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When every nanosecond counts

High Accuracy Network Time Transfer Links Traceable to GNSS Reference

Francisco Girela

Co-author: Ricardo Píriz

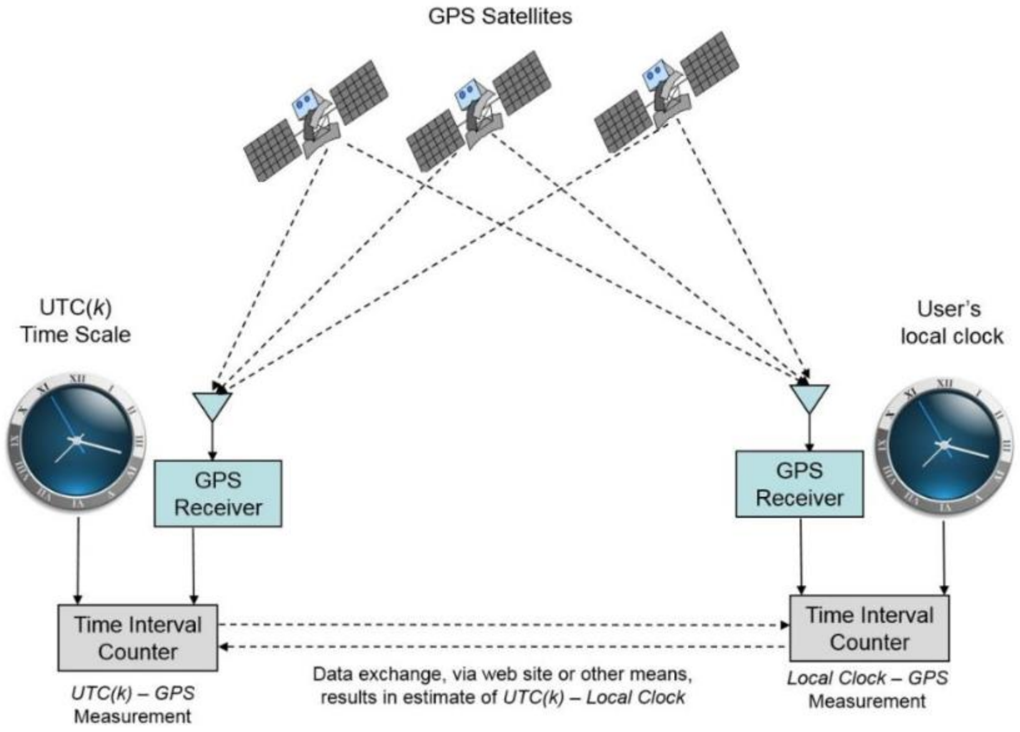
www.sevensols.com

Summary

- Introduction
- White Rabbit technology
- White Rabbit and its Integration with GNSS
- GNSS Timing and its Calibration
- Testing GPS in Combination with White Rabbit
- Time Traceability and Error Budget
- Long Haul links using White Rabbit

Introduction

The International Telecommunications Union (ITU) defines traceability as “the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties”



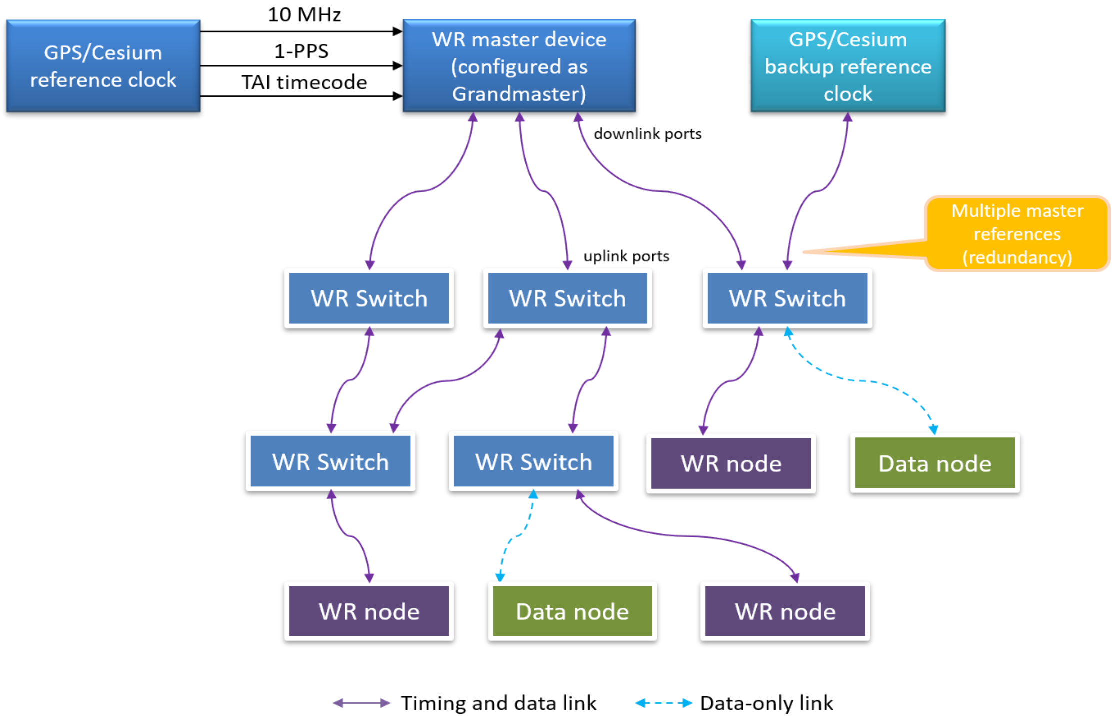
Demetrios Matsakis, Judah Levine, and Michael A. Lombardi, “Metrological and legal traceability of time signals”, 49th Annual Precise Time and Time Interval Systems and Applications Meeting (PTTI), January 29 - 1, 2018, Reston, Virginia.

White Rabbit

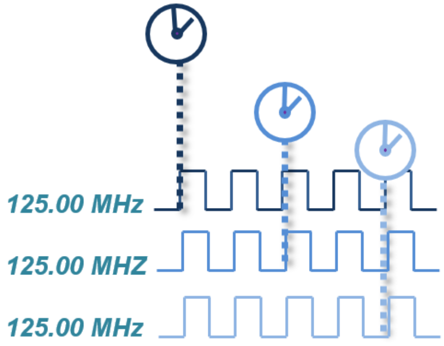
White Rabbit (WR) is a technology born at CERN which achieves sub-nanosecond accuracy in Ethernet based networks. It allows easy deployments of scalable and reliable networks with high accuracy synchronization requirements.

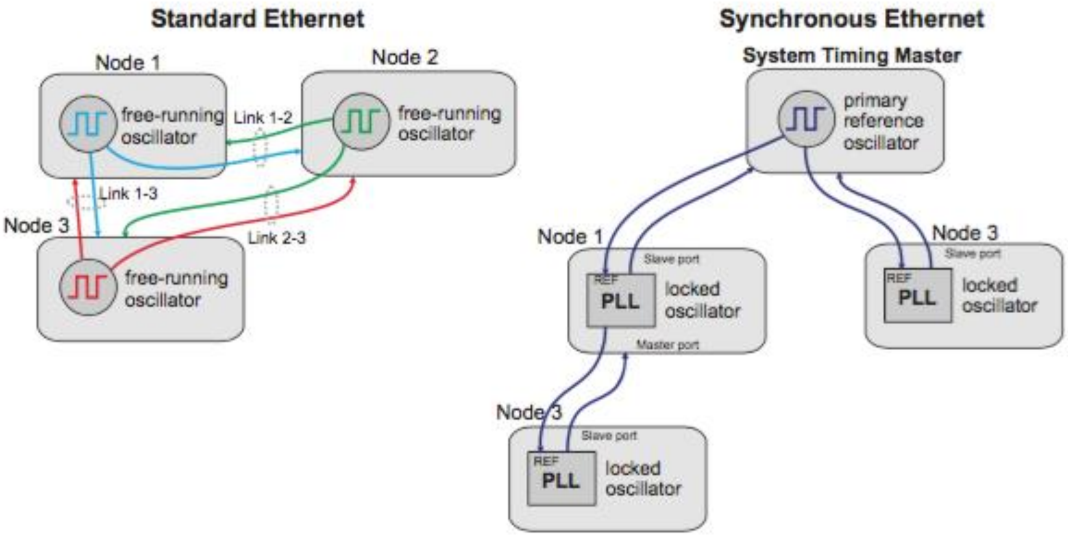
White Rabbit

- WR devices have a master/slave relationship. Master device uses its downlink ports to connect to uplink ports of other slave devices and discipline their time.
- The uppermost WR switch in the hierarchy is usually called the “grandmaster”.
- The grandmaster receives its notion of time through external One Pulse Per Second (1PPS), 10 MHz and ToD inputs.



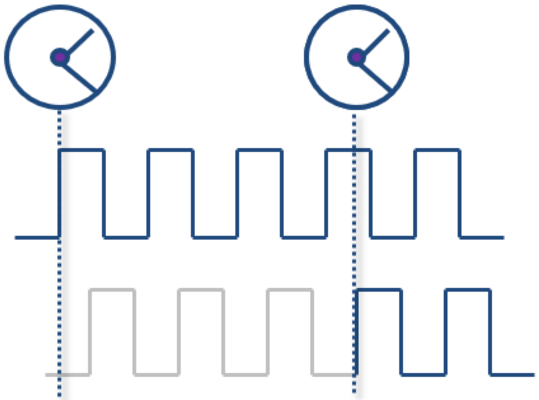
- Based on optical Gigabit Ethernet networks
  - Network syntonization
    - Synchronous Ethernet

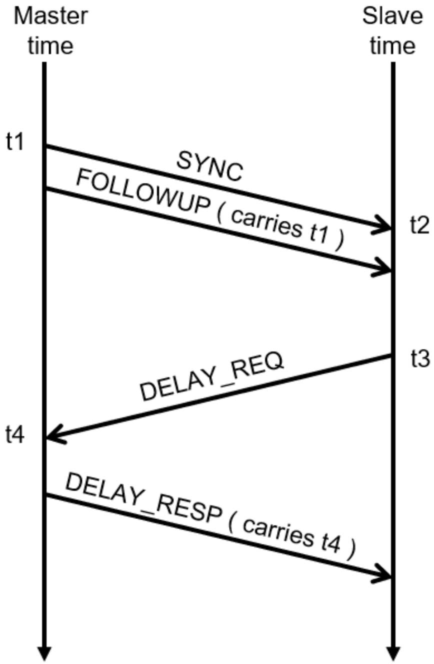




White Rabbit

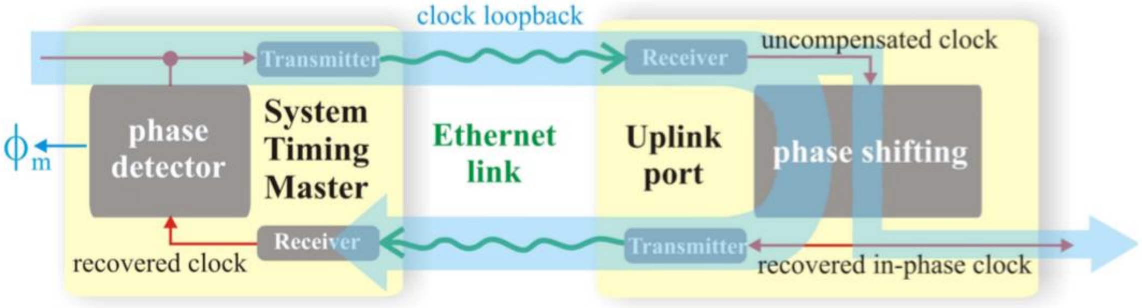
- Based on optical Gigabit Ethernet networks
  - Network synchronization
    - Precision Time Protocol (IEEE 1588v2)





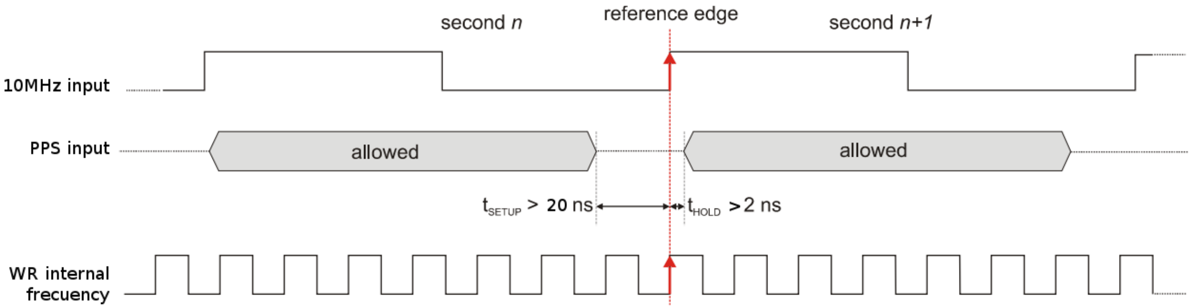
White Rabbit

- Based on optical Gigabit Ethernet networks
  - Additional mechanisms
    - Phase offset measurements
    - Hardware timestamps
    - Dynamic link assymetry compensation
    - Pre-calibration



White Rabbit and its Integration with GNSS

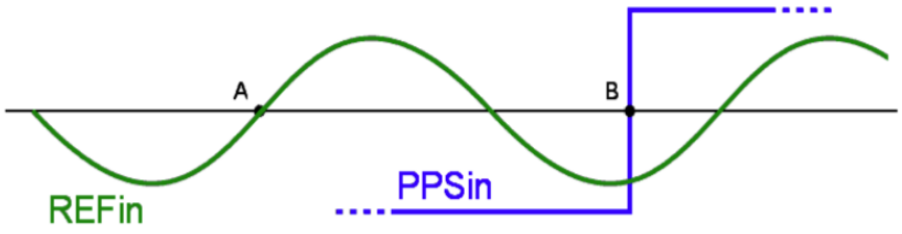
- Typical WR grandmaster uses as main reference its input 10-MHz frequency to retrieve time from other devices.
- The input 1PPS is only used at start-up to determine the nearest zero-crossing of the input frequency signal. Afterwards, the 1PPS is no longer used.
- Thus the time origin for WR is actually the initial zero-crossing of the input frequency signal, not the input 1PPS.
- **PROBLEM:** Indeterministic synchronization error between power-ups that requires calibration.



White Rabbit and its Integration with GNSS

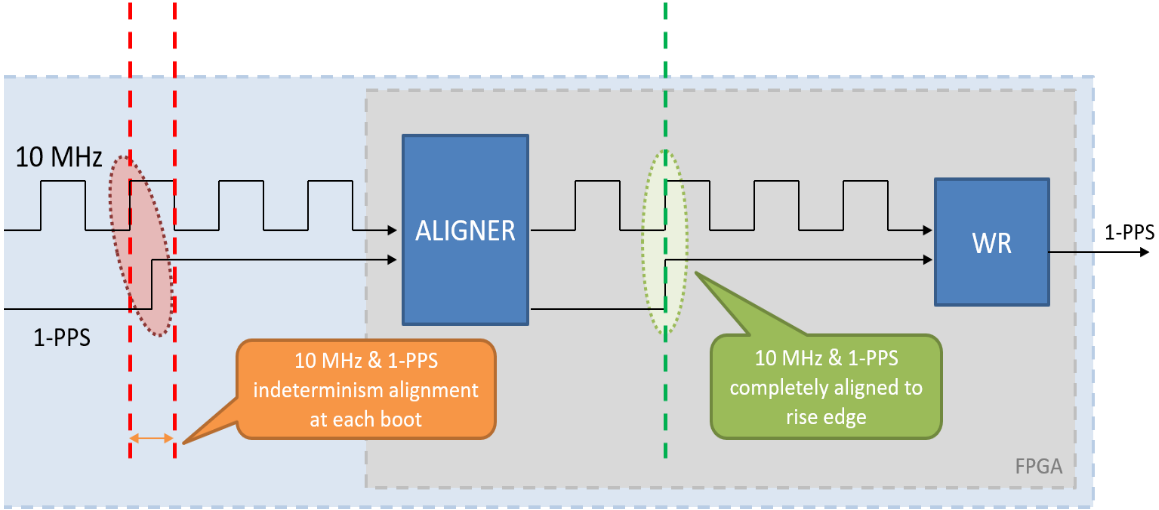
- Correct phase alignment between GNSS and WR timing signals is essential for an unbiased and deterministic time distribution downstream.
- Typical GNSS receiver provides the time reference through its output 1PPS signal.
- The output 10-MHz frequency signal from GNSS “follows” the 1PPS coherently.

- **PROBLEM:** phase relationship between 1PPS and 10 MHz outputs is normally arbitrary. Calibration is not possible.



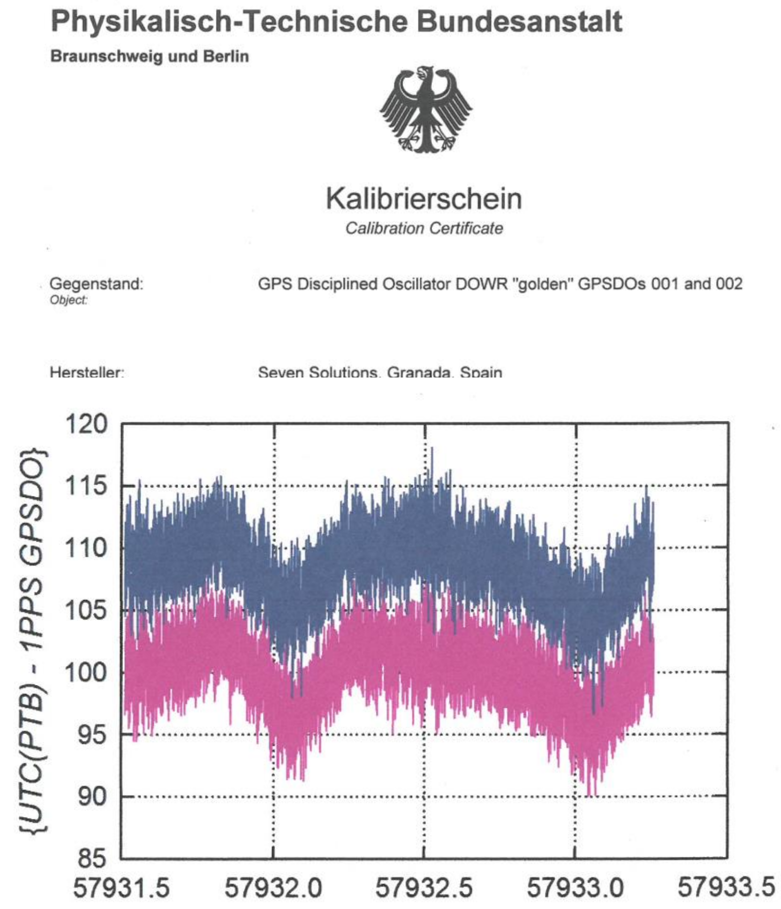
White Rabbit and its Integration with GNSS

- **SOLUTION:**
  - Seamlessly integrate a GNSS receiver and a WR grandmaster.
  - GNSS receiver is based on an industrial single-frequency GPS chip.
  - Novel method to continuously align the WR phase to the 1PPS from GNSS.
  - Dedicated FPGA aligner module.
  - Alignment inaccuracy bounded within ± 1 ns after power-up.



GNSS Timing and its Calibration

- Delay of hundreds of nanoseconds because of the GNSS antenna, the antenna cable and the receiver.
- GMV collaboration with the ESA and the ROB in the AKAL project to consolidate a procedure for absolute calibration of GNSS receiver chains with an uncertainty around 1,5 nanoseconds.
- Industrial GNSS receiver was calibrated by PTB comparing its 1PPS output with the 1 PPS of UTC(PTB) with an uncertainty of 2,5 nanoseconds.
- Relative calibration comparing an absolute calibrated receiver chain and the PTB calibrated receiver chain showed an estimated uncertainty around 2,0 nanoseconds.



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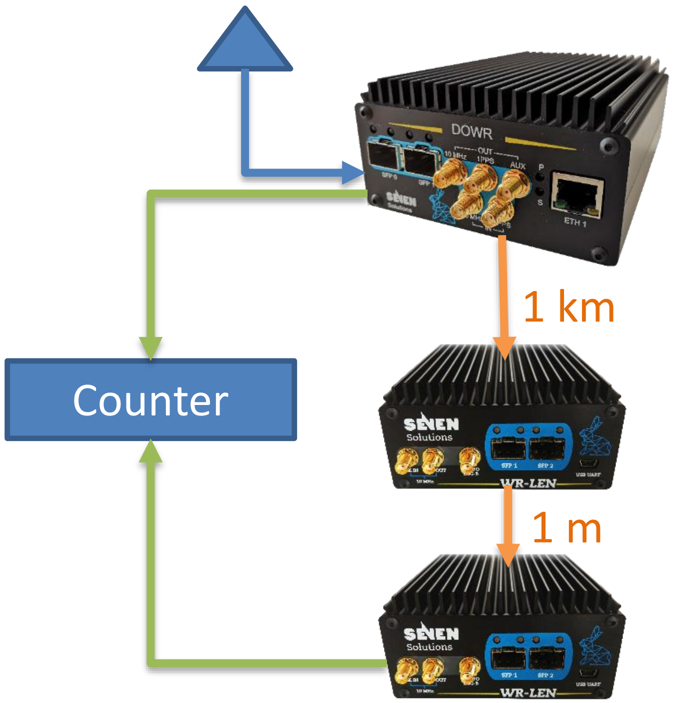
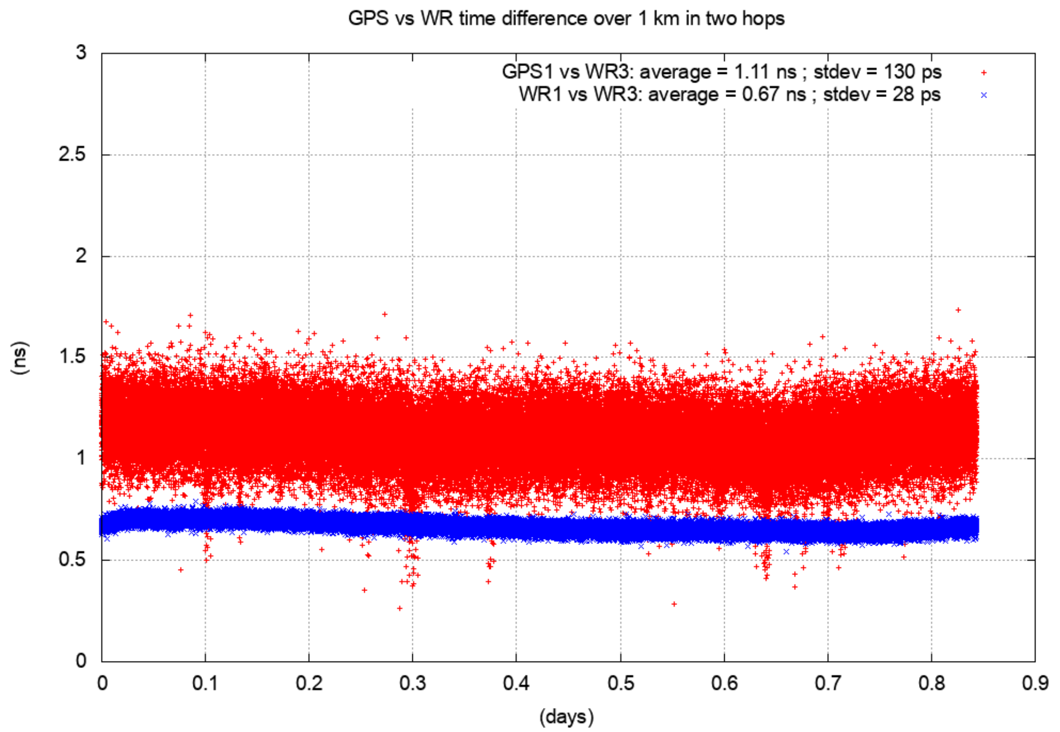
Testing GPS in Combination with White Rabbit

- 24 hours test under non-controlled temperature conditions with off-the-shell devices: Mean offset of 0.7 ns and standard deviation of 33 ps.





Time Traceability and Error Budget

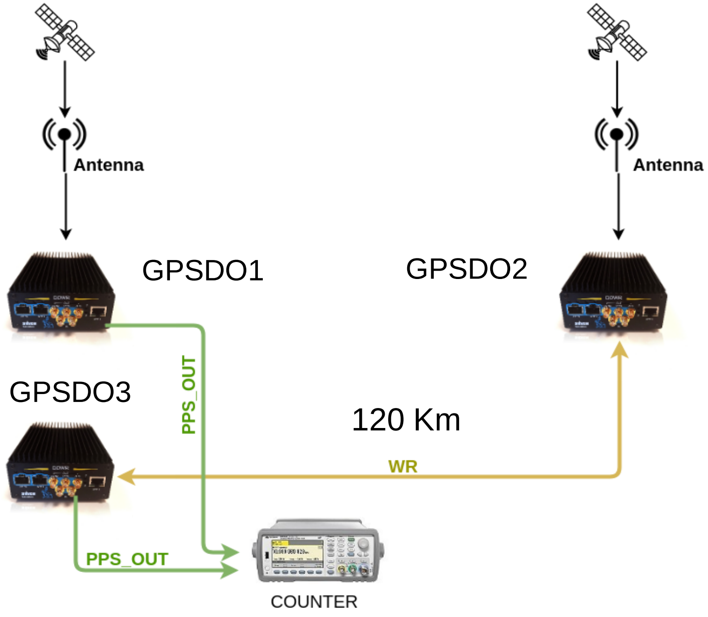
- Metrological and legal traceability requires an "unbroken chain of calibrations that relate to a reference, with each calibration having a documented measurement uncertainty".

ID	Source of Error	Single-Frequency GPS(C1), at 1 sigma (ns)	Dual-Frequency GPS(P1/P2), at 1 sigma (ns)
A	URE: satellite clock and ephemeris error	2.5	2.5
B	URE: TGD error	1.5	0
C	URE: residual iono error	4	0
D	URE: residual tropo error	1	1
E	URE: receiver noise and multipath	1	3
F=RSS (A,B,C,D,E)	**TOTAL GPS User Range Error (URE)**	**5.1**	**4.0**
G	GPS antenna position error	1	0.1
H	GPS 1PPS/10-MHz jitter	1.5	1.5
I	GPS calibration error	2	3
J = RSS(G,H,I)	**TOTAL non-URE GPS error**	**2.7**	**3.4**
K = RRS(F,J)	**TOTAL GPS error (vs GPS Time)**	**5.8**	**5.2**
L	Initial GPS-WR mis-alignment	0.5	0.5
M	WR distribution error	1	1
N = RRS(K,L,M)	**TOTAL error at WR end-point (vs GPS Time)**	**5.9**	**5.4**
O	Error in predicted UTC(USNO) via GPS vs "true" UTC	3	3
P = RRS(N,O)	**TOTAL error at WR end node (vs "true" UTC)**	**6.6**	**6.1**
Q = RSS(M,M)	**Synchronization error between two WR end nodes in the same datacenter (using the same GPS receiver)**	**1.4**	**1.4**
R = RRS(E,E, J,J,L,L,M,M)	**Synchronization error between two WR end nodes in the same datacenter (using two different GPS receivers)**	**4.4**	**6.6**
S = RSS(N,N)	**Synchronization error between two WR end nodes in two separate datacenters**	**8.4**	**7.6**

R. Píriz, E. Garbin, J. Díaz and P. Defraigne, "Scalable, Traceable Time for Datacenters Using GNSS and White Rabbit", Inside GNSS, February 7, 2019.

Time Traceability and Error Budget

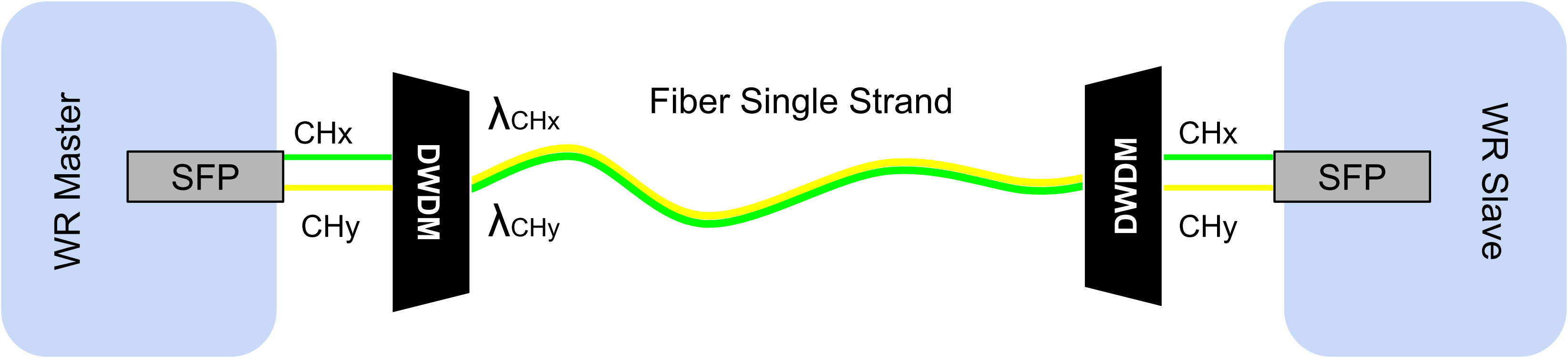
- Evaluation of WR on long distance links assisted by GPS
  - Pre-calibrated WR GNSS Receivers
  - Analyze the transfer of PPS on 120 Km FO.



	GPSDO1 - GPSDO2	GPSDO1 - GPSD03@120km
mean(ΔPPS)	7.7 ns	7.2 ns
std(ΔPPS)	1.7 ns	2.1 ns
excursion(ΔPPS)	6.0 ns	5.1 ns

Long Haul links using White Rabbit

- Fixed latency of WR equipment calculated using WR Model
- Resolves calibration problems of tech and “complex” OF networks:
  - Uncertainty of the wavelength long distance BiDi SFPs
  - Uncertainty of chararteristics among OF vendor
  - α in networks with mixed version of OF (G652b/d)
- Reduces impact of $\alpha_{DWDM} \sim 10^{-6} < \alpha_{BiDi} \sim 10^{-4}$



Long Haul links using White Rabbit

- Resolves calibration in mixed FO networks G652b and G652d

Device	SFP	Fiber Optic	Offset (ps)
WRS	BiDi	50 km G652b	225
WRS	BiDi	50 km G652d	2860
WRS	DWDM	50 km G652b	11
WRS	DWDM	50 km G652d	8
WRS	DWDM	20 km G652b	52
WRS	DWDM	100 km G652b/d	46

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White Rabbit Around The World

When every nanosecond counts