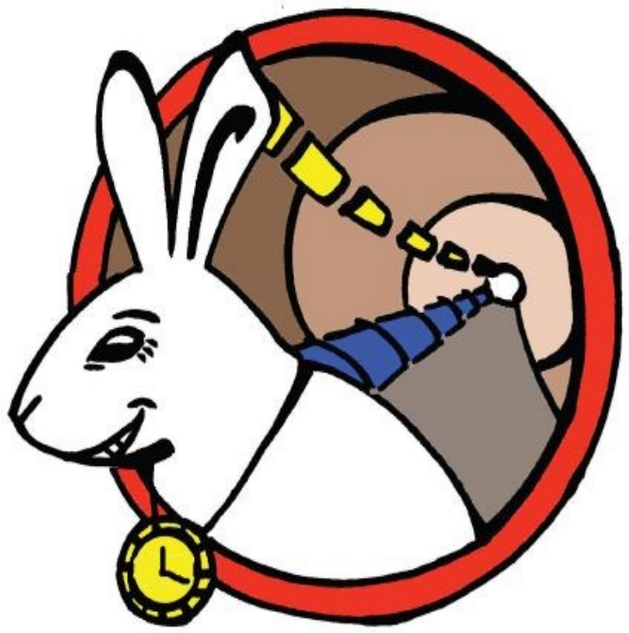
Laboratoire de Physique des 2 infinis Irène Joliot-Curie

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace



The WhiteRabbit & The R & T TIMED

Antoine Back, Chafik Cheikali, **Daniel Charlet**, Eric Plaige, Paul-Eric Pottie, Monique Taurigna, Cédric Viou

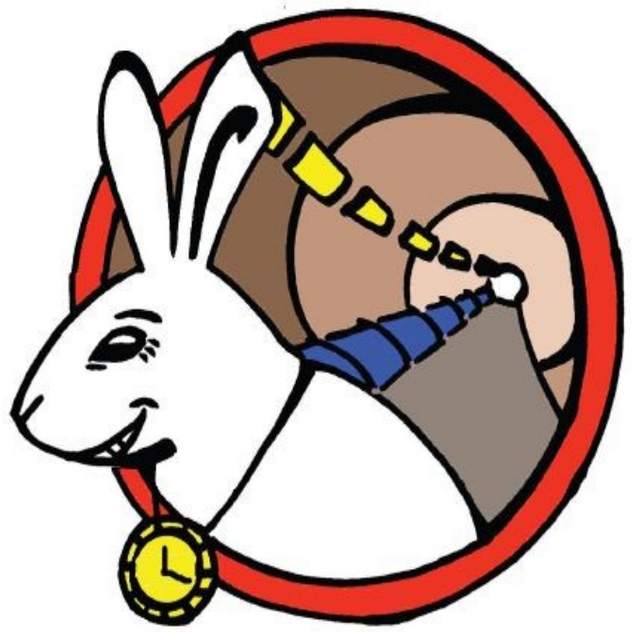
cnrs

Nantes July 2023

Station de Radioastronomie de Nançay

Outline

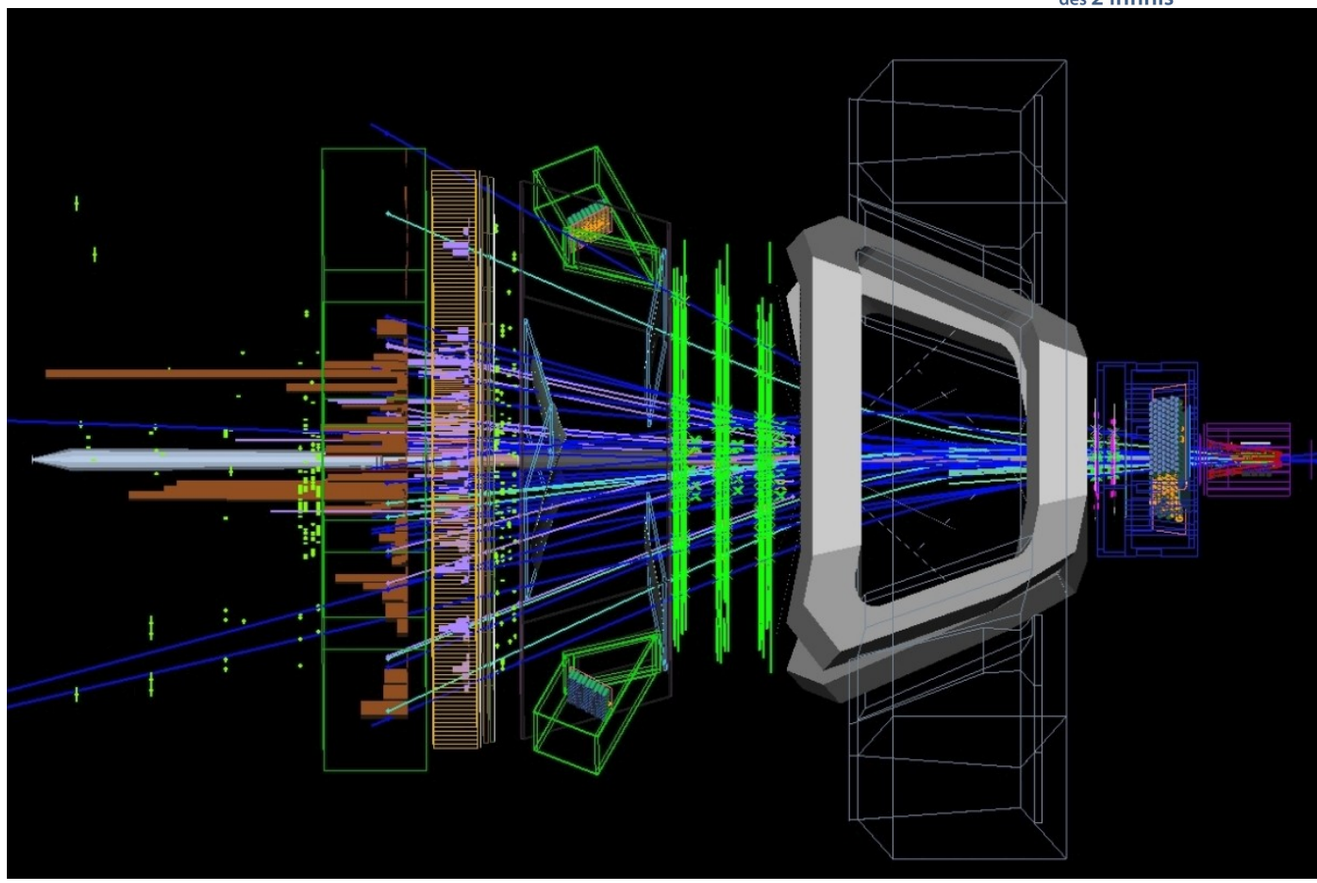
- WhiteRabbit promising sector
- WhiteRabbit theory of operation
- System WhiteRabbit
- WhiteRabbit enhancement : R &T Timed

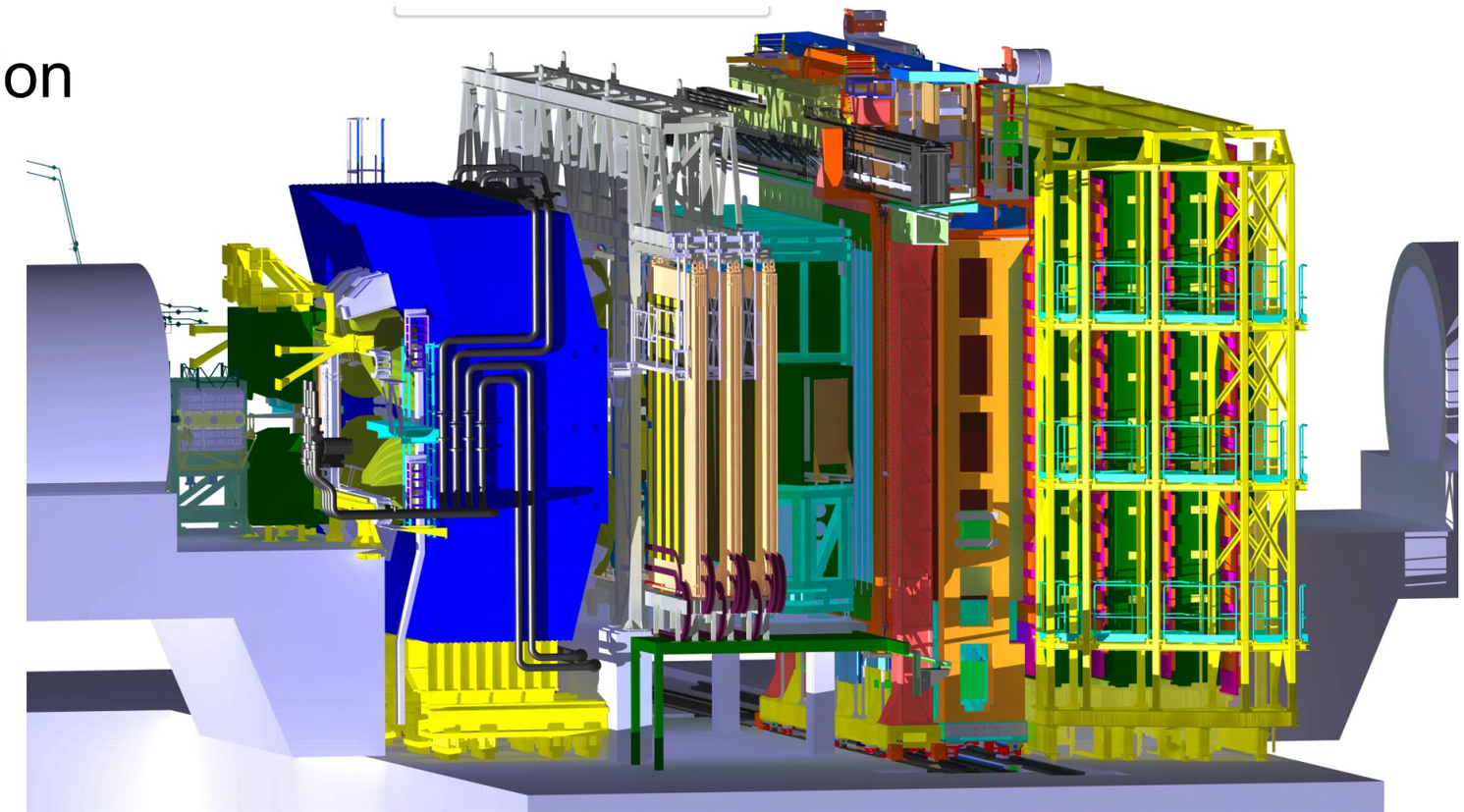


WhiteRabbit

WR Motivations : Multi-detectors LHCb

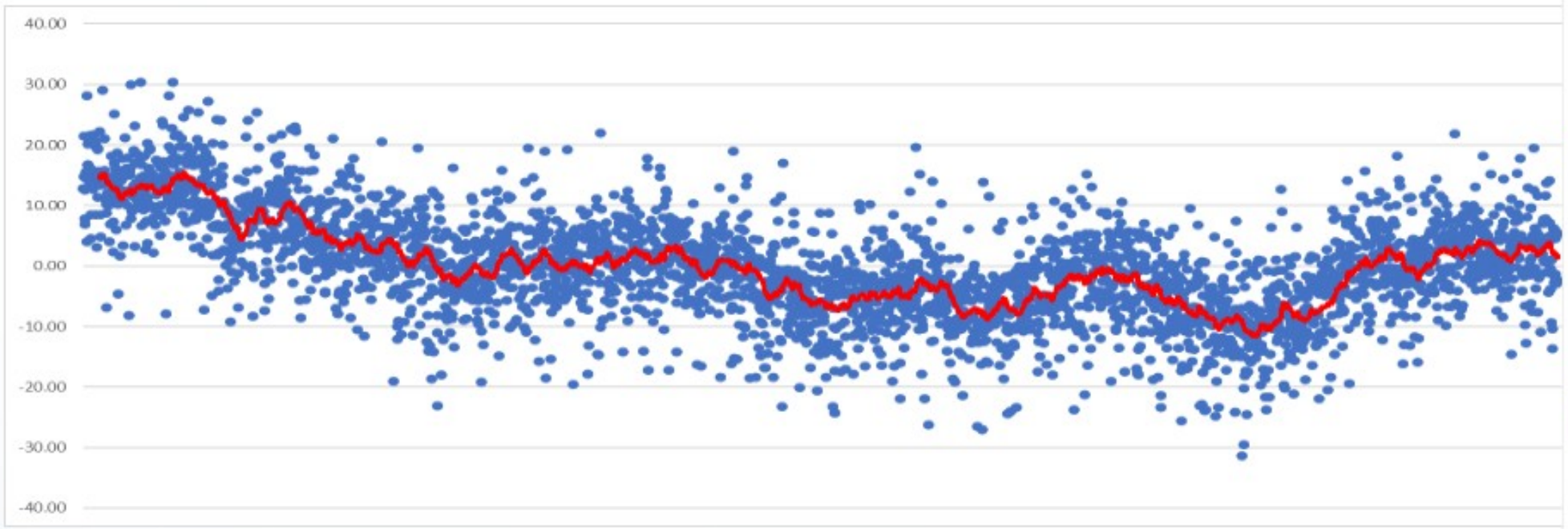
- LHCb detector
- 7 sub-detectors
- 20m x 20m
- Further million of acquisitions chanels
- All systems must be synchronize with the same clock (40MHz)
- A complex and long calibration time is mandatory
- Clock drift during physic aquistion

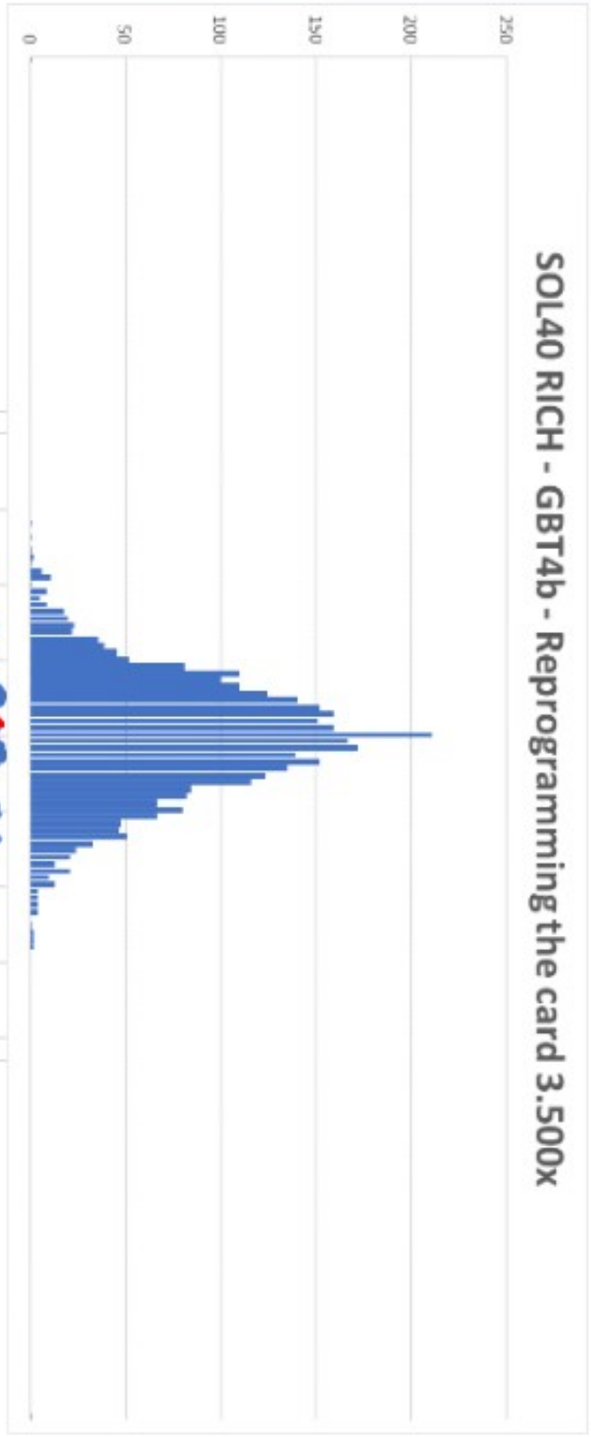




Clock drift over time

SOL40 RICH – GBT4b – Reprogramming SOL40 3500x
Over 5 days of test
Center of recovered clock distribution drifted over ~25ps
Most likely due to temperature

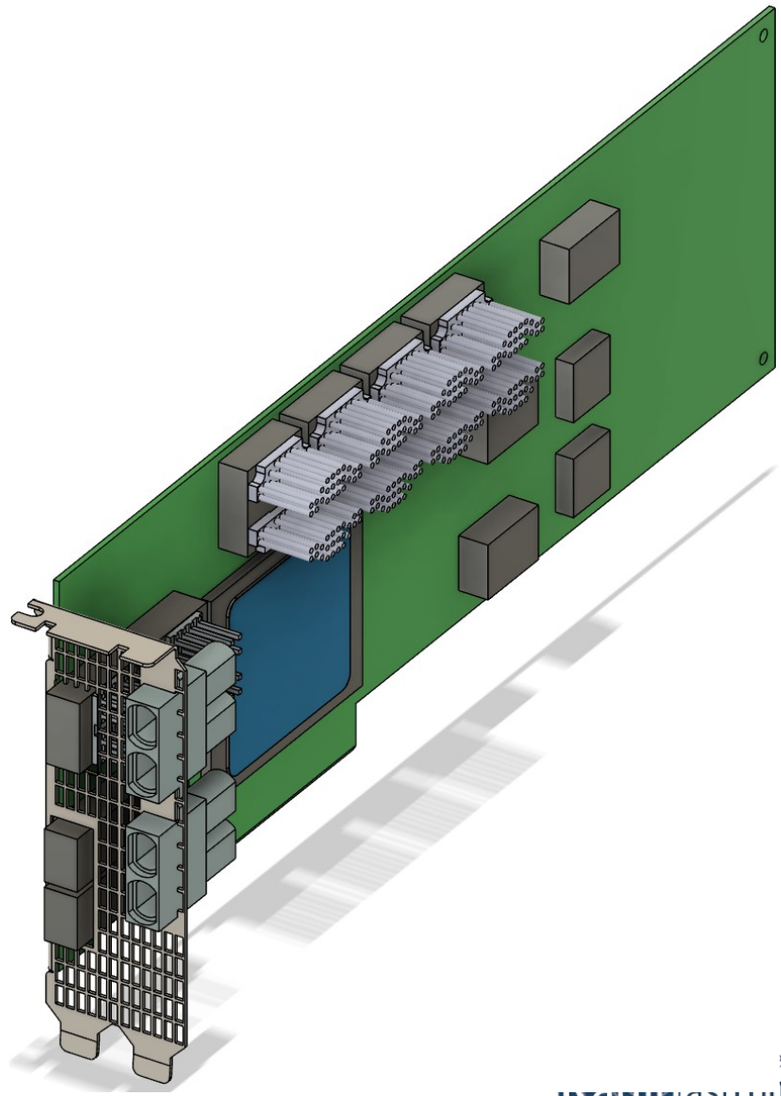




The resolution of the SOL40 PLL shift is ~100ps

WR Motivations : Multi-detectors PCIE400

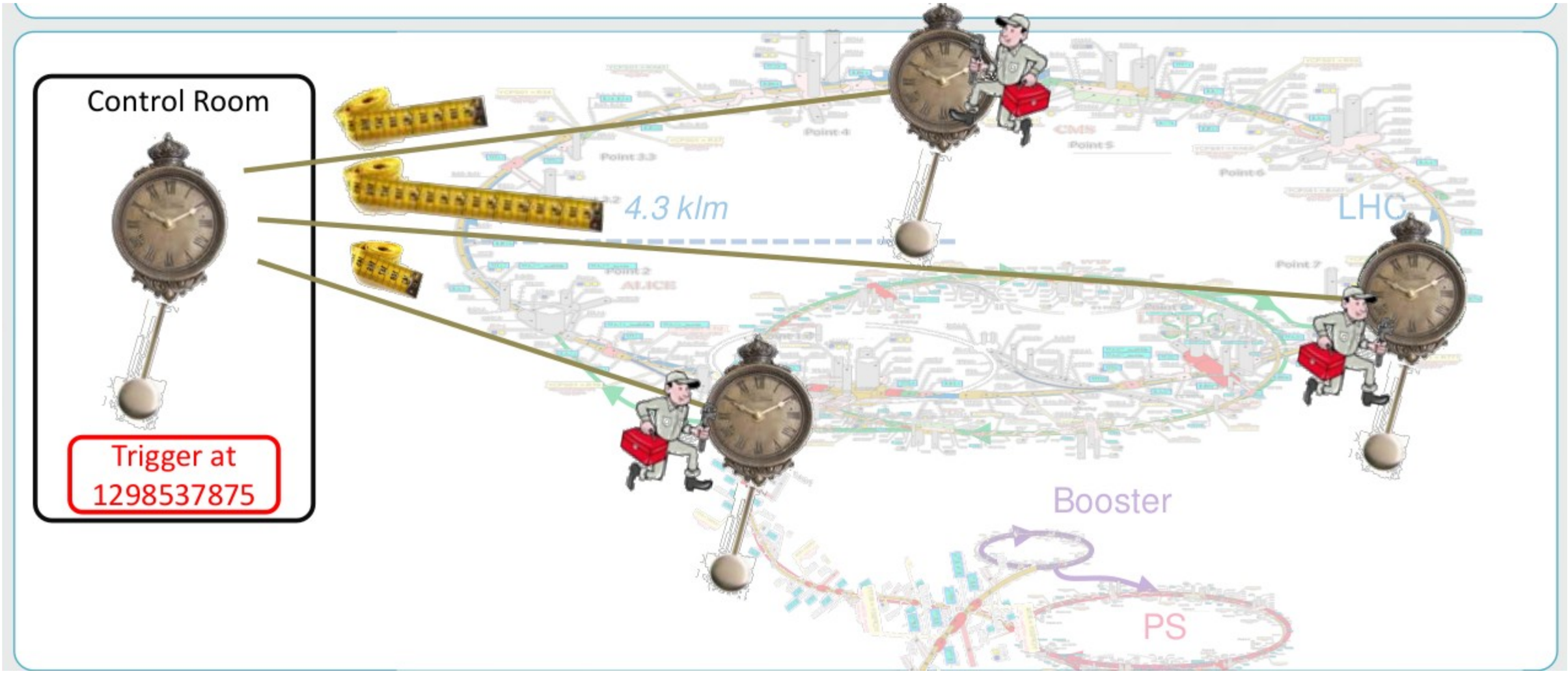
- Data acquisition and event formatting board for the futur LHC upgrade
- More than to 500 boards for a detector
- WhiteRabbit clock distribution (5ps)
- Foreseen characteristics
  - Agilex7 M-series AGMF039R47A1E2V
  - No DDR memory
  - Use of PC RAM or HBM2e instead
  - Up to 48x26Gbps NRZ for FE
  - PCIe Gen 5 / CXL or 400GbE
  - Low jitter PLL < 100 fs RMS
  - White Rabbit clock distribution (3ps/13ps) (SFP+)



Systèmes de Référence Temps-Espace

Accelerator : Master oscillator distribution

- Real-timed communication system : tight time constraints
- Long distances between nodes : long transmission delays
- Numbers of nodes : several hundred
- Dynamic changes to the numbers of nodes : not easy



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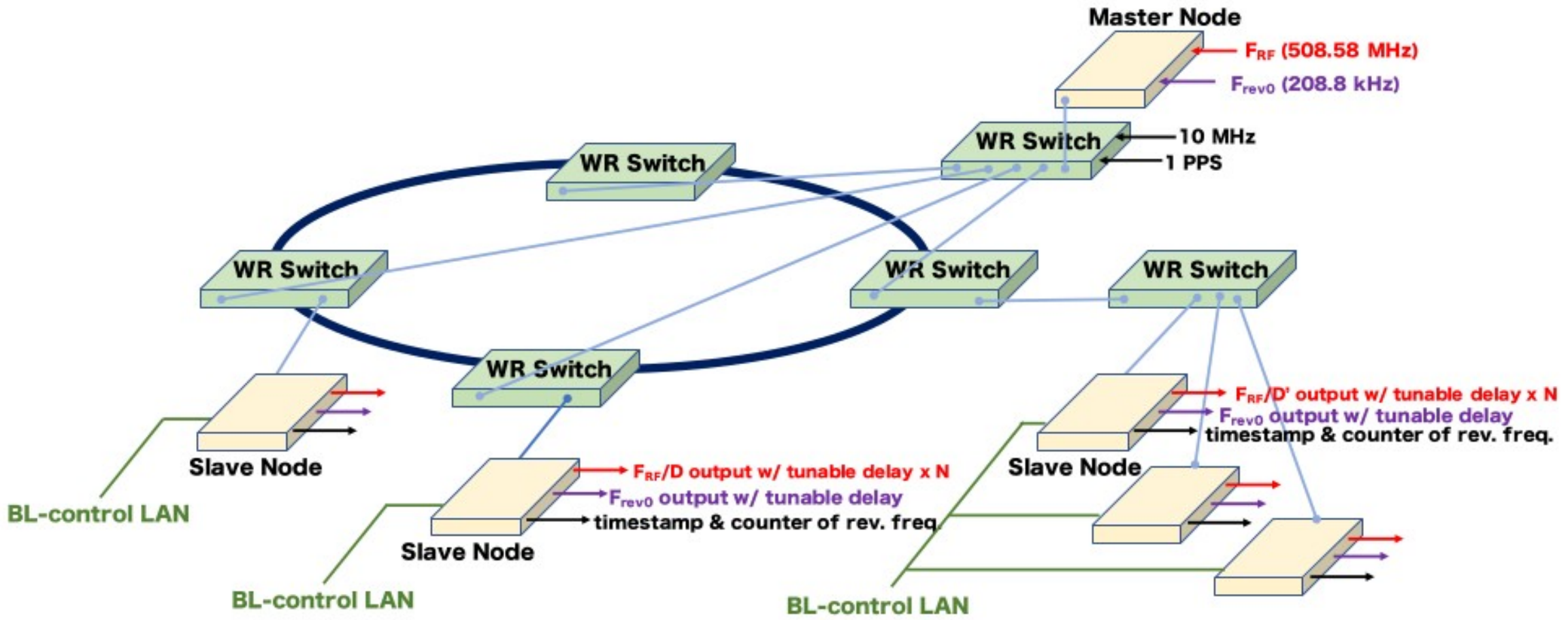
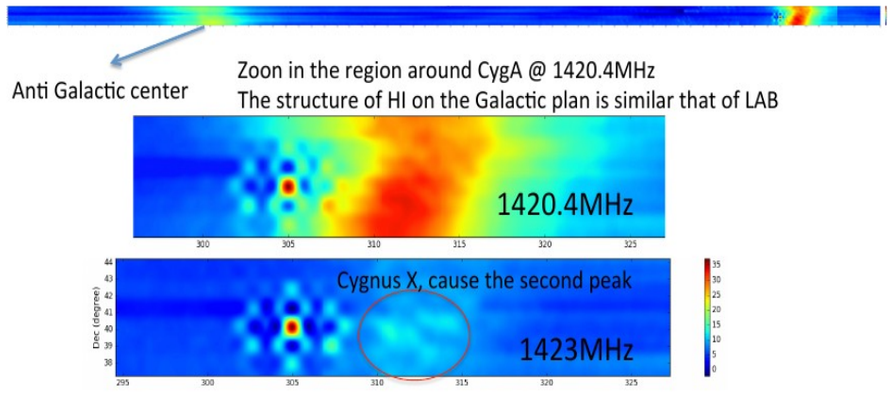
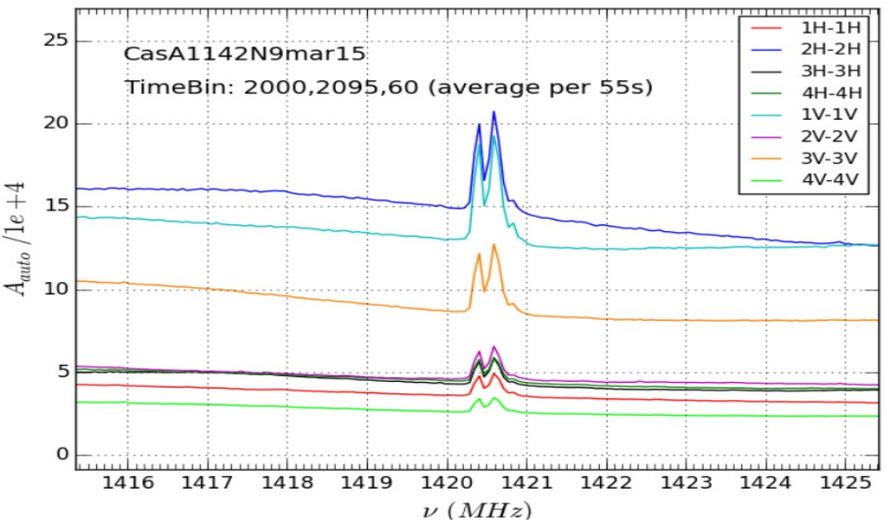
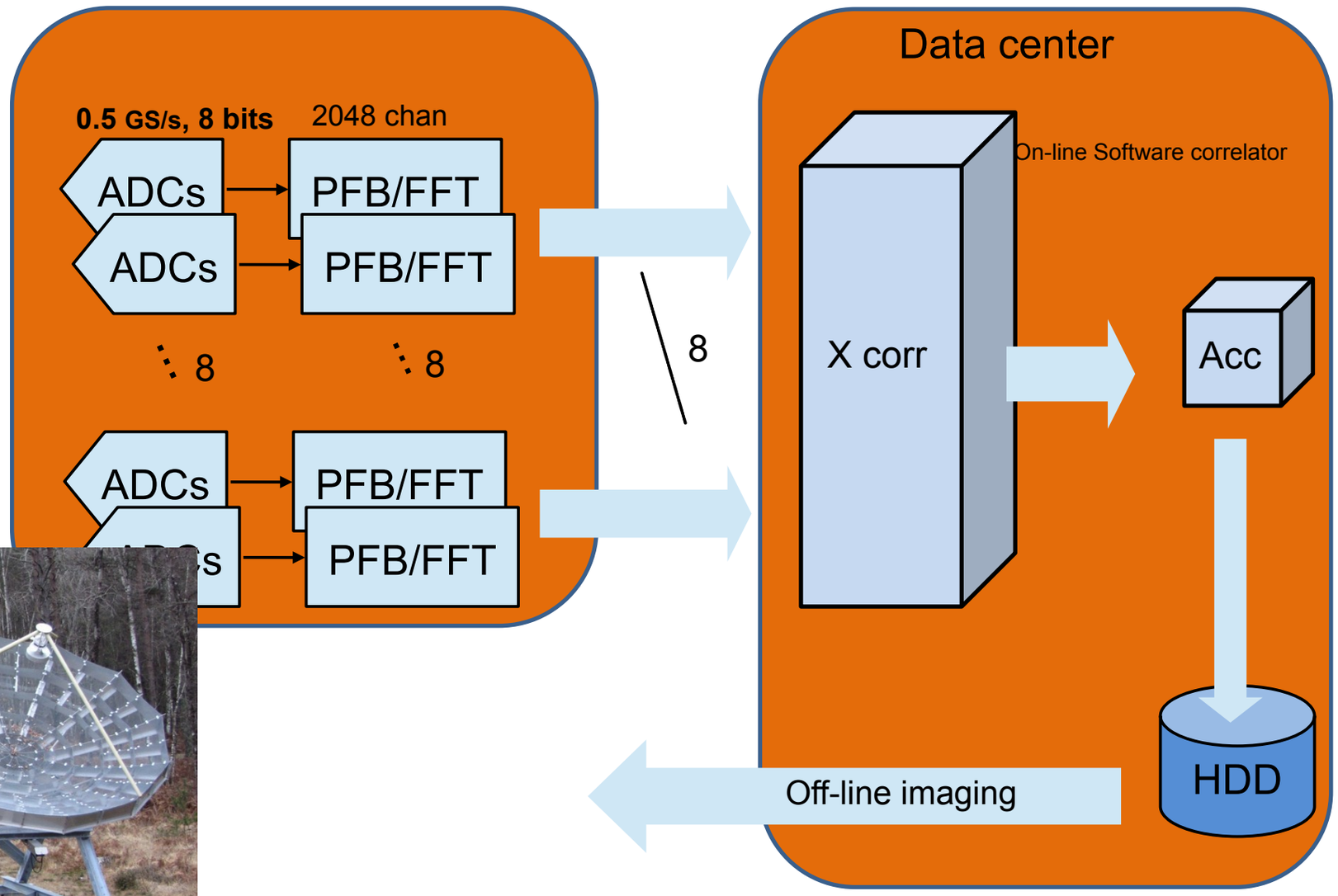


WR motivations : Radio astronomy PAON IV

Radio telescope demonstrator for mapping in 3D of the atomic hydrogen in the universe

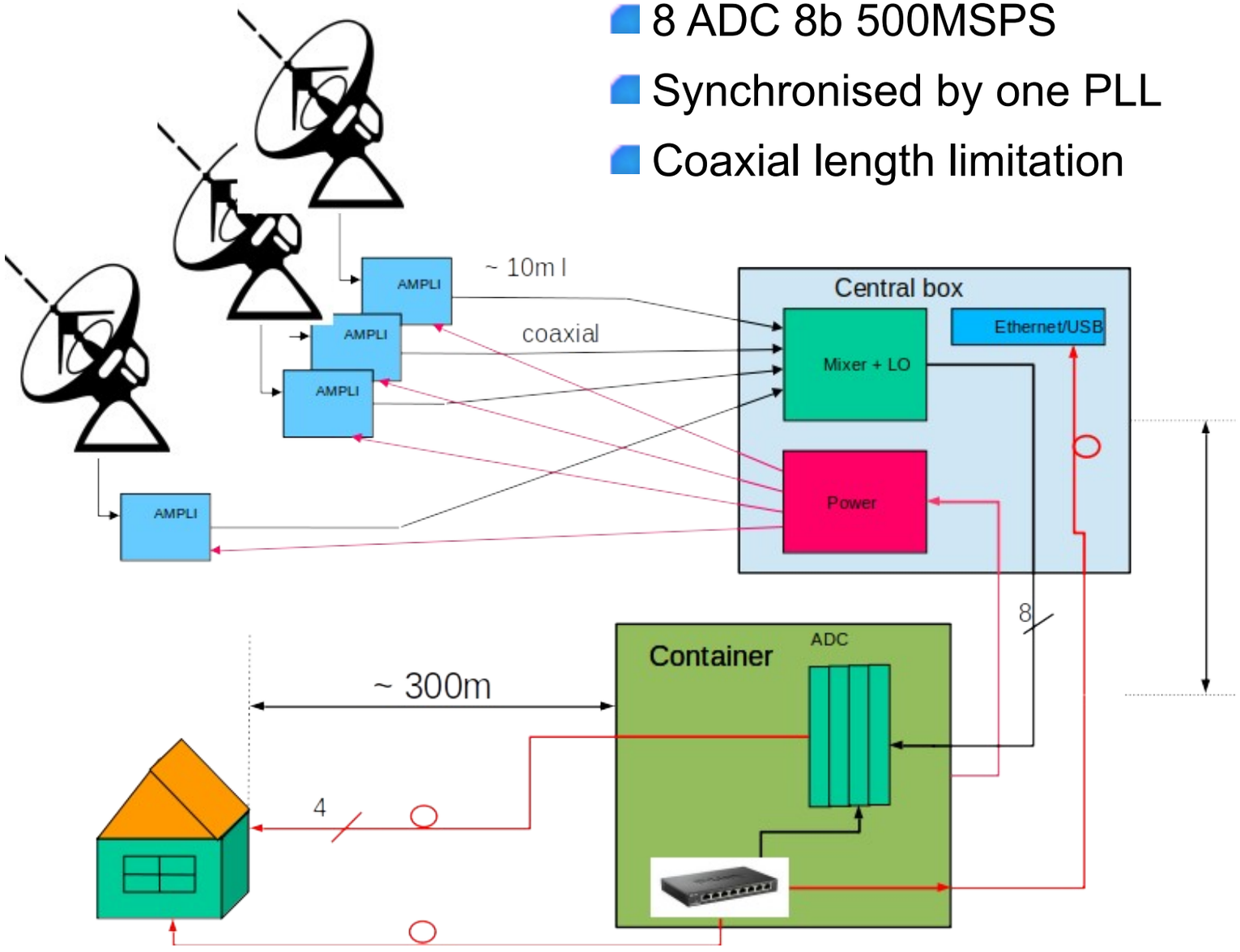




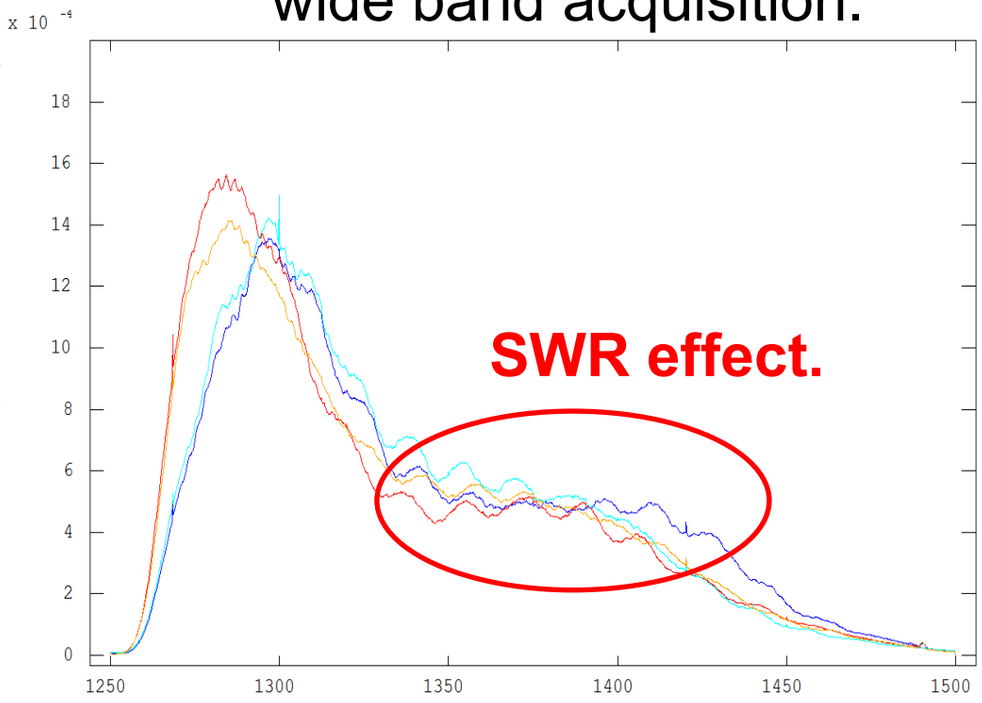


PAON IV : previous architecture

- Interferometer 4 radio dishes of 5m
  - Centralized coding architecture
  - High bandwidth : 250MHz
  - 8 ADC 8b 500MSPS
  - Synchronised by one PLL
  - Coaxial length limitation



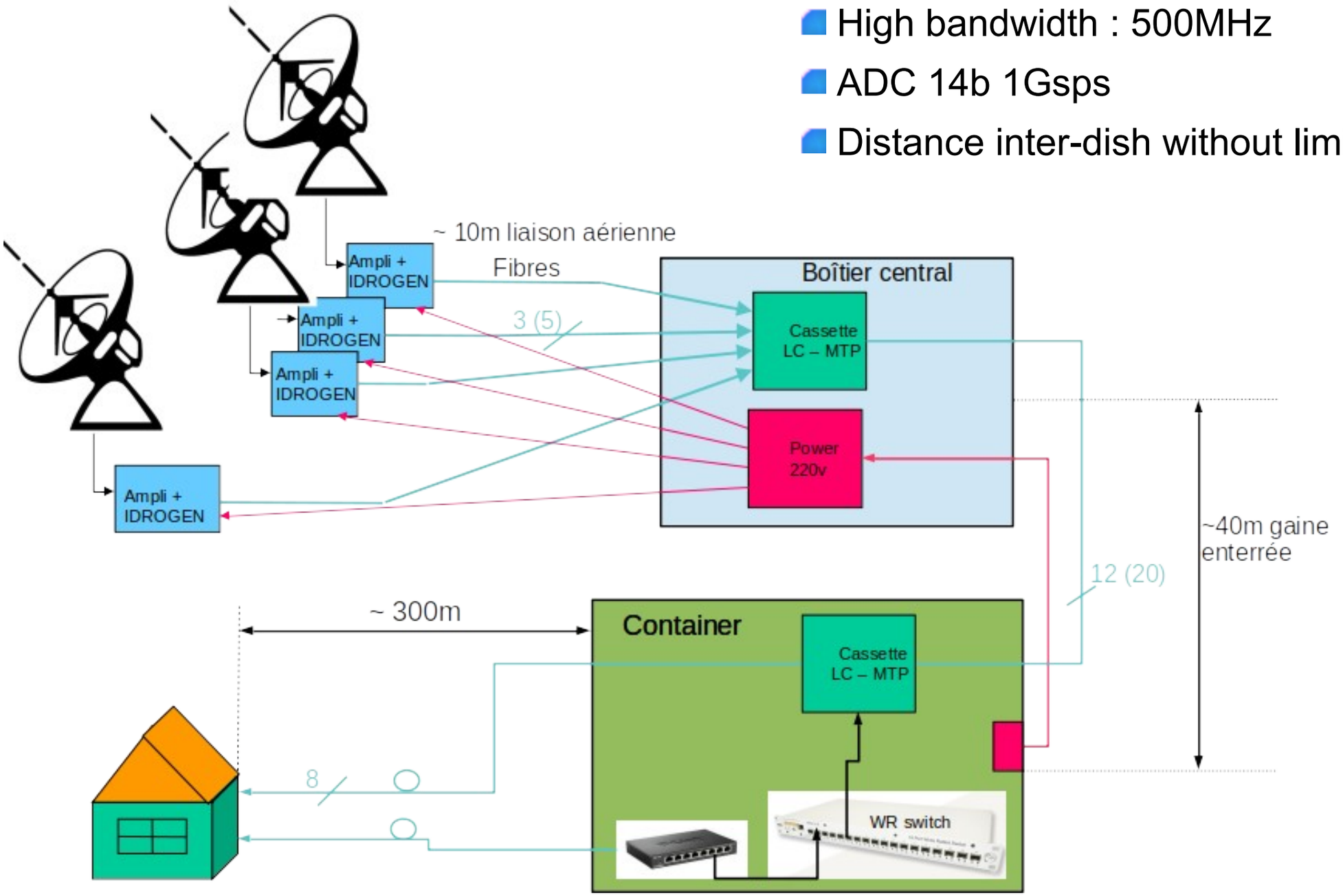
SWR depends of:
RF cable length,
Adaptation mismatch,
wide band acquisition.



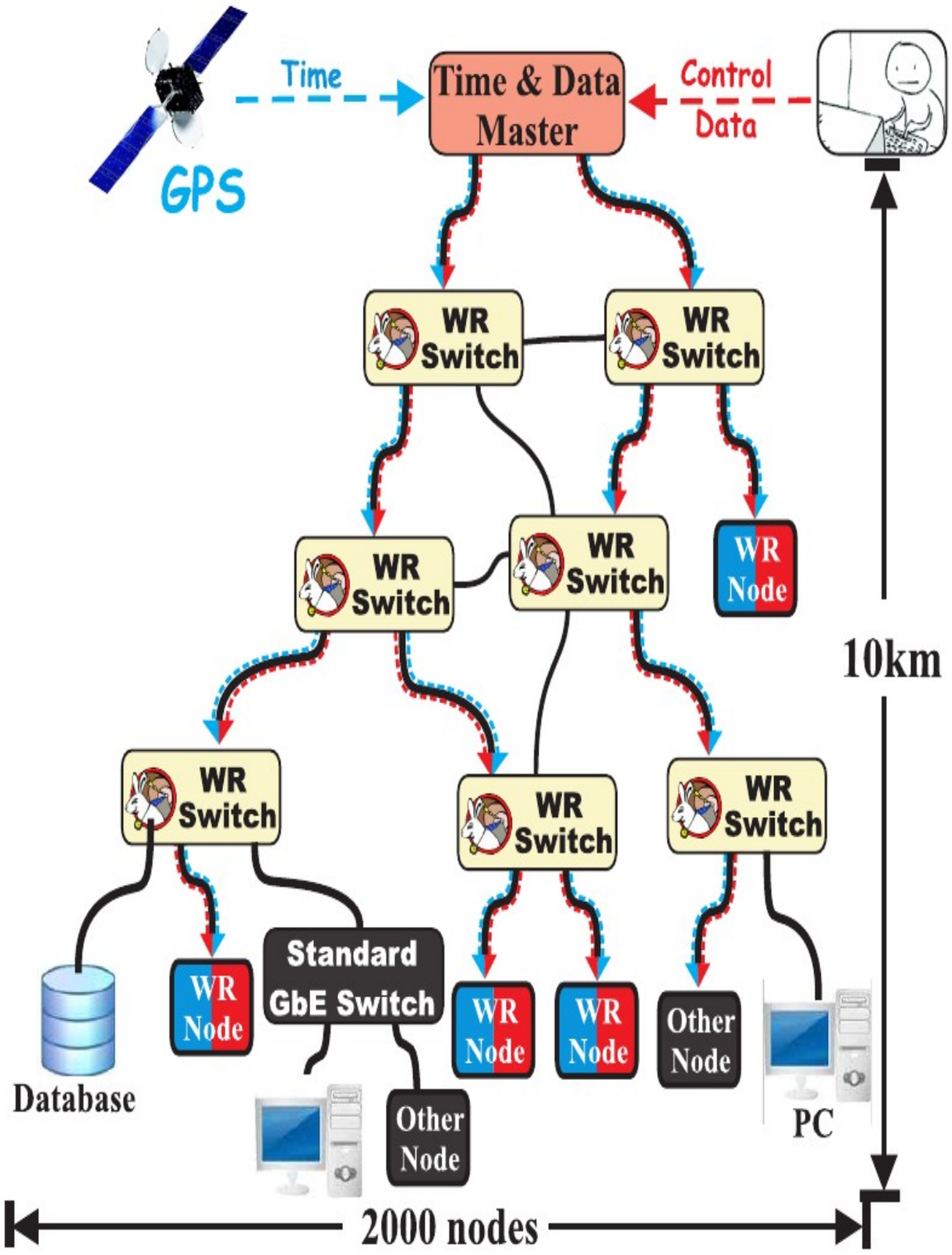
Systèmes de Référence Temps-Espace

PAON IV : new architecture

- Interferometer 4 radio dishes of 5m
  - Synchronised by the WhiteRabbit
  - High bandwidth : 500MHz
  - ADC 14b 1Gsps
  - Distance inter-dish without limitation

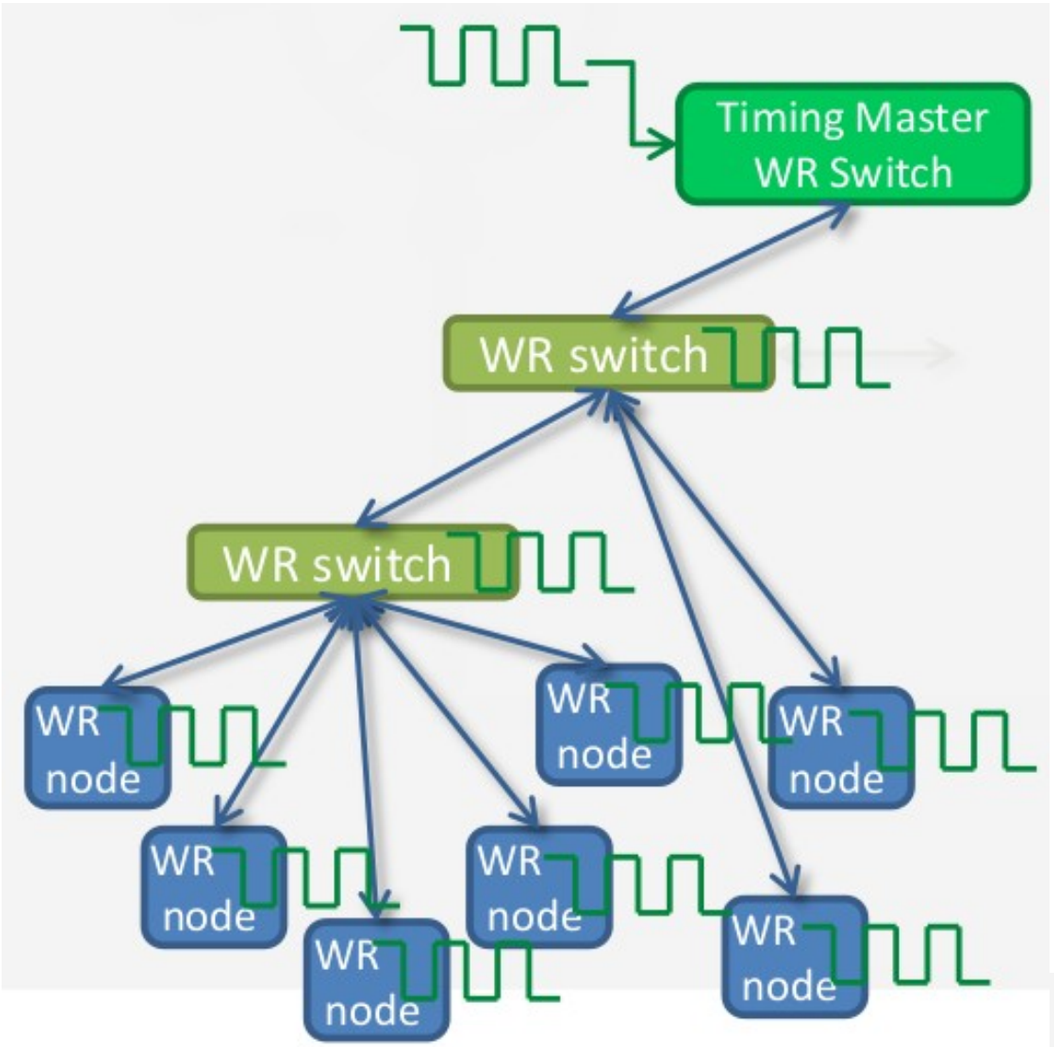


White Rabbit principle : Enhanced Ethernet

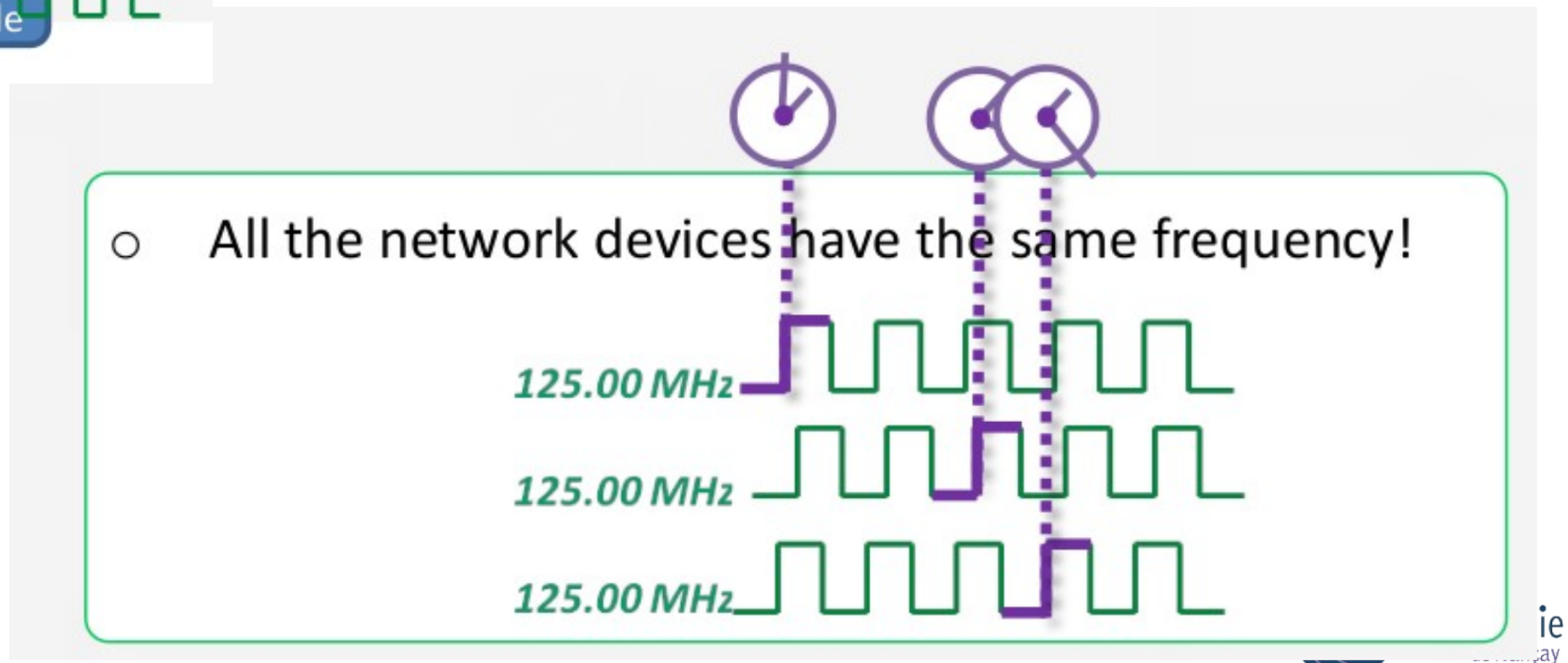


- An extension of Ethernet which provides :
  - Synchronous mode (Syn-E) – common clock for physical layer in entire network, allowing for precise time and frequency transfer
  - Deterministic routing latency – a guarantee that packet transmission delay between two stations will never exceed a certain boundary.
- Technology overview
  - Precision Time Protocole (IEEE1588)
  - Synchronous Ethernet
  - DDMTD Phase tracking (Digital Dual Mixer Domain) …
- Delivering signal :
  - Clock : usually10MHz ;
  - 80Mhz<IDROGEN<3Ghz (LMK4828)
  - Pulse per seconde
  - Temps Atomic International (48b)

Synchronous Ethernet (Sync-E)

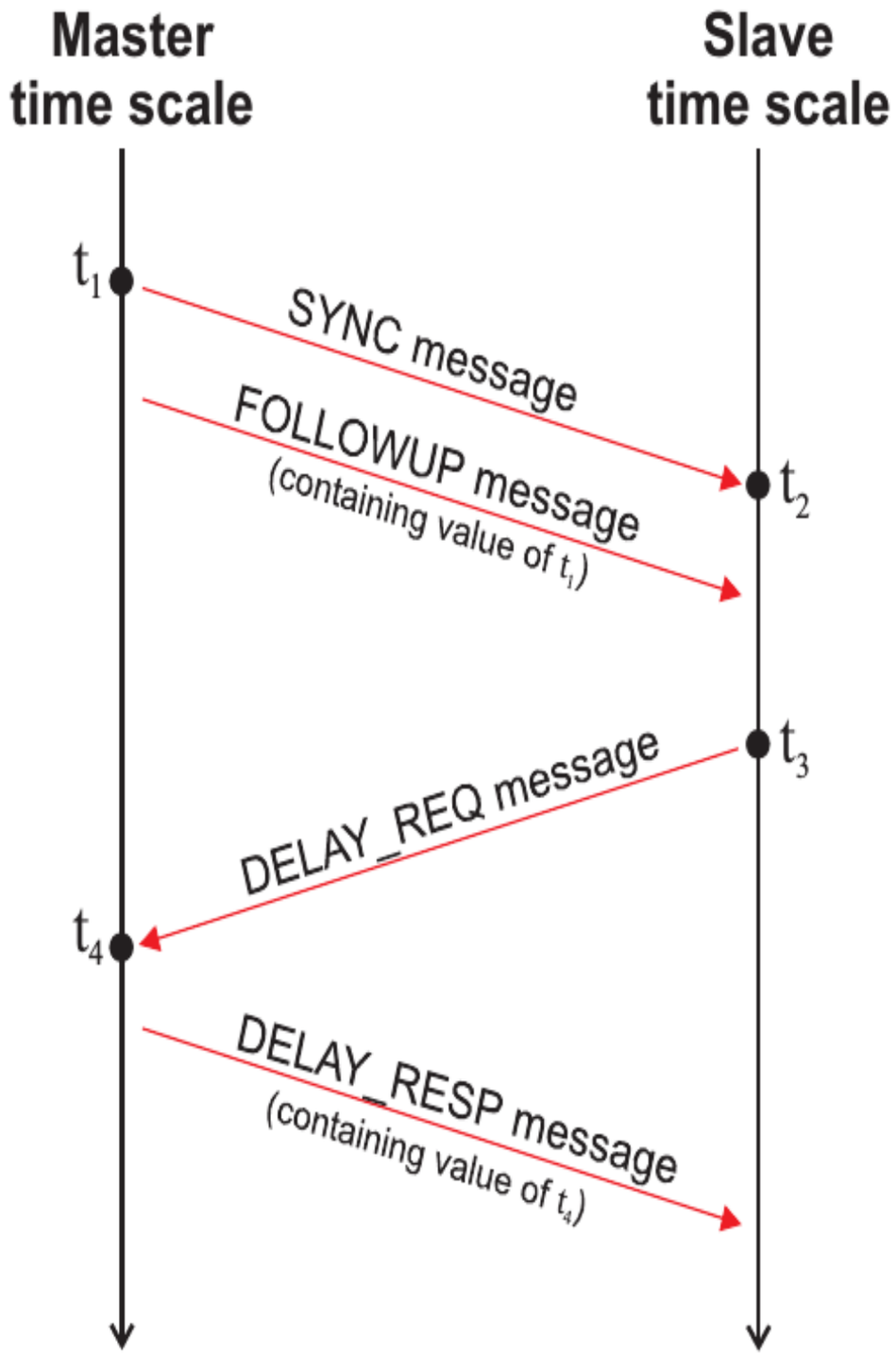


- All network nodes use the same physical layer clock,
- Clock is encode in the Ethernet carrier and recovered by the receiver chip(PHY)
- A master and unique clock for the whole network
- Synchronous digital hierarchy
- High precision clock definition, 20 better than standard Ethernet clock



Systèmes de Référence Temps-Espace

Precision Time Protocol (IEEE1588)



- Packet-based synchronization protocol
- Synchronizes local clock with the master clock by measuring and compensating the delay introduced by the link.
- Link delay evaluated by measuring and exchanging packets tx/rx timestamps
- PTP is used only for compensation of the clock offset

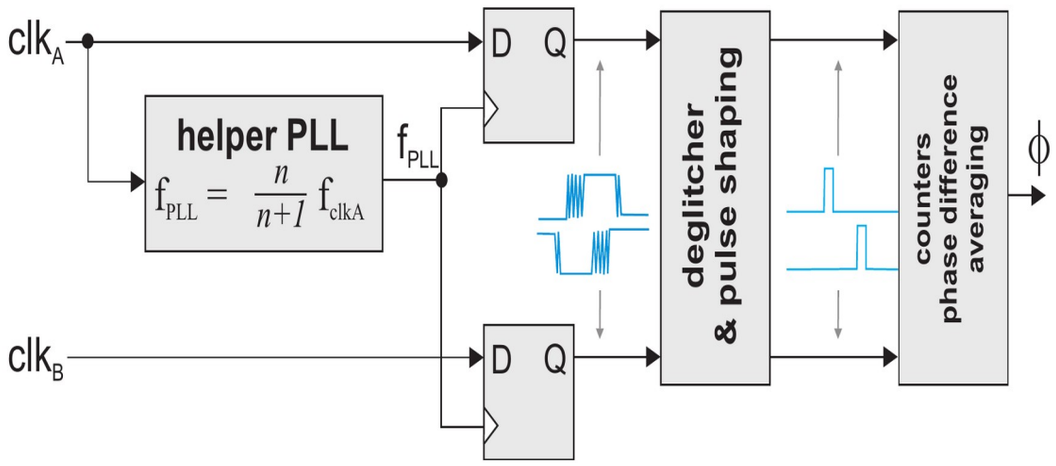
Having values of t1 ...t4 , slave can:

- calculate one-way link delay:

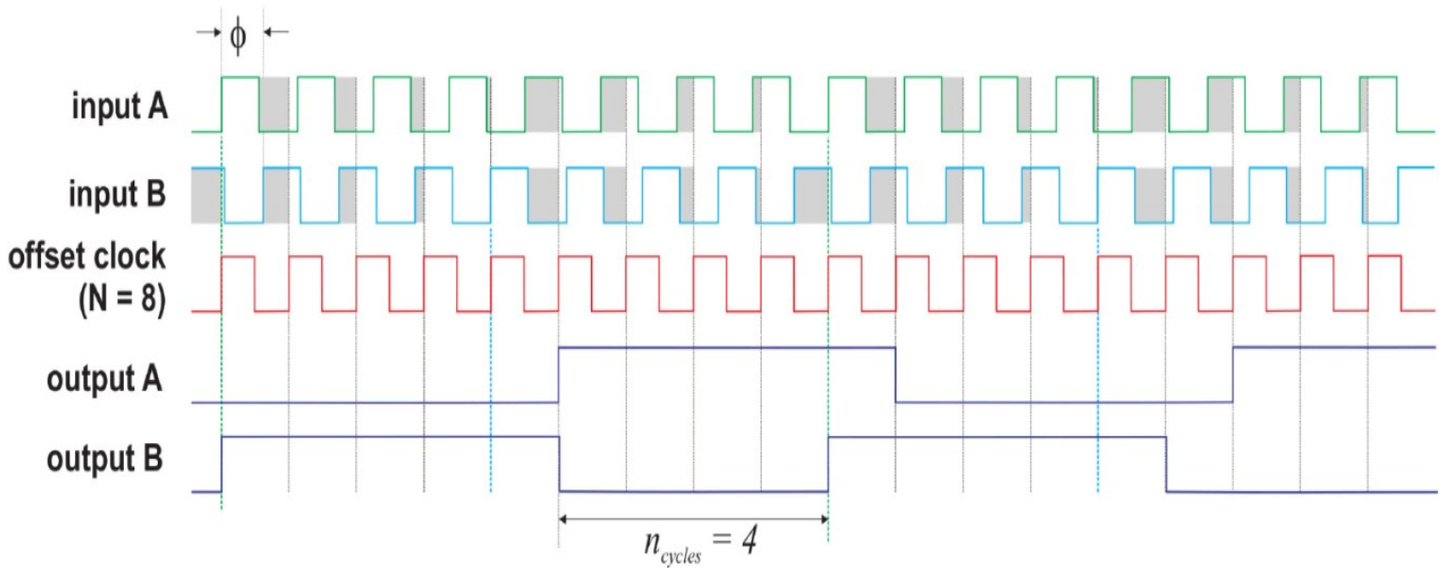
$$\delta ms = ((t4 - t1) - (t3 - t2))/2$$

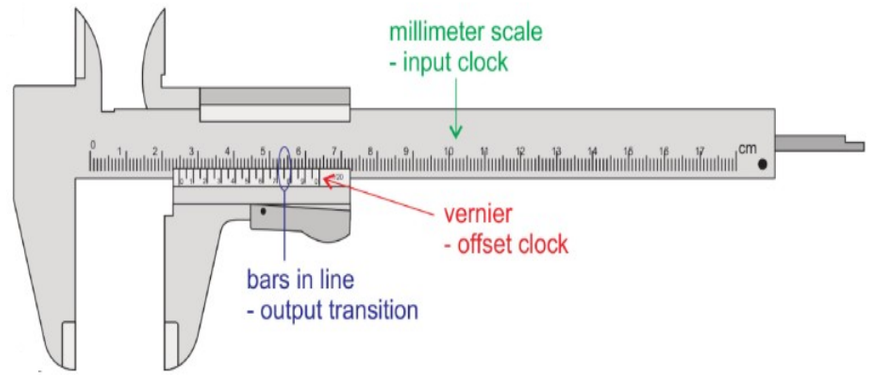
- syntonize its clock rate with the master by tracking the value of
  t2 − t1
- compute clock offset:
  offset = t2 − t1 + δms

Digital Dual Mixer Time Domaine phase detector (DDMTD)



- Measure the phase shift between transmit and receive clock on
- the master side, taking the advantage of Synchronous Ethernet.
- Monitor phase of bounced-back clock continuously.
- Phase-locked loop in the slave follows the phase changes measured by the master.

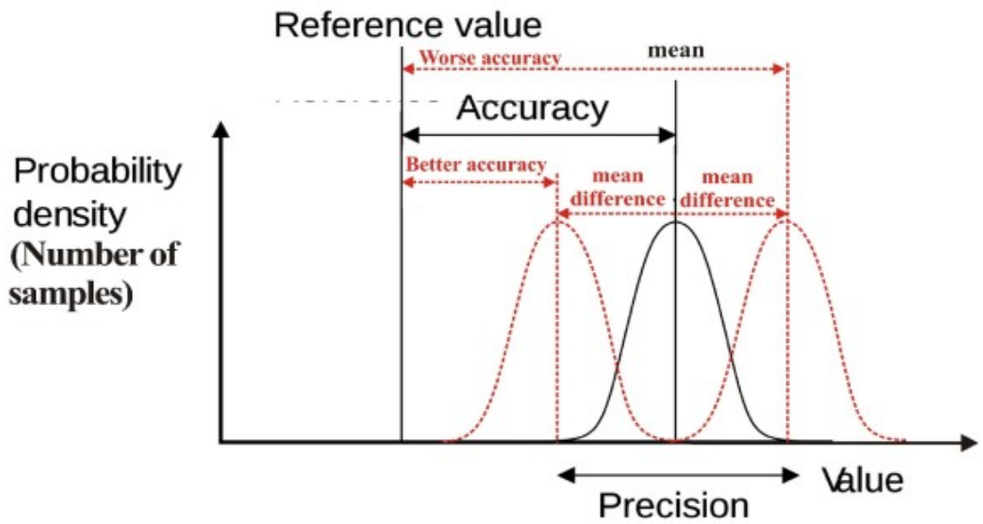




Systèmes de Référence Temps-Espace

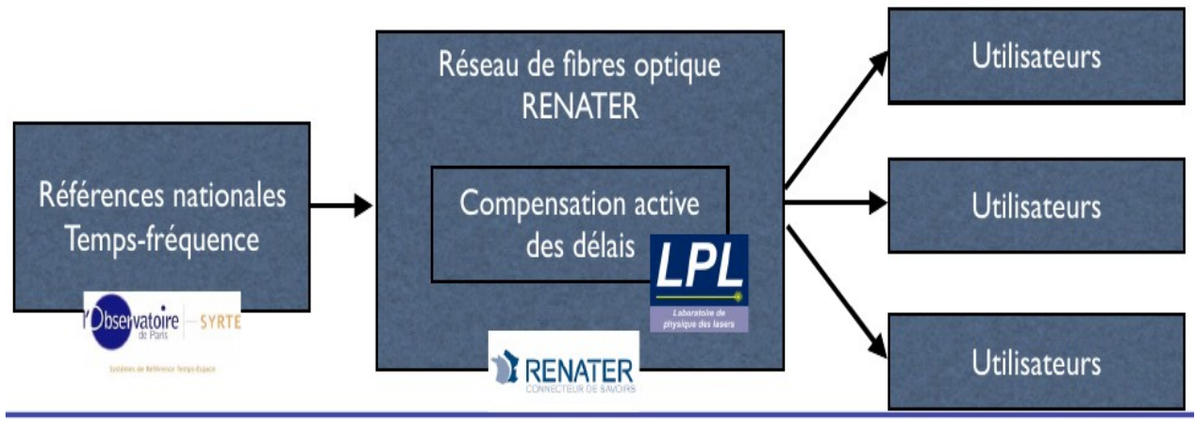
WhiteRabbit performance

System	accuracy	note
GPS	10ns -200ns	Propagation in non-stationary disruptive environment. Problem of the mutli-way
GPS-IPPP	2 – 3 ns	Resolution of phase ambiguities using RIMEX data. More complex implementation
WR switch without calibration	500ps - 100ns	Swich Orollia : Master configuration
WR switch with calibration	200ps – 2 ns	Swich Orollia : Master configuration
IDROGEN	13 ps	Swich Orollia : Grand Master configuration
IDROGEN with external synchronisation	3 ps	2 IDROGEN board on WR switch configure in Grand Master and synchronyse by T+ REFIMEVE
IDROGEN & external function	300fs	Aim of T+REFIMEVE



Systèmes de Référence Temps-Espace

Time & frequency distribution : T+REFIMEVE

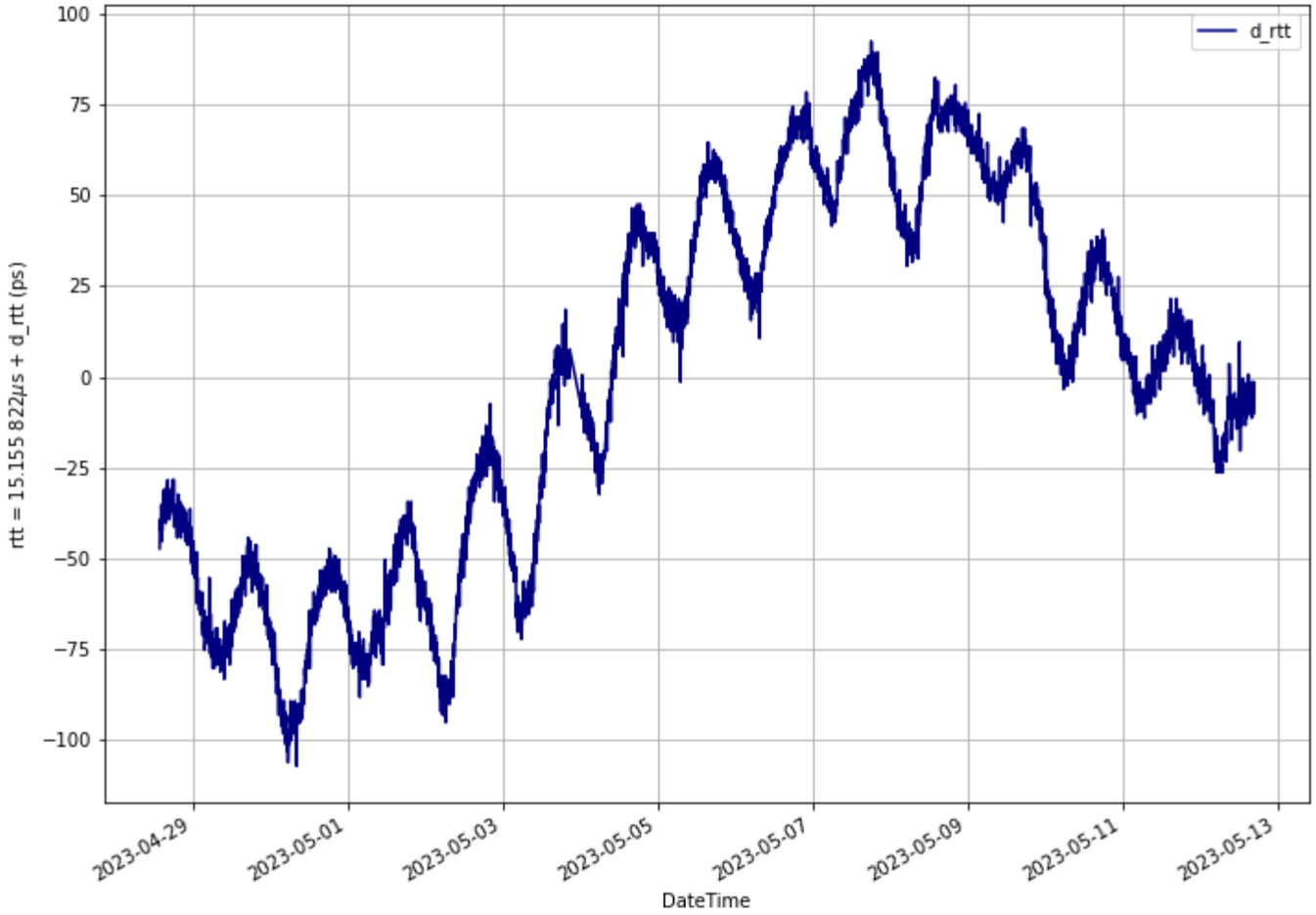


- For long time stability reference clock is mandatory
- International time reference provider
- Optical fiber distribution

Signal provided by T-REFIMEVE		Stability @1s	Stability @1day	Uncertainty	
				routine	dedicated
Radiofrequency	1st pillar - 10 MHz (White Rabbit)	10^{-12}	10^{-15}	10^{-14}	10^{-15}
	2nd pillar - 1 GHz	10^{-13}	3×10^{-16}	10^{-14}	2×10^{-16}
Time	1st pillar (White Rabbit)	1 ns	1 ns	10 ns	10 ns
	2nd pillar	20-50 ps	500 ps	10 ns	2ns to 100ps
Optical frequency (194,5 THz - 1542 nm)	Today	10^{-15}	3×10^{-16}	10^{-14}	2×10^{-17}
	Expected progress in 5 years	10^{-16}	2×10^{-17}	10^{-14}	10^{-18}

WhiteRabbit supervision

```
WR PTP Core Sync Monitor v 1.0
Esc = exit

TAI Time:                   Thu, Jan 1, 1970, 00:03:48

wru1: Link up   (RX: 685, TX: 281), mode: WR Slave   Locked  Calibrated
IPv4: BOOTP running

PTP status: slave

Synchronization status:

Servo state:                TRACK_PHASE
Phase tracking:             ON
Synchronization source:
Aux clock status:

Timing parameters:

Round-trip time (mu):    691831 ps
Master-slave delay:      349132 ps
Master PHY delays:       TX: 46407 ps, RX: 168643 ps
Slave PHY delays:        TX: 46407 ps, RX: 175043 ps
Total link asymmetry:       -6433 ps
Cable rtt delay:         255331 ps
Clock offset:                 0 ps
Phase setpoint:             528 ps
Skew:                         5 ps
Manual phase adjustment:      0 ps
Update counter:             174
--
```



- WR debugging
  - Small operating system include in the WR core
  - Serial communication by USB or Ethernet
  - Status of the link : Delay, transceiver
  - Control of the link : PPS,configuration
- WR supervision at LAC laboratory
- Monitoring at user equipment level
  - Fibers time propagation delays
  - 1.4Km of fiber
  - 5 levels of netwok stratum
  - 10 days of measurement
  - Zen-TP system

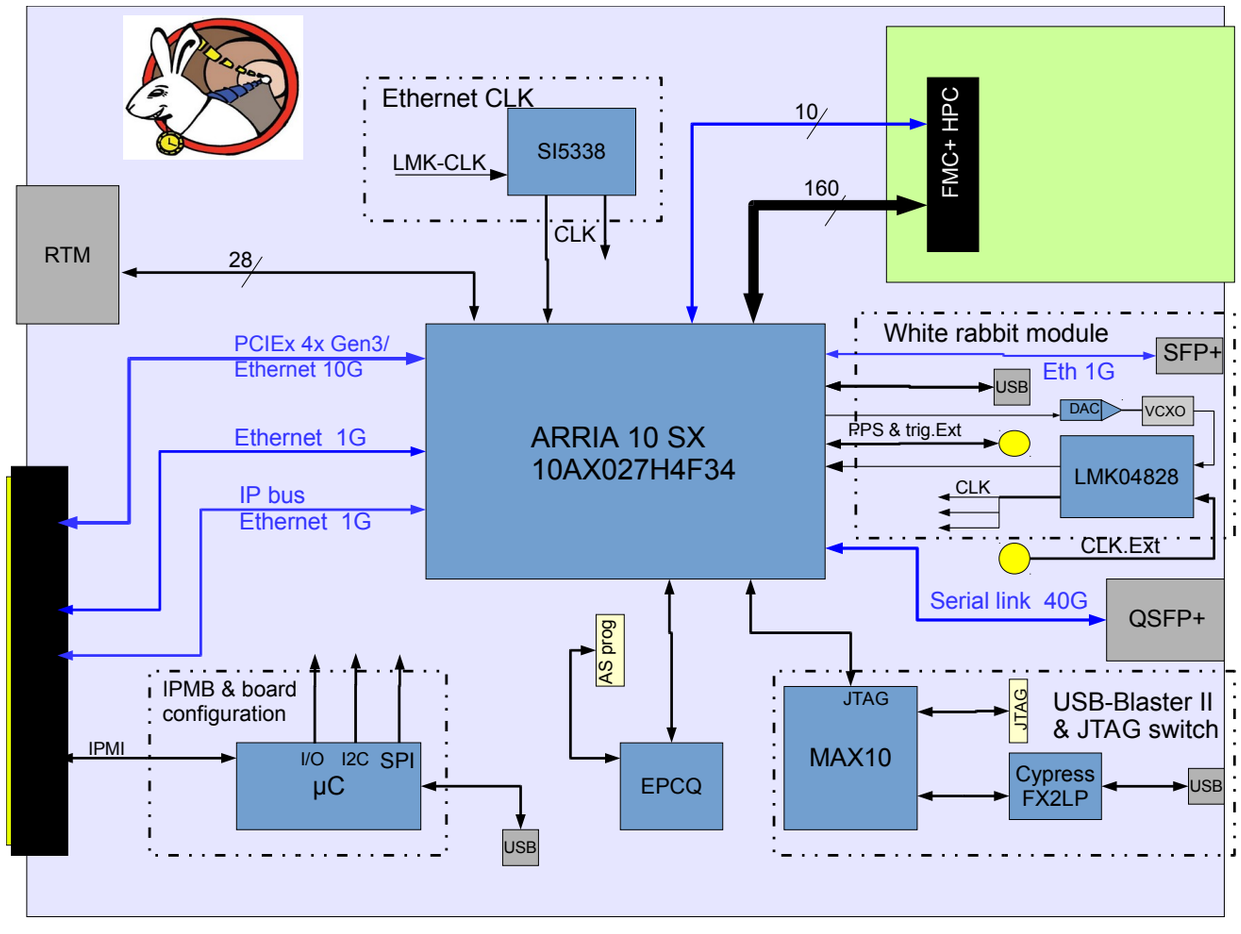
Off the shelf system

- Seven Solution (Orollia) :
  - WR-Zen : Low jitter WR master
  - WRS : switch 18ports
  - WR-LEN : WR node

Low phase noise WR -PTP : IDROGEN board

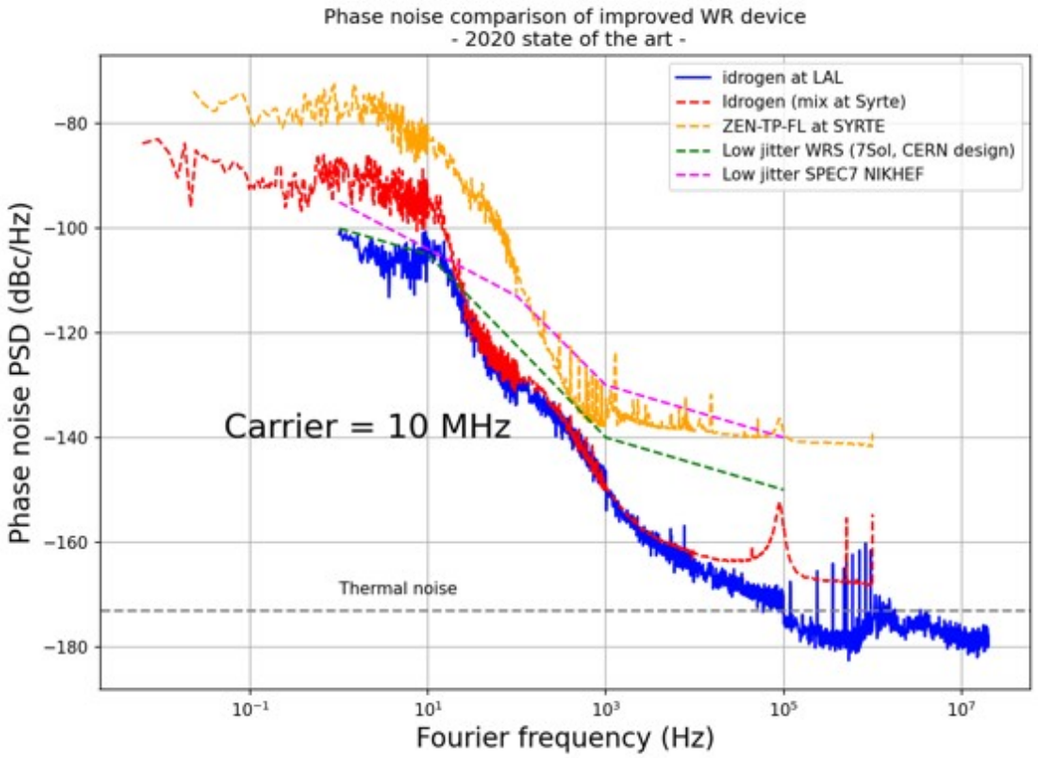
- High performance WR low jitter node
- High performance data aquisition system
- FMC+ carrier board
- Design & realization by IJCLAB
- Firmware by Nancay Observatory
- Clock expertise ans qualification by SYRTE
- Measures at SYRTE and IJCLAB

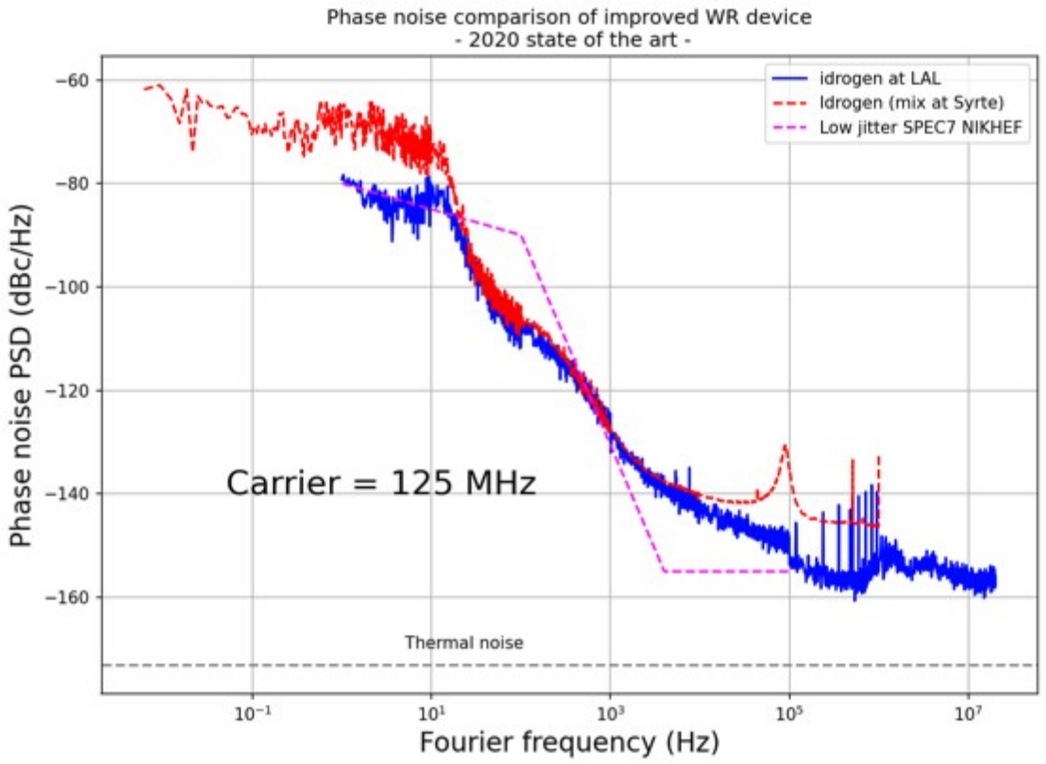
IDROGEN board main features



- MTCA 4.0 standard, double width full-size
- Stand-alone mode
- VITA57.1 (FMC slot)
  - 160 single-ended I/Os (80 LVDS) and/or up to 10 serial transceivers in a 40 x 10 configuration
- Full WhiteRabbit compliant.
- Configurable output clock
- Front panel connectivity
  - WR SFP+
  - QSFP+ 40G, USB
- Backplane connectivity
  - 1Gbe IPbus,PCI 4x Gen3,
  - IPMB, CLK & trigger lane.
  - RTM connector : J30

IDROGEN performance

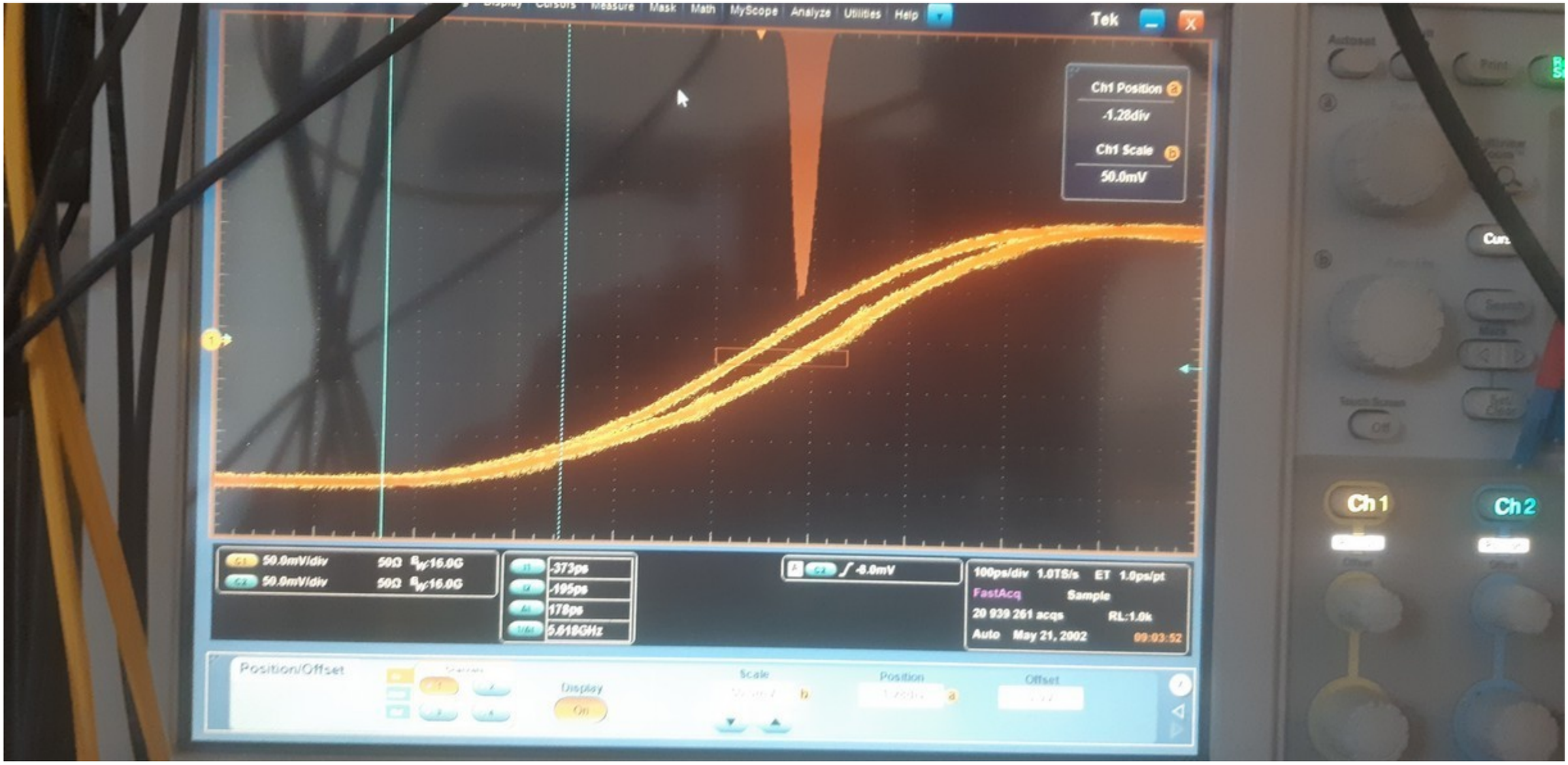


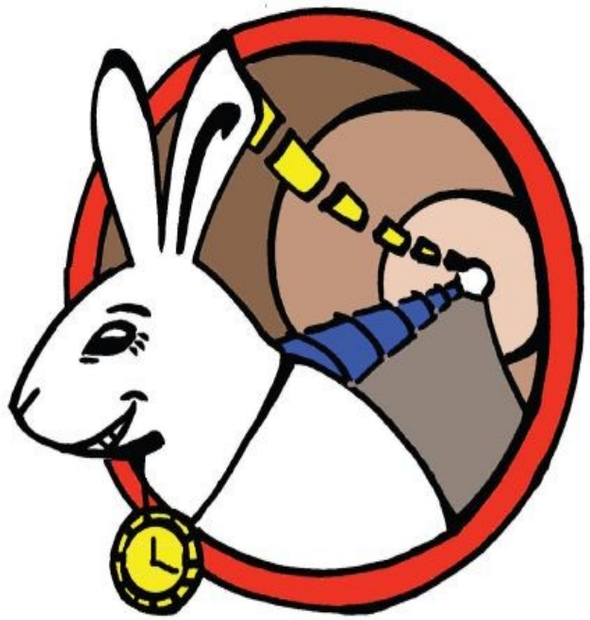


- Transfer from one WR switch to two IDROGEN boards with a short link (few meters)
- For the test we measure the phase difference between 2 nodes (IDROGEN board)
  - Best result, one order of magnitude than the « challenger »
  - Clock phase jitter
  - PPS time precision 3ps RMS

Pulse Per Second : IDROGEN

- PPS 2 IDROGEN board
- 25m & 125m of optic fiber
- ~50ps of dispersion of the PPS with calibration





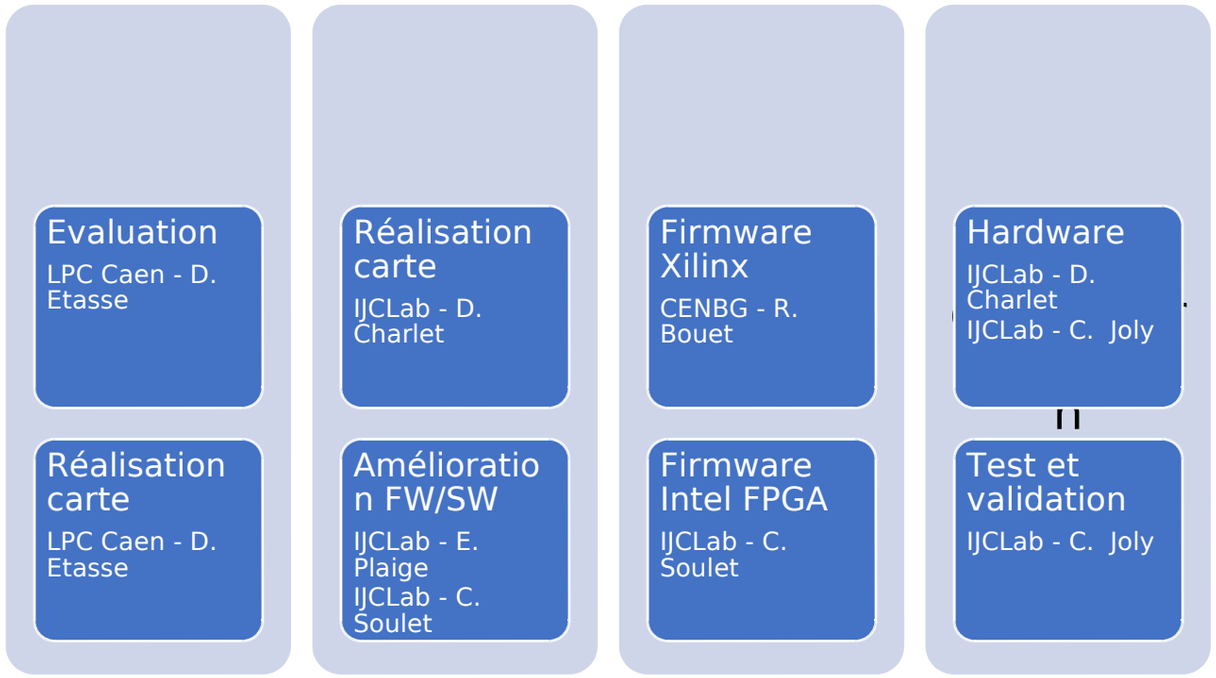
R & T TIMED

Research & Technology : TIMED

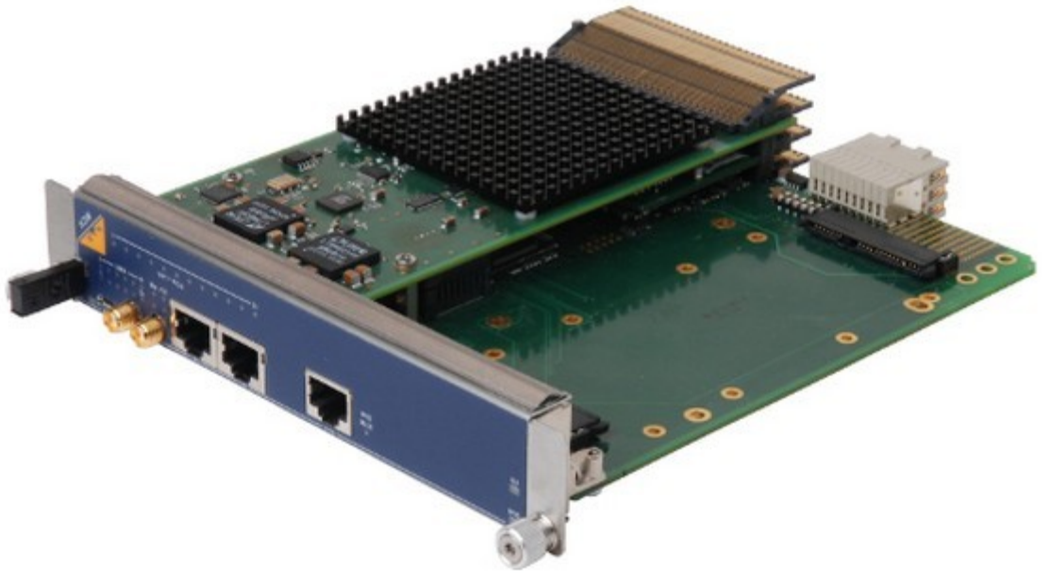
- Observatory of Paris & IN2P3 laboratories collaboration
- Extended domain of WhiteRabbit : Crate implementation
- WhiteRabbit node simplification of technical integration
- Improvement of WR performance
- Integration of external components by firmware function
- High stability frequencies distribution

Research & Technology : TIMED

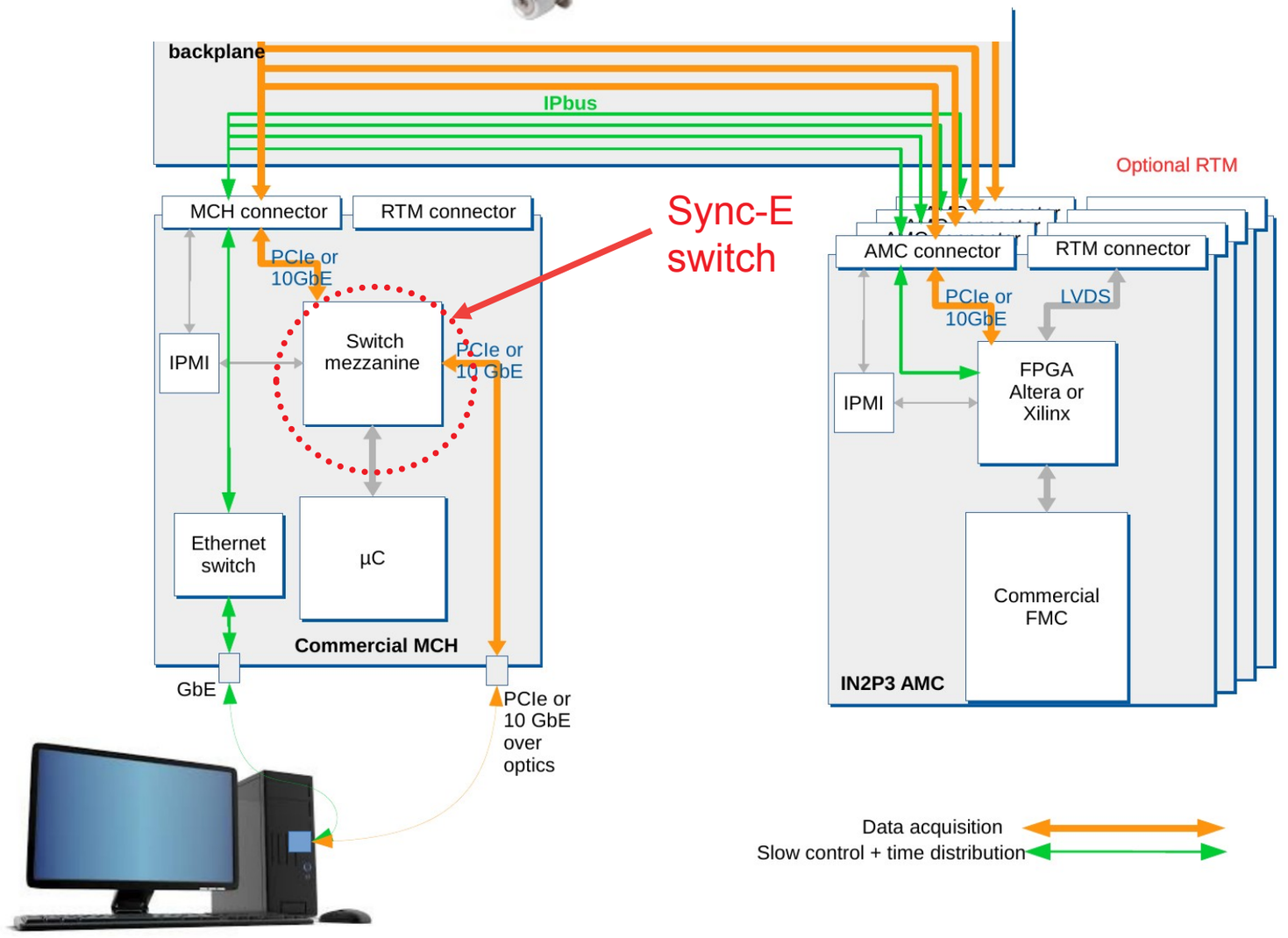
- 5 Laboratories , 2 instituts
- Shedules : 3 years
- Budget : 66K€
- Contributions :
  - LPC Caen : Integration of WR in a crate (Off the shelf evaluation)
  - LP2IB : WR external VCXO integration
  - LPSC : Integration of WR in a crate (custom development)
  - IJCLAB : WR simplification, enhance WR, WR ref design, master oscillator
  - Observatoire de Paris : enhance WR

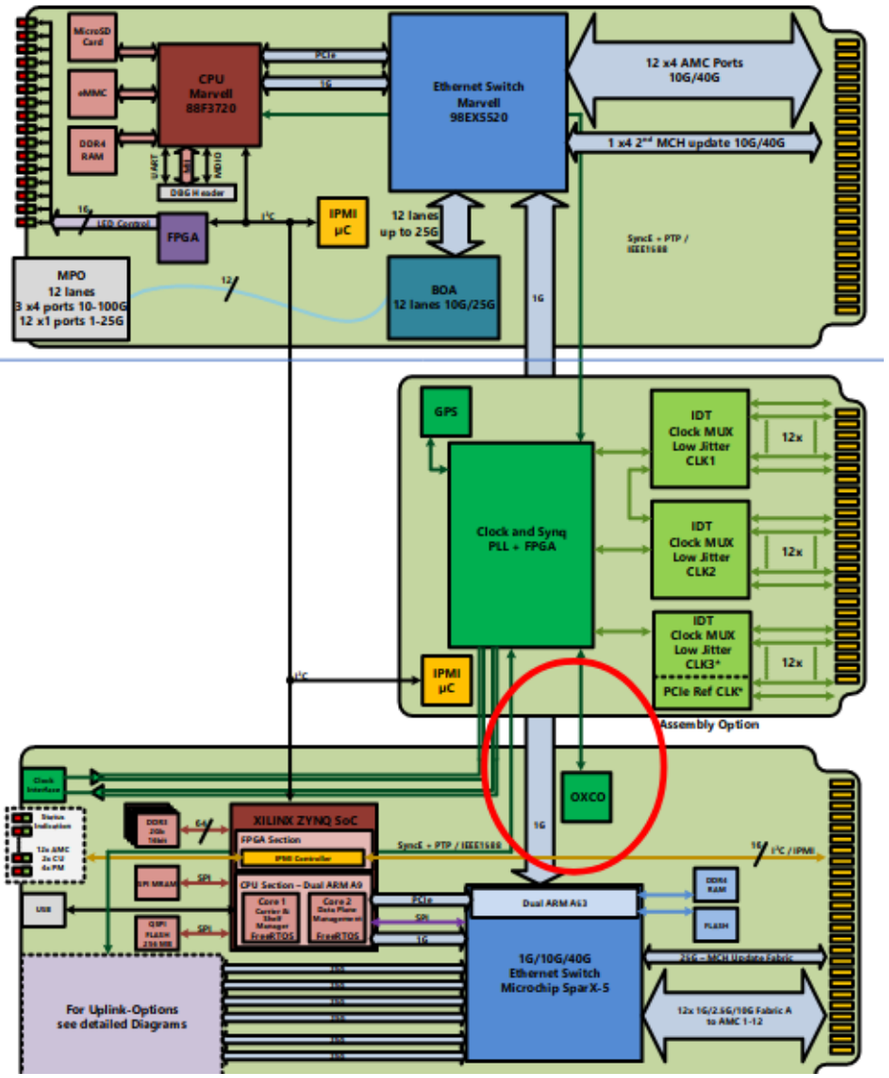


R & T TIMED 1 : WR Crate integration

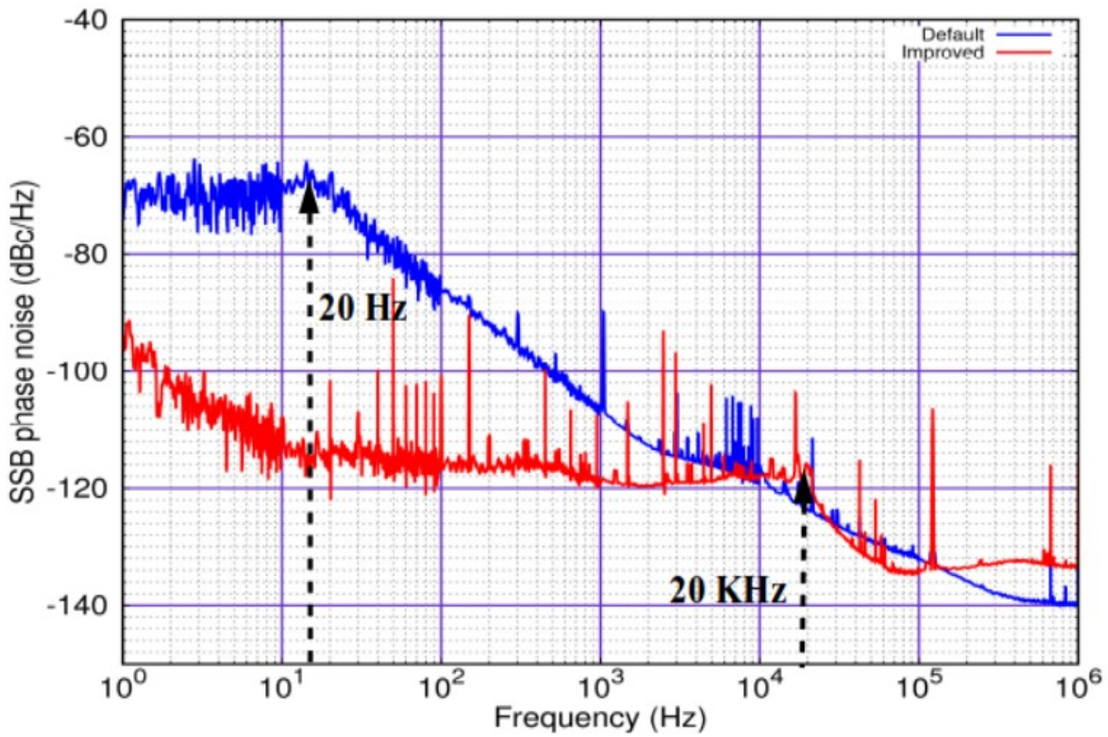


- WhiteRabbit on µTCA
  - Only switch functionality (no master)
  - WhiteRabbit on copper link
  - Sync-E function on MCH board
  - NAT-MCH-4
    - IEEE1588V2 compliant switch





R & T TIMED 3 : Increasing performances



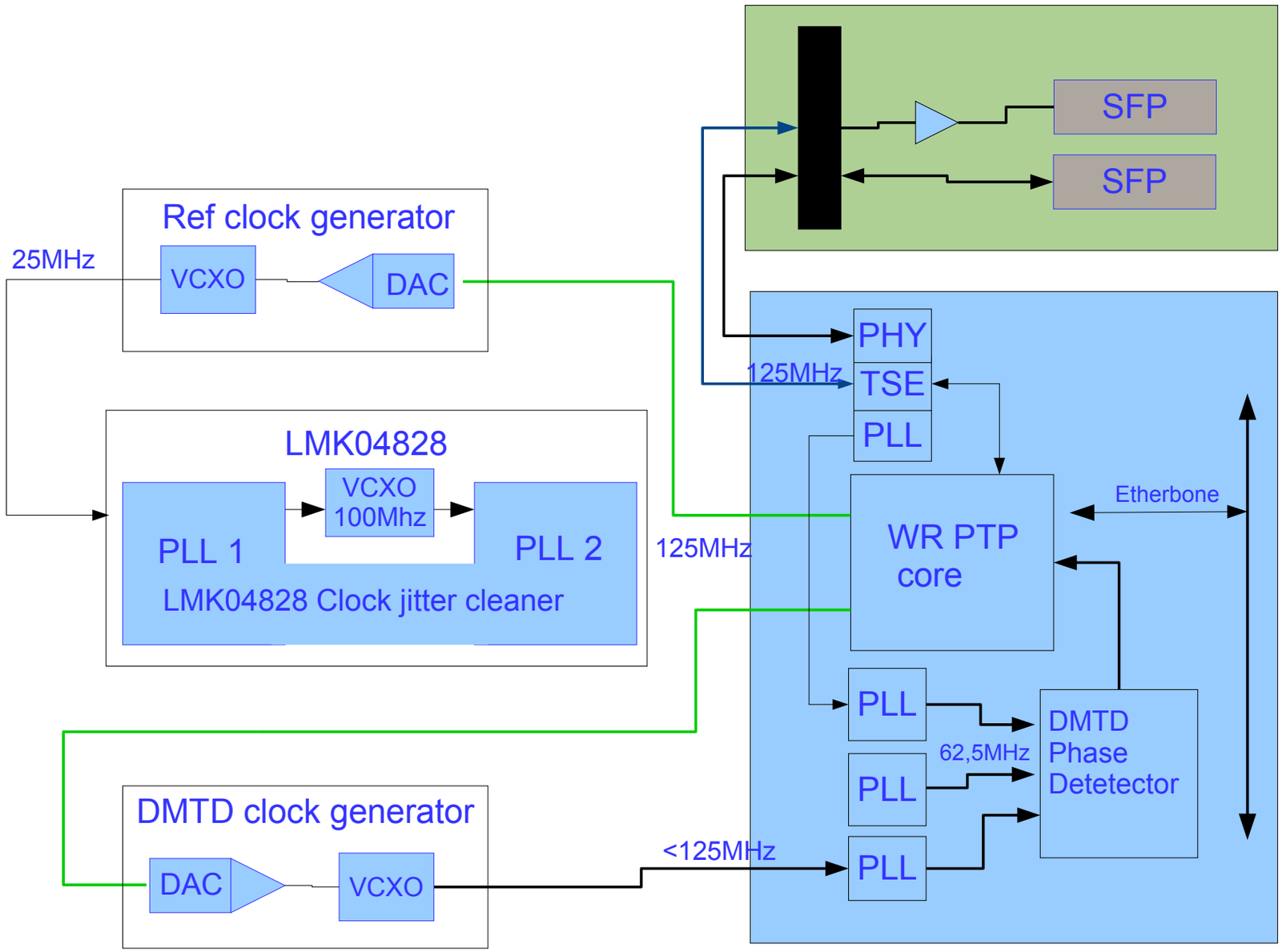
- Collaboration with Paris Observatory Laboratory
  - Goal 1 : ~ 1ps
  - Goal 2 : < 100fs
- Soft PLL modification
  - Decreases the response time of software PLL
  - µP upgrading :Replacement of the universal µP based on logic bloc by dedicated µP (NIOS) or hardware µP (SOC)
  - Gain integrator optimization
- Increased PLL bandwidth of the GM Local oscillator
- Components upgrading
  - VCXO selection
  - Increased internal Frequency (PLL number reduction)
- Modification of WR principle
  - phase modulation and demodulation of an ultra-stable optical carrier
  - Replacement of message protocol by timecode
  - Phase measurement in optic

Conclusion

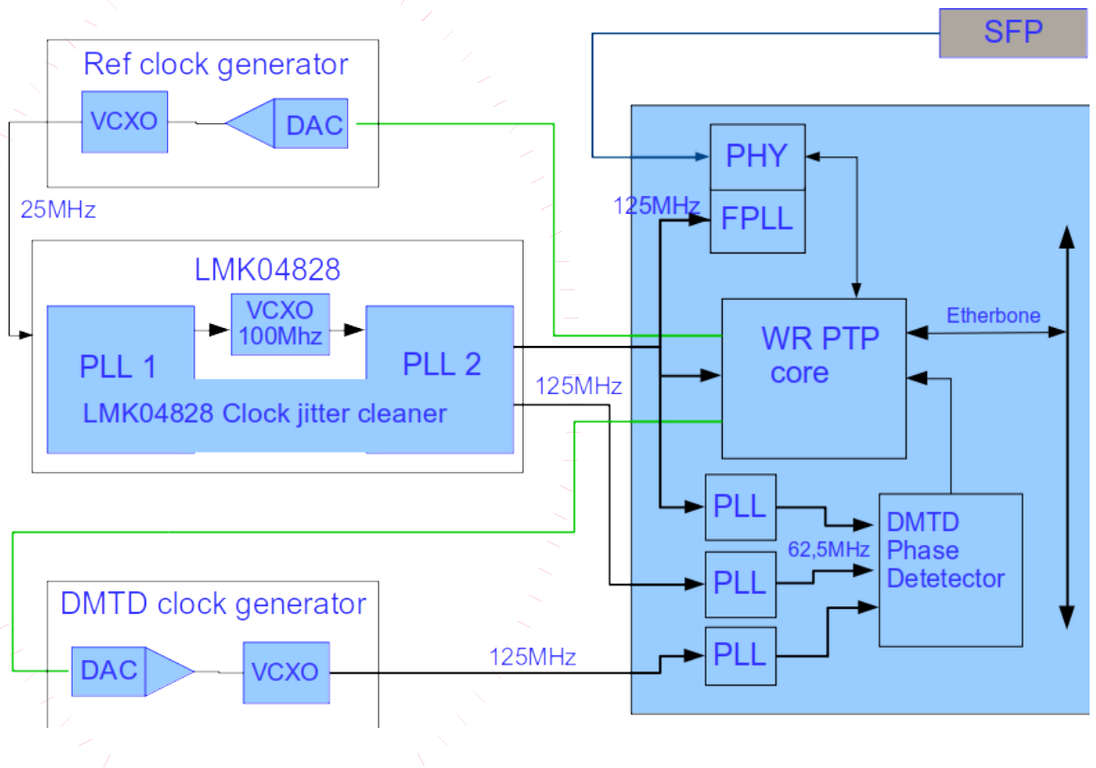
- The White Rabbit is a technological breakthrough
- A majority of new physics experiences will use the WR protocol : CERN detector & accelerator, KEK, Hyper Kamiokande, Enstein telescope...
- A lot of physics experience will be upgrade using WR : CERN experiences, ...
- The new development will offer new physics opportunities :
  - Multi-messenger astronomy
  - Geodesie chronométrique relativiste
  - ….

R & T IMED 2 : Simplification of WR integration

- Replacement of GXB by DDR I/O (up to 800MHz capability)
  - IP Native-PHY by IP TSE Pcs only (FMC in production)
  - Integrated PHY functionality replaced by RTL code (limitation by FPGA type)
- Integration of external PLL by internal one



R & T TIMED 4 : Firmware integration



- External PLL integration
  - Internal reconfiguration
  - µP Software upgrade
- VCXO integration
  - Derived from video IP
- FPGA manufacturer dependent

- More challenging that I can imagine ...

Application Note: 7 Series FPGAs and Zynq-7000 AP SoCs

XILINX
ALL PROGRAMMABLE

XAPP589 (v2.3) April 29, 2015

All Digital VCXO Replacement for Gigabit Transceiver Applications (7 Series/Zynq-7000)

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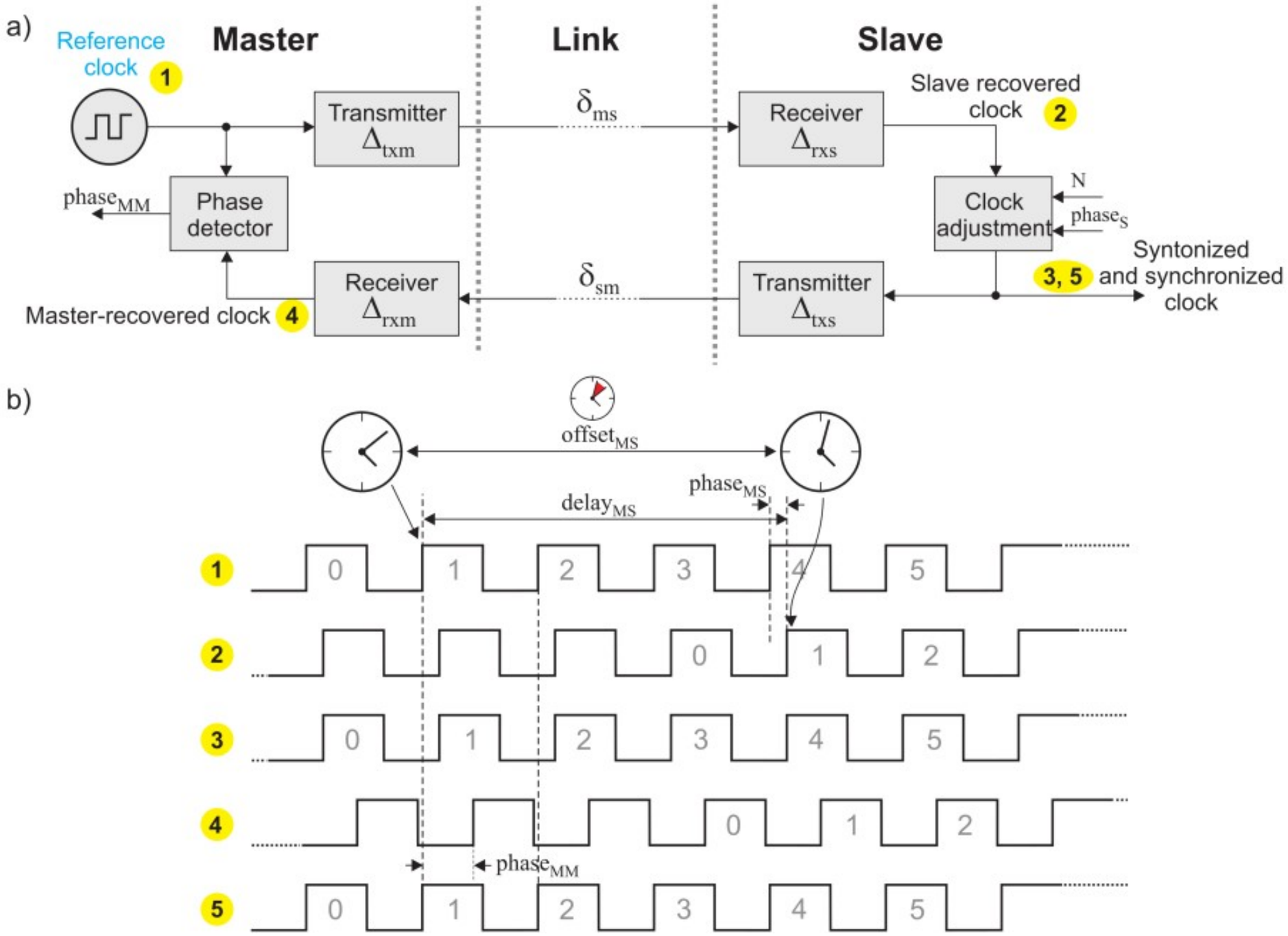
Summary

This application note delivers a system that is designed to replace external voltage-controlled crystal oscillator (VCXO) circuits by utilizing functionality within each serial gigabit transceiver.

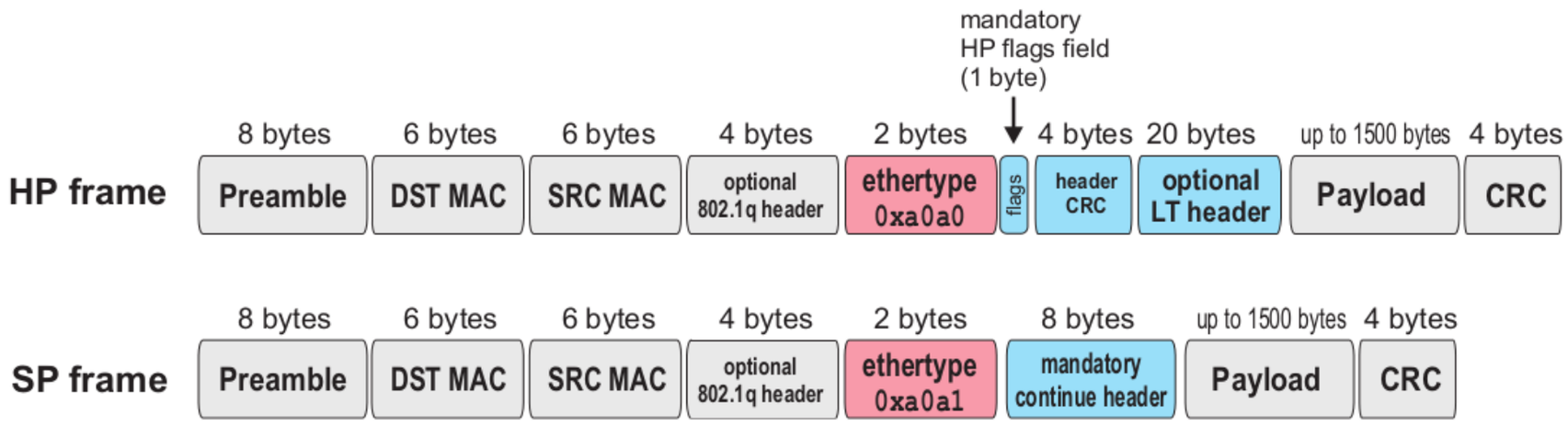
Note: In this application note, *transceiver* refers to these types of transceivers:

WR : Fine delays adjustment



Systèmes de Référence Temps-Espace

WR protocol

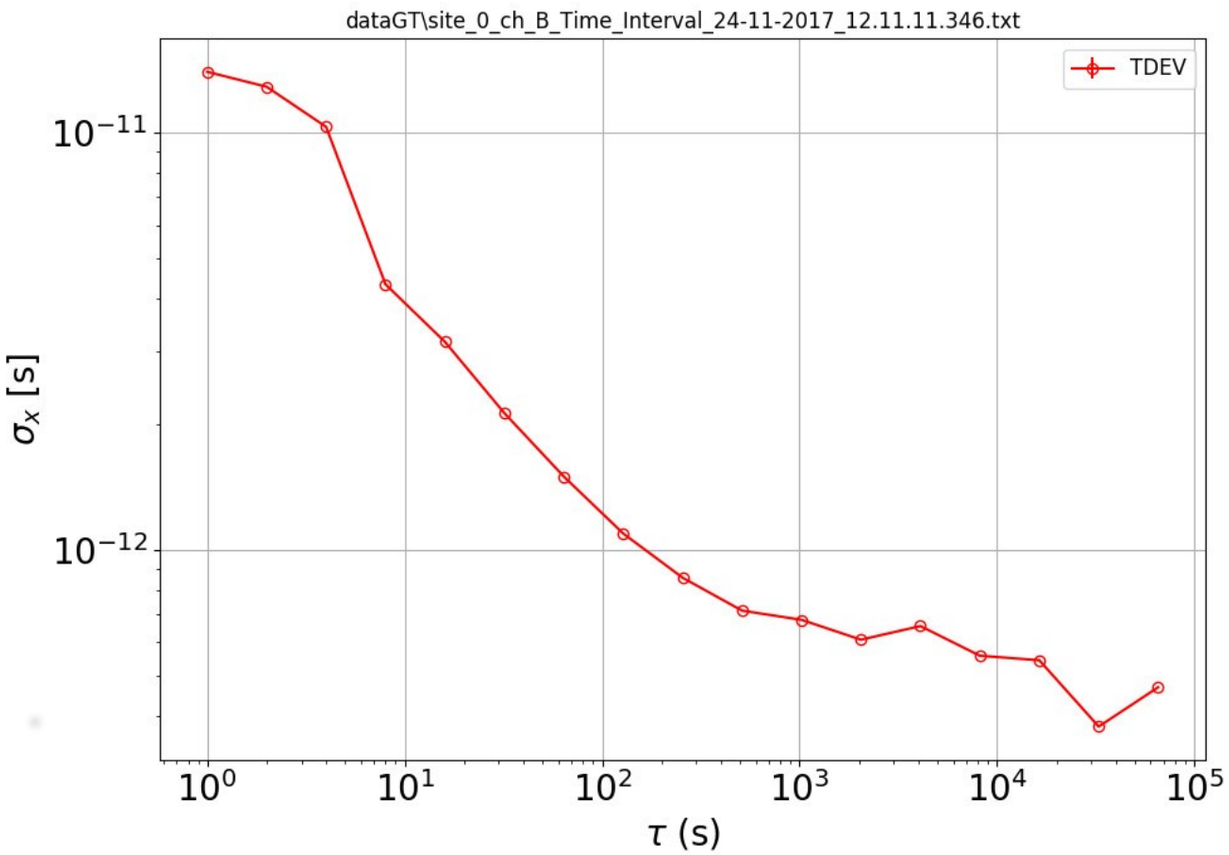


- Traffic divided into High Priority (HP) packets and Standard Priority (SP) packets.
- HP packets use a special value in the Ethertype field of the frame.
- Quality of Service (QoS) in the 802.1Q VLAN standard does this and more $\Rightarrow$ will study full compliance in the future.
- HP packets can preempt other types of packets “on-the-fly”.

Signal to be provided by T-REFIMEVE

		Stability or relative stab. @1s	Stability or relative stab. @1day	Uncertainty	
				routine	dedicated
Radiofrequency	**1st pillar - 10 MHz (White Rabbit)***	1,00E-12	1,00E-15	1,00E-14	1,00E-15
	2nd pillar - 1 GHz	1,00E-13	3,00E-16	1,00E-14	2,00E-16
Time	**1st pillar (White Rabbit)***	1 ns	1 ns	10 ns	10 ns
	2nd pillar	20-50 ps	500 ps	10 ns	2ns to 100ps§
Optical frequency (194,5 THz/1542 nm)	**Today**	1,00E-15	3,00E-16	1,00E-14	2,00E-17
	Expected progress in 5 years	1,00E-16	2,00E-17	1,00E-14	1,00E-18

NEBULA performance



- IDROGEN version -1
  - 400fs after 1000s
  - Same design as IDROGEN
  - IDROGEN system qualificationTest
    - With SYRTE test setup