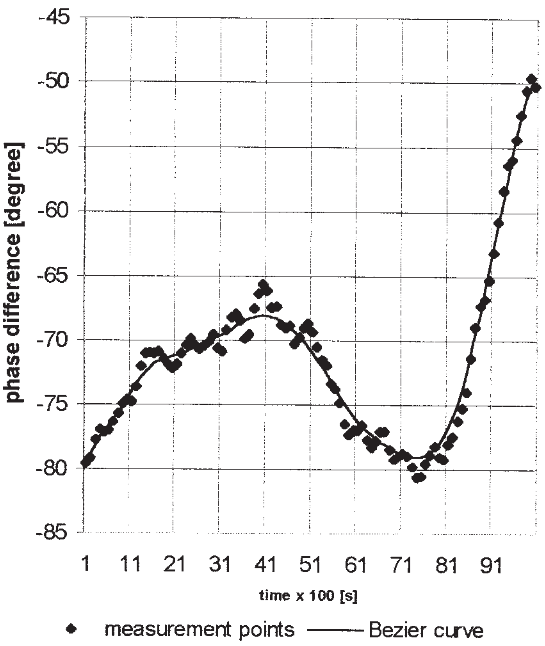

Fig. 3. Quality of the fit of measurement results by Bezier curve shown over 10000 s period.

The Bezier approximation of measurement results was used because it enabled the calculation of instantaneous frequency inaccuracy as a derivative of phase time error. No attempt has been made to remove the HP 5071A drift estimated at $1{\cdot}10^{-13}$ relative to UTC by GPS Common View method. The calculated relative frequency inaccuracy of the source is shown in fig. 4. As can be seen, the relative frequency inaccuracy has never been worse than 10^{-1} and the RMS of this inaccuracy is well below $5{\cdot}10^{-12}$.

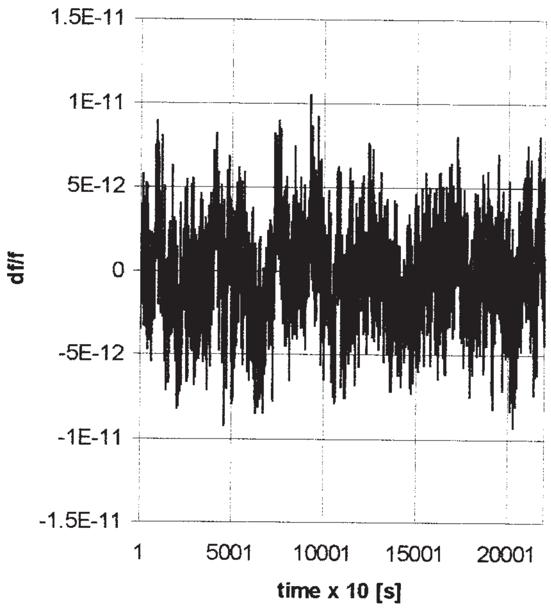

Fig. 4. Relative frequency inaccuracy of the source working in locked-in mode.

3.2.2 Free running mode

Measurement results of the source working in the free running mode over a period of slightly over one day are presented in fig. 5.

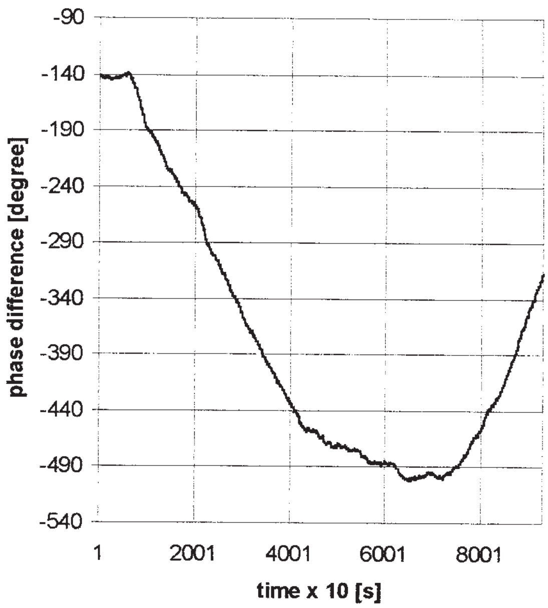

Fig. 5. Measurement results of the source working in free running mode.

Frequency stability of the free running source is an indication of the quality of internal quartz oscillator and prediction algorithm [Ref. 3,4]. The relative frequency inaccuracy in free running mode was calculated by the same method as in locked-in mode and the results are presented in fig. 6. The aging effect was compensated almost perfectly by the prediction algorithm.

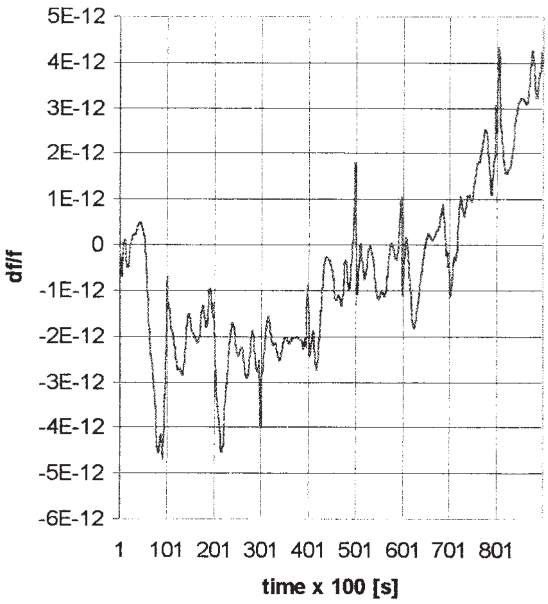

Fig. 6. Relative inaccuracy of the source working in free running mode.

4. CONCLUSION

The feasibility of construction of GPS disciplined quartz frequency source with measured instantaneous relative frequency inaccuracy not worse than 10^{-11} has been proved. The RMS value of this inaccuracy is of the order of $3\cdot10^{-12}$. The source has been equipped with battery backup of quartz oscillator power supply which can maintain the oscillator in warmed-up state for ten hours. Such source is a cheap alternative to rubidium source as it can achieve the relative frequency inaccuracy on the order of 10^{-11} after approximately one hour after transferring it to new location assuming that GPS receiver starts with no data about its position.

Although termination of S.A. effect eased the task of designing the source, still the crucial components such as quartz oscillator and digital to analog converter have to be carefully selected.

5. REFERENCES

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[4] A. Lisowiec, A. Czarnecki, GPS controlled frequency and time standard with high immunity from temporary absence of 1 pps signal, Proc. of 11th EFTF, Neuchatel, March 1997