White Rabbit for long-haul fiber-optic distribution of high-precision clocks for VLBI

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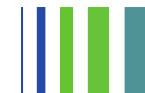Javier Diaz (Univ. Gr.)
Jeroen C. J. Koelemeij (VU)

Institute for Lasers, Life and Biophotonics
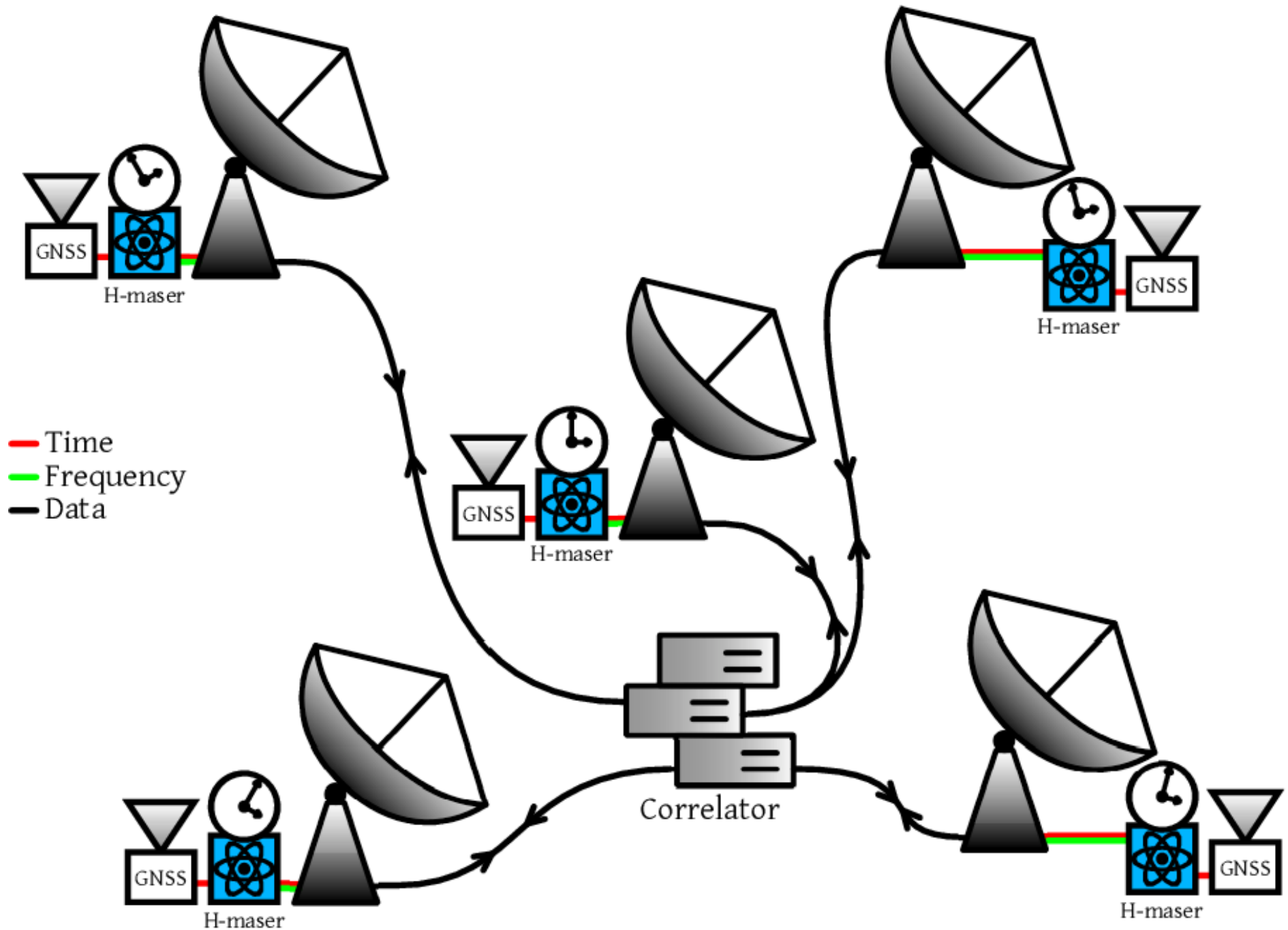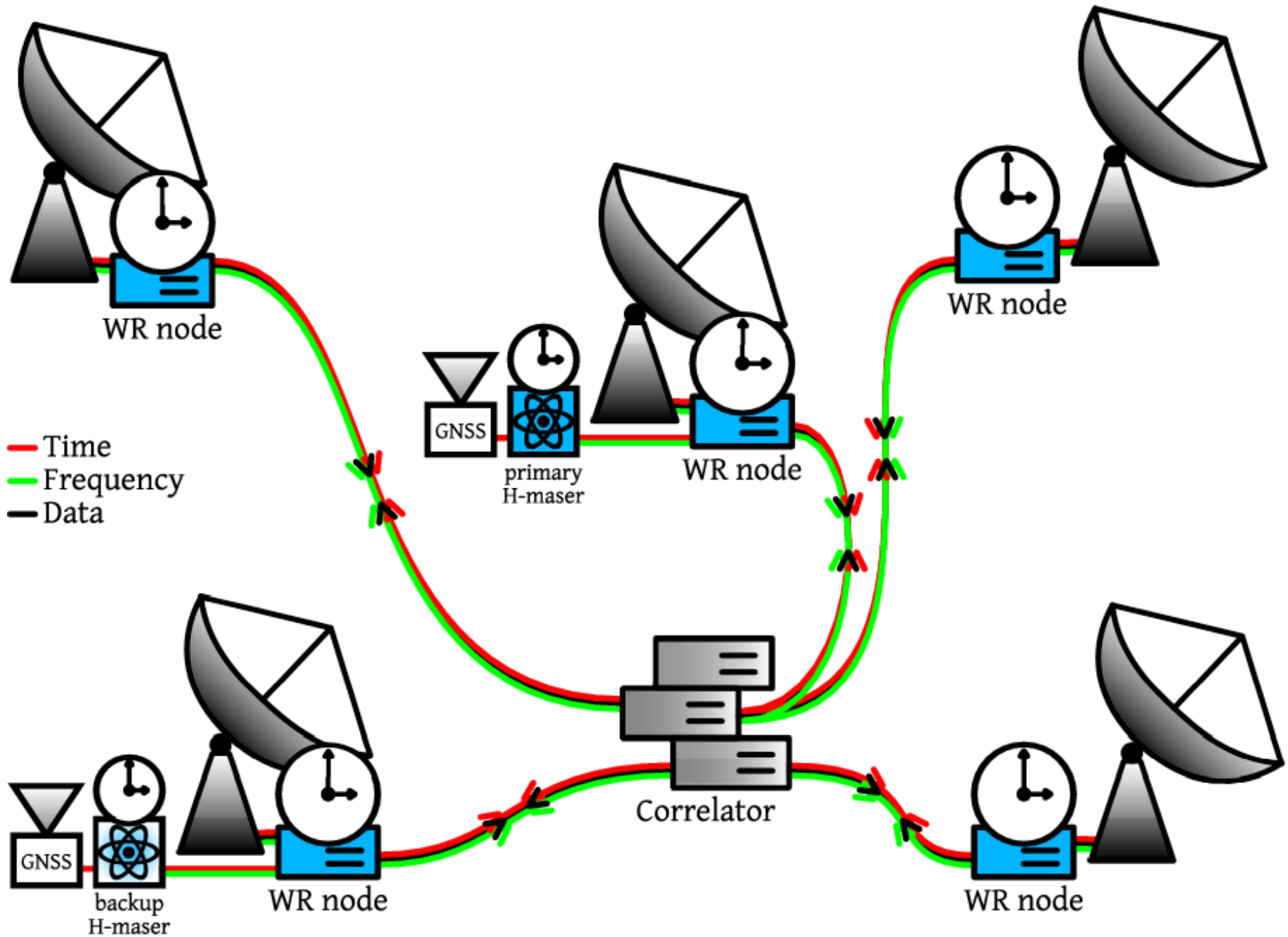Vrije Universiteit Amsterdam

ASTERICS and CLEOPATRA

- ASTERICS: Astronomy ESFRI and Research Infrastructure Cluster, €15 Million granted (H2020)
  - SKA, CTA, E-ELT, KM3NeT and smaller parties involved
  - see: www.asterics2020.eu
- CLEOPATRA (WP5.1):
  - **C**onnecting **L**ocations of **E**SFRI **O**bservatories and **P**artners in **A**stronomy for **T**iming and **R**eal-time **A**lerts.
  - Partners in WP5.1:
    ASTRON, CNRS, **JIVE**, **Vrije Universiteit**, Universiteit van Amsterdam, **Universidad de Granada**, Stichting Fundamenteel Onderzoek der Materie, Institut d'Estudis Espacials de Catalunya, GTD Systems & Software Engineering, STFC, Deutsches Elektronen-Synchrotron, and **SURFnet**

Fibre-optic time distribution for VLBI
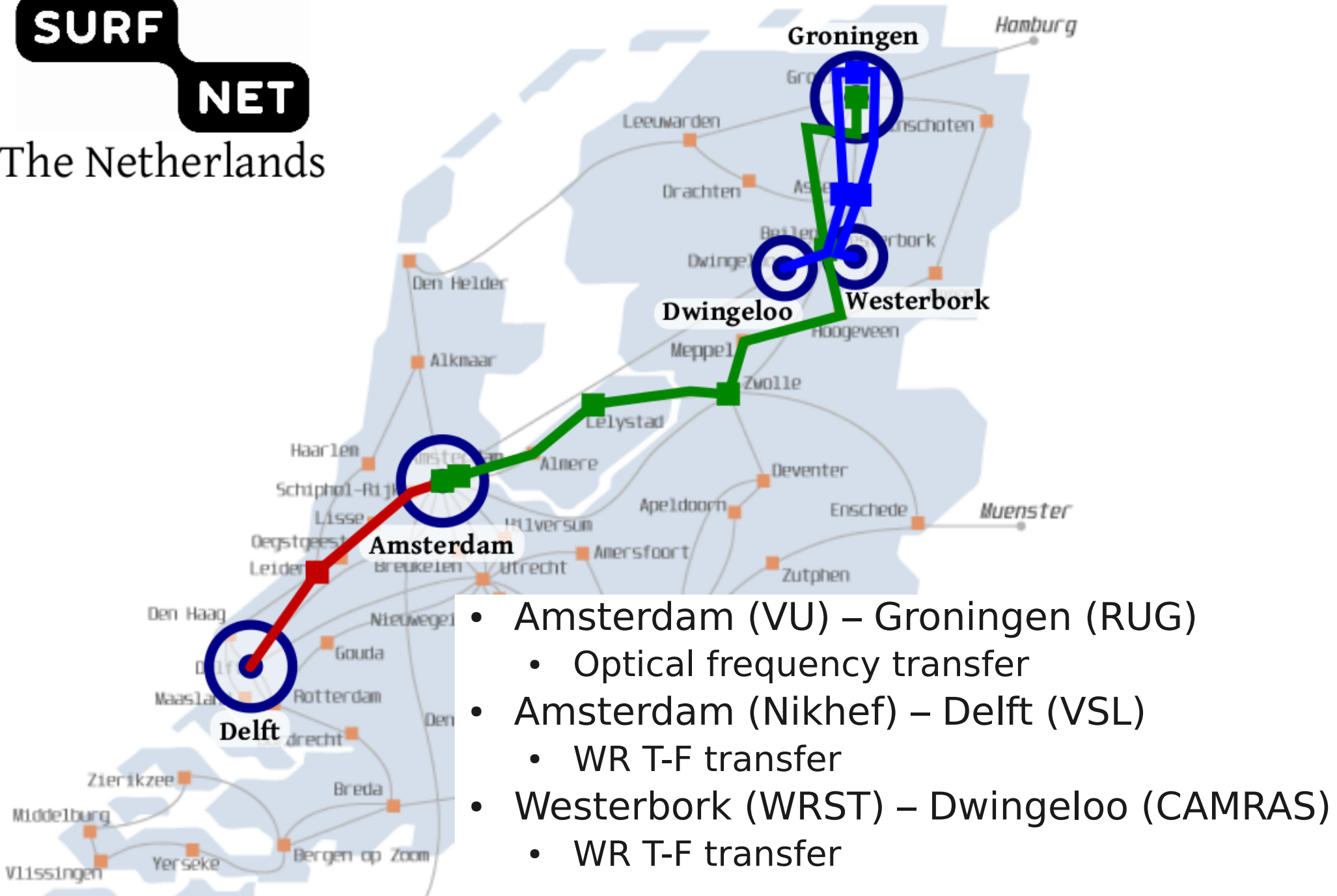
White Rabbit instead of H-masers

Time
Frequency
Data

GNSS
H-maser

GNSS
H-maser

GNSS
H-maser

GNSS
H-maser

GNSS
H-maser

Correlator

White Rabbit instead of H-masers

- Time
- Frequency
- Data

GNSS

primary H-maser

backup H-maser

WR node

Correlator

Optical T-F transfer in the Netherlands

- Amsterdam (VU) – Groningen (RUG)
  - Optical frequency transfer
- Amsterdam (Nikhef) – Delft (VSL)
  - WR T-F transfer
- Westerbork (WRST) – Dwingeloo (CAMRAS)
  - WR T-F transfer

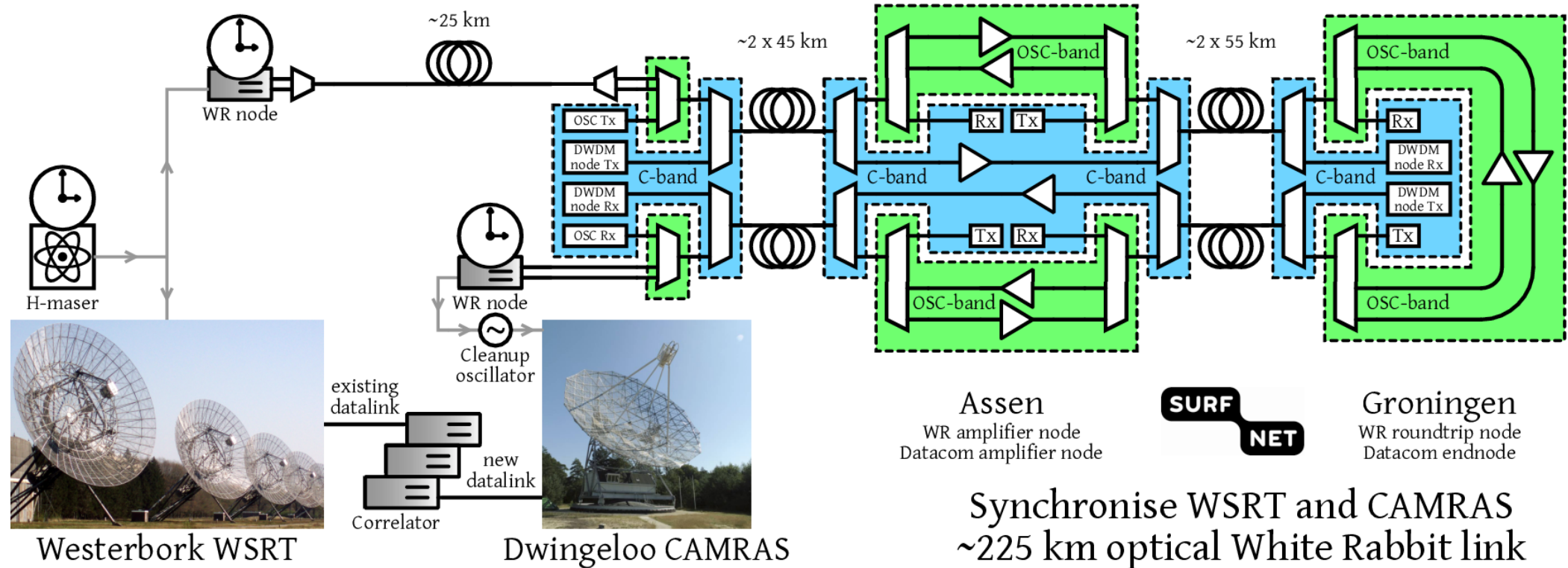# Frequency and time transfer for VLBI

- H-maser over fiber
 - $<10^{-12}$ frequency stability at 1 s
  - $<10^{-14}$ frequency stability at > 1000 s
  - translates roughly into < 10 ps timing jitter/drift at 1000 s
- Piggyback on existing fibre networks
  - outside of C-band
  - bidirectional fibre channels
  - bidirectional optical amplifiers

Patent no: WO2012161581A1

# Review of White Rabbit technology
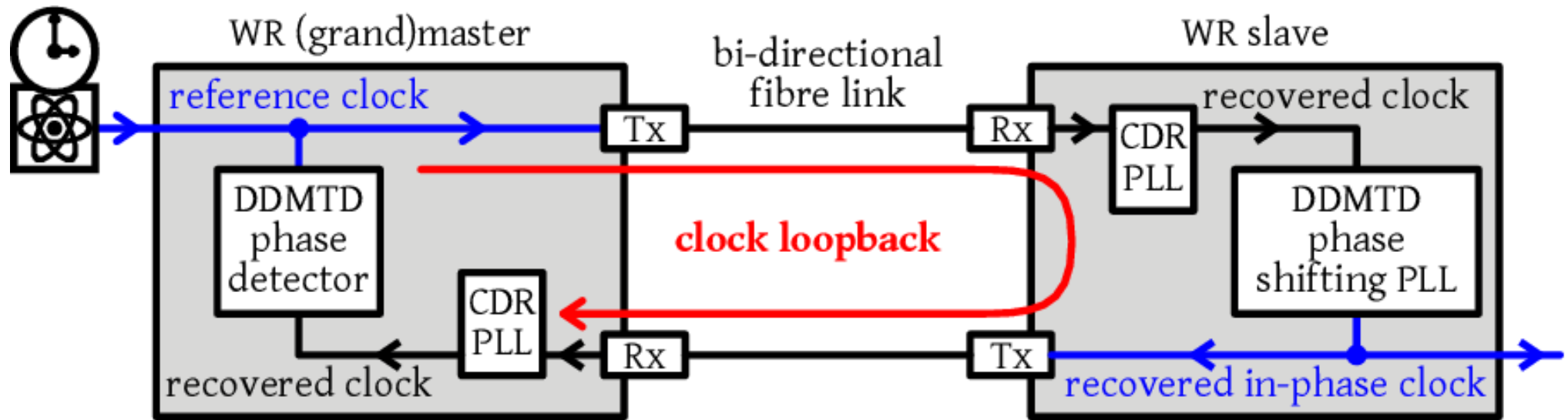

- Combination of:
  - Synchronous Ethernet (SyncE)
    - syntonisation of the clocks
  - Precision Time Protocol PTPv2 (IEEE1588)
    - time synchronisation of the clocks
  - Digital Dual Mixer Time Difference (DDMTD)
    - clock phase measurement and phase correction
- Bidirectional communication channel on **single** fibre
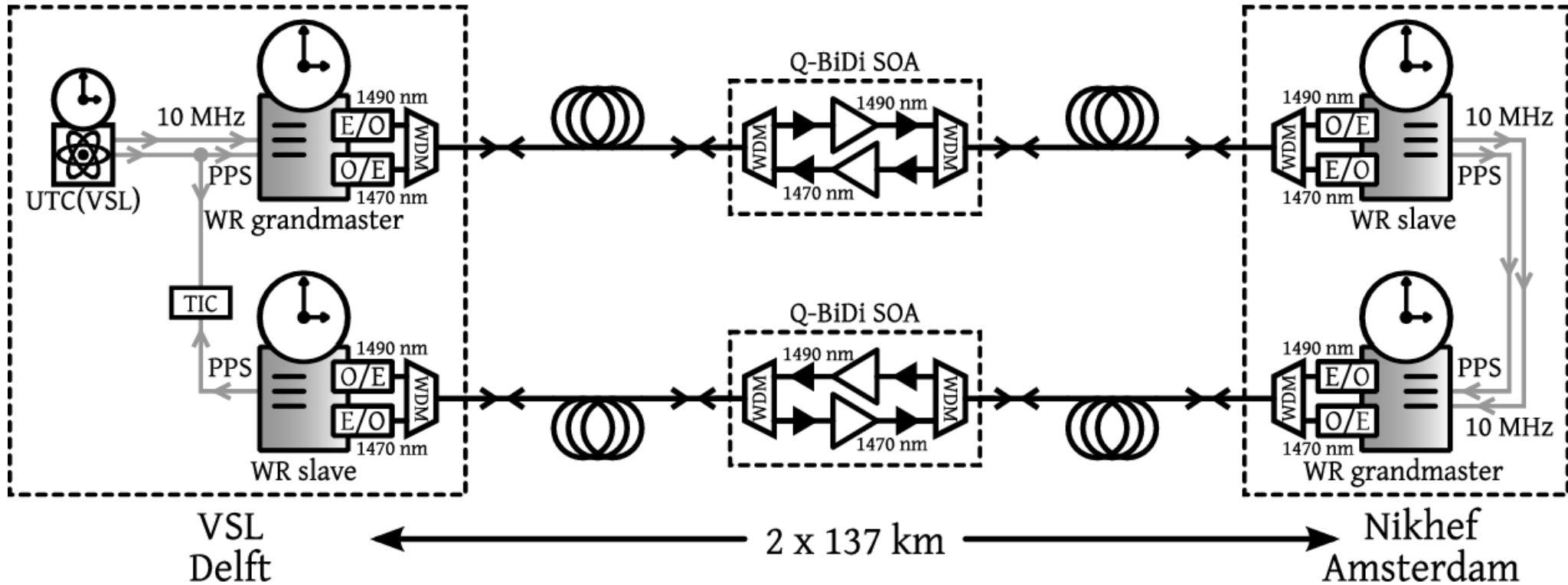- Bidirectional SFPs

http://www.ohwr.org/projects/white-rabbit
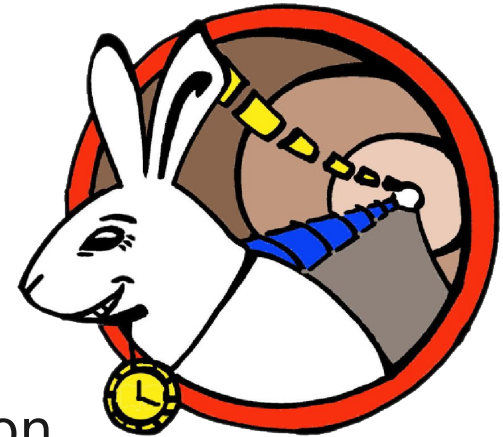
Long-haul link topologies

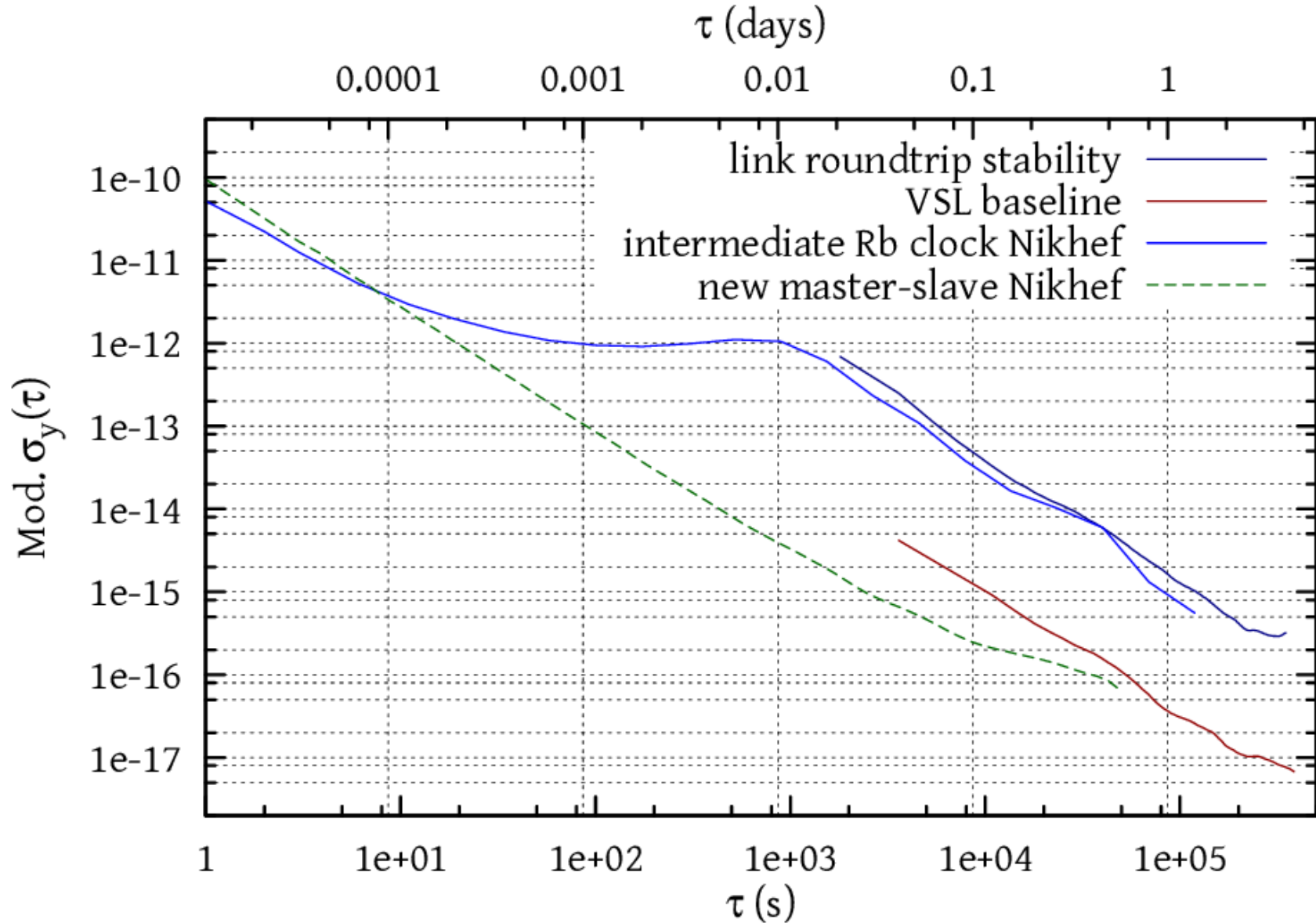- Create a bidirectional link in a unidirectional fibre-network
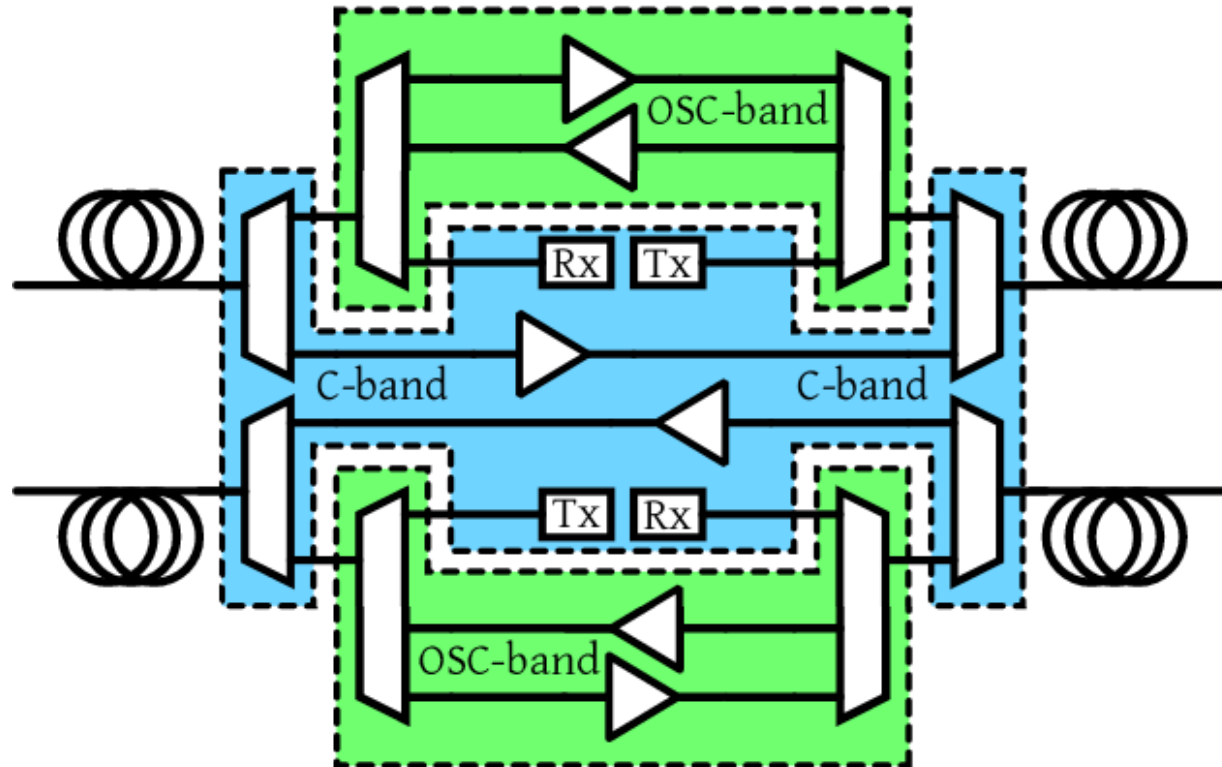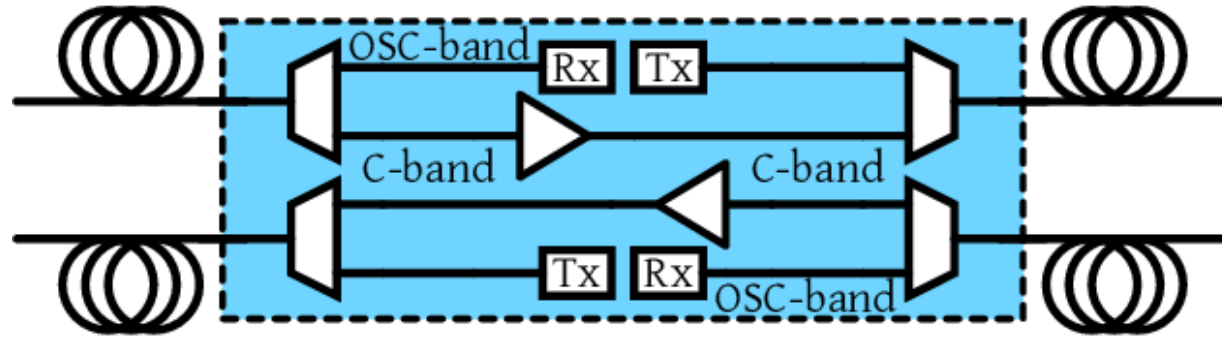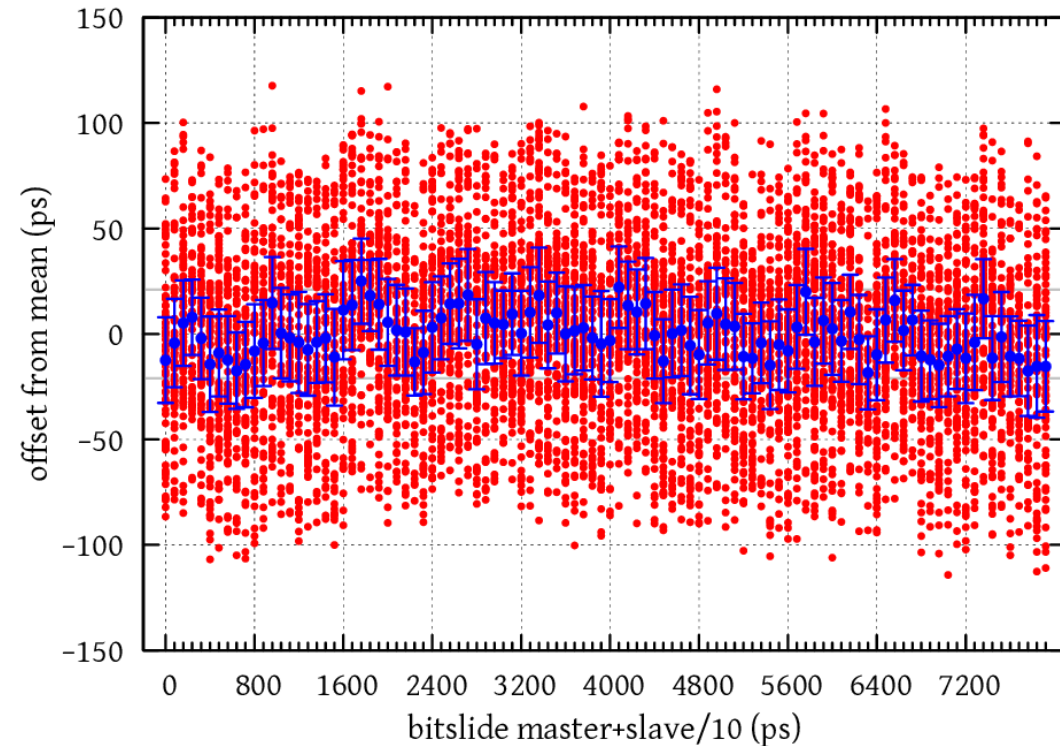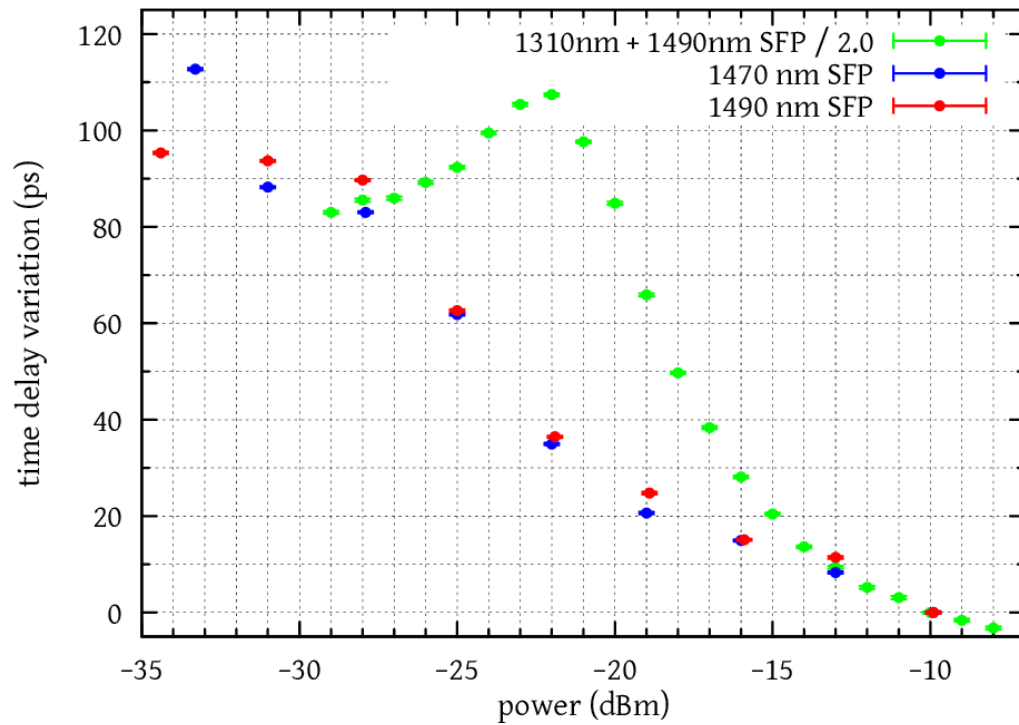
Delft – Amsterdam: link topology

- Connect VSL and Nikhef
- Double WR link with Grandmaster and Slave
- Two quasi bidirectional optical amplifiers

Delft – Amsterdam: results

- Time accuracy 2(8) ns
- Frequency limited to 10^{-14}@3.10^4s
  - several known issues, but for now we focus on better calibration

Ongoing delay calibration efforts

- Measurements of systematic effects
  - Receiver power dependence
  - Link restart accuracy
  - Temperature dependence (see [1,2])
- Delay calibration of *all* system components
- *In situ* chromatic dispersion determination

[1] H. Li *et al., IEEE Trans. on Nuclear Science*, 2014 (arXiv: 1406.4223)
[2] M. Lipinsky, May 2013, Torture report (ohwr.org)

Ongoing delay calibration efforts
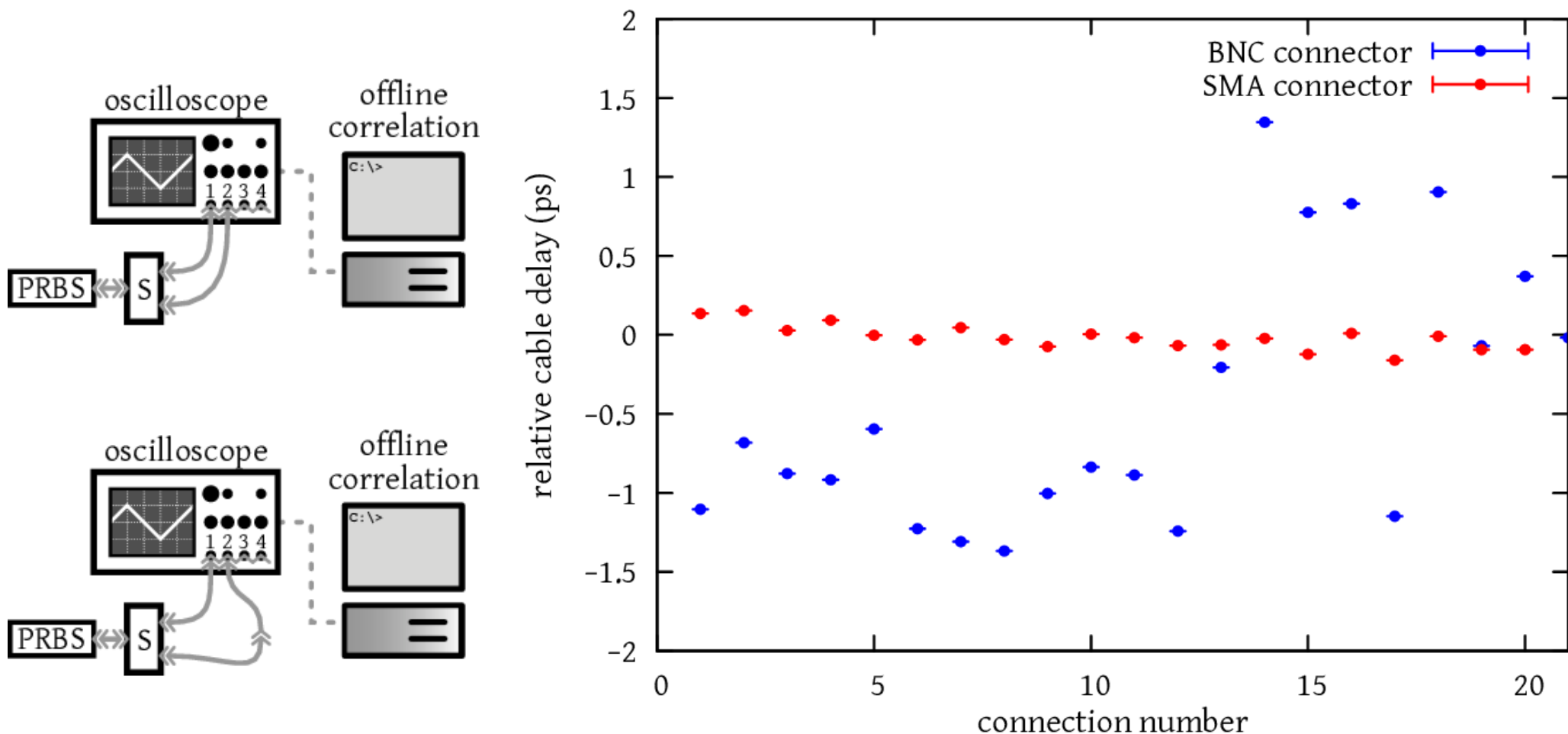
- High accuracy delay measurements [3]
  - using cross correlation on Gbit ethernet signals
- Measure "optical to electrical" and "electrical to optical" delays
- example shows measurement of connector reproduceability

[3] N. Sotiropoulos *et al.*, Opt. Express **21**, 32643-32654 (2013)

Clock requirements for VLBI
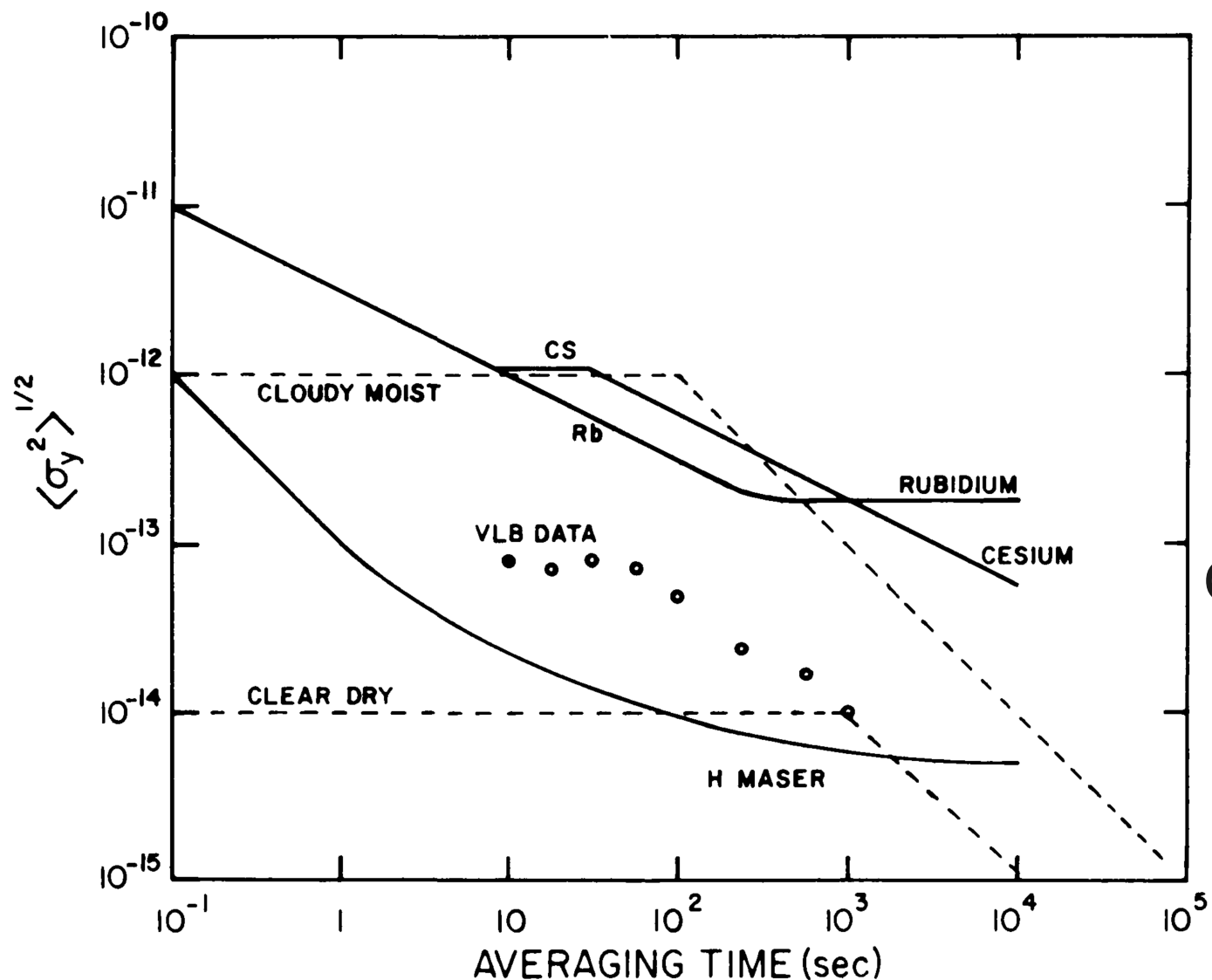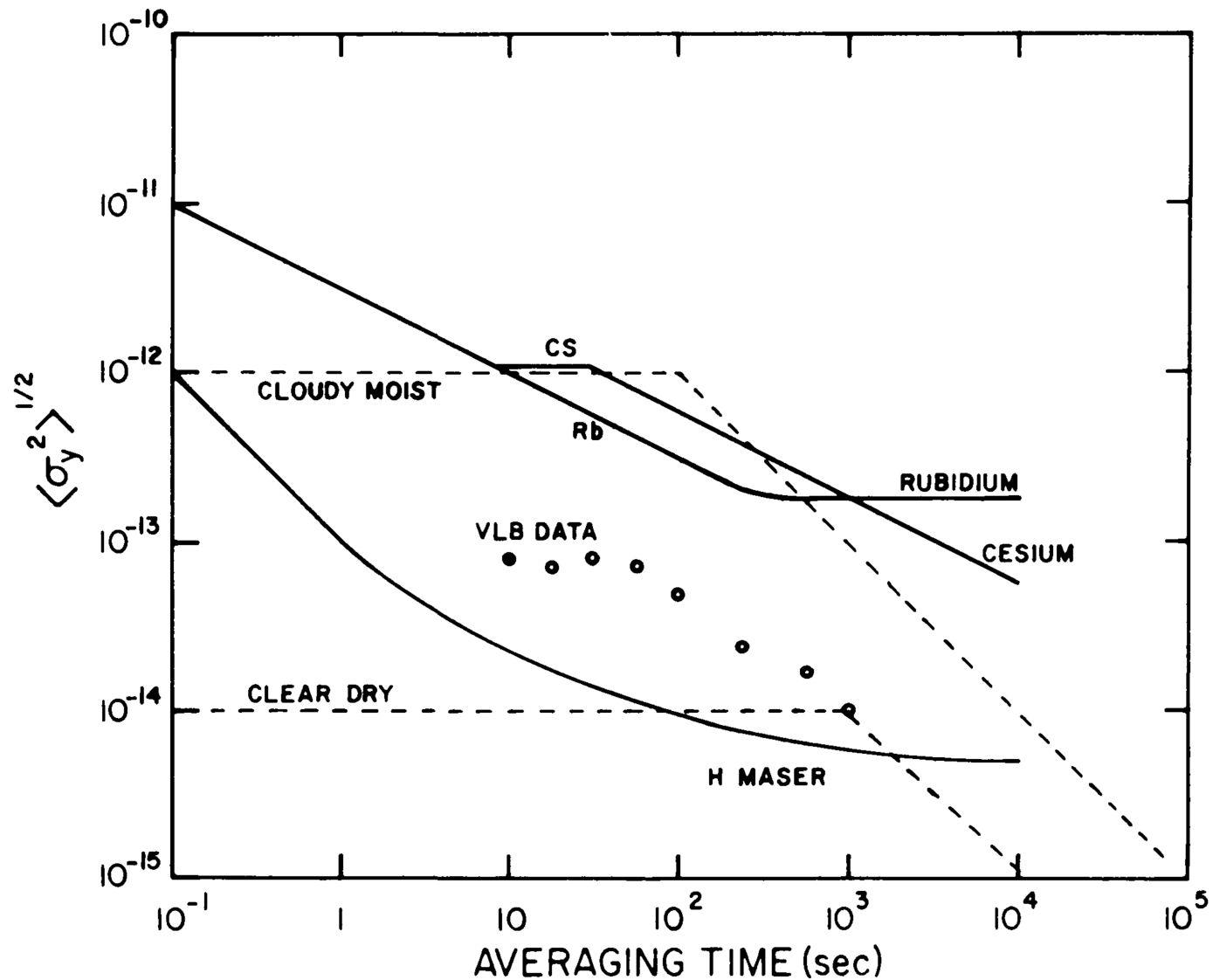

VLBI datapoints for 22 GHz

Even a H-maser is not yet an ideal clock for VLBI

our goal: VLBI at < 5GHz
  Rb oscillator is good enough

Our aim:
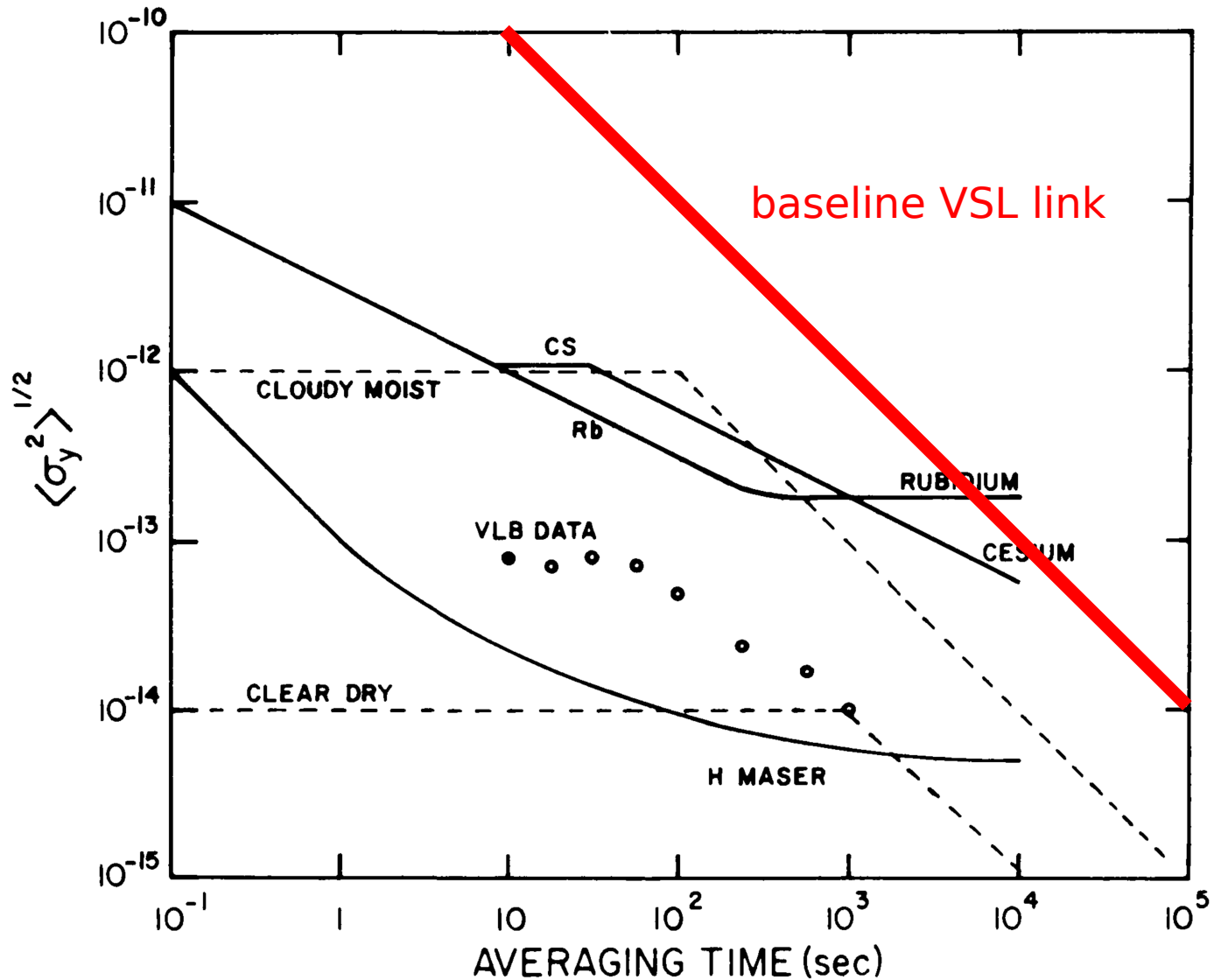 make White Rabbit as good as H-maser

- Ideal clock: $\sigma_y \leq 10^{-14}$ at 0.1 to 1000 seconds

  $\sigma_y < 10^{-11}/\tau$ at > 1000 seconds

White Rabbit for VLBI

- multiple PLL's involved in locking bitclocks
- slow feedback on slave phase (with PTP rate 1/s)
- short term stability in slave comes from local clock

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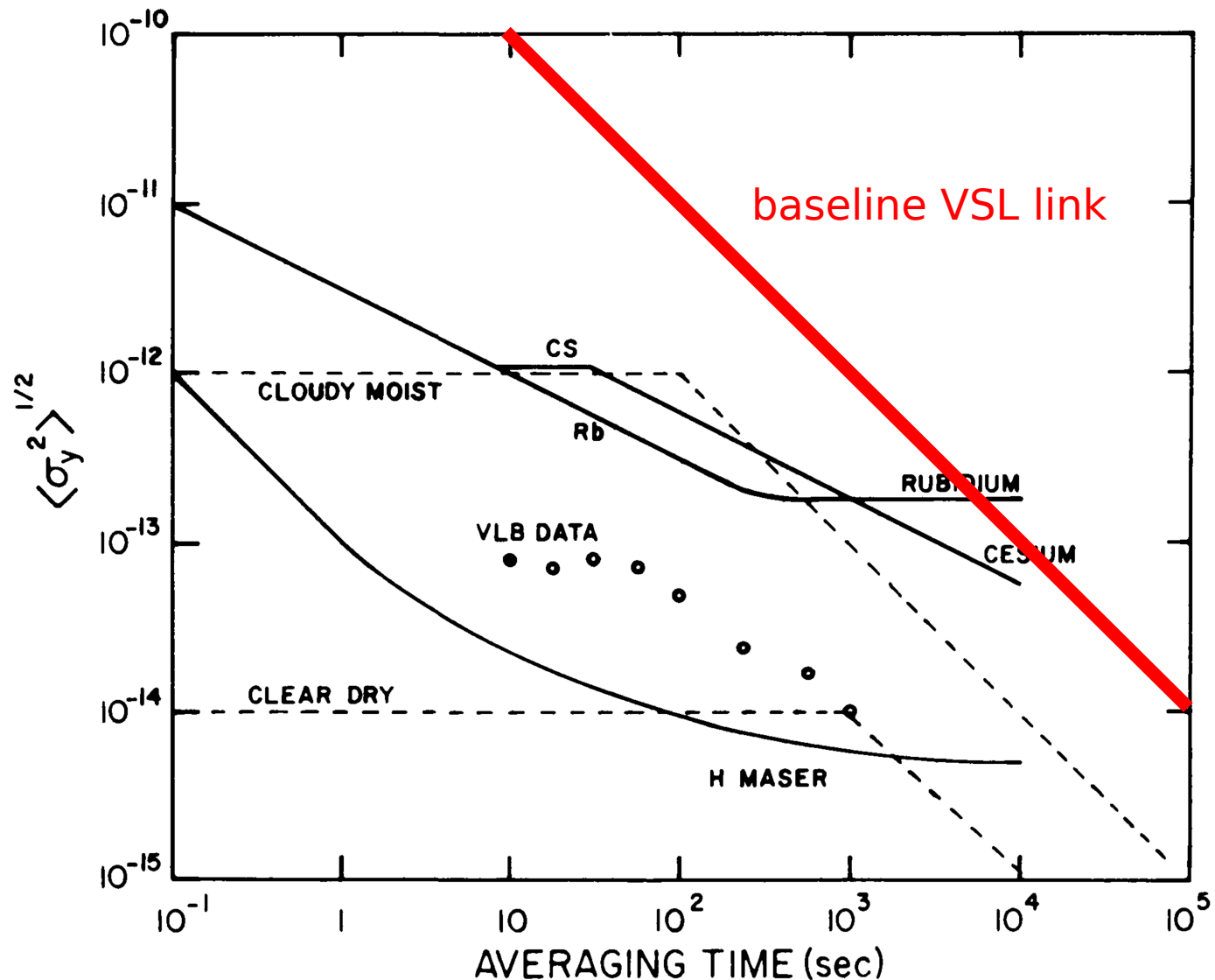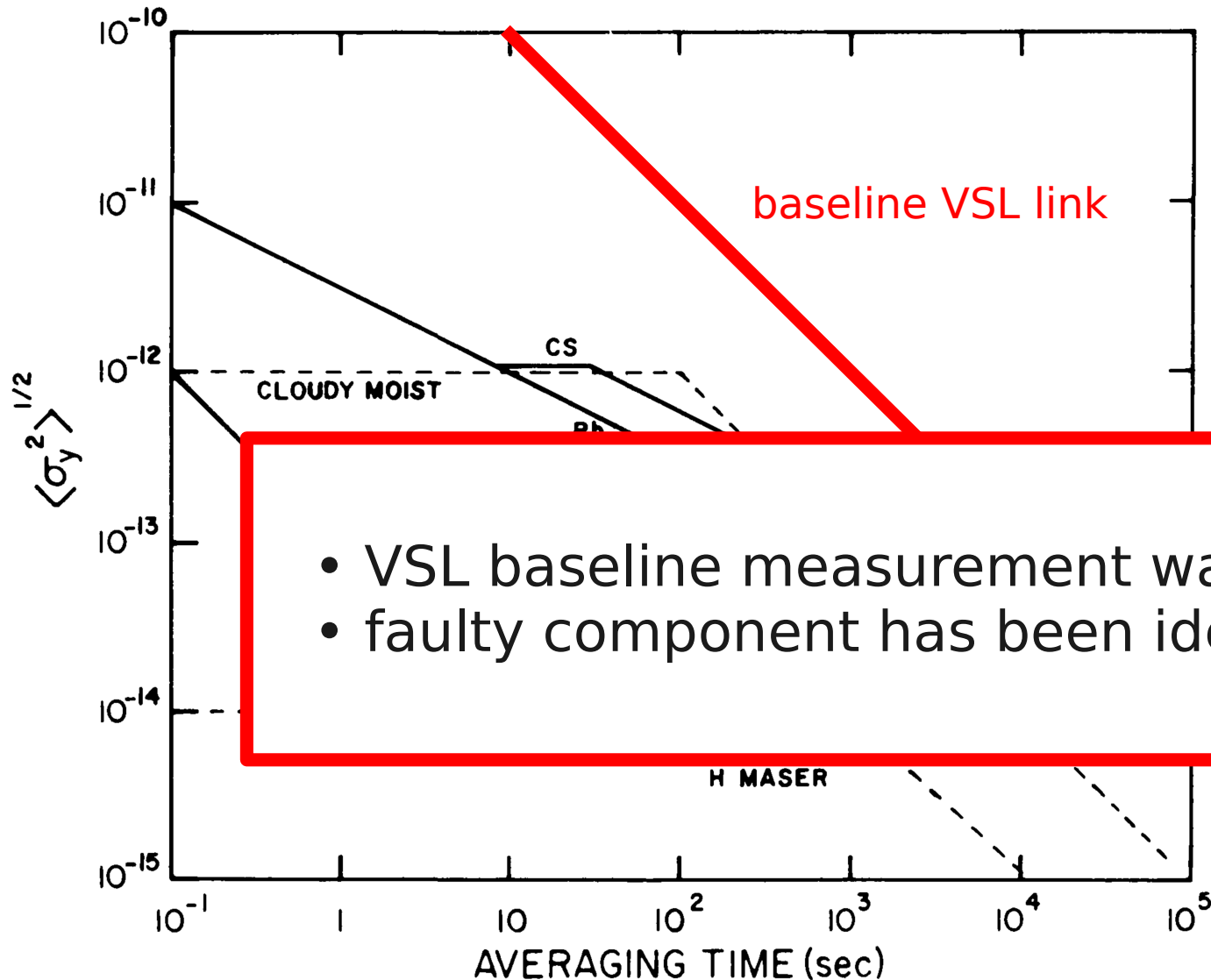

can it be done?

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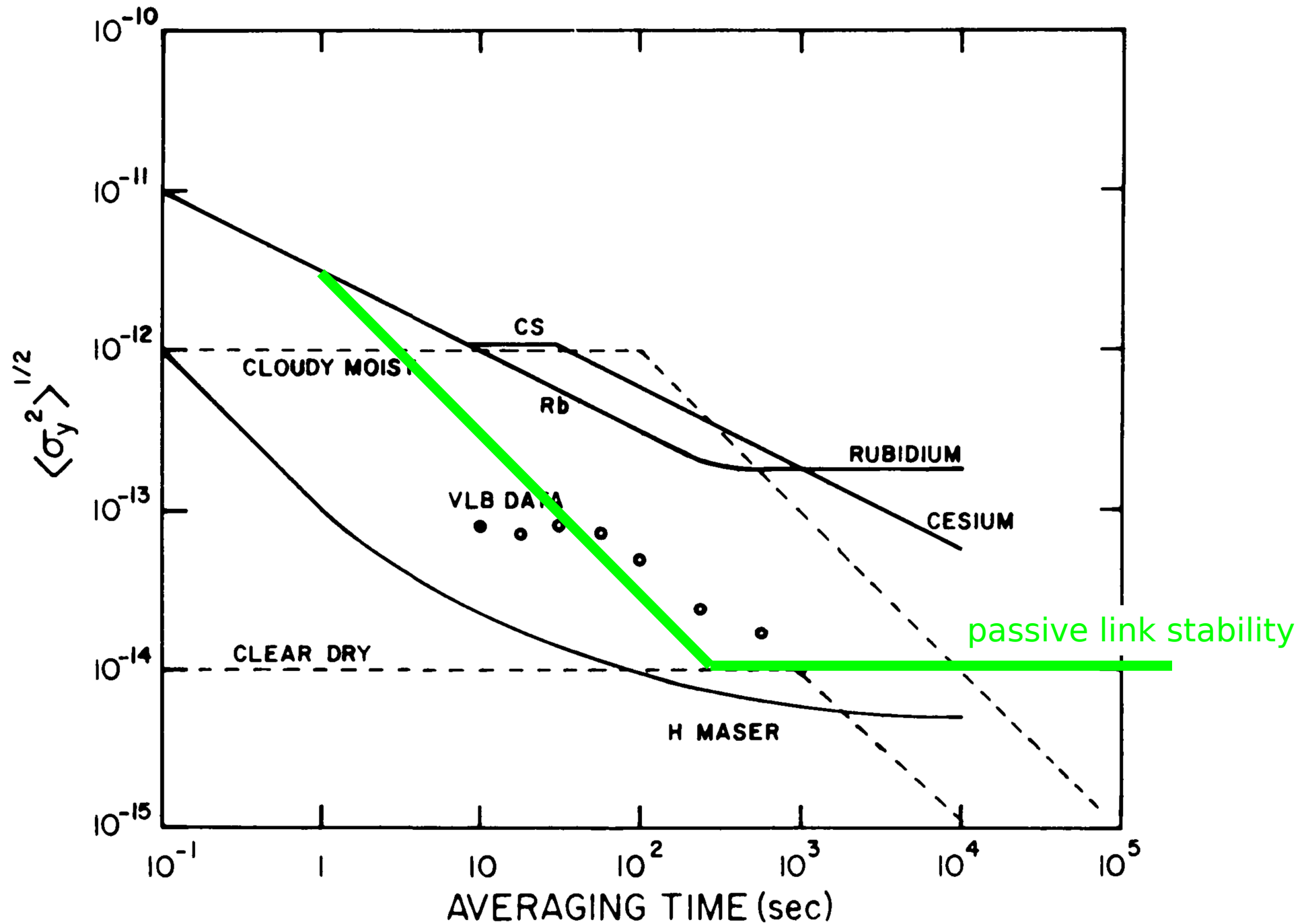
White Rabbit for VLBI

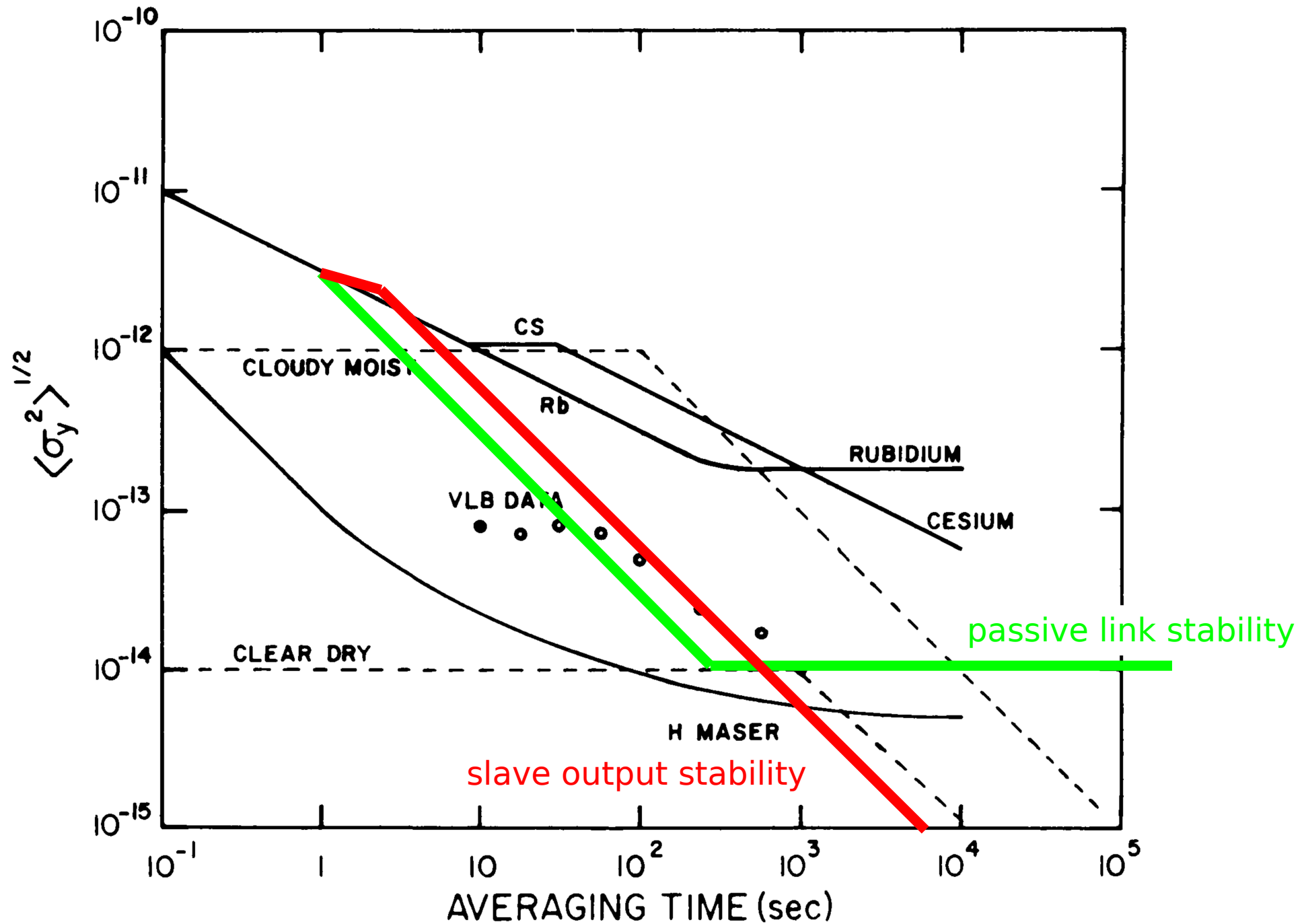

baseline VSL link

can it be done?

- VSL baseline measurement was flawed
- faulty component has been identified

- multiple PLL's involved in locking bitclocks
- slow feedback on slave phase (with PTP rate 1/s)
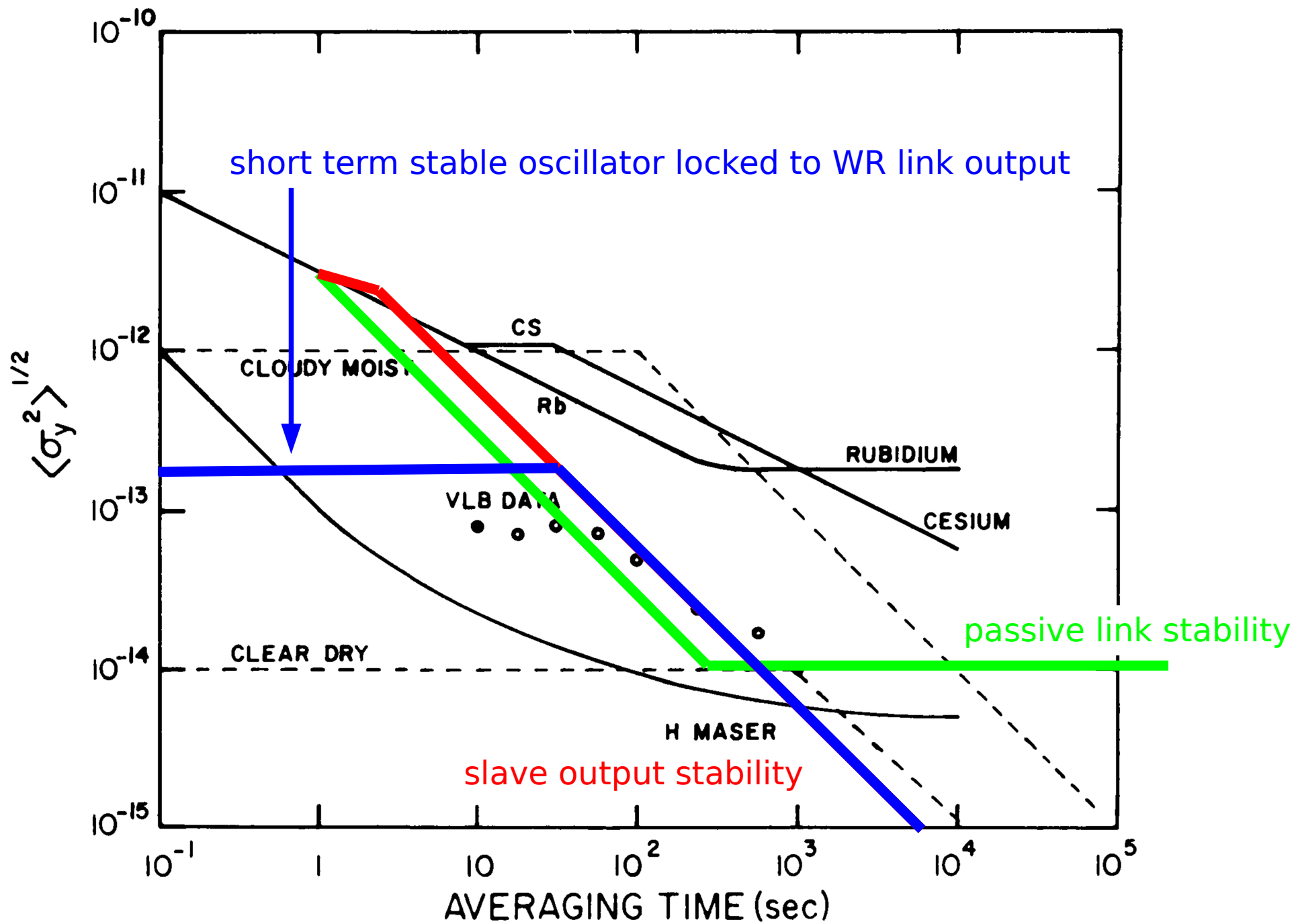- short term stability in slave comes from local clock

White Rabbit for VLBI, WR internal data

White Rabbit for VLBI, WR internal data

White Rabbit for VLBI, WR internal data

Conclusions:

- Analysis shows feasibility
- System components available
  - White Rabbit boards
  - Bidirectional amplifiers
  - Low phase-noise oscillators
- Westerbork – Dwingeloo link: building can start

Outlook:

- Test cleanup oscillator strategy
- Study WR behaviour on long link
  - implement dispersion compensation
- Do VLBI
- Improve system further
  - better White Rabbit nodes

White Rabbit for VLBI, WR internal data

Figure with axes labeled $\langle \sigma_y^2 \rangle^{1/2}$ (vertical) and AVERAGING TIME (sec) (horizontal). Annotations: "short term stable oscillator locked to WR link output", "external measurement on short fiber", "passive link stability", "slave output stability". Chart labels include CLOUDY MOIST, Cs, Rb, RUBIDIUM, CESIUM, VLB DATA, CLEAR DRY, H MASER.