Time and Frequency Requirements for Radio Astronomical Interferometry

JIVE
Joint Institute for VLBI
ERIC

EUROPEAN VLBI NETWORK

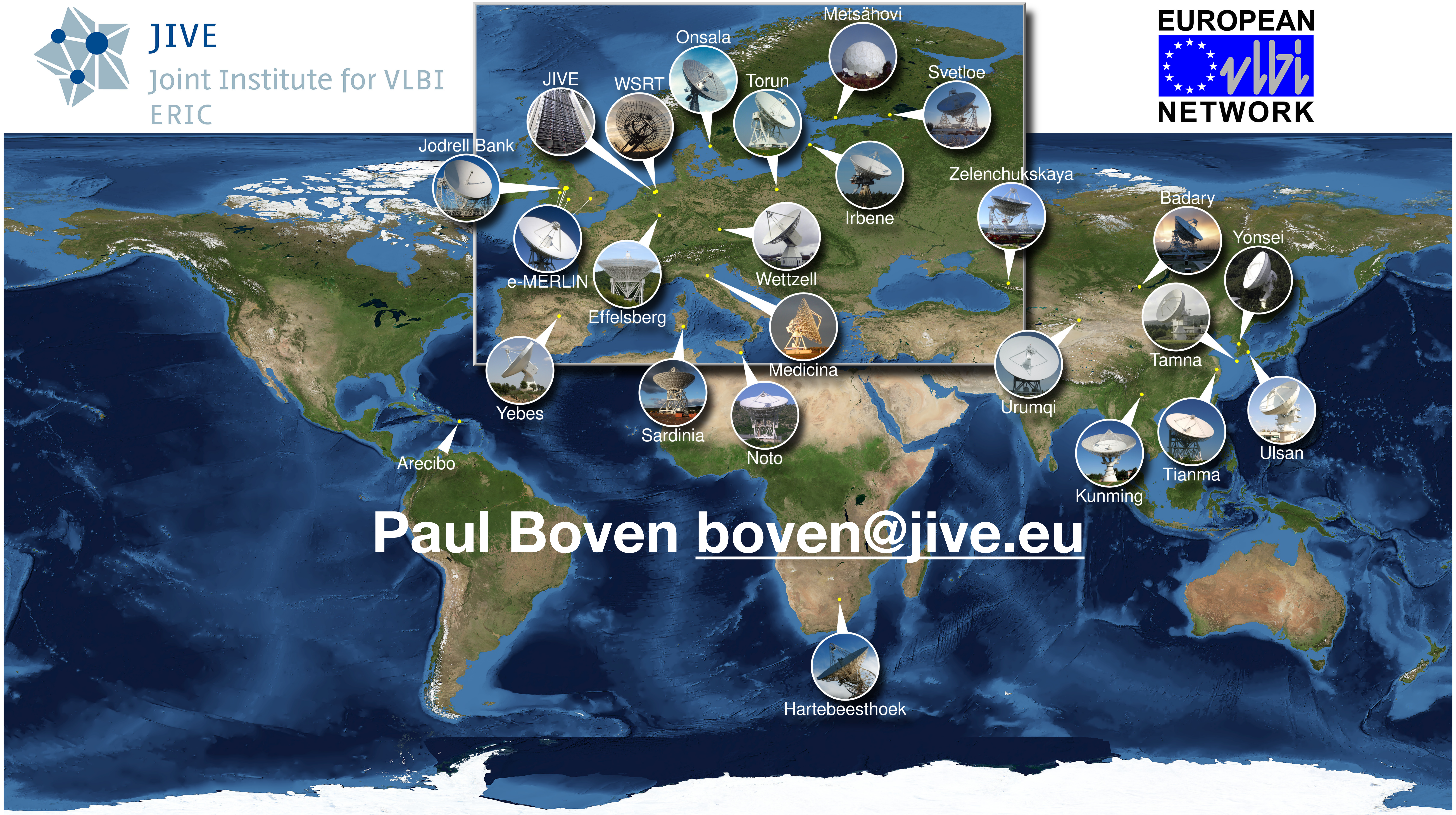

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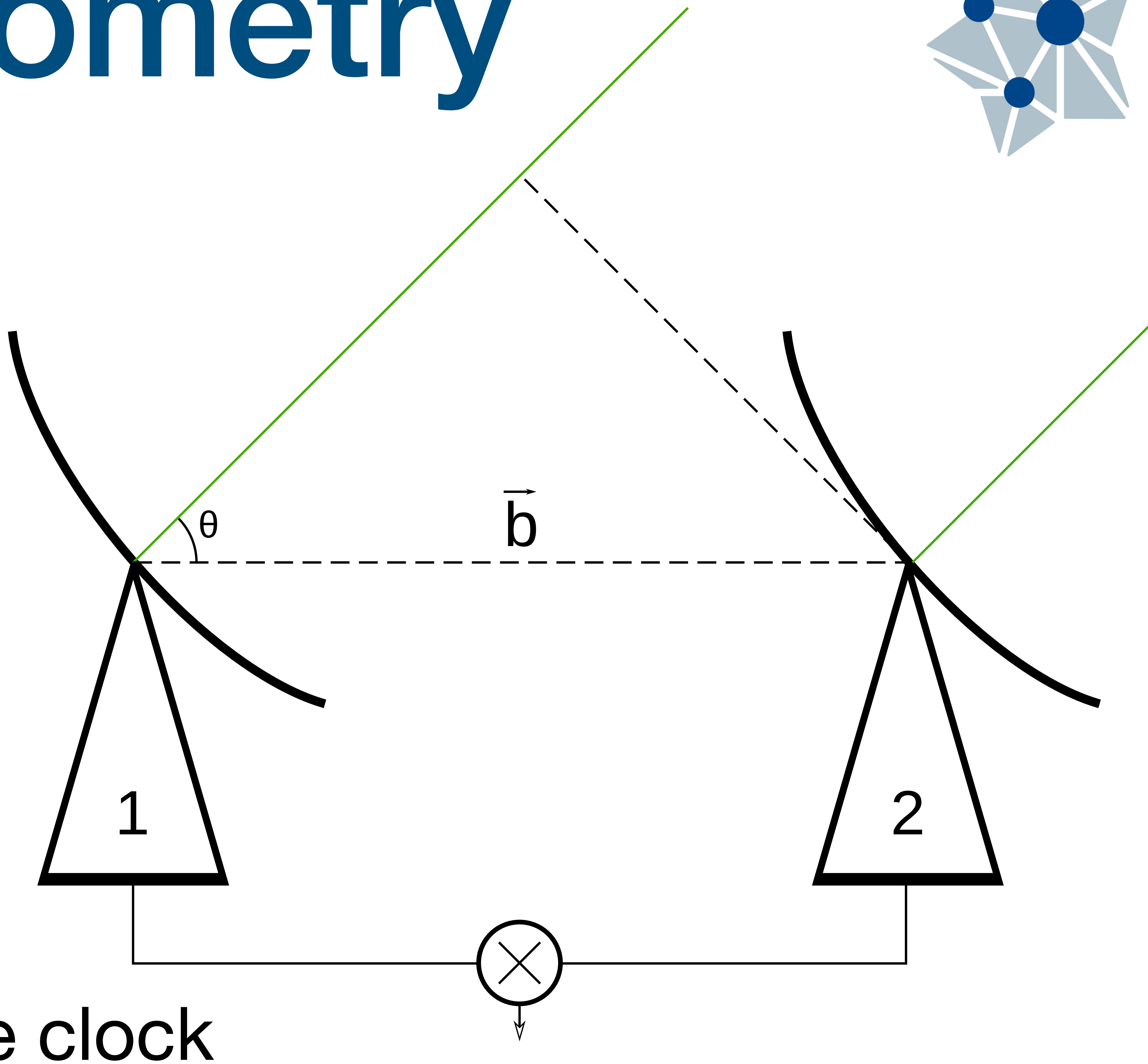
Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

Radio Interferometry

- A virtual radio telescope, where resolution increases with the distance between the dishes, and the observing frequency
- Phase / delay measurement can be transformed back into a radio ‘image’ of the sky
- Requires identical or at least very stable clocks at each receiver
  - ‘Connected Interferometers’ distribute a single clock
  - VLBI (Very Long Baseline Interferometry): stations at (inter)continental distances, each with its own H-maser
- VLBI provides unsurpassed resolution (sub milli-arcsecond)



Stability Requirement

- Stable to within a fraction of the phase at the observing frequency
  - 10 GHz: period is 100ps

- Integration time limited by ionosphere / troposphere
  - 1000s at 10 GHz requires ~1E-14 ADEV @ 1000s
  - Requires active H-maser (or better…)

- To mitigate against ionospheric effects, we use ‘phase referencing’
  - Iterate between a strong, compact radio source, and the science target
  - Cycling period of just a few minutes
  - Also removes reference frequency errors

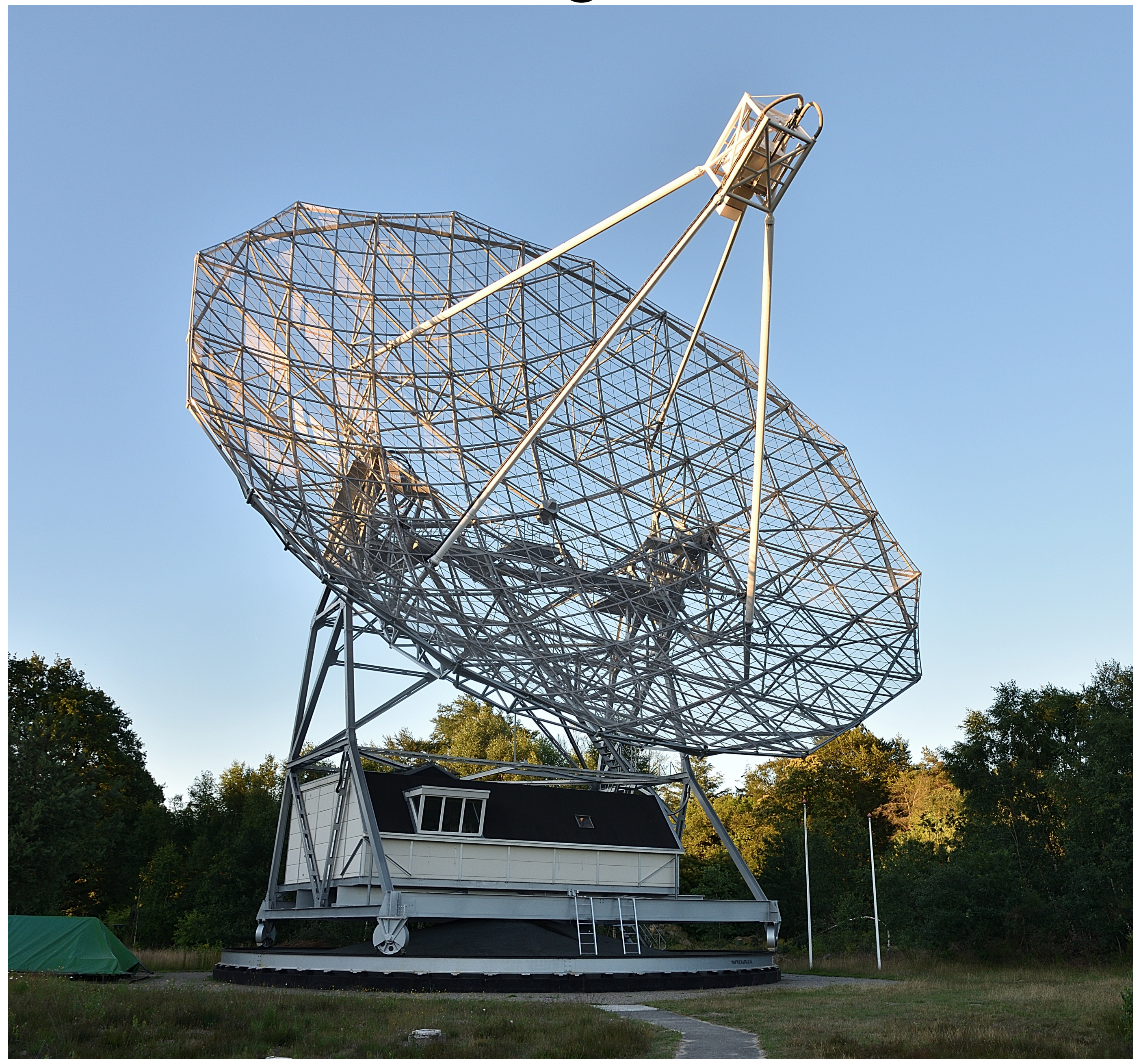
- ‘Clocks searching’ at start of observation by looking at strong source
  - Calibrate initial H-maser time and frequency offset, and drift

The Asterics Project

WSRT

ASTRON

Dwingeloo



169 km SURFnet DWDM

35 km of dark fiber

- Operated by ASTRON
- Member of EVN
- Hydrogen Maser

- Owned by ASTRON
- Operated by Volunteers
- No Hydrogen Maser

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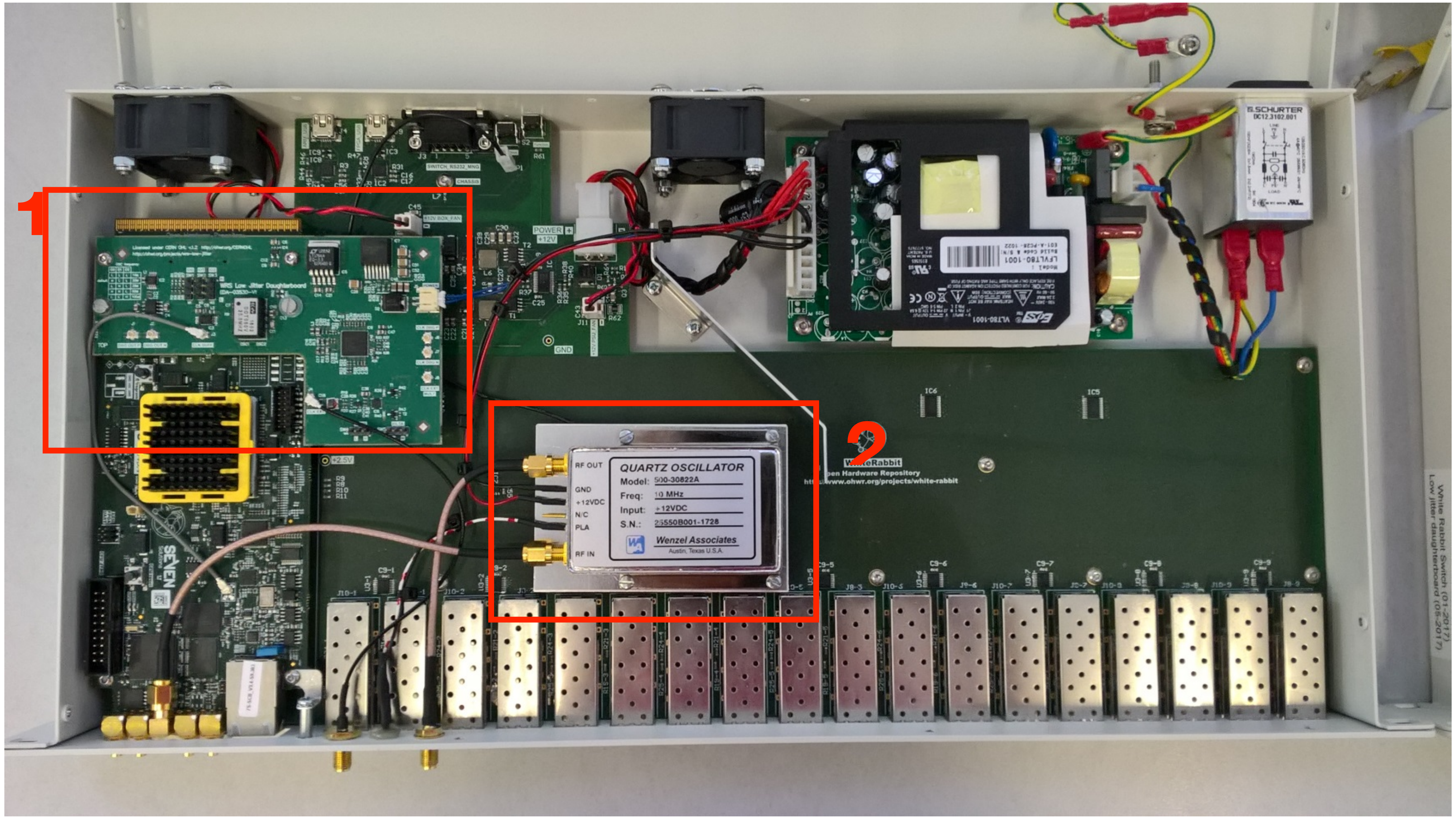
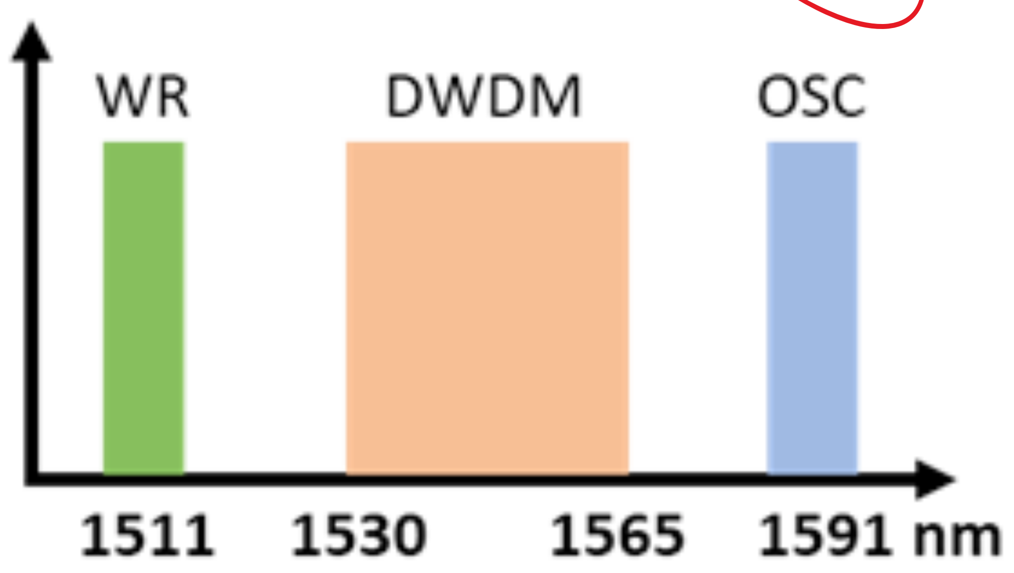
Improved White Rabbit



1. Low Jitter Daughterboard (M. Rizzi e.a., https://www.ohwr.org/projects/wrs-lowjitter)
2. Cleanup Oscillator
3. Use of DWDM stabilised laser SFPs, and external DWDM filters

WR in a DWDM Network

- Bi-directional WR traffic on conventional (two fiber) DWDM
- Wavelengths outside of C-band get demuxed
  - Normally used for the ‘Optical Supervisory Channel’



- Insert CWDM filters to separate out the two WR wavelengths in the OSC path
  - We used 1511.05 nm / 1511.81 nm
- Bi-Directional Optical amplification of WR
  - SOA: Semiconductor Optical Amplifiers

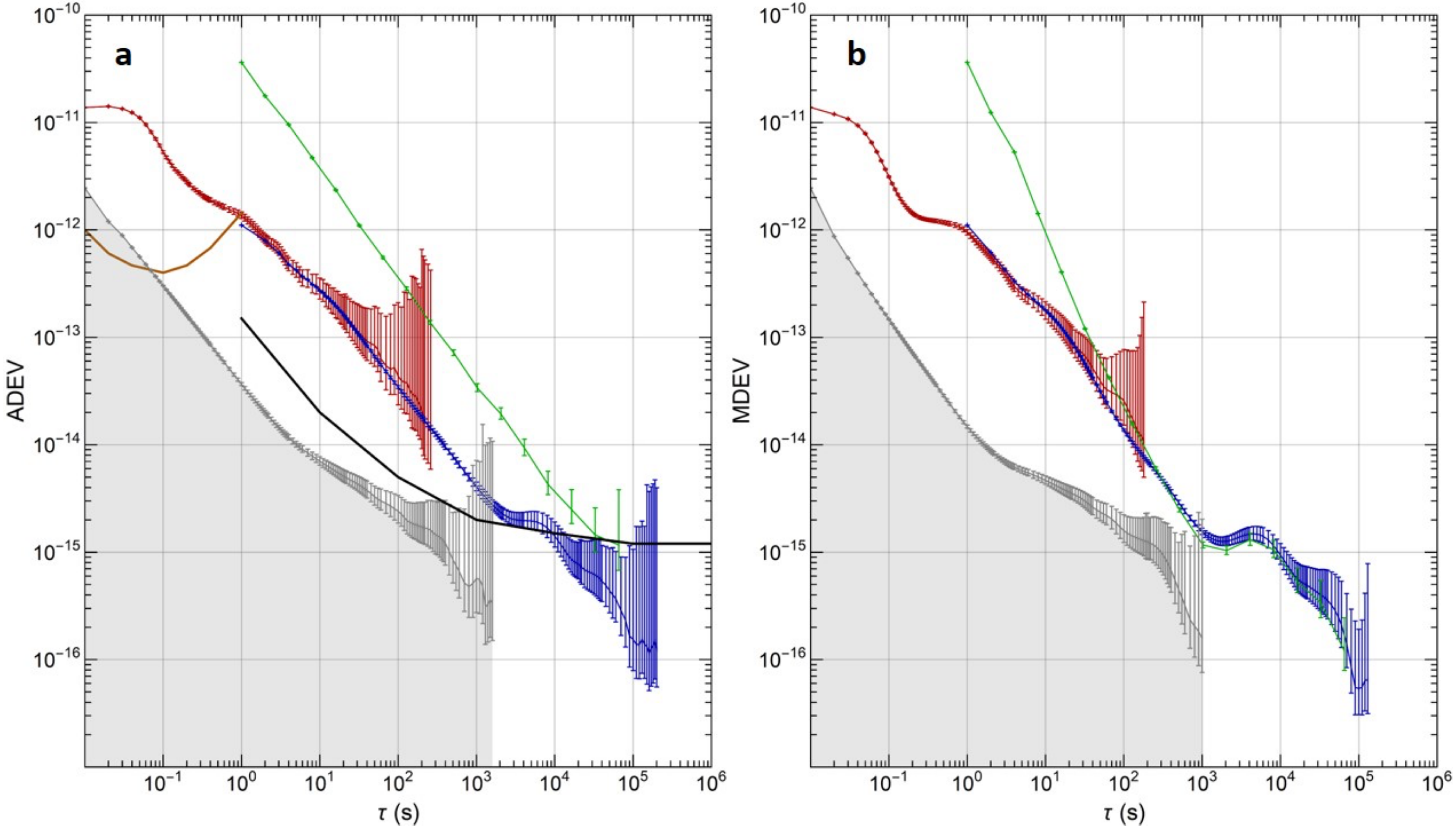
ASTERICS White Rabbit Link

- Three parallel links:
  - DWDM (169km)
  - 2x Dark Fibre (35km)
- LOFAR core connected to Groningen

- DWDM Link: 2x 67 km + 35 km = 169 km
  - On SURFnet production network SN8

- Dark Fibre Link: 35 km

Link Performance (2x 67km)



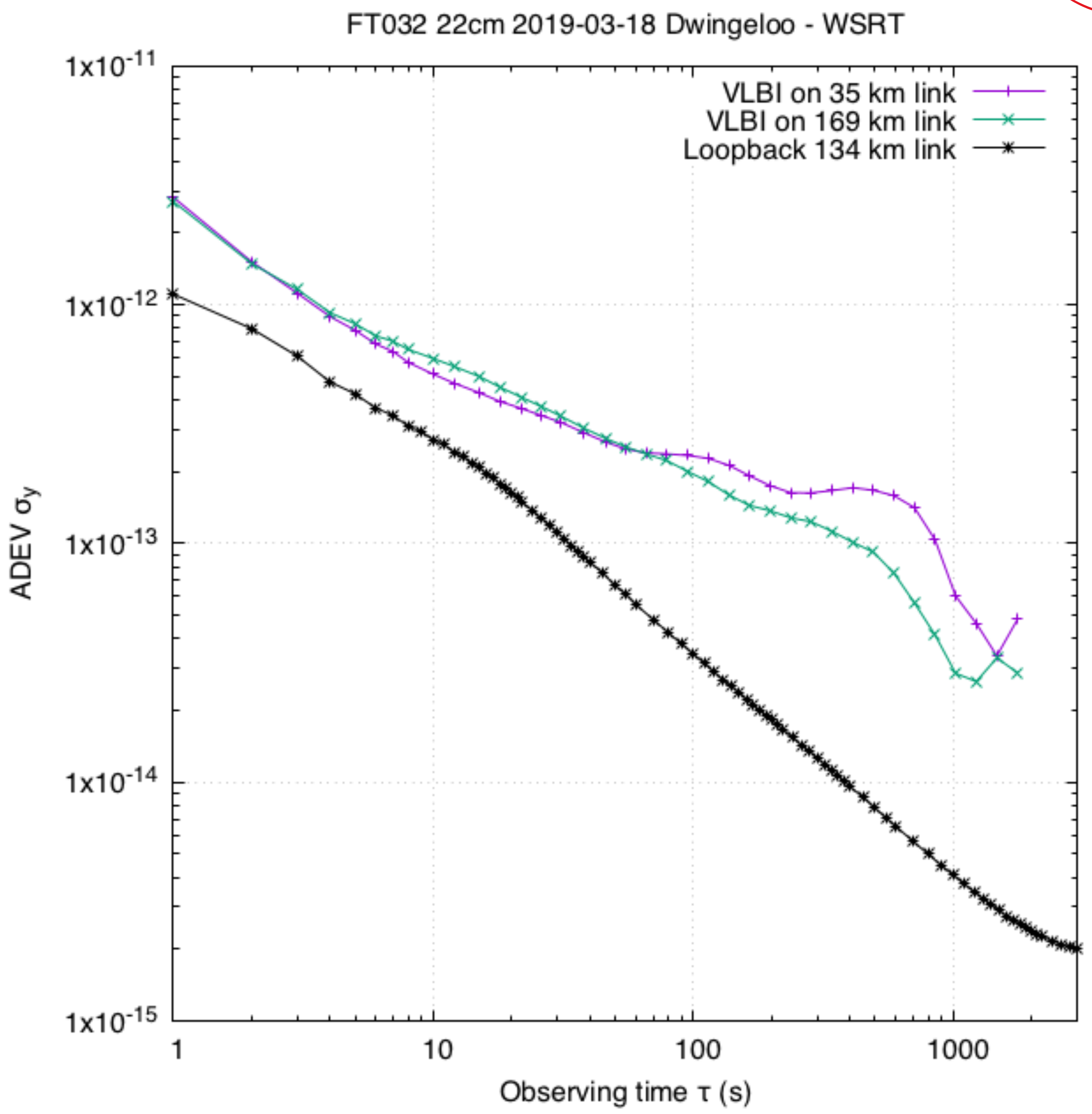
Phase Noise measured using MicroSemi 3120A between H-Maser and 10 MHz output of WR switch with cleanup oscillator

PPS measured on SR620

Red: 50 Hz
Blue: 0.5 Hz
Grey: 3120A Noise Level
Brown: Cleanup Osc.
Green: PPS (SR620)
Black: H-maser nominal performance

VLBI Phase ADEV

- At longer timescales: ADEV limited by ionosphere, atmosphere
- Observations are not simultaneous, so different atmospheric contribution
- No significant performance difference between 35km and 169km link



LOFAR 2.0

- Upgrade to the 38 Dutch LOFAR stations
- Design phase complete, starting roll-out
- Adds sensitivity, more simultaneous bandwidth
- T&F distribution using WR
  - ASTERICS link from WSRT H-maser to LOFAR core (132 km)
  - WR link over dark fiber to the stations
- Replaces many GPS locked Rb clocks
  - Difficult to calibrate, high failure rate
  - Large upgrade to image quality

T&F distribution in VLBI

ELSTAB

- Polish system, links up to 350km
- 2 UTC(k) labs, a Sr clock
- Torun Radio Telescope
- Local H-maser vs. Remote H-maser
  - Same performance
- Remote Sr optical clock
  - Improved VLBI RMS phase noise
- Replaced failing H-maser

LIFT

- Italian system
- Coherent optical transfer
- INRIM UTC(k), H-masers & Yb clock
- Medicina Radio Telescope (550 km)
- Matera Radio Telescope (1800 km)
- Local H-maser vs. Remote H-maser
  - Same performance
- Two telescopes on the same clock
- Expanding to Noto and Sardinia

(see last slide for references)

VLBI Requirements

- Network Bandwidth: 1 - 4 Gb/s per station (with future increases)
- Frequency Stability: Active H-Maser level or better
    - Lower observing frequencies will work with higher ADEV
    - Lower ADEV can improve observation, but limited by ionosphere/troposphere
- Timing accuracy: 1 μs (not critical for VLBI)
    - Other use cases, e.g. pulsar timing, require ns level timing
- Redundancy / Availability / Performance Monitoring
    - Availability has to be comparable to using a local clock
- Remote locations, long optical links
    - Radio telescopes are usually far away from cities and industry
    - 'Last Mile' challenge

References

Asterics Project

- D5.4 Hardware for masers-level time & frequency distribution in public networks
  https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.4_ec_ref._ares_2017_4054843_16082017.pdf
- D5.6 Tools and methods for delay calibration before installation and in situ
  https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.6.pdf
- D5.7 Time Transfer in SURFnet/LOFAR Network & general design rules
  https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.7.pdf
- D5.14 Demonstration of VLBI Synchronization via the SURFnet/LOFAR network
  https://www.asterics2020.eu/sites/default/files/documents/asterics-d5.14.pdf

LIFT

- A VLBI experiment using a remote optical clock via a coherent fiber link
  https://www.nature.com/articles/srep40992

ELSTAB

- Fiber-optic delivery of time and frequency to a VLBI station
  https://www.aanda.org/articles/aa/pdf/2017/07/aa30615-17.pdf