Mid-Frequency AA Technology

Andrew Faulkner

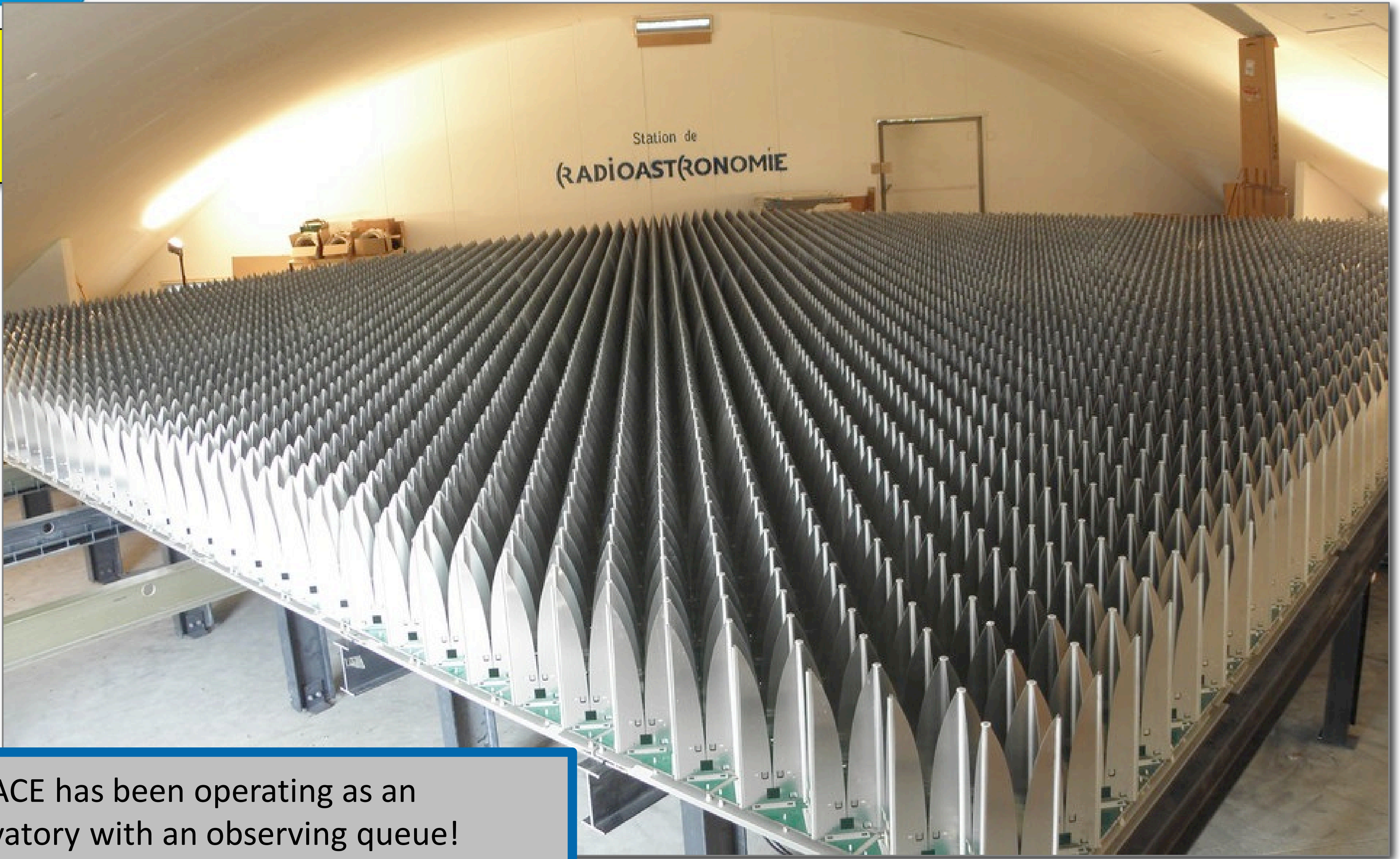
AA-MID Science

Science	Detail	MFAA Benefit
Transient radio sky	Fast Radio Bursts, FRBs	Very wide FoV capability Look-back buffer Highly configurable in frequency and beams
History of Hydrogen	Cosmology Galaxy Evolution	Fast survey speed Configurable FoV vs frequency
Pulsars	Search, incl galactic Timing, basic timing Extended study	~1.2-1.4GHz good for searching Galactic plane Many beam capability for timing “Extended time” beams
Magnestism	Origin and evolution of cosmic magnetism	Survey speed

And, other Mid-Frequency Science

EMBRACE demonstrator – SKADS!

Since 2010



- EMBRACE has been operating as an Observatory with an observing queue!
- Phase calibration tables good for >6 months
- EMBRACE is very stable!

MFAA System design aims

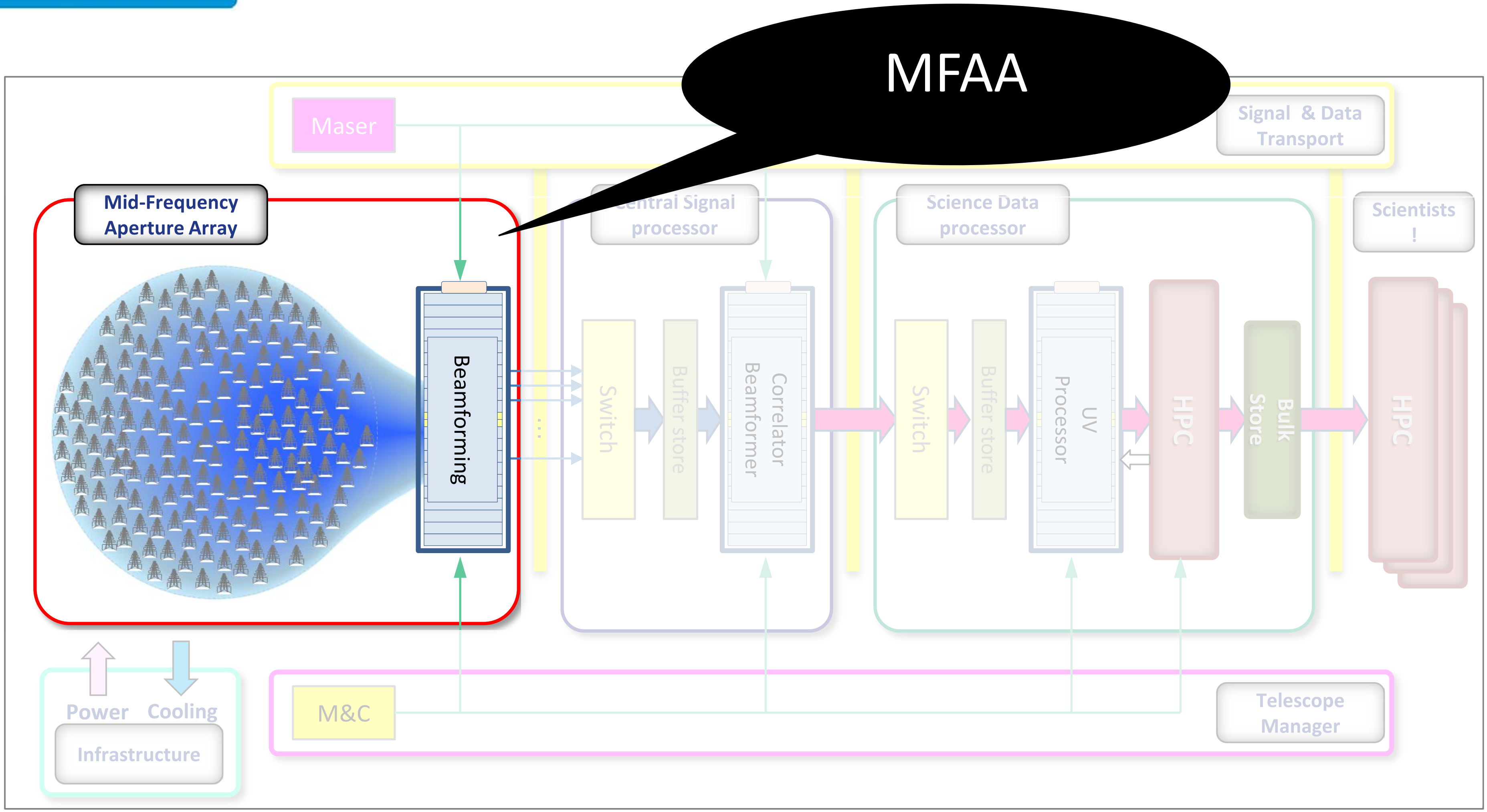
Operation

- Meet performance requirements:
  - Bandwidth
  - Sensitivity
  - Polarisation
  - Frequency range
  - Precision beams
  - Massive data output
- A “software controlled aperture”:
  - Stations
  - Location
  - Appodization
- Highly configurable systems
- Precise calibration capability
- Resilient to sub-system failure
- Extendable performance
- Ability to implement new processing options

Implementation

- Minimise equipment in the field
- Very, very low EMI
  - Ideally no digital systems outside processing facility
  - Optical comms links
- Easy maintenance
- Low power
- Low cost
- Simple infrastructure
- Deployable for *very* large contiguous arrays (100’s of metre dia)

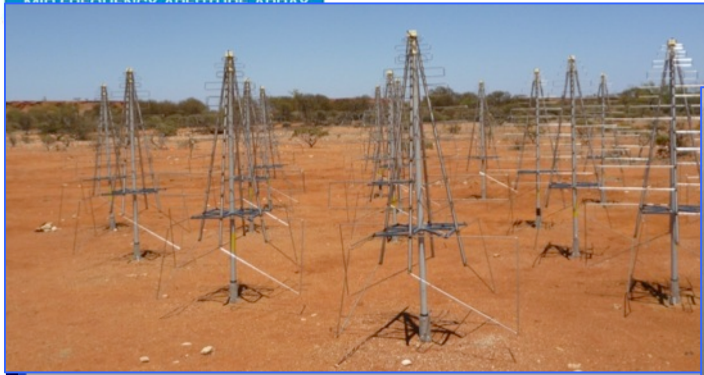
AA-MID telescope: end-to-end

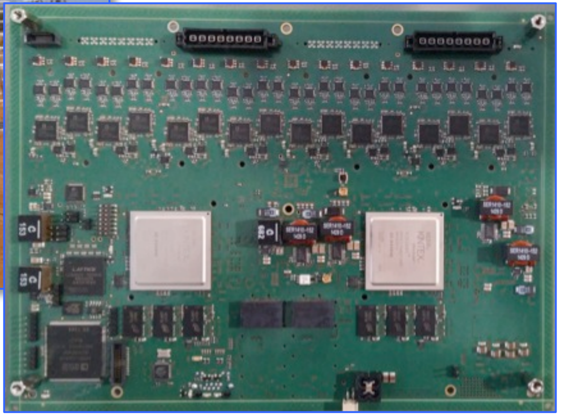


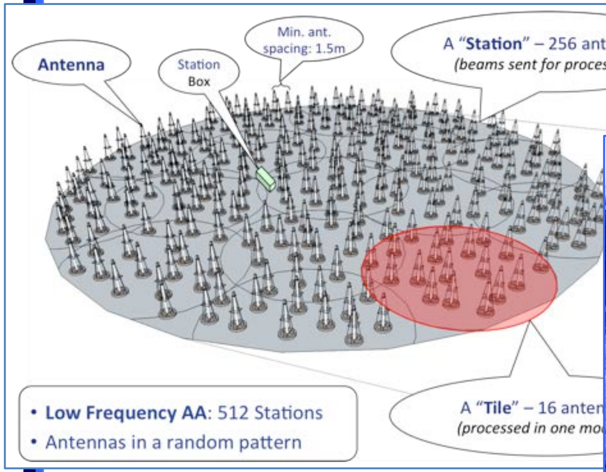
Outline Specification…

Parameter	Essential	Desirable	Comments
Frequency – low	450 MHz	<400 MHz	Scientifically the low frequency is for HI at z=3.
Frequency – high	1450 MHz	>1450 MHz	Reach at least HI line; further science at higher frequencies
Polarisations	2-linear 30dB purity	2-linear 40dB purity	Essential to have orthogonal polarisations Purity is post calibration
Sensitivity	10,000m^2/K @ 800MHz	10,000m^2/K @ 1GHz	Sensitivity may be higher at lower frequencies Sensitivity is at zenith, will reduce with scan angle.
Optical FoV	100deg^2	>±45° from zenith	More FoV (at narrower BW) gives better survey speed and is important for transients
Bandwidth (max)	1000MHz	>1000MHz	Should be capable of having beams of the full bandwidth
Beams*bandwidth Product	>50GHz	>250GHz	Data rate determines telescope performance. Likely limited by post processing capability.
# of beams (max)	Fill optical FoV	Fill ±45° from zenith	Depends upon bandwidth required. Beams should be completely configurable for BW/Number etc.
Beam precision	<2% error at all freqs	<1% error at all freqs	This requires accurate analogue calibration; good beam prediction sims; ability to "measure" the beam on-line.
Buffer	10 sec	100 sec	Element/tile level buffering, flexibly applied
Configurability	Beams/BW	Station size Station location	Modify processing across the array – new approaches. Station size and location can tune for experiment

.. a lot learned from LFAA







Parameter	Value
Frequency range (basic)	50 – 350MHz
Frequency range (ext.)	50 – 650MHz
Number of antennas	131,072
Number of stations	512
Station diameter	~35m
Antennas per station	256
Antenna type	Log periodic
Min. Antenna sep.	1.5m
Inst. bandwidth	300MHz
Number of beams	Up to 6
Digitisation	8-bits
Beamforming	All-digital
Beamforming type	Distributed
Interconnect	40/56GbE

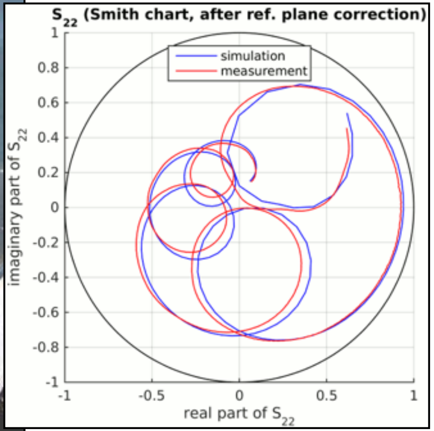
Some LFAA lessons in Phase 1

- **Calibration, Calibration…**:
  - /ant.: phase & ampl’d
  - “Surface” precision <λ/20
- Predict **station beamshape** to ~1% is essential:
  - For normal station and with failed antennas/tiles.
  - Sidelobe knowledge
- >30dB **Polarisation** separation
- **Post processing** is very expensive in power and money
- **# of Stations** will probably increase to e.g. 1024

- LFAA system **architecture** important:
  - Calibration, flexibility, unknowns
- “**Sea of elements**” capability
  - Station size, position, apodisation
- **Infrastructure** is *very* expensive
- **RFI** mitigation is *extremely* challenging. Easiest in a single big facility
- **Power** is at a premium. Losses are substantial (linear PSU etc).
- **Maintainability** is crucial

Antenna options - Dense

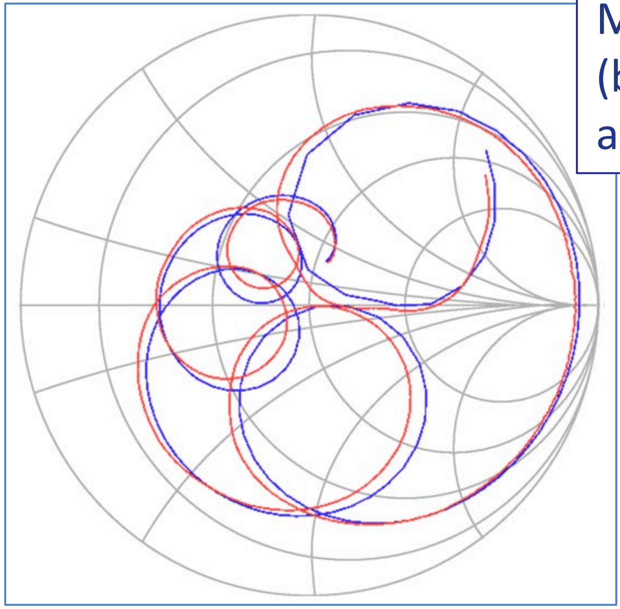
Planar - ORA



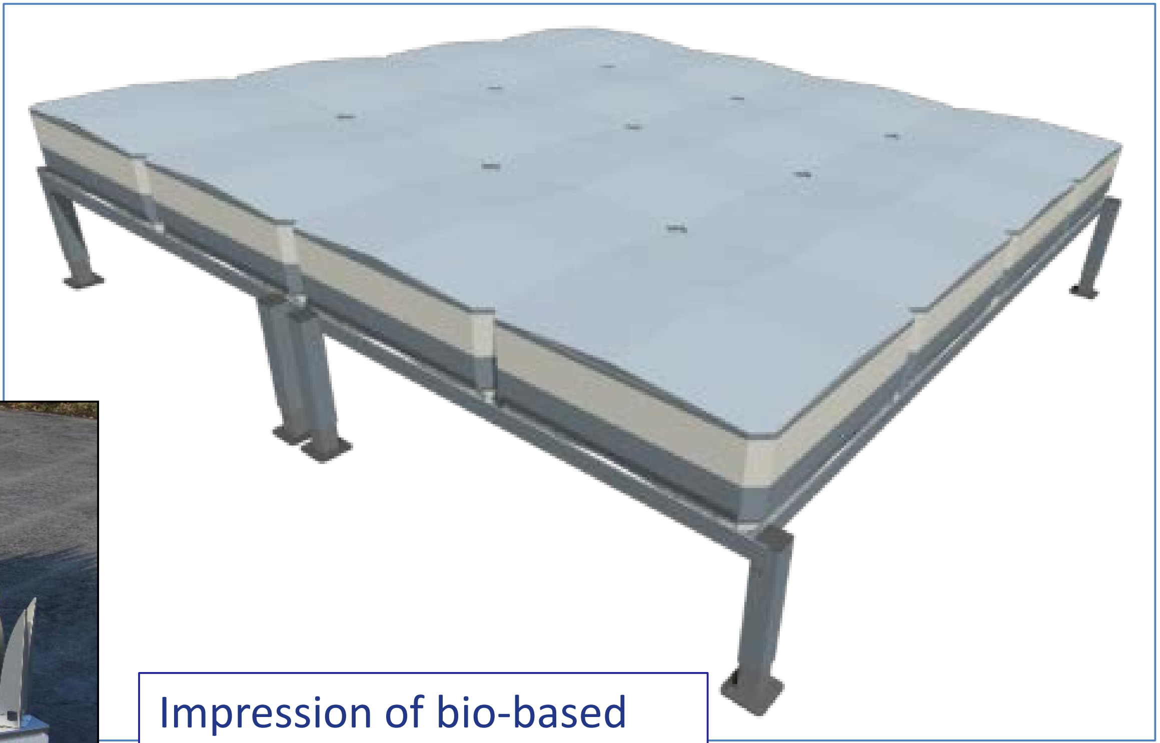
Vivaldi elements

- Regular layout
- Spacing λ/2 @ ~max. frequency

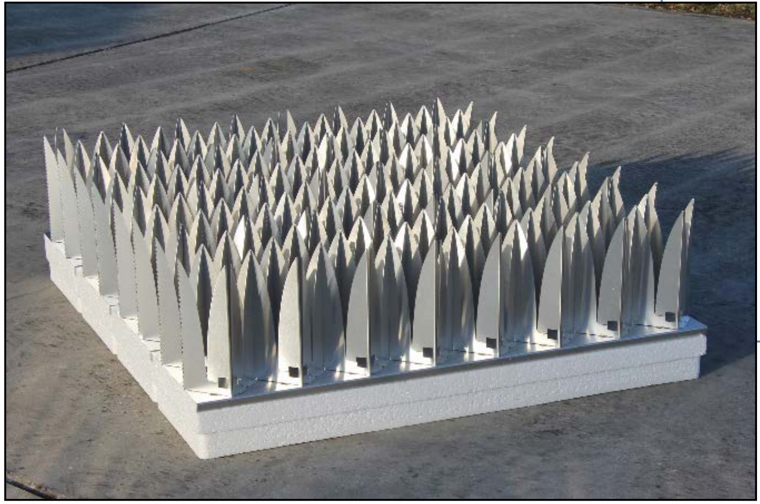
Regular implementation concept



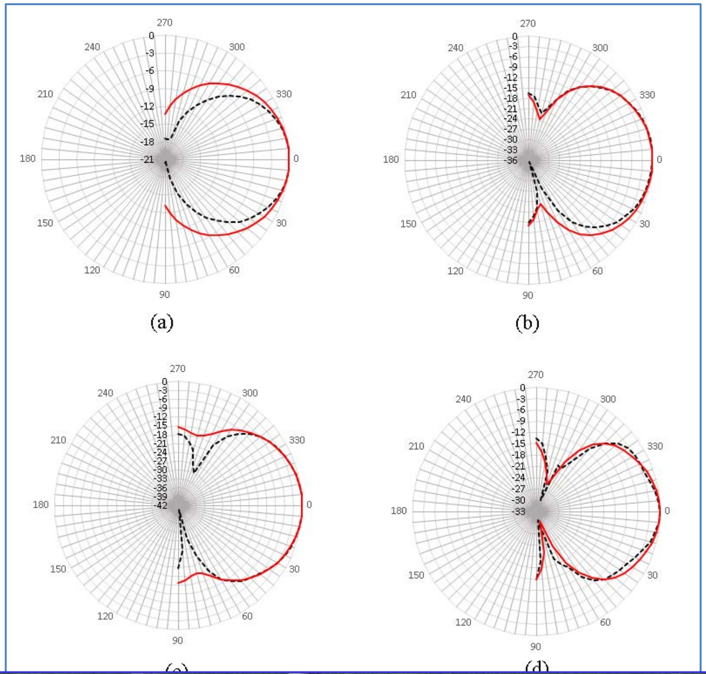
Measured (red) vs. Simulation (blue) results of passive reflection in a 16 element array



Impression of bio-based prototype with coated biofoam© cover



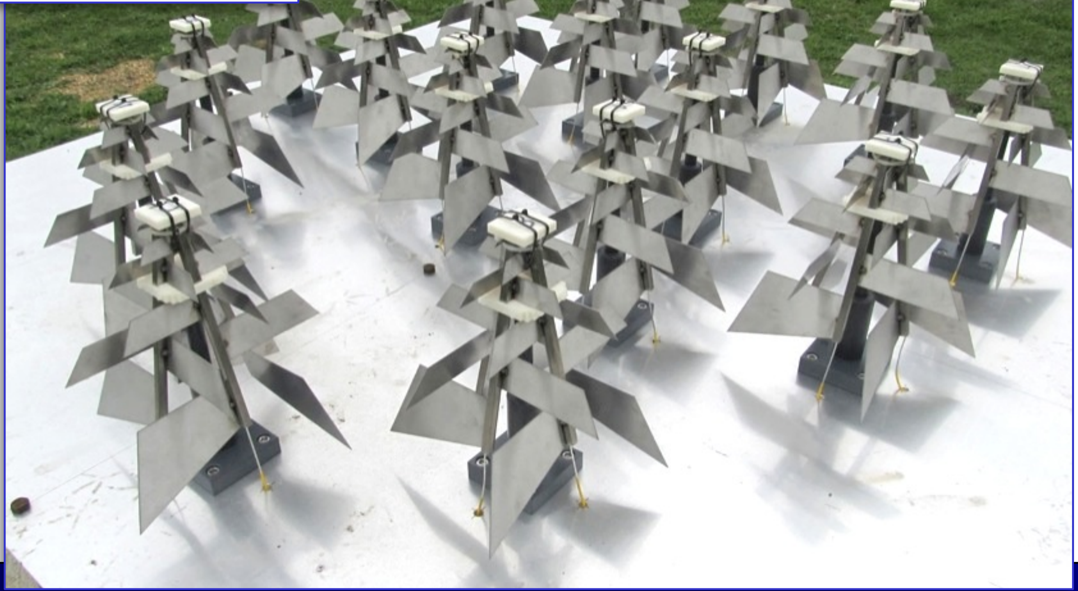
Antenna - Sparse



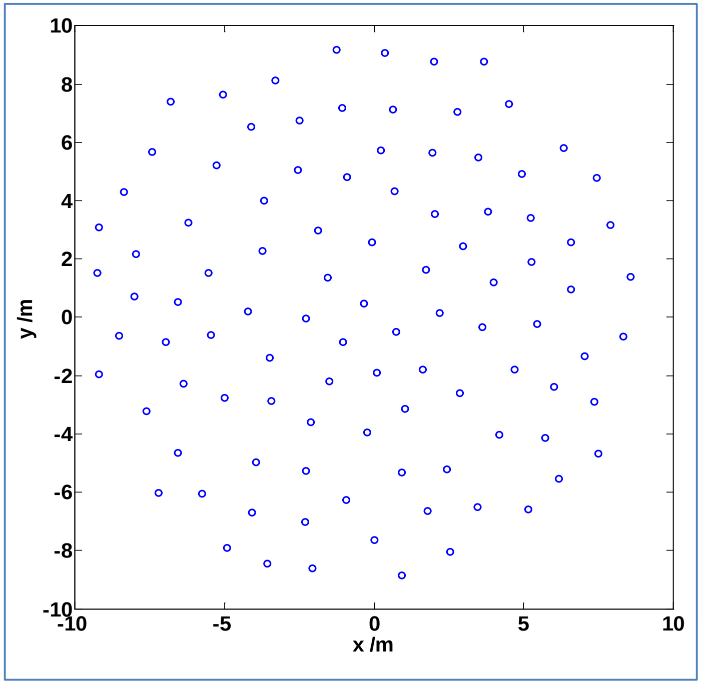
- Log-periodic antenna
- Random layout
- Spacing λ/2 @ **low** frequency

Same concept as

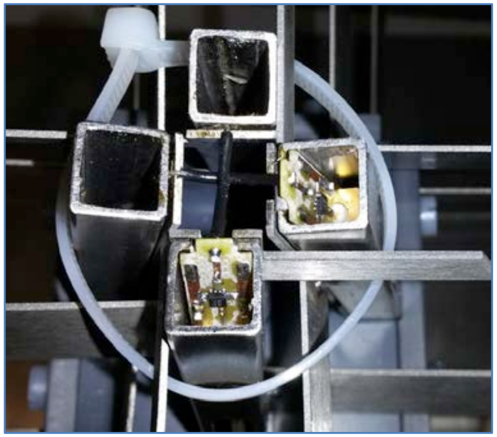
LFAA



Sparse, irregular array (2)



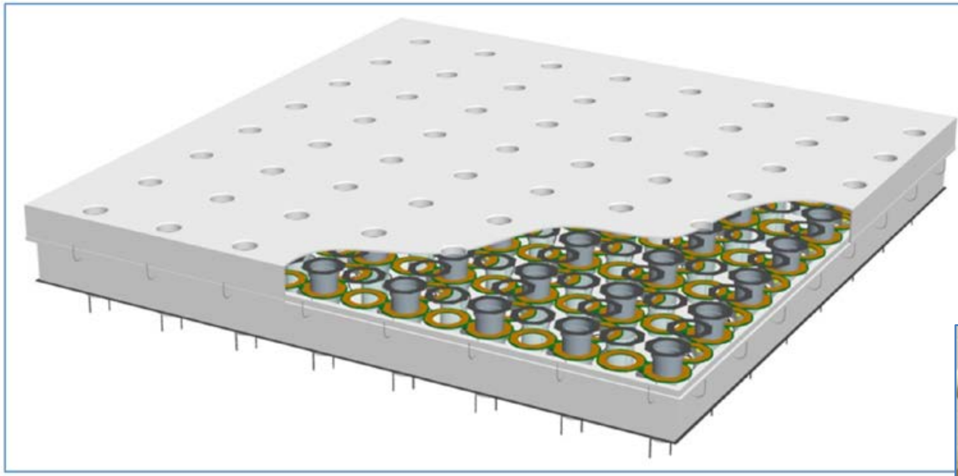
Example of a sparse irregular configuration

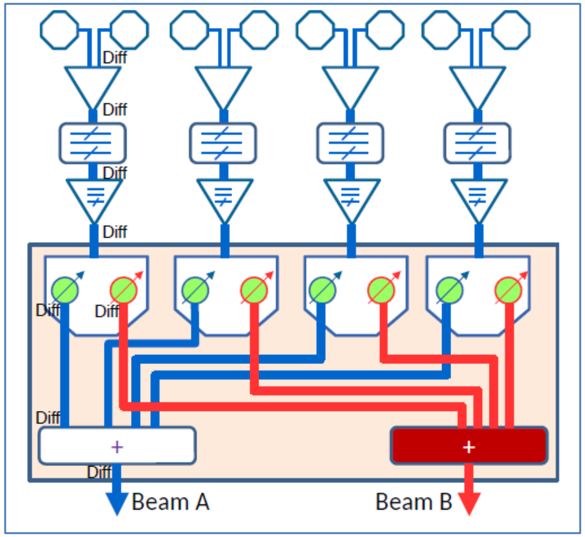


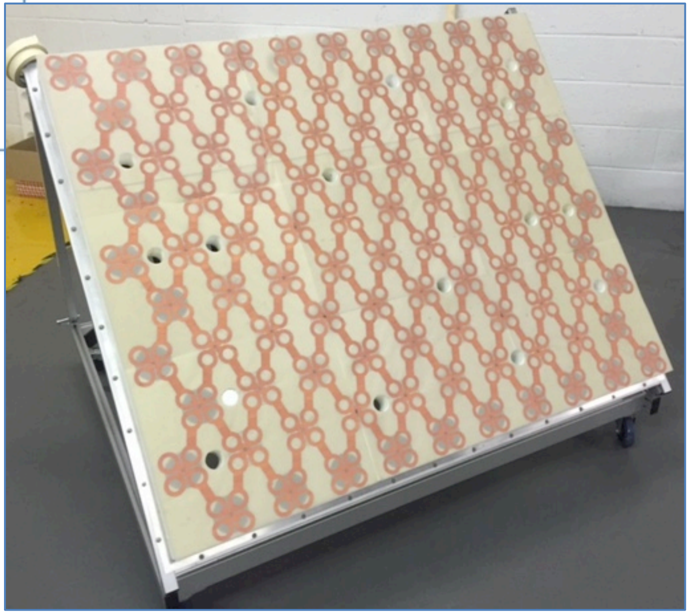
LNA physical implementation on prototype antenna showing LNAs inside the spine tubes.

Octagon rings…

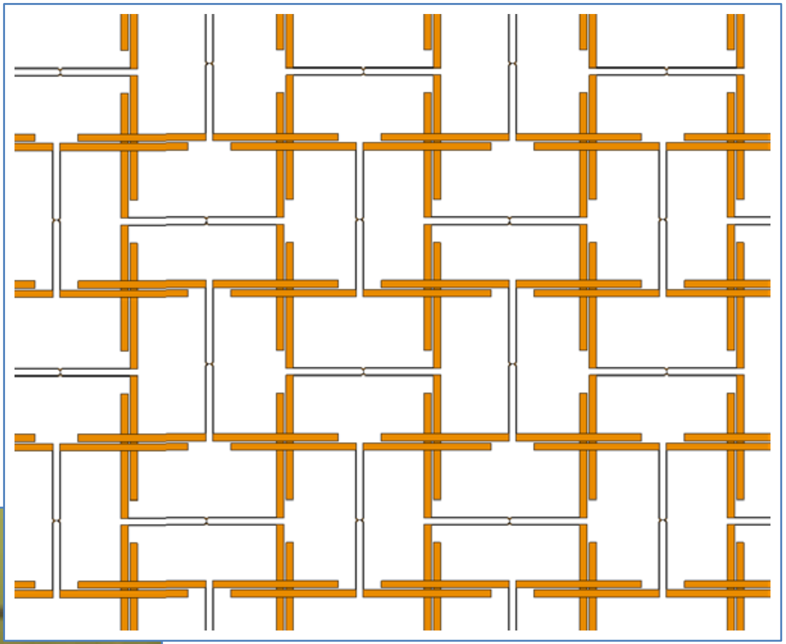
Planar, innovative

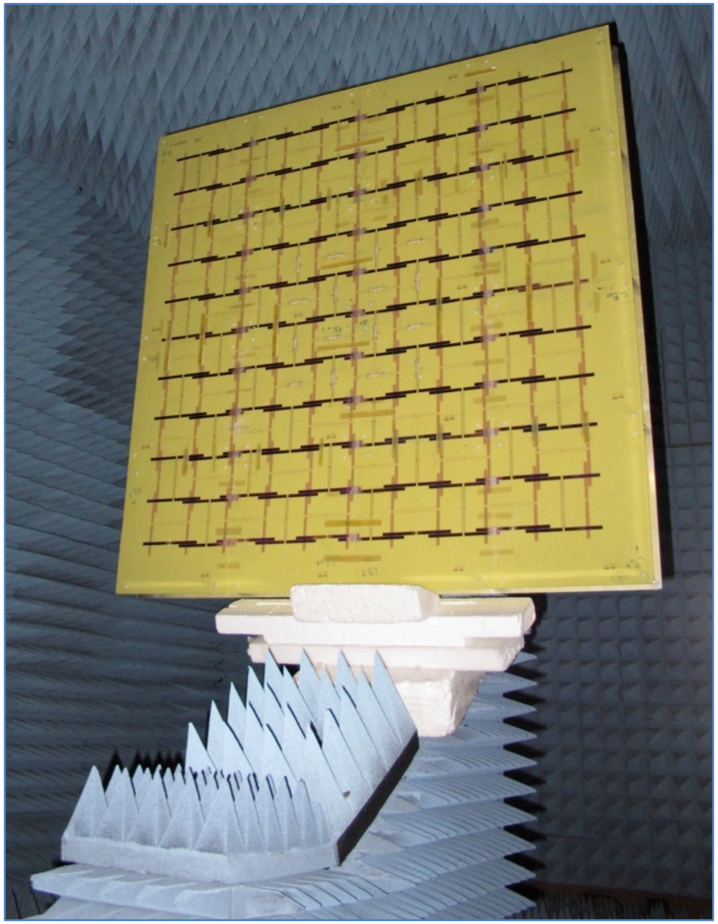






Dense Dipole Array

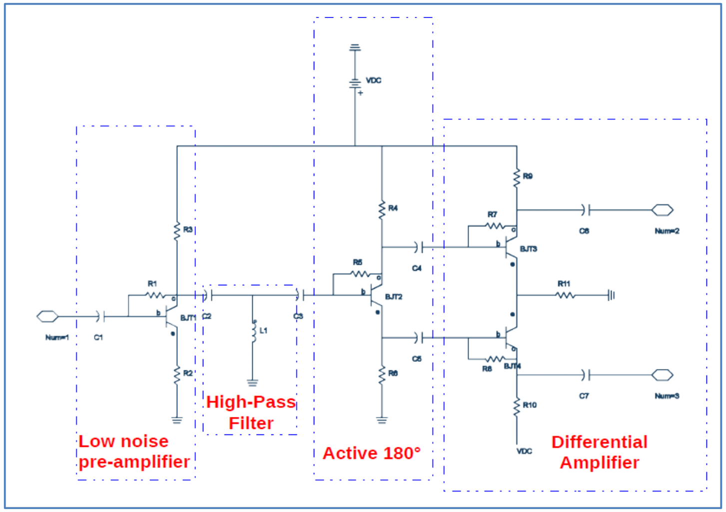


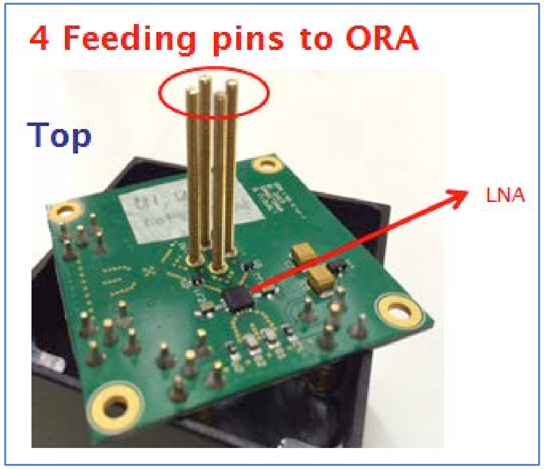


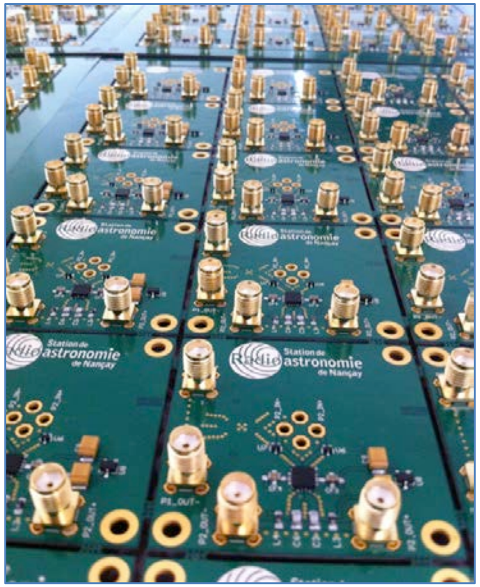
Planar array

Developing dual pol version

LNAs – choices…

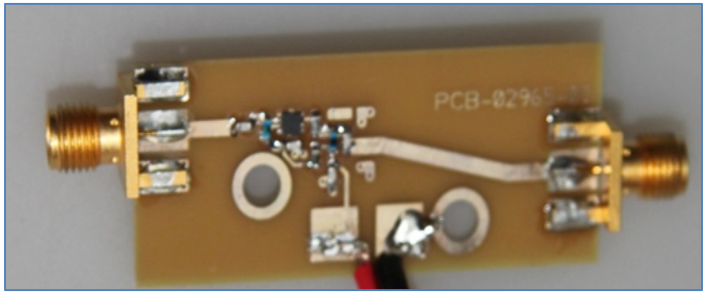


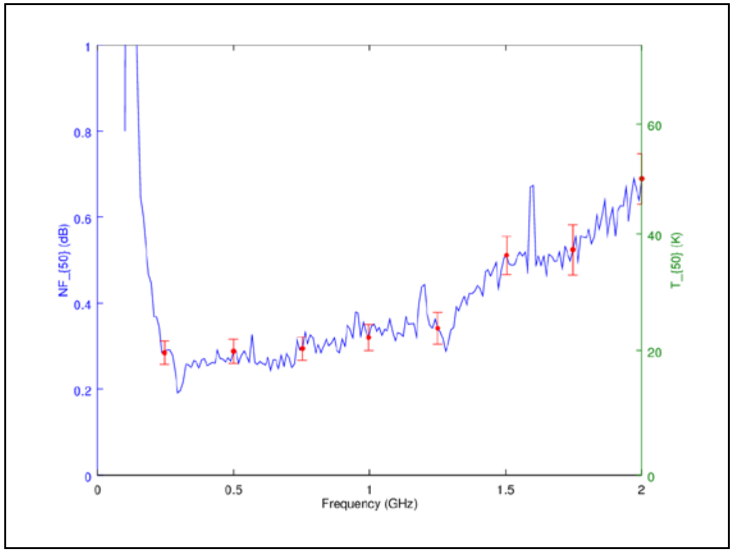


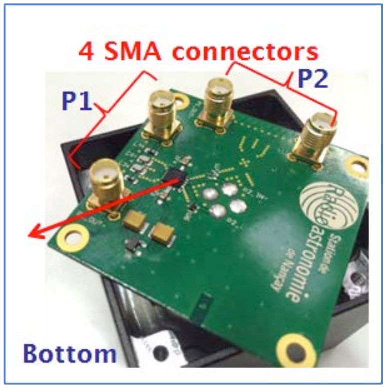


≤30K Rx temp

Differential/
single ended



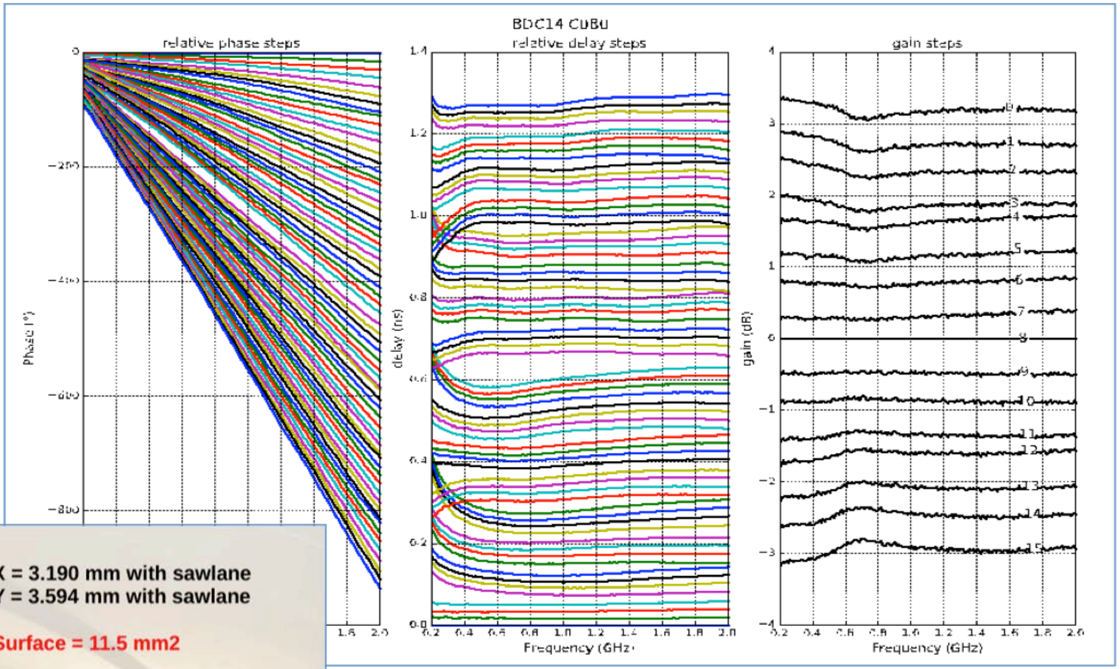


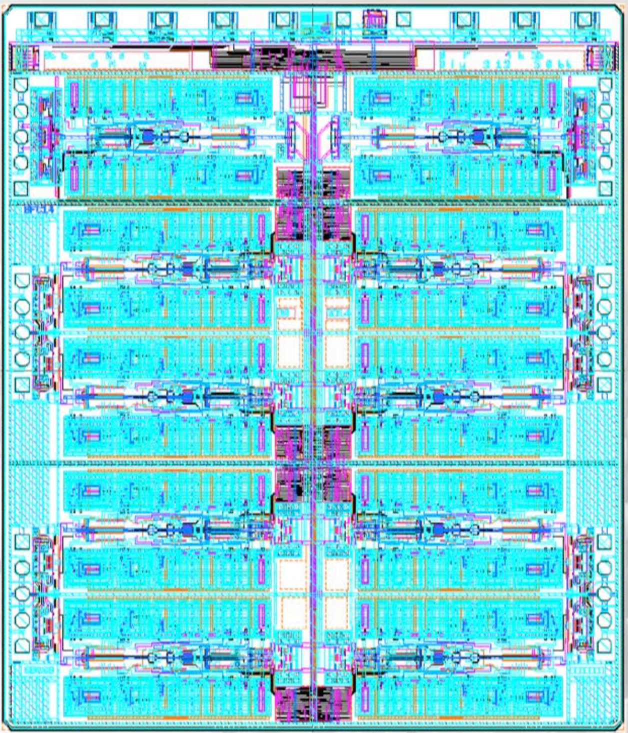


Beamforming comparison

Technology	Antenna signals are:	Pros	Cons
Digital – Frequency Domain	Digitised Channelized in polyphase filter Calibrated by frequency Weighted and summed for beamforming.	Very flexible. Can be accurately calibrated Can readily form many beams with minimal additional processing Can account for many errors.	Channeliser is computationally expensive. May not represent fast transients accurately
Digital – Time domain	Digitised Correct Pass band w/FIR filter Digitally delayed using interpolation Summed for beamforming	Computationally cheap Good for fast transient signals	Calibration techniques not well understood, even if they are possible Each beam requires additional hardware. Cannot necessarily have partial beams to share bandwidth.
Analogue – Time domain	Delayed by programmable periods with delay lines or electronic systems Summed in the analogue domain	Low cost and low power. Reduces digitisation and processing costs Reduces analogue signal transport requirements	Subject to analogue drift Cannot calibrate at antenna level Limits optical FoV Possibly inaccurate station beams Implemention difficult for random arrays
Analogue – Phase shift	Delayed by programmable periods with phase shifting electronics Summed in analogue domain	Cheaper and lower power than other approaches. Reduces digitisation and processing costs Reduce analogue signal transport requirements	Causes beam “squint” with wide B/W Subject to analogue drift Cannot calibrate at the antenna level Limits optical FoV Possibly inaccurate station beams Only implement on regular arrays

Analogue beamforming





X = 3.190 mm with sawlane
Y = 3.594 mm with sawlane

Surface = 11.5 mm2

Current < 220 mA
Power supply = 3.3 V

Power consumption ≈ 720 mW

Frequency Band = [0.5 – 1.5 GHz]

Process Qubic4Xi NXP version 9.4

Differential Beamformer
4 channels 2 Beams

Delay = 1200 ps *2 , step = 20 ps

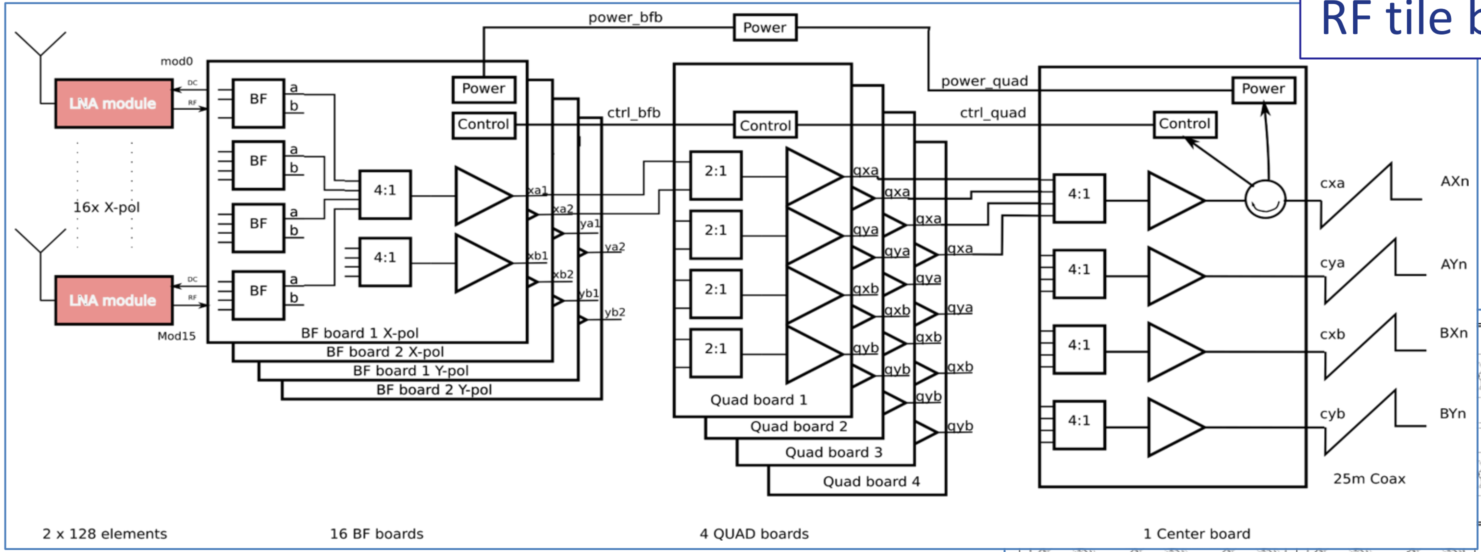
VGA = 6 dB 4 bits

Differential Input imp. matching
= 150 ohms
Differential Output imp. matching
= 150 ohms

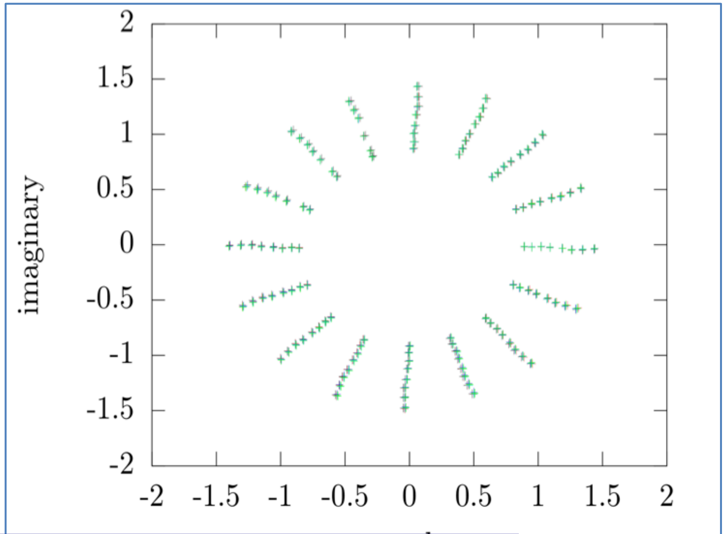
Digital control : I2C or SPI

True time delay chip…

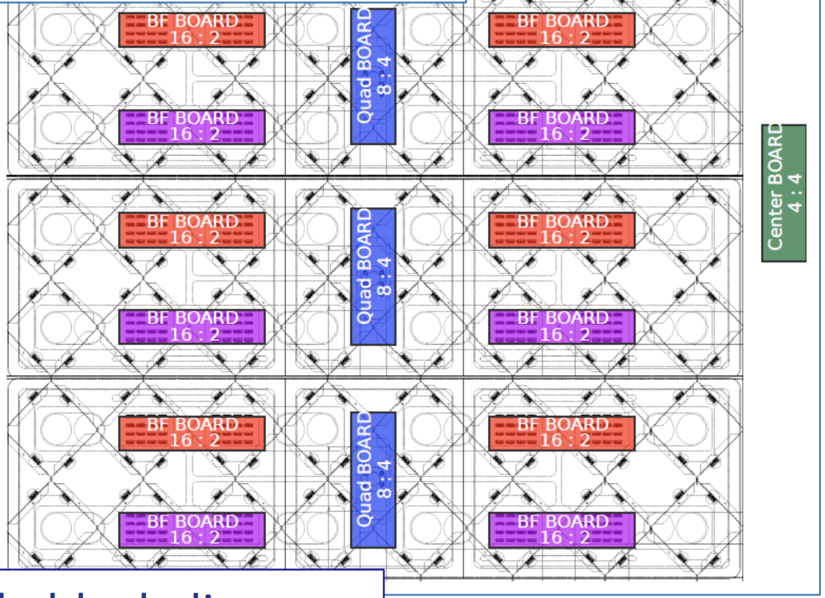
Tile based analogue beamforming



RF tile block diagram

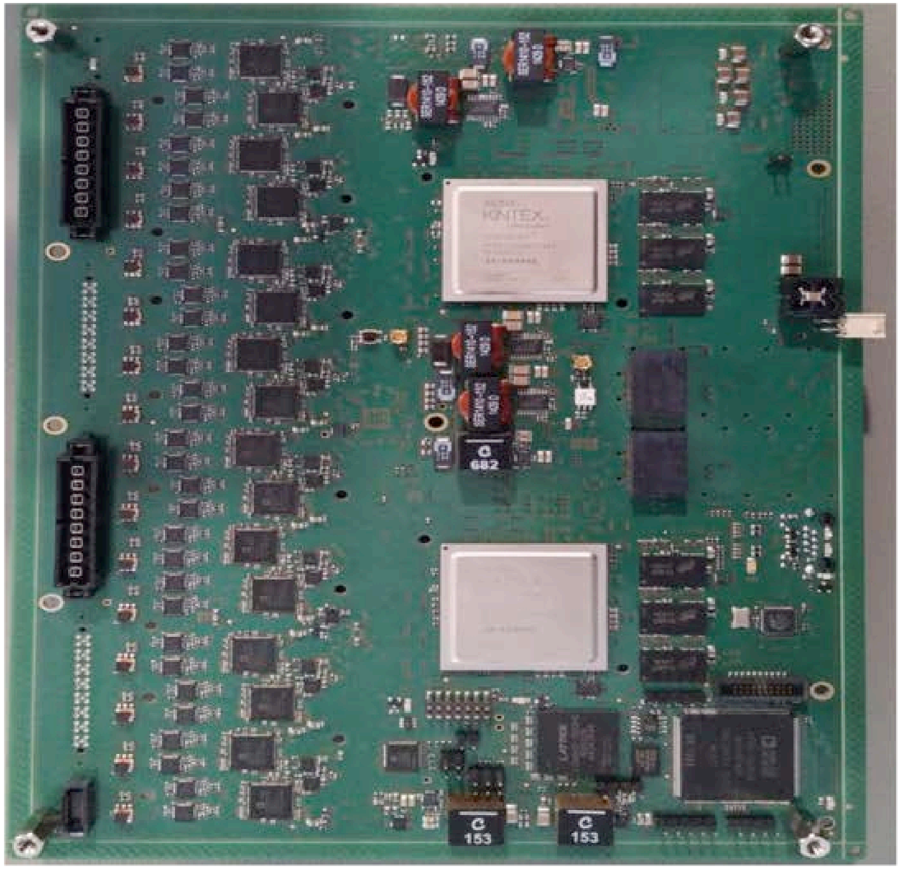


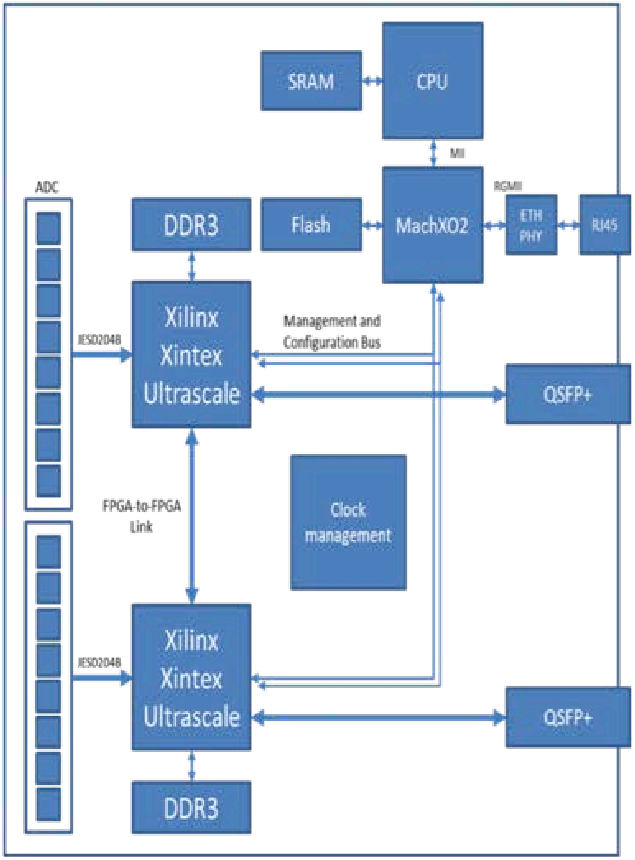
Measured phase/gain states



RF tile block diagram

Digital beamforming



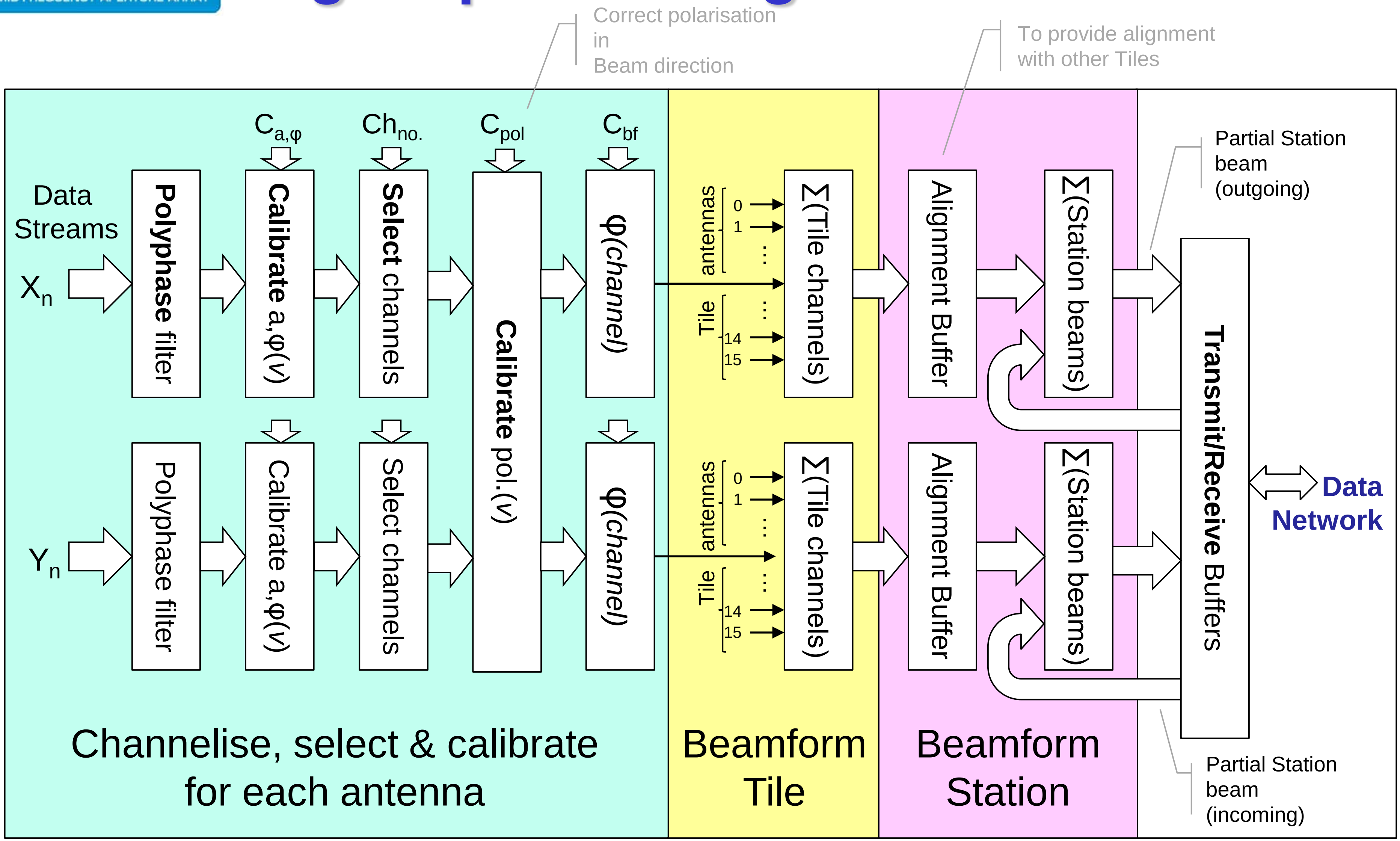


LFAA system:

16 input x 2 pols
ADCs 8-12 bits
Buffer memory

Network connection
Beamforming processing
Calibration

Digital processing data flow



Correct polarisation in Beam direction

To provide alignment with other Tiles

Data Streams

X_n

Y_n

$C_{a,\varphi}$ $Ch_{no.}$ C_{pol} C_{bf}

Polyphase filter

Calibrate a,φ(ν)

Select channels

Calibrate pol.(ν)

φ(channel)

Polyphase filter

Calibrate a,φ(ν)

Select channels

φ(channel)

Tile antennas

0
1
⋮
14
15

Σ(Tile channels)

Alignment Buffer

Σ(Station beams)

Transmit/Receive Buffers

Partial Station beam (outgoing)

Partial Station beam (incoming)

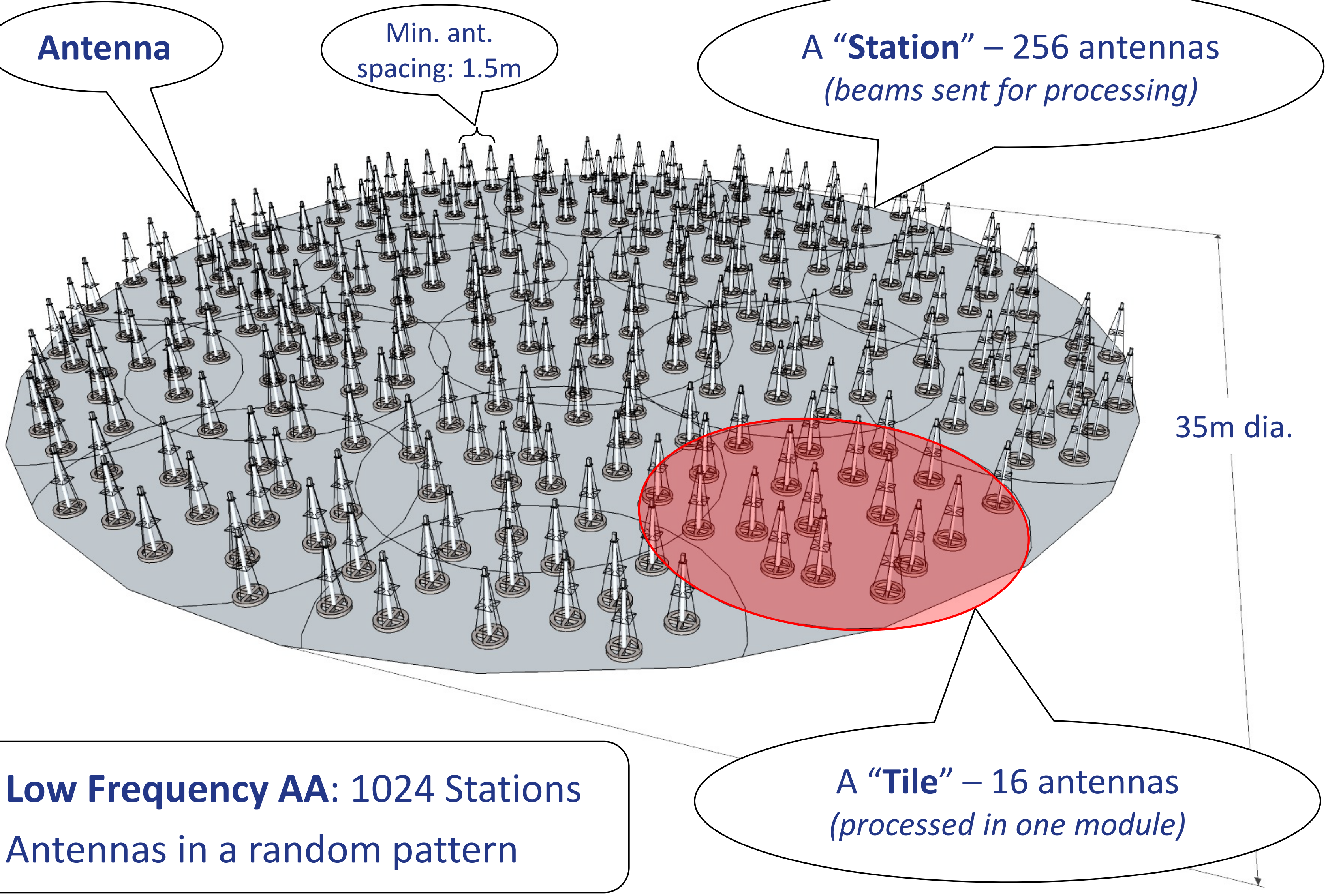
Data Network

Channelise, select & calibrate for each antenna

Beamform Tile

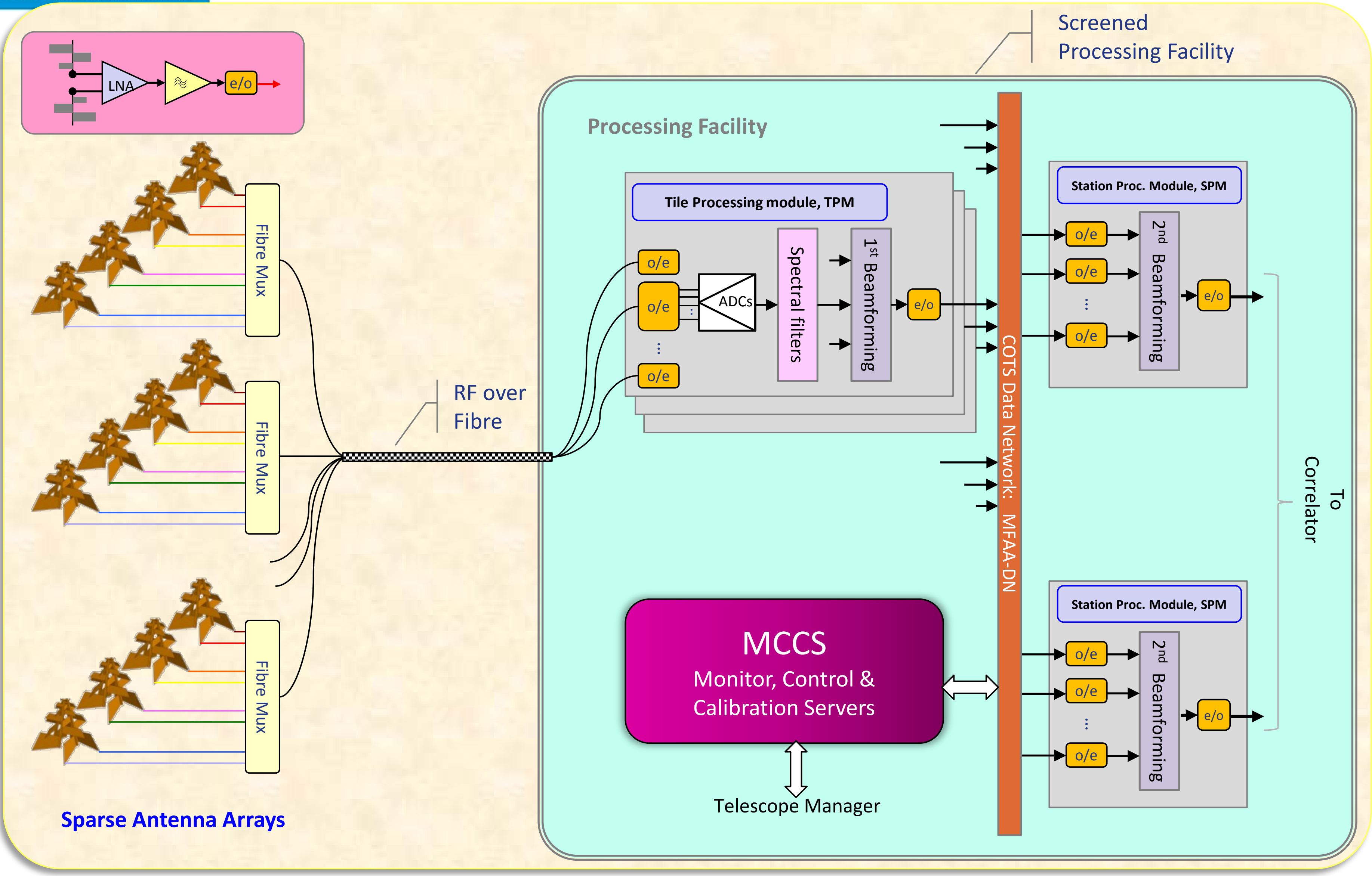
Beamform Station

LFAA station…

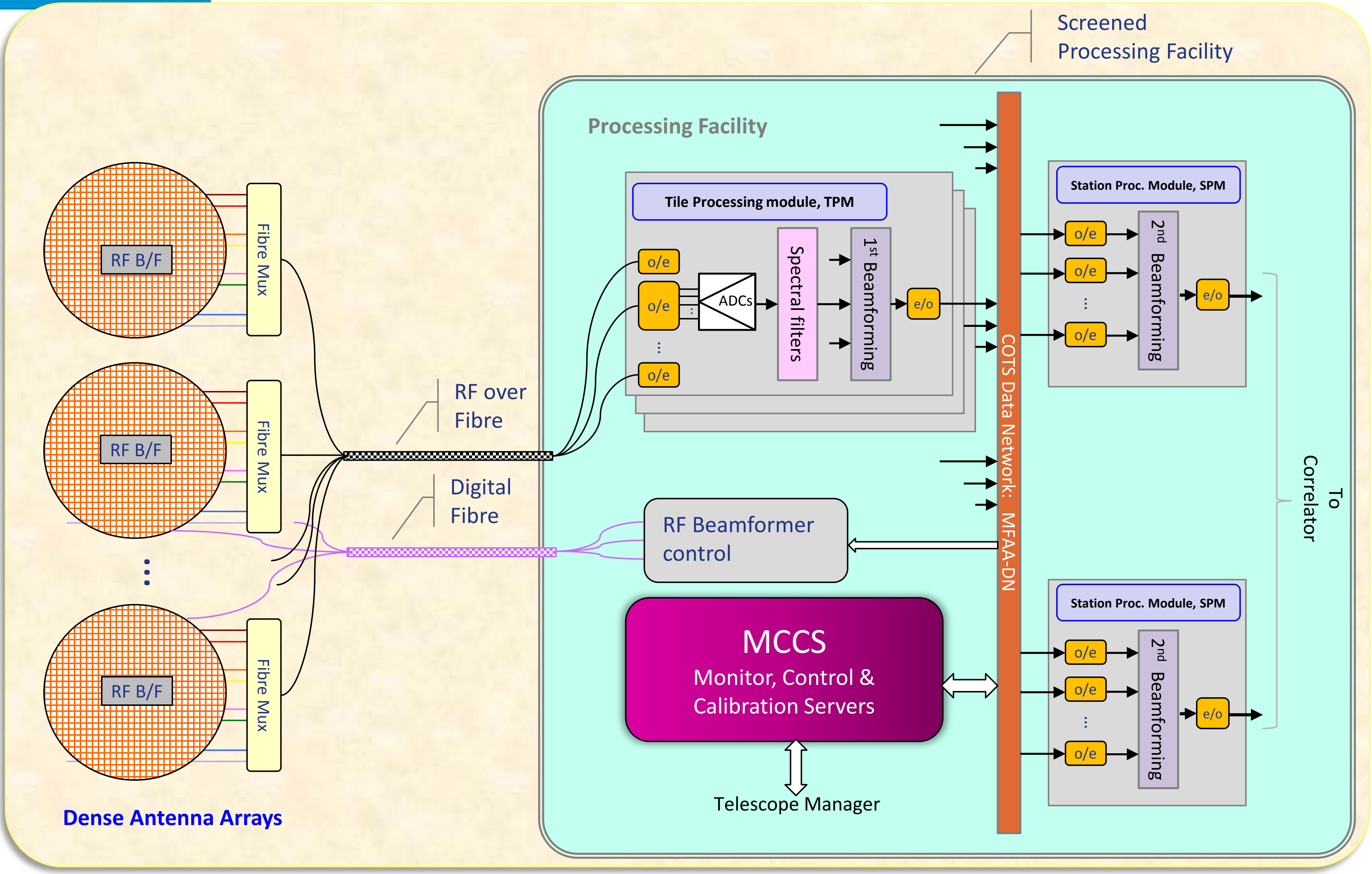


- **Low Frequency AA**: 1024 Stations
- Antennas in a random pattern

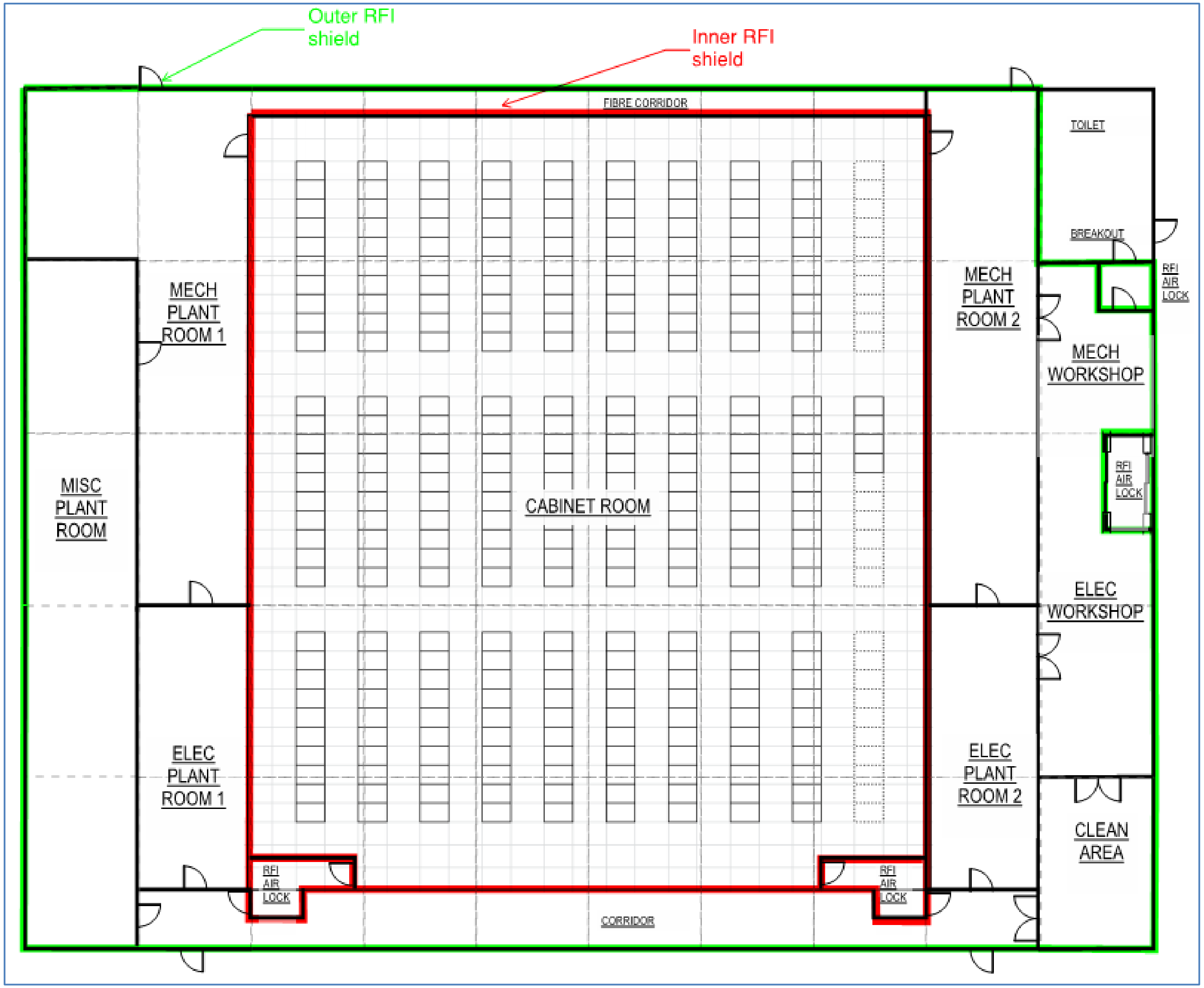
System architecture (all-digital B/F)



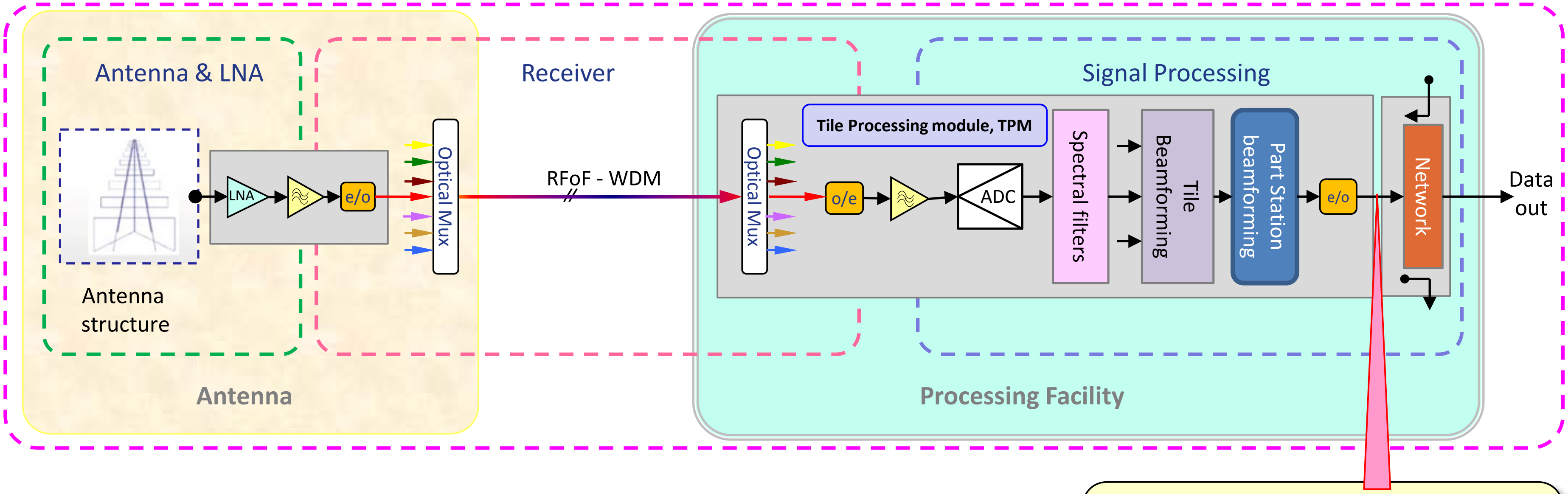
System architecture (tile level analogue B/F)



Processing Facility design



Signal path - sparse



- Control data
- Calib. coefficients
- Partial beam in #x..
- Partial beam in #2
- Partial beam in #1

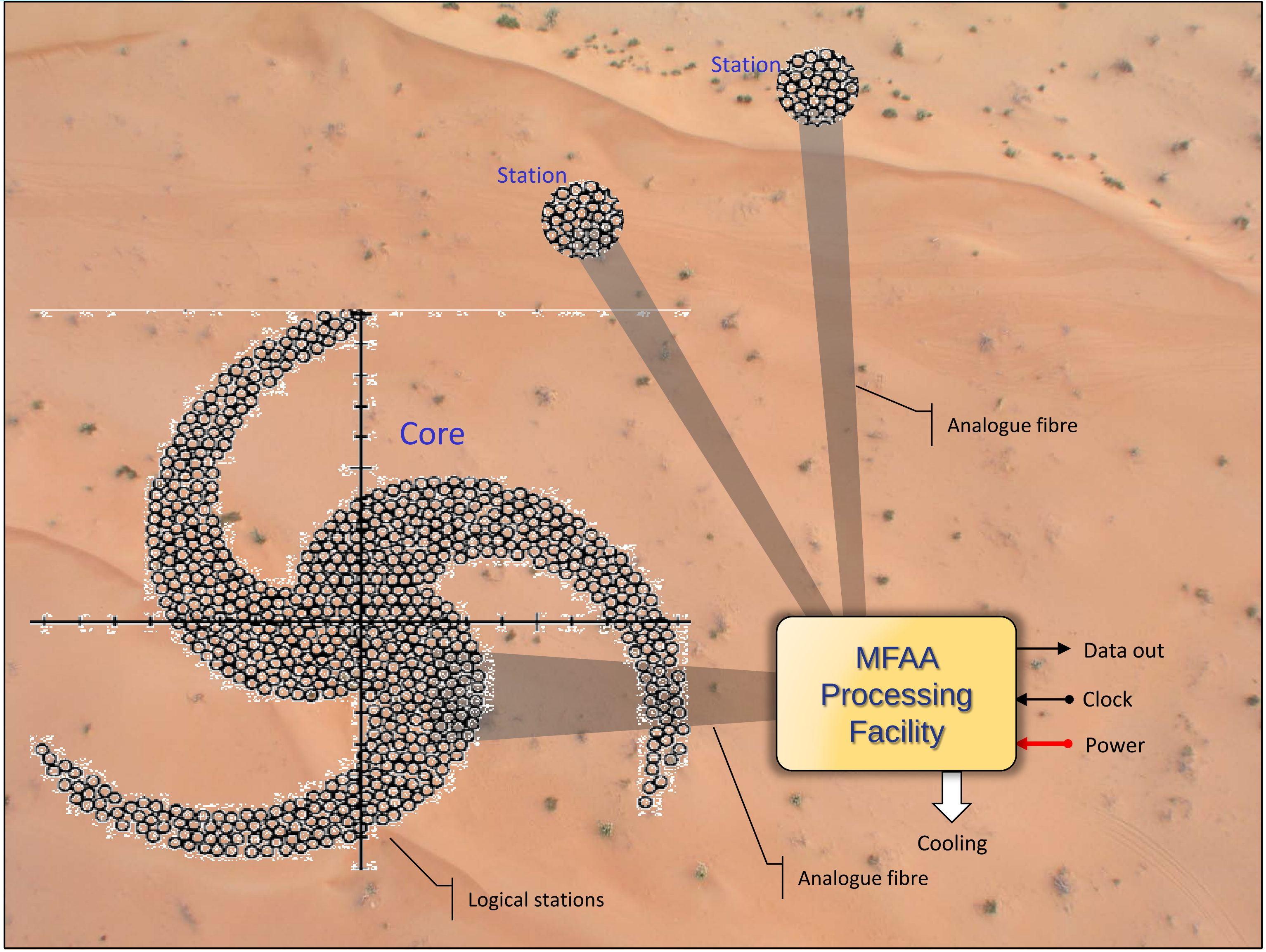
Data Network

- Beam out #1 *(Partial)*
- Beam out #2 *(Partial)*
- Beam out #x.. *(Partial)*
- Data for calibration
- Tile monitoring data

Proposed requirements of MFAA TPM

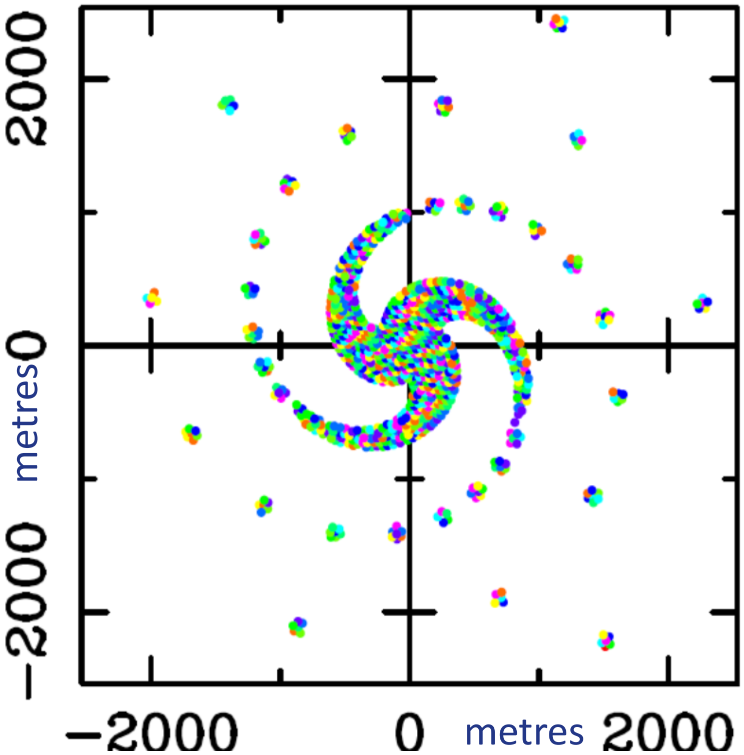
Parameter	Essential	Desirable	Comments
Number of input antennas or tiles	128	256	The capability to process a large number of antennas or tiles of antennas that have been analogue beamformed is essential.
# of signal channels	256	512	2-Polarisations per signal
Antenna signal input	8-colour analogue mux. optical	16-colour analogue mux. optical	Analogue fibre ensures min. digital electronics at the antenna. Multiplexing reduces the large number of fibres into the processing facility. Also ensures that all the signals can be entered into the MTPM.
Frequency – low	450MHz	400MHz	Scientifically the low frequency requirement is for HI at z=2.5. Functionally, a sensible cross over frequency with which LFAA operates to 450-500MHz at high sensitivity.
Frequency – high	1450 MHz	>1450 MHz	Essential to cover the rest HI line frequency of 1421MHz. Also: [1] Transients, specifically FRB detection [2] Galactic pulsar search & timing [3] History of HI to z=2.5. Desirable to reach higher frequencies e.g. 2000MHz: • OH observation at ~1700MHz • Precision timing of pulsars
Bandwidth (inst.)	1000MHz	>1000MHz	It is essential to be able to form a full bandwidth beams across the HI observing frequencies.
Number of bands	1	1 or 2	The band has to cover the 1GHz from 450MHz to 1450MHz. A 2nd band using a higher Nyquist zone could be used for extended freq. range – ideally all covered in one band.

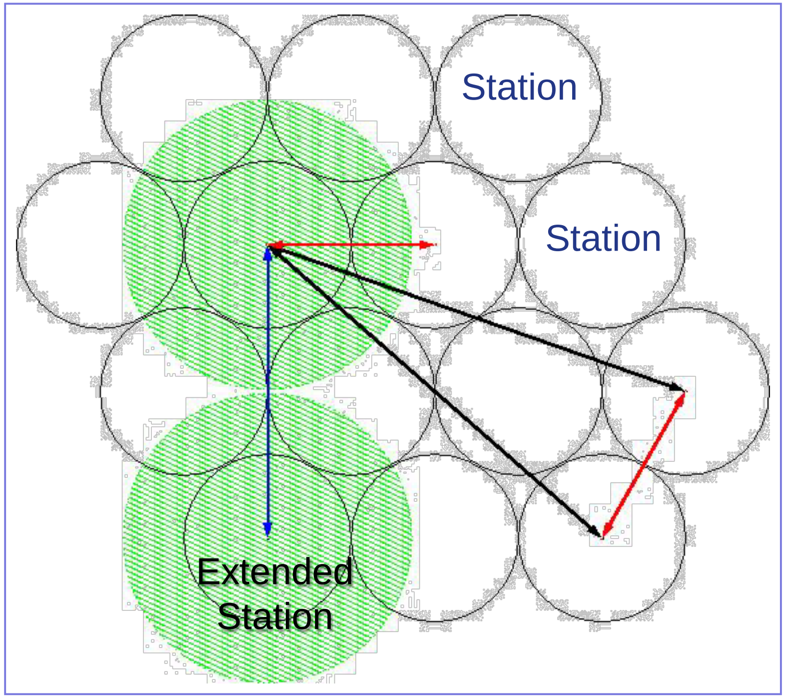
Possible configuration



Flexibility e.g. Appodisation

Core Area layout



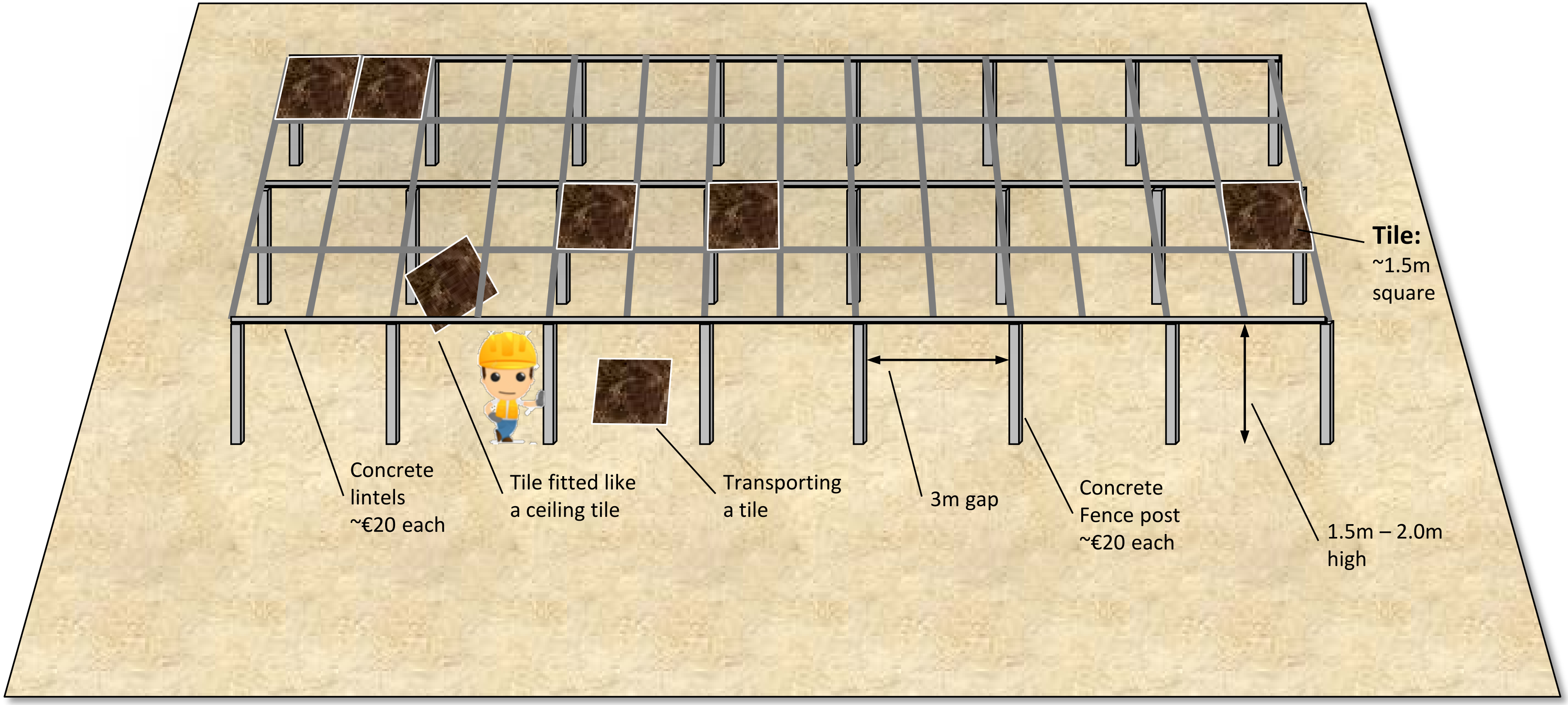


Credit: Keith Grainge

- Sea-of-antennas in core
- Shared antenna usage
- Change/move station size

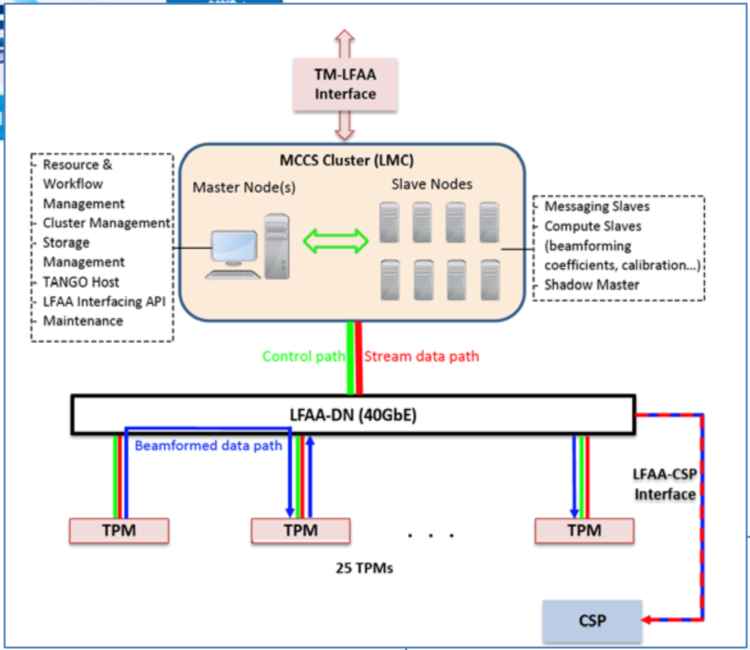
- Flexible calibration schemes
- Alternative processing structure: Correlation, Post proc

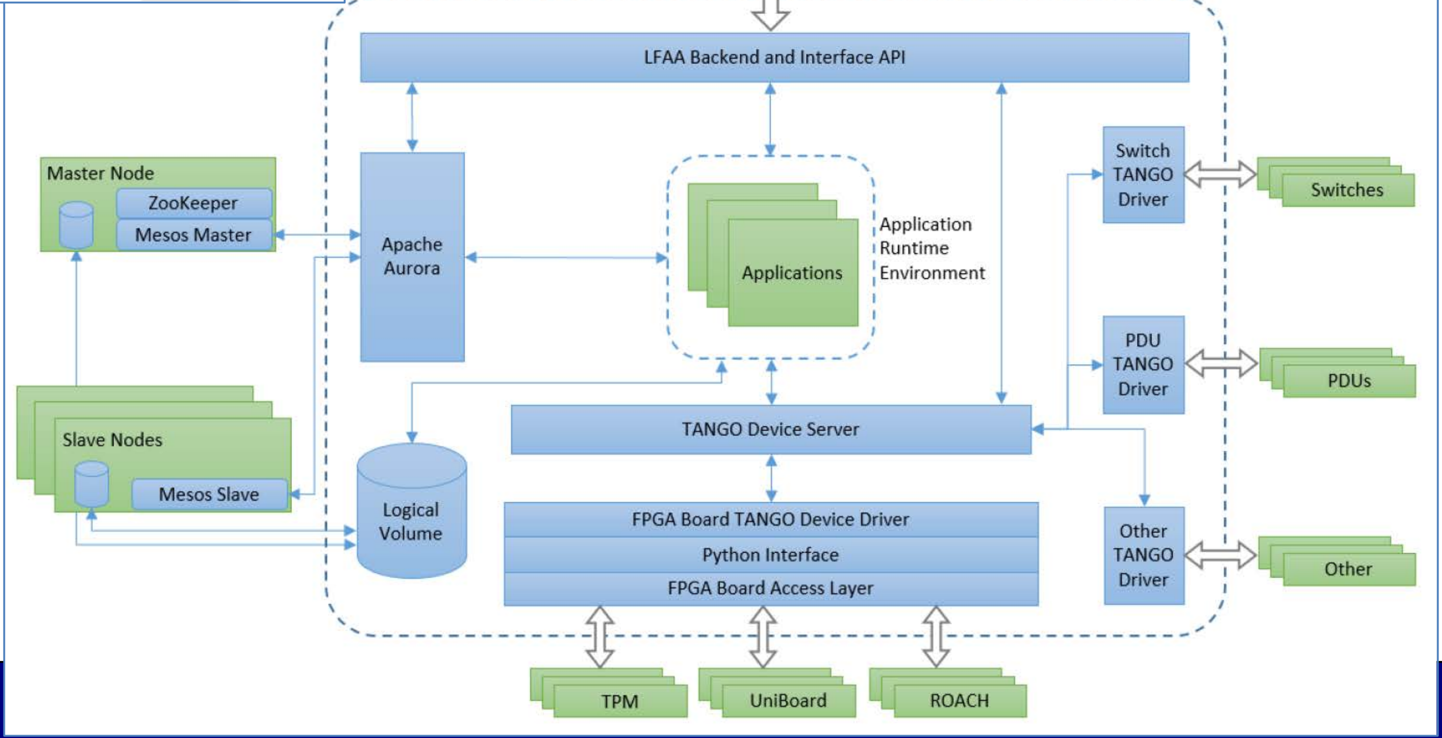
Construction suggestion for MFAA



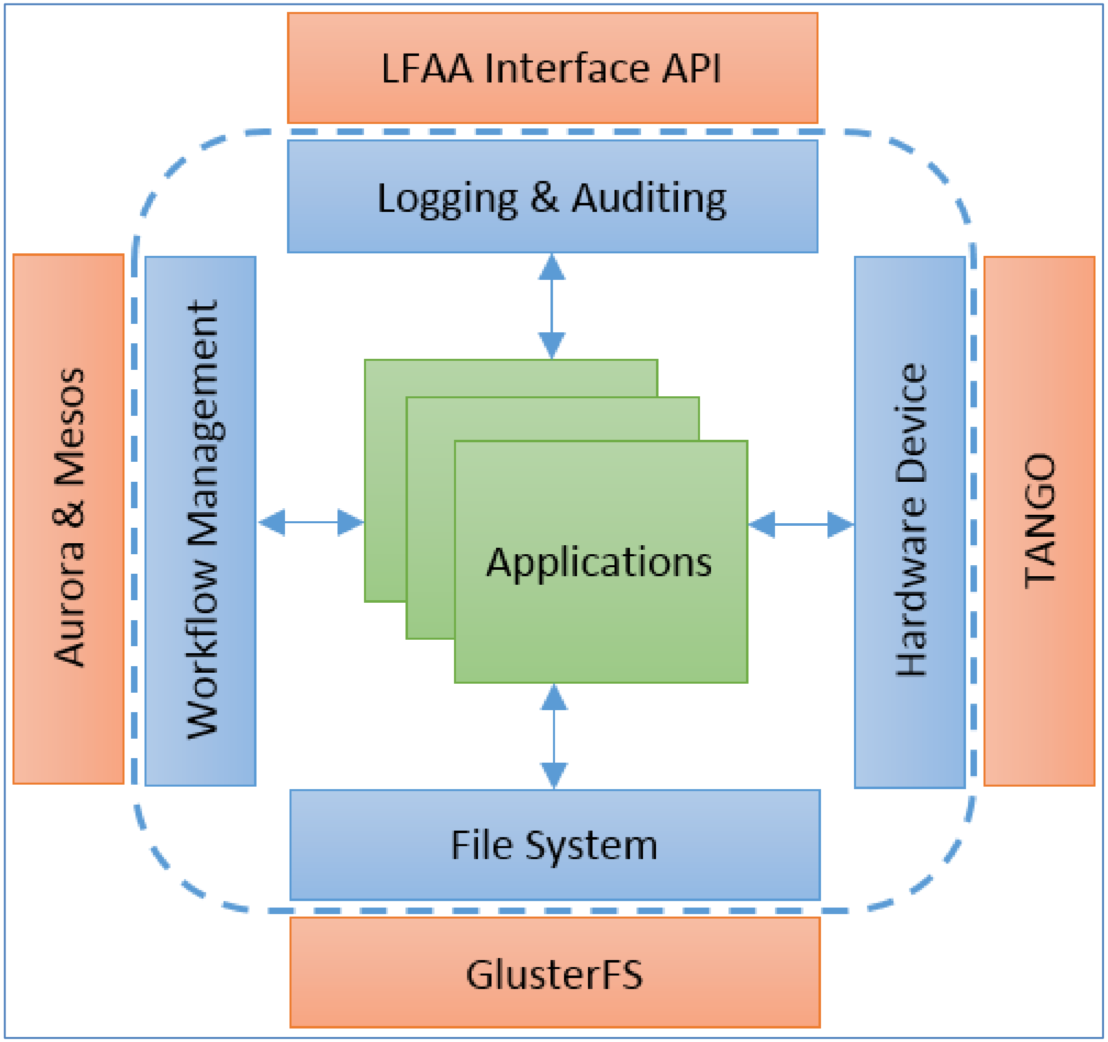
MCCS software structure
(from LFAA)

Hardware Interface:	TANGO
File System:	GlusterFS
Resource Management:	Apache Zookeeper Apache Mesos Apache Aurora



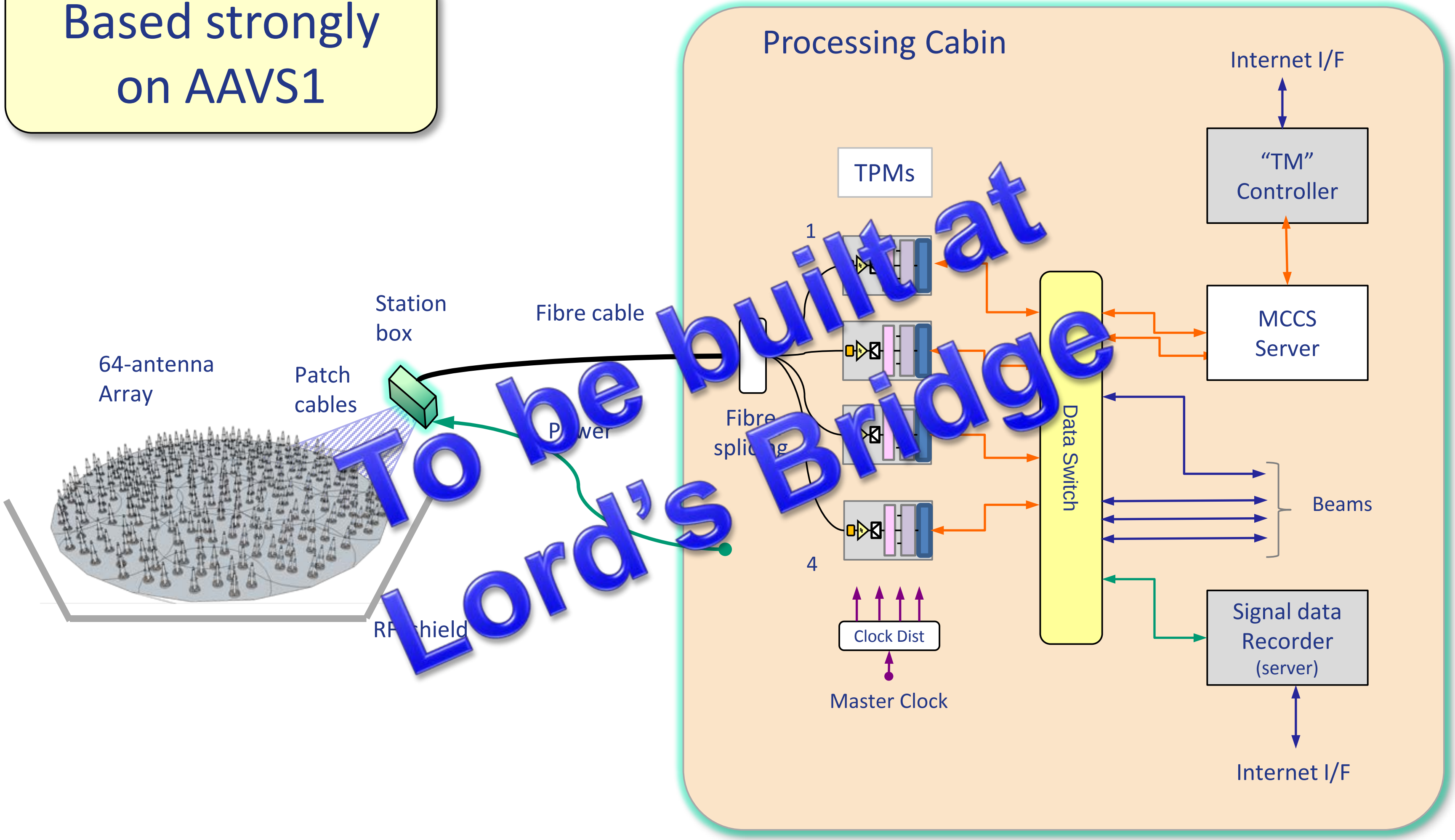


MCCS: Application Runtime Environment



Verification array #2

Based strongly on AAVS1

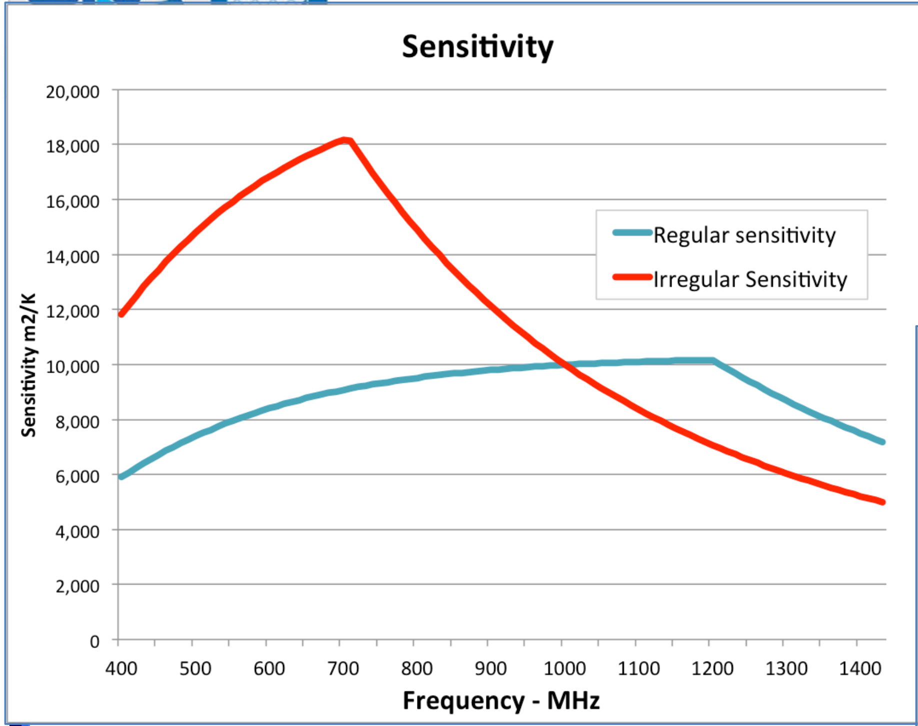


To be built at Lord's Bridge

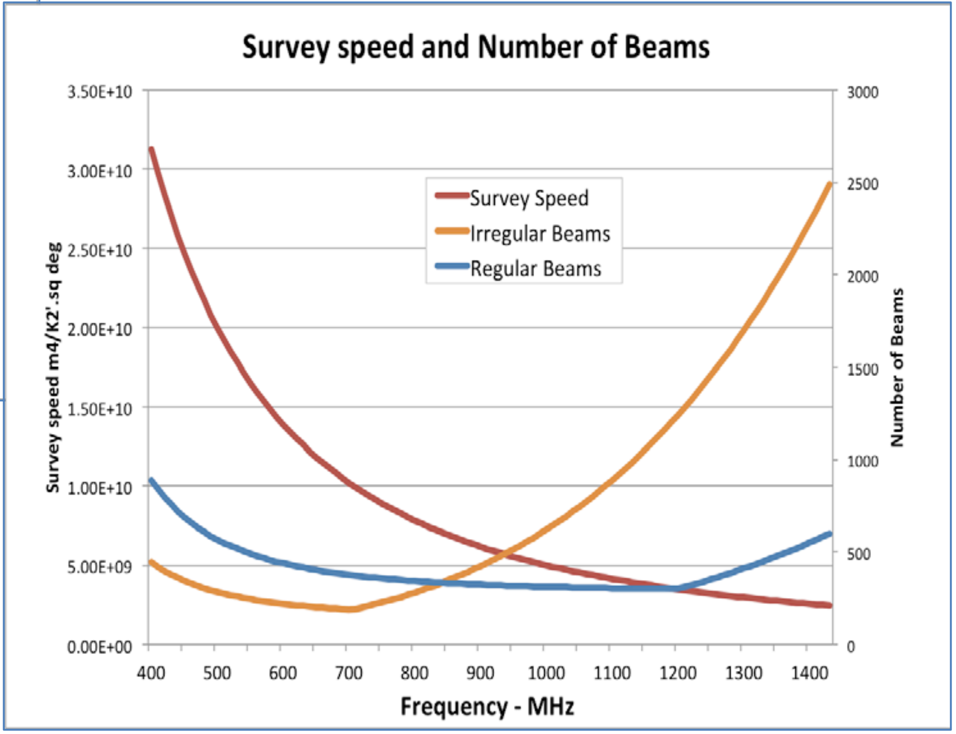
Sample array designs…

	Sparse	**Dense**
Frequency range	400MHz – 1.4GHz (2.0GHz)	450MHz – 1.4GHz
# of stations	256	256
Diameter of station	60.5m	42.3m
T_{sys}	35	35
Beamforming	All digital	RF for 16 elements Digital thereafter
# Digital channels (2-pol)	16 million	~3 million
Optical FoV	±45 deg from zenith	~200 sq deg
Antennas/station	32,000	90,000
Antenna spacing	300 mm	125 mm
Total # of antennas	8 million	23 million

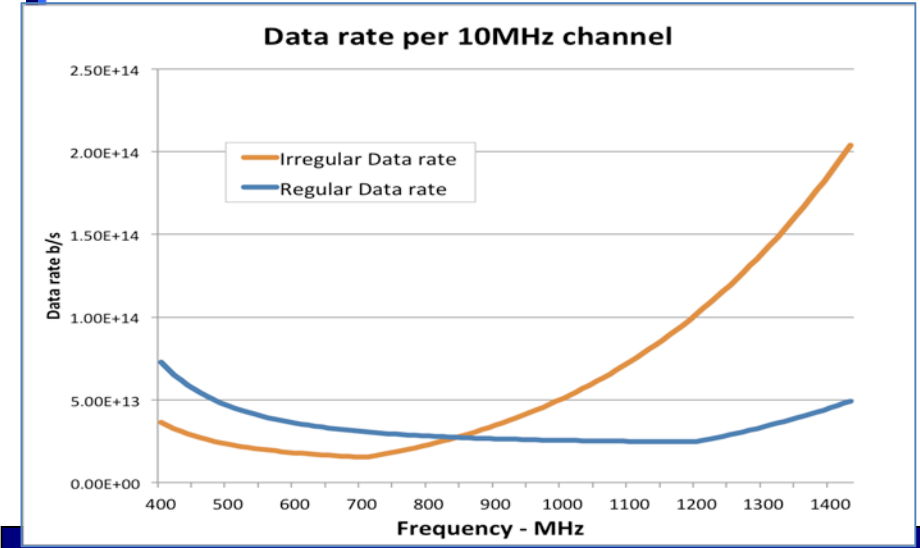
Performance estimates



Sensitivity



Survey speed and Number of Beams



Data rate per 10MHz channel

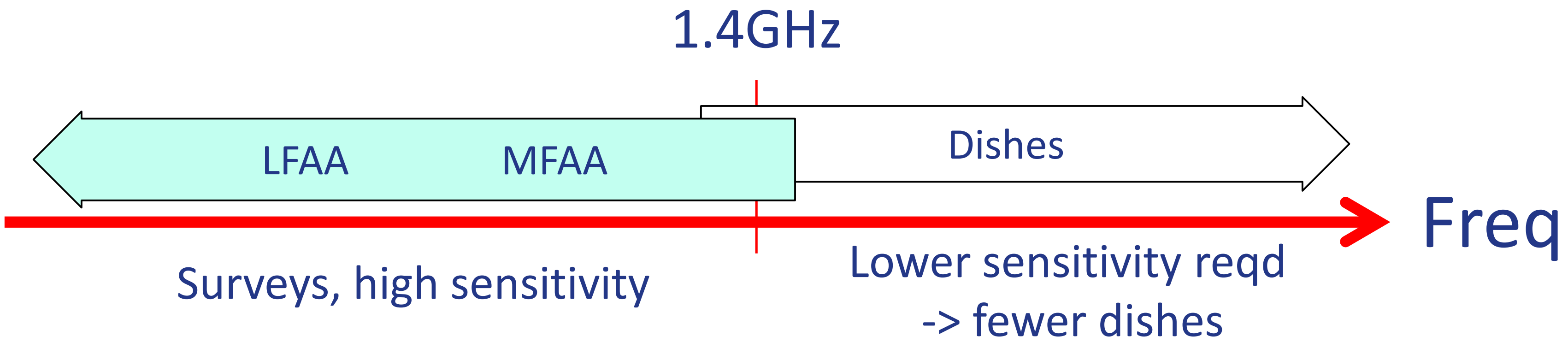
A practical focus…?

- It is difficult to afford extreme survey speed soon:
  - Massive data rate from stations
  - Huge correlation
  - Very large post processing
- Consider performance, cost and benefits … **SO:**

AA Cost < Dish

“Surface” controlled and known

AA processing options



1.4GHz

LFAA

MFAA

Dishes

Freq

Surveys, high sensitivity

Lower sensitivity reqd
-> fewer dishes

Choices, choices….

Architecture: Station level --- Overall array

Array type: Regular dense --- Irregular sparse

Beamforming: Tile level analogue --- All-digital

Antenna type: Planar --- 3-D

Analogue Sig. transport: Analogue fibre --- Copper

Processing location: Distributed --- Centralised

Finally….

AA-mid *is*:

The DREAM Machine

It will be, by far, the most capable and technically advanced telescope in SKA2