Long Distance White Rabbit
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SKA1-Low
Australia
50 MHz - 350 MHz
256,000 antennas in 512 stations
65 km baselines

SKA1-Mid
South Africa
350 MHz - 13.4 GHz
197 dishes
160 km baselines
One of the SADT (Signal and Data Transport) work packages:

Deliver local realisation of UTC from the central atomic clocks to the receptors in the field
  • Phasing up the (sub)-arrays (aid in fringe search)
  • Tying measurements to absolute time (e.g. pulsar timing)

Challenges:
  • Distance (up to 173 km)
  • Climate
  • Overhead Fiber in South Africa
  • Mixed fiber types
  • Accuracy: 2 ns (1σ) over decades
Stewing White Rabbits

Test: 0 °C to 50 °C
Step 10 °C every hour
Run for several days

- WR-Zen: 4 ps/K
- WR-Switch: 8 ps/K
- WRS (repeater): 0
Temperature, Wavelength and Dispersion

Effect of Dispersion on WR: \[ \Delta PPS = \frac{1}{2} \Delta T \text{ TC}_{SFP} D\lambda L \]

E.g.: \[ \frac{1}{2} \times 25^\circ C \times 0.09 \text{ nm/}^\circ C \times 13 \text{ ps/nm/km} \times 173 \text{ km} = 2.5 \text{ ns} \]

- Note: only passive cooling in Dish pedestals (0°C < T < 45°C)
- Contributed code to WR-switch to read out DOM SFP laser temperature, could be used to correct for SFP TC
- Wavelength spread between SFPs is a much larger effect
TDEV of 32.6 and 65.2 km overhead link

32.6 km: 1310 / 1490 nm

65.2 km: 1490 / 1550 nm

Counter (20ps jitter)

SFP Temperature (airco cycling)

Variation of $\alpha$ (diurnal, outside temp)
Variation of $\alpha$

- White Rabbit assumes a constant ratio of refractive indices
  \[ \alpha = (\delta_{MS}/\delta_{SM}) - 1 = \frac{v_g(\lambda_S)}{v_g(\lambda_M)} - 1 \]

- Temperature Dependent Sellmeier Coefficients\(^1\):
  \[ n^2 = A + \frac{B}{1 - C/\lambda^2} + \frac{D}{1 - E/\lambda^2} \]

- Calculate Group Velocities:
  \[ v_g(\lambda,T) = \frac{c}{n(\lambda,T) - \lambda \frac{dn(\lambda,T)}{d\lambda}} \]

- Calculations
  1490/1550: $\alpha = 2.4E-4 - 2.1E-8 * t$  \(\text{measured:} \ 1.8E-4\)
  C21/C23: $\alpha = 7.5E-6 - 5.5E-10 * t$  \(\text{measured:} \ 6.8E-6\)

- Measured temperature dependence seems to fit

\(^1\) G. Gosh e.a., Temperature Dependent Sellmeier Coefficients and Chromatic Dispersions for some Optical Fiber Glasses, Journal of Lightwave Technology Vol 12 No 8, August 1994
DWDM with WR

• DWDM: Dense Wavelength Division Multiplexing
  Telecom uses >80 wavelengths near 1550nm (C-band) on 1 fiber

• Wavelength stable to within 0.1nm (Peltier on laser)

• Available as SFP
  • Not as BiDi, needs WDM filter
  • C21 = 1560.61 nm, C23 = 1558.98 nm (one guard channel)
  • Can be as cheap as €170 (+ €35 for filter)
  • Needs about 1A per SFP (careful with WR-SW PSU)
WR with DWDM for the SKA1

**TFR Room**

- **WR Switch (10x)**
- **DWDM SFP (18x)**
  - C21
  - C21
  - ...
- **DWDM Filter (10x)**
  - C23
  - P
  - E
- **PatchPanel**
- **Optional Attenuator**
- **Optional Attenuator**

**Dish Pedestal**

- **WR-Zen**
- **NSDN Switch**

**Legend**
- **LC/PC connector**
- **LC/APC connector**
- **DWDM Filter Ports:**
  - C = Common
  - P = Pass (Transmit)
  - E = Express (Reflect)

**From SAT.Clocks**
- 10 MHz
- 1 PPS

**Calibration TIC**
- Start
- Stop
- 14.6 ps

**PPS output**
- 1 PPS to Dish

**NSDN TOR Switch**

**Calibration WR-Zen**
- C23/C21

- **Using a 2\textsuperscript{nd} fiber for calibration of α, e.g. yearly**
- **Also allows ongoing monitoring of one link**
- **DWDM filters close to the SFPs**
**Mechanical Integration**

Designed in-house together with ASTRON, 3D-printed

- Holder for DWDM filters, 3D printed
- Fiber splice tray with DWDM filters
  - Holds up to 20 filters
- Holder for DWDM filter, fits FMC slot
- ‘Exploded’ view
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 is: 
  \[ \Delta t = 4A \omega / c^2 = 413 \text{ns} \]
  With \( A \) = surface area inside the loop, \( \omega \) 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 \( \phi \), and \( l \) the length of the path (pretending Earth is a sphere)

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

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

(Relativistic Corrections for Time and Frequency Transfer in Optical Fibres, J. Geršl e.a., Metrologia Volume 52 Number 4; https://arxiv.org/abs/1603.05428 )
Link Restart - now fixed?

Random variation in PPS offset on link restart (i.e. reboot, or unplug fiber, or restart WR daemon).
Variation (sample stdev) up to 25 ps
## Worst Case PPS Error

- **80 km**: Longest link in SKA1-Low
- **173 km**: Longest link in SKA1-Mid, with 2x repeater

<table>
<thead>
<tr>
<th></th>
<th>1310/1490</th>
<th>1490/1550</th>
<th>1490/1550 + TC</th>
<th>DWDM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 km</td>
<td>80 km</td>
<td>173 km</td>
<td>80 km</td>
</tr>
<tr>
<td>Delay Calibration</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>10</td>
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<tr>
<td>Link Restart</td>
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<td>75</td>
<td>225</td>
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<tr>
<td>Received Power Var.</td>
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<td>30</td>
<td>90</td>
<td>30</td>
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<tr>
<td>Determination of $\alpha$</td>
<td>75</td>
<td>75</td>
<td>225</td>
<td>75</td>
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<tr>
<td>Wavelength Uncert.</td>
<td>141</td>
<td>1240</td>
<td>2682</td>
<td>1240</td>
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<tr>
<td>Temp. dependence $\alpha$</td>
<td>25</td>
<td>100</td>
<td>216</td>
<td>100</td>
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<tr>
<td>TC of WR-Zen (25K)</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
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<td>TC of WR-Switch (1K)</td>
<td>8</td>
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<td>8</td>
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<tr>
<td>Uplink SFP temp</td>
<td>2.5</td>
<td>1400</td>
<td>1580</td>
<td>280</td>
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<tr>
<td>Downlink SFP temp</td>
<td>14</td>
<td>68</td>
<td>422</td>
<td>68</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>475</strong></td>
<td><strong>3100</strong></td>
<td><strong>5550</strong></td>
<td><strong>1915</strong></td>
</tr>
</tbody>
</table>

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See: P. Boven, DWDM stabilised optics for White Rabbit  
DOI: 10.1109/EFTF.2018.8409035  IEEE Proceedings, EFTF 2018
ASTERICS: Working together on multi-messenger challenges

• Bringing together the astronomy, astrophysics and particle physics communities

MULTI-MESSENGER ASTROPHYSICS
Multi-messenger astrophysics helps obtaining a more comprehensive understanding of events and objects in space by looking at different messengers and wavelengths simultaneously with different instruments.

DATA
The astrophysical ESFRI projects will generate rich and complex, multi-dimensional datasets, and the exploitation of this unique combination of astronomy "Big Data" requires a common data infrastructure for data discovery, access and interoperability.

TIMING
The scientific drive towards combining and aligning data from different facilities in order to comprehensively study multi-messenger and transient events requires interoperability between hybrid data streams with unprecedented time synchronization across.

CITIZEN SCIENCE
Part of our mission is to engage with the general public as well as technical audiences. That is why we are developing citizen science experiments that address science questions, while involving the public in knowledge discovery.

ASTERICS is a project supported by the European Commission Framework Programme Horizon 2020 Research and Innovation action under grant agreement n. 653477
Task 5.1: Synchronisation (VU, ASTRON, JIVE, UGR, FOM, DESY, SURFnet)

Task 5.1a: Compatibility with long haul telecom networks
   Improved ADEV (from 2E-11@1s to 2E-13@1s) for VLBI

Task 5.2a: Calibration and characterisation tools for WR
   10G capability for WR

Frequency Stability

Can we transport a H-maser reference for VLBI?

- Uses WR devices with ‘Low Jitter Board’ improvement
- WR in Dwingeloo Telescope also has a high quality cleanup oscillator
- Bi-directional Optical Amplifiers to extend the link (Silicon Optical Amplifiers)
- Runs on existing SURFnet production DWDM network
Improved Phase Noise WR Switch

1) Low Jitter Board 2) Clean Up Oscillator
Work carried out at VU and OPNT b.v.
Link Calibration

- Fixed delays in BDOA (Bidirectional Optical Amplifier) and bidi-multiplexers
- Measured PPS shift
  - Sum: 544 ±47 ps (shift + fixed)
- Predicted dispersion: 635 ±117 ps
- Matches within uncertainties
Test Setup on 67km WSRT-Groningen-WSRT
Test Setup on 67km WSRT-Groningen-WSRT
Results over 2x 67km
WSRT - Groningen - WSRT

SRS SR620 TIC on PPS ports
(Red: samples, Blue: avg of 100)

Microsemi 3120a on 10MHz ports
Results over 2x 67km

WSRT - Groningen - WSRT

Red: ADEV/MDEV, 50 Hz. Blue: ADEV/MDEV, 0.5 Hz. Green: ADEV/MDEV 1PPS
Recorded 10 s of data (LCP only) using SDR, locked to Rubidium + GPS
Processed using GNU Radio flowchart. Correlated at JIVE using the SFXC correlator.
Next: Dig 300m fiber to complete WR link!