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Evaluation of performance of GPS controlled rubidium clocks

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Global Positioning System (GPS) controlled rubidium clock systems are now being used widely for many precise timing applications. They also play the role of the reference time and frequency source in many laboratories. This demands the evaluation of performance of such clocks to assess their reliability. For this purpose, a special experimental campaign has been planned. The epoch time has been found to be reliable within 60 ns and frequency offset does not exceed few parts in 10^{-12}. But the receiver takes few hours to achieve initial lock. Short-term stability in locked condition has been poorer than that of the rubidium clock in free running condition.

Keywords: Rubidium clock, GPS

1 Introduction

Time is one of the important parameters for the measurement. The basic component of the timing system is a clock. In course of the time, the technology of the clock has advanced to a stage that it makes use of the inherent characteristics of an atom. Thus, Rubidium clock, Hydrogen Maser and Cesium clock are now commercially available in the market. Cesium atomic clock has been established as the primary standard of the frequency and the time[1]. With the help of the cesium atomic clock, most of the countries maintain the respective national time scale. National Physical Laboratory, New Delhi, India (NPLI – acronym given by BIPM) maintains Indian Standard Time (IST) with the help of a cesium atomic clock which is traceable to Universal Coordinated Time (UTC) coordinated by Bureau International des Poids et Mesures (BIPM). It is, thus, desirable that the standard laboratory should have a cesium clock as the reference source for the frequency and the time. But a cesium clock being very expensive (nearly US $ 60000), it is not always affordable for many organizations.

In the meantime, the Global Positioning System (GPS) has emerged as a very reliable tool for precise navigation and timing. GPS has become an important tool to time keeping community as the heart of GPS is the atomic clock system. GPS satellites carry on board atomic clocks which always remain synchronized to the time scale maintained by US Naval Observatory [i.e. UTC (USNO)]. GPS signals are derived from this atomic clock[1-5]. Further, the development of GPS timing receiver has gone through many phases of advancement[6,7] and millions of users have been generated. Lately, GPS controlled Rubidium Clocks (GCRC) - a special type of GPS timing receiver, have become popular and are being used for precise timing applications. Some effort[8] has been made to evaluate the performance of the GPS controlled rubidium clock. But after the removal of selective* availability (SA)[1], these clocks are being used as the reference standard for the frequency and the time as a less expensive alternative for a cesium clock. Thus, it has become all the more important to have much more elaborated study on the performance of this type of GPS timing receivers. Keeping this in mind, the performance of such GPS timing system has been studied and the observed data have been carefully analyzed. This paper describes the details of the plan of the experiment and discusses the findings of the analysis.

2 Configuration of GPS Controlled Rubidium Clock

The GPS controlled rubidium clock (GCRC) is different from the usual GPS timing receiver. So, to evaluate the performance of GCRC, it is necessary to

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*Selective Availability (SA) is an intentional degradation of GPS signals to deny unauthorized users access to the full accuracy for positioning and timing. Since March 25, 1990 it had been intermittently affected by dithering the satellite clock and by truncating the transmitted navigation message for ephemeris. The US government discontinued the use of Selective Availability since May 01, 2000.

note its basic functional behaviour. The GCRC consists of a commercial GPS receiver, a rubidium clock, a phase comparator and a microcontroller as shown in Fig. 1. The phase comparator has two inputs (one from the GPS receiver and the other from the rubidium clock). Its output generates a voltage proportional to the phase difference between two inputs. This output, in turns, controls the frequency of rubidium clock. This is achieved through a phase locked loop - preferably a digital one (i.e. digital phase locked loop –DPLL) in which rubidium clock plays the role of a voltage controlled oscillator (VCXO) and 1 pps of the GPS receiver is the reference oscillator. For DPLL, it is easy to implement a low pass filter with long time constant which is desirable here. Further, it is always convenient to store the output of the phase comparator in a memory as the record of the history of the performance of the rubidium clock. When the rubidium clock is locked to the GPS time, the frequency and the time of rubidium clock almost follows the behaviour of clock abroad GPS satellite. All the outputs like time pulse (i.e. 1 pulse per second-1 pps) and frequency output of 5/10 MHz etc. are derived from the locked Rubidium clock. The recorded history helps in maintaining the frequency of the Rubidium clock as close as in locked condition at least for sometime while GPS signal is not actually available or lost.

The GCRC has the following four basic modes of operation. The respective mode may be identified by the status indicators either by two LEDs (e.g. Track LED and Lock LED) as shown in Table 1. It may be noted that the operation of some models of GCRC is controlled by a computer with the help of the executive software supplied along with the GCRC. In such cases, the status of the operation is shown on the computer screen.

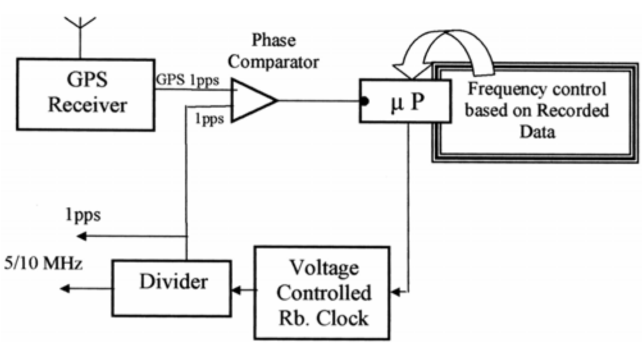

Fig. 1—Basic Functional Blocks of GPS Controlled Rubidium Clock (GCRC)

Table 1—Different modes of operation of GPS controlled rubidium clock

Mode	Track LED	Lock LED	Remarks
Pre-lock Unlock	ON	OFF	Tracking in the presence of GPS signals but not locked yet
Lock	ON	ON	Locked in presence of GPS Signal
Pseudo-lock	OFF	ON	Maintained lock in absence of GPS signal
Post-lock Unlock	OFF	OFF	Lost lock in absence of GPS signal

Pre-lock Unlock Mode—The GPS receiver starts tracking GPS signals when the antenna is connected. Two 1 pps are phase compared to synchronize the phase of 1 pps as well as the frequency of the Rubidium clock with respect to GPS timing system. This mode is prior to achieving lock while the receiver continues to track the GPS signals.

Lock Mode—When the Rubidium clock achieves lock with respect to the GPS signals, it follows the phase and frequency of GPS time. During this period, the phase detector output is also recorded as the history of the behaviour of the Rubidium clock.

Pseudo-lock Mode—When antenna is removed, the GPS signal is not available. But in the absence of GPS signal, the Rubidium clock still continues to maintain a “Pseudo Lock” for sometime based on the prior history of the recorded data.

Post-lock Unlock Mode—In this mode, after few hours of withdrawal of the antenna, Rubidium clock loses pseudo lock. Rubidium clock gradually restores to the free running condition. This mode has been called as post-lock unlock mode to distinguish it from the unlocked condition obtained immediately after the switching-on of the GCRC. After switching-on of GCRC, the phase of the clock starts at any arbitrary point without any correlation with UTC.

It may be noted that pre-lock unlock mode and post-lock unlock mode may not be of any importance for evaluation but, nevertheless, the study of these modes gives an insight of the operation of the system and also helps in the comprehensive evaluation of locked modes.

3 Experimental Details

It is well known that GPS time is synchronized to the time scale of UTC (USNO) which is maintained within few nanoseconds[7] of UTC. As the clock of NPLI [designated as UTC (NPLI)] is traceable to

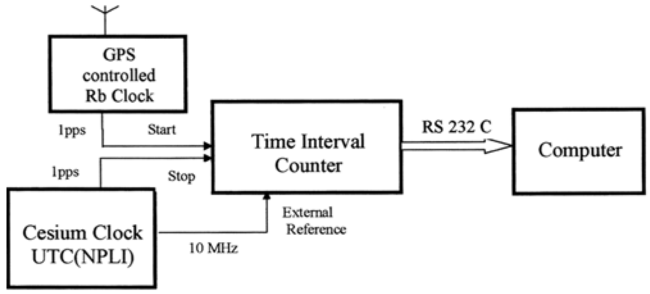

Fig. 2—Experimental set-up to record data for the evaluation of GPS Controlled Rubidium clock (GCRC)

UTC, it has been possible to conduct this evaluation campaign at NPLI.

The experimental set-up to conduct this study has been shown in Fig. 2. The time interval counter (TIC) that has been used for this purpose has a high resolution of 150 ps. Its measurement data can be accessed through its serial RS232C port. 1 pps of UTC (NPLI) starts the TIC and it is stopped by the 1 pps from GCRC to measure the phase difference between the two pulses. The computer is connected to TIC through the respective RS232C ports. Computer programme records the measurement data. Communication of the data being slow in the serial mode, this TIC can transfer only one set of measured data every four seconds. Few days of observation have been recorded, but here one typical set of observations is presented for discussion without any loss of generality.

When GPS antenna is connected to the receiver after the unit is switched on, it goes into pre-locking process (i.e. pre-lock unlock mode). This mode has continued for little more than three hours prior to locking. Longer time required to achieve lock may be attributed to the following fact. The phase comparator compares two 1 pps and the phase adjustment is done with the smallest possible increment or decrement once in a second for the closest phase and frequency alignment. For a typical set, the unit was been made to operate in locked mode for two hours after which the antenna was removed. The receiver continued to maintain pseudo lock with the help of the recorded data. It has been observed that this status continued for more than four hours till the loss of lock as indicated by LEDs. After this, Rubidium clock of GCRC runs independently in post-lock unlock mode and it gradually restores to its free running state.

4 Morphology of Data

The performance of an oscillator may be assessed not only by the values of the phase and the frequency but also by the corresponding fluctuations. According to the experimental plan, recorded data by the TIC correspond to the measurement of phase difference [φ(t)] between two 1 pulse per second. As the measured data are in the unit of time (in this case in nanoseconds), the measured phase difference may be expressed as $x(t)$ which is given by the relation:

$$x(t) = \frac{\varphi(t)}{2\pi f_o} \quad \ldots(1)$$

where f_o is the nominal frequency and φ (t) is the phase difference in radian.

The frequency offset $y(t)$, being the rate of change of phase difference, may be expressed as:

$$y(t) = \frac{dx}{dt} = \frac{1}{2\pi f_o}\frac{\partial \varphi}{\partial t} \quad \ldots(2)$$

y(t) is the normalized instantaneous frequency offset or the fractional frequency offset. The measurement of the instantaneous samples of $y(t)$ cannot be done by known methods of measurement. It is a common practice that the frequency measurement is always carried out by finding the phase difference over a finite time τ. Thus, $\bar{y}_k$ may be estimated by:

$$\bar{y}_k = \frac{x(t_k + \tau) - x(t_k)}{\tau} \quad \ldots(3)$$

The terms $x(t_k+\tau)$ and $x(t_k)$ are proportional to instantaneous phase difference obtained from the comparison between two clocks at date t_k and $t_{k+1}=t_k+\tau$. For very precise oscillators, x(t) and y(t) may be considered as random processes with normal distribution so that they may be evaluated by well known statistical methods. To characterize the frequency fluctuations, there are two main methods of analyzing the measurements results. They are Time-domain analysis and Frequency-domain analysis. Frequency domain analysis deals with the problem of knowing the spectral density process and thus, is not very commonly used. In time domain analysis, if probability distribution is assumed to be normal, then variance or the standard deviation of a set of samples may be used as a quantitative indications of fluctuations or frequency stability.