White Rabbit in Radio Astronomy

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JIVE
Joint Institute for VLBI
ERIC

SKA
SQUARE KILOMETRE ARRAY
SIGNAL AND DATA TRANSPORT

Asterics
Astronomy ESFRI & Research Infrastructure Cluster

CAMRAS
DWINGELOO TELESCOOP

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White Rabbit in a Nutshell

WR: 1ns accuracy for distances up to 10 km
Standardized on 1000base-BX10 SFPs
(10km reach, bi-directional 1310nm / 1490nm)

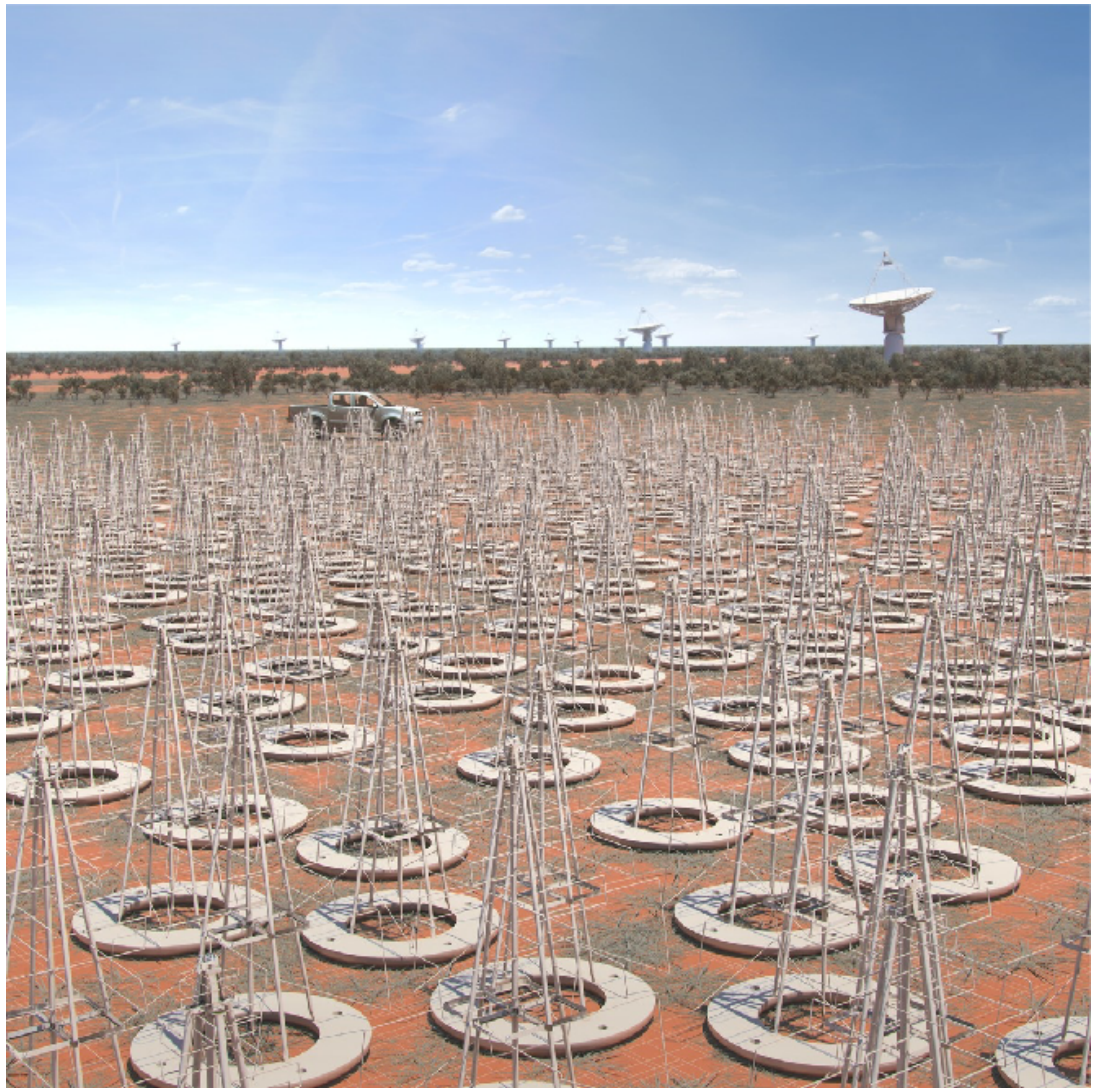
- Calibration:
  - Determine fixed delays (WR equipment, SFPs)
  - Determine differential delay $\alpha = (\delta_{MS}/\delta_{SM}) - 1$
- Operation:
  - Measure RTT, subtract fixed delays; gives cable round trip CRTT
  - Determine one way delay: CRTT * $(\alpha+1)/(\alpha+2)$ + applicable fixed delays
  - Advance local clock to be this much ahead of received timestamps

Images: SevenSolutions and FiberStore

The Square Kilometre Array

SKA1-Low
Australia
50 MHz - 350 MHz
256,000 antennas
65 km baselines

SKA1-Mid
South Africa
350 MHz - 13.4 GHz
197 dishes
160 km baselines



UTC Distribution in the SKA1

One of the SADT work packages:
Deliver local realisation of UTC from the central atomic clocks to the receptors in the field

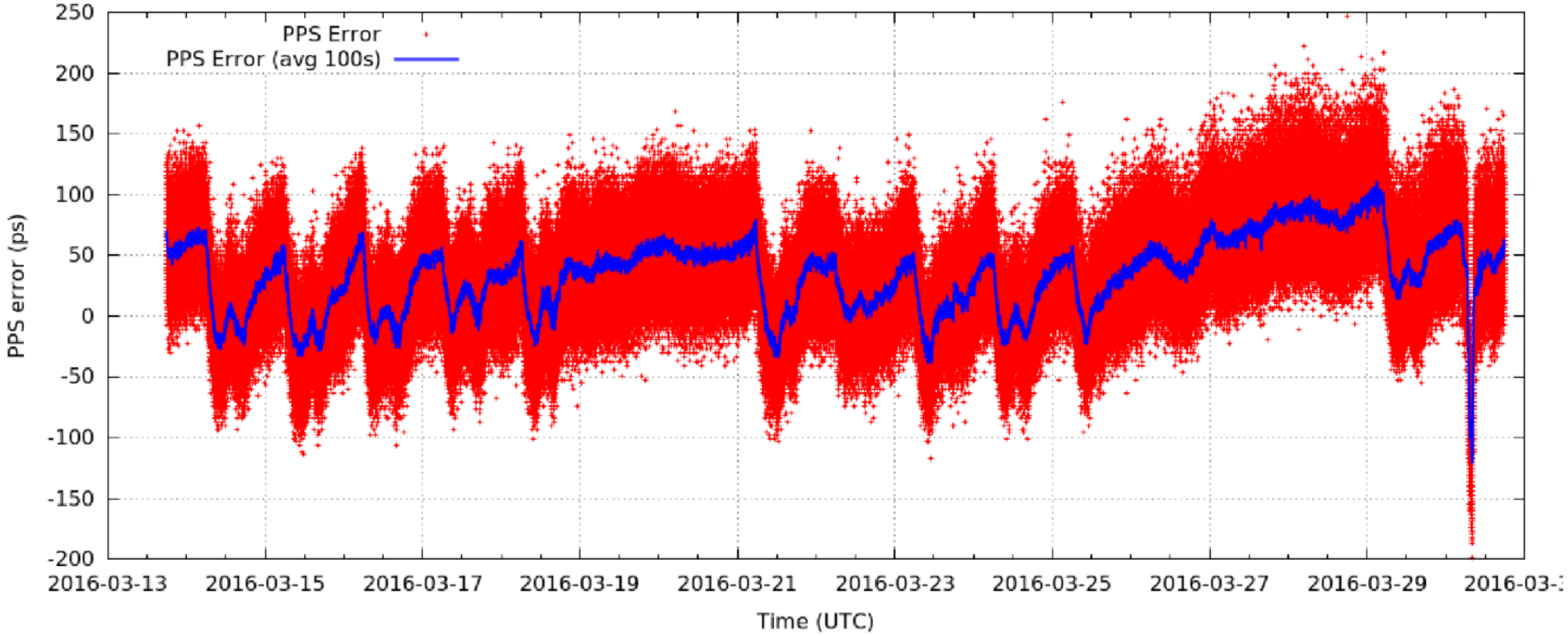
- Phasing up the (sub)-arrays
- Tying measurements to absolute time (e.g. pulsar timing)

Challenges:

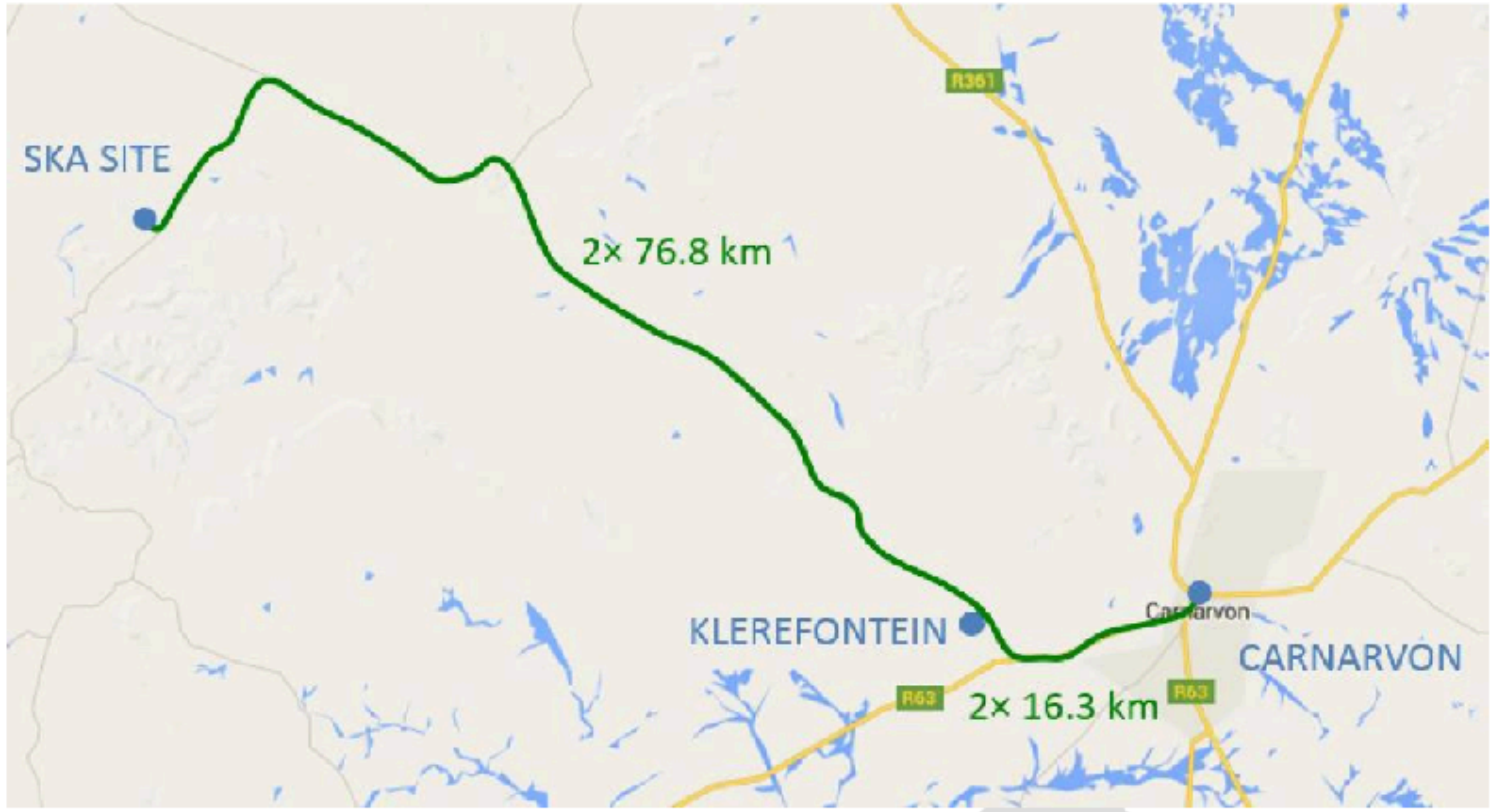
- Distance (at least 160km)
- Climate
- Overhead Fibre in South Africa
- Mixed fiber types
- Accuracy: 2 ns (1σ) over decades

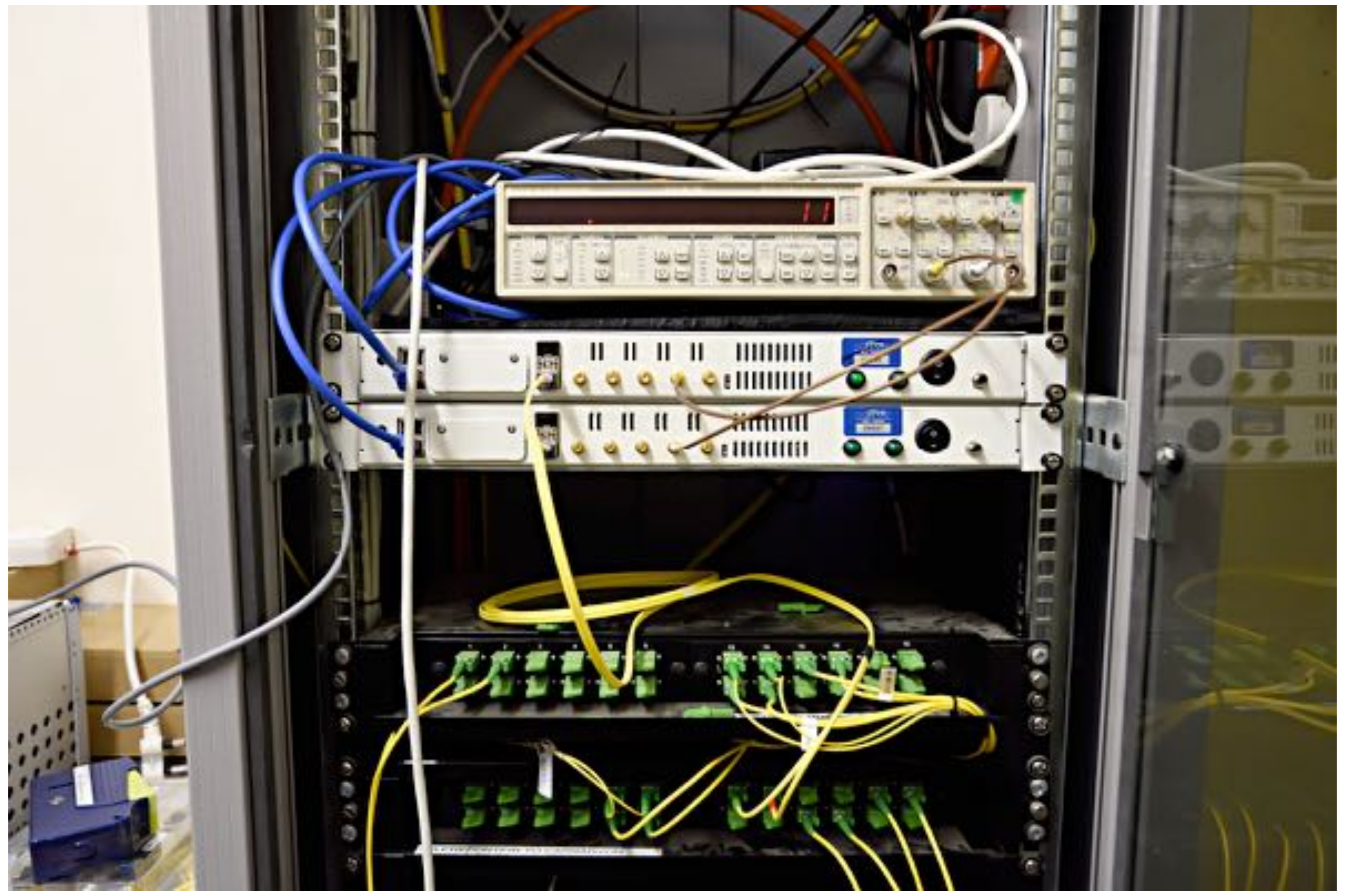
Extending the reach of WR

- BiDi 1310nm / 1490nm exist for 10km - 60km reach
- BiDi 1490nm / 1550nm exist for 80km - 120km reach
- Tested 60 and 80km reach SFPs on a 70km path
- Also cascaded to 140km (JIVE - WSRT and back, see below)

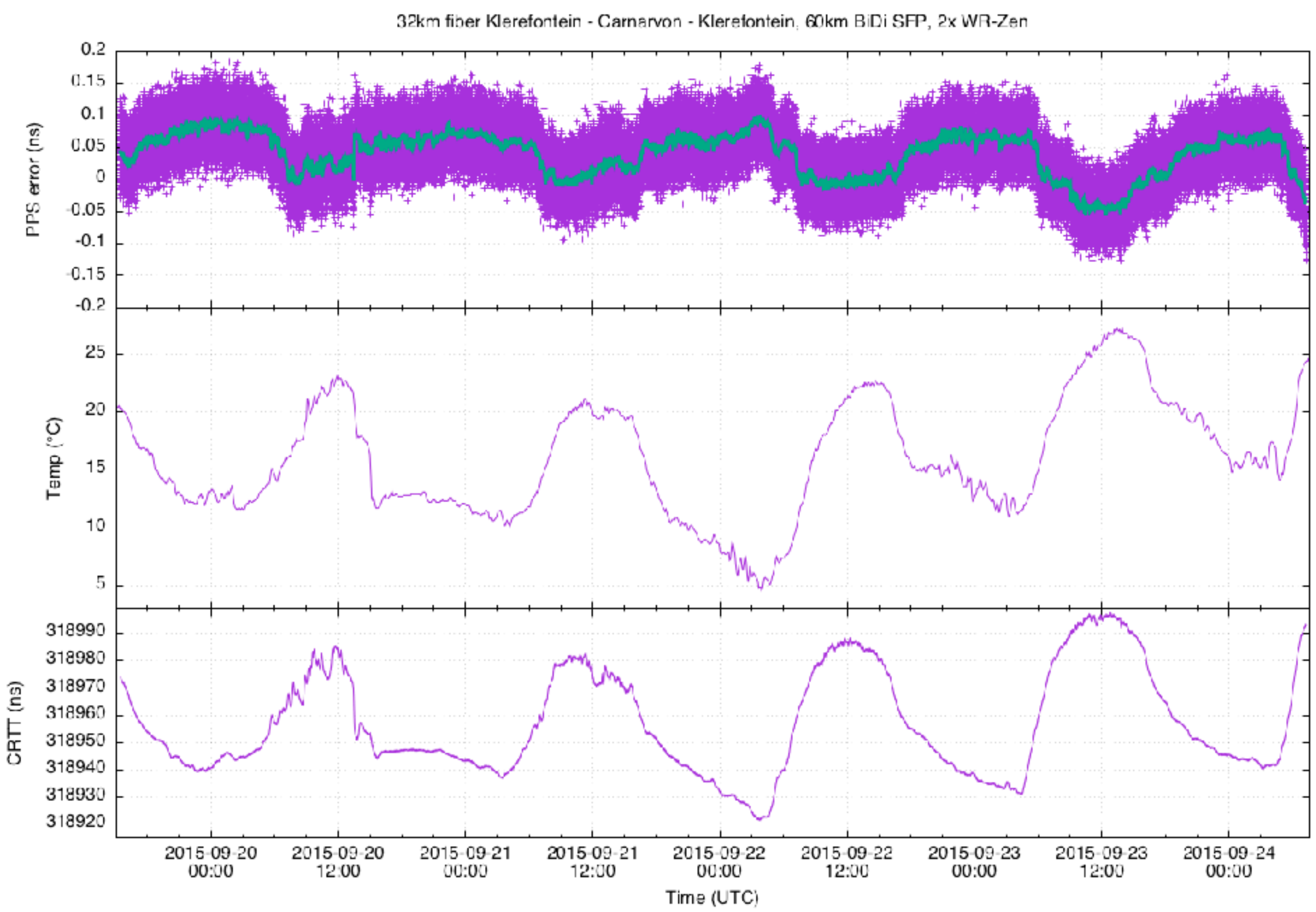


Testing in South Africa

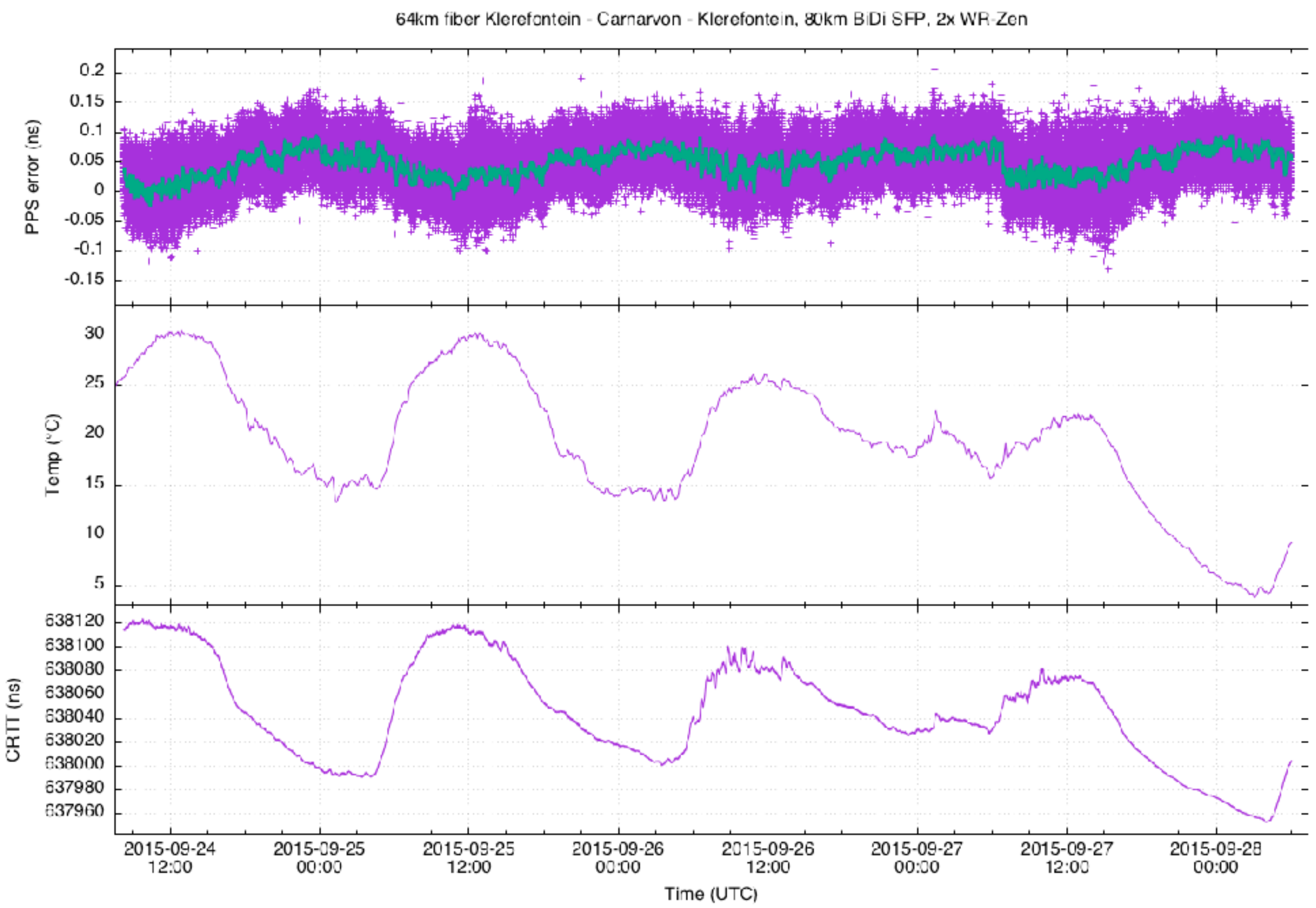




Testing in South Africa

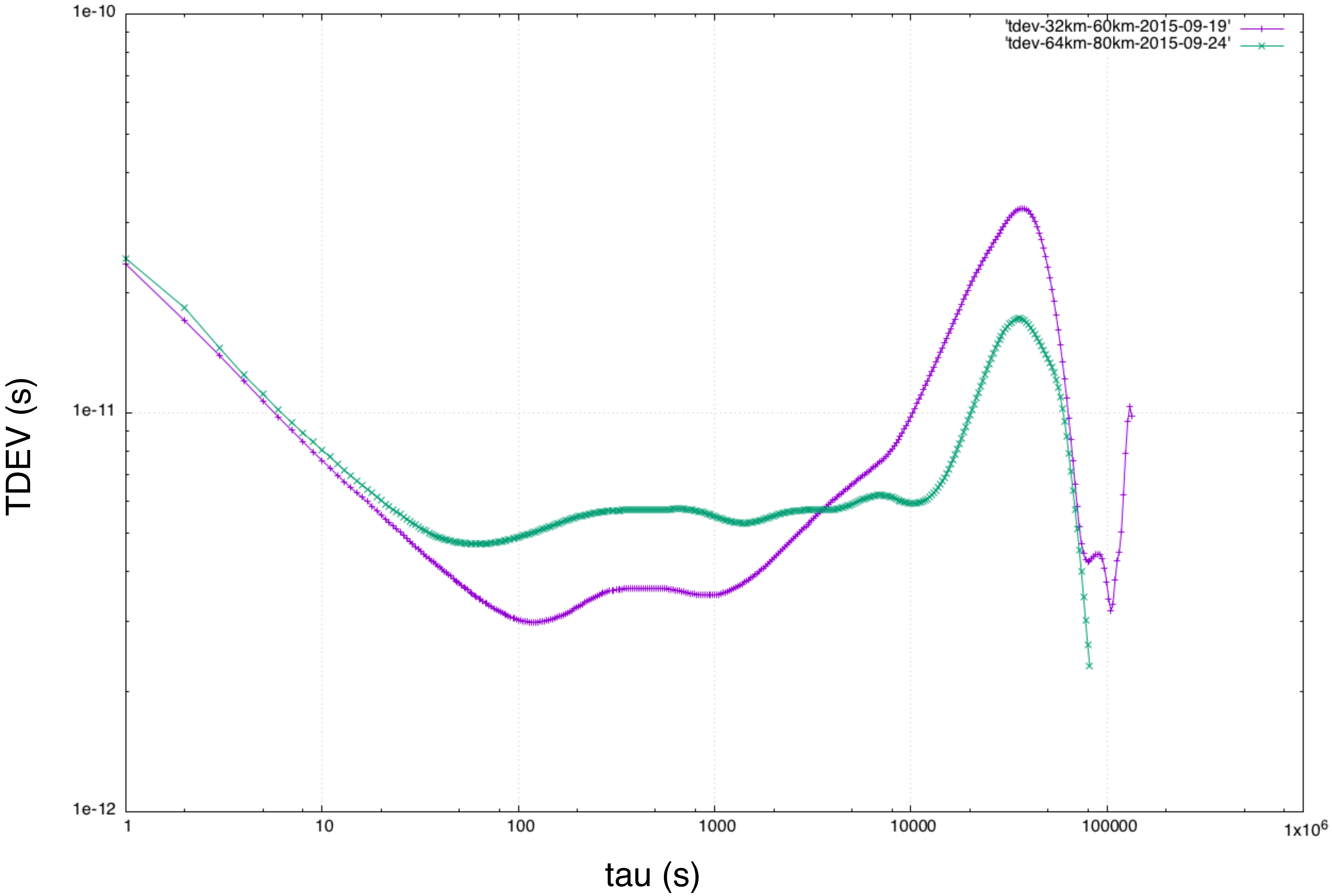


32.6 km, 1310/1490 nm BiDi SFPs



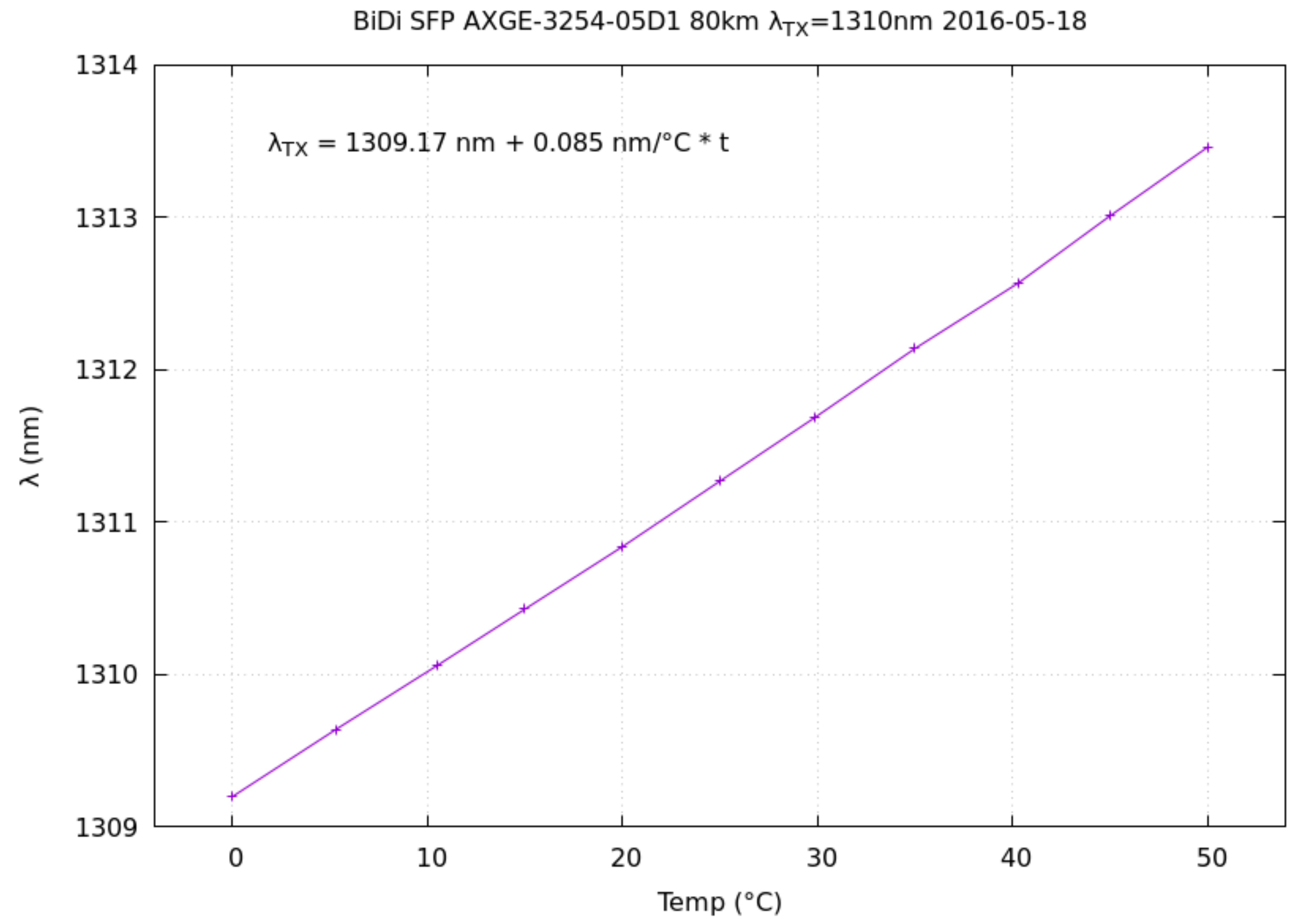
65.2 km, 1490/1530 nm BiDi SFPs

Testing in South Africa



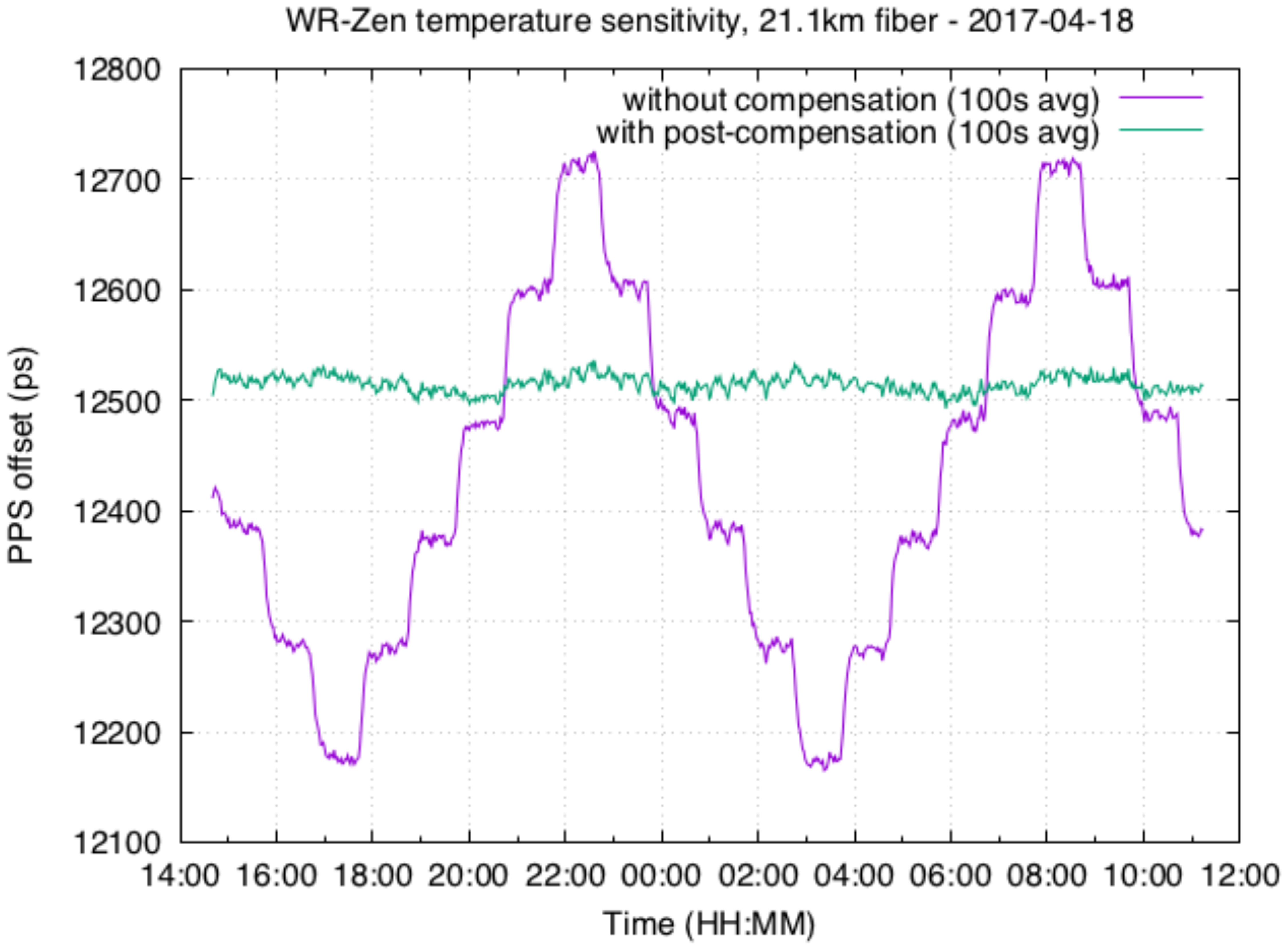
- 1 - 30s:
  Time Interval Counter noise
- 100 - 1000s:
  Server room temperature
- 43200s:
  Diurnal changes, outside temp (imperfect calibration, or temp dependence α)

Temperature effect on SFP wavelength



Chromatic Dispersion for G.652.D fiber

λ (nm)	Dλ (ps nm^{-1} km^{-1})
1310	~0
1490	~13
1550	~17



$$\Delta PPS = \tfrac{1}{2}\,\Delta T\ \ TC_{SFP}\ D_\lambda\ L$$

$$0.5 * 25°C * 0.09\ nm/°C * 13\ {}^{ps}/_{nmkm} * 160km = 2.4ns$$

- Contributed code to WR-switch to read out DOM SFP temperature

“Absolute” Calibration of WR links

- Loopback calibration is easy - challenge is absolute calibration of distant endpoints
- alpha is a fudge factor to get PPS back in position for one pair of SFPs on one link
- All SFPs have wavelength offsets and temperature coefficients
- ΔCRTT = L D_λ $\Delta\lambda$

  Example: 17ps/nmkm * 80km * 9nm = 12ns
  (ΔPPS = 6ns)

- Measure the Tx wavelength of every SFP used in the field (or at least long distance links)
  - Store λ_{TX}, SFP delays and TC_λ in SFP EEPROM
  - Goal of the WR-HA project

- DWDM SFPs are great: 0.1nm wavelength accuracy
  - Cost estimate for SKA1-Mid: 100k€ - 300k€ (>200 links)
  - Power draw > 1W per SFP, just about possible in WR switch
  - Requires external WDM splitters (more rackspace)

Measuring α on long WR links

- Links in SKA1 will be made of mixed fiber types (e.g. G.652.D, ULL, Bend Insensitive, patches)
  - Cannot easily predict α

- Measurement of α requires having both fiber ends together, or a return path
  - Every link in SKA1 will have a parallel return fiber for calibration
  - Create a return WR link (WR-Zen have 2 SFP slots) to a calibration WR endpoint
  - Swap 'Up' SFP for 'Down' (and v.v.) on production link, measure PPS shift
  - Swap SFPs on calibration link to test closure
  - Swap for equivalent but not the same SFP (80km desert drive)

- In normal WR calibration, α hides chromatic dispersion due to SFP wavelength differences.

  On long links, this matters because we need a very accurate α
  - In theory: $\alpha = (\delta_{MS}/\delta_{SM}) - 1 = (n_{down}/n_{up}) - 1$
  - With different SFPs: $\alpha = ((n_{down} + c\ D_{down}\ \Delta\lambda_{down}) / (n_{up} + c\ D_{up}\ \Delta\lambda_{up})) - 1$
  - Must measure wavelength (and perhaps TC) for the SFPs

Sagnac Effect

- Rotation of a light path will make co-rotating light arrive seemingly late, and counter-rotating light arrive early, as the speed of light itself is constant.

- For the full circumference of the Earth, the difference between those two is:

$\Delta t = 4A\omega/c^2$ = 413ns

With A = surface area inside the loop, ω the Earth's rotation rate

- The one-way delay for an E-W path at a particular latitude:

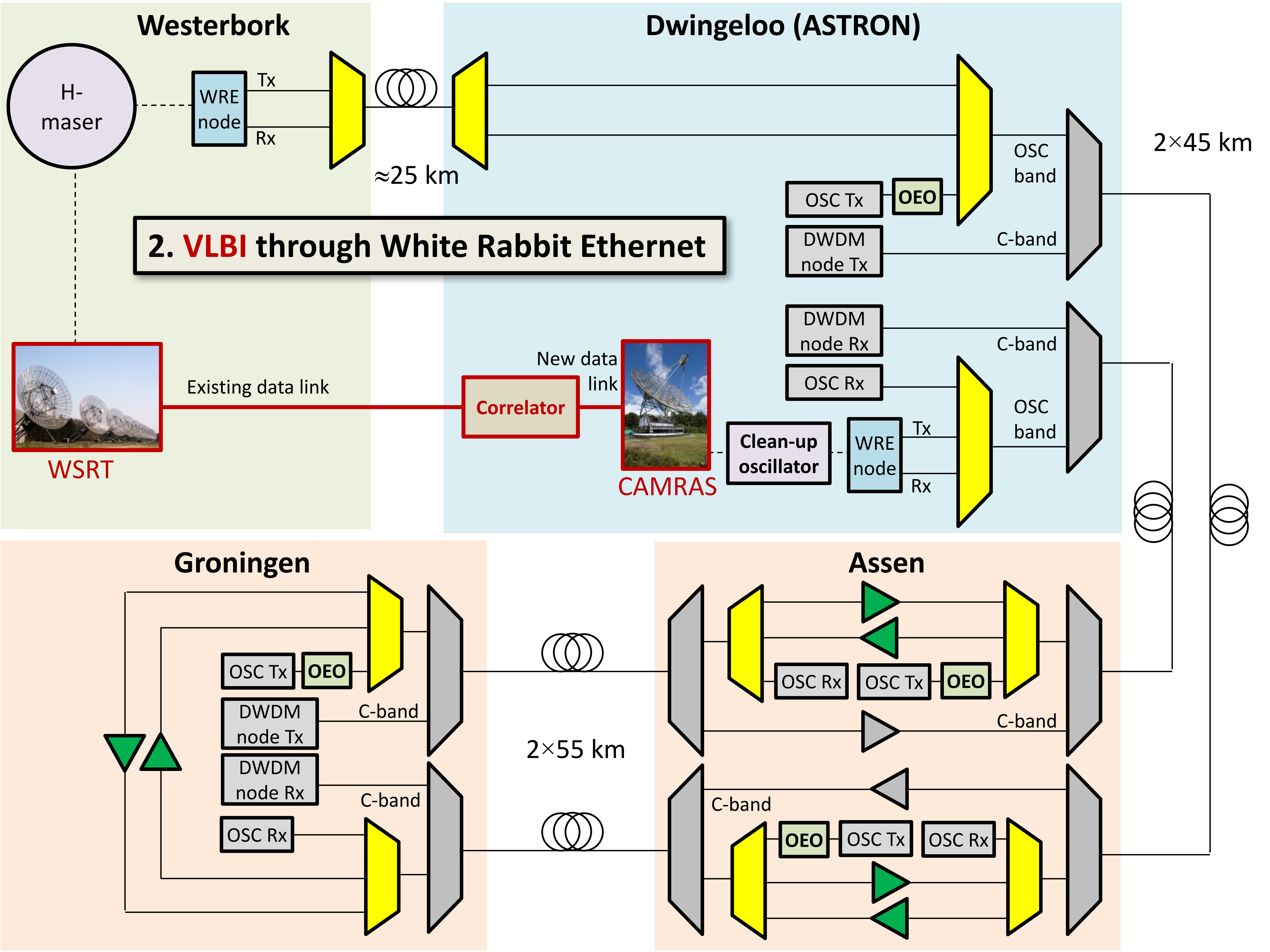
$\Delta t = r\, l \cos(\phi)\, \omega/c^2$ with r equatorial radius of Earth, latitude ϕ, and l the length of the path.

- An 80km E-W path at the Karoo latitude of -31°: 350ps

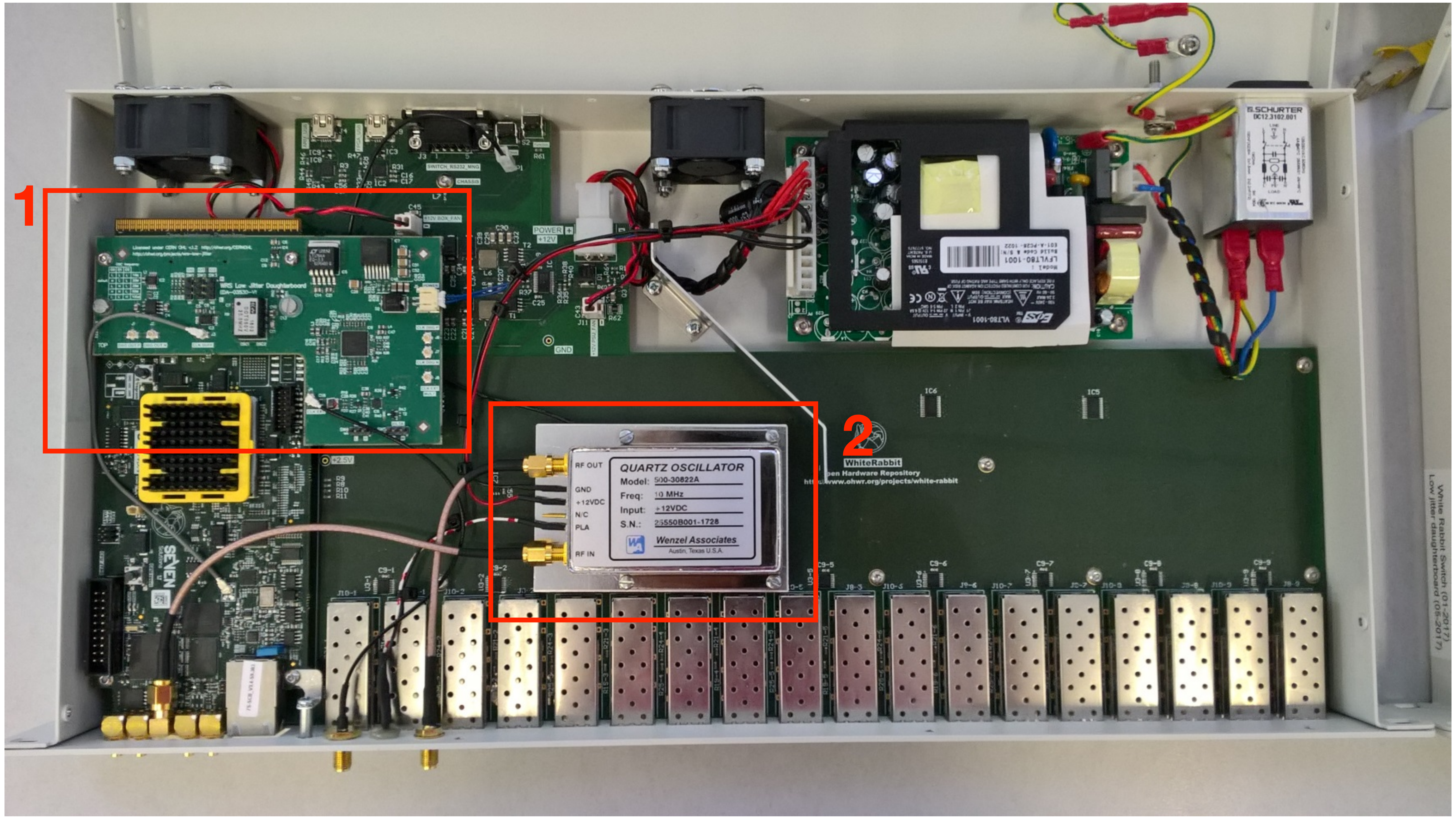
- Knowing the fiber path to a 100m accuracy, and using the WGS84 geodetic model, allows full calculation of the Sagnac effect to better than 1ps.

VLBI with WR

- Very Long Baseline Interferometry
- Requires phase coherence at observing frequency, for up to 1000s
- Fractional frequency error must be really small, especially for higher observing freqs
- Typically VLBI requires H-Masers at each observatory
- To use WR instead, we need to improve WR ADEV by about 3 orders of magnitude
- Use WR on shared fiber infrastructure
- Cooperation of JIVE, VU, ASTRON, SURFnet, CAMRAS



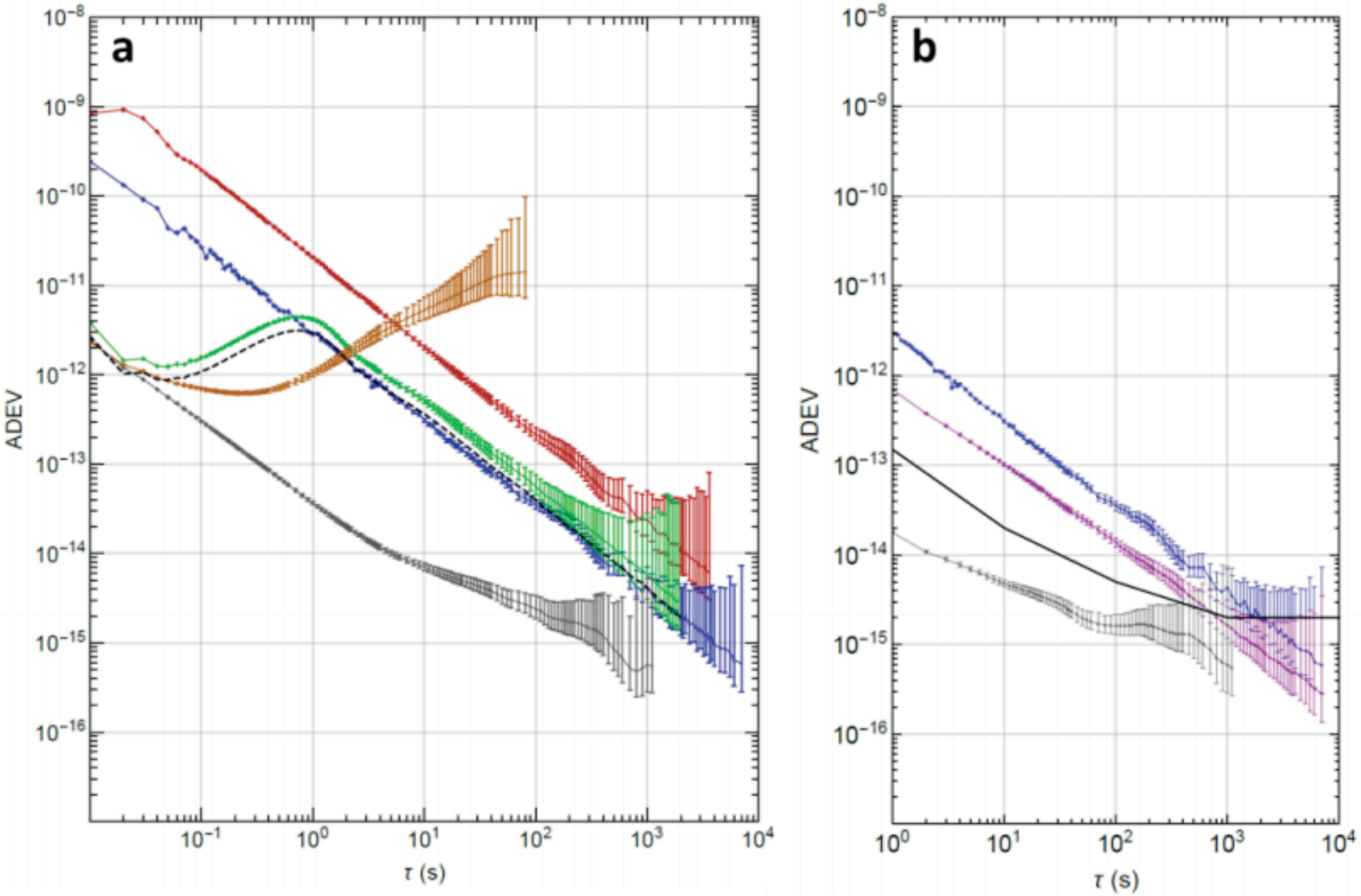
Improved Phase Noise WR-Switch



Work carried out at VU and OPNT bv

1. Low Jitter Daughterboard
2. Phase Locked Oscillator

Initial results WR-SW mod v2



Source: ngNVLA Memo #22, van Tour & Koelemeij

(a)
Long-term frequency stability (ADEV, ENBW 50 Hz) of WR over a short (2 m) fiber link, for the different configurations studied here.
Red curve: default WR;
Blue curve, WR equipped with LJD in both the WR GM and WR Slave
Green curve , WR enhanced by both LJD and PLO (with 1 Hz PLL bandwidth);
Dashed curve, WR enhanced by both LJD and PLO(theoretical single-device stability)
Brown curve, two free-running PLOs versus each other;
Grey curve, measurement system noise floor.

(b)
Frequency instability measured at different ENBWs
Blue curve, ADEV (ENBW 50 Hz) obtained with WR switches equipped with LJD;
Purple curve, same as blue curve, but ADEV obtained with 0.5 Hz ENBW
Black curve, active hydrogen maser ADEV obtained with 0.5 Hz ENBW (manufacturer specification)
Grey curve, noise floor ADEV (ENBW 0.5 Hz).

Conclusions

- WR is becoming a very useful tool for Radio Astronomy
- Absolute Timing Distribution design for the SKA1, both Mid and Low
  - 197 dishes in SKA1-Mid and 36 stations in SKA1-Low in desert climate
- Frequency distribution tests for VLBI
  - Getting close to H-Maser performance, can possibly surpass it
  - Distribution over shared fiber infrastructure