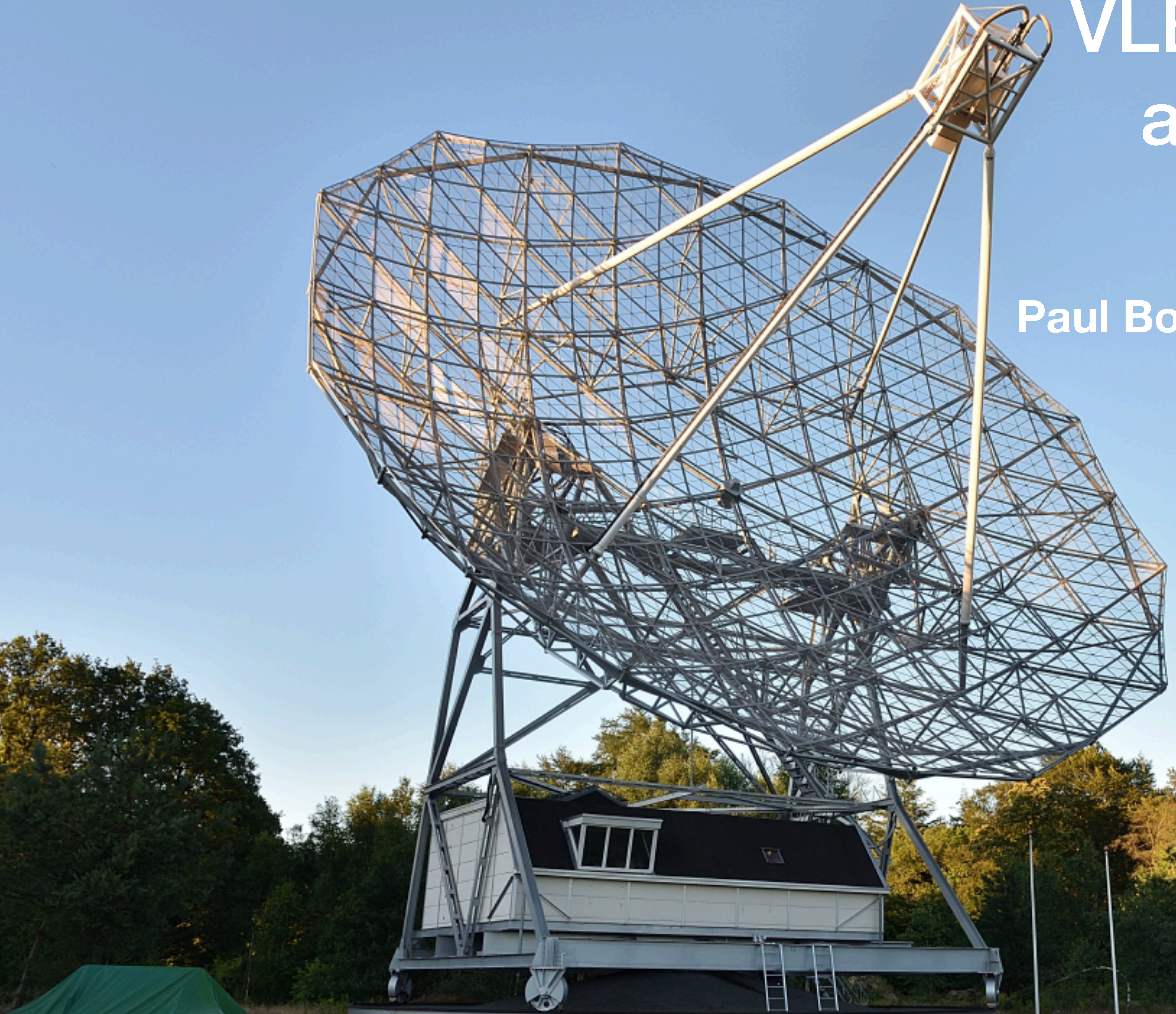
VLBI with GNU Radio and White Rabbit



Paul Boven (PE1NUT) - JIVE/CAMRAS

Chantal van Tour - OPNT/VU

Rob Smets - SURFnet

Jeroen Koelemeij -OPNT/VU

Arpad Szomoru - JIVE

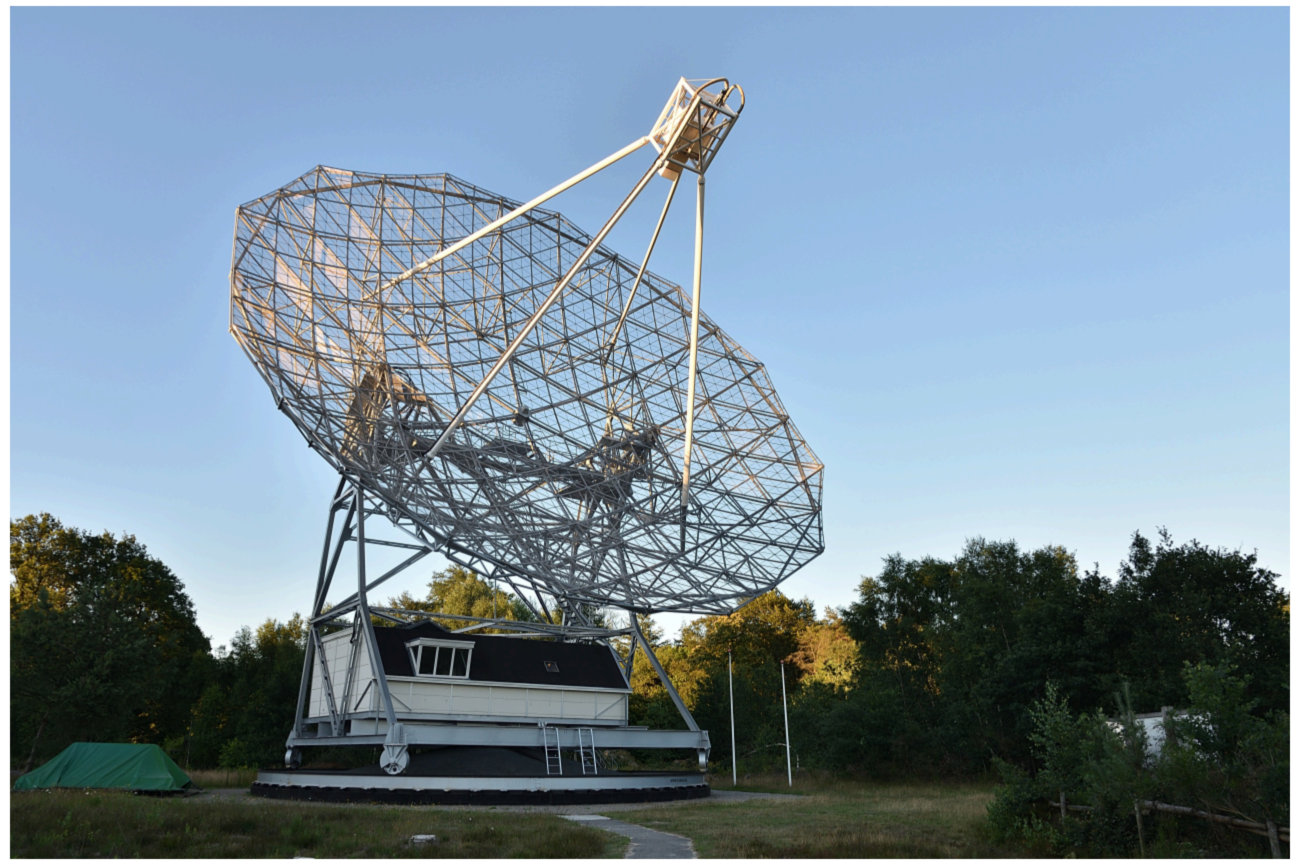
GR Conf 2019-09-18, Huntsville

Antenna Beam Size and Resolution

$\theta \approx 70\lambda/D$ (λ = wavelength, D = diameter, θ in degrees)

Hubble Space Telescope:
λ = 600nm (visible light)
D = 2.4m
θ = 0.06” (arcsecond)

Dwingeloo radio telescope
λ = 6cm (5GHz)
D = 25m
θ = 600” (arcsecond)



For an equivalent radio resolution, we’d need a 250km dish!

Very Long Baseline Interferometry

JIVE
Joint Institute for VLBI
ERIC

EUROPEAN vlbi NETWORK

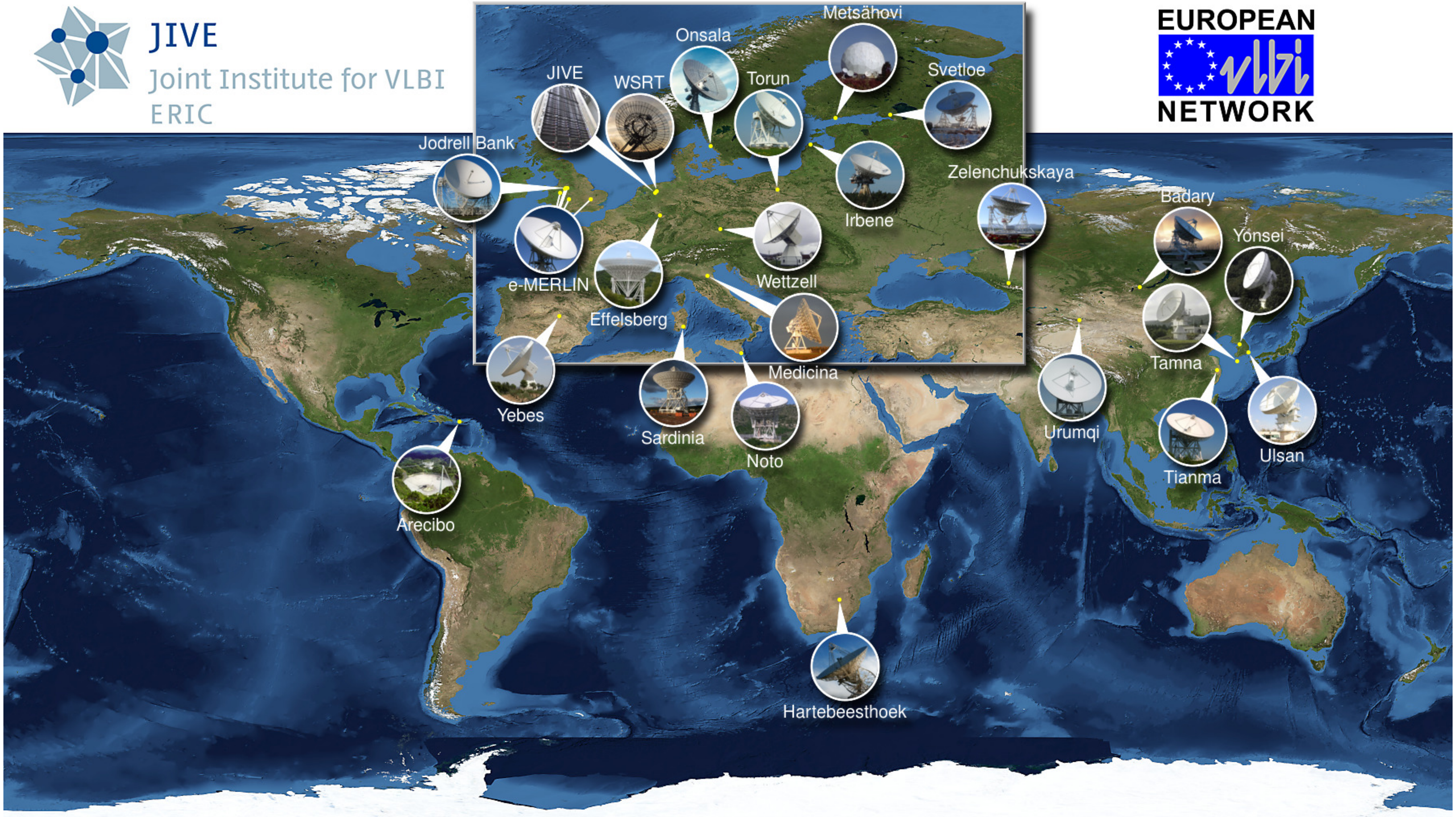
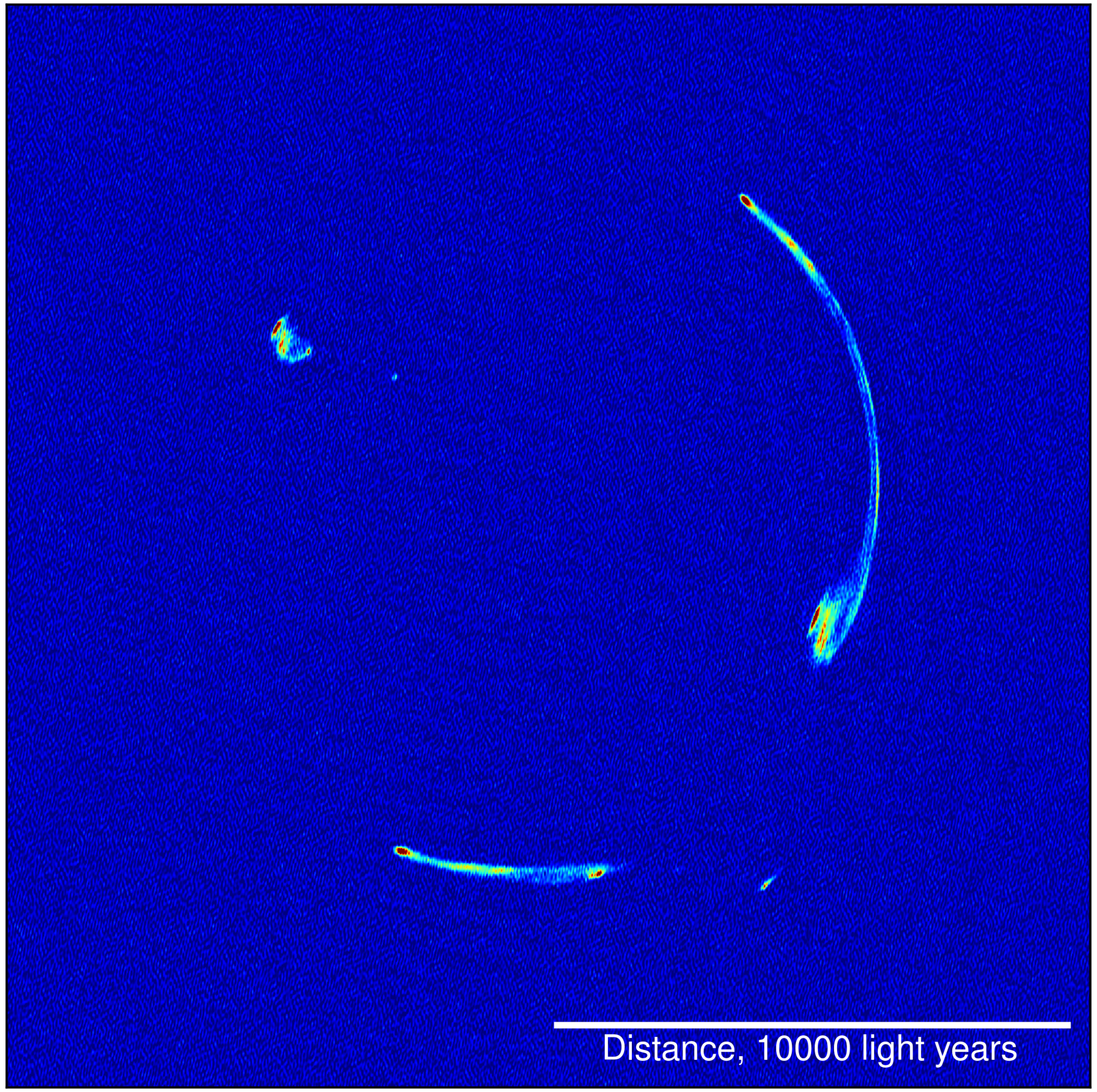


Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

VLBI Examples

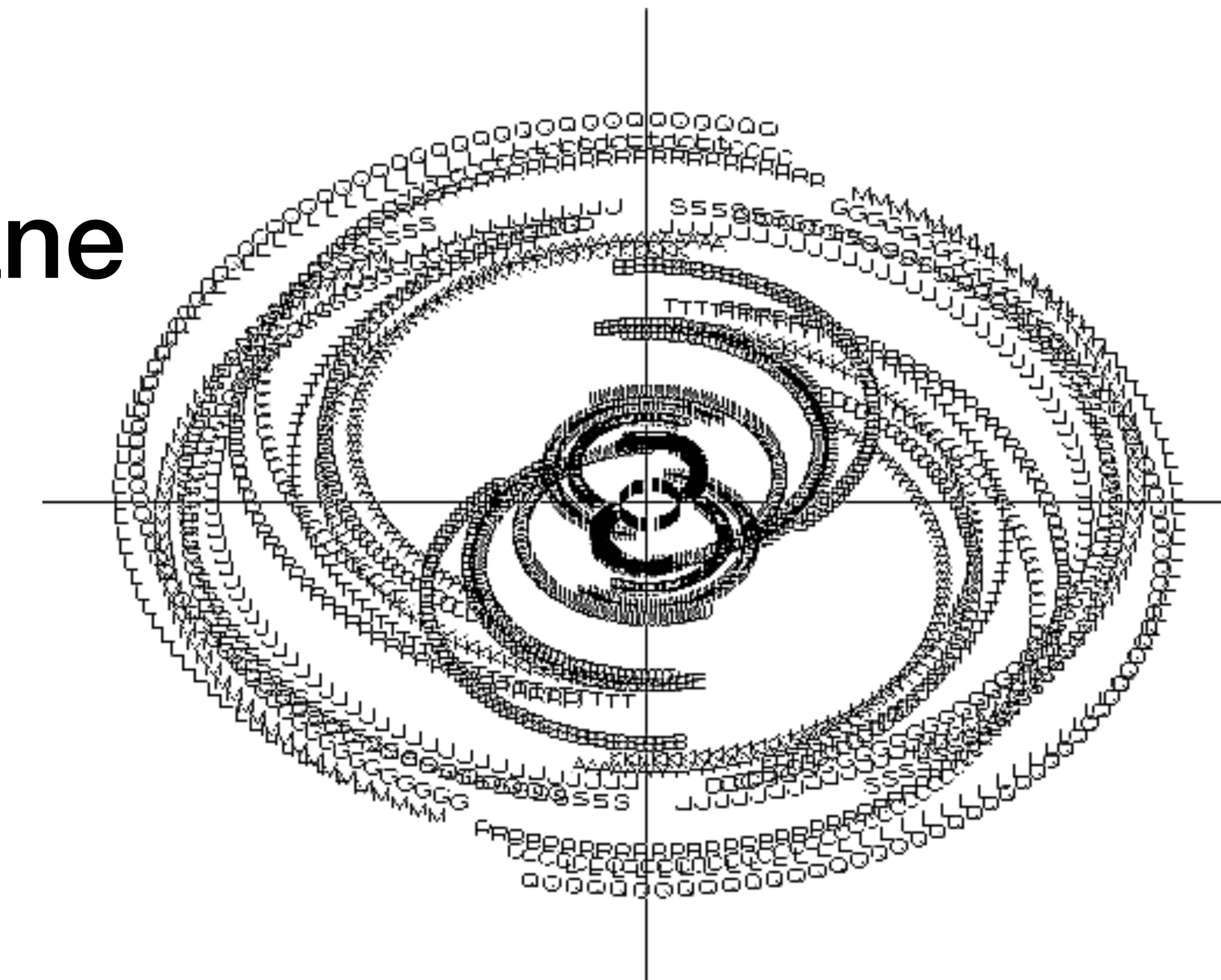
M87 central black hole event horizon
EHT Consortium



Einstein Ring - C. Spingola e.a.

VLBI in a Nutshell

- Virtual radio telescope, size comparable to longest baseline
  - Resolution on order of milli-arcsecond, or even better
- Each telescope looks at the same source
- Remove doppler shift due to Earth rotation (up to 465 m/s)
- Complex cross correlation on each baseline
    - There are N*(N-1)/2 baselines
- For each baseline, put complex 'visibility' on the UV plane
- After 12 hours, run inverse FFT to create 'dirty' image
- Use algorithms like 'clean' to make the final image



What you need for VLBI

- A Radio Telescope (the bigger, the better)
  - More than one (as many as you can find, short and long distances)
- A very stable frequency reference (usually a hydrogen maser)
  - Stable to a fraction of a phase at observing frequency, up to 1000s
  - Beyond 1000s, ionosphere destroys coherence (use phase referencing)
- High Bandwidth receiver (sensitivity scales with $\sqrt{BW}$)
- Correlator (supercomputer, calculating the complex x-cor on each baseline)
- Accurate Telescope Location, Earth Rotation Parameters,

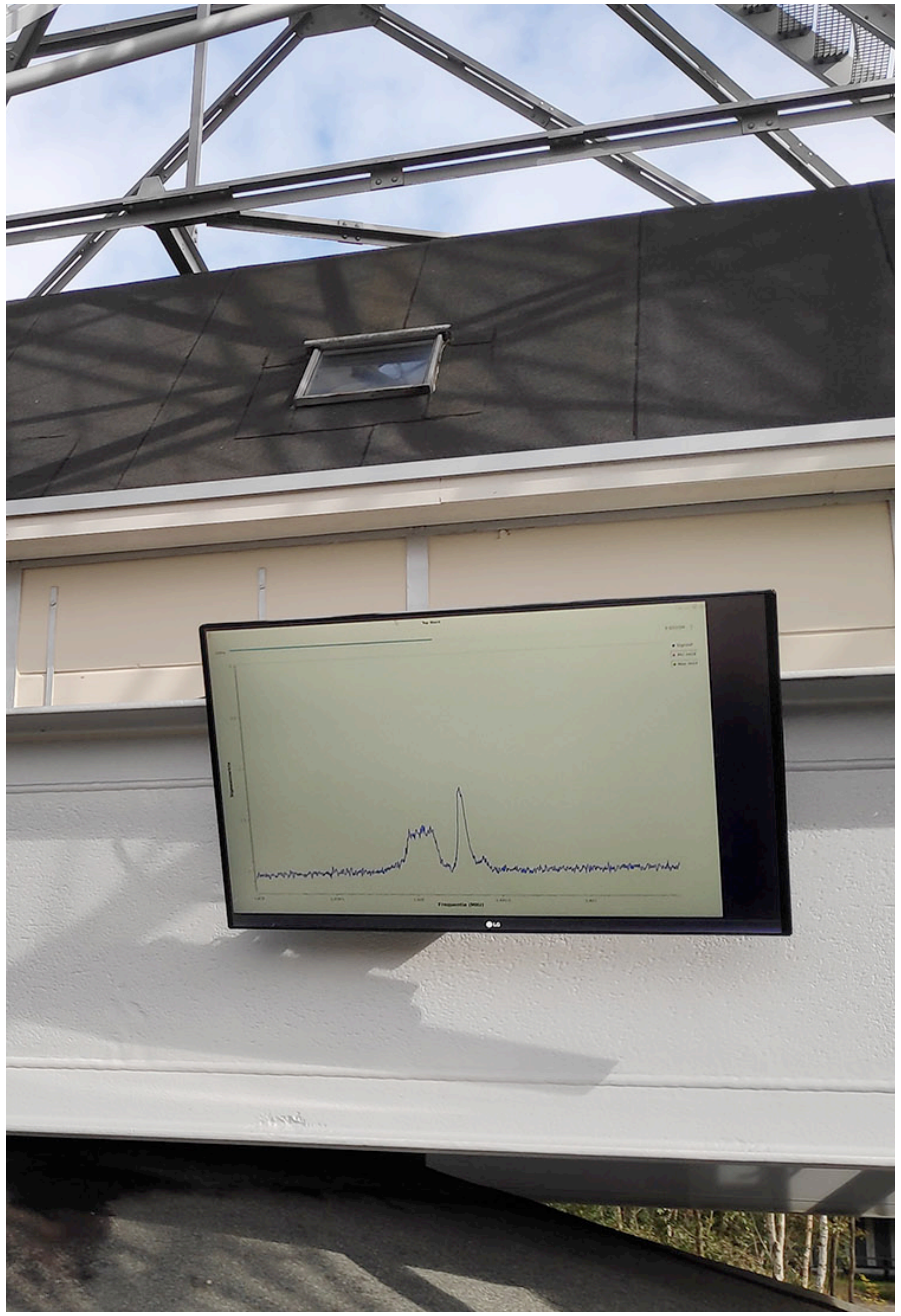
  Tidal Deformation model, Noise Source, Storage Capacity, Network, etc, etc…

The Dwingeloo Radio Telescope

- April 12th 1956: Opening by Queen Juliana
- 25m diameter
- Stainless mesh surface 7.7mm
- Rails: 12m diameter
- 120 ton
- Nowadays it is a national monument
- Operated by the CAMRAS foundation
  - http://www.camras.nl/
- We do maintenance, radio astronomy, ham radio, education/outreach, satellites, SETI, art, and much more

Yesterday's Royal Visit

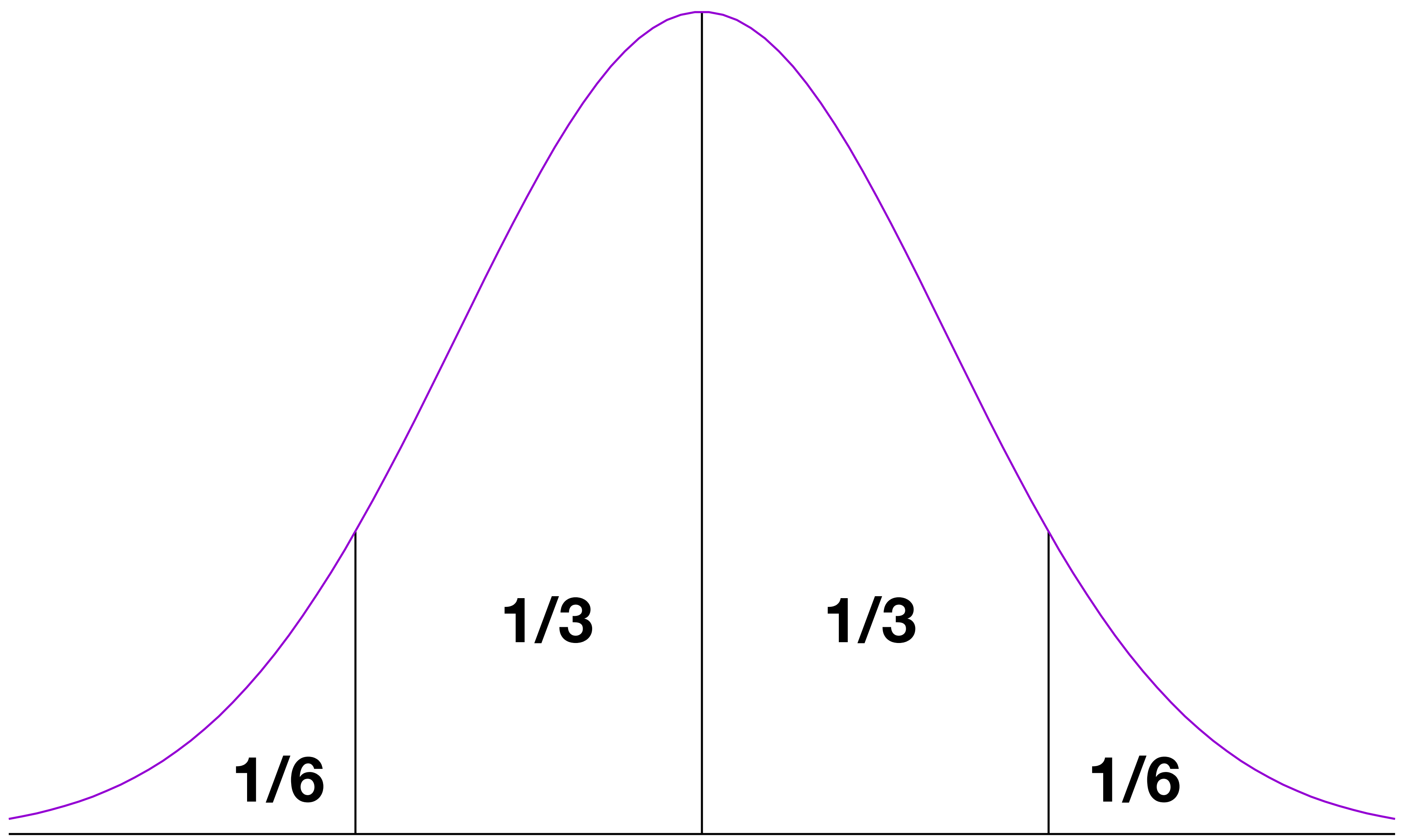
Image Source: Dagblad van het Noorden



Real-Time 21cm display in GRC

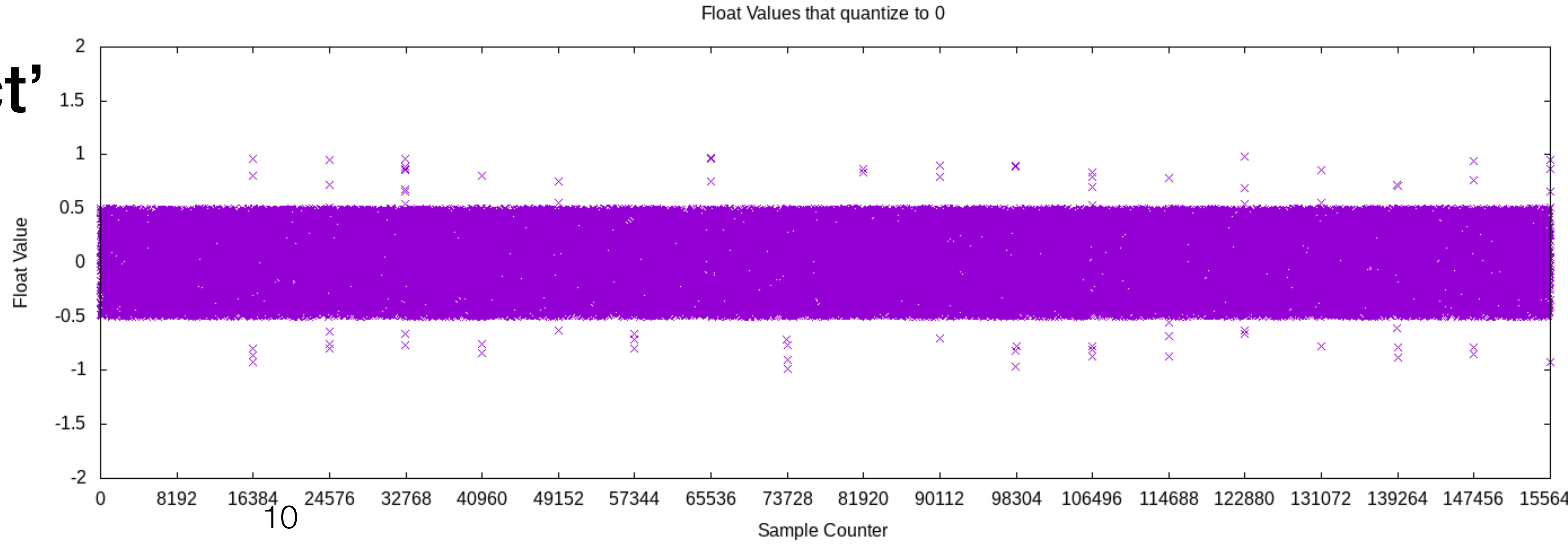
Bandwidth, Sensitivity and Bits

- For wideband sources, VLBI sensitivity scales with $\sqrt{BW}$
- Limit is often disk storage capacity, or networking bandwidth
- Recording fewer bits per sample allows for more samples
  - Trade-off against increasing quantisation noise
- VLBI recordings are usually done at only 2 bit/sample resolution
  - Requires AGC for optimum 'sampler stats'
  - Separate noise power measurement



Two Bit Quantisation

- There are two[1] styles of rounding:
  - C-style (truncation): <-1 : 1> → 0
  - Signal Processing: <-0.5 to 0.5] → 0
- When converting float to char (32f_s32f_convert_8i)
  - GR would usually do the second, but occasionally the first
- https://github.com/gnuradio/volk/issues/188
- VOLK optimised was 'correct' (performed by SSE)
- End of block (8192 samples) would be done in C



1) There are many, many more

High Speed Recording

- TwinRX Bandwidth: 2x 80 MHz, sampled at 100MS/s each (complex)
- Recorded as Shorts (16 bit): 3.2 Gb/s (all four chans: 12.8 Gb/s)
- Recording to /dev/shm: no problem (but only for really short recordings)
- Recording to disk immediately leads to lost packets and other issues
- ‘specrec’ is part of gr-analysis (Lincoln + Graver)
    - Samples go into circular buffers
    - Get flushed to disk quickly
    - Dies as soon as it runs out of buffers

Image: SuperMico

- On a 18 disk mdadm stripe (raid-0), we sometimes managed 50MS/s for hours
    - Lots of room for improvement (FS tuning, use memory, core affinity etc. etc.)

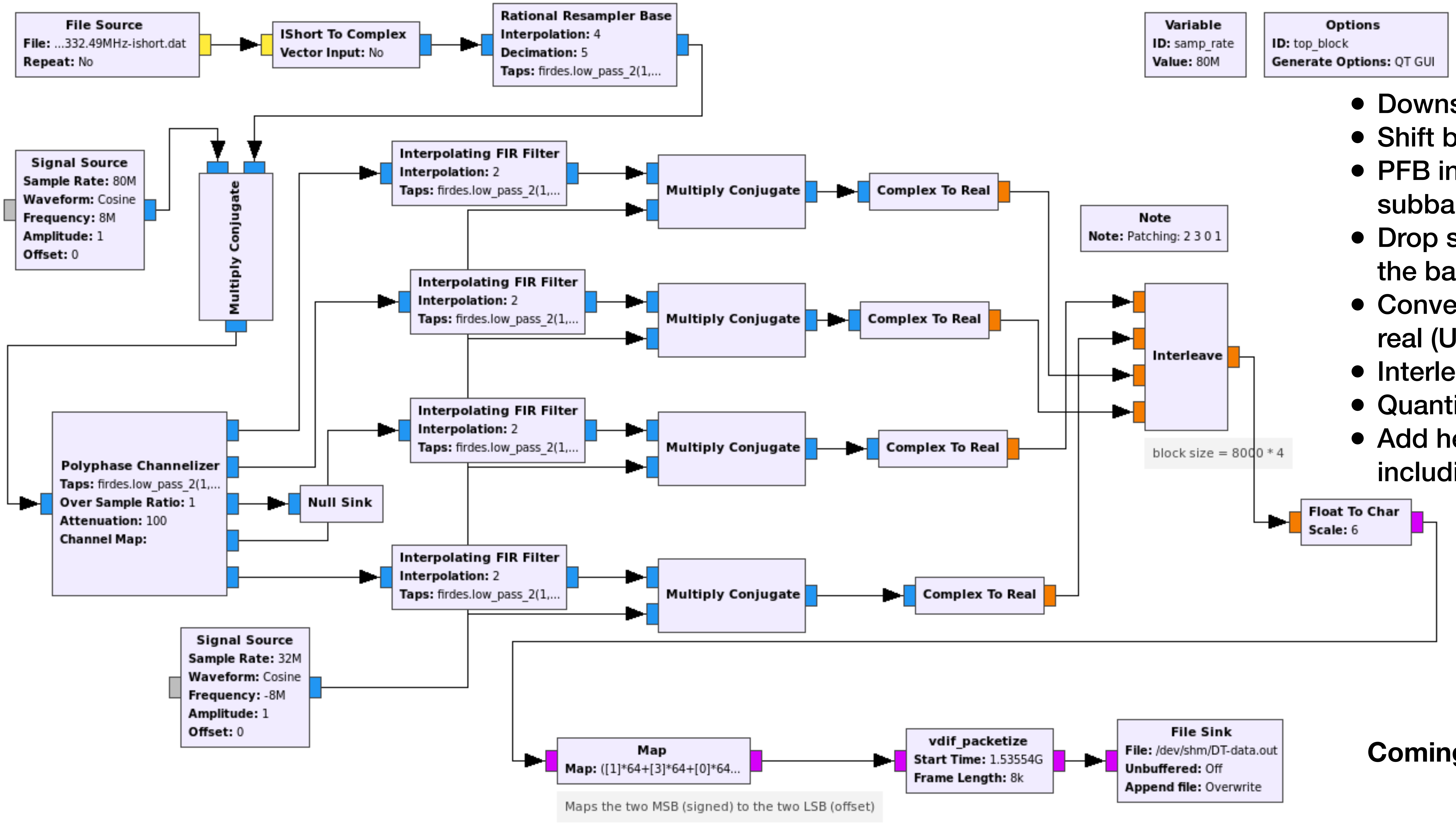
Timed Recording

- GNU Radio and UHD generally support 'GPS timing', and 'Unknown PPS'
- We can't use GPS (insufficient stability for VLBI)
- 'Unknown PPS' always starts clock at 0 at the PPS edge
- Procedure to set time from PPS:
    - Wait for a PPS edge
    - Wait half a second more
    - Read out PC (NTP) time
    - Set USRP time at next PPS to time+1
    - Wait another half second, so this PPS has actually happened
- Implemented this in uhd_rx_cfile, and later in 'specrec'

Added to uhd_rx_cfile:

```
last_pps_time = self._u.get_time_last_pps()
while last_pps_time == self._u.get_time_last_pps():
    time.sleep(0.1)
time.sleep(0.5)
self._u.set_time_next_pps(uhd.time_spec(int(time.time())+1))
time.sleep(0.5)
```

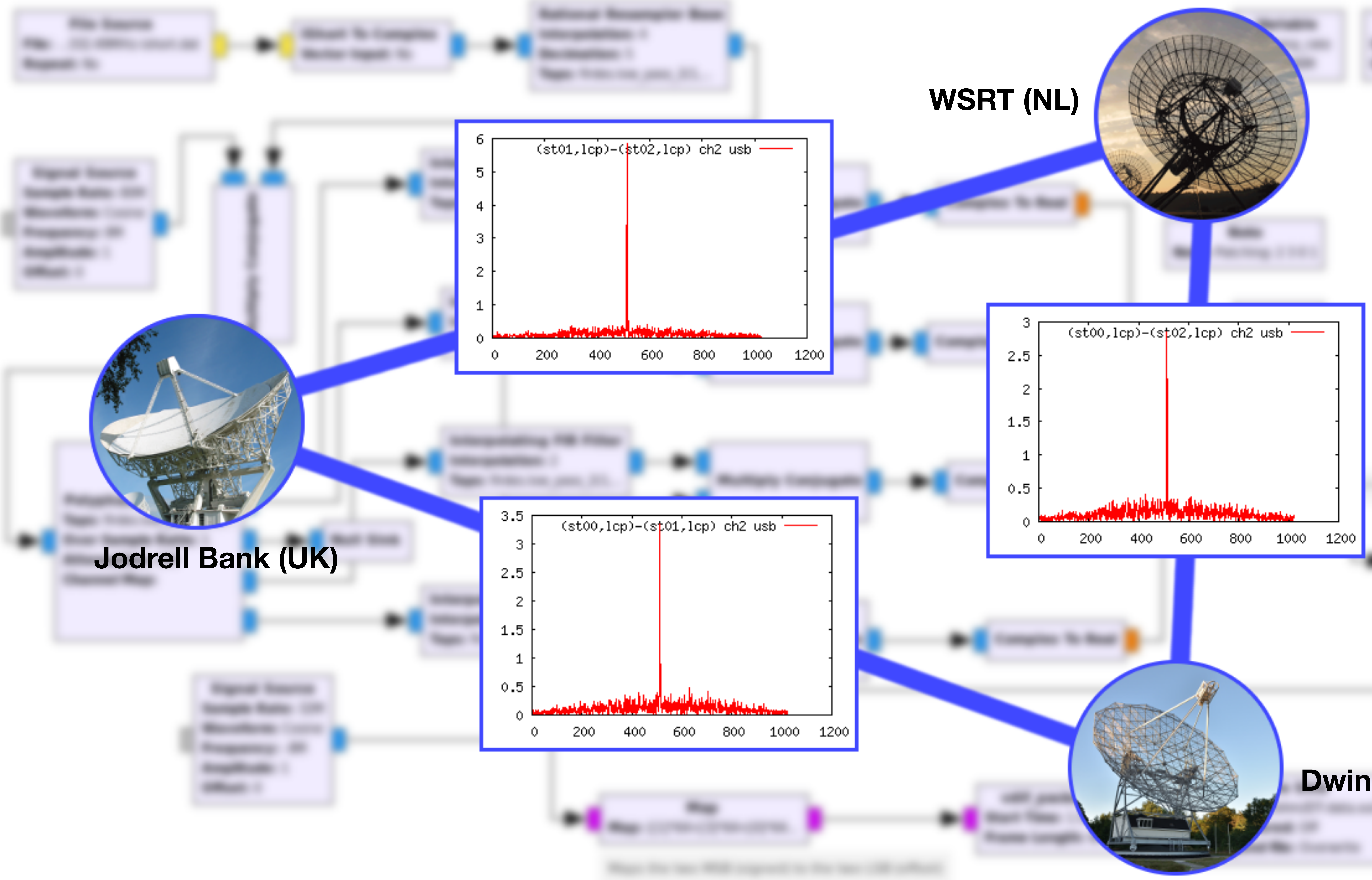
A VLBI Flowchart



- Downsample to 80 MS/s
- Shift by 8 MHz
- PFB into 5 subbands of 16MHz
- Drop subband with the band-edges
- Convert complex to real (USB)
- Interleave by 8000 bytes
- Quantize 2 bits (2 steps)
- Add headers including timestamps

Coming soon to Github!

Dwingeloo Fringes (Again)



- Dwingeloo first fringes: 1978
- 2018-08-29:
  - Fringes again!
  - Only 10s at a time (/dev/shm size)
  - Not real-time i9900-k: 20% speed
  - 256 Mb/s
  - Rubidium Timebase

ASTERICS / CLEOPATRA

- EC ‘Horizon 2020’ research project
- “Bringing together the astronomy, astrophysics and particle astrophysics communities”
  - Address interdisciplinary issues:
    - Multi-Messenger Astrophysics
    - Large Data Sets
    - Timing (Cleopatra Workpackage) -> lots of White Rabbit research
    - Citizen Science

ASTERICS is a project supported by the European Commission Framework Programme Horizon 2020 Research and Innovation action under grant agreement n. 653477

White Rabbit

- An open protocol/standard for distributing time and frequency, accurate to 1ns over 10km, to 1000s of nodes

- Initial design at CERN for beam control of the LHC, released as open hardware



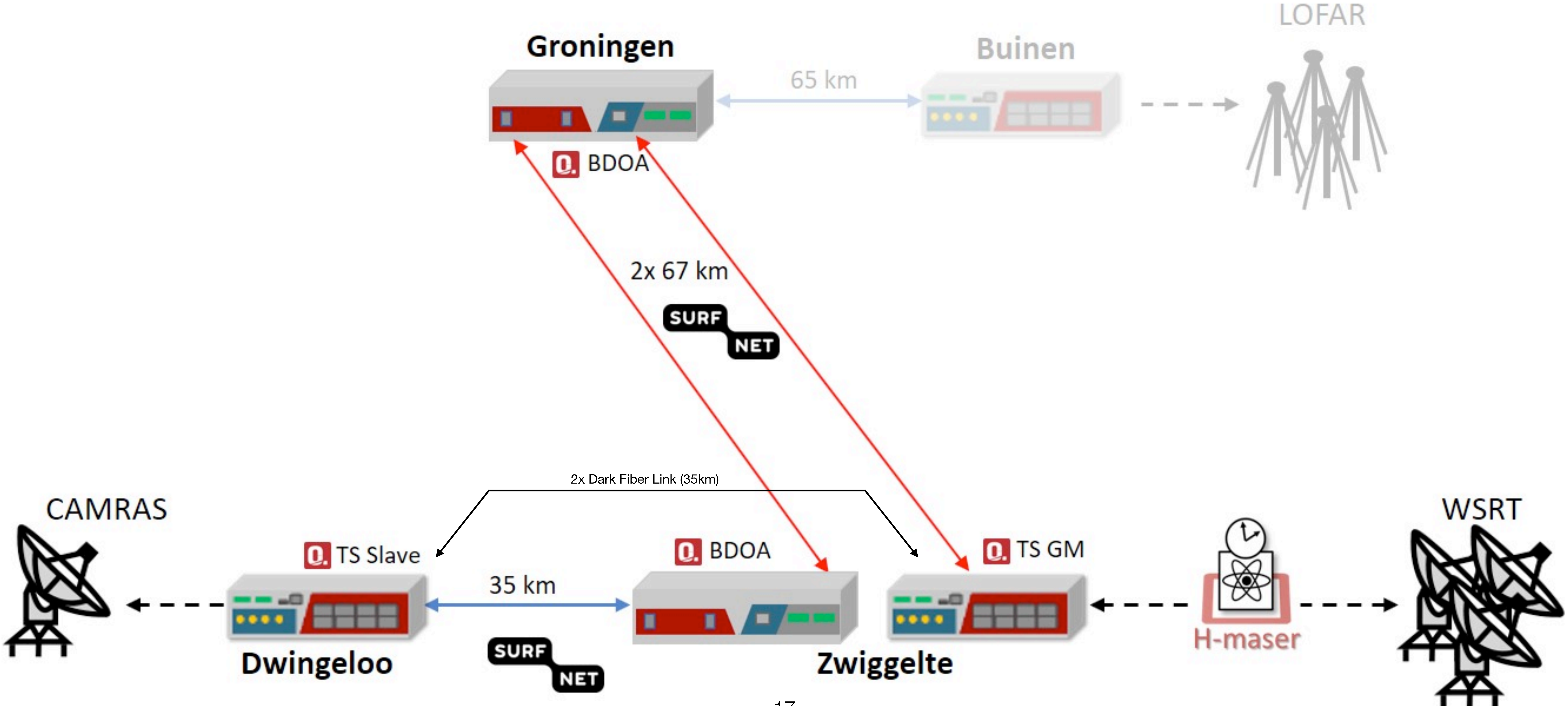

- Uses a single fiber (bi-directional)

- Measures round-trip time (with ps resolution)

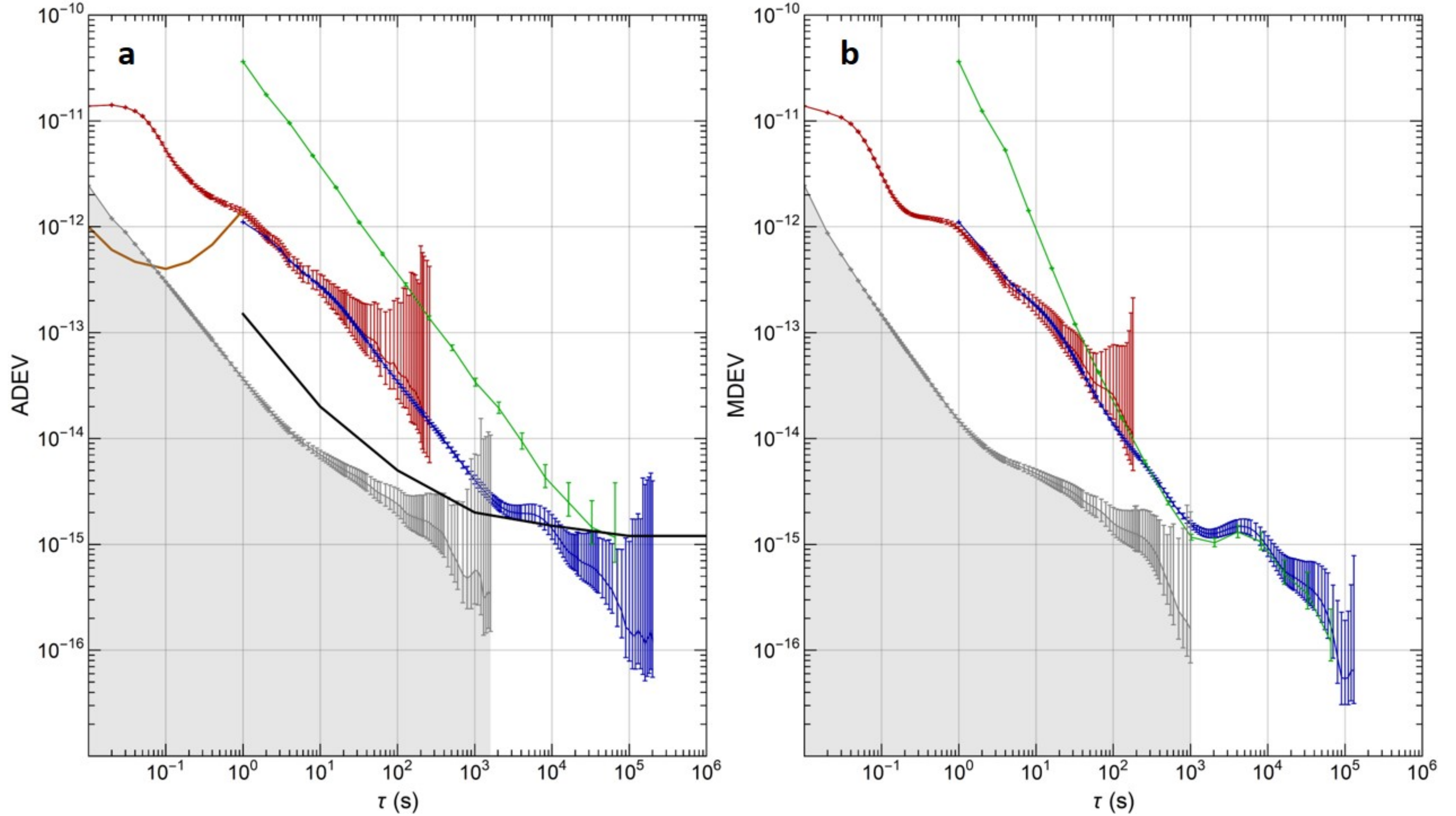
- Compensates for changes (due to e.g. temperature)

ASTERICS / CLEOPATRA

- Long distance, high stability WR over production (DWDM) networks



Link Performance (2x 67km)



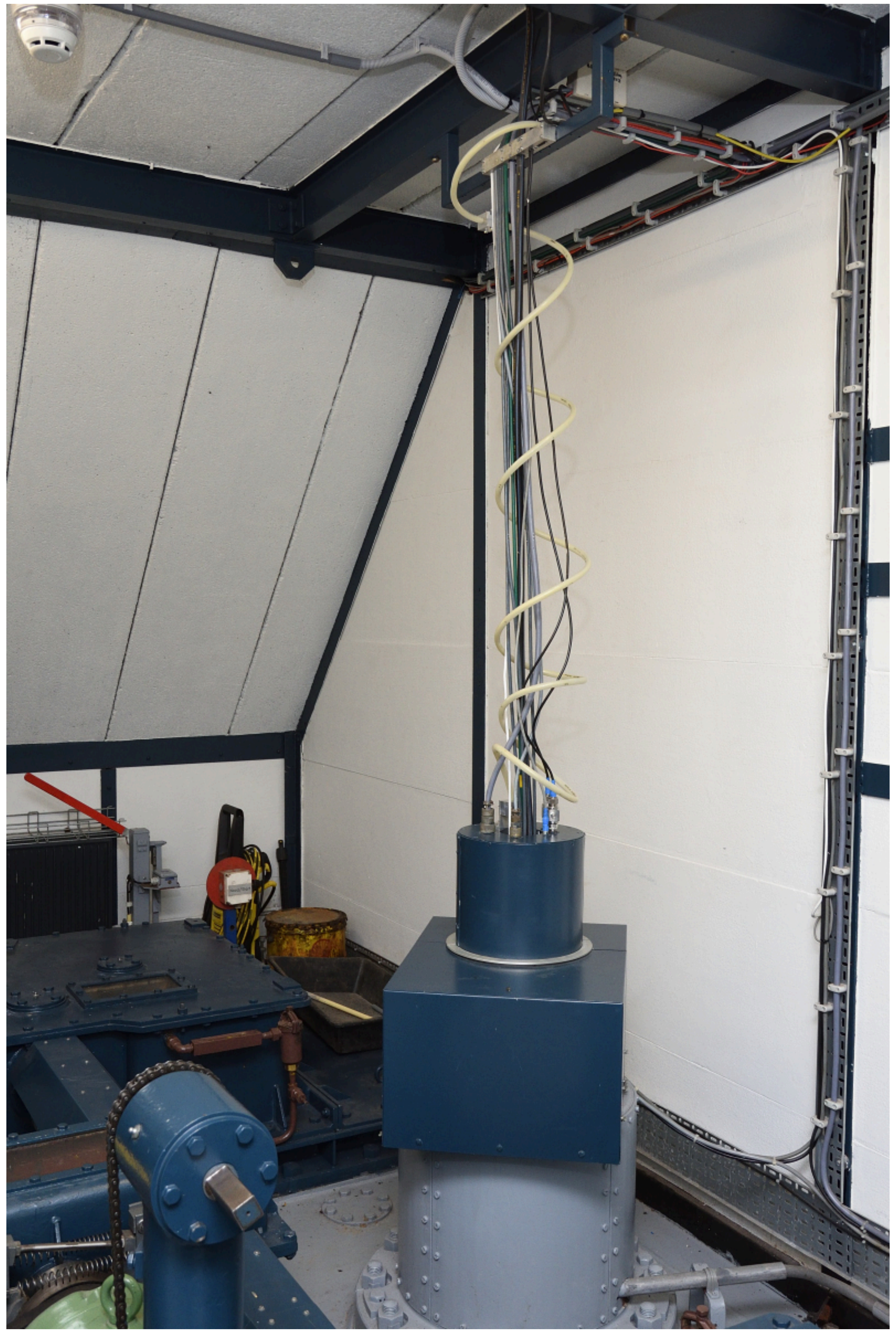
a): ADEV, b): MDEV. Red: Link, 50 Hz BW. Blue: Link, 0.5Hz BW. Green: 1 PPS (SR620). Grey: Noise Floor (B3120A). Black: H-maser specs. Brown: Cleanup-Osc specs.

New Single-mode Fiber

- Leftover fiber, donated by ASTRON
- 510m, 144 strands, G.652.D (single mode) outdoor (unarmored)

Digging your own Fiber

Installing your own Fiber



Splicing your own Fiber

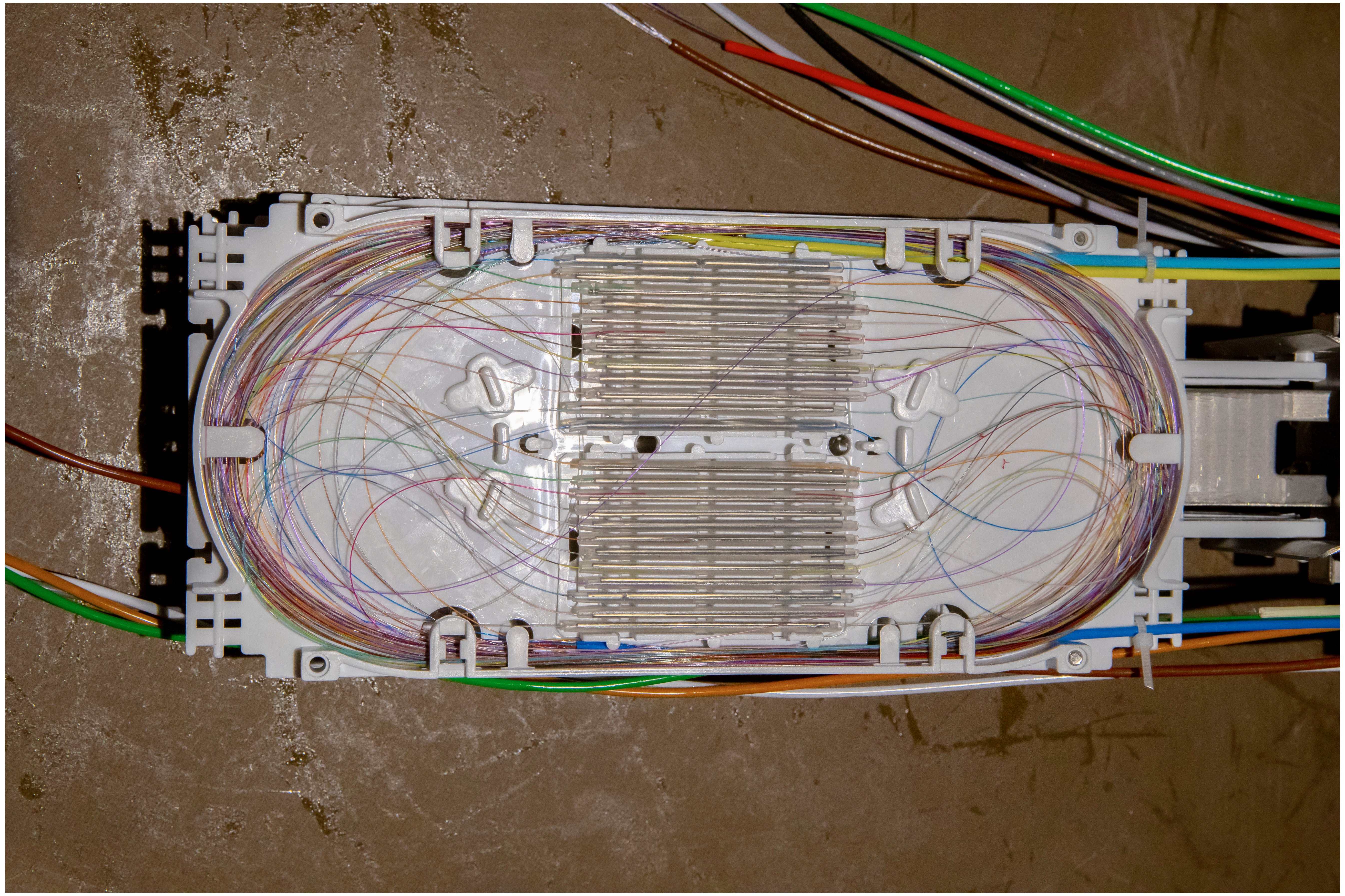
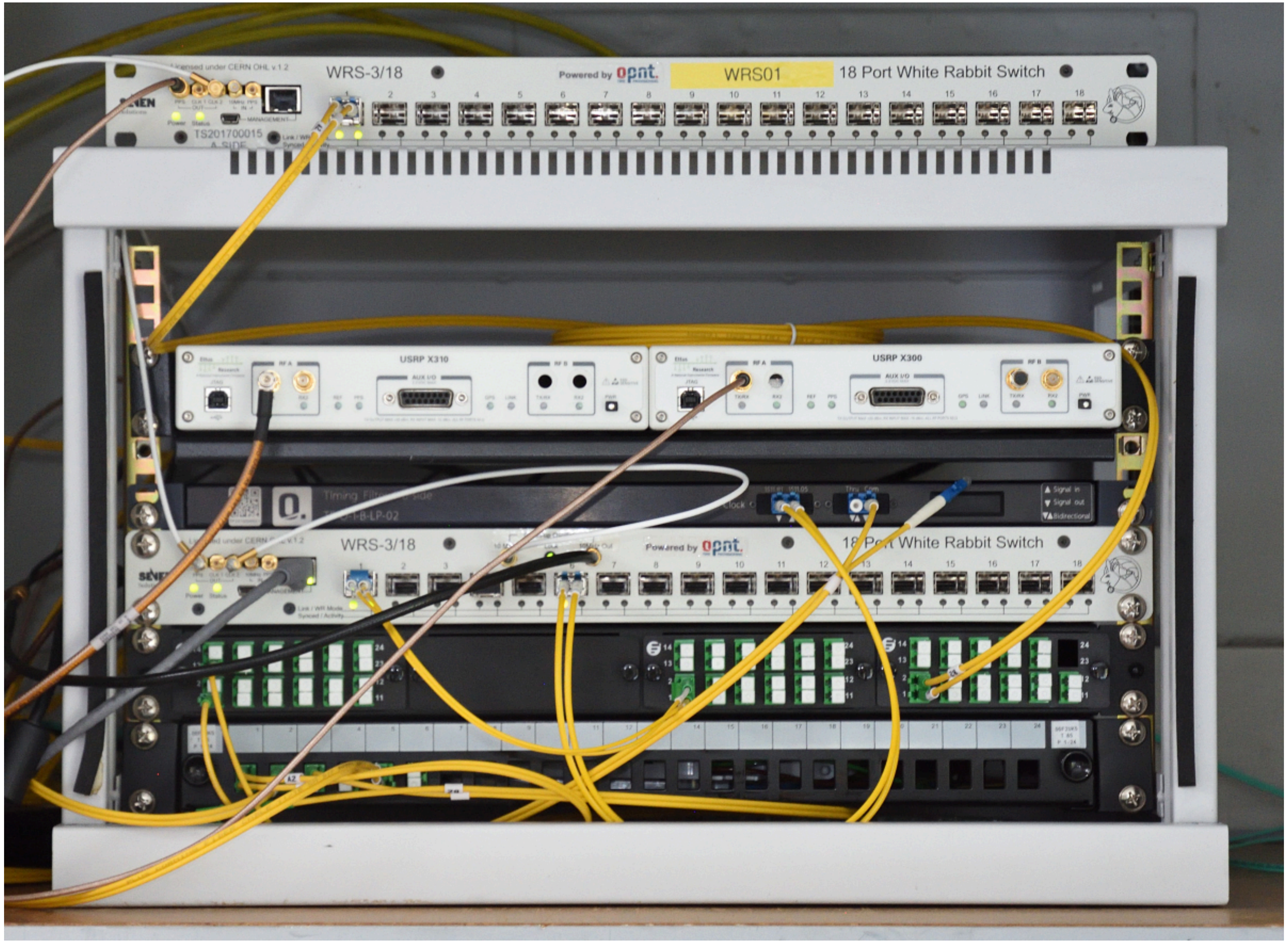


Image by H. Keizer

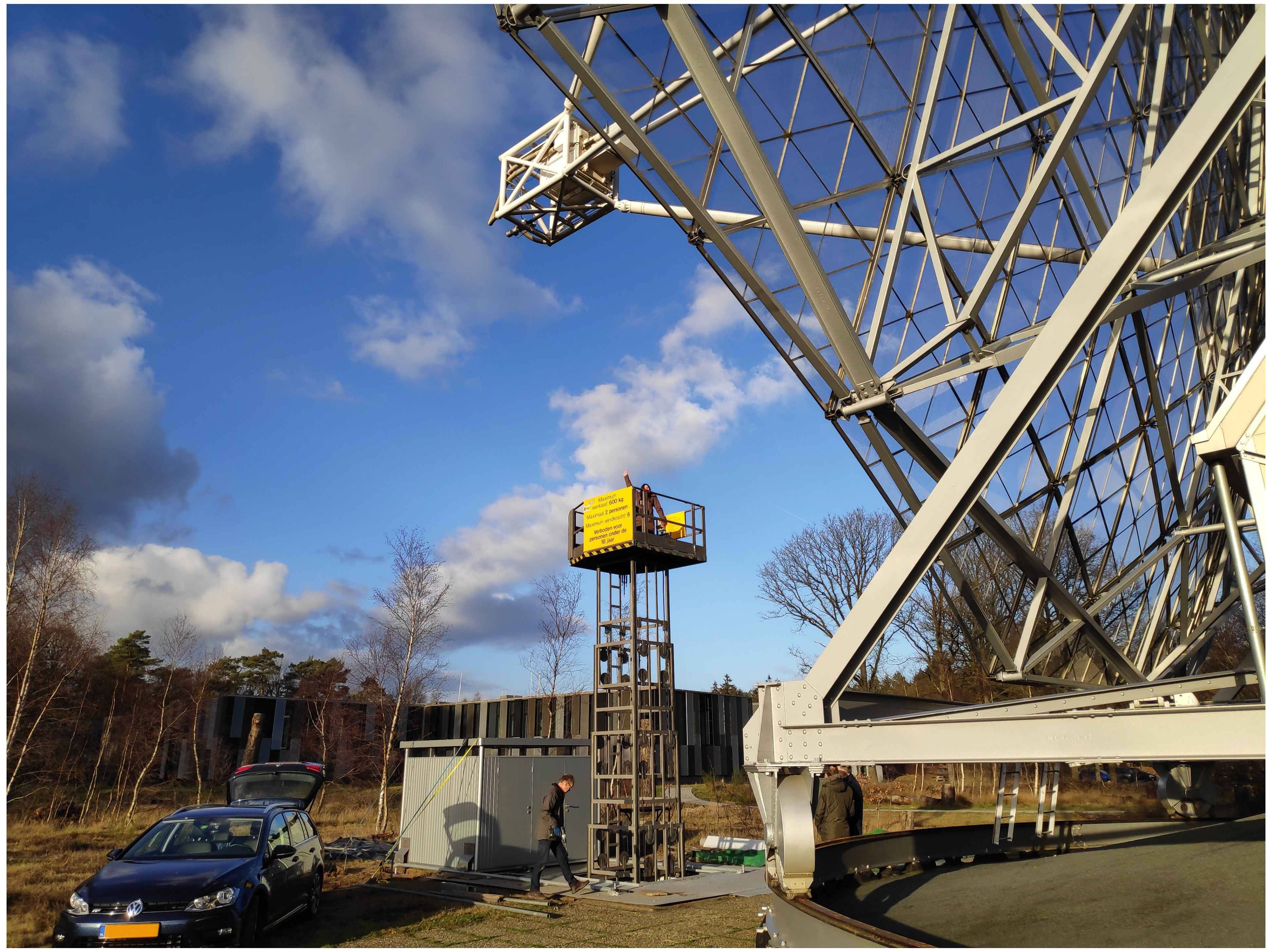
- So far, spliced 24 out of 144 fibers
- Room for expansion!

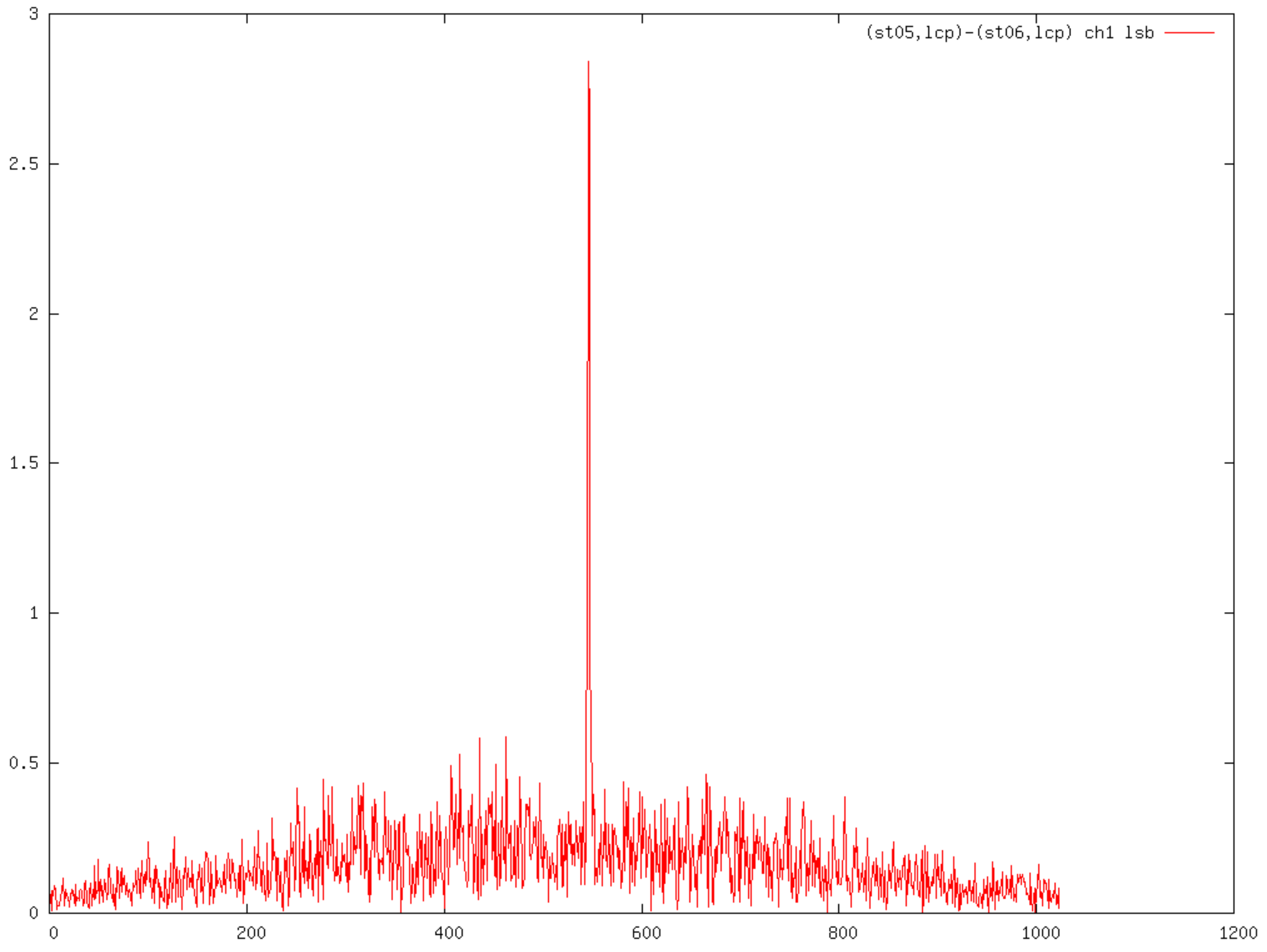
WR + SDR Setup



- Inside Faraday cage in telescope
- 35km and 169km WR link
  - Compare Performance
- Ettus X310 + TwinRX
- Borrowed second X300
- WR switches with LJD
  - One with cleanup-oscillator

N19L1: VLBI with the Big Dishes

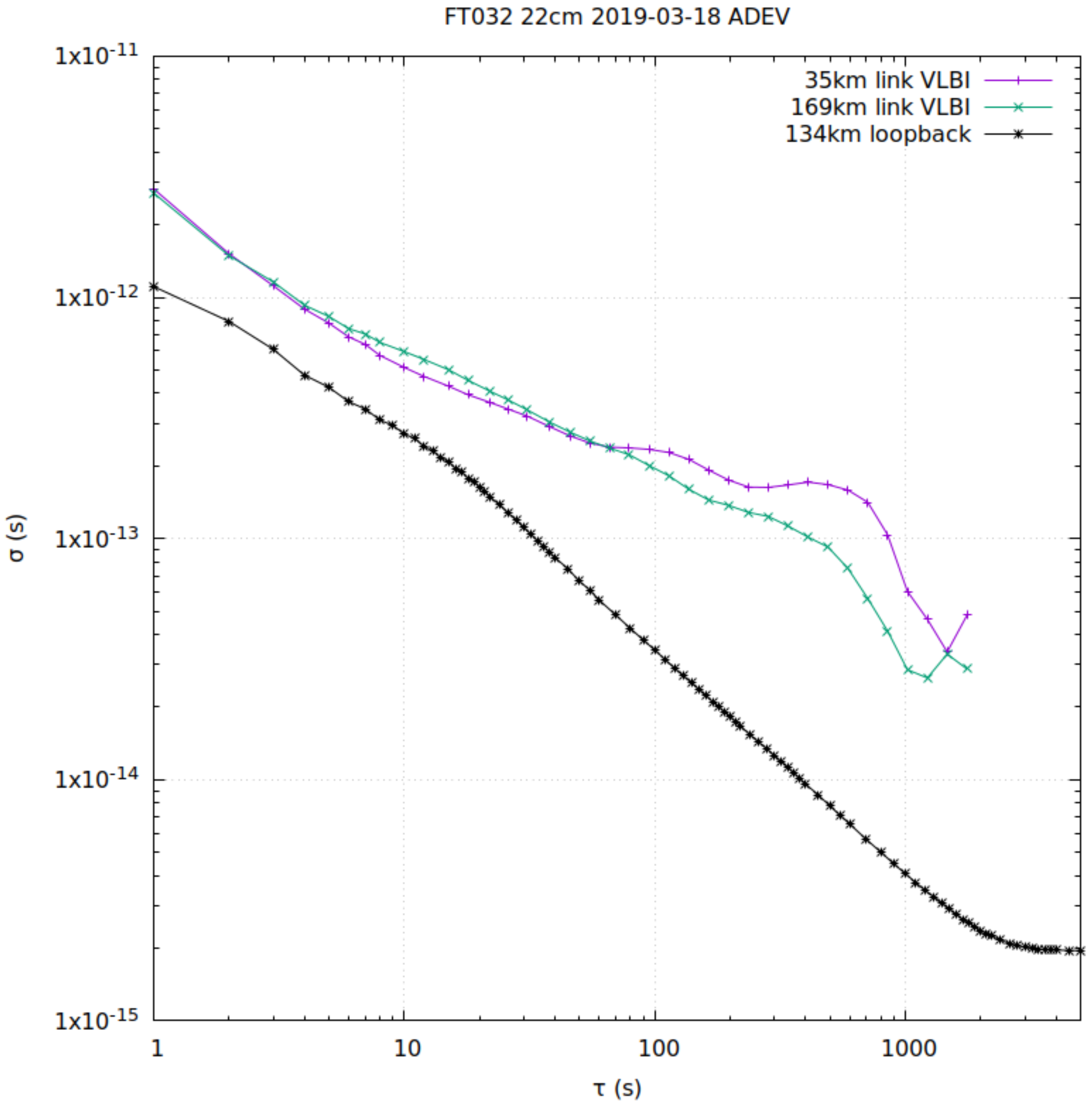




Effelsberg - Dwingeloo Fringe, 2019-03-08

- EVN Network Monitoring Experiment
- 20 dishes from Europe and beyond
- 18cm (1650 MHz)
  - But Dwingeloo only goes to 1500MHz
  - Install new Low Noise Amplifiers
- First Fringes with WR Remote H-maser!
- Tuning error of 0.186 Hz
- Insufficient gain with the new LNAs
  - Some sensitivity loss

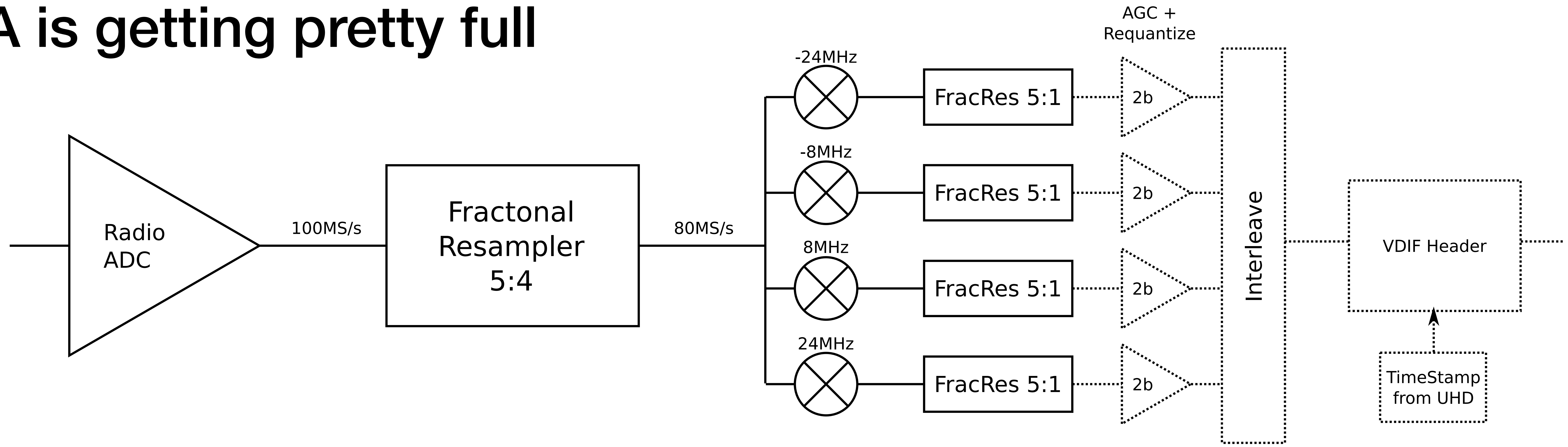
VLBI to measure link performance



- Strong source (3C84)
- At 1332 MHz, 32 MHz BW
- Observations of 1h30m
- Short baseline (25 km)
- Black line: Link performance
- Green/Purple: VLBI ADEV
- Beyond 100s, adev starts to rise due to ionosphere, and source structure

RFNoC

- For one TwinRX channel, SDR output is 3.2 Gb/s
    - After channelizing to 4x 16 MHz and 2 bit quantization: 256 Mb/s
- Can we offload the processing to the FPGA?
    - X310: Xilinx7-410T (406,720 cells, 1540 multipliers)
- Progress so far (dotted is not yet implemented)
    - FPGA is getting pretty full



Conclusions

- A working VLBI backend using a COTS SDR and GNU Radio processing
  - Real-time RFNOC design needs more work

- Reference clock transfer using White Rabbit over a production DWDM net
  - With frequency stability sufficient for VLBI up to ~ 14 GHz
  - Tested distance of up to 169km, no performance difference to 35km link
  - Timing accuracy better than 1 ns