Methods for data, time and ultrastable frequency transfer through long-haul fiber-optic links

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Outline

- Our interest in fiber-optic timing through 'White Rabbit' Ethernet

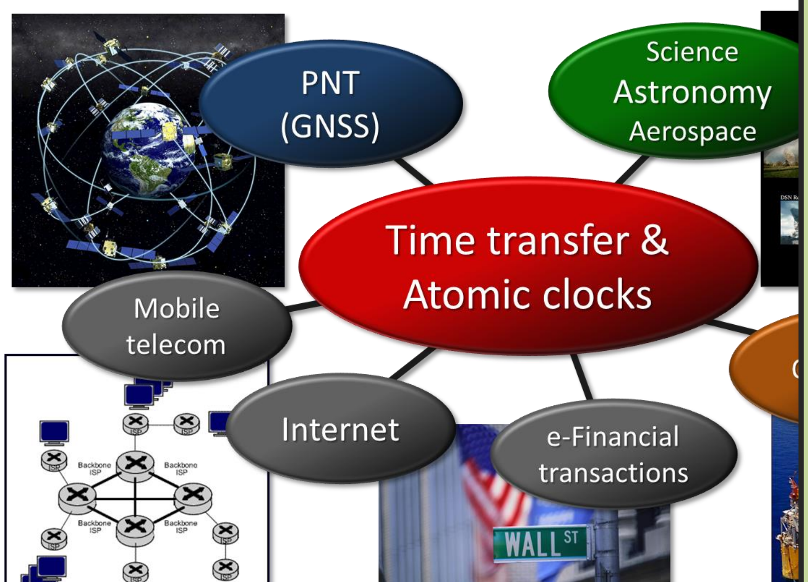
- Long distance fiber-optic time & frequency transfer in the Netherlands

  - Bidirectional optical amplifiers for long-haul TFT

- TFT through DWDM networks for e-VLBI
  - To be continued in next talk (Paul Boven, JIVE)

Motivation

Timing is everything



Scientific motivation:

Radio astronomy (VLBI) needs timing over medium-to-long distance

VU Amsterdam: high-precision frequency measurements of atoms and molecules for tests of fundamental physics (QED/GR searches for dark matter and higher dimensions, etc.):
Need SI second with highest accuracy!

GPS 12-13 decimals
Stand-alone Cs 13 decimals
UTC realization at VSL Delft 14 decimals
Fiber-optic link VSL-VU (137 km)?

Societal/economical motivation

GPS back-up facitility needed

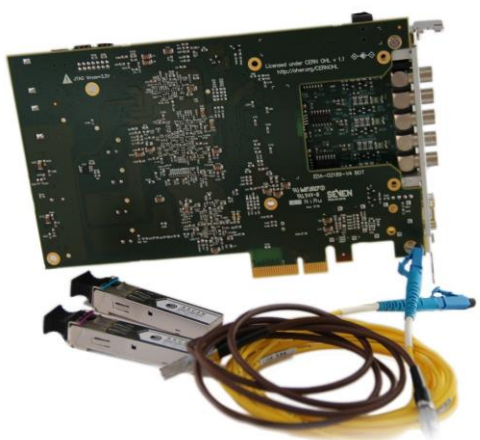
Integrate accurate time & frequency in fiber-optic telecommunications

The White Rabbit project

From CERN’s open hardware website:

http://www.ohwr.org/projects/white-rabbit

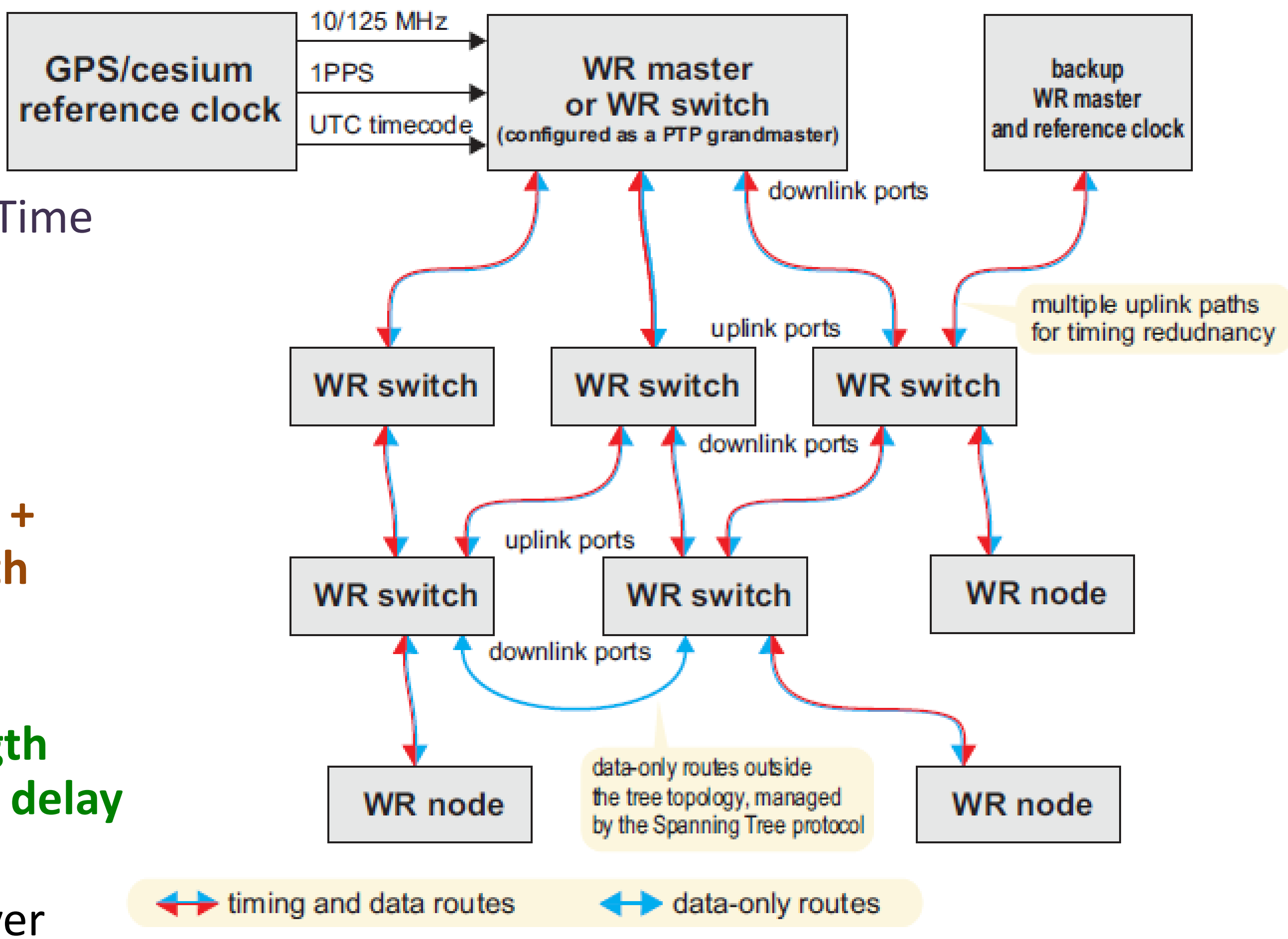
“White Rabbit is a fully deterministic Ethernet-based network for general purpose data transfer and synchronization. It can synchronize over 1000 nodes with sub-ns accuracy over fiber lengths of up to 10 km. Commercially available.”



Designed to synchronize and trigger the LHC at CERN, but also used in other RIs (KM3NeT, CTA, GSI, DESY, LHAASO, …)

White Rabbit functionality

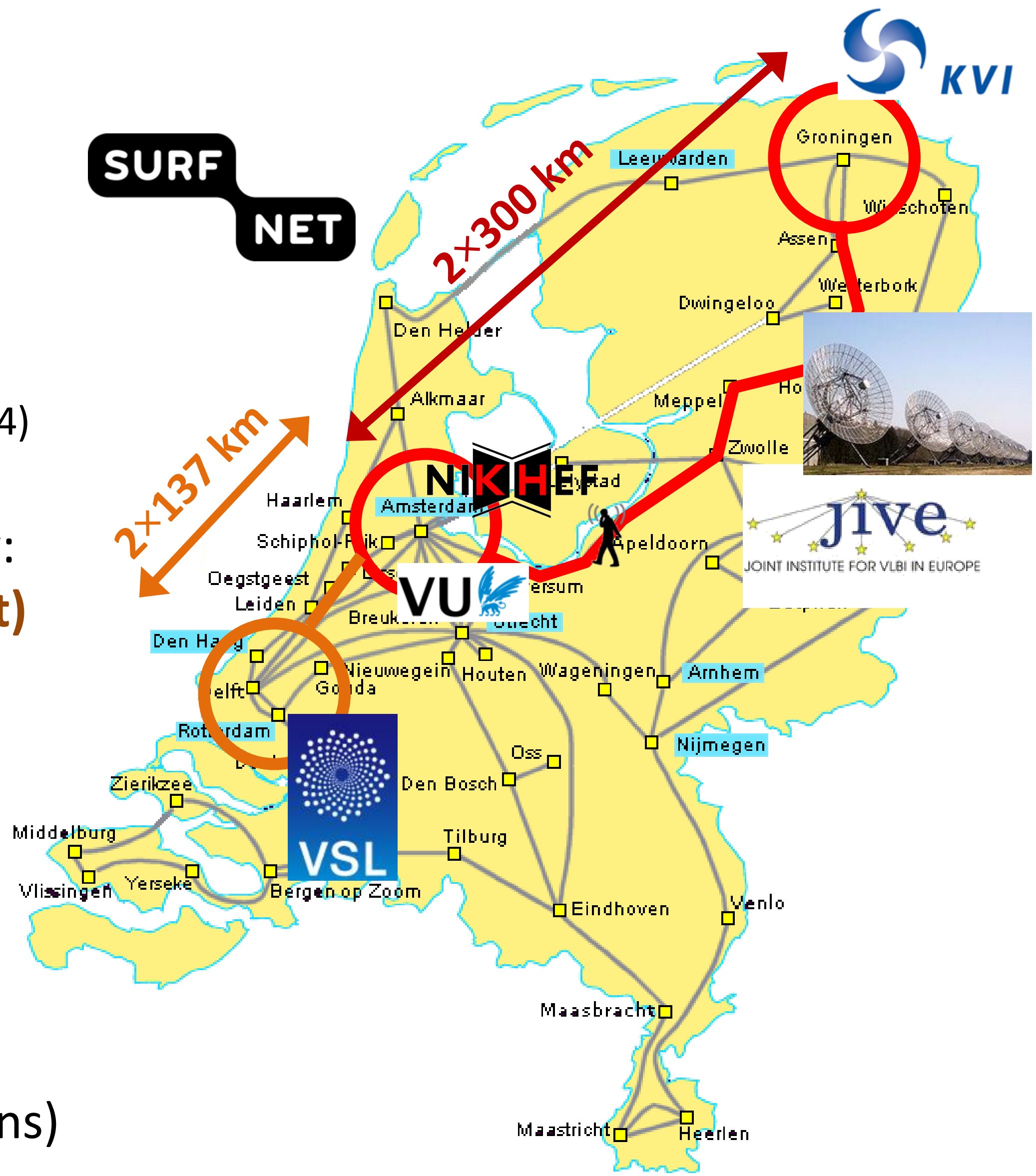
- Builds on Synchronous Ethernet and Precision Time Protocol (IEEE 1588v2)
- Likely included as High Accuracy Profile in IEEE 1588v3
- **1 Gb/s Ethernet + Time + Frequency network with branches and loops**
- **WR electronically compensates fiber length variations by roundtrip delay measurements**
- Our interest: use WR over distances >> 100 km in live telecom networks (see also talk by Anders Wallin/MIKES)



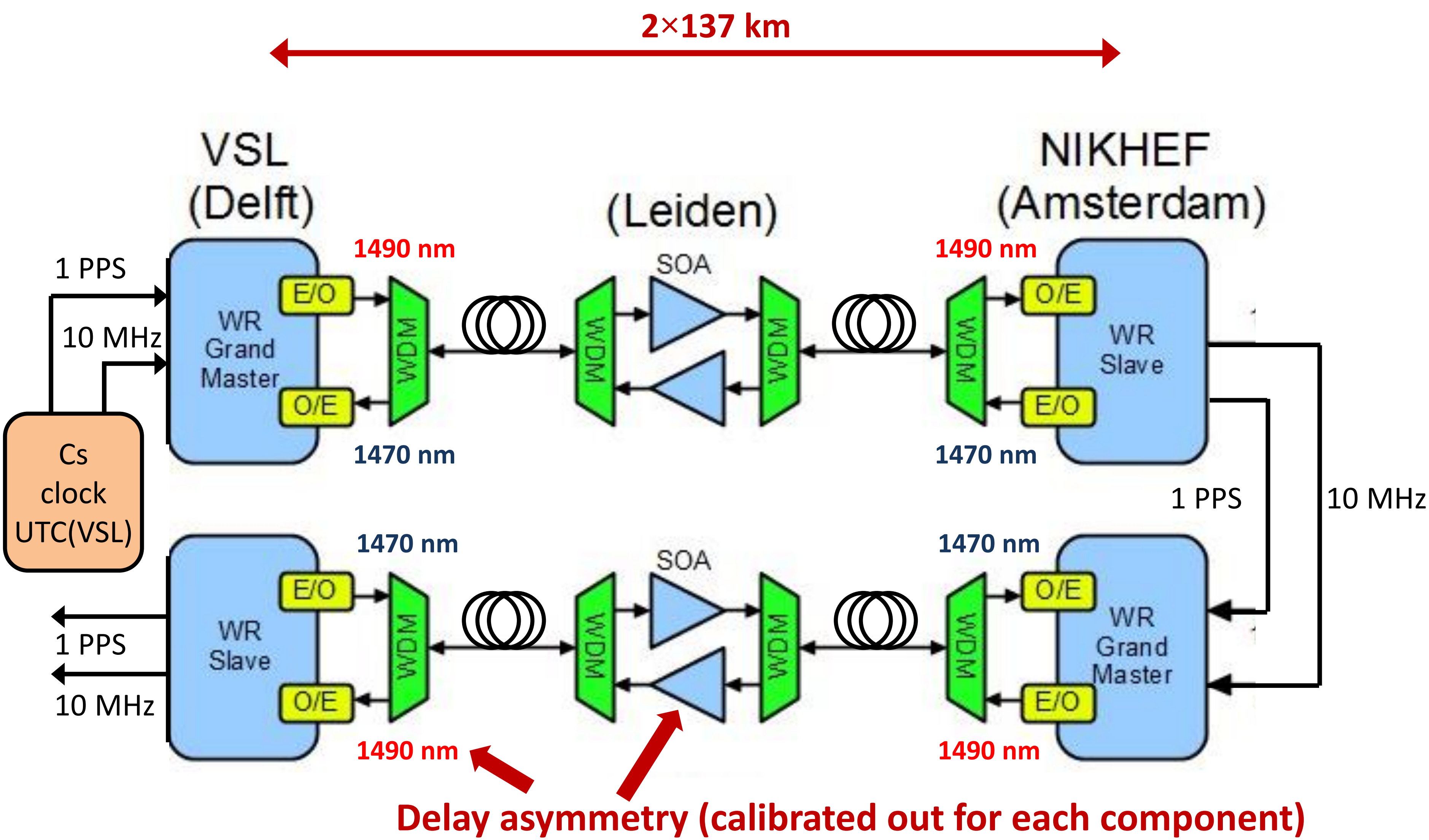
- Phase-coherent 10/125 MHz in all nodes
- Synchronized 1 PPS in all nodes

Fiber-optic T&F links in the Netherlands

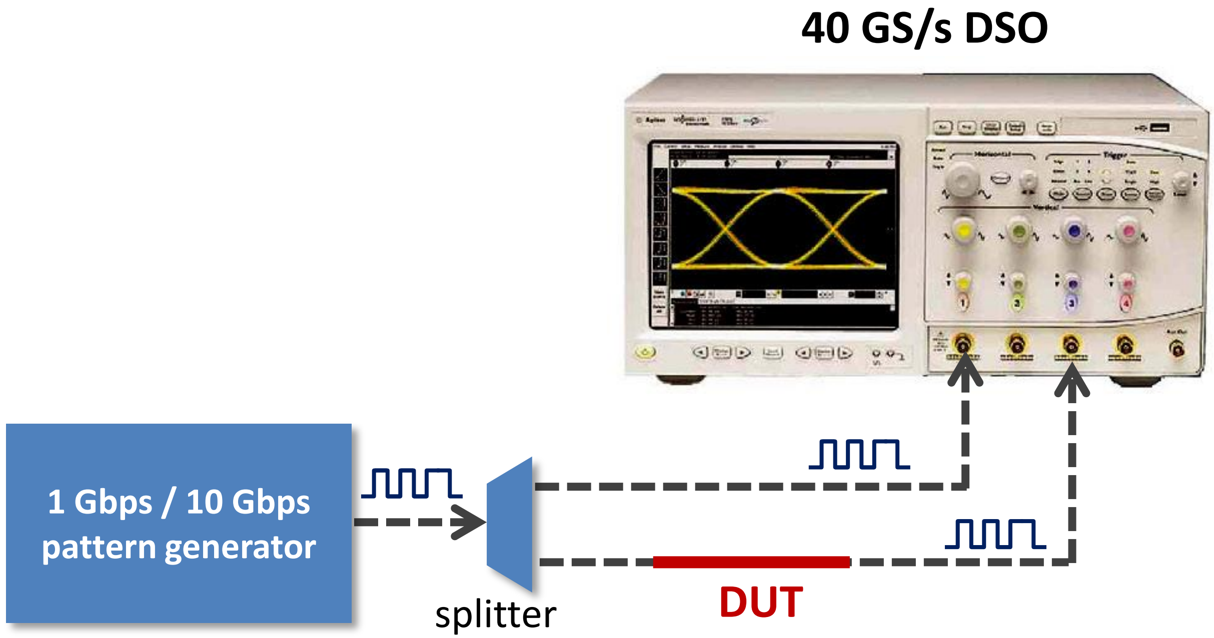
- Provided by **SURFnet**
- 2 x 300 km DWDM unidirectional fiber roundtrip VU-KVI-VU
  T. J. Pinkert et al. arXiv 410.4600v1 (2014)
- Time transfer for science & society: 2 x 137 km WR link from **VSL (Delft)** to **NIKHEF (Amsterdam)**
- Amplified fiber link to distribute UTC(VSL) via WR
- Target performance:
  <<10^{-14} frequency stability
  << 1 ns time uncertainty (0.1-0.3 ns)

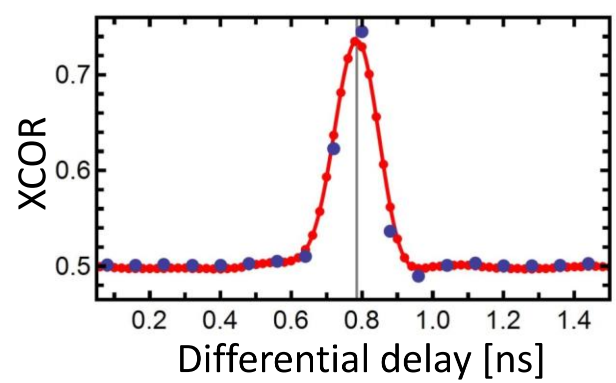


2×137 km WR link through dark fiber



Delay measurements through fast sampling and cross correlation





- High resolution (~150 fs / shot)
- Works for electrical and optical transmission lines

*N. Sotiropoulos *et al. Optics Express* **21**, 32643 (2013)

Dealing with fiber chromatic dispersion

- Measure roundtrip delays for two different wavelength pairs (λ_1, λ_i)*
- Exchange one SFP for another with slightly different λ:
  - $\lambda_2 \rightarrow \lambda_3$ (λ_1 stays the same)
  - Two Different RTDs (t_{AC}^{12}, t_{AC}^{13})
  - Measure all λ_i
- Use formula to find estimated OWD :

$$\theta_{AB} = \frac{1}{2\left(\lambda_2^{\,2} - \lambda_3^{\,2}\right)} \Big[\Big\{ \left(t_{AC}^{12} - \Delta^{12}\right) - \left(t_{AC}^{13} - \Delta^{13}\right) \Big\} \lambda_1^{\,2} + \left(t_{AC}^{13} - \Delta^{13}\right) \lambda_2^{\,2} - \left(t_{AC}^{12} - \Delta^{12}\right) \lambda_3^{\,2}$$

$$- L\lambda_1^{\,2} \left(\lambda_1 - \lambda_2\right)\left(\lambda_1 - \lambda_3\right)\left(\lambda_2 - \lambda_3\right) n'''(\lambda_1) / c \Big].$$

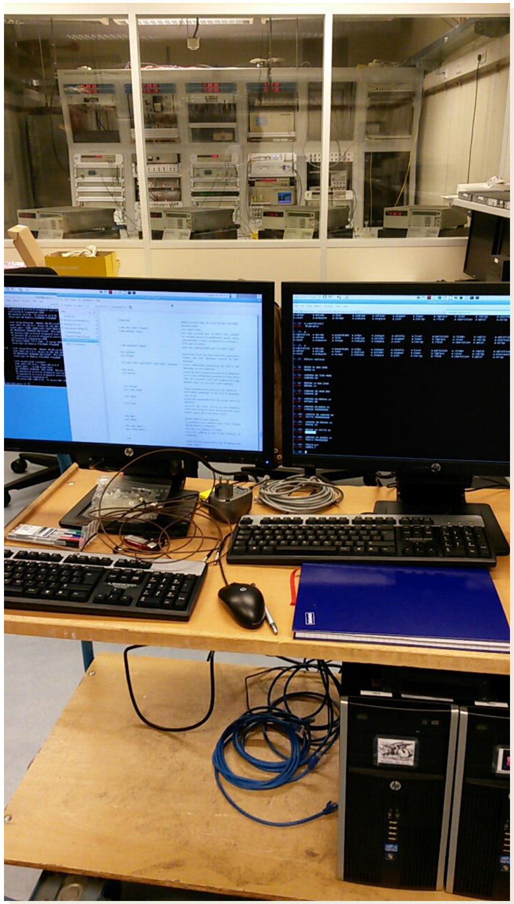
< 10ps/100 km if $\lambda_1 - \lambda_2$ ~ 1-2 nm

~ 200 ps/100 km if $\lambda_1 - \lambda_2$ ~ 20 nm

*N. Sotiropoulos *et al. Optics Express* **21**, 32643 (2013)

Pictures from the lab

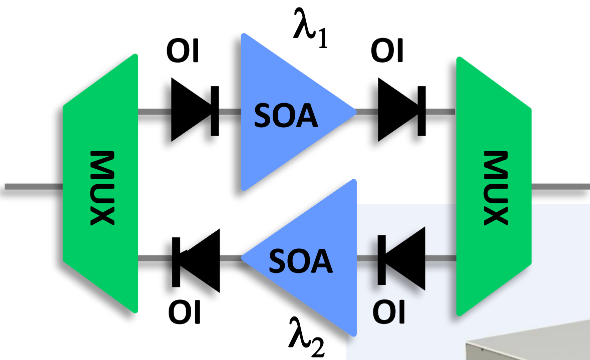
Initial calibration of equipment at VSL



WR + Cs ensemble + TWSTFT + GPS equipment @VSL

Quasi bi-directional amplifier

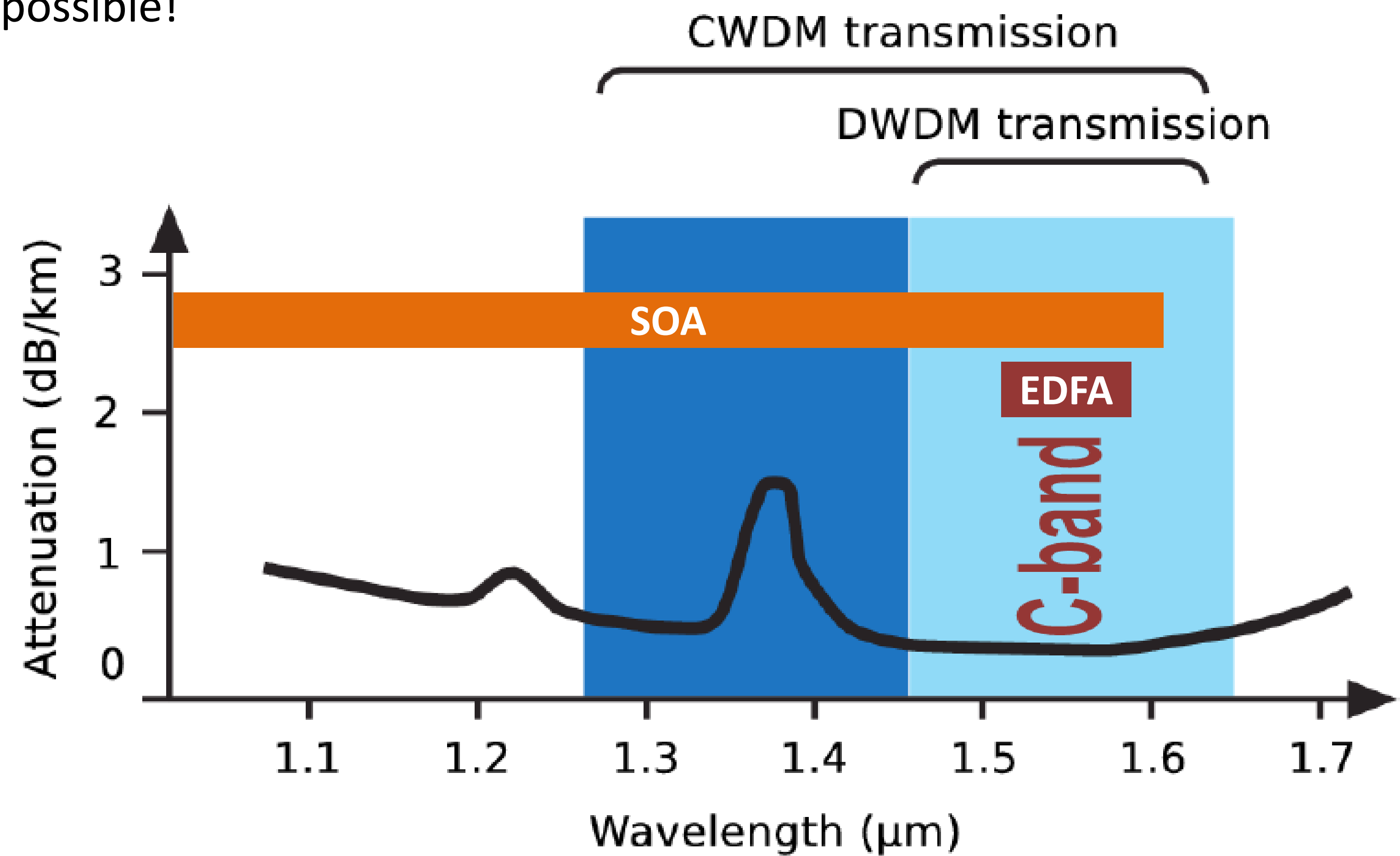
VU Amsterdam / TU Eindhoven / SURFnet



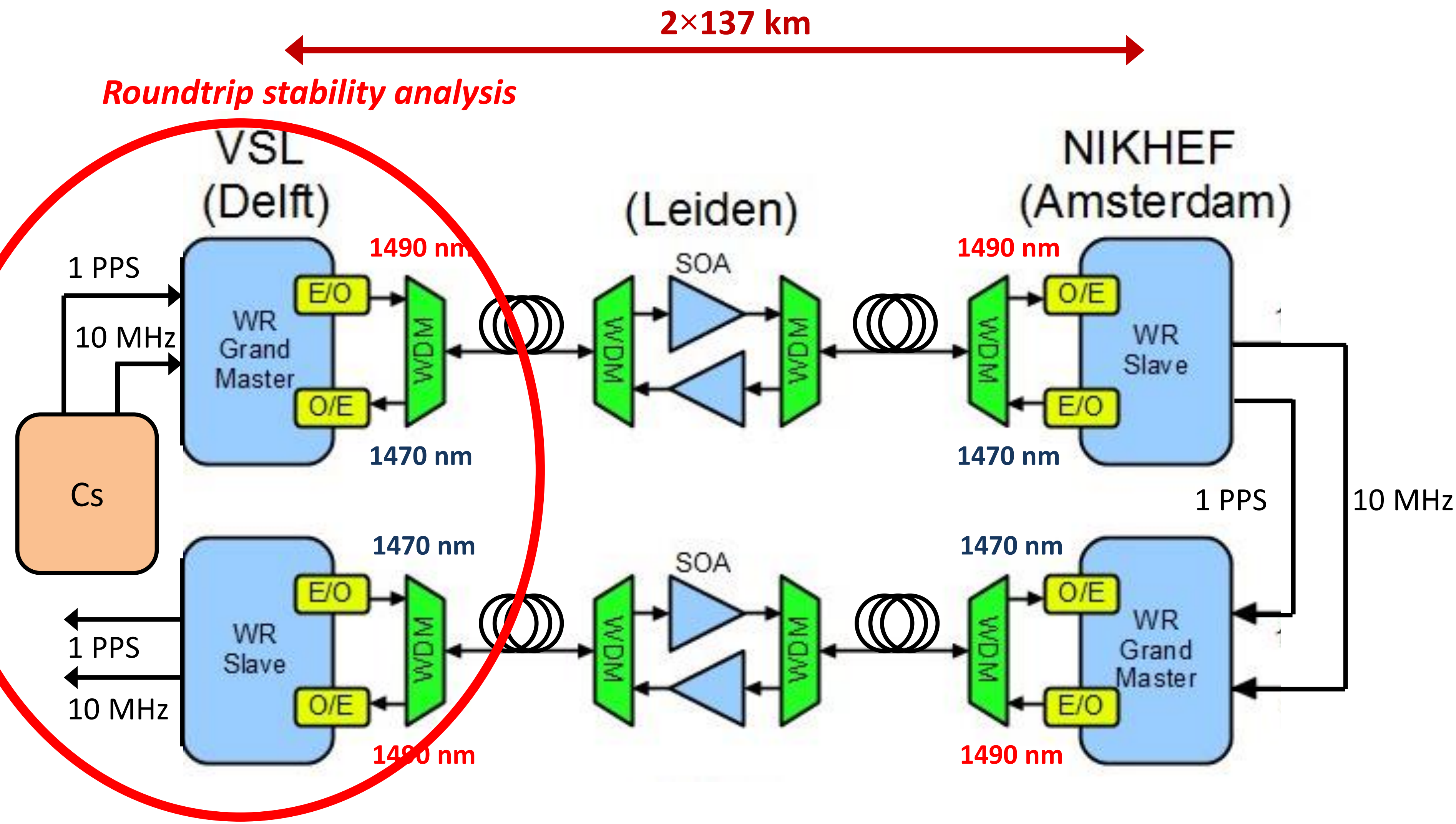
- Commercially available end of 2014 from OPNT B.V.
- Quasi-bidirectional and truly bidirectional
- Remote control & monitoring (gain, LoS, power levels)
- Delay asymmetry calibrated at <10 ps level
- Should be possible to cascade multiple amplifiers
- Current version SOAs, EDFAs also possible

SOAs vs EDFAs

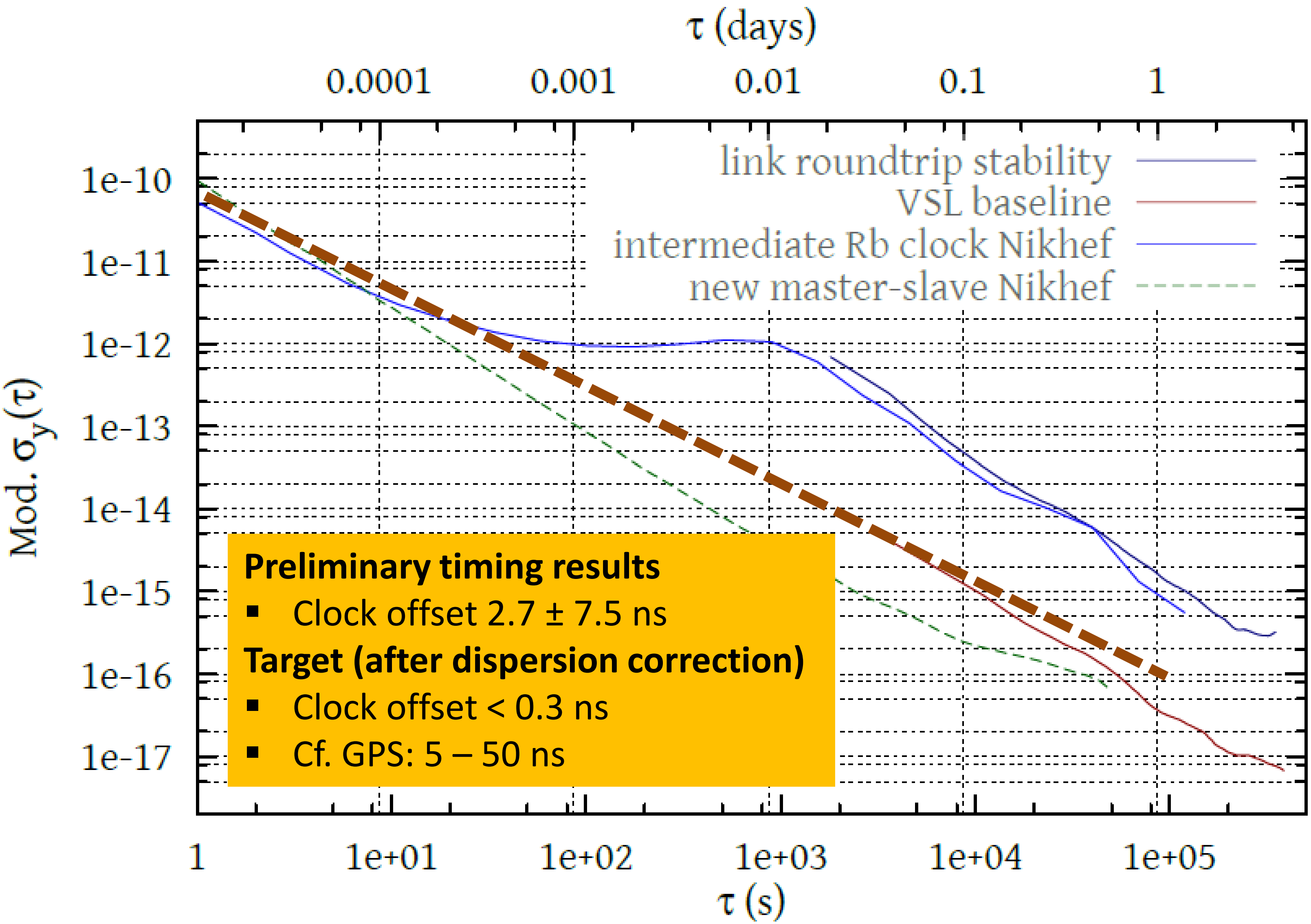
- SOAs: somewhat smaller gain and larger noise figure than EDFAs, but much larger wavelength range ⇒ enables out-of-band transmission
- Experiments in our lab: ultrastable frequency transfer with SOAs well possible!



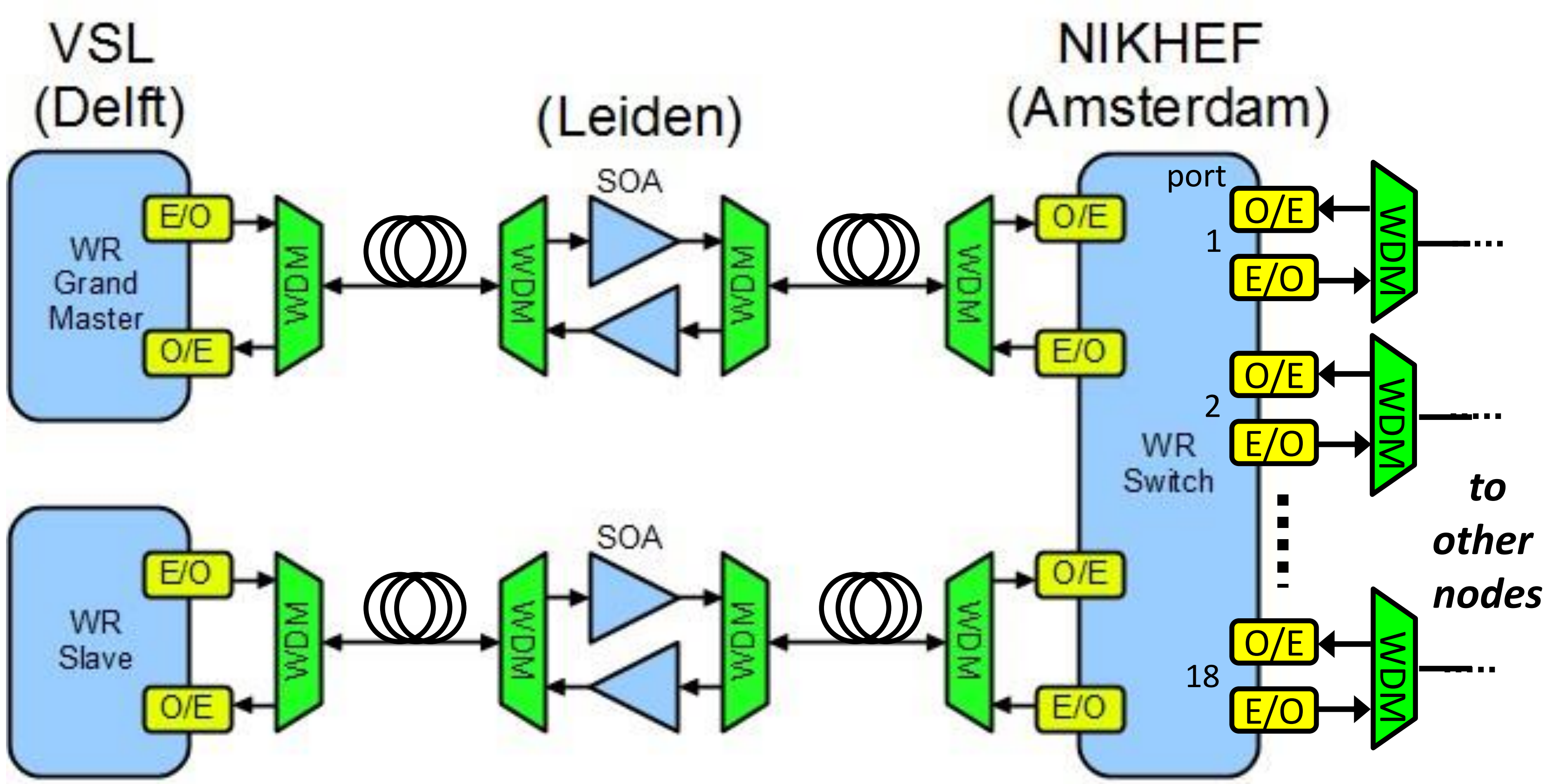
Roundtrip delay measurements



Frequency stability (preliminary result) (2×137 km dark fiber)



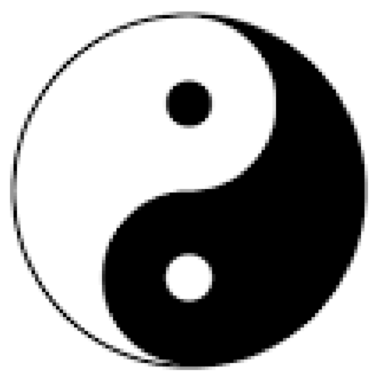
WR link VSL – NIKHEF (Next configuration)



Sending time & frequency through DWDM networks…

Challenges:

- DWDM links are unidirectional (duplex fiber)
- DWDM network owners are responsible for/run business by transporting data with high reliability



- We would like to have time & frequency (in addition to data)
- We need bidirectional links + amplifiers
- We use equipment which is not (yet) fully certified and compliant

Solutions so far (with excellent TFT performance)

See talks by Harald Schnatz & Gesine Grosche, Anne Amy-Klein

- Dark fiber + custom bidi amplifiers
  - Expensive! And not readily standardized
- Dark channel: install OADMs to route time+frequency channel around EDFA (Univ. Paris 13, LNE-SYRTE, RENATER)
  - Interrupts C-band traffic, decreases link budget, requires sacrificing telecom capacity

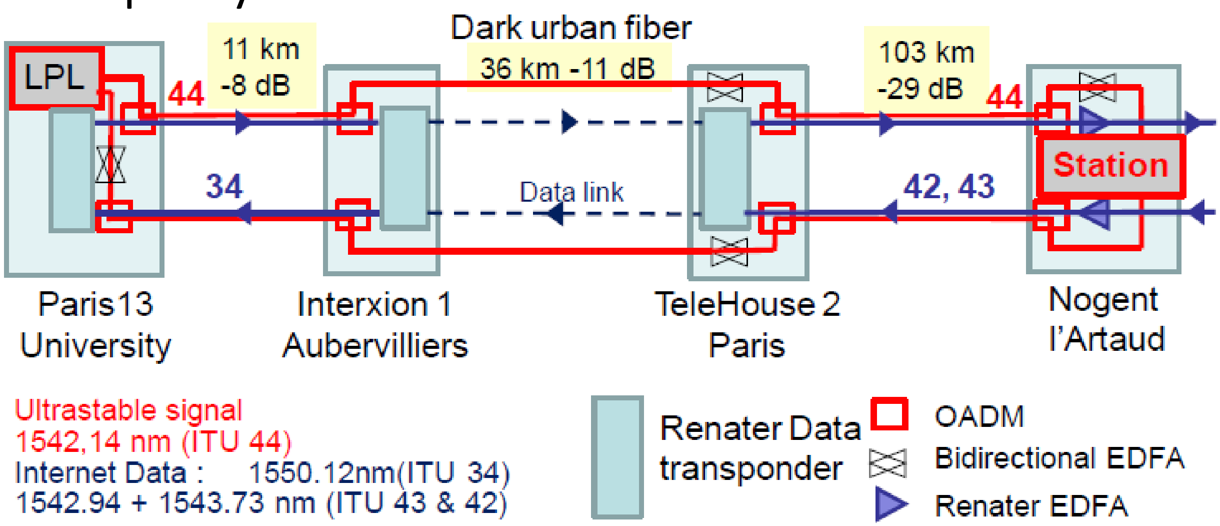
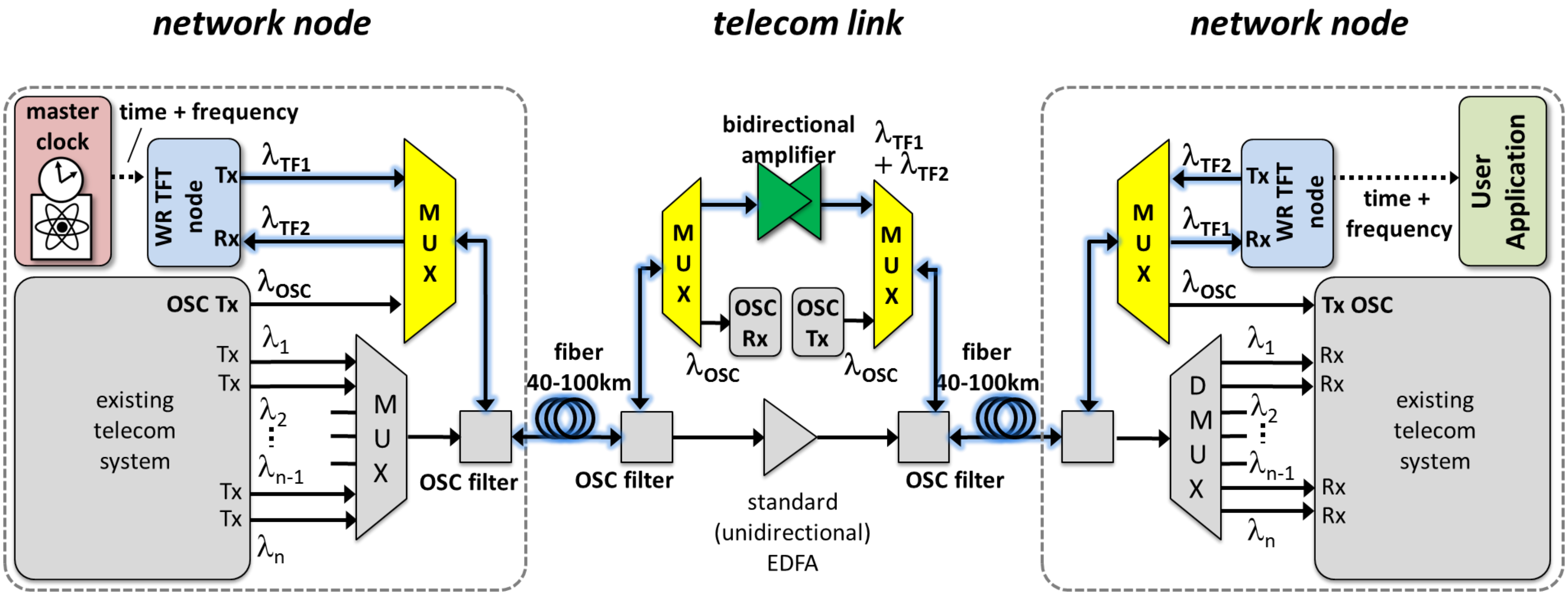


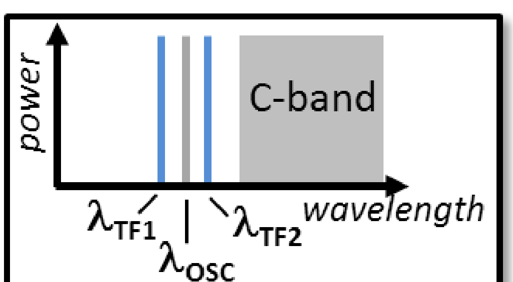
Fig. 3. Scheme of the 2 x 150 km cascaded optical link.

Lopez *et al.*, Opt. Express **18**, 16849 (2010)

Proposed solution
Patent application nr. PCT/NL2012/050367



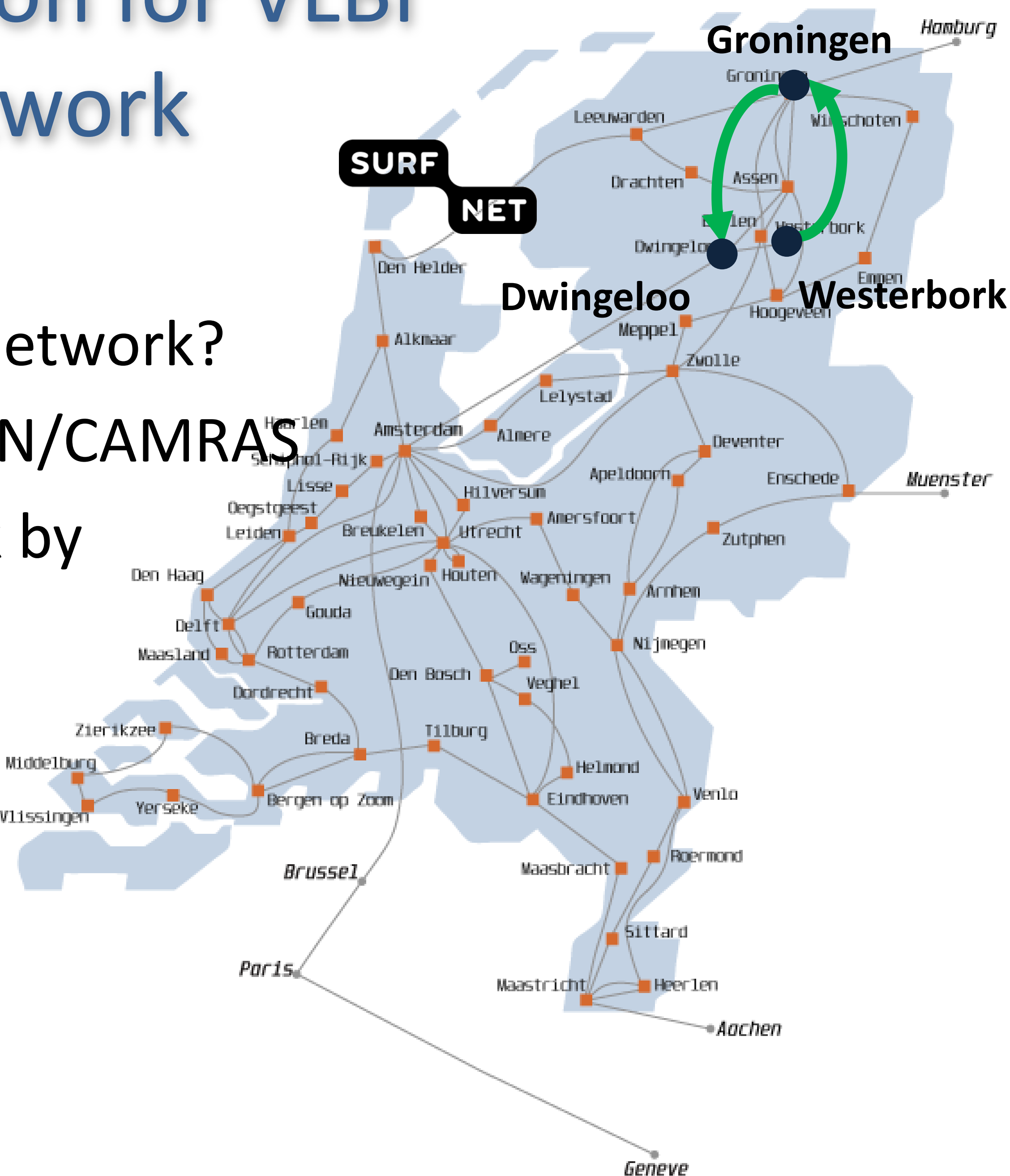
Wavelength plan:

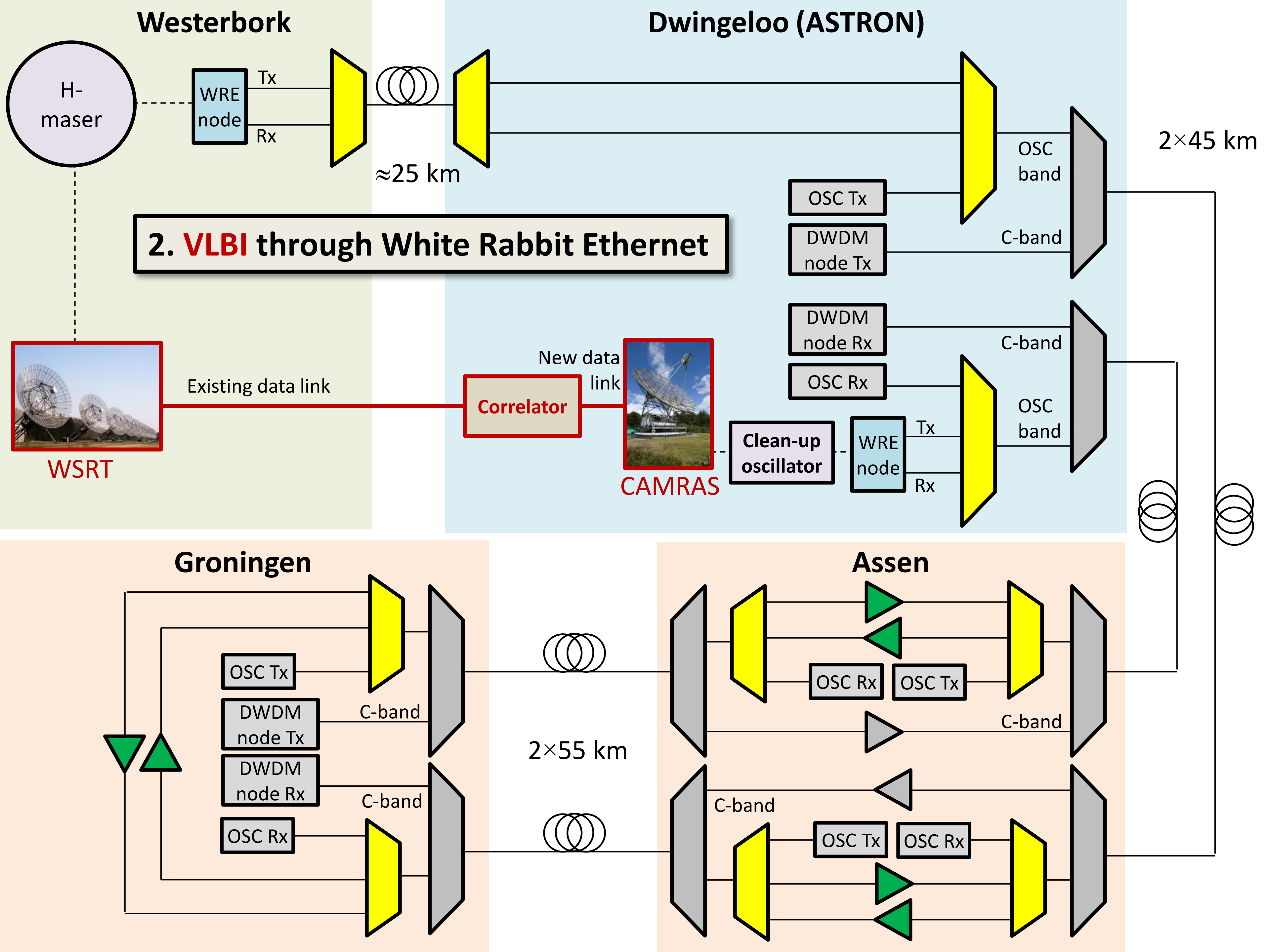


- No need to insert components in main fiber, no C-band capacity lost
- Installed in-service (only OSC taken offline)
- T+F channels very close to OSC wavelength, travel through OSC filters together
- T+F wavelengths: ITU DWDM grid
- Shown: WR Ethernet implementation, but works also for ultrastable frequency transfer (optical carrier)

Implementation for VLBI in DWDM network

- Test in SURFnet network?
- With JIVE/ASTRON/CAMRAS
- See also next talk by Paul Boven (JIVE)



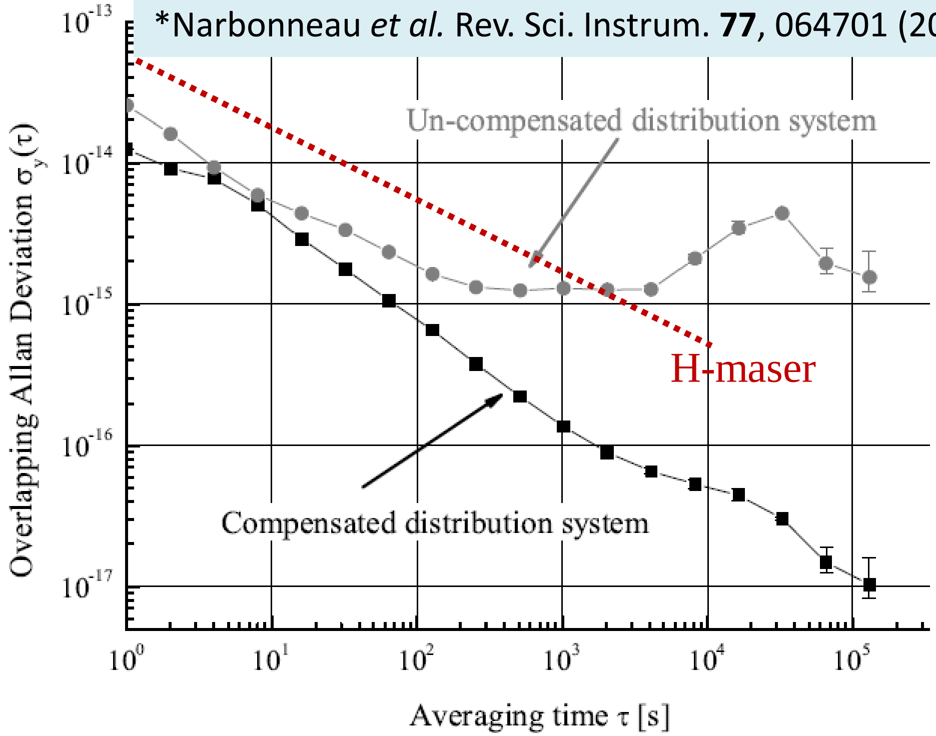

Westerbork
Dwingeloo (ASTRON)
H-maser
WRE node
Tx
Rx
≈25 km
OSC band
2×45 km
OSC Tx
DWDM node Tx
C-band
2. VLBI through White Rabbit Ethernet
DWDM node Rx
C-band
OSC Rx
OSC band
Existing data link
New data link
Correlator
WSRT
CAMRAS
Clean-up oscillator
WRE node
Tx
Rx
Groningen
Assen
OSC Tx
DWDM node Tx
C-band
DWDM node Rx
C-band
OSC Rx
2×55 km
OSC Rx
OSC Tx
C-band
C-band
OSC Tx
OSC Rx

Clean-up oscillator

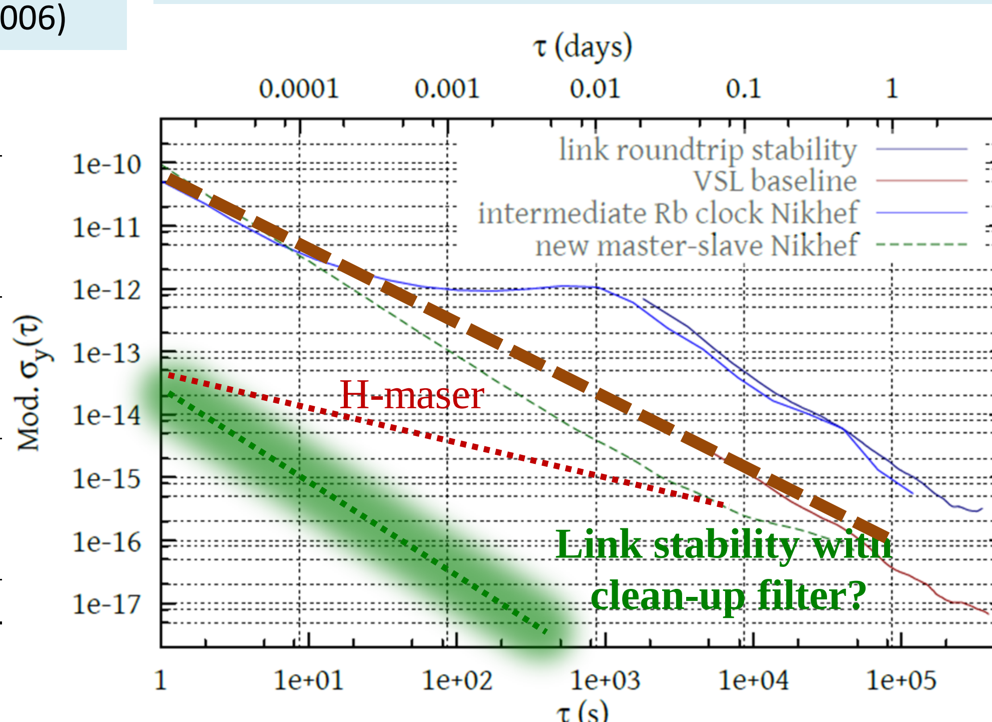
- H-maser local oscillator (-130 dBc@1 Hz, 10 k€)
- Low BW phase lock to WR output at time scale > 1 s
- WR runs at 125 MHz clock ⇒ H-maser frequency stability through fiber possible*

100 MHz clock

*Narbonneau *et al.* Rev. Sci. Instrum. **77**, 064701 (2006)



WR with clean-up oscillator (planned)



Thank you!

Questions?
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€€ STW
€€ FOM
€€ EMRP NEAT-FT
€€ SURFnet

Special thanks to:
WR people CERN/Univ. Granada
VLBI people JIVE
KVI/RU Groningen