ELECTRONICS & DEFENSE

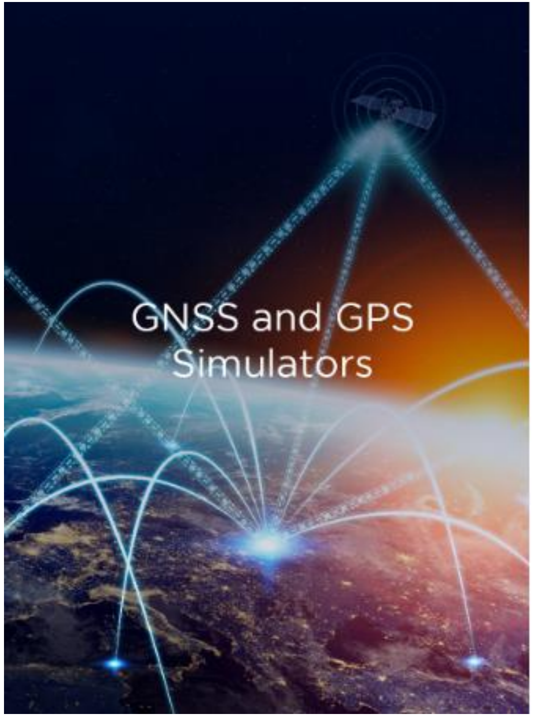
WR Use case: Distributing time for SKA, the largest telescope in the world

Benoit Rat, Specials Project Unit
2024-Mar-22

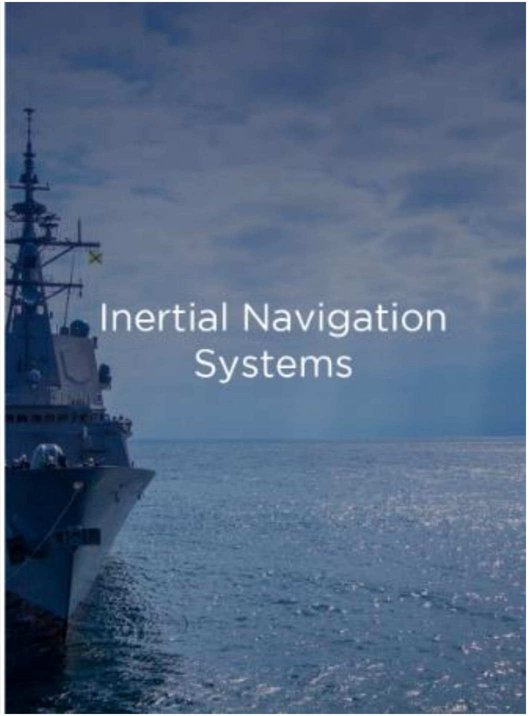
SAFRAN

Index

Safran PNT


GNSS and GPS Simulators

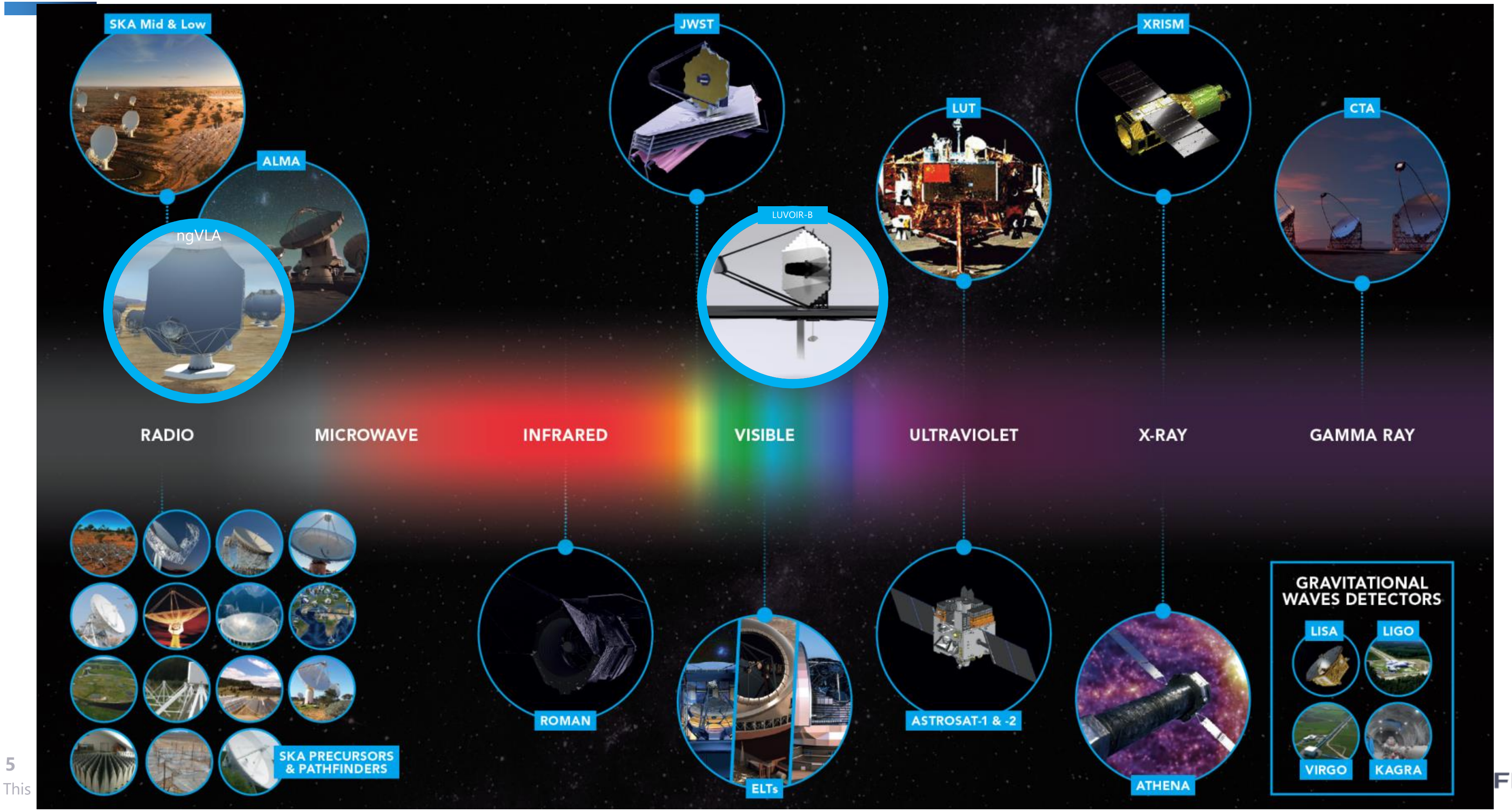

Timing and Synchronization


Inertial Navigation Systems

01
INTRO TO SKA

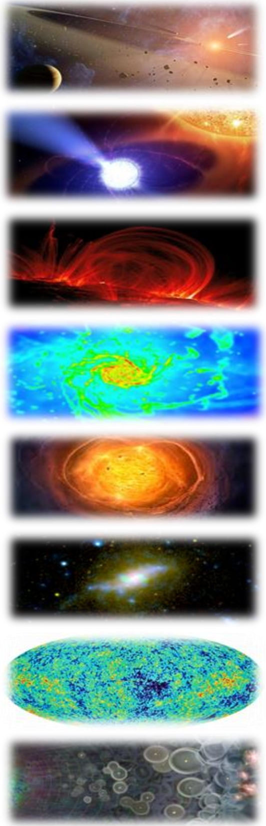
Department / Company / Date (menu "Insert / Header and footer" – "Insertion / En-tête et pied de page")

21^{st} Century Astronomy



Some of the big SKA Science questions

- **The Cradle of Life & Astrobiology**
  - *How do planets form? Are we alone?*
- **Strong-field Tests of Gravity with Pulsars and Black Holes**
  - *Was Einstein right with General Relativity?*
- **The Origin and Evolution of Cosmic Magnetism**
  - *What is the role of magnetism in galaxy evolution and the structure of the cosmic web?*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *How do normal galaxies form and grow?*
- **The Transient Radio Sky**
  - *What are Fast Radio Bursts and how can we best utilise them? What haven't we discovered?*
- **Galaxy Evolution probed in the Radio Continuum**
  - *What is the star-formation history of normal galaxies?*
- **Cosmology & Dark Energy**
  - *What is dark matter? What is the large-scale structure of the Universe?*
- **Cosmic Dawn and the Epoch of Reionization**
  - *How and when did the first stars and galaxies form?*



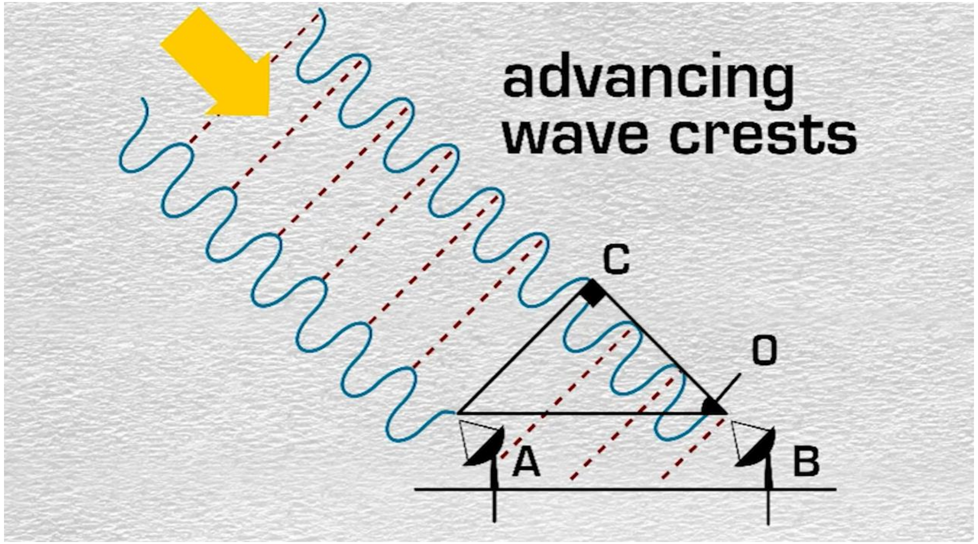
Interferometry

Rather than big repeater ➔ Combine many smaller elements together using “aperture synthesis“ technique

Phase offset when reaching antena A vs B tell us about the position of object in the sky

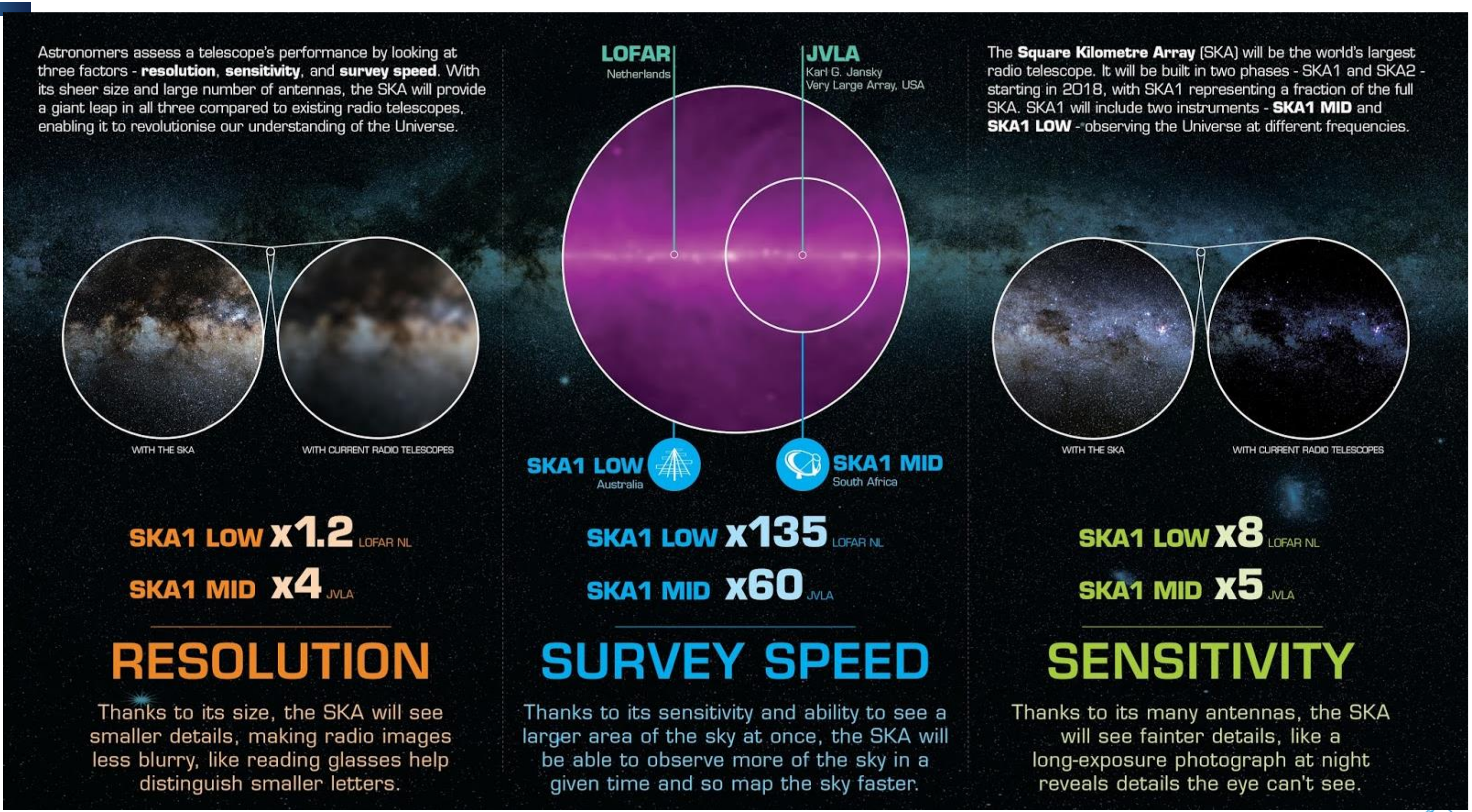
+ By increasing the number of antena we also increase the sens

+ Can be expanded gradually without dramatic impacts → SKA2



Strong need of synchronization to properly combine those radios waves into a higher resolution image.

Aiming to be the best telescope



Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.

SKA1 LOW x1.2 LOFAR NL

SKA1 MID x4 JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW x135 LOFAR NL

SKA1 MID x60 JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW x8 LOFAR NL

SKA1 MID x5 JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

Two sites

SKA1-Mid

the SKA's mid-frequency telescope

Location: South Africa

Frequency range:
350 MHz
to
15.4 GHz
with a goal of 24 GHz

197 dishes
(including 64 MeerKAT dishes)

Maximum baseline:
150km

SKA1-Low

the SKA's low-frequency telescope

Location: Australia

Frequency range:
50 MHz
to
350 MHz

131,072
antennas spread between
512 stations

Maximum baseline:
~74km

SKA1-Mid

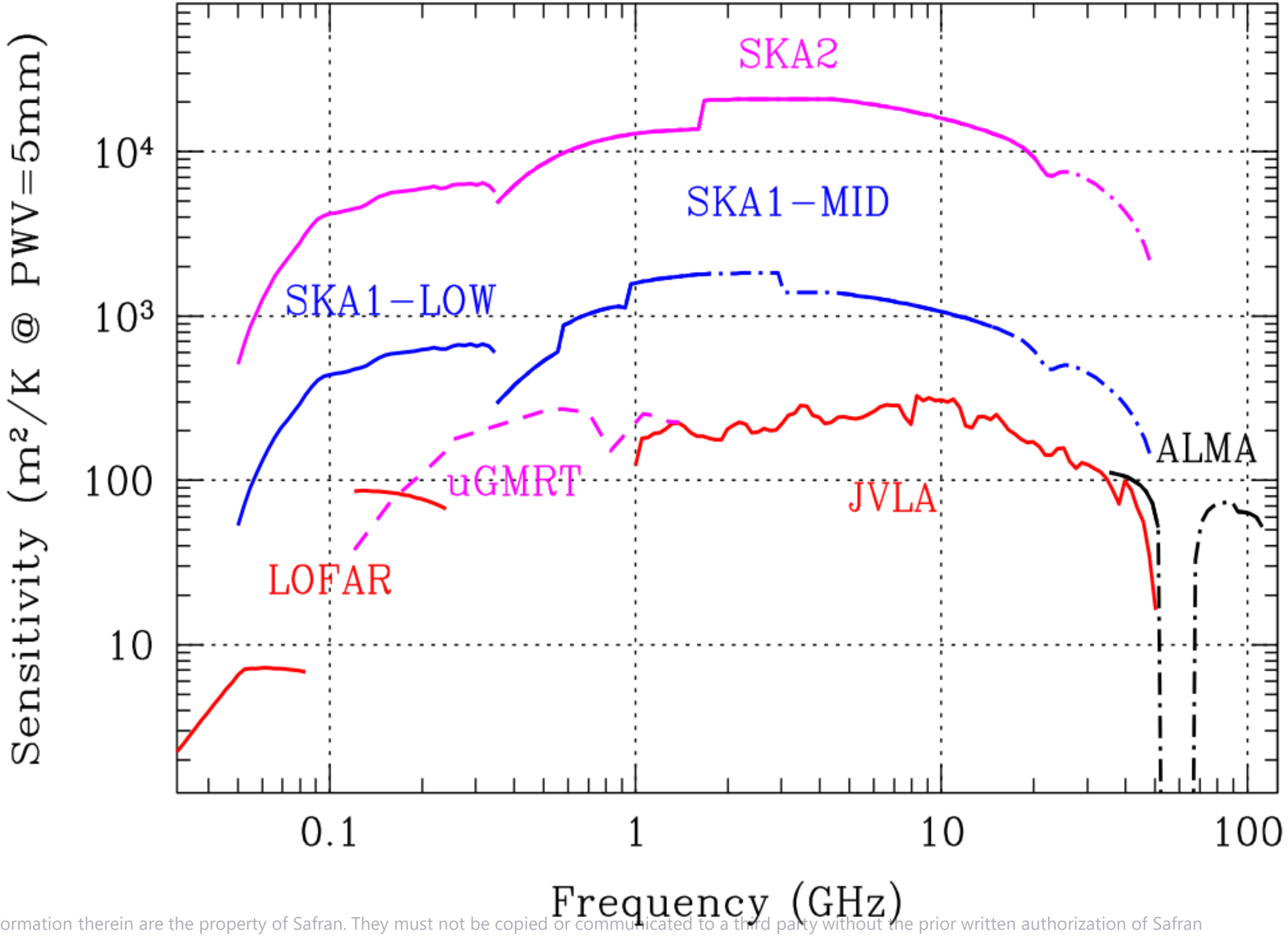
SKA-Low | SKAO

Away from human made electrical noise

Radio astronomy requires radio quietness - the absence of all the electronic noise that human beings create with their technology.

CSIRO's Murchison Radio-astronomy Observatory, Wajarri Yamaji, Western Australia

MeerKAT precursor, Karoo, South Africa



SKA2
SKA1−MID
SKA1−LOW
uGMRT
LOFAR
JVLA
ALMA
10⁴
10³
100
10
0.1
1
10
100
Sensitivity (m²/K @ PWV=5mm)
Frequency (GHz)

02

SKA-LOW

Stations & RPFs

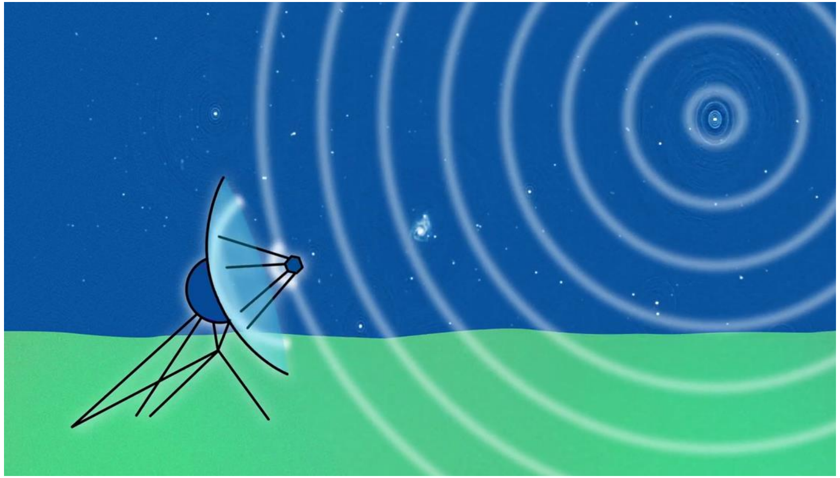
256 antenas per stations

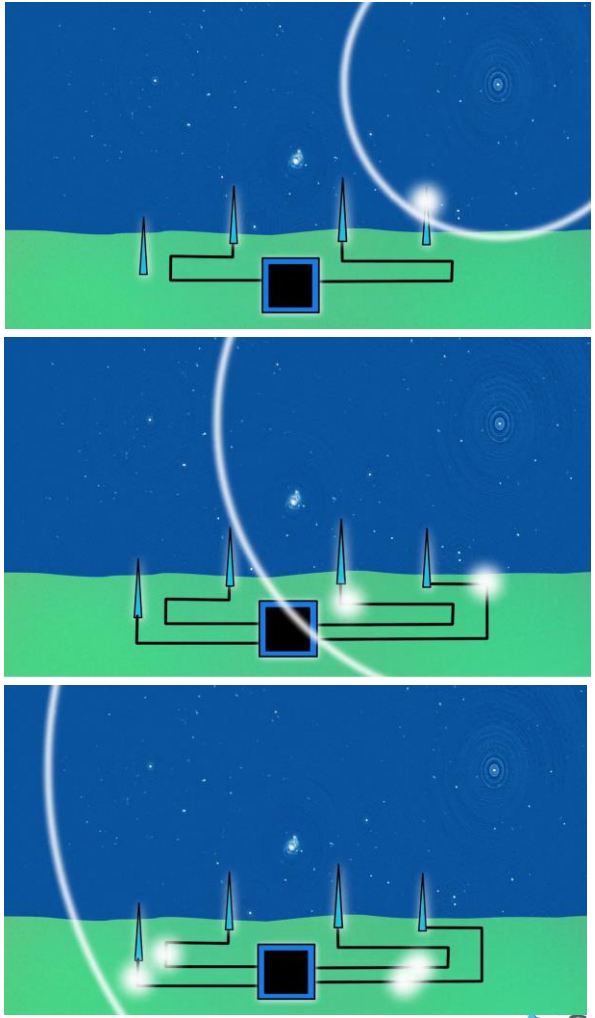
512 stations

108 remotes stations
→ 3x per RFPs

36 RPFs

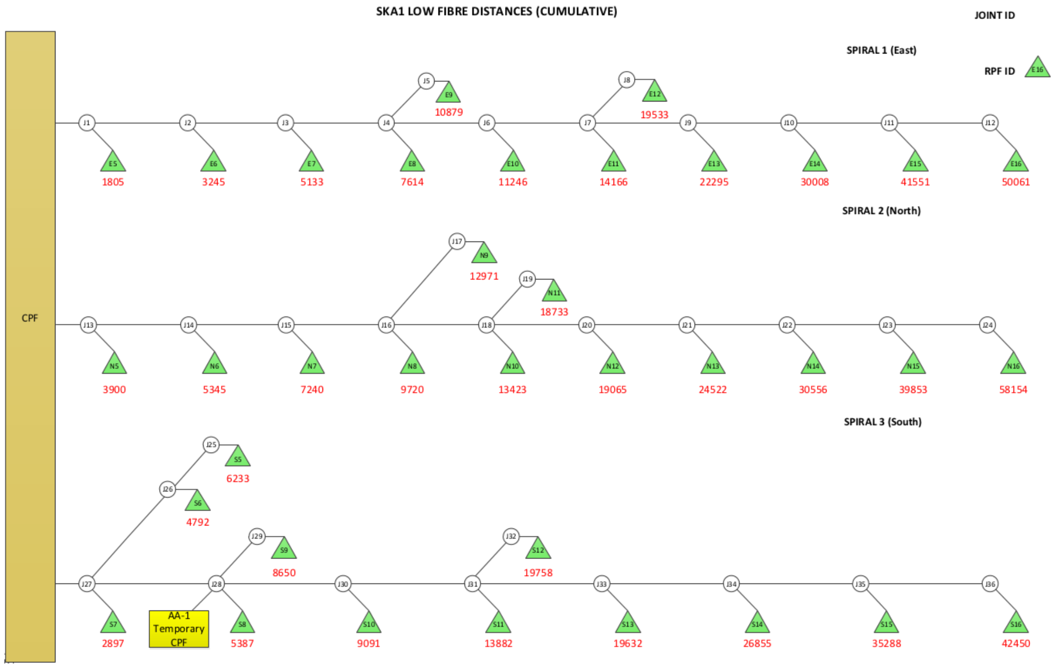
Parabolic shape vs Beamforming

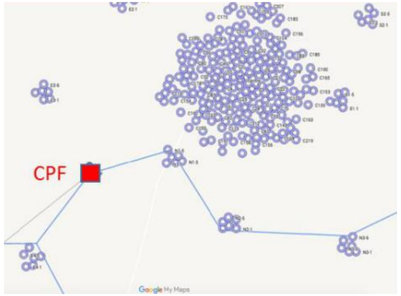


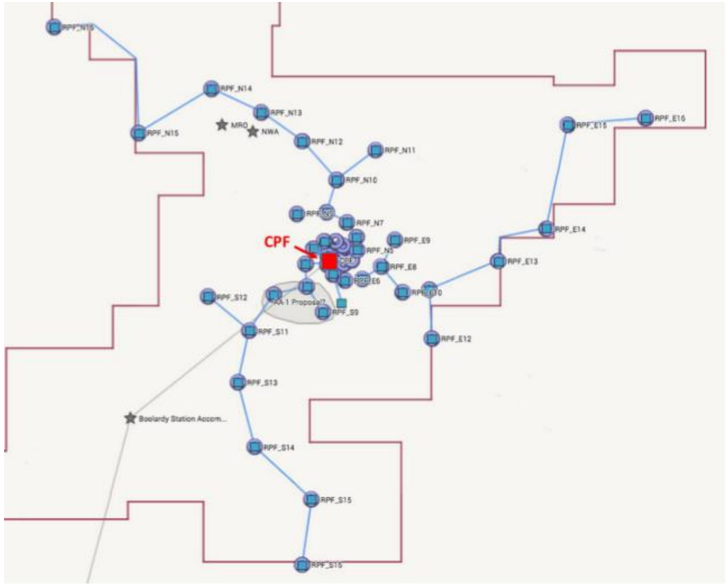


https://youtu.be/9Zlh0nQJMfg

SKA LOW Topology







News: First SKAO LOW Antenna (March 2024)

[First SKA-Low telescope antennas deployed in Australia]()

… only 131071 left

03

SKA-MID

SKA MID

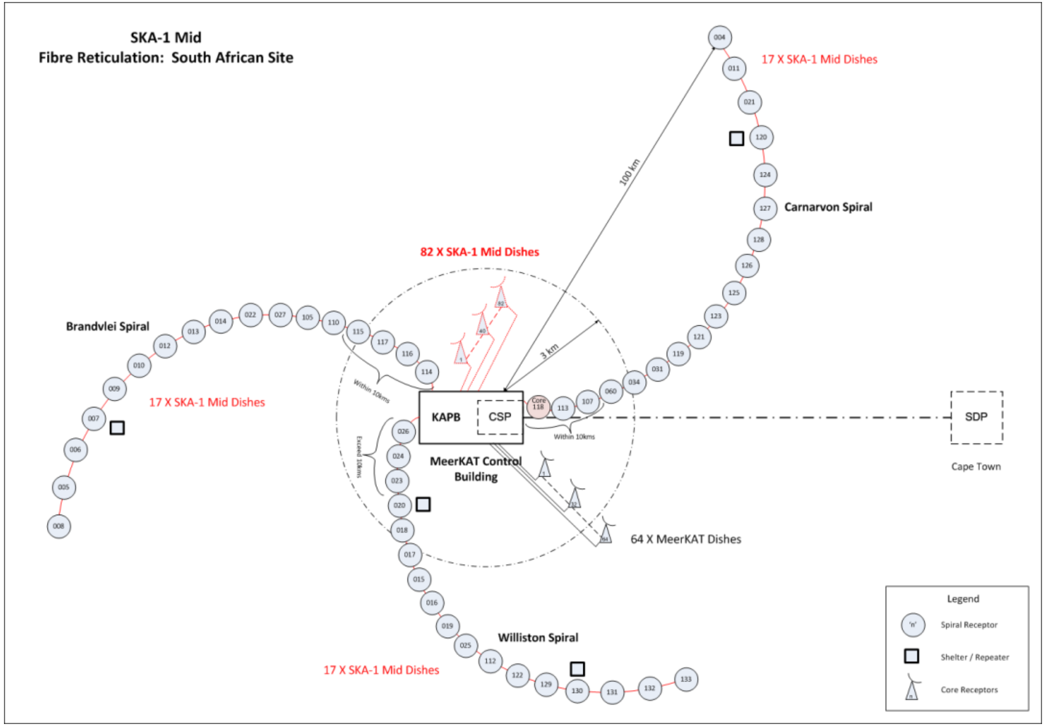
197 dishes

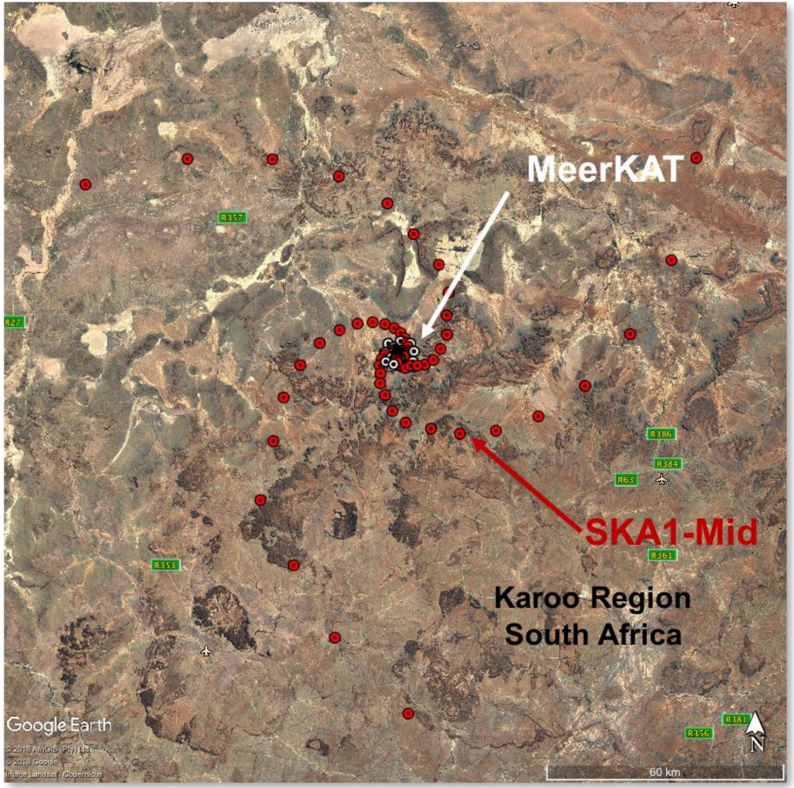
↓

64 meerkat dishes
+133 SKA dishes

(82 dishes < 5km)

SKA MID


SKA-1 Mid
Fibre Reticulation: South African Site
Brandvlei Spiral
17 X SKA-1 Mid Dishes
008
005
006
007
009
010
012
013
014
022
027
105
110
115
117
116
114
82 X SKA-1 Mid Dishes
1
40
82
3 km
100 km
Within 10kms
KAPB
CSP
Core 118
113
107
060
034
031
119
121
123
125
126
128
127
124
120
021
011
004
17 X SKA-1 Mid Dishes
Carnarvon Spiral
Within 10kms
SDP
Cape Town
MeerKAT Control Building
Exceed 10kms
026
024
023
020
018
017
015
016
019
025
112
122
129
130
131
132
133
Williston Spiral
17 X SKA-1 Mid Dishes
1
32
64
64 X MeerKAT Dishes
Legend
'n'
Spiral Receptor
Shelter / Repeater
n
Core Receptors


MeerKAT
SKA1-Mid
Karoo Region
South Africa
R357
R27
R353
R386
R384
R63
R361
R381
R356
Google Earth
© 2018 AfriGIS (Pty) Ltd
© 2018 Google
Image Landsat / Copernicus
60 km
N

An incremental deployment

Name	Low Stations	Date for Low	Mid Dishes (SKA+MeerKAT)	Date for Mid
AA0.5	4	Apr 2024	4+0	Aug 2024
AA1	18	*C0+35*	8+0	*C0+34*
AA2	64	*C0+47*	64+0	*C0+44*
AA3	256	*C0+58*	120+8	*C0+58*
AA4	512	*C0+70*	133+64	*C0+67*

04

CHALLENGES

The challenges

- **1,5ns timing budget from central points**
  - Long distance links
  - SFP power consumption
- **Temperature gradiants**
  - At dishes
  - On fiber
- **Fiber over the air**
  - Winds vibrations
- **Challenging Maintenance/Operation costs**
  - Up to 1 day drive to replace a device and come back
  - UTC System Availability at 99,9%
  - Planning for 50 years

SFP Tx Wavelength

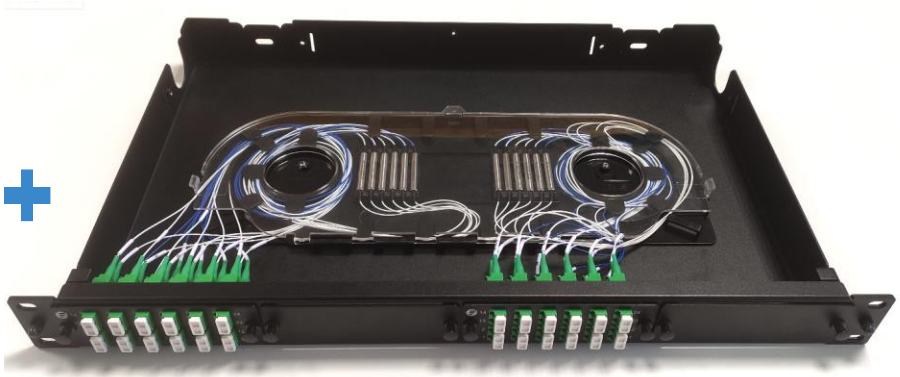
PN	km	Tx wavelength (nm)				Comments
		nominal	Min	Max	Pk2pk	
AXGD-1254-0531	10	1310	1270	1355	85	
AXGE-3454-0531	10	1490	1480	1500	20	
DWDM-SFP1G-ZX-C23	40	1558,98	1558,955	1559,005	0,05	
DWDM-SFP1G-ZX-C21	40	1560,61	1560,585	1560,635	0,05	
DWDM-SFP1G-ZX-C23*	40	1558,98	1558,88	1559,08	0,2	EoL
DWDM-SFP1G-ZX-C21*	40	1560,61	1560,51	1560,71	0,2	EoL

DWDM SFPs

VN	PN	Distance (km)	Tx power (dBm)		Rx power (dBm)		Overload (dBm)	Power Budget (dBm)	Power Draw (W)
			Min	Max	Min	Max			Max
FS	dwdm-sfp1g-zx-40km	40	0	5	-8	-24	13	24	1
FS	dwdm-sfp1g-zx-80km	80	0	5	-3	-24	8	24	1.5
FS	dwdm-sfp1g-ezx-100km	100	0	5	-8	-32	13	32	1
FS	dwdm-sfp1g-ezx-160km	160	1	6	-10	-33	16	34	1

Products for SKA

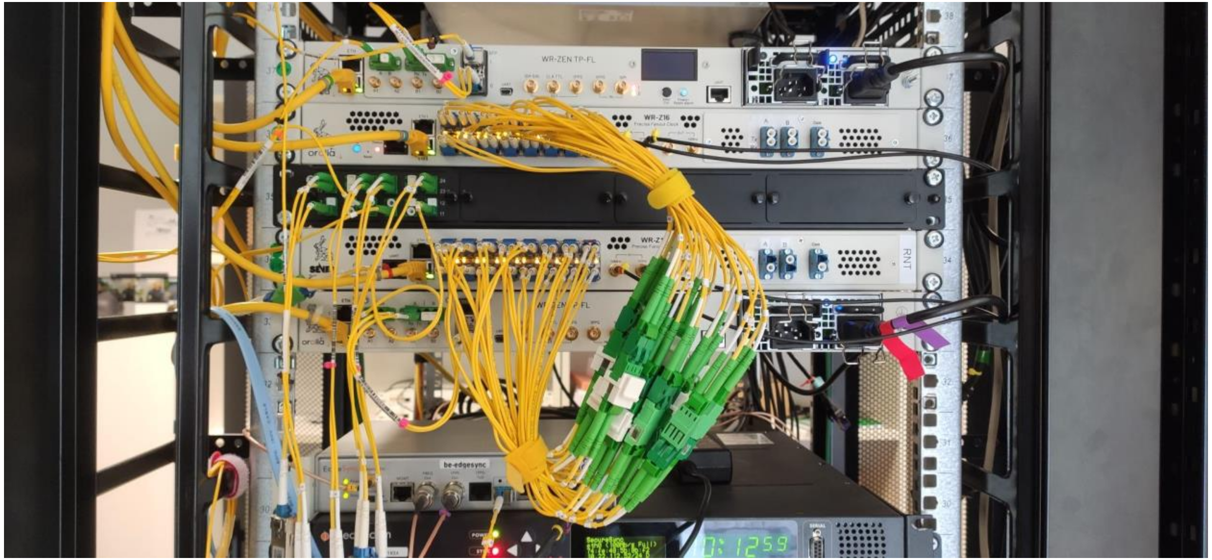
WR-Z16 LJ



DWDM 1U Rack Filters Box

WR-ZEN TP-FL + FPO + C21/C23 filters

Temperature & Power Consumption

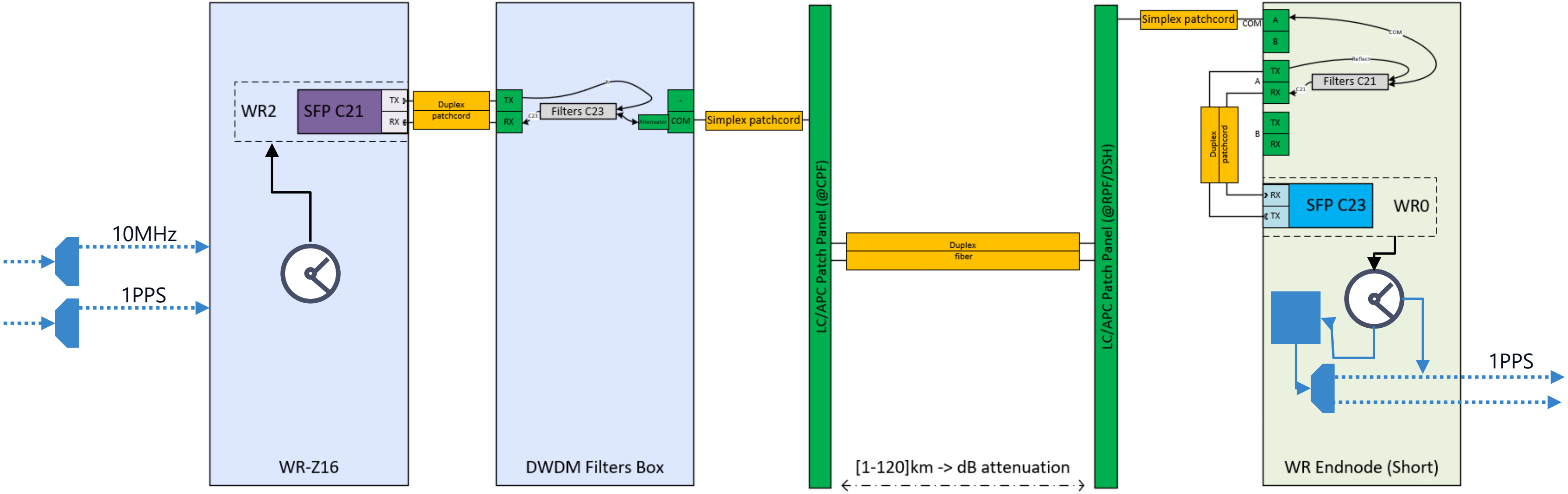


Types of delay

- ## Dynamic delay:
  - This delay is primarily influenced by dynamic components such as temperature, airflow, vibration, aging, etc., which vary over time. Effective design limitations or compensation strategies are essential. The characterization of behaviour under diverse external constraints, such as the asymmetry parameters on a specific type of fiber, is essential to estimate the dynamic behaviour of this kind of delay.
- ## Semi-static delay:
  - The semi-static delay refers to the different components of the system with varying delays between each relock cycle but remaining constant within the same lock states. This is often caused by phase-locked loops (PLLs) not precisely aligning at the same position after each relock or power cycle. Calibration or characterization (e.g., bitslide) is possible in some cases, but achieving a precise approximation may be challenging when dealing with the relocking delay.
- ## Static delay:
  - Static delay is directly linked to the equipment or setup deployed and should remain constant over time or, at the very least, within a specified tolerance for an extended period. This type of delay is typically subject to calibration. As mentioned previously, a proper segregation of the different contributions of static delays makes it easier to replace a sub-part of the system without the need for a new calibration of the whole timing path. It's noteworthy that certain static delays can be characterized per model (hardware version), while others require characterization on a per part-number basis to compensate for chip-to-chip delays.
- ## Noise delay:
  - Ultimately, the noise delay, also known as jitter, needs to be considered in all calibration procedures and delay characterizations. When exhibiting white Gaussian noise characteristics, its impact can be minimized through result averaging across multiple samples. The automatic calibration tool has been designed to reduce the effect of noise delay while performing the calibration.

Timing Budget

Theoritical worst case pk2pk:
1.2ns @ 10km → 900ps (400ps @ lab)
2.4ns @ 160km → 1300ps (600ps @ lab)

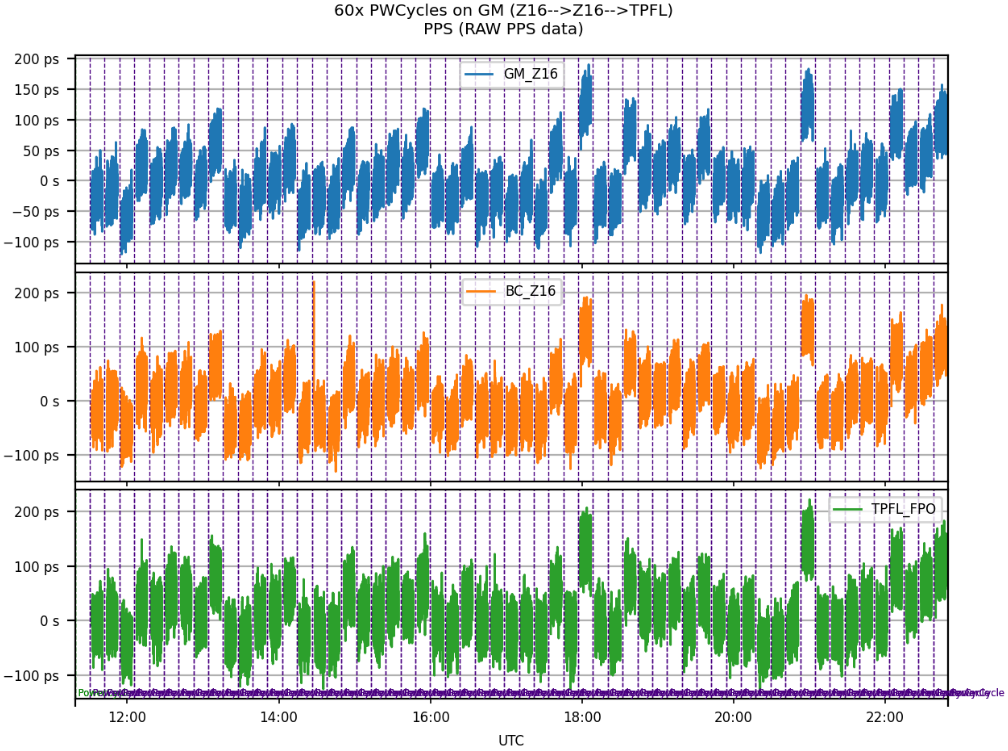


Master port location (i.e, CPF)

Slave port location (i.e, Dish)

Semi-Static delay (Power Cycle @ GM)

- Test on GM with the chain Z16 ==50km=> Z16 ==20km=> TPFL



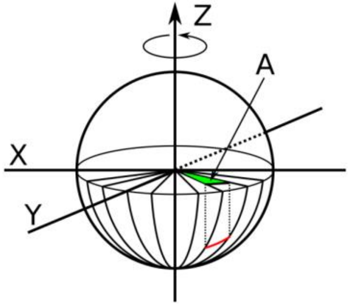
Spliting static calibrations

- **Fast replacement → Device Swapping → Avoid recalibration after swapping**

$$\Delta = \Delta_{port} + \Delta_{SFP}$$

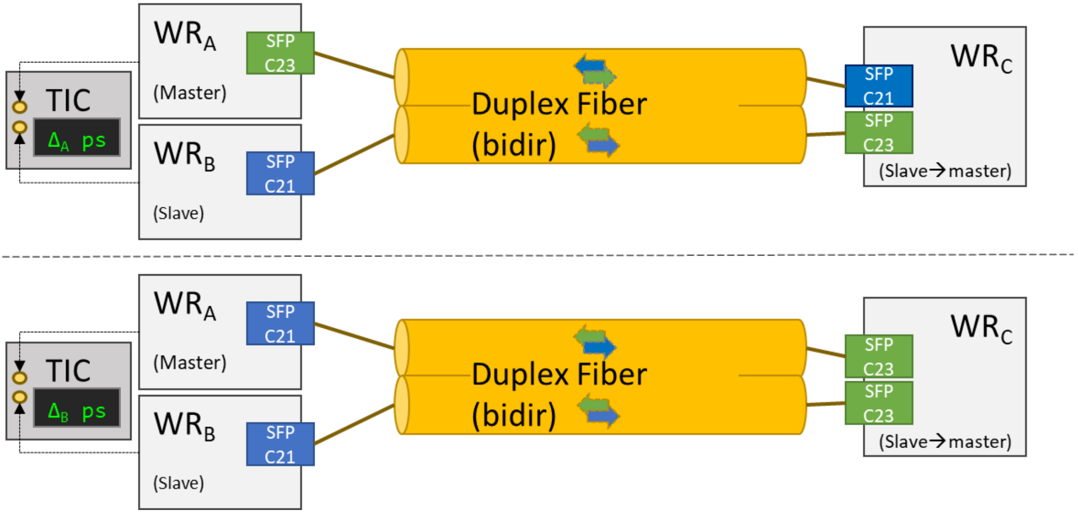
$$\downarrow$$

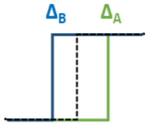
$$\Delta = \Delta_{HW} + \Delta_{GW} + \Delta_{filters} + \Delta_{SFP} + \Delta_{sagnac} + \Delta_{user}$$

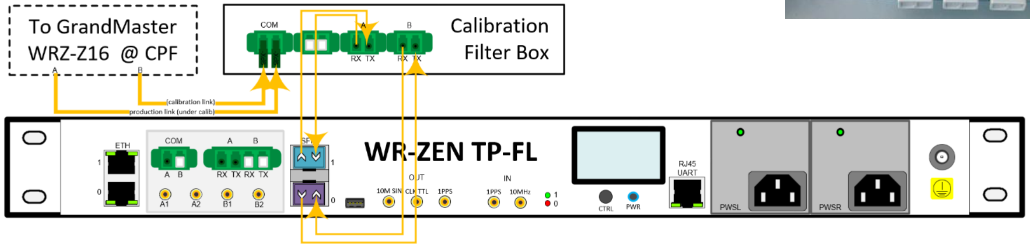


Sagnac contribution (East-West distance)
100km ⬄ ~400ps → 200m < 1ps

Fiber swapping (link asymetrie)



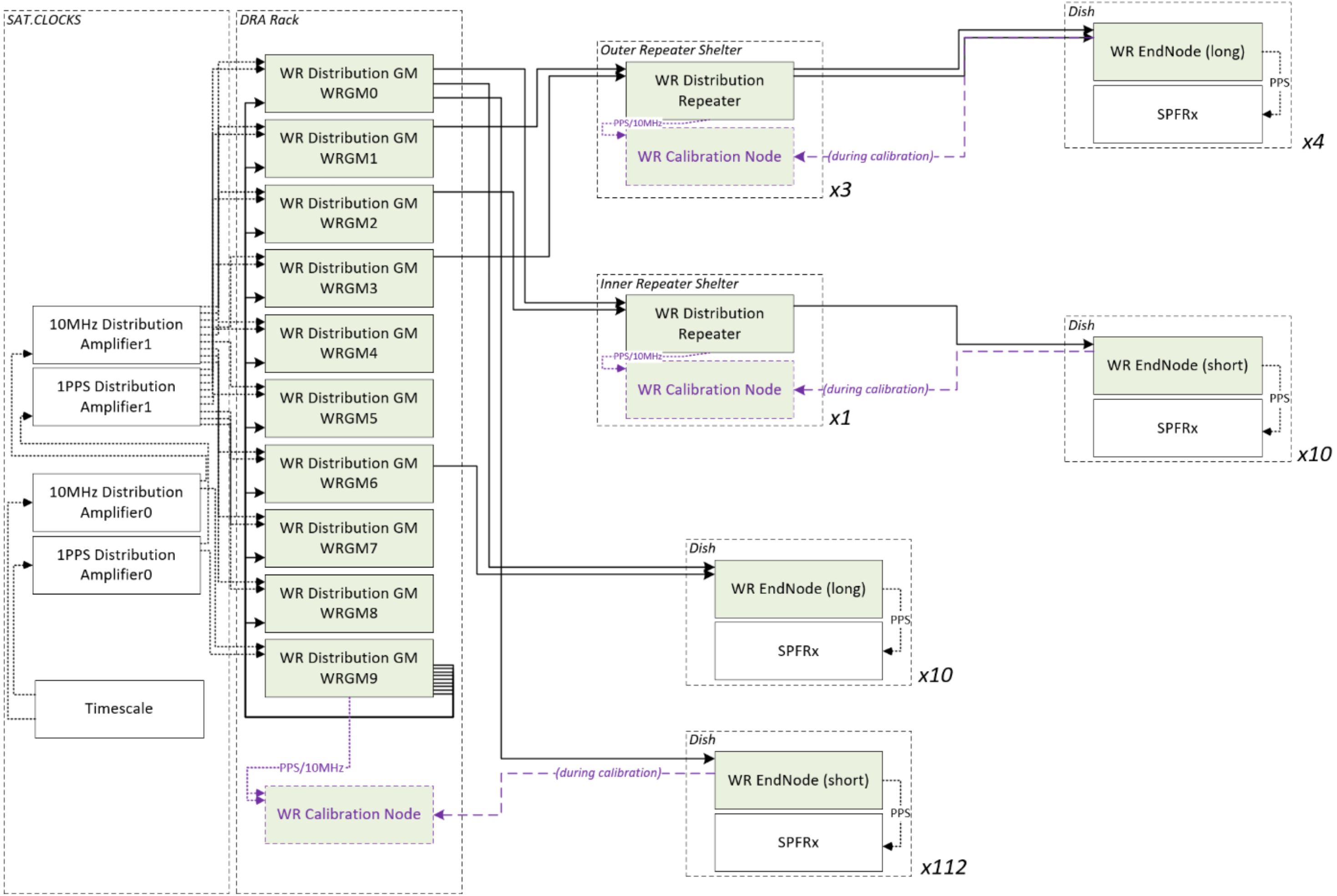




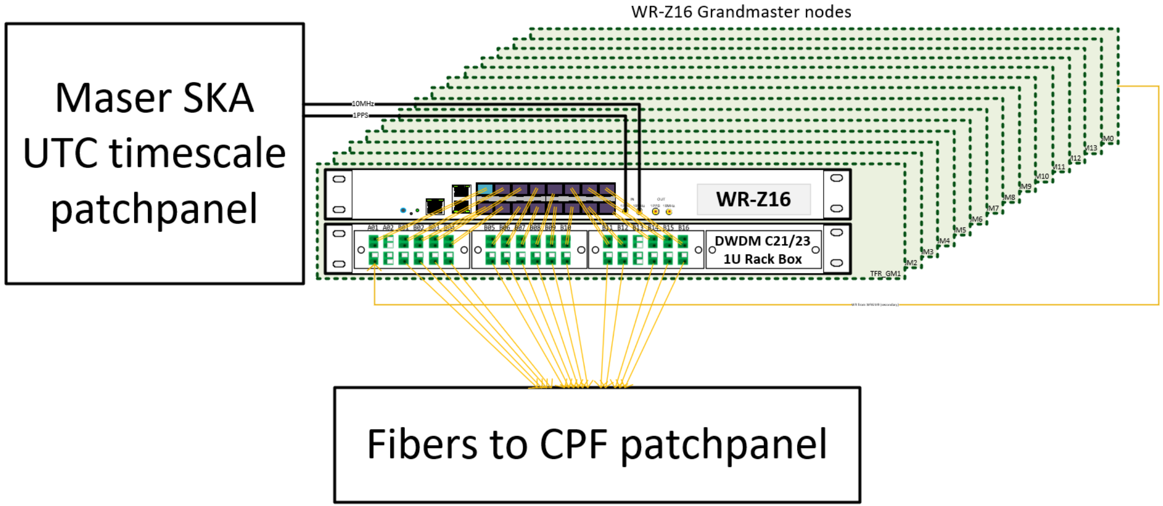
05

TOPOLOGIES

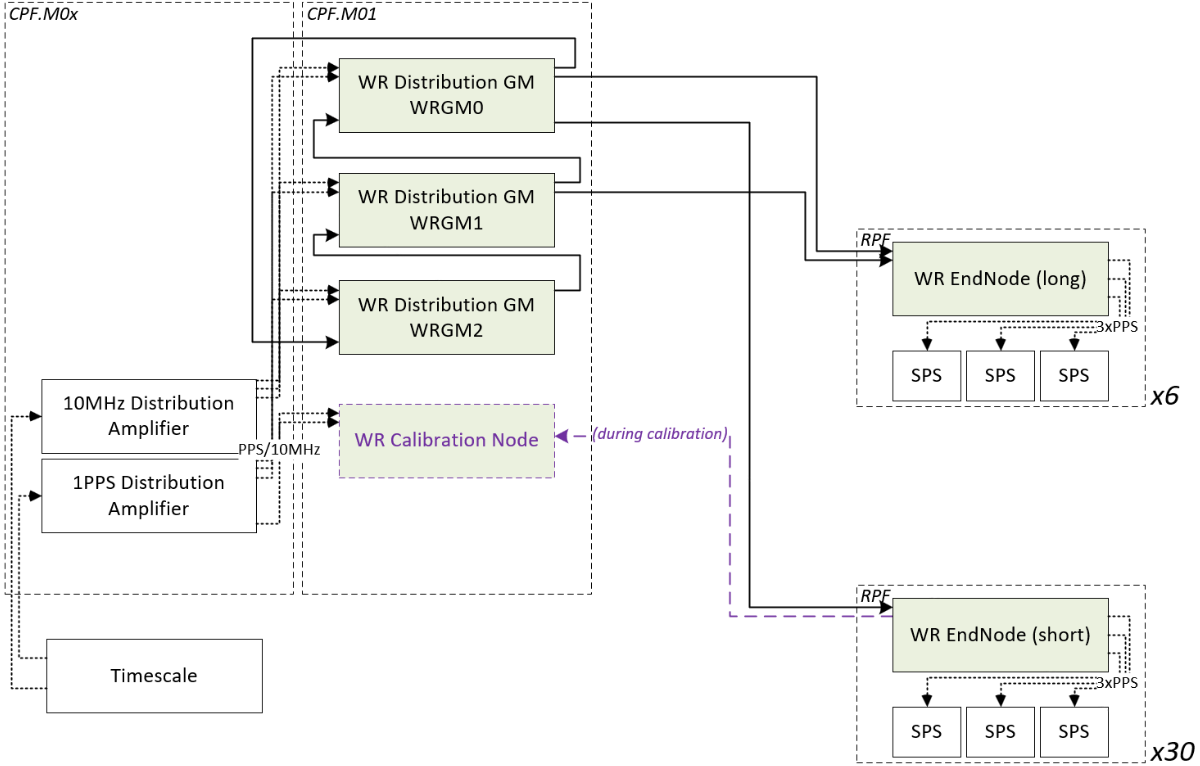
MID


SAT.CLOCKS
DRA Rack
WR Distribution GM WRGM0
WR Distribution GM WRGM1
WR Distribution GM WRGM2
WR Distribution GM WRGM3
WR Distribution GM WRGM4
WR Distribution GM WRGM5
WR Distribution GM WRGM6
WR Distribution GM WRGM7
WR Distribution GM WRGM8
WR Distribution GM WRGM9
10MHz Distribution Amplifier1
1PPS Distribution Amplifier1
10MHz Distribution Amplifier0
1PPS Distribution Amplifier0
Timescale
PPS/10MHz
WR Calibration Node
Outer Repeater Shelter
WR Distribution Repeater
PPS/10MHz
WR Calibration Node
(during calibration)
x3
Dish
WR EndNode (long)
PPS
SPFRx
x4
Inner Repeater Shelter
WR Distribution Repeater
PPS/10MHz
WR Calibration Node
(during calibration)
x1
Dish
WR EndNode (short)
PPS
SPFRx
x10
Dish
WR EndNode (long)
PPS
SPFRx
x10
Dish
(during calibration)
WR EndNode (short)
PPS
SPFRx
x112

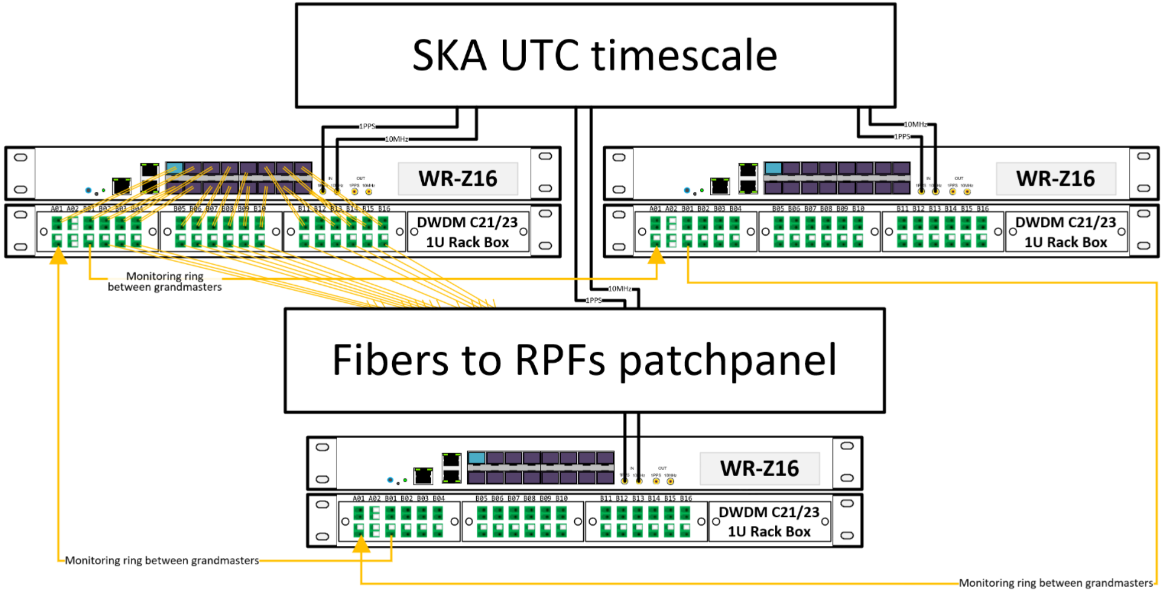
MID CPF


WR-Z16 Grandmaster nodes
Maser SKA UTC timescale patchpanel
10MHz
1PPS
IN
OUT
1PPS
10MHz
WR-Z16
A01 A02 B01 B02 B03 B04
B05 B06 B07 B08 B09 B10
B11 B12 B13 B14 B15 B16
DWDM C21/23 1U Rack Box
TFR_GM1
M0
M13
M12
M11
M10
M9
M8
M7
M6
M5
M4
M3
M2
Fibers to CPF patchpanel

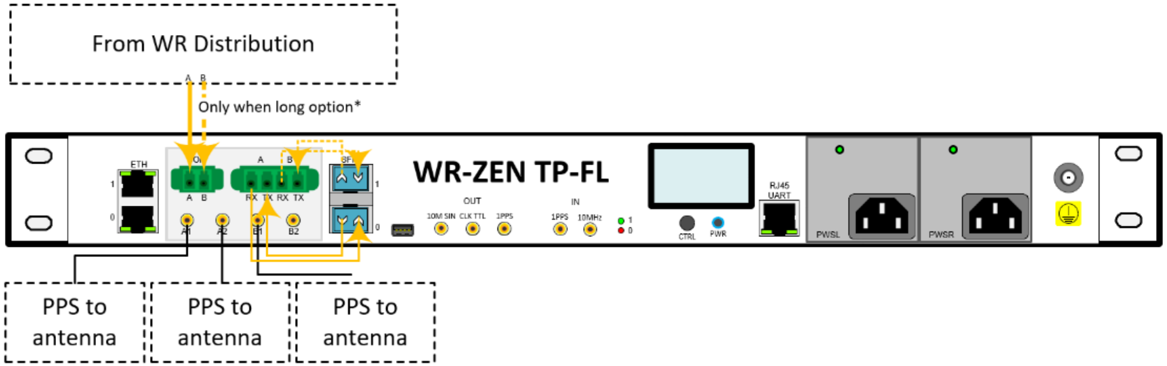
LOW


CPF.M0x
CPF.M01
WR Distribution GM WRGM0
WR Distribution GM WRGM1
WR Distribution GM WRGM2
WR Calibration Node
(during calibration)
10MHz Distribution Amplifier
1PPS Distribution Amplifier
PPS/10MHz
Timescale
RPF
WR EndNode (long)
3xPPS
SPS
SPS
SPS
x6
RPF
WR EndNode (short)
3xPPS
SPS
SPS
SPS
x30

LOW CPF


SKA UTC timescale
1PPS
10MHz
10MHz
1PPS
WR-Z16
DWDM C21/23
1U Rack Box
WR-Z16
DWDM C21/23
1U Rack Box
Monitoring ring
between grandmasters
10MHz
1PPS
Fibers to RPFs patchpanel
WR-Z16
DWDM C21/23
1U Rack Box
Monitoring ring between grandmasters
Monitoring ring between grandmasters

EndNode



From WR Distribution

Only when long option*

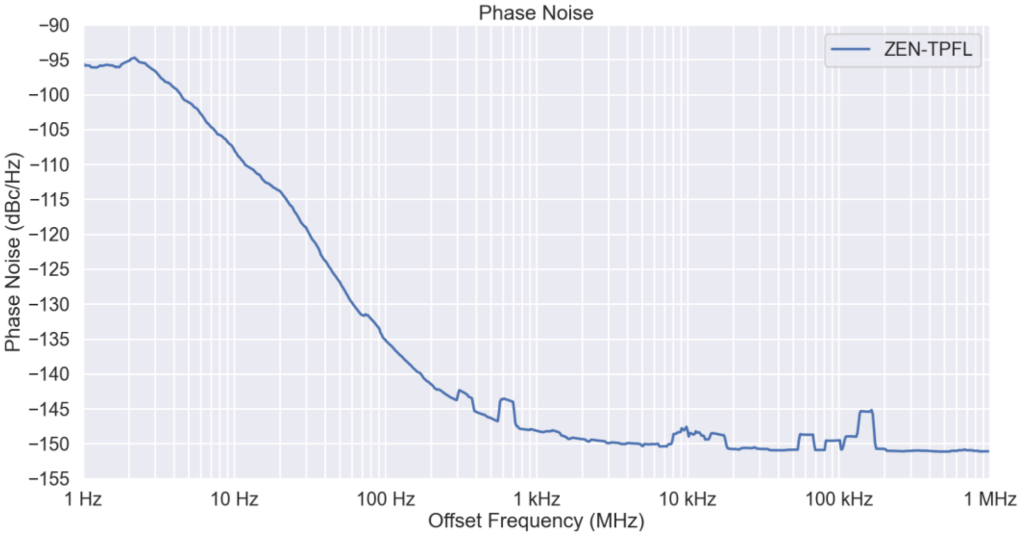
PPS to antenna

PPS to antenna

PPS to antenna

What about frequency distribution?

- **Now reaching requirements for LOW with WR-Z16 LJ**
  - WR will be temporarily used during AA0.5 phase
- **Still need improvement for MID → Ultra low jitter in WRSv4 ?**



Chapter 03

HEP

SAFRAN

High Energy Physics (HEP)

UK Research and Innovation
EUROPEAN SPALLATION SOURCE
FUSION FOR ENERGY
iter
ALBA
ESS bilbao
EUROfusion
SOREQ
Soreq Nuclear Research Center
CERN
GSI
GSI Helmholtzzentrum für Schwerionenforschung GmbH
IFMIF LIPAc
cea
Ciemat
QST

Team areas of expertise:

- Ultra-stable **low-noise RF electronics**
- Customized or standard crates (Compact PCI-e Serial, **uTCA** or standalone solutions).
- Embedded system based on the **latest FPGAs and SoCs** (Zynq Ultrascale, RFSoC)
- Individualized **Control system Solutions** based on EPICS frameworks (EPICS, TANGO).
- **RF distribution**
- High reliable and real-time **diagnosis and post-mortem analysis**
- Fast **data acquisition** systems
- Adaptive **Fast-control** systems

Products:

- LLRF – Precise Low Level RF generators
- BPMs – Beam Position Monitors
- Timing systems – Precise triggers generation
- RF generation and distribution
- Software & Services

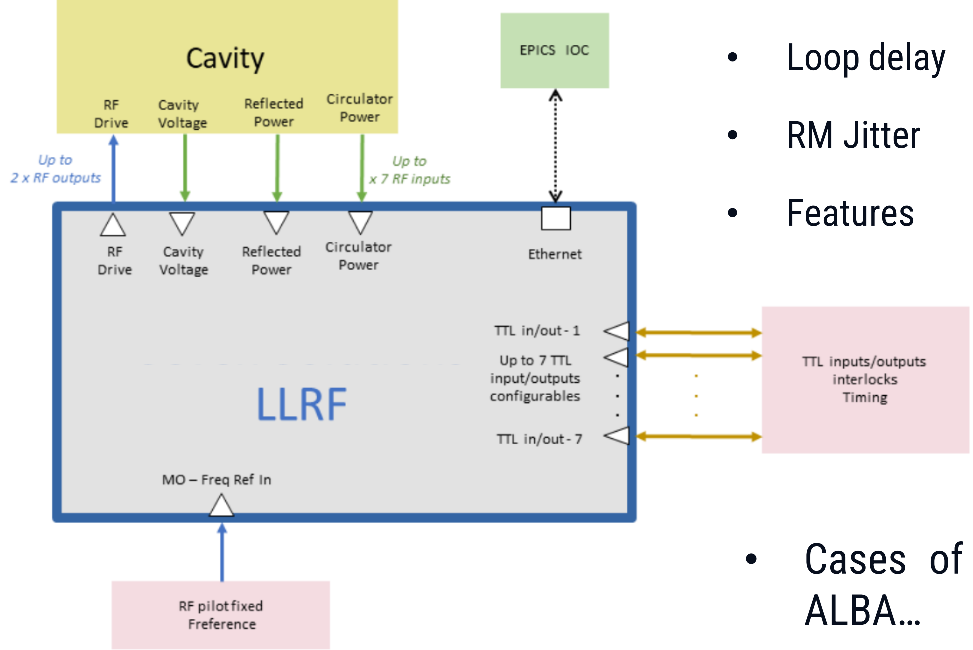
Radiofrequency control, monitoring, timing system and services






Relevant use case @ HEP

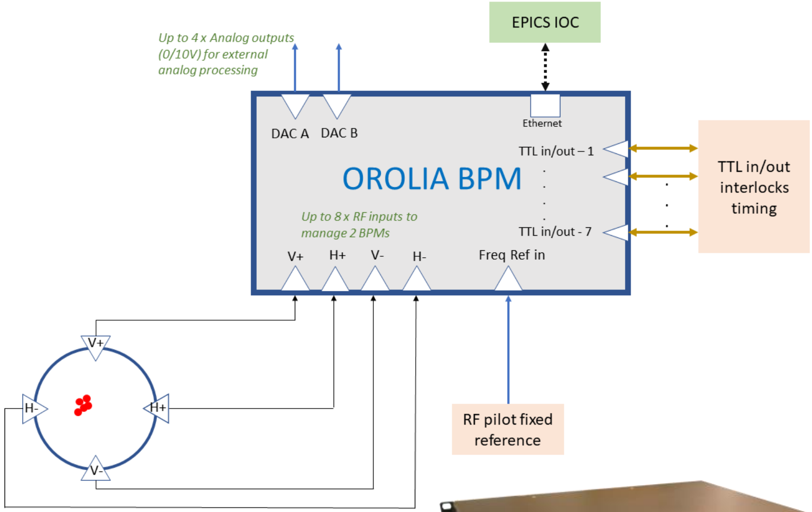
Control for accelerators:



Amplitude/Phase Stability	**<0.3% - 0.3 degree**
Amplitude/Phase precision	**<0.03% - 0.03 degree**
Loop delay	**< 1us**
RM Jitter	**182fs**
Features	**Continuous and Pulse mode** **Feedforward** **Frequency shifting** **Frequency tracking (digital PLL)** **Fast output interlock system (Machine protection)** **White Rabbit compatible**

- Cases of success: IFMIF, SARAF, CEA, CIEMAT, ALBA…

Relevant use case @ HEP

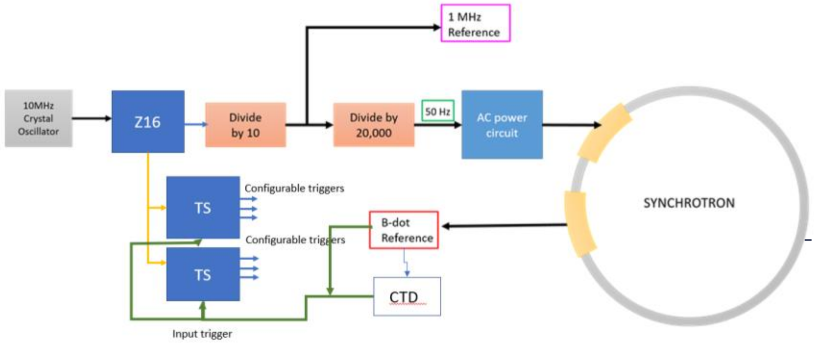


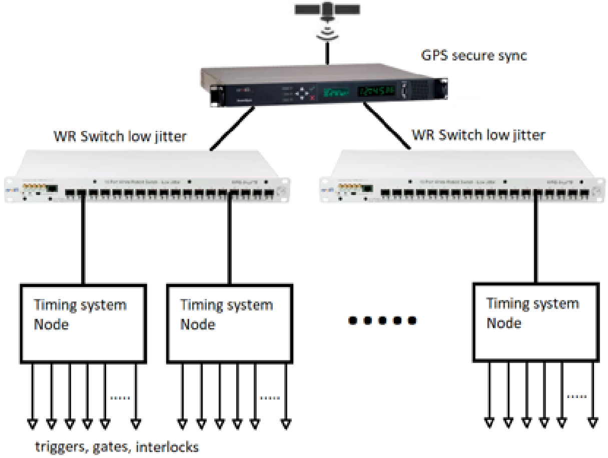
- Dynamic range: **[-75, 0] dBm**
- Position precision **< 25um**
- Phase precision **< 0.1°**
- Position, phase and current alarms with response time < 2us:
  - Position precision **< 250u**
  - Phase precision **< 1°**
- Electronic and cables autocalibration

- Cases of success: IFMIF, SARAF, CEA, CIEMAT, ALBA…

Relevant use case @ HEP

Diagnostics for scientific installations:





- Programmable step size granularity of delay:
  - ○ Coarse Adjustment: 5ns (based on 200MHz internal FPGA frequency)
- Configurable delay range: 0 to >20 seconds
- Delay triggering phase leading edge is:
  - ○ Synchronous with RF Ref Input
- Pulse width specification: any width in 5 ns step size.
- Accuracy and Jitter
  - ○ 10 ps RMS when delay is specified on Coarse Delay 5 ns boundaries
  - ○ Peak-to-Peak Jitter: around 100 ps

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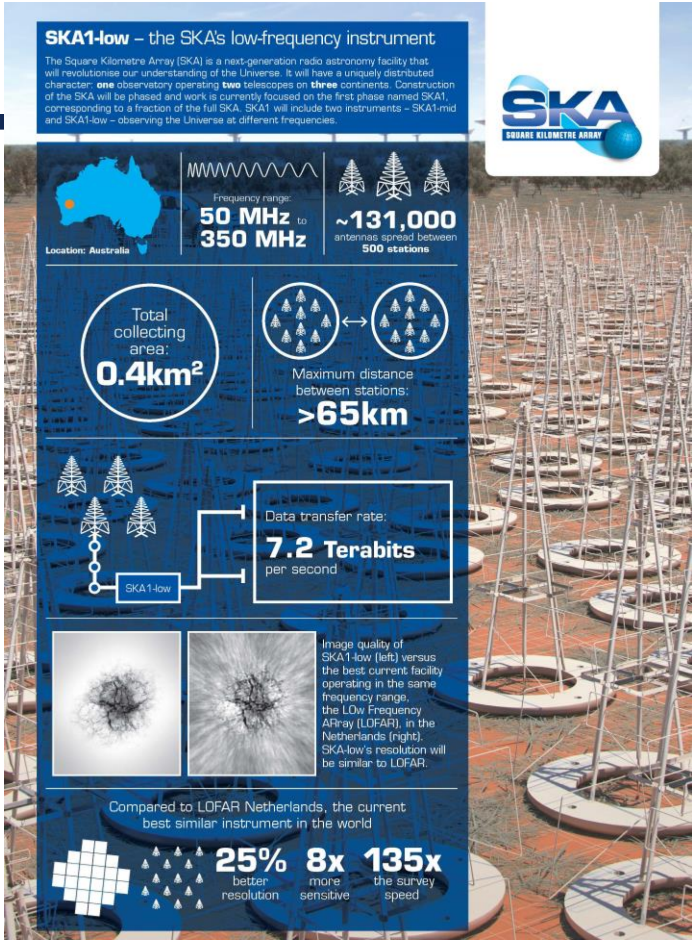


SKA1-low – the SKA's low-frequency instrument

The Square Kilometre Array (SKA) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: **one** observatory operating **two** telescopes on **three** continents. Construction of the SKA will be phased and work is currently focused on the first phase named SKA1, corresponding to a fraction of the full SKA. SKA1 will include two instruments – SKA1-mid and SKA1-low – observing the Universe at different frequencies.

Location: Australia

Frequency range:
50 MHz to **350 MHz**

~131,000
antennas spread between **500 stations**

Total collecting area:
0.4km²

Maximum distance between stations:
>65km

Data transfer rate:
7.2 Terabits
per second

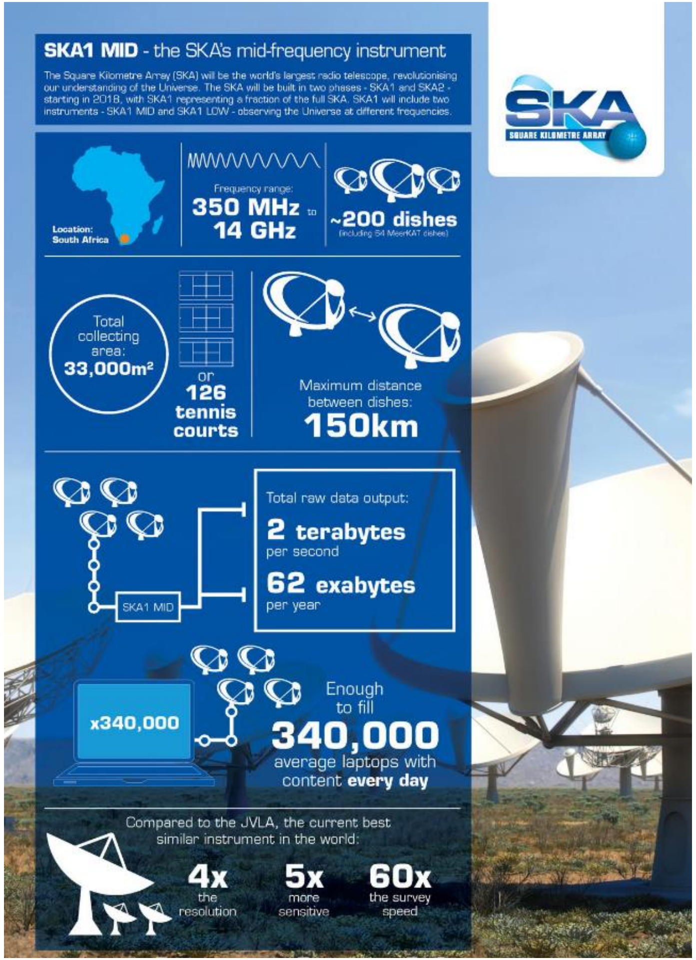
Image quality of SKA1-low (left) versus the best current facility operating in the same frequency range, the LOw Frequency ARray (LOFAR), in the Netherlands (right). SKA-low's resolution will be similar to LOFAR.

Compared to LOFAR Netherlands, the current best similar instrument in the world

25% better resolution

8x more sensitive

135x the survey speed



SKA1 MID - the SKA's mid-frequency instrument

The Square Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LOW - observing the Universe at different frequencies.

Location: South Africa

Frequency range:
350 MHz to **14 GHz**

~200 dishes
(including 64 MeerKAT dishes)

Total collecting area:
33,000m²
or **126 tennis courts**

Maximum distance between dishes:
150km

Total raw data output:
2 terabytes per second
62 exabytes per year

Enough to fill
340,000
average laptops with content **every day**

Compared to the JVLA, the current best similar instrument in the world:

4x the resolution

5x more sensitive

60x the survey speed