High Performance Frequency Dissemination by White Rabbit

Introduction

The **White Rabbit** synchronization protocol, on which the new IEEE-1588-2019 High Accuracy PTP profile is based, is usually associated with distributed systems that have very demanding time requirements (sub-nanosecond accuracy and picosecond (ps) precision) for different markets such as: science, defence, finance, telecom (5G), smart grid, broadcast, etc. However, there are numerous applications whose synchronization needs are based on frequency dissemination instead of time distribution and that is why we wanted to analyze the performance of our equipment for these applications.

The objective of this document is to study the behaviour of our devices in frequency distribution using as a reference the **MuClock** from Muquans, which is the world's first and one of the two commercially available time and frequency references based on quantum manipulation of laser cooled atoms. This will show together the performance of two timing company leaders with the most advance systems for generation and dissemination of time.

Set-up

Figure 1 shows the set-up used to test the capabilities of the **White Rabbit** (WR) frequency distribution network by **Seven Solutions** when the **MuClock reference** from **Muquans** is used as input to the system.

The equipment used for this setup is listed below:

Muquans

- MuClock.

Seven Solutions

- White Rabbit switch Low Jitter.

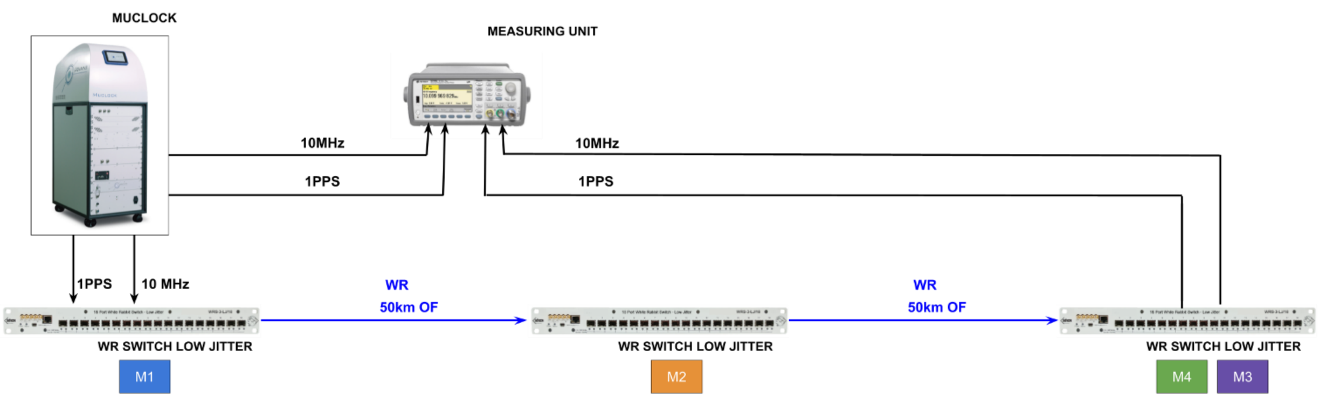

Figure 1: Test set-up

In this set-up, the **MuClock**, whose performances are shown in **Figure 2**, is used to provide a reference to the first WR switch Low jitter via 1PPS (Pulse Per Second) and 10 MHz signals. The measurement units used are:

- For the 1PPS, an Agilent DSO9254A High-bandwidth oscilloscope with a resolution down to 3 ps (measured independently before the actual measurement),
- and for the 10 MHz, a K+K FXE High-Resolution Multichannel Synchronous Phase Recorder with a resolution of 9e-13 at 1 second (measured independently and in parallel of this measurement) in averaged (lambda) mode. τ

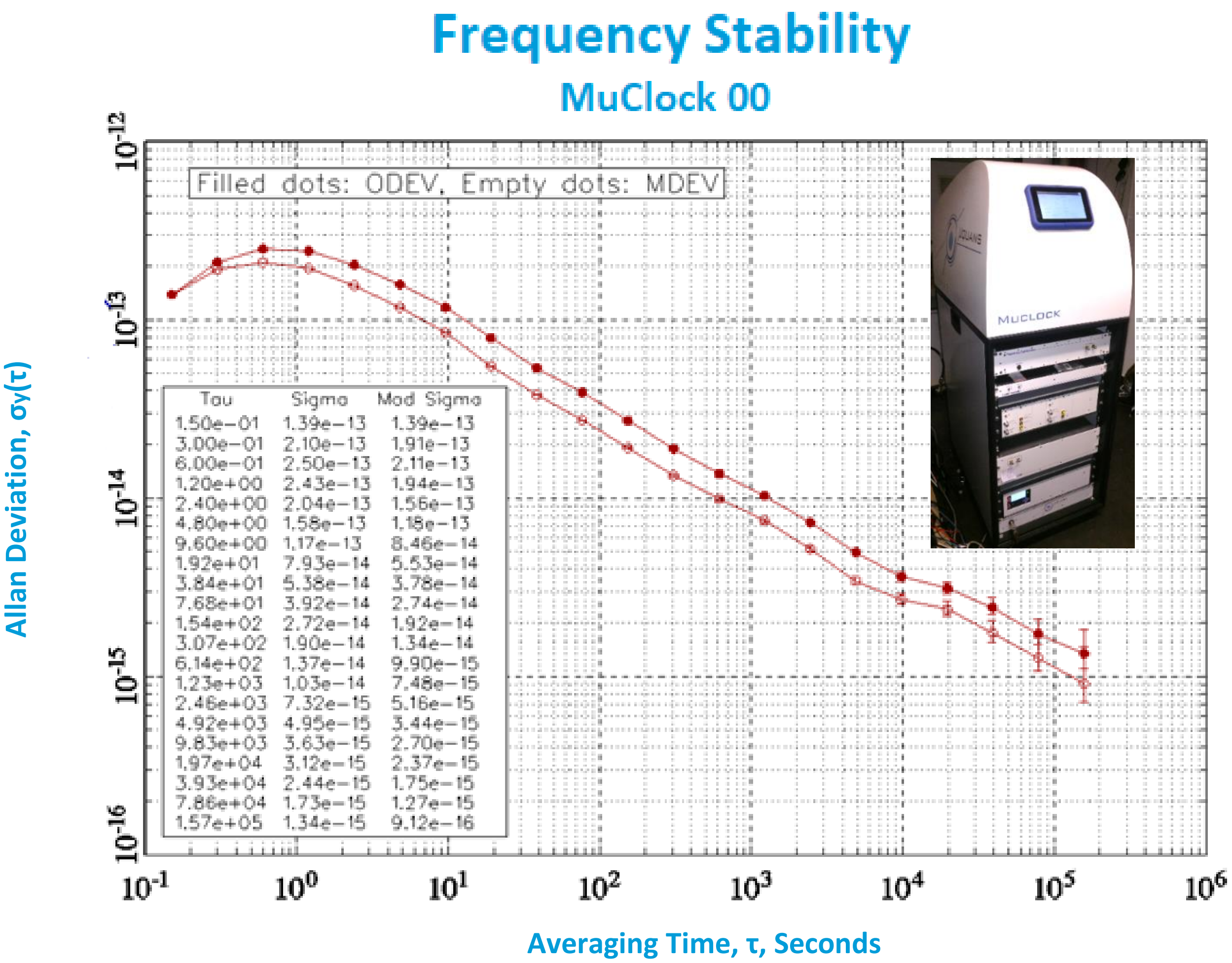

Figure 2: MuClock as a reference clock in the measurement

The first **WR switch Low Jitter** acts as a **WR Grandmaster**, locked to the external reference, and as a **WR time distribution device** for the next time node of the network. Then, the topology is completed using 100 Km of optical fibres spitted in two sections of 50 Km by White Rabbit switch Low Jitter as an intermediate and an end node.

To measure the synchronization performance of the network architecture, the **1PPS** and **10 MHz** outputs signals are provided to a frequency counter which will compare them with respect to the given reference.

Results

10 MHz measurement – Temporal analysis

Figure 3 shows the relative **clock frequency fluctuations** at three different points in the network (see Figure 1 - M1, M2 and M3).

In order to emphasize the middle-term behaviour, a smoothing average of 30 min is applied on the temporal data of Figure 3. As it can be seen, the frequency slightly degrades with the distance and the number of hops (higher jitter is visible for long distances), but in no case, this variation is greater than ±2.5e-14 after an averaging of 30 min which is a great result. If no smoothing average is used, the raw data shows no variation above ±7e-12.

It is worth noting that at certain periods of the measurement some fast frequency variations appeared, as it can be seen between 7-10 x 10^5 seconds or 12.5-14.5 x 10^5 seconds. These peaks corresponding to fast frequency variations are well correlated with temperature changes in the room presented in **Figure 4** and might find their origin in the induced optical phase variations in the optical fibers that the WR switches cannot fully compensate yet.

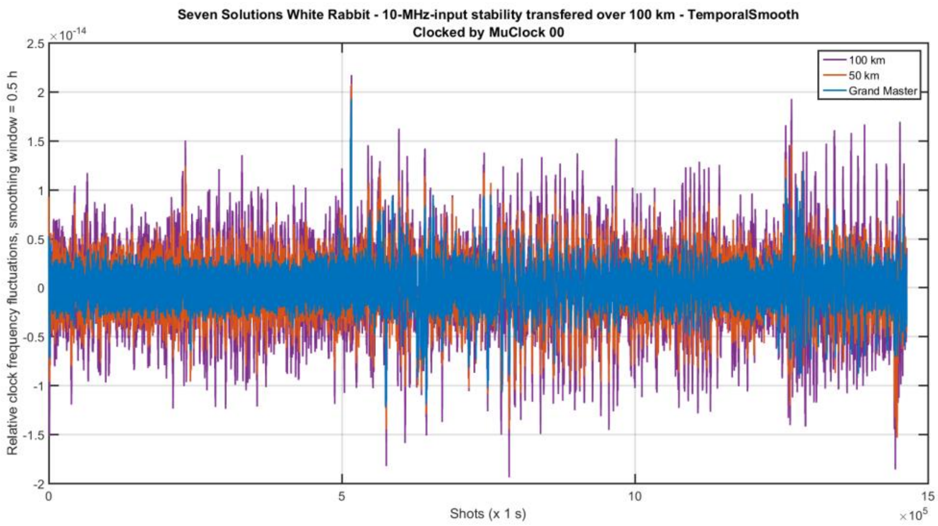

Figure 3: Clock frequency fluctuations

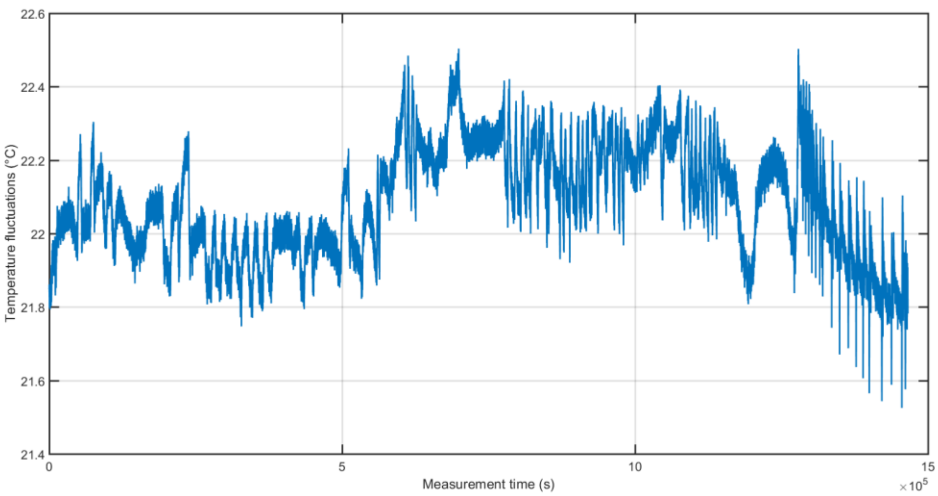

Figure 4: Room temperature

10 MHz measurement – Frequency analysis

Figure 5 shows the **Modified Allan Deviation** (MADev) over 18 days at three different points in the network (see Figure 1 - M1, M2 and M3) and includes the measurement M4 for the 1 PPS signal along with the White Rabbit switch Low Jitter specification as a reference. The error bars are not plotted for clarity's sake. In addition, a dashed line integrating as $1.5x10^{12}/\tau$ is also plotted to guide the eye.

For the **frequency signal** (10 MHz – blue, orange, and purple curves), the Modified Allan Deviation shows a slight degradation with the distance and the number of hops and, although 1.5e-12/τ can be considered as the level in the **short term**, some bumps appeared at time about 2000 seconds exceeding that level in the **middle term**. Those bumps are real since they are also present at 50 and 100 Km and their origin might be the phase noise due to the temperature variations. This point will be studied as future work, but it is strongly related with the optical fiber propagation issues.

In the **long term**, 2e-16 appears to be the noise floor, but this could be limited by the frequency counter, as the 1 PPS signal goes well below 1e-16. However, to stay conservative, it has been considered that all measurements that exceed 1e-16 would have too large confidence intervals and the measurements would have less reliability.

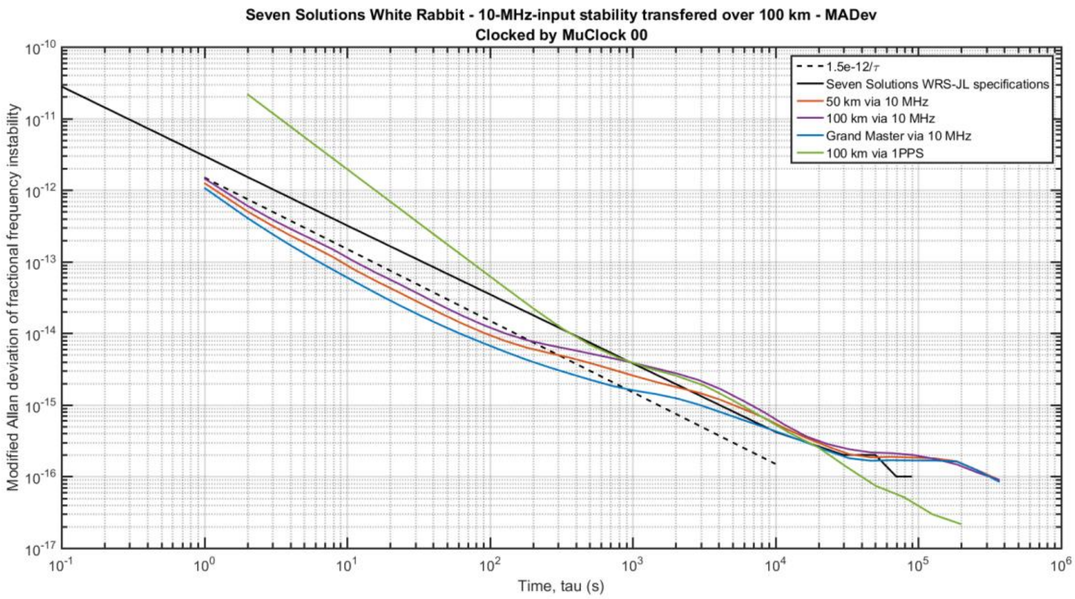

Figure 5: Modified Allan Deviation over 18 days

Finally, it is interesting to note that the Modified Allan Deviation was chosen because it allows distinguishing between White and Flicker PM (resp. in $\tau^{-3/2}$ and τ^{-1}). In this way, as the 10 MHz signal is integrating faster than τ^{-1} we could assume that the noise process which affects the signal is White Phase Noise, although to be totally sure, this point should be analysed more carefully later.

1 PPS measurement – Time

Once the frequency analysis was finished, without any additional consideration and on the same setup (without calibrating), some measurements on the 1PPS signal were taken.

As it can be seen in **Figure 5**, the Modified Allan deviation shows that the 1PPS signal, when it exhibits a fully stabilized behaviour, integrates as $\tau^{-3/2}$ so it would be only affected, as occurs in the best of cases, by White Phase Noise.

On the other hand, making use of more common measurements when dealing with time distribution systems, **Figure 6** shows that the 1PPS delay or Time error, between the first White Rabbit switch Low Jitter and the last White Rabbit switch Low Jitter (100 km away), has a mean close to 400 ps, a standard deviation of 35 ps, and a peak-to-peak variation of about 200 ps. As expected, the White Rabbit protocol achieves a sub-nanosecond accuracy and a few tens of picoseconds stability at 1 s, integrating below the femtosecond stability even over long-distance links without calibrating.

During these measurements, some signal jumps between the MuClock and the last White Rabbit switch Low Jitter (end node) were detected. In addition, as the histogram in **Figure 6** shows, a tail centered at 350 ps appears in the measurements and, although it does not affect the system in the long-term, it is thought that it could be an effect of the oscilloscope trigger since it is not usual to find similar behaviours in White Rabbit time distribution systems.

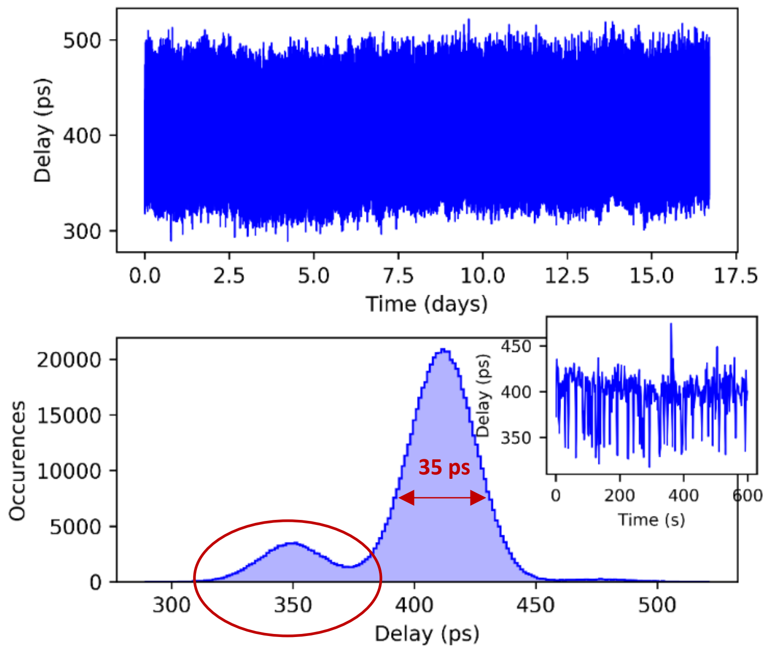

Figure 6: PPS delay (Time error)

Conclusions

The White Rabbit synchronization protocol (base of the new IEEE-1588-2019 High Accuracy PTP profile), normally used to distribute the 1 PPS time signal in systems with very demanding time requirements, has been tested in terms of frequency and 1PPS distribution capacity.

On the frequency side, as it can be seen in both the temporal and the frequency stability analysis, the White Rabbit protocol allows replicating the reference signal in long-distance deployments. So, if that reference signal is very stable (as it happens with the MuClock from

Muquans), the signal delivered to the end nodes will also show that behaviour, thereby achieving excellent frequency dissemination that many applications can take advantage of.

Finally, some measures regarding time synchronization were taken. These measurements show the expected behaviour in the White Rabbit protocol even over long-distance links without calibrating, accuracy below sub-nanosecond and picosecond precision, so it can be concluded that the performance in both, time, and frequency synchronization of the White Rabbit protocol, is outstanding and useful for very demanding time and frequency requirements. Future works will explore the ways to improving the frequency dissemination stability for periods beyond the 2000 seconds as already identified on the MADEV plots.

About Muquans

Muquans is an innovative French SME that manufactures and commercializes high-precision quantum sensors based on laser-cooled atoms. We are committed to providing reliable high value-adding scientific instruments in various fields such as Geophysics, metrology and dissemination of Time and Frequencies, as well as research-grade laser systems. Founded in 2011, we are used to supporting cutting-edge research and industrial endeavours. https://www.muquans.com/

About Seven Solutions

Seven Solutions S.L. is a telecommunications company leader in accurate sub-nanosecond time transfer for reliable industrial and scientific applications. We have more than 15 years of expertise in embedded systems design and control (electronics, firmware, and embedded software), with a remarkable track-record in cutting-edge projects at different sectors such as fintech, avionics, telecommunications, smart-grid, space, defence and scientific facilities as particle accelerators and distributed radio-telescopes.

We are leaders in ultra-accurate time transfer and synchronization based on White-Rabbit technology and derived standards (PTP IEEE-1588-2019-HA) in the Fintech and Science segments. We were born in the framework of Large Scientific Infrastructures (Industry for Science). In this segment we are continuously growing and consolidating creating break-through solutions for timing and for advanced control systems and diagnosis in particle accelerators. www.sevensols.com