JIVE
Joint Institute for VLBI
ERIC

Synchronization for Interferometry through White Rabbit

Paul Boven
JIVE, Leiden University, CAMRAS

2023-03-30

Contents

- White Rabbit
- Interferometry
- Coherence
- Allan Deviation
- White Rabbit Performance
- Connecting White Rabbit to your SDR
- Extending White Rabbit
  - Longer Links
  - Co-existence on DWDM networks
- Dwingeloo VLBI Results

White Rabbit

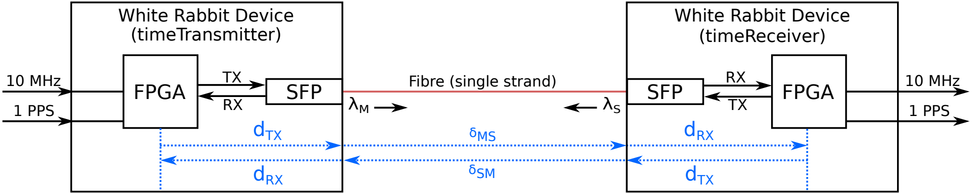
White Rabbit is an open source (OHWR) project to distribute accurate timing and deterministic control traffic. It originated at CERN as an effort to improve and simplify the LHC beam control. It offers 1 ns accuracy, and much better stability.

It makes use of some COTS Ethernet parts, and several existing networking standards:

- Synchronous Ethernet (SyncE)
- Precision Time Protocol (PTP)
- Bi-directional use of single fiber (1Gbase-BX10 SFP, 1310 nm / 1490 nm)
- Carries regular Ethernet data traffic as well

WR is now also part of PTP (IEEE 1588-2019) as High Accuracy Profile

White Rabbit - under the hood



- A WR link transports the input 10 MHz clock, and PPS, and TIA
- Compensates for the unknown, and variable, delay in the fiber
- System measures the RTT at ps resolution
- Before use: Calibrate out all the fixed delays (d_{TX}, d_{RX})
- Removing the fixed delays leaves the fiber RTT
- Dispersion calibration: $\alpha = v_g(\lambda_s)/v_g(\lambda_m) - 1$
- WR calculates the one-way fiber delay, and corrects for it

Interferometry

The science (and art) of measuring the amplitude and phase structure over a field, in order to reconstruct the incoming wavefront, and from that an image of the source.
In radio astronomy we use arrays of antennas, and measure the phase difference between each pair of receptors. Phase is usually measured against a reference phase at each of the antennas.

Left: Very Large Array (Image: NRAO)

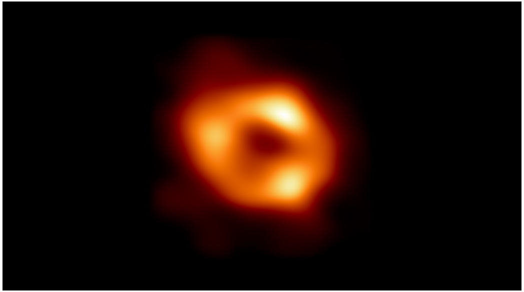
Right: Square Kilometre Array (Image: SKAO)

Interferometry

- Over integration time τ, calculate complex cross correlation on all baselines:

$$f \star g = \int_{\tau} \overline{f} \cdot g$$

- Inverse 2D transform, advanced imaging methods
- Sky brightness distribution (i.e. image)



SagA*, EHT Collaboration

Coherence and Coherence Loss

Given one perfect sinusoid, and one with phase noise $\varphi(t)$,

$$V_a(t) = V_0 \cos 2\pi\nu_0 t \qquad\qquad V_b(t) = V_0 \cos(2\pi\nu_0 t + \varphi(t))$$

The coherence C over an integration time T due to phase error $\varphi(t)$

$$C(T) = \left| \frac{1}{T} \int_0^T e^{i\varphi(t)} \mathrm{d}t \right|$$

Coherence Loss

$$L_C(T) = 1 - \sqrt{\langle C^2(T) \rangle}$$

Coherence loss results in reduced sensitivity
SKA1 design limit: $< 2\%$ coherence loss (clock distrubition)

B. Alachkar e.a., Frequency Reference Stability and Coherence Loss in Radio Astronomy Interferometer Applications for the SKA
Journal of Astronomical Instrumentation, DOI 10.1142/S2251171718500010

Calculating Coherence

Assuming stationarity, Gaussian phase noise: Express clock behaviour as Allan Variance $\sigma_y^2(\tau)$

$$\langle C^2(T)\rangle = \frac{2}{T}\int_0^T \left(1-\frac{\tau}{T}\right) e^{-(\pi\nu_0\tau)^2[\sigma_y^2(\tau)+\sigma_y^2(2\tau)+\sigma_y^2(4\tau)+\cdots]}\mathrm{d}\tau$$

Analytic solutions for two cases:

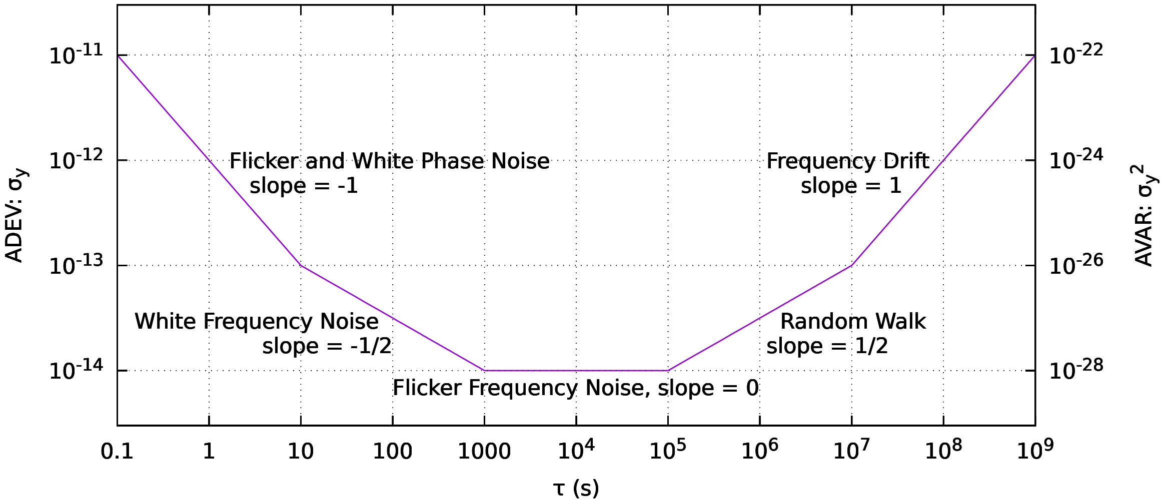
- White Phase Noise: ADEV slope $=-1$ (AVAR slope $=-2$)

$$\lim_{k\to\infty}\sum_{n=0}^{k}\left(\frac{1}{4}\right)^{-n} = \frac{4}{3} \qquad \Rightarrow \qquad L_C = 1-\sqrt{e^{-h_2 f_h \nu_0^2}}, \quad \sigma_y^2(\tau) = \frac{3h_2 f_h}{(2\pi)^2\tau^2}$$

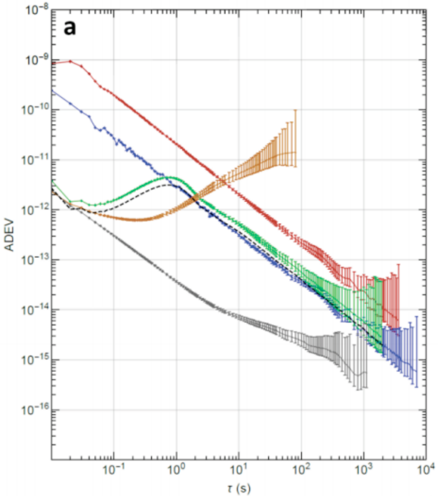
- White Frequency Noise: ADEV slope $=-\frac{1}{2}$ (AVAR slope $=-1$)

$$\lim_{k\to\infty}\sum_{n=0}^{k}\left(\frac{1}{2}\right)^{-n} = 2 \qquad \Rightarrow \qquad L_C(T) = 1-\sqrt{\frac{2(e^{-aT}+aT-1)}{a^2T^2}}, \quad a=\pi^2\nu_0^2 h_0$$

Clock Characterization: Allan Deviation (fractional frequency stability)



White Rabbit ADEV

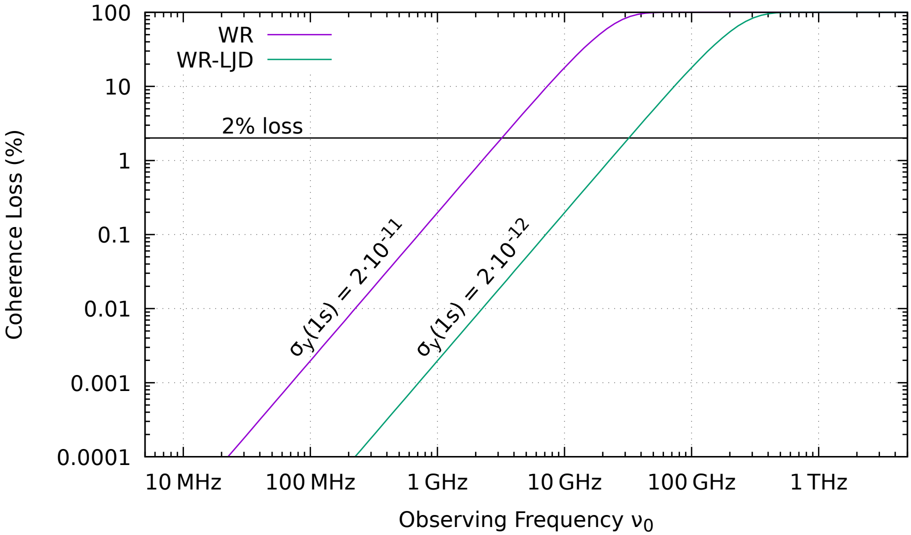


- Due to phase lock, ADEV slope stays at -1

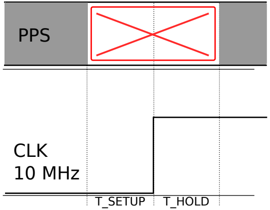
- Graph: ADEV, 50Hz ENBW
- Red: Standard White Rabbit
- Blue: White Rabbit + Low Jitter Daughterboard
- Green: above, + clean-up oscillator
- Brown: two free-running clean-ups
- Grey: System noise floor

van Tour & Koelemeij, ngVLA memo #22

White Rabbit Predicted Coherence Loss (short link)



Connecting your SDR to WR

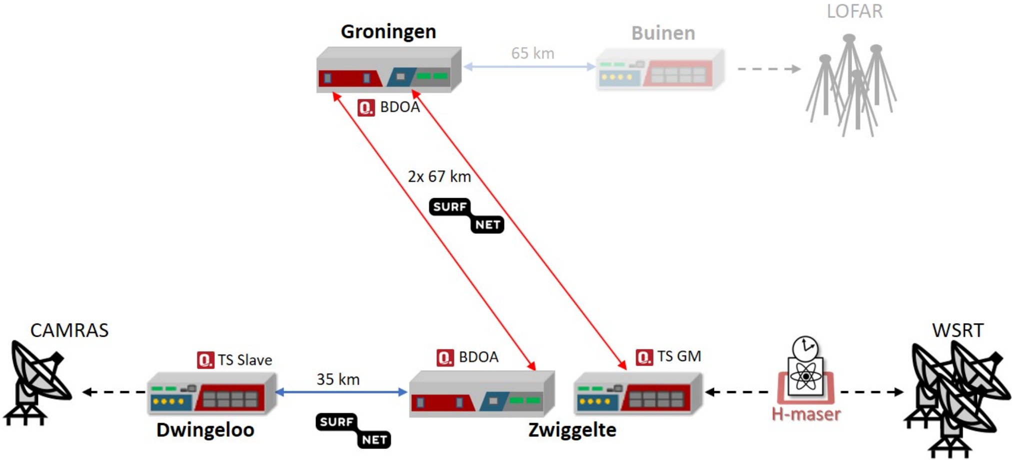


- Your atomic clock: 10 MHz and PPS rising edge is aligned to UTC
- Your SDR, and WR switch:
    - PPS indicates that the next 10 MHz edge starts the second
    - PPS must be stable during the 10 MHz edge
- Setup time: PPS signal must be stable T_S ns before clock edge
- Hold time: PPS signal must stay stable T_H ns after the clock edge
- If these are violated: wrong data in Flip Flop, or even metastability
- Ettus publishes (published?) these with their devices. So does WR.
- Delay the 10 MHz signal by a few ns, using a few m of coax.
- Don't simply use the falling edge of the 10 MHz or 1 PPS!

Extending White Rabbit

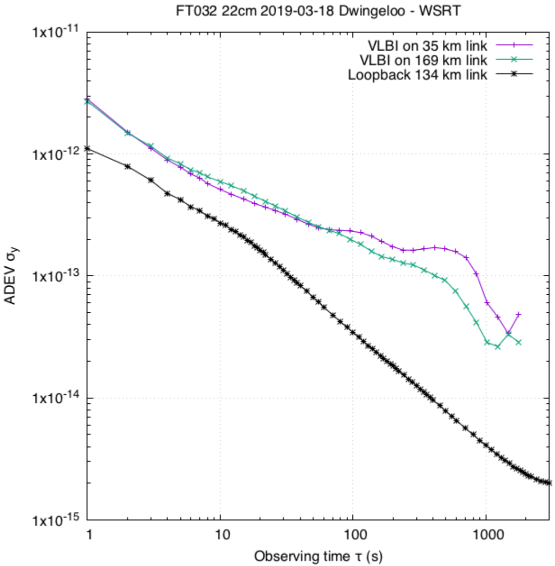
- Original spec: 1Gbase-BX10 optics, 10 km reach, 1310 nm / 1490 nm
- Links can be cascaded a few times
- 80 km reach BiDi optics: 1490 nm and 1550 nm (less attenuation)
- Higher dispersion (17 ps/nm/km) and longer links
  - Wavelength drift (e.g. temperature) causes timing offsets
- Solution: use stabilized (DWDM) optics, COTS
  - With external diplexers to use single fiber link
- Built a 35 km dark fiber link
- And a 169 km WR link, running over existing SURFnet DWDM network
  - Uses out-of-band wavelengths for WR
  - Uses bi-directional Silicon Optical Amplifiers
  - Co-exists with production 100 G network traffic

Extending White Rabbit: The ASTERICS Project



C. van Tour, ASTERICS Deliverable 5.7, 5.14

VLBI with the Dwingeloo Radio Telescope



- Observing 3C84 for 90 minutes
- At 1330 MHz
- Dwingeloo and WSRT
- Using WSRT H-maser via WR
- SNR $>$ 200
- Same ADEV for 35 km and 169 km
- Two separate observations
- Diverges for $\tau > 300$s, due to ionosphere

Conclusions

- White Rabbit is a useful way to distribute a reference clock for interferometry
- For signals up to 2.5 GHz - with LJD up to 25 GHz
- For distances up to at least 169 km, likely much longer
- Can co-exist with other fiber users
- Succesful VLBI observations using 35 km and 169 km links