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Time Transfer in a Wide Area White Rabbit Network

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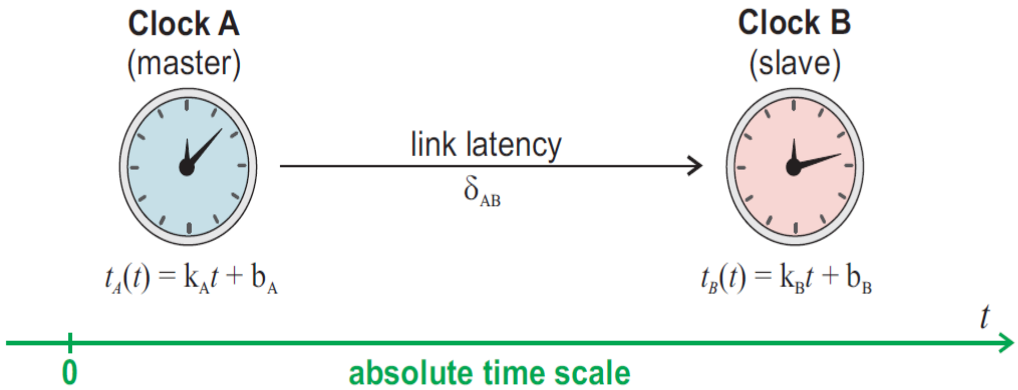
White Rabbit

- Timing & Control of the LHC @ CERN: Deterministic data transfer and accurate clock synchronization
- Open Hardware & Software
- Up to 10 km link length
- < 1ns time offset between more than 1000 nodes

"I'm late, I'm late, for a very important date! No time to say hello, goodbye…"

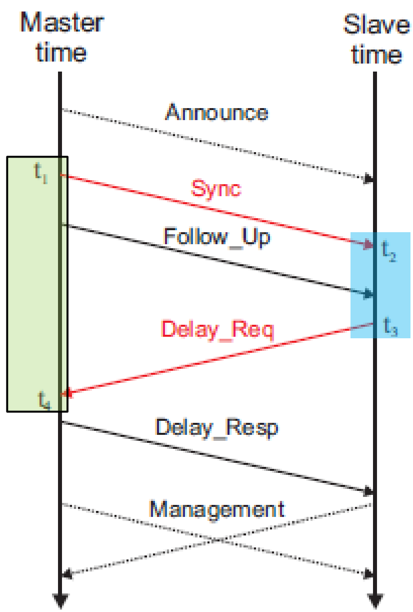


Problem	Solution
$k_A = k_B$ syntonization	Synchronous Ethernet at 1.25 GPS
$b_A = b_B$ synchronization	Precision Time Protocol (PTP) + DMTD

White Rabbit Algorithm

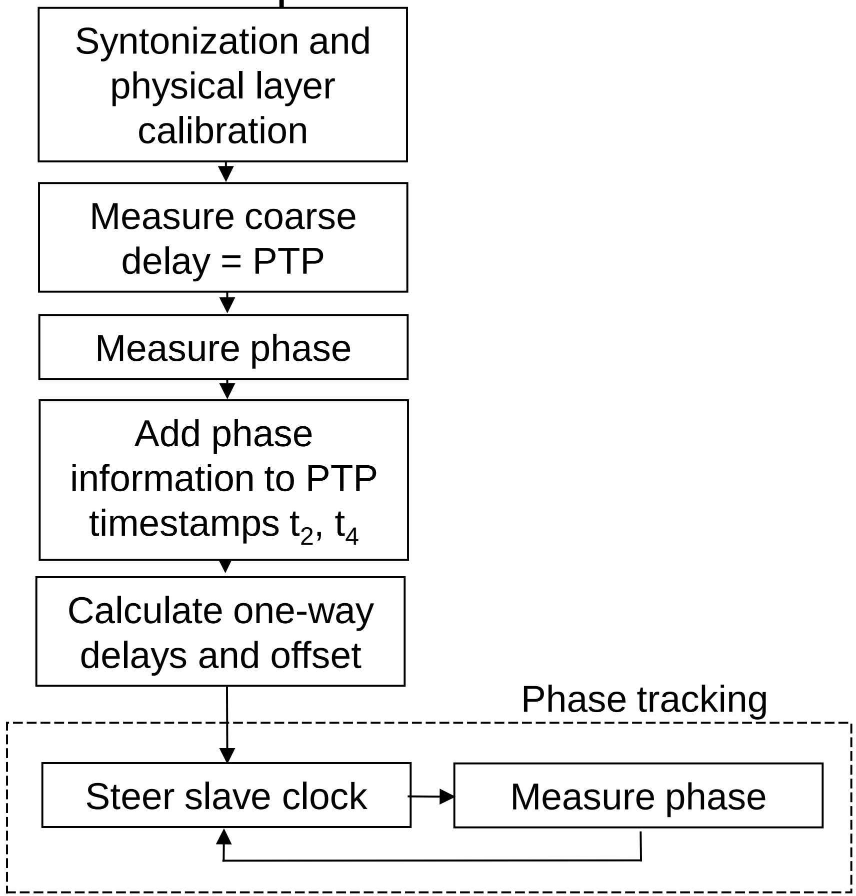
(Step 0: SyncE provides syntonized clocks)

Step 1.
Hardware time-stamping of t_1-t_4
Gives coarse (8 ns) RTT

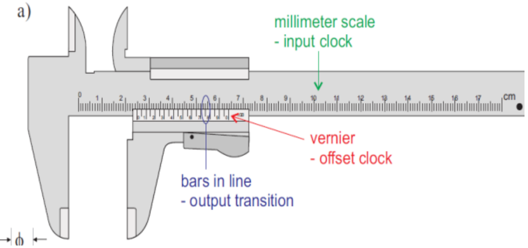


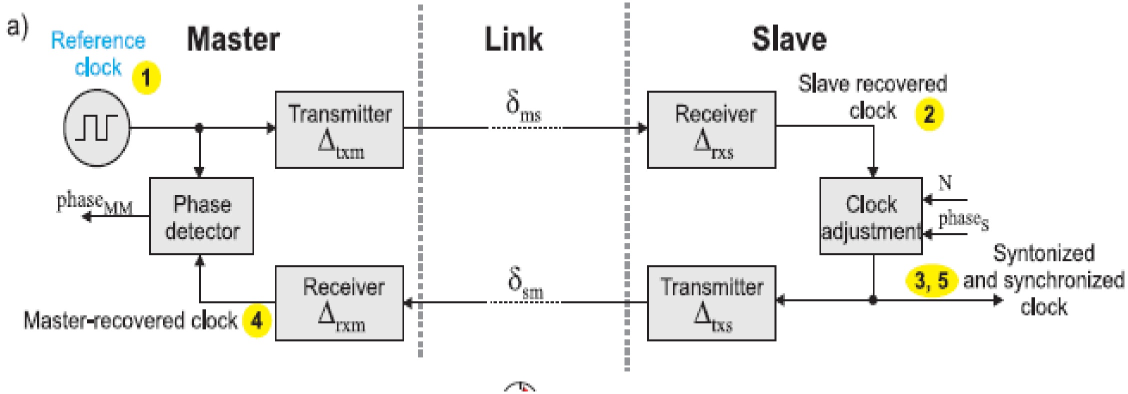
$$delay\_coarse = (t_4 - t_1) - (t_3 - t_2)$$

Step 2: Enhance t_2, t_4
With a phase-measurement

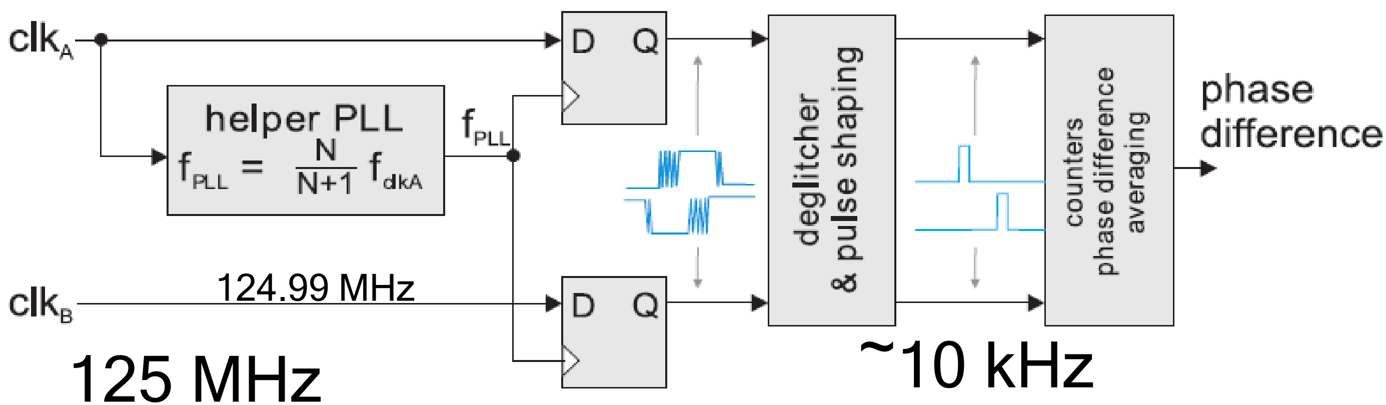


Phase measurement using DMTD = Dual Mixer Time Difference

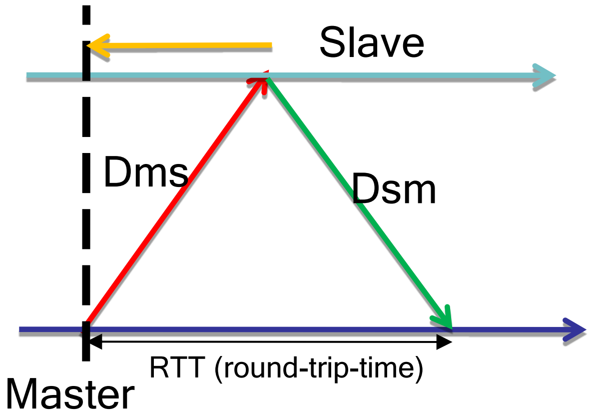




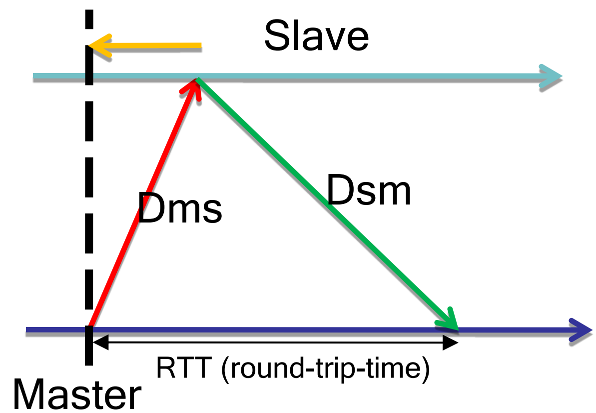
FPGA Implementation in WR-node



Fiber asymetry
not known beforehand, must be calibrated



OR ?

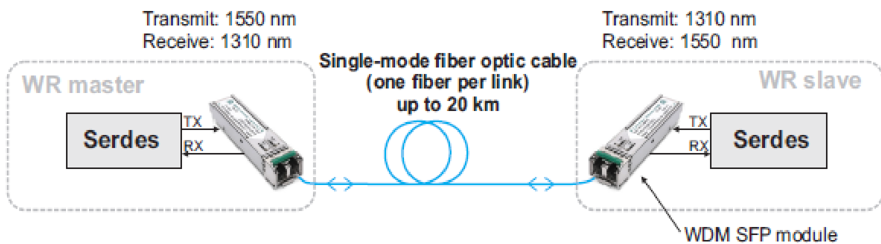


$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

$$\alpha = \frac{\delta_{ms}}{\delta_{sm}} - 1 = \frac{n_{1550}}{n_{1310}} - 1$$

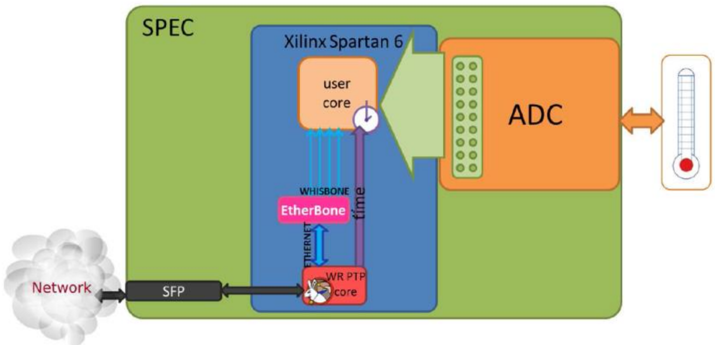
+680 ppm, typically

WR-spec: single-strand, bidir-optics, <10 km



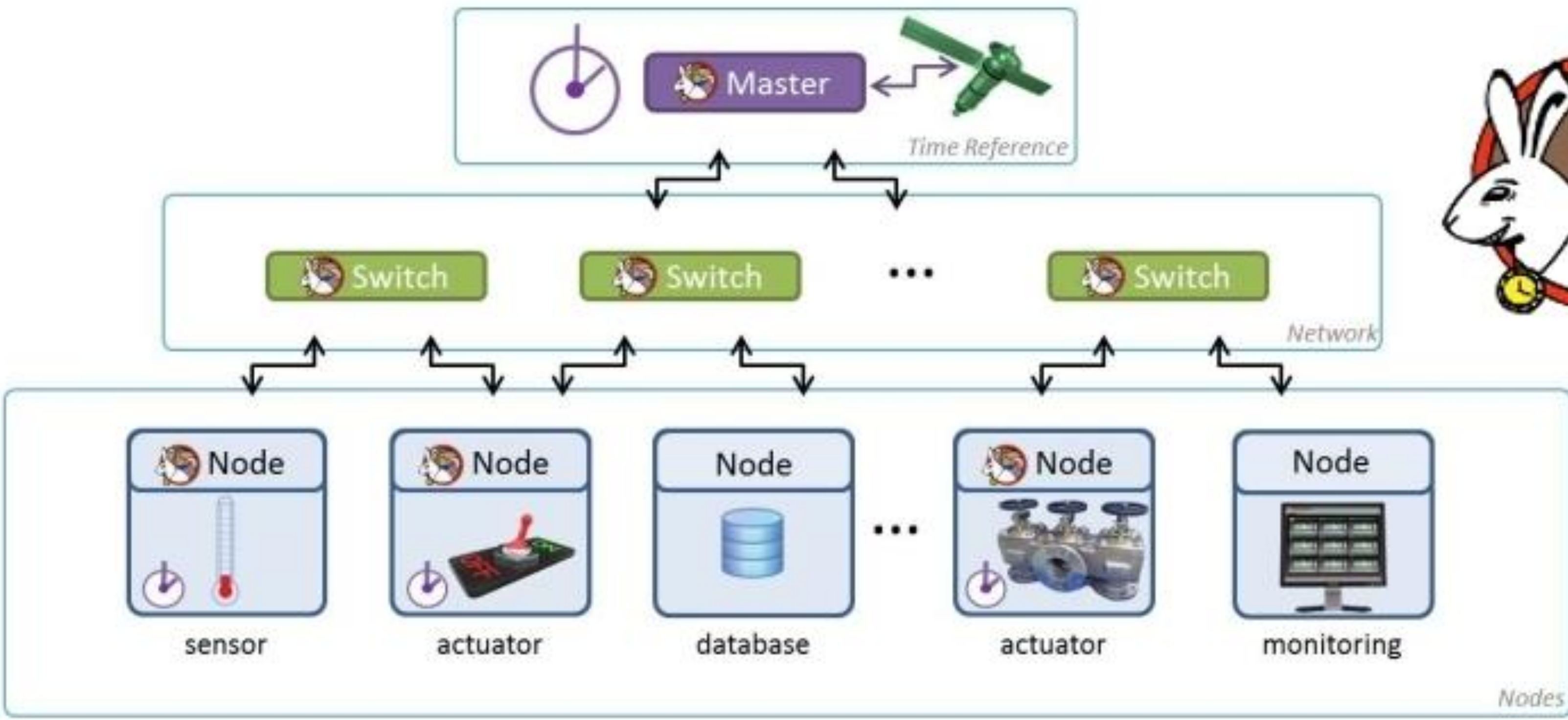
- New SFPs claim up to 160 km reach (with new bidir-amplifiers even further)
- White Rabbit works with duplex (two-strand) SFPs also

Many point-to-point links: WR Network

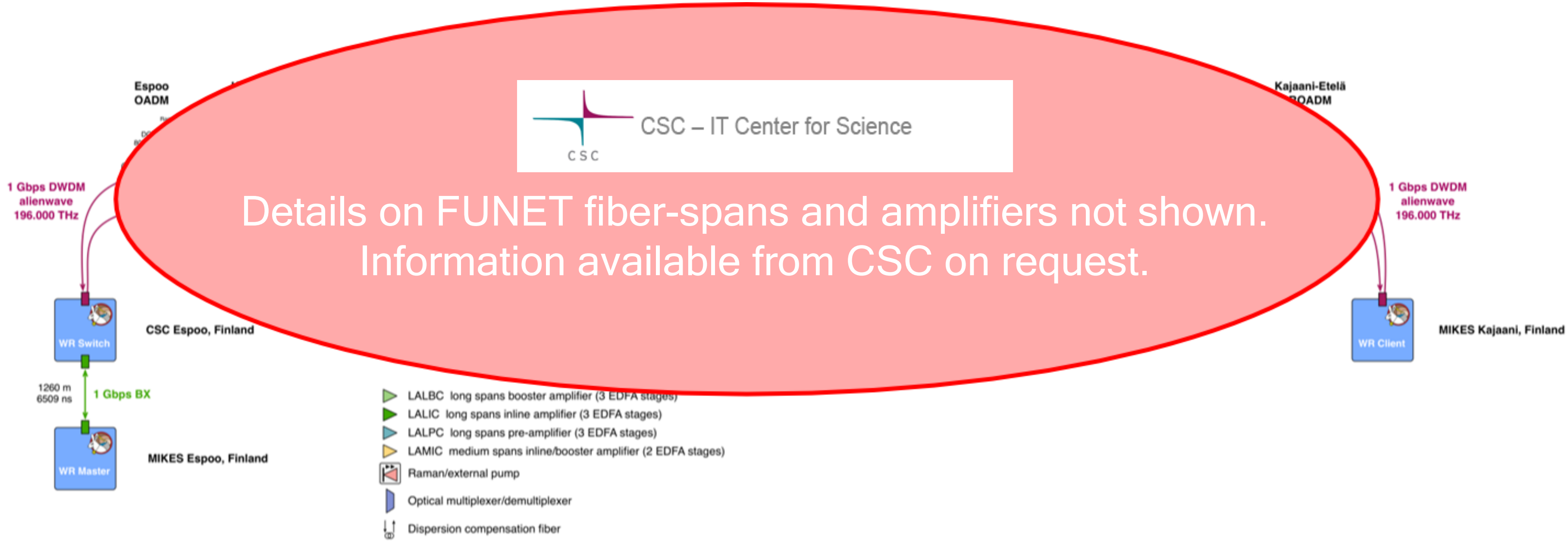


WR Node:

- SFP + FPGA + FMC front-end
- Open hardware
- Open firmware/software

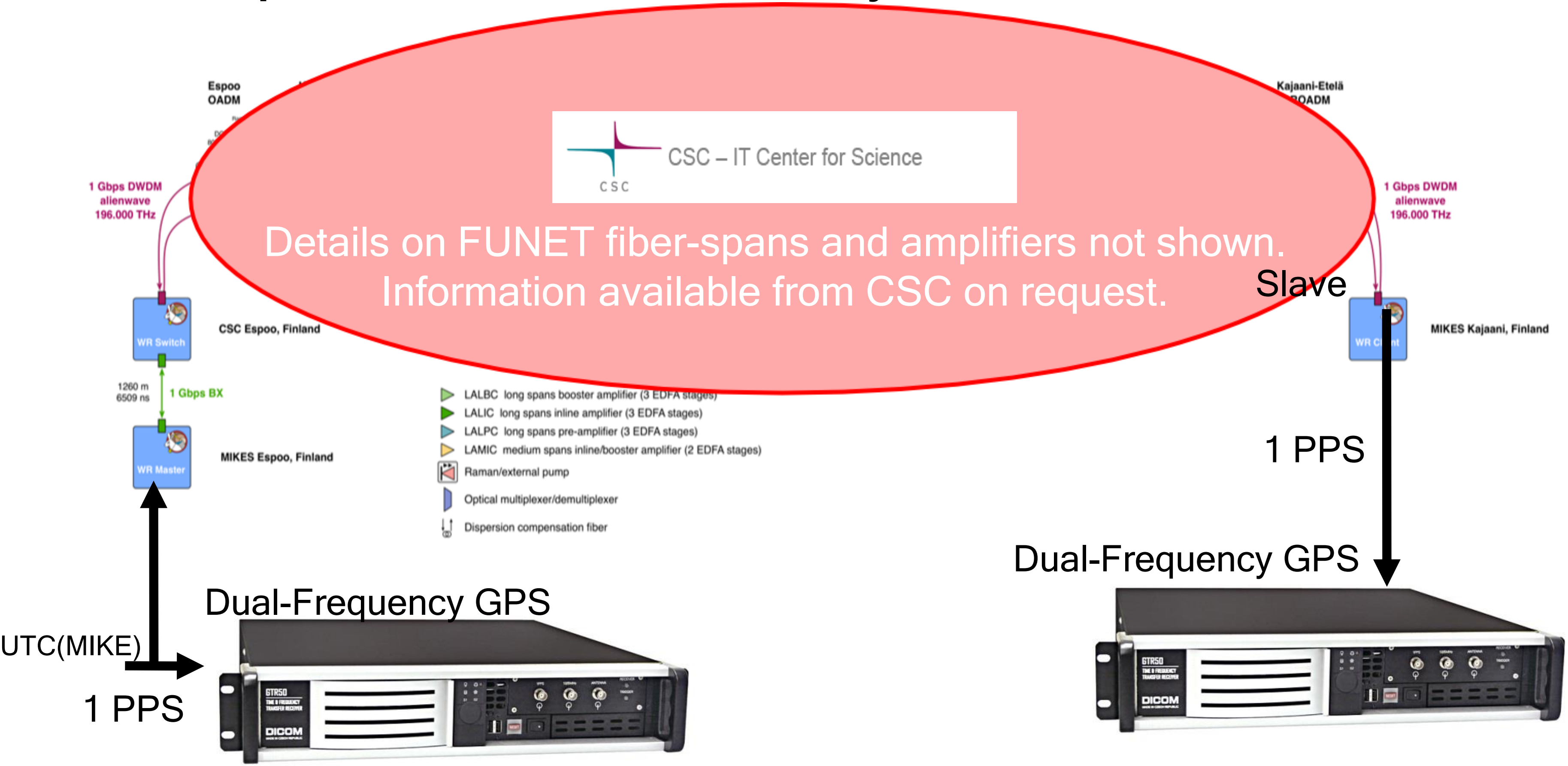


Espoo-Kajaani time-transfer experiment in FUNET



- 1000 km Espoo-Kajaani light-path in FUNET
  - 10% of fiber is in DCF spools
- Duplex (two-strand) SFPs on ITU-T #60 (196 THz)
- GrandMaster node in Espoo locked to UTC(MIKE)

Independent verification by GPS-PPP



1. Receivers colocated, common-clock calibration (5 days)
2. Receivers at Espoo/Kajaani, Fiber-asymmetry calibration (1 day)
3. Data collection (100 days)

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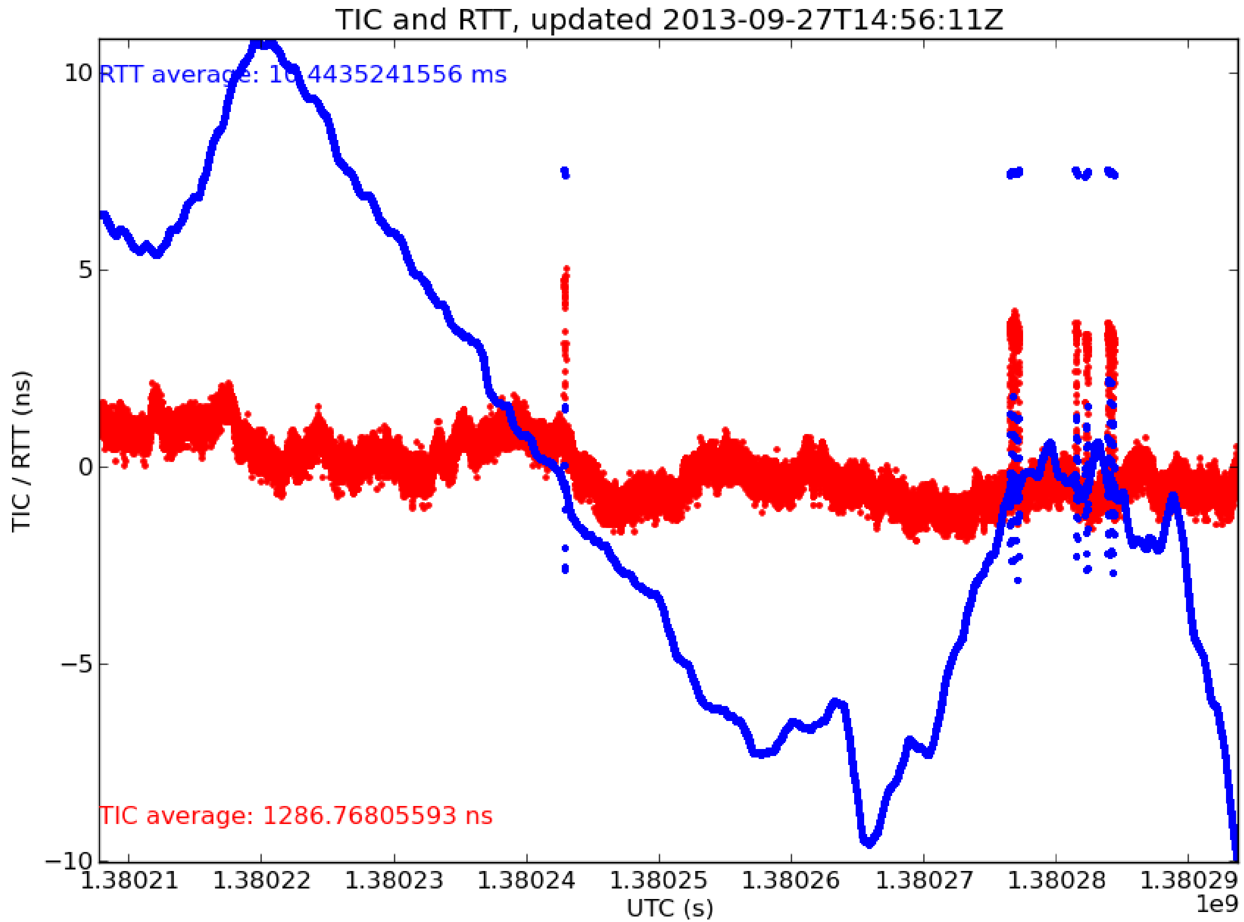
RINEX processing using NRCan GPSPPP

Initial problems with 8 ns RTT jumps



Link operation started 2013 September

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

TAI Time:                   Fri, Aug 16, 2013, 13:55:37

wru1: Link up   (RX: 4290, TX: 1916), mode: WR Slave   Locked  Calibrated

Synchronization status:

Servo state:                TRACK_PHASE
Phase tracking:             ON
Synchronization source:     wru1
Aux clock status:           0:disabled

Timing parameters:

Round-trip time (mu):     10445954558 ps
Master-slave delay:       5223650621 ps
Master PHY delays:        TX: 0 ps, RX: 175200 ps
Slave PHY delays:         TX: 46407 ps, RX: 169443 ps
Total link asymmetry:     -1346684 ps
Cable rtt delay:          10445563508 ps
Clock offset:                     0 ps
Phase setpoint:                 235 ps
Skew:                            -4 ps
Manual phase adjustment:          0 ps
Update counter:                 943
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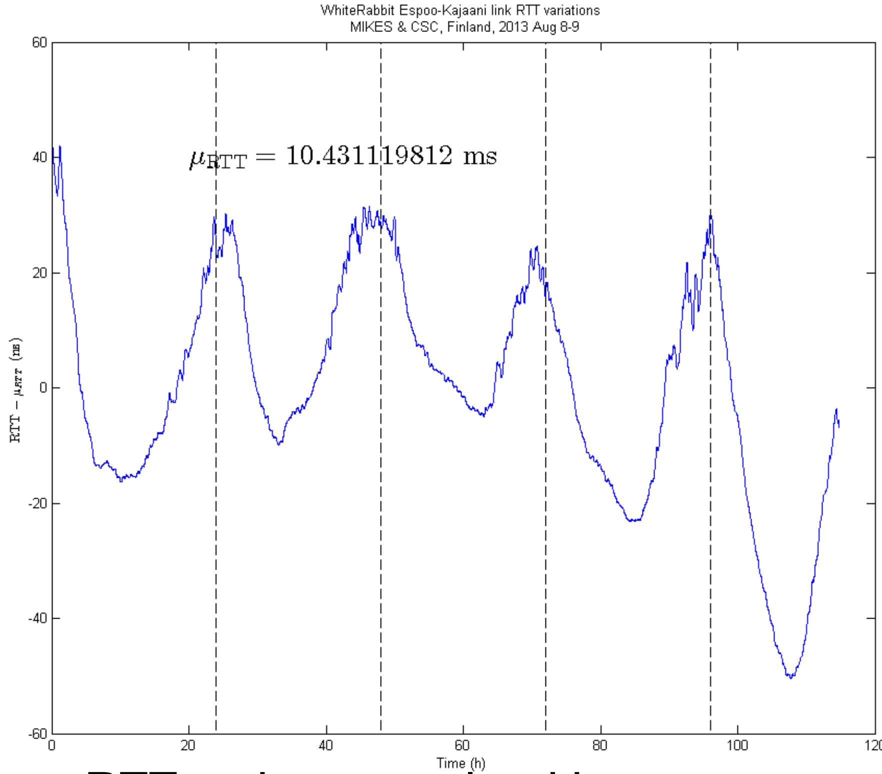
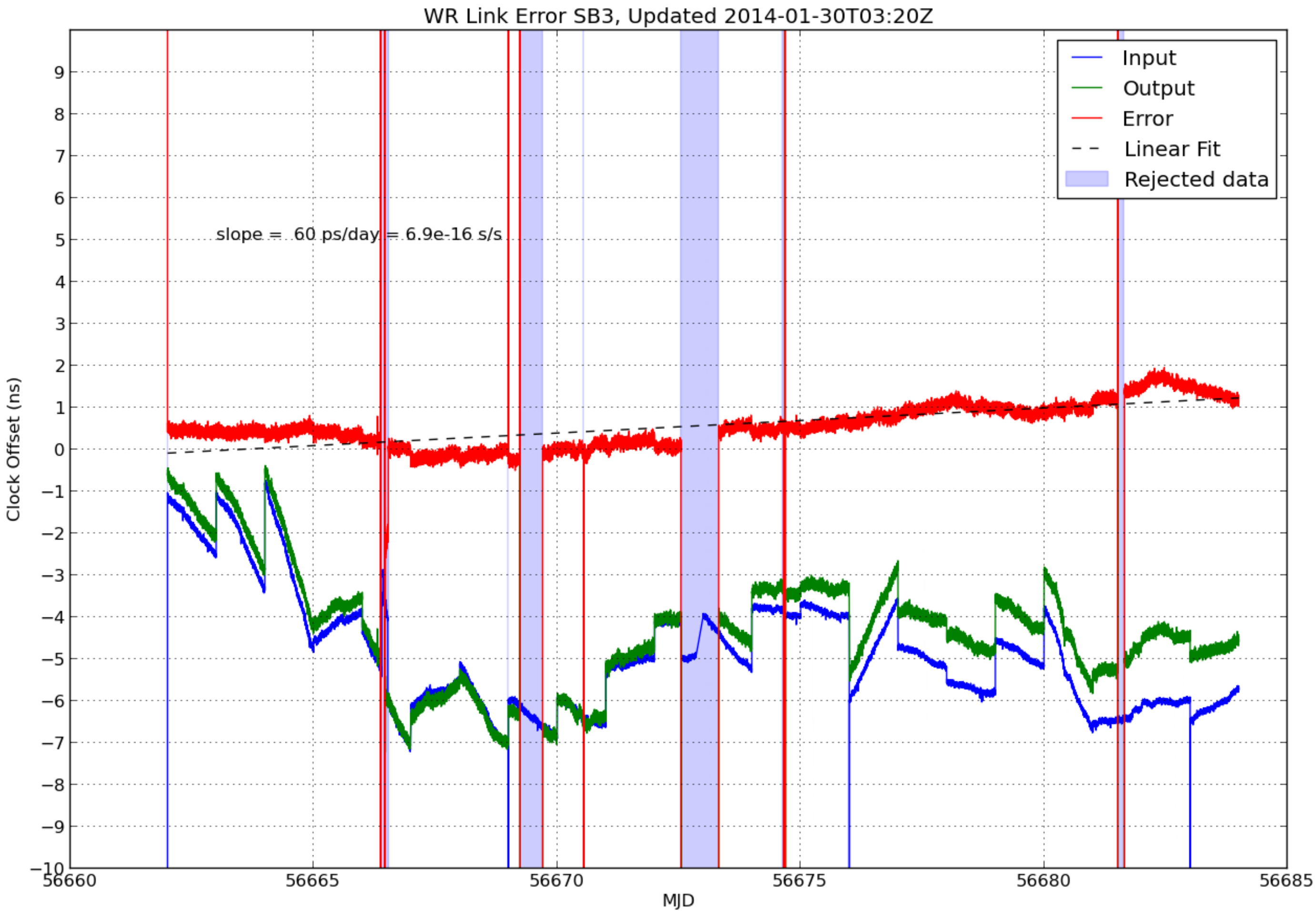
Collaborative testing during 2013 autumn allowed WR-team at CERN to produce firmware that copes with 10.4 ms RTT and eliminated ”8ns jump” problems

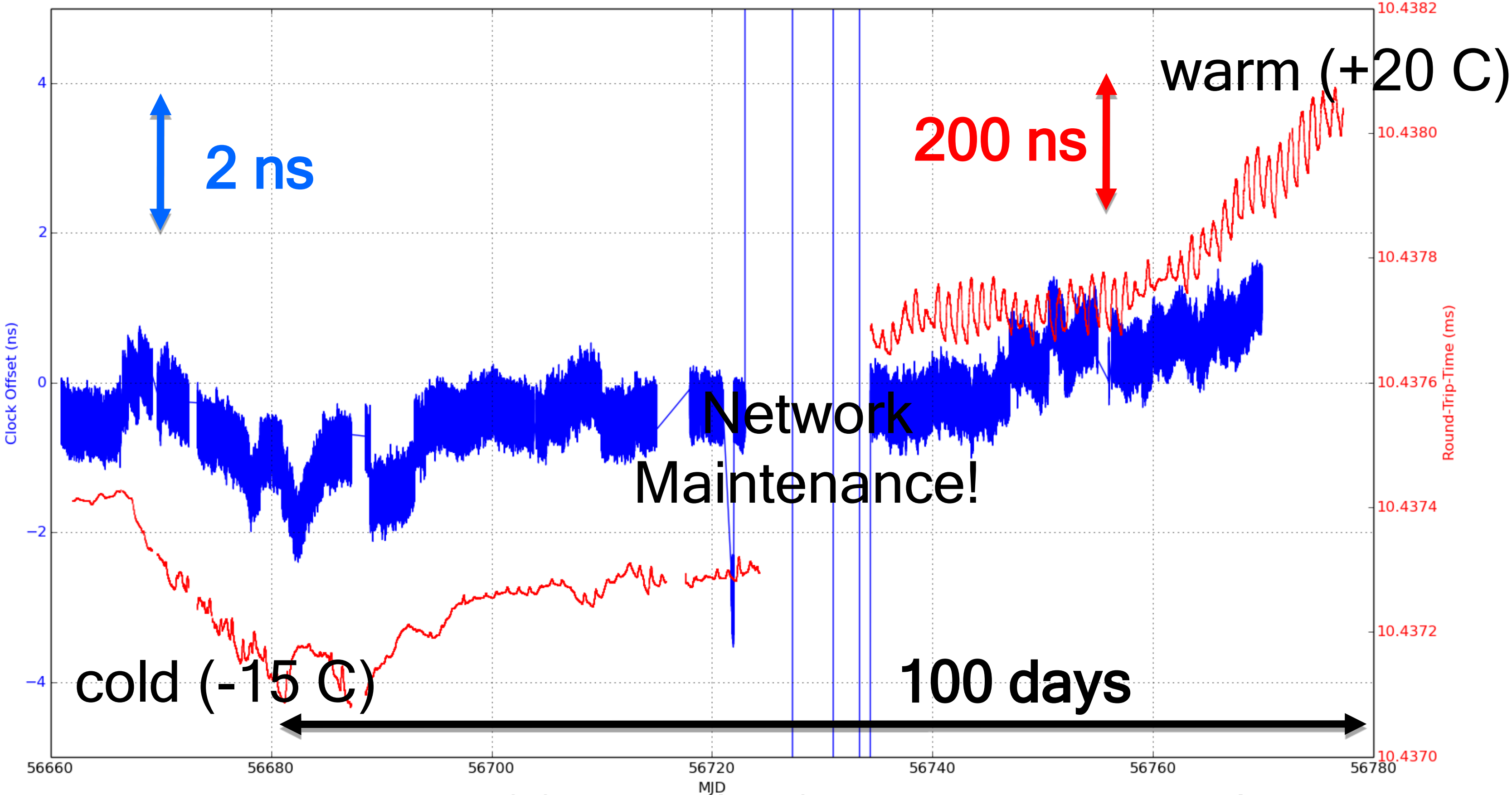


RTT varies strongly with temperature:
-Seasonal +/- 200 ns or more
-Daily +/- 50 ns in spring/autumn
-WR asymmetry parameter is ca. -800 ppm (uplink is 4 us shorter than downlink)

Link Performance



Link Error vs. Round-Trip-Time



alpha = 788 ppm (before maintenance)

alpha = 849 ppm (after maintenance)

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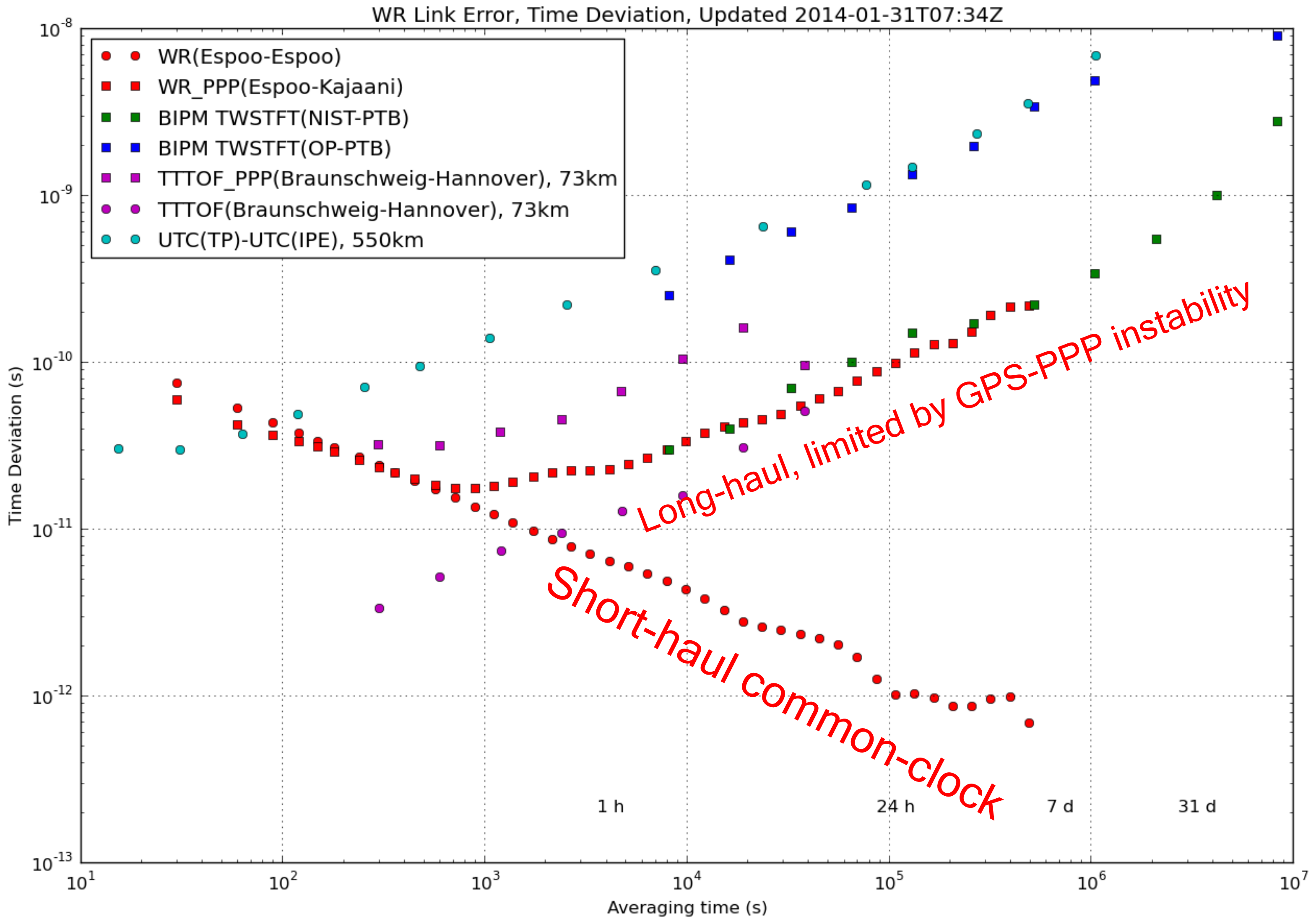
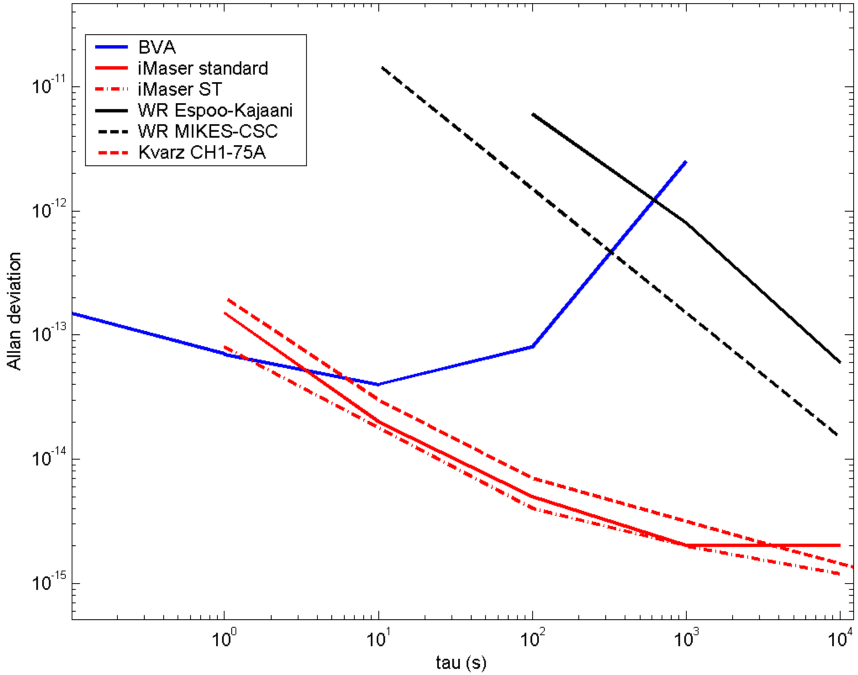
Time Deviation



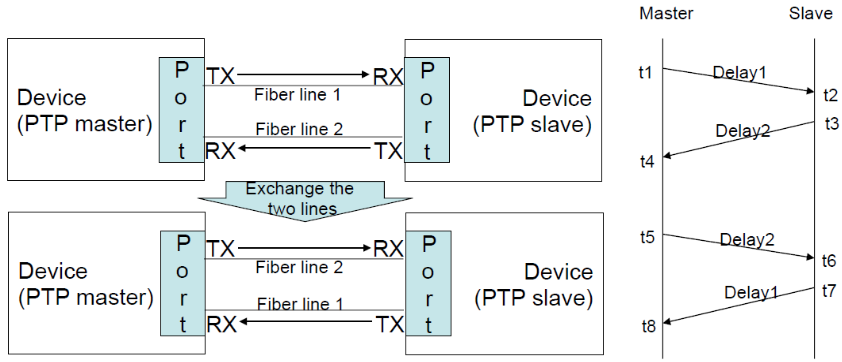
Outlook / Challenges

1. Short-term stability



- Improve PLL between external clock and GM-node
- PLL tuning between Master and Slave
- Better local-oscillator (OCXO) on SPEC (?)

2. Measuring fiber-asymmetry



Delay1=(t2+t8-t1-t7)/2

Delay2=(t4+t6-t3-t5)/2

Reverse asymmetry by:

- Exchanging Tx/Rx fibers (two-strand)
- Exchanging Tx/Rx wavelengths (single-strand) [Huang, China Mobile]

3. Additional Phase-servo inputs

e.g. Temperature (Fiber, DCFs, Nodes)

4. Fiber-Fiber comparisons

Not limited by satellite technique

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EMRP
European Metrology Research Programme
Programme of EURAMET

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Thank You!