Long-haul implementation of *White Rabbit* Ethernet for fiber-optic synchronization of VLBI stations

Jeroen Koelemeij

2nd ngVLA workshop

NRAO Socorro, NM, USA

December 9, 2015

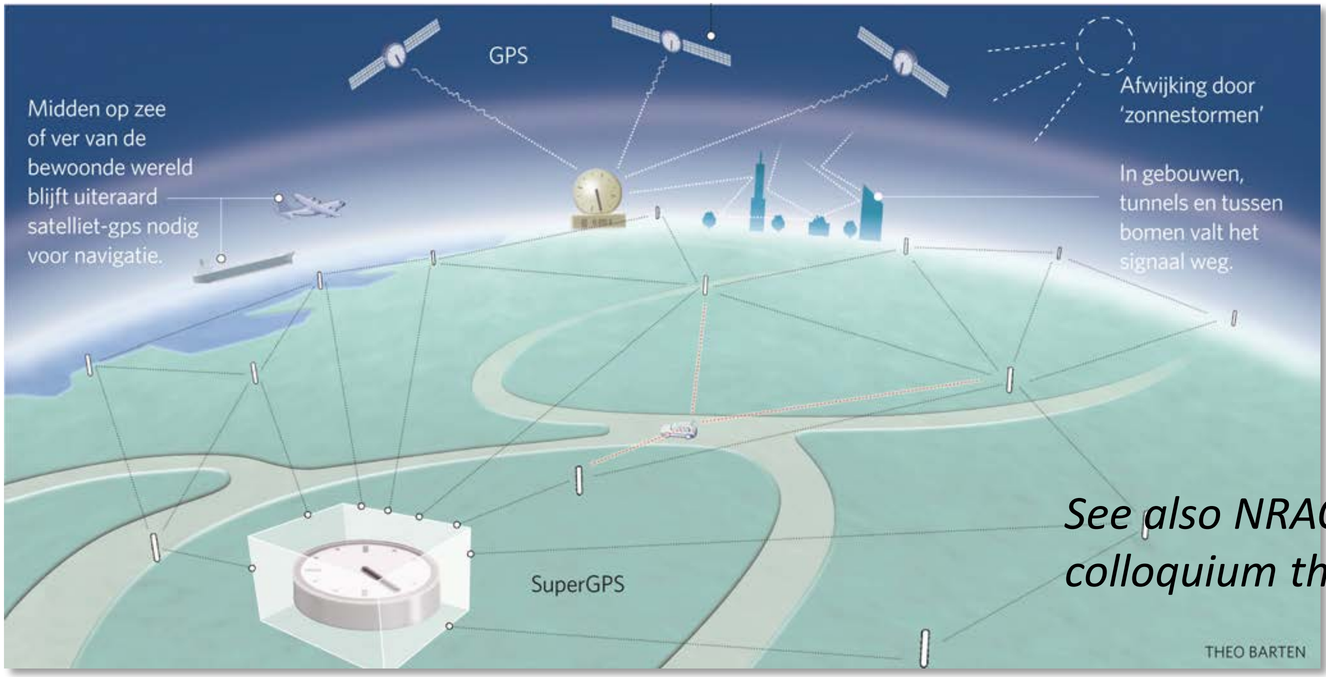
VU VRIJE UNIVERSITEIT AMSTERDAM

LaserLaB Amsterdam

€€€ : STW Enabling new technology · HORIZON 2020 · FOM · EURAMET · SURF NET

Research aims at VU University Amsterdam

- Methods for high-accuracy fiber-optic time and frequency (T&F) distribution
- Key focus: compatibility with existing data/telecom infrastructure and existing TFT protocols
- Long-term objective: a terrestrial infrastructure for telecom, T&F distribution, and (strongly improved) positioning



See also NRAO special colloquium this Thursday

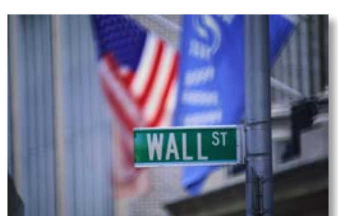
Fiber-optic time and frequency transfer for radio astronomy/VLBI

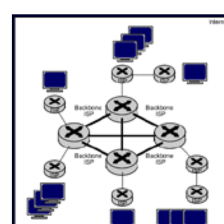
Past: Stand-alone H-masers, telescope data recorded on tape/harddisks, shipped to correlator

Present: Stand-alone H-masers, telescope data transferred to correlator through fiber-optic telecom network

Future: Both T&F reference and telescope data transferred through fiber-optic telecom network

- Lower cost
- Superior time sync (<< 1 ns)
- Important to many stakeholders (GPS back-up for electricity grids, telecom networks, electronic financial transactions)

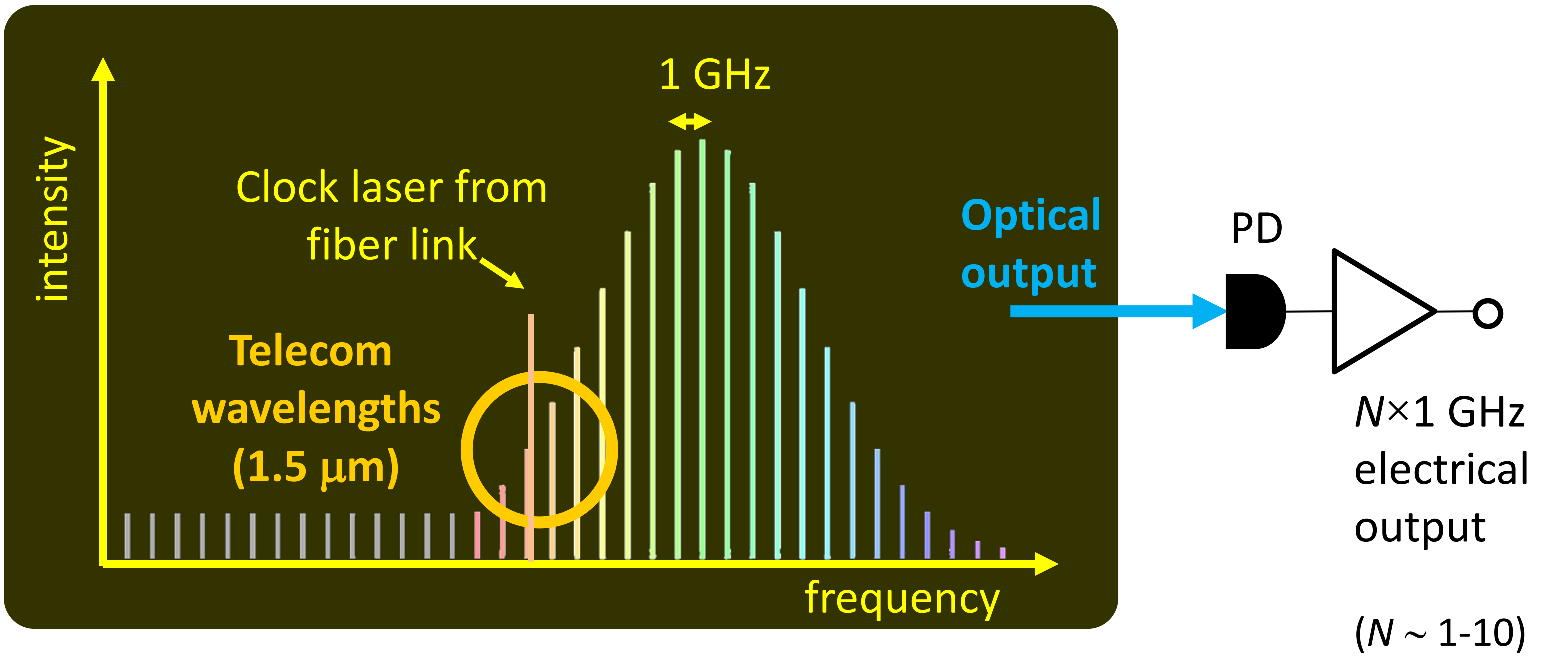




Fiber-optic frequency transfer

Optical frequency transfer (1.5 μm / 2×10^{14} Hz):

- Send ultrastable continous-wave (CW) 'clock laser' down a long fiber-optic link (hundreds to thousands of kilometers)
- Remote end application: lock optical frequency comb laser to CW laser

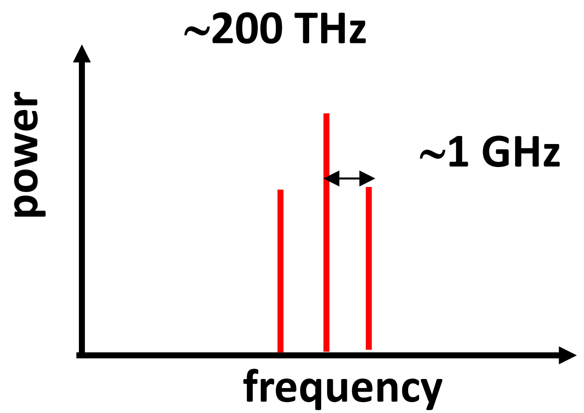


- Advantage: highest stability (ADEV 10^{-15} @1s)
- Disadvantage: frequency comb price comparable to active H-maser

Fiber-optic frequency transfer

RF/Microwave frequency transfer (10 MHz – 10 GHz)

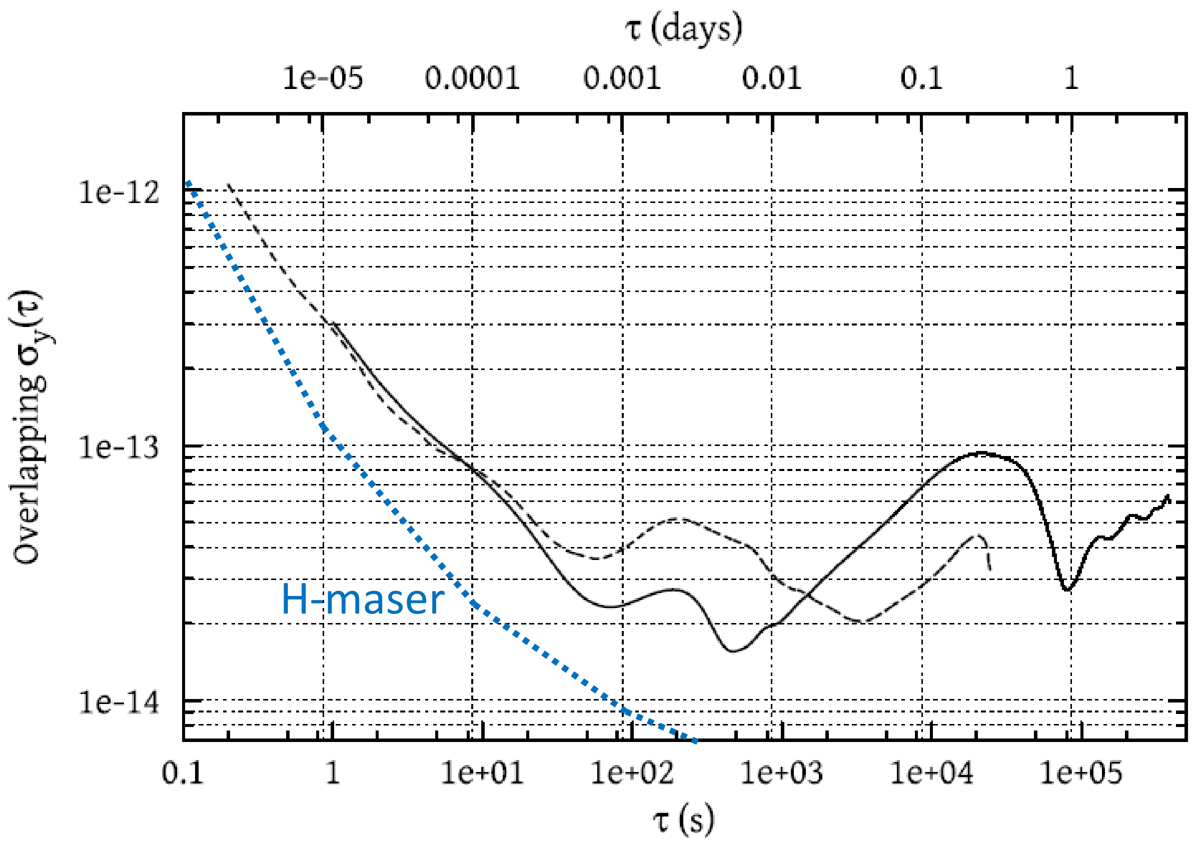
- Modulate link laser (e.g. AM) with reference clock signal
- Remote end: simply detect modulation with photoreceiver (no other laser needed)



- Need to deal with optical path length changes

Optical path length variations

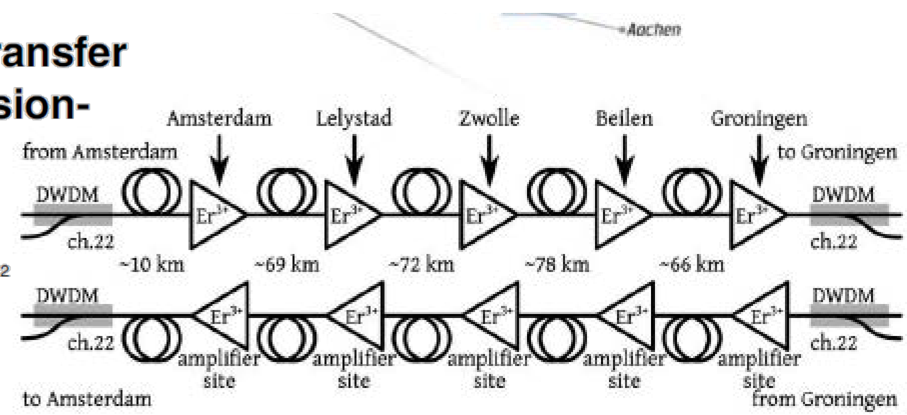
- Acoustic and (soil) temperature variations cl optical path length ⇒ 'noisy' Doppler shift
- Effects investigated* usin 2× 300 km fiber link betw VU Amsterdam and RU Groningen
- Stability limit > 10^{-14}



Appl. Opt. **54**, 728 (20

Effect of soil temperature on optical frequency transfer through unidirectional dense-wavelength-division-multiplexing fiber-optic links

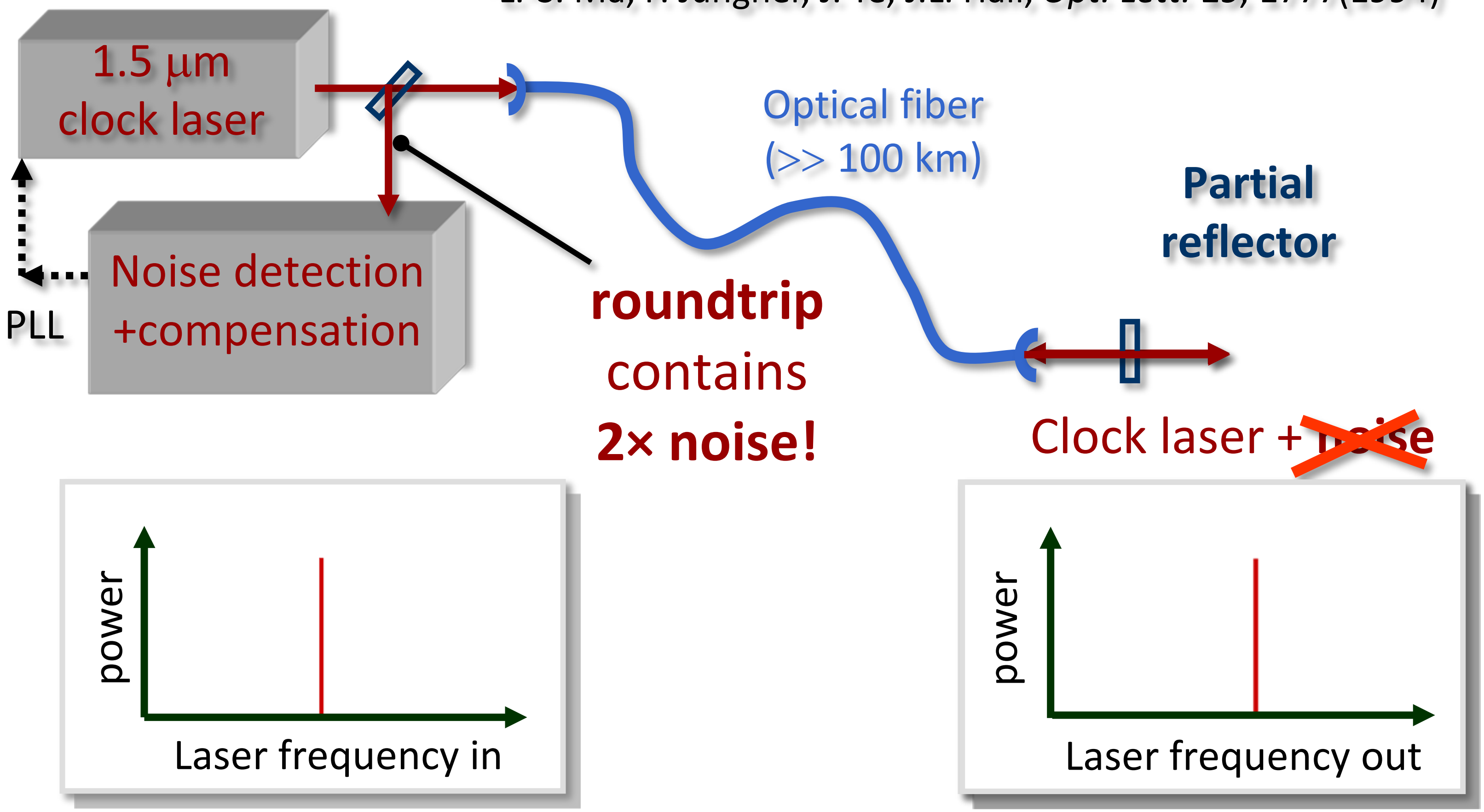
T. J. Pinkert,[1] O. Böll,[2] L. Willmann,[2] G. S. M. Jansen,[1] E. A. Dijck,[2] B. G. H. M. Groeneveld,[2] R. Smets,[3] F. C. Bosveld,[4] W. Ubachs,[1] K. Jungmann,[2] K. S. E. Eikema,[1] and J. C. J. Koelemeij[1,*]



Optical path length stabilization

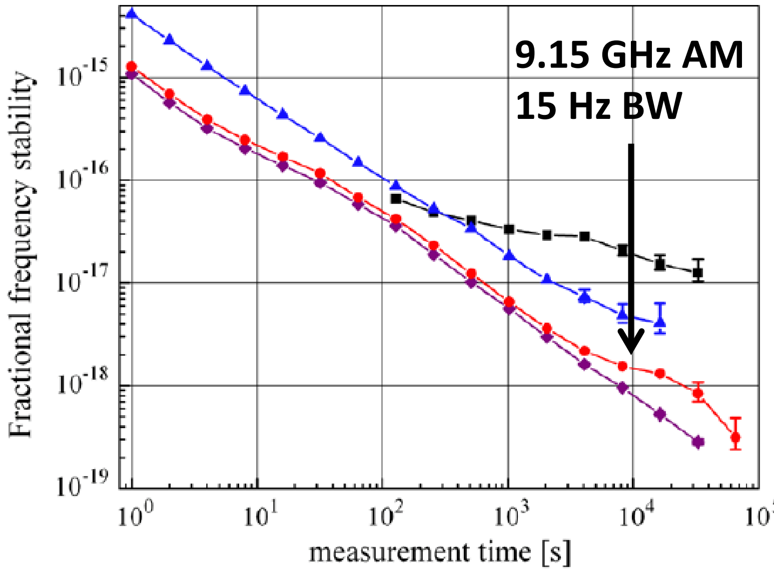
*Compensation of frequency fluctuations due to length fluctuations**:*

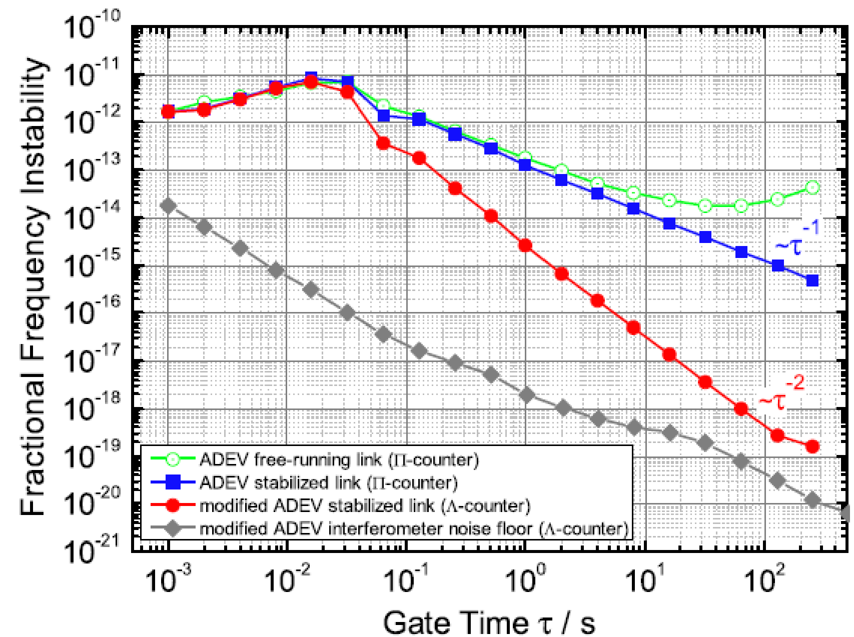
*L.-S. Ma, P. Jungner, J. Ye, J.L. Hall, *Opt. Lett.* **19**, 1777(1994)



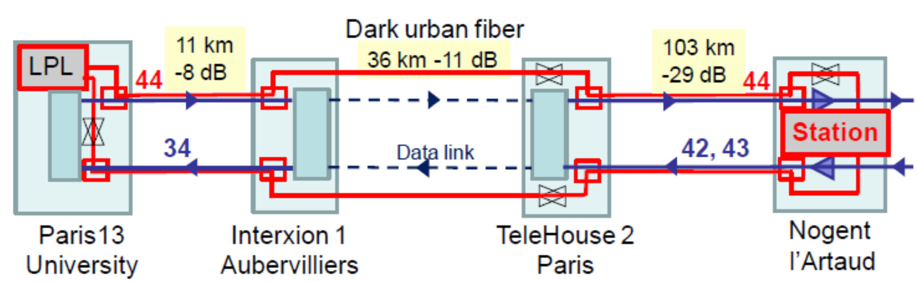
A few historical results

- Model of frequency transfer through compensated optical fiber (NIST)
  P. A. Williams *et al.*, J. Opt. Soc. Am. B **25,** 1284 (2008)
- Compensated fiber-optic link of 1840 km length (PTB Germany):
  S. Droste *et al.*, Phys. Rev. Lett. **111,** 110801 (2013)
- MW-modulated optical carrier over 86 km (LPL and Observatoire Paris):
  O. Lopez *et al.*, Eur. Phys. J. D **48,** 35 (2008)



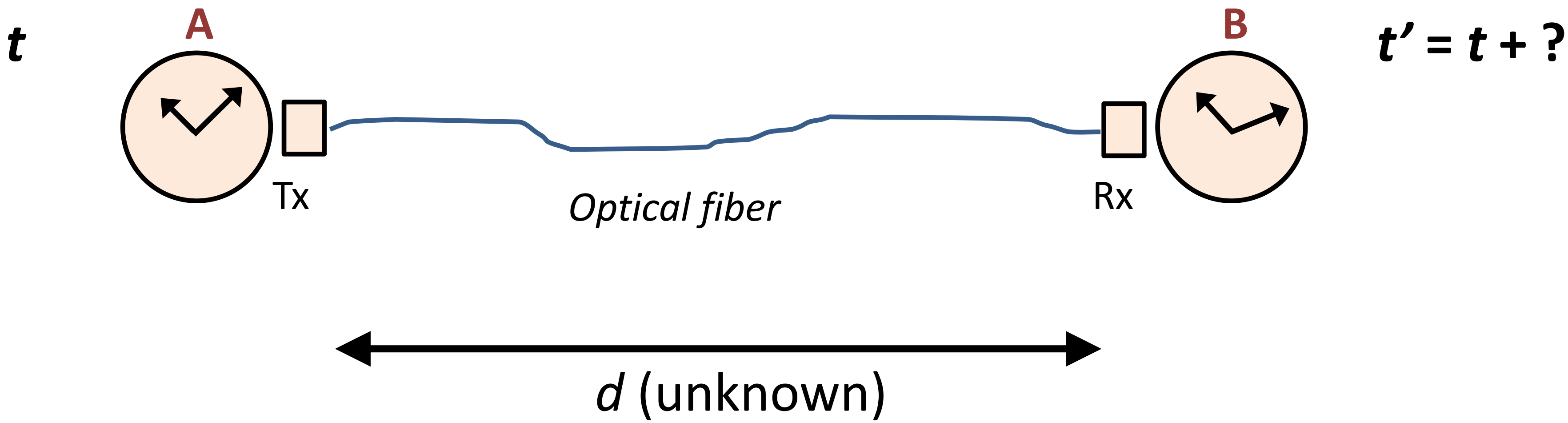


- T&F transfer through 540 km telecom link with live Internet data traffic (LPL & Obs. Paris): O. Lopez, Opt. Express **20,** 23518 (2012)



Fiber-optic time transfer

Synchronization: transmission **delay** must be measured



1. Determine round-trip delay using clock A

2. Assume identical delays A-B and B-A and compute OWD = RTD/2

3. Send correction to clock B taking into account one-way delay

Differential delay

Key assumption in **both** compensated **frequency** and **time** links:
the optical delays A-B and B-A are identical

This can be violated by:

- Path length variations faster than round-trip time
- Differential delay due to separate physical paths of unequal length and/or sensitivity to environmental changes
- Chromatic dispersion (CD)
- Polarization mode dispersion (PMD) (every fiber is a randomly varying birefringent medium: propagation delay depends on polarization state of light)
- Nonlinear (power-dependent) effects (often negligible)

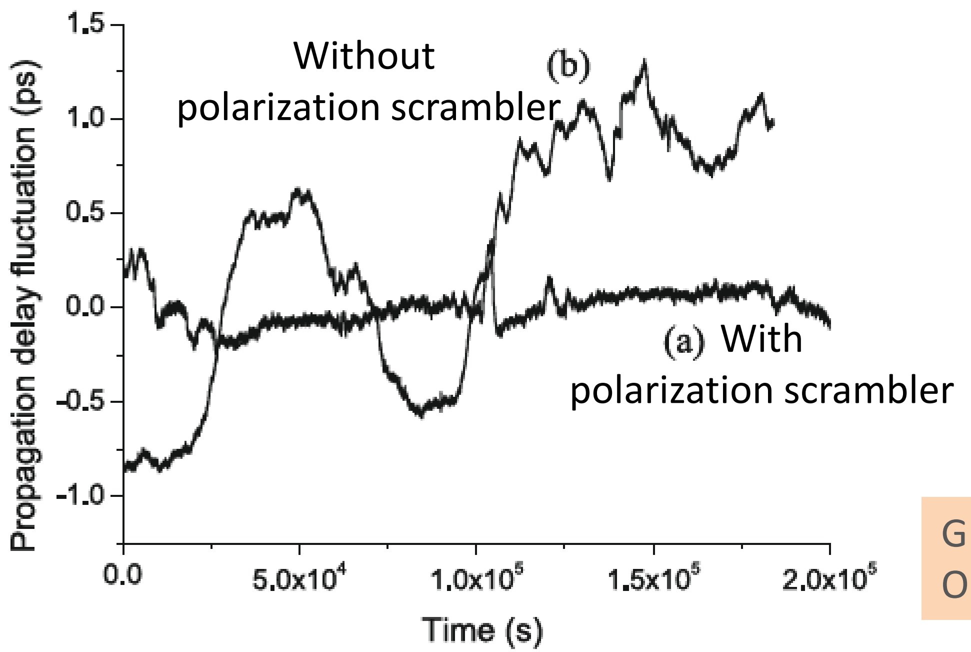
A few example

Solutions:

- Choose nearby wavelengths (~ 1 nm)
- Eliminate dispersion by calibration*

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

- Chromatic dispersion 0- type
- Wavelengths 20 nm apart:
  - Differential delay 2 ns/100 km ⇒ timing offset!
  - Probably leads to uncompensated frequency noise at ~10^{-15} level
- PMD is known to cause timing drift in older legacy fiber:



Graph by LPL and Observatoire Paris; see O. Lopez *et al.*, Eur. Phys. J. D **48**, 35 (2008)

Fiber-optic time transfer methods

- Measuring delays: exchange PPS signal (1 measurement/s)
- Better: use 1-10 Gb/s data (10^{10} measurements/s possible)

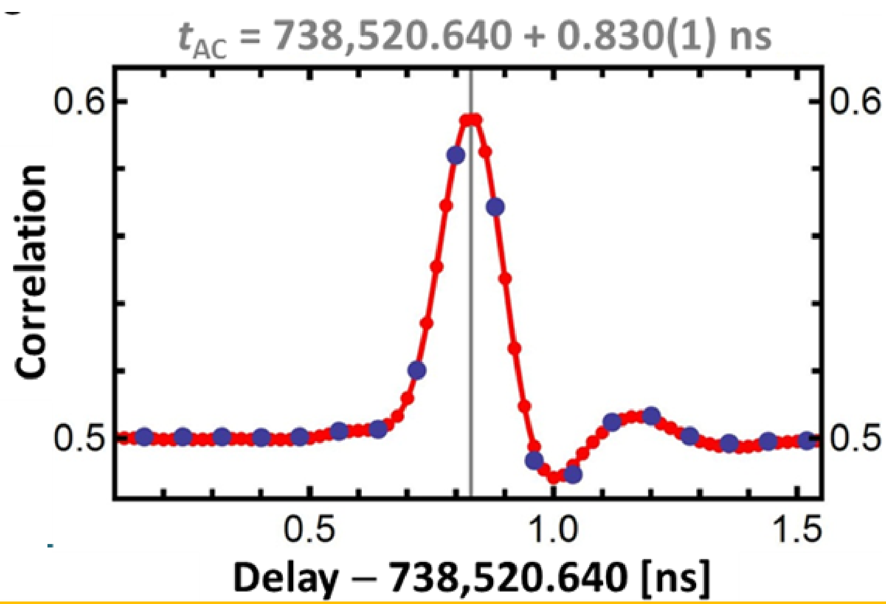
Different methods:

- Cross-correlation of input and roundtrip data (VU, TU/e)

$$(f \star g)(t) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f^*(\tau)\ g(t+\tau)\, d\tau$$

g: original signal
(pseudo-random bit sequence, PRBS)

f : delayed (round-trip) signal



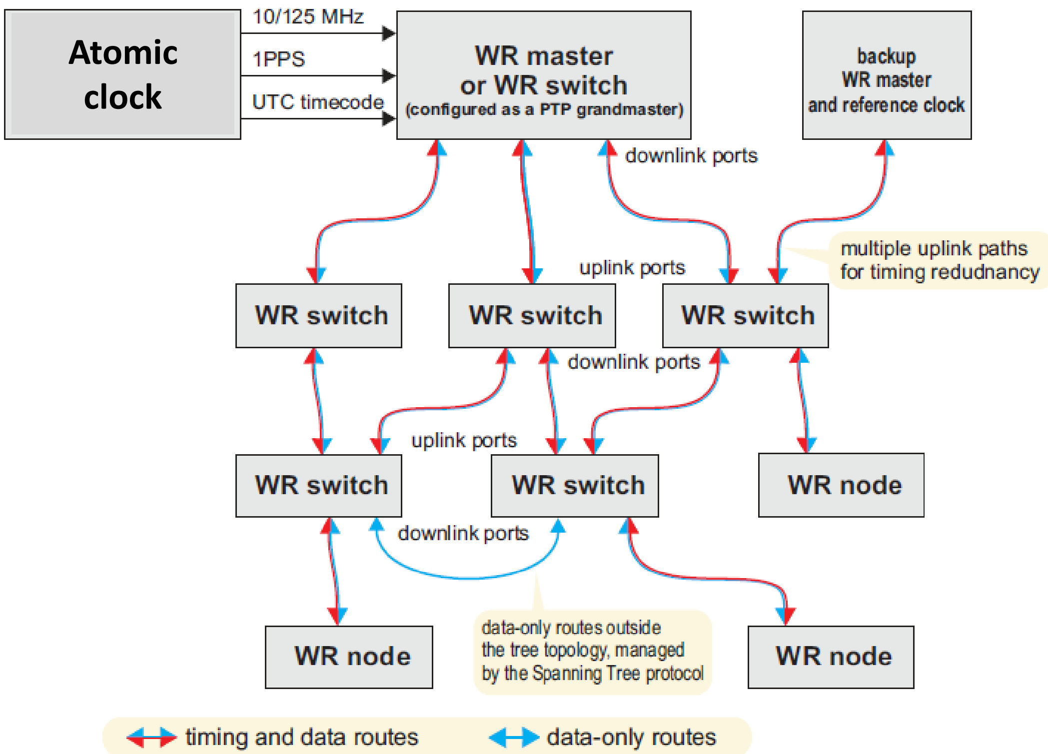
Delay of 75 km fiber: 4 ps uncertainty [Sotiropoulos *et al.*, Opt. Express (2013)]
Resolution <100 fs possible (both in optical and electrical domain!)

Fiber-optic time transfer methods

- Measuring delays: exchange PPS signal (1 measurement/s)
- Better: use 1-10 Gb/s data (10^{10} measurements/s possible)

Different methods:

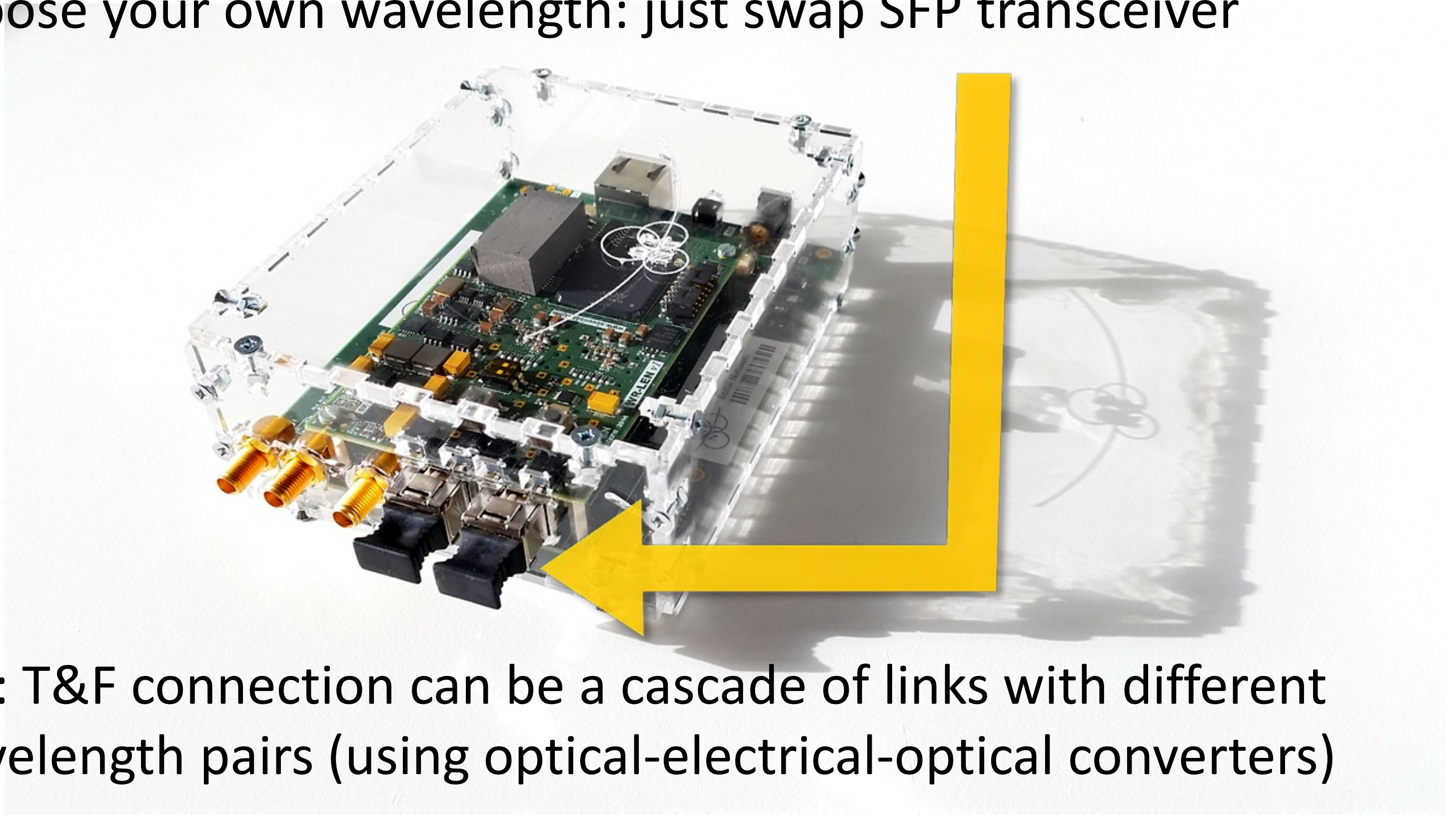
- Cross-correlation of input and roundtrip data (VU, TU/e)
- *White Rabbit* Ethernet (CERN, based on IEEE Precision Time Protocol)



- Time, frequency, and 1 Gb/s data in one
- 1 PPS, 10 – 125 MHz
- Designed for 1 ns timing over distances <10 km (LHC, CERN)
- Commercially available

White Rabbit

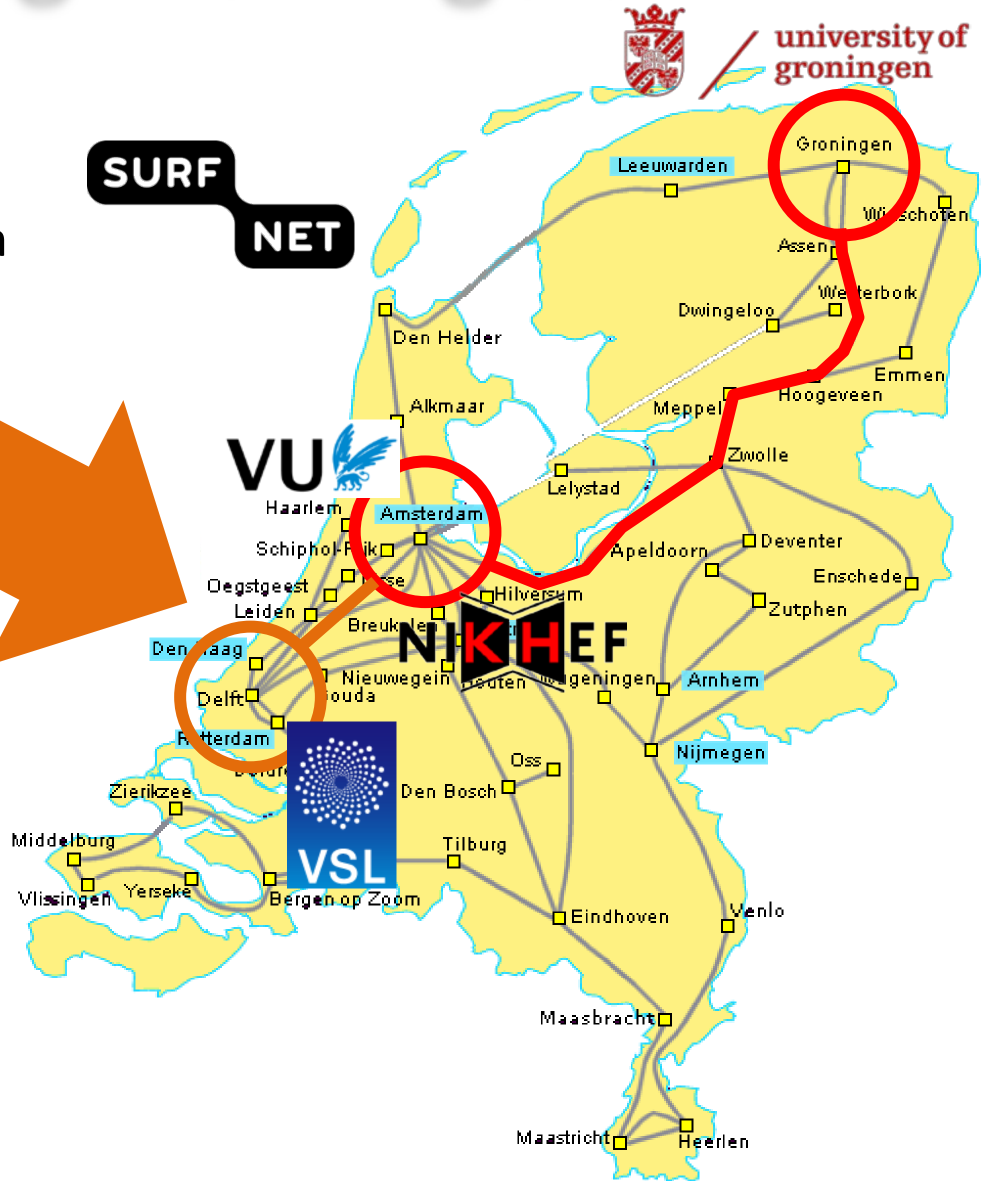
- Communication generally over two different lambdas
- Use Wavelength Division Multiplexing
- Choose your own wavelength: just swap SFP transceiver



- Pro: T&F connection can be a cascade of links with different wavelength pairs (using optical-electrical-optical converters)
- Con: cascade becomes noisy as each O-E-O conversion adds jitter
- For high stability we prefer long spans with optical amplifiers

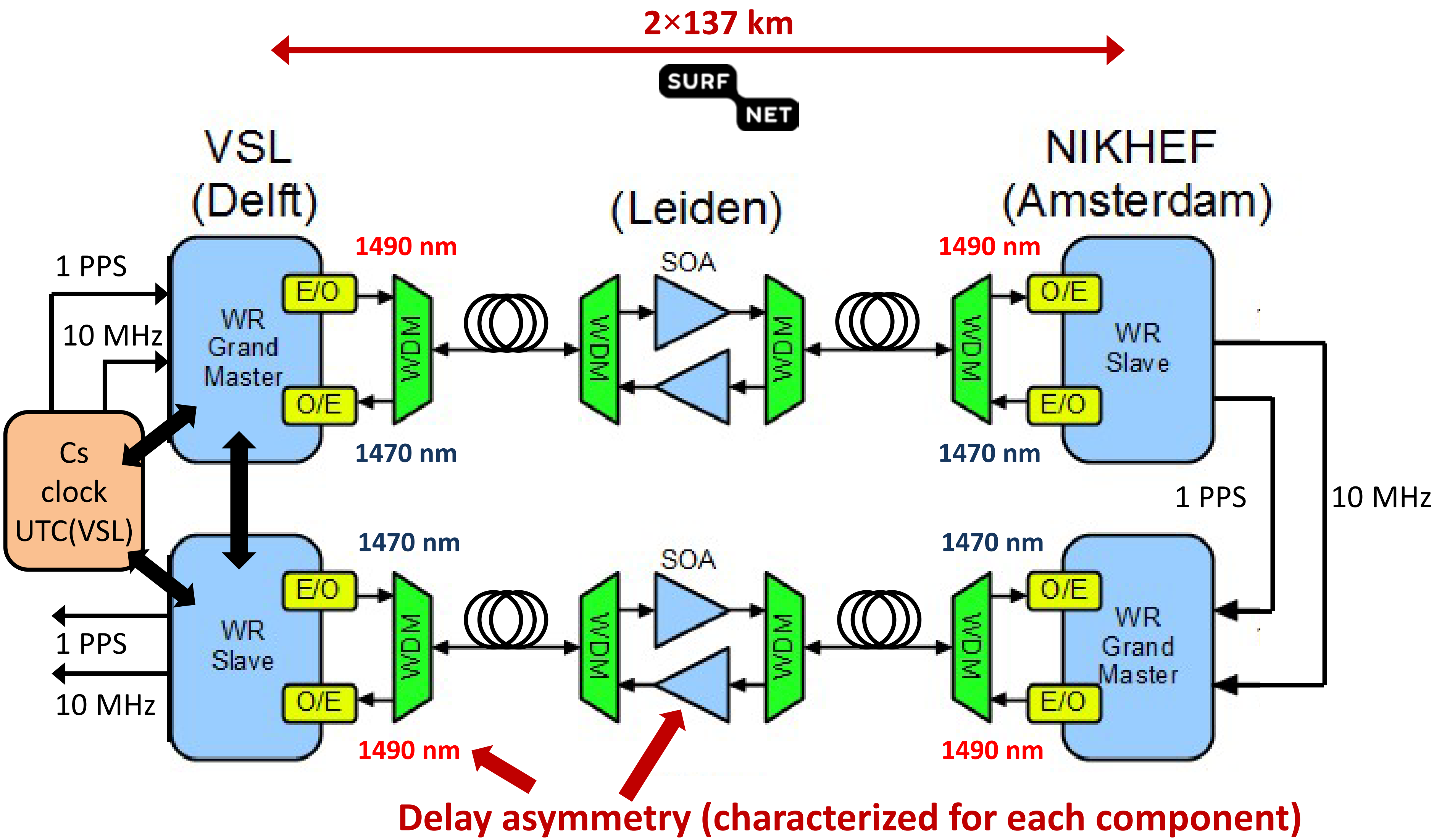
Extending the range of WR

Link VSL Delft-
NIKHEF Amsterdam
(2×137 km)



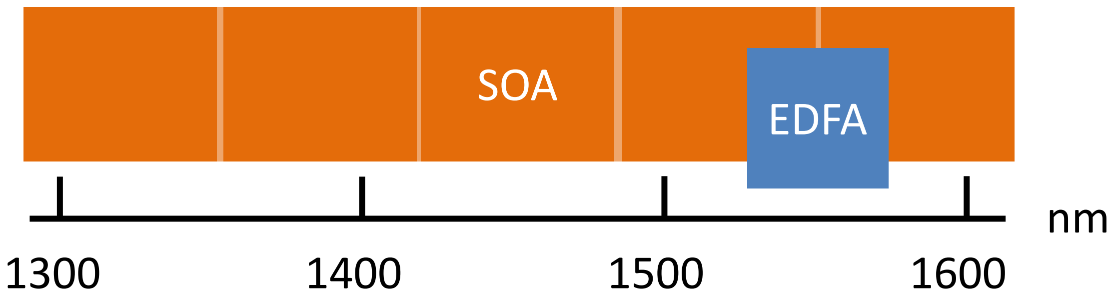
300 km

Extending the range of WR



Optical amplifiers

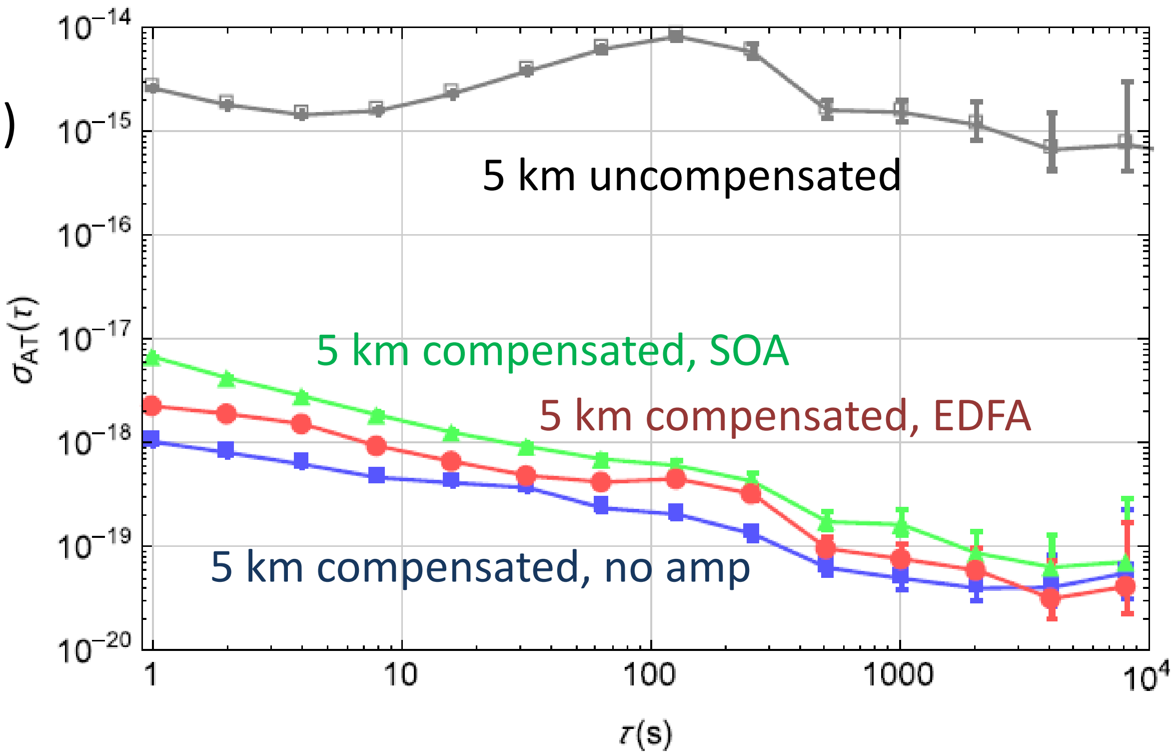
- Need optical amplifiers both inside C-band (EDFAs) and outside C-band (SOAs)



- EDFAs are known to work well for ultrastable fiber-optic T&F transfer (NIST, PTB, LPL/Observatoire de Paris…)
- *SOAs offer a much wider wavelength range. Do they work as well?*

Comparison EDFA vs SOA

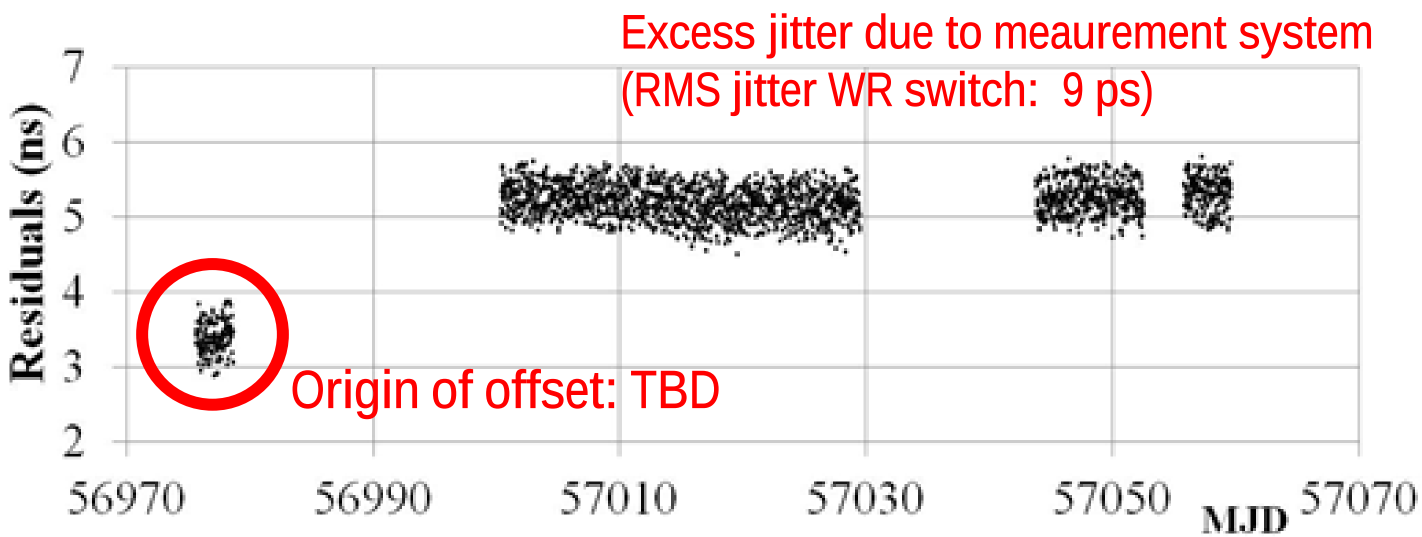
- Use Hz laser and spooled fiber (5, 25, 100 km)
- SOA vs EDFA: small differences, only visible with frequency counters in high-precision mode
- **Rigorous (quantitative) analysis of noise in system**
  - SOAs (ASE, current noise)
  - EDFAs (ASE)
  - Counters (response*)



*E. Rubiola,
Rev. Sci. Instr. **76,** 054703 (2005)

S. T . Dawkins *et al.*, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **54,** 918 (2007)

Results 2×137 km roundtrip



- Time offset 5 ns (within current uncertainty of ±8 ns due to dispersion) *
  - Comparable with state-of-the-art GPS timing
- Uncertainty currently improved towards ±0.1 ns (0.1 ns × *c* ≈ 3 cm)
- In principle, few picoseconds uncertainty is possible (demonstrated using 75 km fiber spools by VU, TU Eindhoven and SURFnet**)
- Work in progress: Tjeerd Pinkert (VU), Henk Peek, Peter Jansweijer (NIKHEF)

**E. Dierikx *et al.*
Transactions on Ultrasonics, Ferroelectrics, and Frequency Control

**N. Sotiropoulos, C.M. Okonkwo, R. Nuijts, H. de Waardt, JK
Optics Express 21, 32643 (2013)

Timing for VLBI

Required clock stability

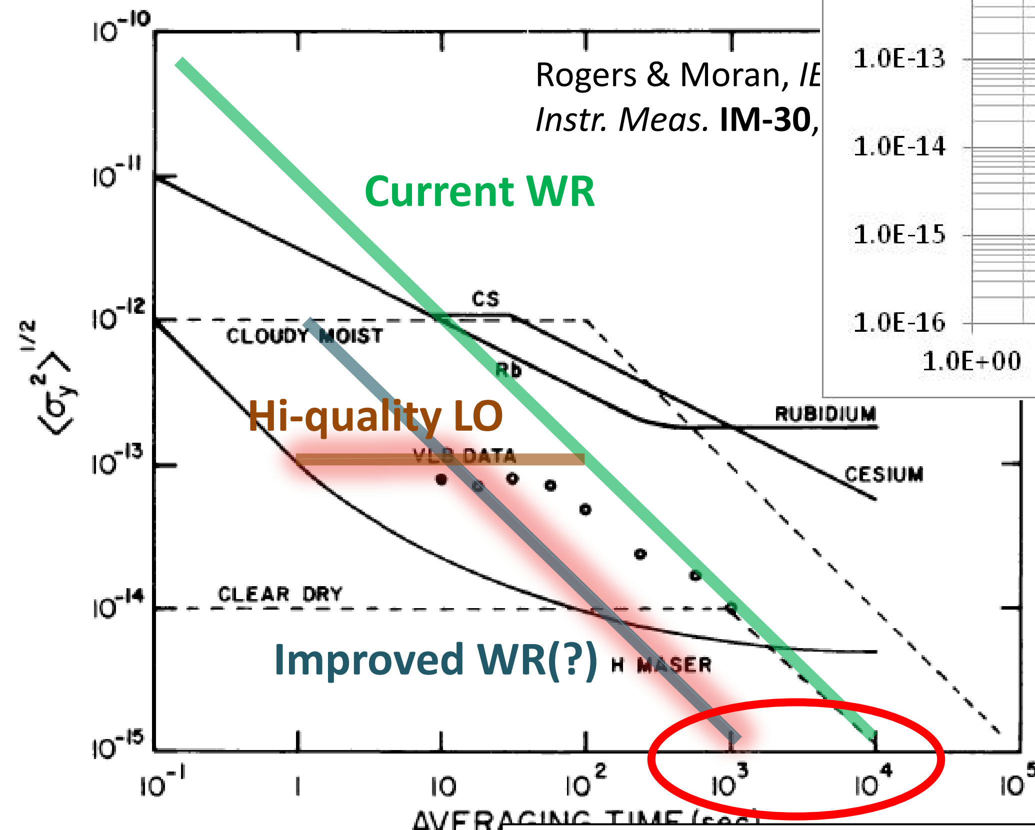
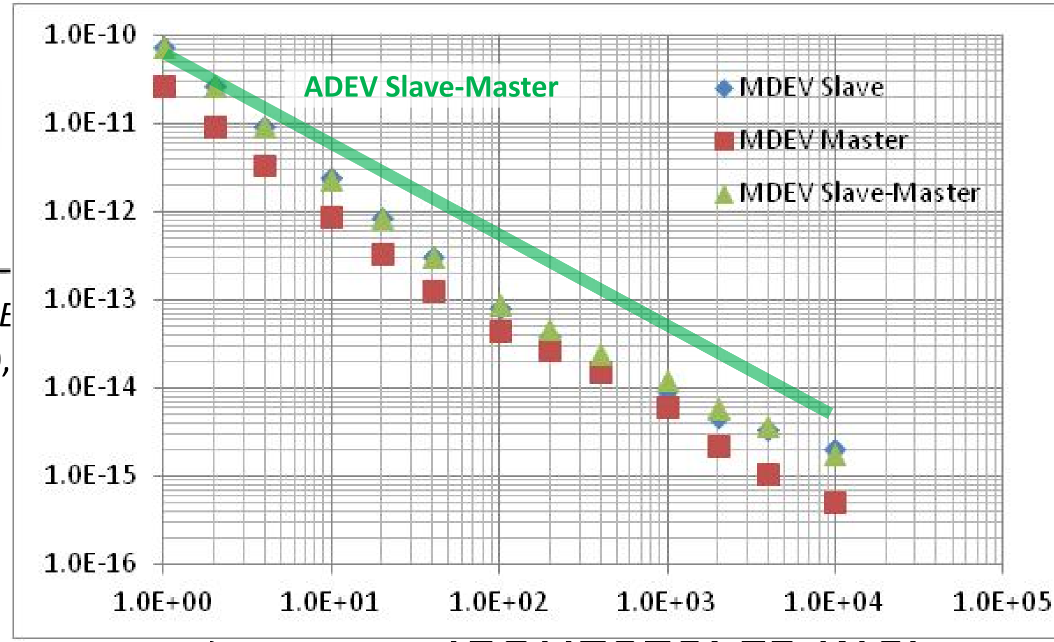


Fig. 1. Allan standard deviation … circles are measured Allan standar… observed during clear weather … (Westford, MA) and the Nat… (Greenbank, WV) using H-maser… limits of the Allan standard devia… conditions, with no allowance for the ionosphere instability.



Requires HW temperature monitoring and active compensation (software) - work in progress*

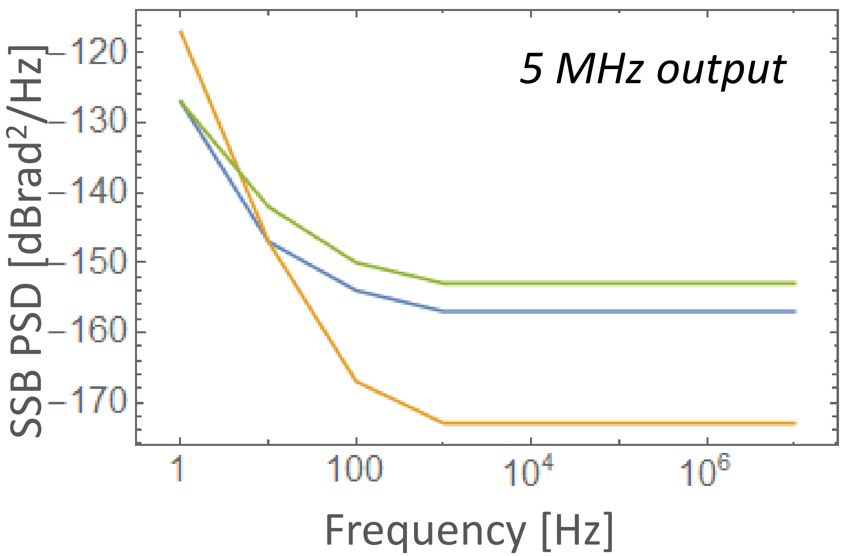
- Coordinated by ASTRON (M. Garett)
- Subtask: VLBI timing
  VU, JIVE, ASTRON, NIKHEF, SURFnet, University of Granada (Spain)
- **Improve WR and demonstrate…**

*G. Gong et al. (LHAASO, 2014)
DOI: 10.1109/RTC.2014.7097462

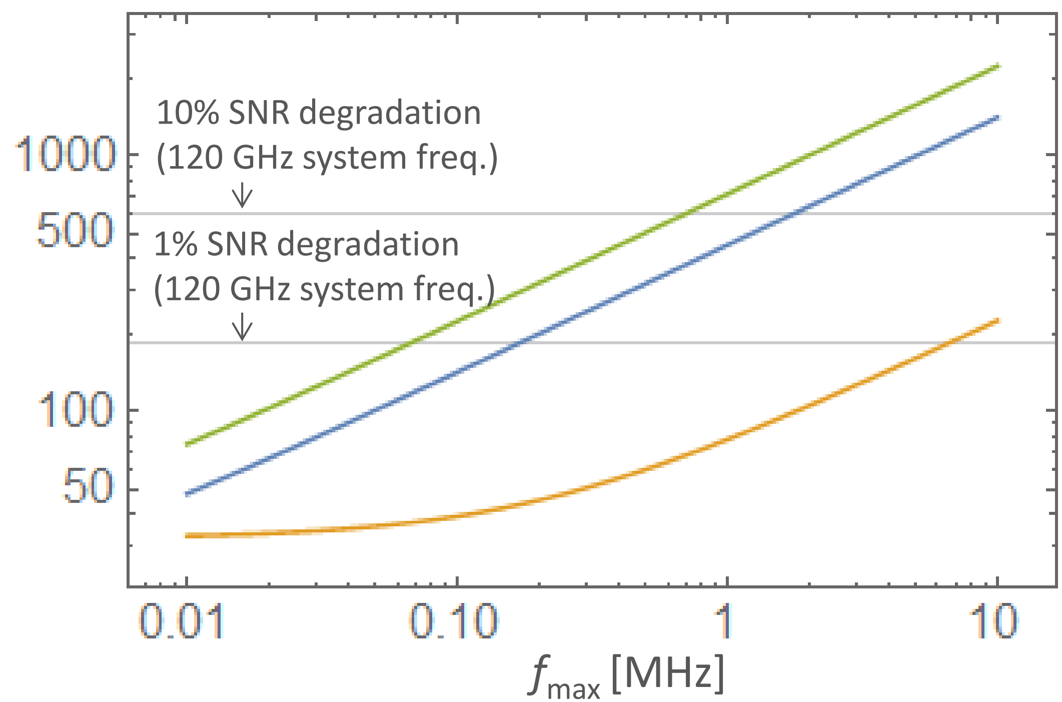
Jitter forecast

- Microsemi 1000C oscillator
- Oscilloquartz BVA
- Wenzel Associates

1000C Ultra High Performance Crystal Oscillator



rms jitter [fs] in interval [1 Hz, f_{max}]

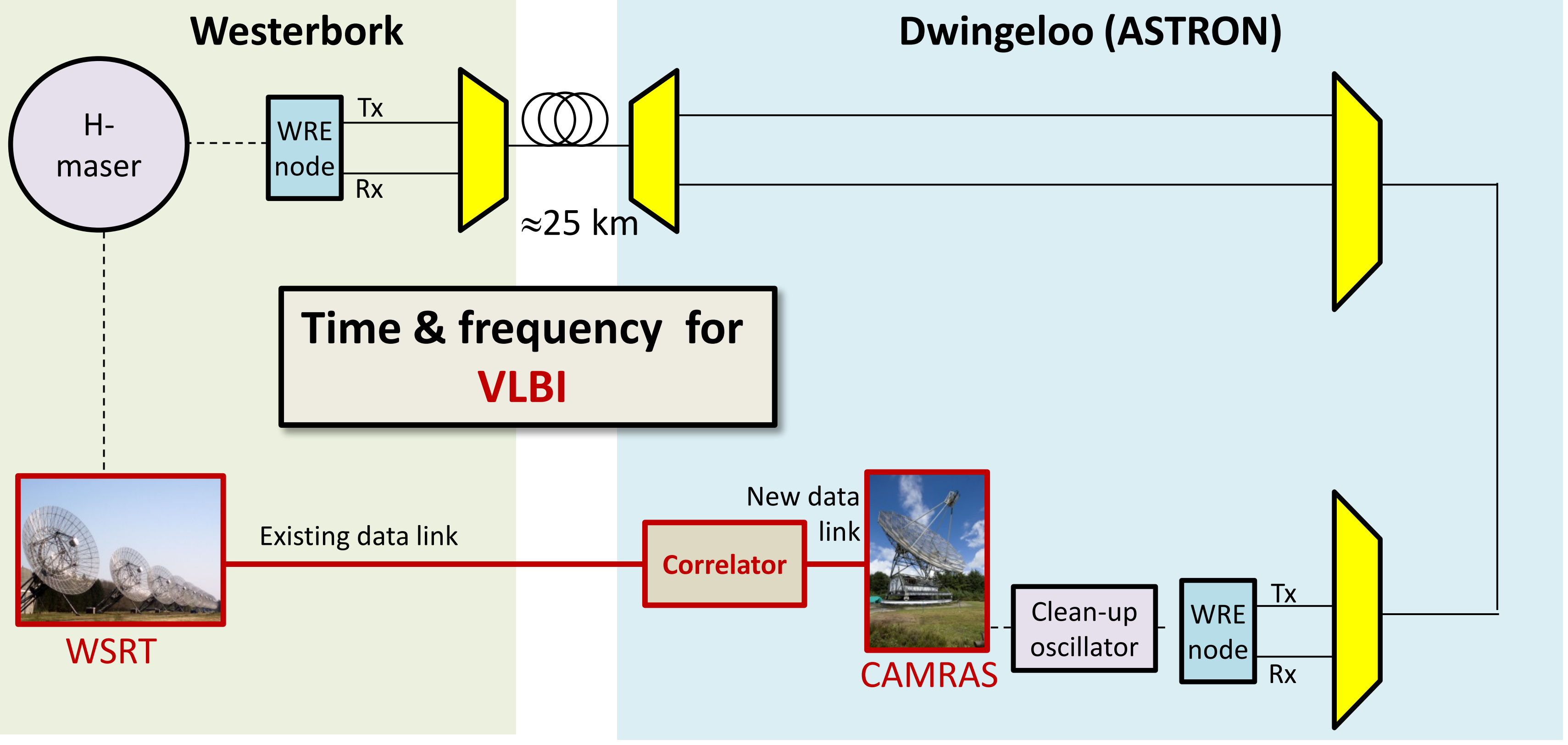


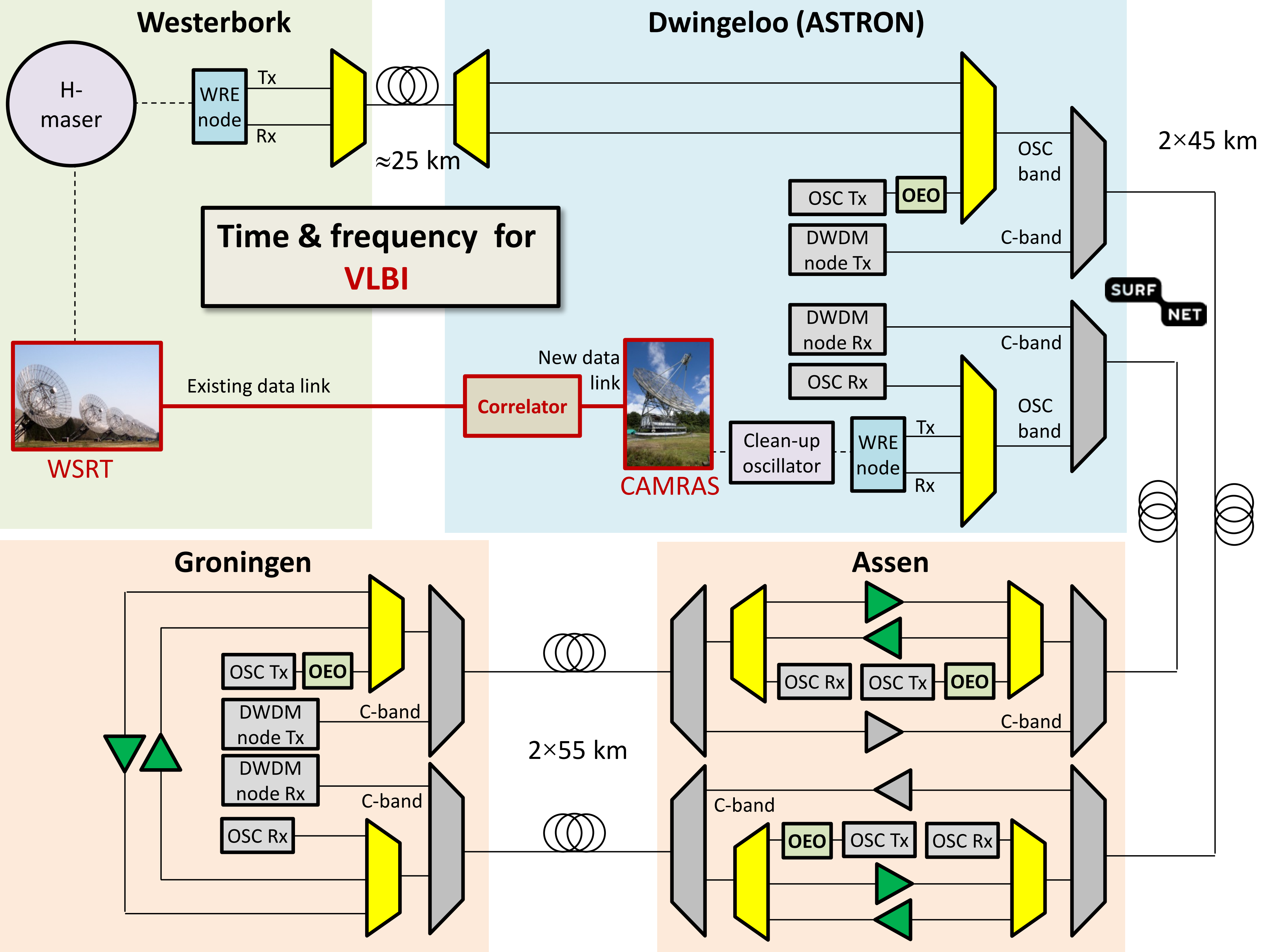
Economical solution (if it works):

WR equipment $1k - $3k

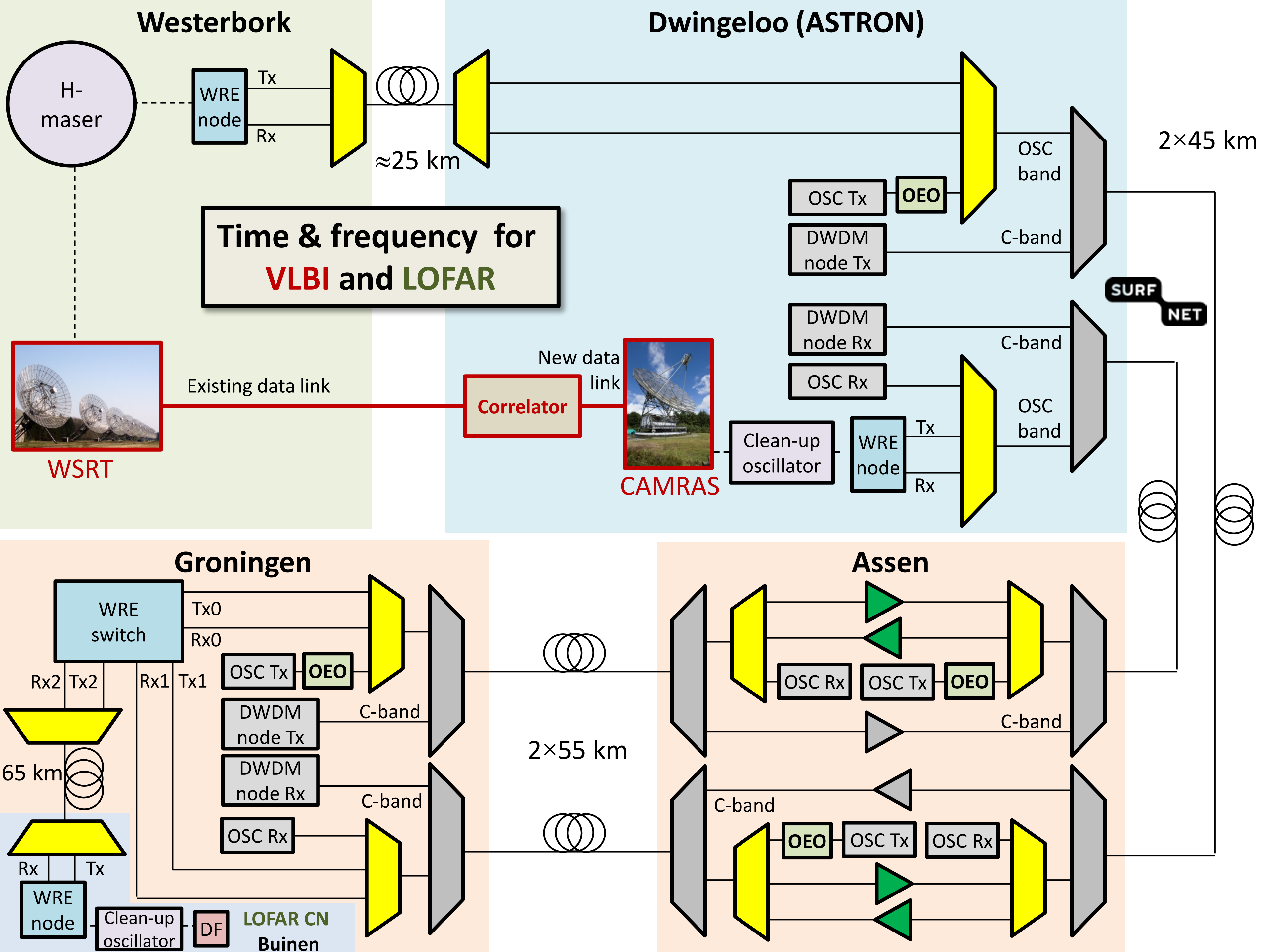
LO < $10k

Implementation of WR T&F distribution for radio astronomy in live telecom network


Westerbork
Dwingeloo (ASTRON)
H-maser
WRE node
Tx
Rx
≈25 km
Time & frequency for VLBI
Existing data link
Correlator
New data link
WSRT
CAMRAS
Clean-up oscillator
WRE node
Tx
Rx



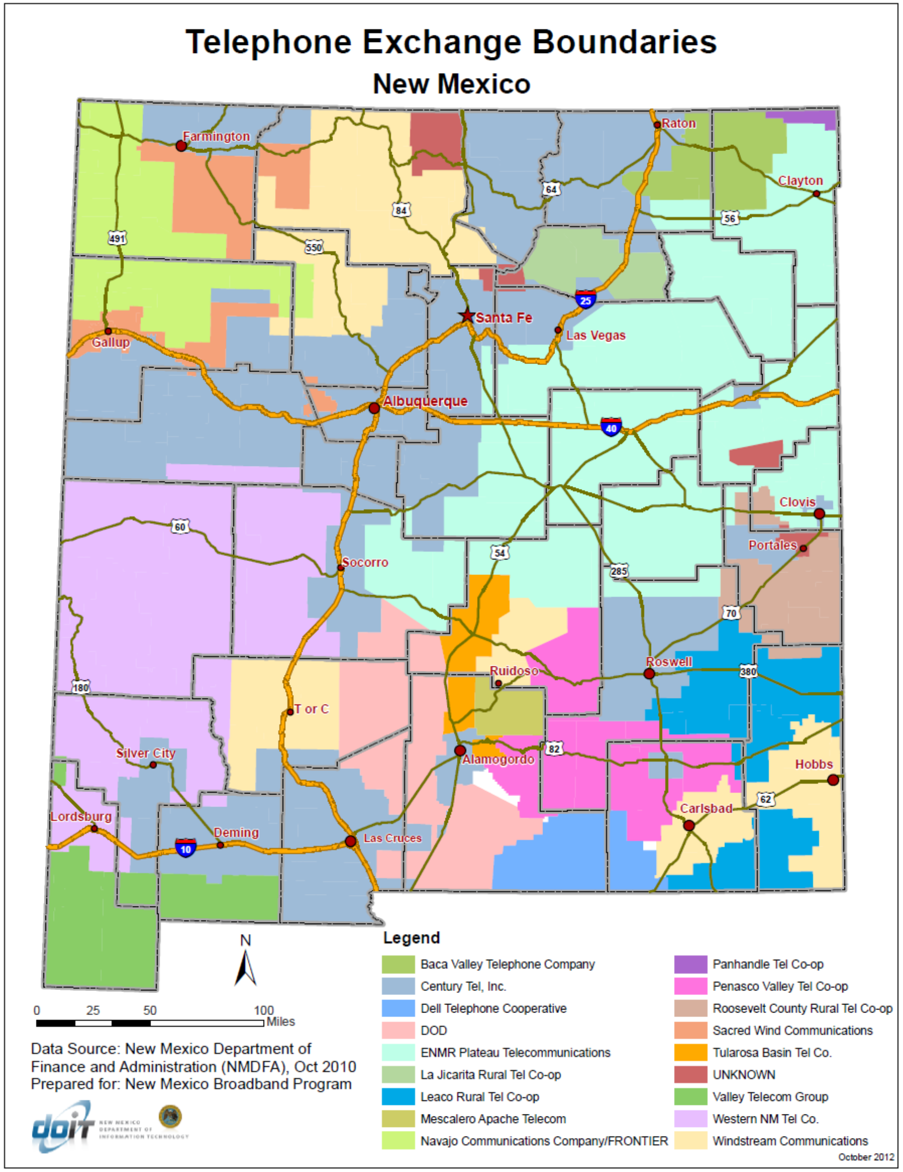
Westerbork
Dwingeloo (ASTRON)
H-maser
WRE node
Tx
Rx
≈25 km
OSC band
2×45 km
OSC Tx
OEO
C-band
DWDM node Tx
Time & frequency for VLBI
SURF NET
DWDM node Rx
C-band
New data link
OSC Rx
Existing data link
Correlator
OSC band
Clean-up oscillator
WRE node
Tx
Rx
WSRT
CAMRAS
Groningen
Assen
OSC Tx
OEO
OSC Rx
OSC Tx
OEO
DWDM node Tx
C-band
C-band
2×55 km
DWDM node Rx
C-band
C-band
OSC Rx
OEO
OSC Tx
OSC Rx



Westerbork
Dwingeloo (ASTRON)
H-maser
WRE node
Tx
Rx
≈25 km
2×45 km
OSC band
OSC Tx
OEO
DWDM node Tx
C-band
Time & frequency for VLBI and LOFAR
SURF NET
DWDM node Rx
OSC Rx
New data link
Existing data link
Correlator
WSRT
CAMRAS
Clean-up oscillator
Groningen
Assen
WRE switch
Tx0
Rx0
Rx2
Tx2
Rx1
Tx1
65 km
2×55 km
LOFAR CN Buinen
DF

Transport through DWDM in NM?

- Technologically feasible
- Is there an owner/operator of ‘interstate’ DWDM? (there has got to be!)
- Can the concept of T&F distribution/GPS-backup be escalated to an ‘issue of national importance’?
- Timing also helps 4G operators to upgrade to 4G LTE-TDD!



Can timing help phase calibration?

- Reduce time window for fringe search?
- Facilitate tropospherical phase drift retrieval algorithms?

Contributions by (among others)

… and collaborators at:

CERN ASTRON TU/e ugr Universidad de Granada university of groningen

Thanks!

Questions:
j.c.j.koelemeij@vu.nl