EVALUATION OF SHORT AND LONG-TERM STABILITY OF THE 2998 MHZ REFERENCE-CLOCK TRANSFER SYSTEM

P. Lemut[1,2], B. Batagelj[2,3], M. Leskovec[2], J. Tratnik[3], S. Zorzut[1]
[1]Instrumentation Technologies, d. d., 5250 Solkan, Slovenia
[2]COBIK, Velika Pot 22, 5250 Solkan, Slovenia
[3]University of Ljubljana, Faculty of Electrical Engineering, 1000 Ljubljana, Slovenia

Abstract

During the development of the reference-clock transfer system, we encountered several issues, related to the phase drift and phase noise (jitter) measurements. Drift as a phase noise of low frequency, both with random and periodic character, we observe in an offset less than 1 Hz from the carrier. Very few instruments are available for this kind of measurement. We created a prototype of a new instrument – a phase detector that enables long-term drift measurements. A phase detector prototype has been carefully designed and its performance has been evaluated. Besides phase difference measurements, some extended capabilities have been built in to enable full reference-clock transfer system evaluation. On the other hand, commercial-off-the-shelf instruments like Signal Source Analyzers (SSA) are available for the phase noise measurement above 1 Hz from the carrier.

INTRODUCTION

Large physical experiments like particle accelerator facilities need a reference-clock distribution system for their stable operation. The role of the clock-distribution system is to distribute reference clock to the end user with a constant propagation delay. There are various systems used in the particle accelerator environments. In this article we are focusing on the system where 2998 MHz reference signal is also used for compensation of changes in the optical fiber path. Other systems are mostly based on detection of optical phase. Nevertheless, if the reference signal is available as an electrical signal at the source and at the end point, all the presented methods are applicable. To verify clock-distribution system, performance, development and production testing need to be performed. Phase drift and added jitter need to be measured. Maximum allowed drift and added jitter are both in the range of a few tens of femtoseconds.

MEASUREMENT SETUP AND PROCEDURES

To confirm proper operation of a reference-clock transfer system a group of measurements of phase and amplitude stability need to be performed. While amplitude stability is rather straight-forward to maintain and measure we will focus on the phase stability. The required stability of 5 fs or roughly 0.005 degrees for the 3 GHz reference clock is difficult to achieve and even more difficult to measure precisely. Absolute value of jitter at the output of the transfer system is important, but users are mostly interested in the added jitter, introduced by the transfer system. Phase noise and its representation as a jitter in the time domain can be divided into a few frequency ranges. Most of the attention is paid to the phase noise in the frequency offsets from 10 Hz to 10 MHz from the carrier frequency. This frequency range can be further divided into several sub-ranges of interest. Usually, within this frequency range most of the spurious signals can be efficiently removed by carefully designing the transfer system. We may assume that only random components like flicker and thermal noise are present. The second frequency range that gives a valuable information of the system stability is for the frequency offset below 1 Hz or even below 0.1 Hz. Phase changes in this range consist of both periodic components due to for example day-night changes or HVAC operation and of random components due to weather changes, solarization, human presence etc. For the transfer system improvements it is of importance to know how the transmission media or the transmitter/receiver electro-optical subsystems are influenced. For the overall performance estimation, only the behavior of the transfer system between the input and output RF connector matters, regardless of the contributions of individual influences.

Probably the easiest measurement is the added jitter for the frequency range from 100 Hz to 10 MHz. A Signal Source Analyzer (SSA) can be used for this purpose. If no discrete spectral components are present, we may simply calculate the added jitter from the generator jitter J_g and the transfer-system output jitter J_{out} (Fig. 1) as:

$$J_{add} = \sqrt{J_{out}^2 - J_g^2} \tag{1}$$

Figure 1: Added jitter measurement.

* The operation Centre of Excellence CO BIK is financed by the ERDF and MHEST, Republic of Slovenia

For the frequency offset bellow 100 Hz, the added jitter measurement is more demanding, as the SSAs own phase noise level is comparable to the measured phase noise. This limitation originates from the local oscillator inside the SSA. In this case a correlated delay-line method is more suitable as it shows added jitter directly without additional calculations.

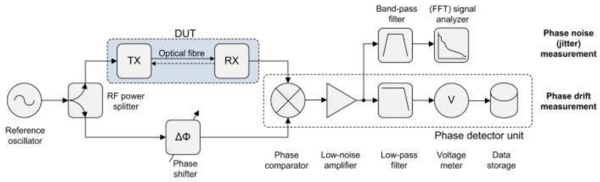

Figure 2: Measurement setup using a phase comparator.

Figure 2 is showing a block diagram of the basic measurement setup. The core of this setup is a phase comparator that can be implemented with a mixer or with a dedicated phase-comparator integrated circuit, depending on the type of measurement. For the added jitter measurement a mixer with a low added jitter needs to be used. The output signal from the mixer is fed through the low-noise amplifier and the band-pass filter to the signal analyzer. Band-pass filter in fact consists of an external low-pass filter and a high-pass filter inside the baseband analyzer. A 300 m or longer connection media between the reference clock transmitter and the receiver is used as a delay line. If we analyze separately the frequency range below 100 Hz, a quality 24-bit sound card with 96 ksps sampling rate or a SSA with a baseband input can be used for this purpose. The measurement is valid when the measured added phase noise of the mixer, LNA and the sound card is below the added phase noise of the DUT and the frequency range of the measurement is at least three-times smaller than 1/delay time.

The final result of this measurement can be combined with the result from the SSAs RF-input measurement to get the total added jitter from 1 Hz or 10 Hz to 10 MHz.

Table 1: Possible Combinations of Instruments for the Added Jitter Measurements

1 Hz -100 Hz	**100 Hz – 10 MHz**
Mixer + SSA baseband input	Mixer + SSA baseband input
Mixer + Sound card (2Hz-48 kHz)	Mixer + SSA baseband input
Mixer + Sound card (2Hz-48 kHz)	SSA RF input

However, when using a sound card, the frequency limit can be anywhere between 10 Hz and 48 kHz. Another possibility is to feed the signal from the low-noise amplifier, followed by the band-pass filter to the baseband input of the SSA that covers the entire range from 1 Hz to 10 MHz.

For the measurement of the phase drift with resolution of less than 1 fs and stability of a few fs no appropriate instruments are available. The phase detector instrument also needs to be highly amplitude invariant within 0.5 dB range. The output from a mixer in a function of a phase detector within a closed loop is typically close to zero and thus relatively amplitude independent. In an open loop a mixer is not suitable to measure phase difference with a high precision. Luckily there are a few dedicated phase detector integrated circuits (IC) available. The AD8302 from Analog Devices is probably most widely used phase detector IC. This IC is almost perfect for regular phase measurements in the Vector Network Analyzers and similar applications. It has some drawbacks for the precise phase difference measurement. First, to minimize the effect of AM to PM conversion it requires relatively stable input power that has to be within limited regions. Secondly it needs to be well temperature stabilized to prevent logarithmic amplifier and voltage reference drift, as already proposed in [1]. Further, as most of the voltage references ageing is needed that the transition effects roll out. Nevertheless, its upper cutoff frequency is officially limited to 2.7 GHz. In long-term use it turned out it can be used without significant side effects at 2.998 GHz. There will definitely be needed a different solution for higher frequencies, 6 GHz for example.

We created a series of phase detector test circuits to determine actual performance for our application and we sketched possible implementations. Thermal stabilization was one of the first tasks we approached. After the dynamic thermal properties have been identified, a dedicated and optimized temperature controller was designed and tested. Thermal, low-frequency electrical and RF design were tightly connected.

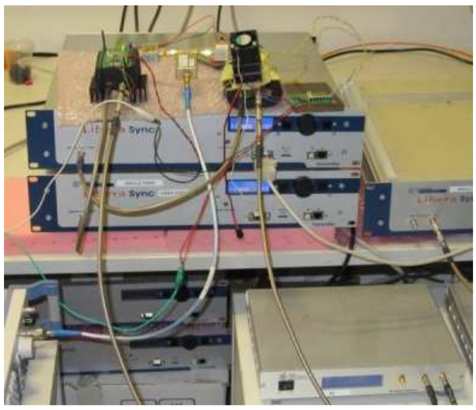

Figure 3: Long-term stability measurement setup.

In the absence of a real test environment a custom made optical cable spool was used, that proved really well. The insulating foam around the fibers is slowing-down the heat propagation what makes conditions similar to a real installation site.

RESULTS

We created a prototype of the phase detector (Figure 4) that enables long-term phase measurements with data logging. Besides phase measurement it enables measurement of environmental conditions (temperature, relative humidity and barometric pressure). This additional information is valuable in post analysis when looking for correlations between phase drifts and external influences. The unit is configurable and can also be accessed remotely over Ethernet.

Figure 4: Phase detector prototype.

Long-term stability of the phase detector alone has been measured first. The RF signal, split into two branches was fed to both RF inputs using low temperature dependent cables of equal lengths. The RF splitter provided 90° phase shift and was also thermally stabilized. A long term stability of 20 fs_{pp} and 8 fs_{RMS} was measured over 180 hours as shown in the Figure 5.

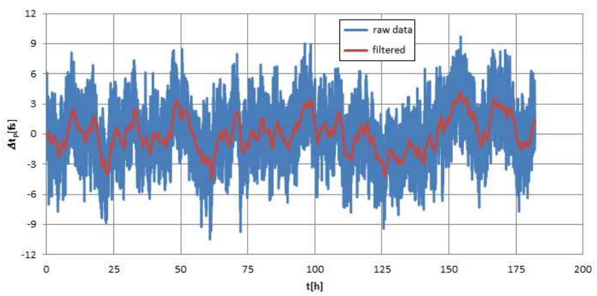

Figure 5: Phase detector stability over 180 hours.

With additional moderate digital filtering 8 fs_{pp} and 3 fs_{RMS} stability was measured. Afterwards, long-term stability measurements of the reference-clock system was measured, using a phase detector and a spool of fibers, placed in a thermally non-stabilized environment. The test setup is shown in the Figure 3 .

In the Figure 6 it can be observed that a long-term stability of the improperly operating reference-clock transfer system is closely correlated with environmental temperature.

The phase noise has been measured using the proposed methods and then integrated into the jitter. The comparison of results is presented in the Table 2.

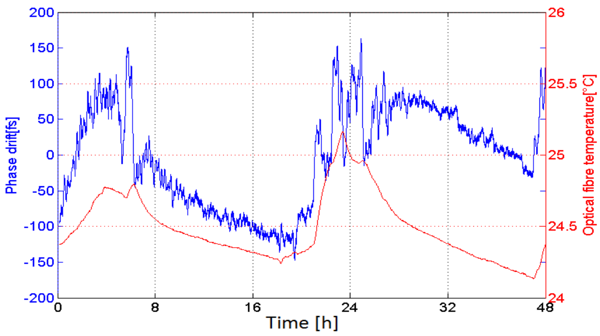

Figure 6: Long term stability result.

Table 2: Measured Added Jitter

Freq. range	**Delay Line Method /w sound card**	**Measured /w SSA in baseband**	$J_{add} = \sqrt{J^2_{add\_1} + J^2_{add\_2}}$
10 Hz – 10 MHz	(10 Hz – 48 kHz)	(48 kHz – 10 MHz)	9.11 fs
	Δt_{add_1} = 7.76 fs	Δt_{add_2} = 4.78 fs	
100 Hz – 10 MHz	(100 Hz – 48 kHz)	(48 kHz – 10 MHz)	7.77 fs
	Δt_{add_1} = 6.13 fs	Δt_{add_2} = 4.78 fs	

In the Figure 7 two phase noise plots from 10 Hz to 48 kHz, measured with different methods are compared. Some differences that result in different calculated added jitter in the particular frequency range may be observed.

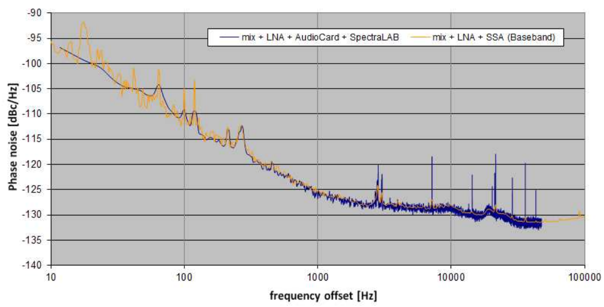

Figure 7: Phase noise measurements.

CONCLUSIONS

The developed measurement instruments and proposed methods are for the moment sufficient for the evaluation of the reference-clock transfer system at 2998 MHz. Further improvements are foreseen in particular for evaluation at higher reference-clock frequencies. Long-term stability measurements are extremely time consuming and therefore they need to be fully automated.

REFERENCES

[1] K. Hacker at al., “Design and Drift Performance of the FLASH Master Laser Oscillator RF-Lock”, FEL’09, Liverpool, August 2009, WEPC69, p. 663 (2009).