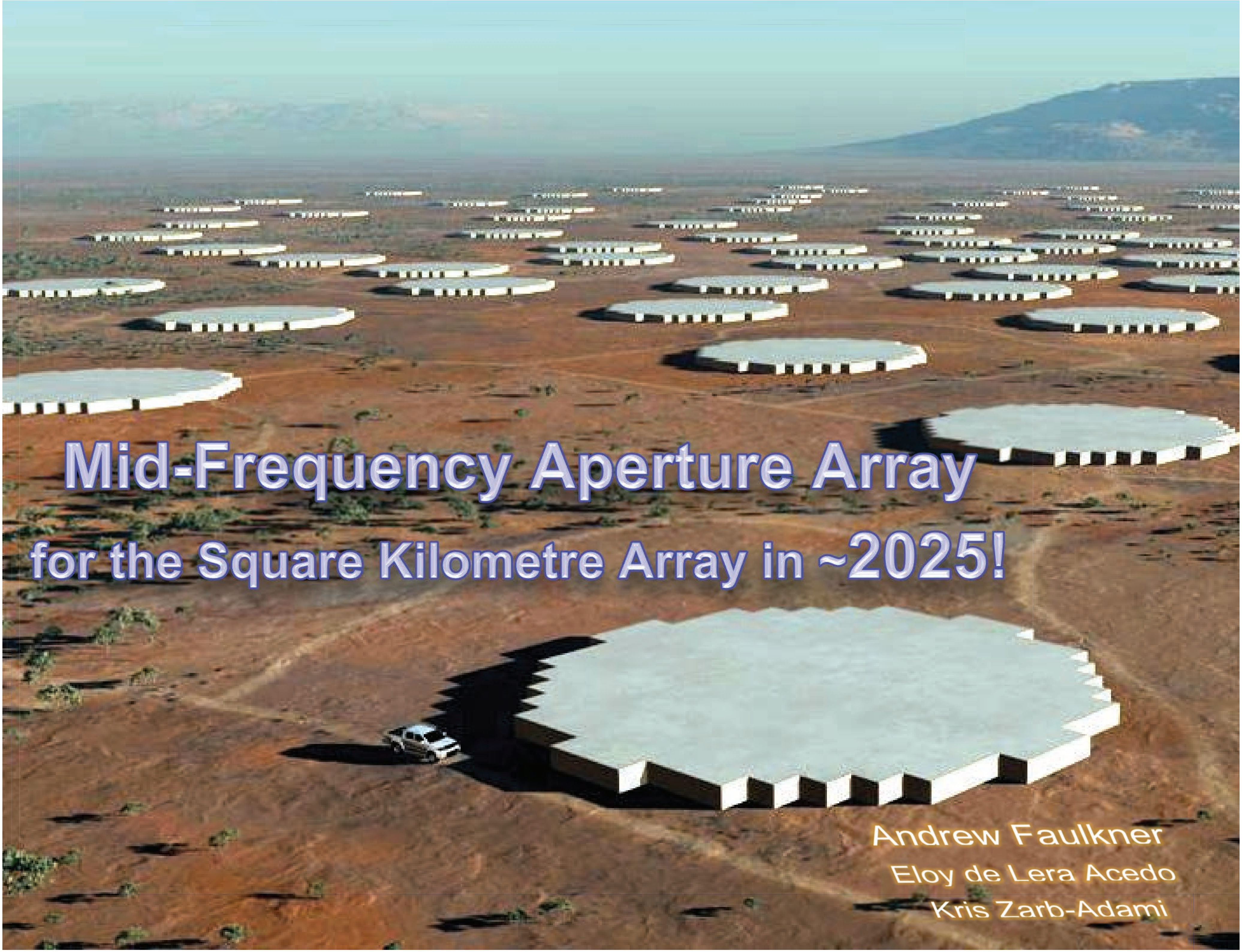


Mid-Frequency Aperture Array for the Square Kilometre Array in ~2025!

Andrew Faulkner
Eloy de Lera Acedo
Kris Zarb-Adami

What is AA-mid conceived for?

Survey HI to z ~3

AA-mid

fulfills the *original* concept of

SKA!

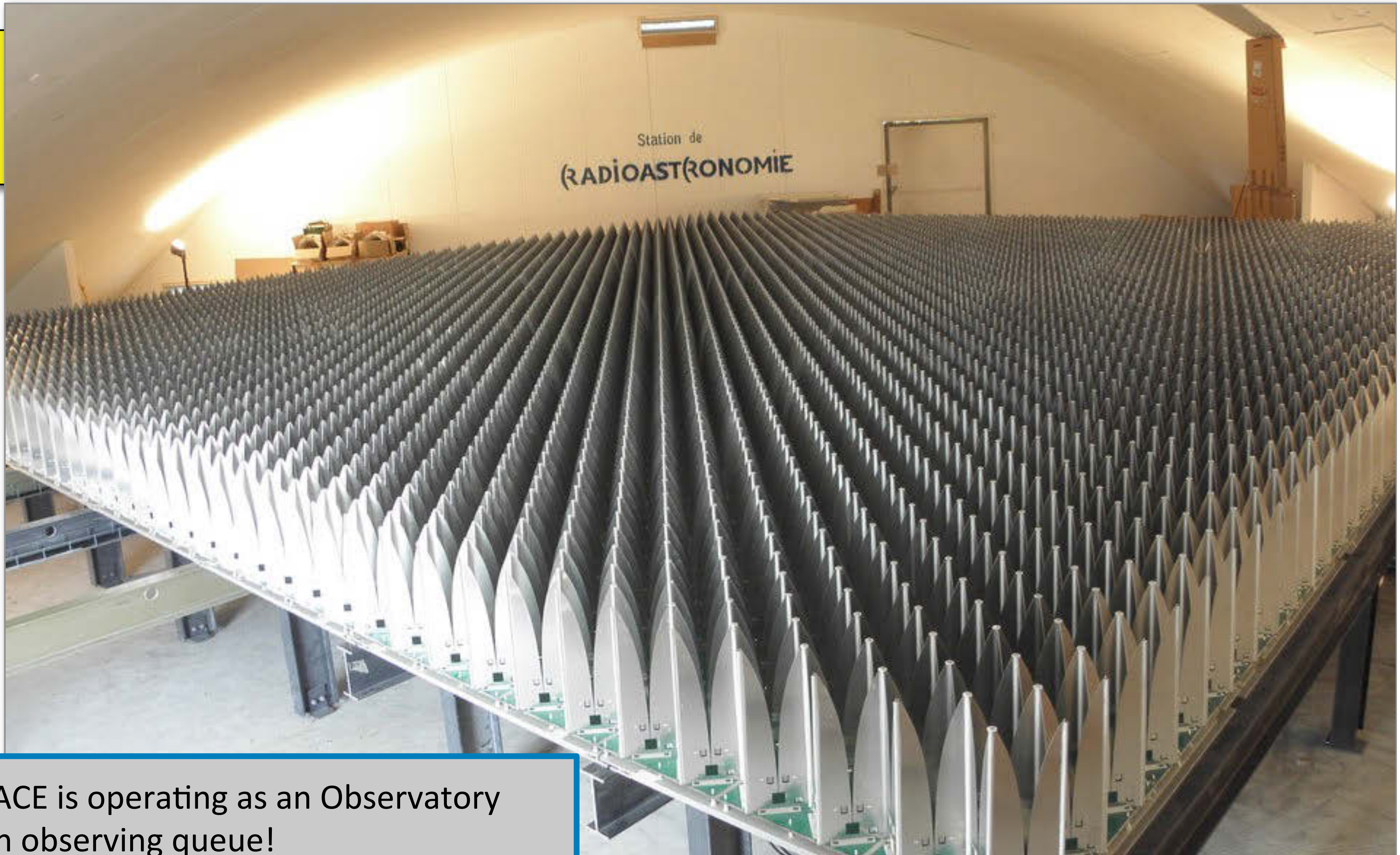
AA-MID Science

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; up to, possibly, **2GHz**

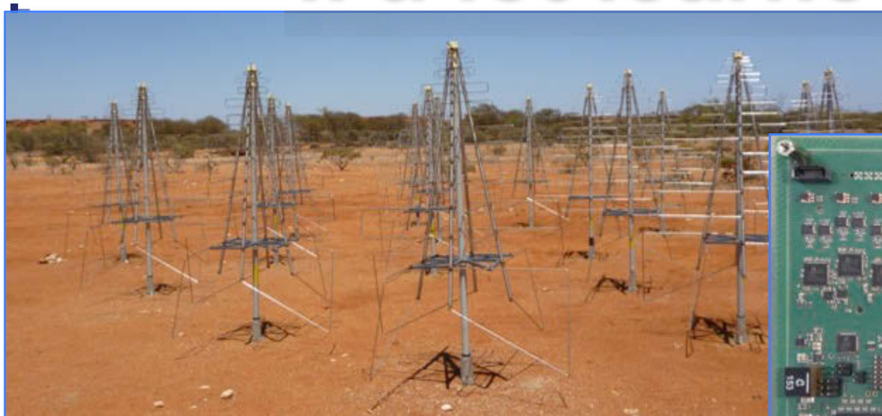
EMBRACE demonstrator

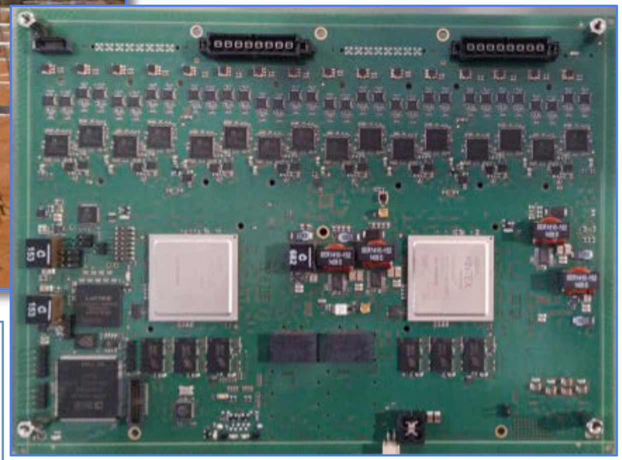
Since 2010

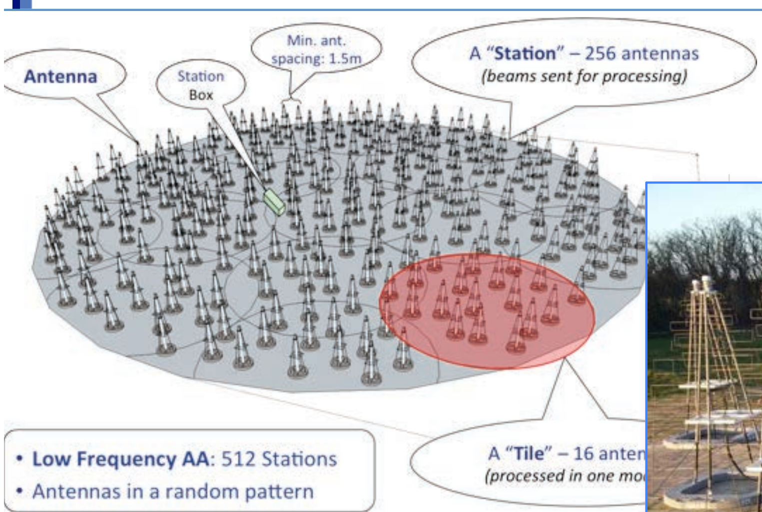


- EMBRACE is operating as an Observatory with an observing queue!
- Phase calibration tables good for >6 months
- EMBRACE is very stable!

.. a lot learned from LFAA

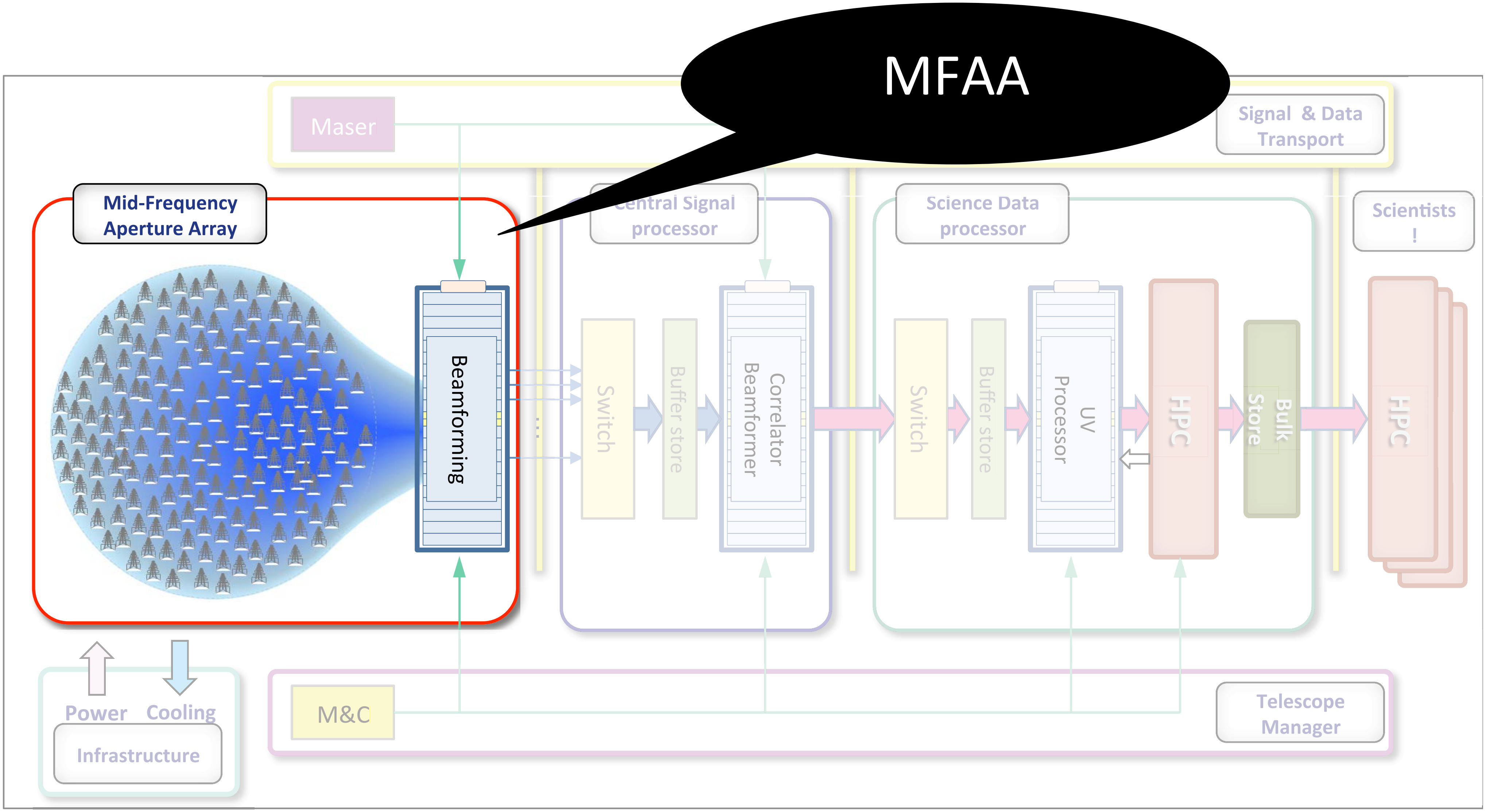






Parameter	Value
Frequency range (basic)	50 – 350MHz
Frequency range (ext.)	50 – 650MHz
Number of antennas	131,072
Number of stations	512
Station diameter	35m
Antennas per station	256
Antenna type	Log periodic
Min. Antenna sep.	1.5m
Inst. bandwidth	300MHz
Number of beams	Up to 6
Digitisation	8-bits
Beamforming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

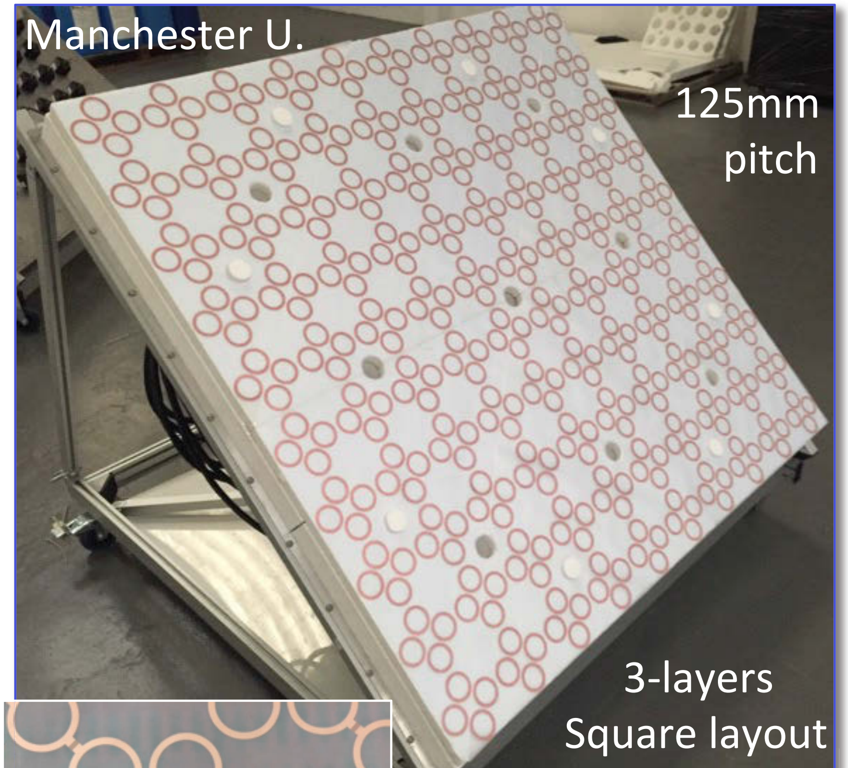
AA-MID telescope: end-to-end

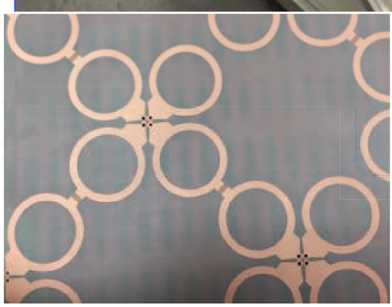


Outline Specification…

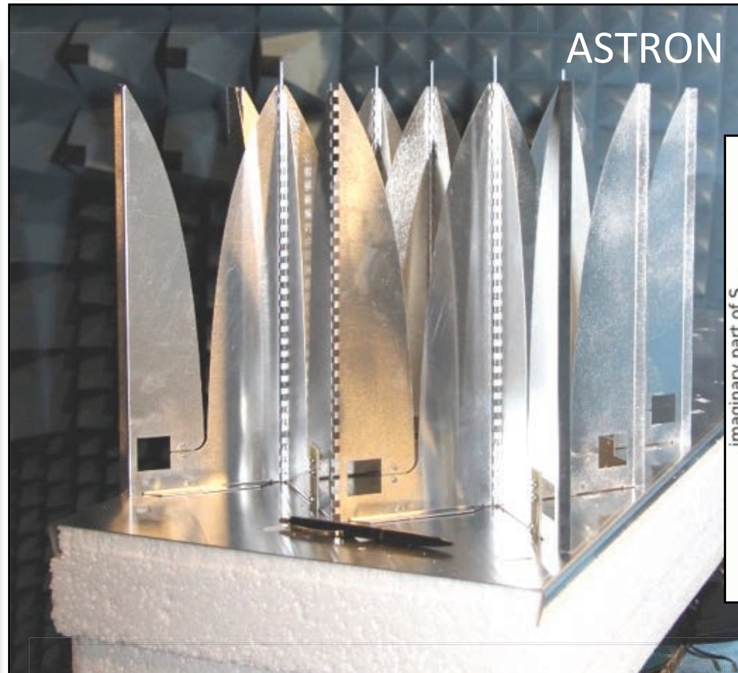
Parameter	Essential	Desirable	Comments
Frequency – low	450 MHz	<400 MHz	Scientifically the low frequency is for HI at z=3.
Frequency – high	1450 MHz	2000 MHz	Reach at least HI line; further science at higher frequencies
Polarisations	2-linear 30dB purity	2-linear 40dB purity	Essential to have orthogonal 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.
OpticalFoV	100deg^2	>±45° from zenith	More FoV (at narrower BW) gives better point survey speed and is important for transients
Bandwidth (max)	1000MHz	1600MHz	Should be capable of having beams of the full bandwidth
Data rate to post processing	>1Pb/s	>5Pb/s	Data rate determines telescope performance. Likely limited by post processing capability.
# of beams	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

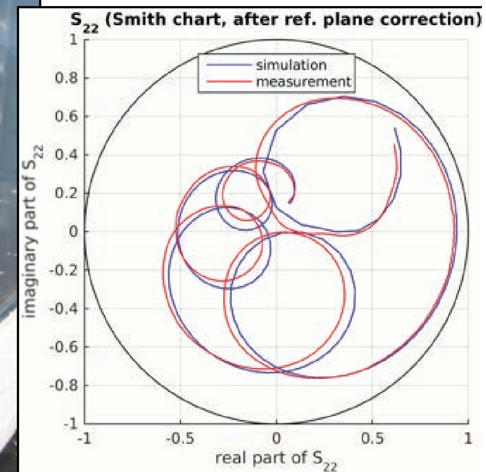
Antenna options - Dense





Planar - ORA

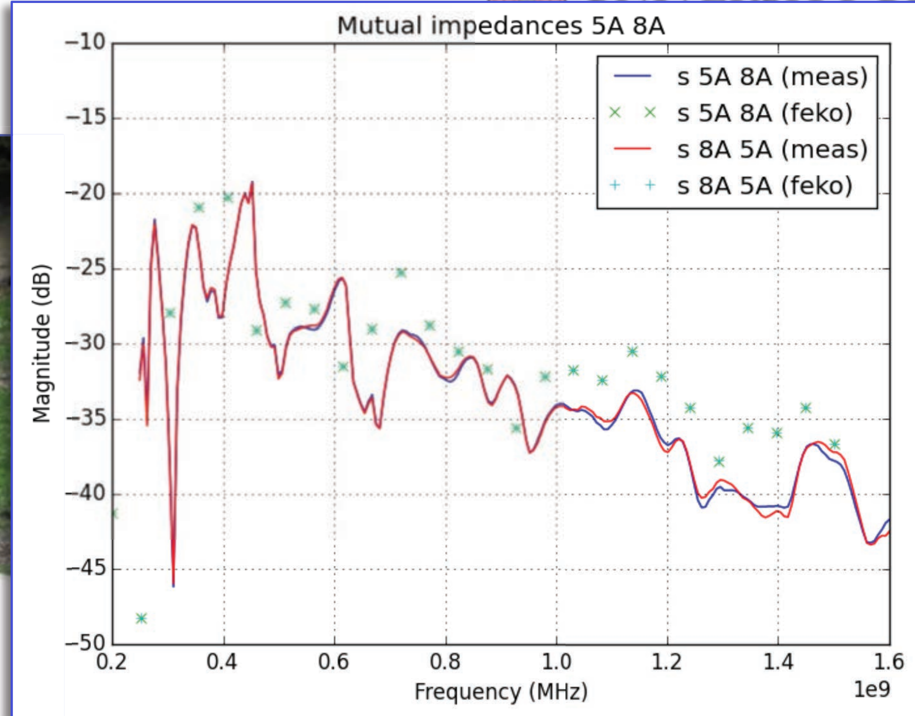




Vivaldi elements

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

Antenna - Sparse



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

Same concept as LFAA!

System design aims

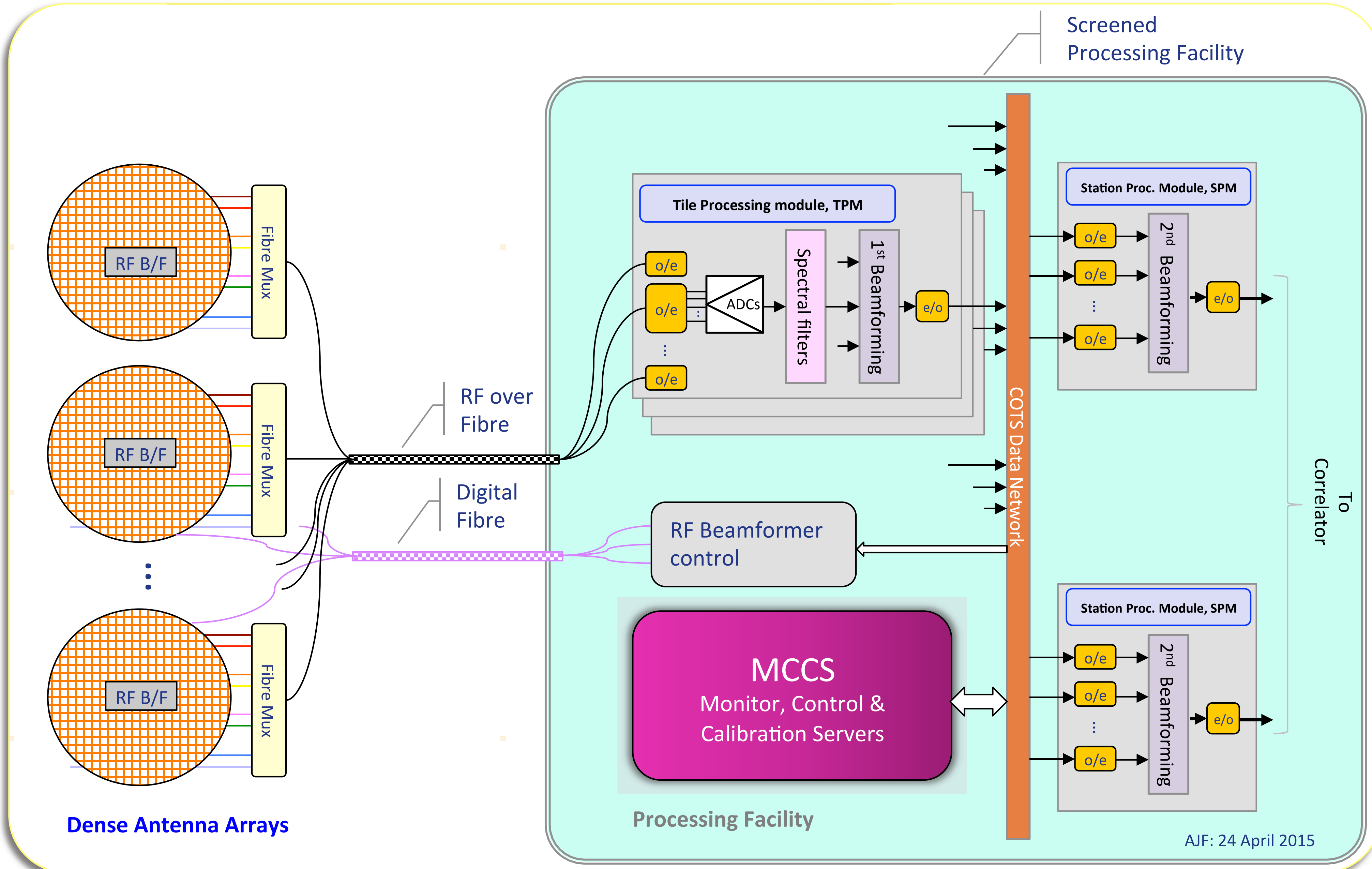
Operation

- Meet performance requirements:
  - Bandwidth – Frequency range
  - Sensitivity – Precision beams
  - Polarisation – Massive data output
- A "software controlled aperture":
  - Stations – Appodization
  - Location
- Highly configurable systems
- Precise calibration capability
- Resilient to sub-system failure
- Extendable performance
- Ability to implement new processing options e.g. **MOFF??**

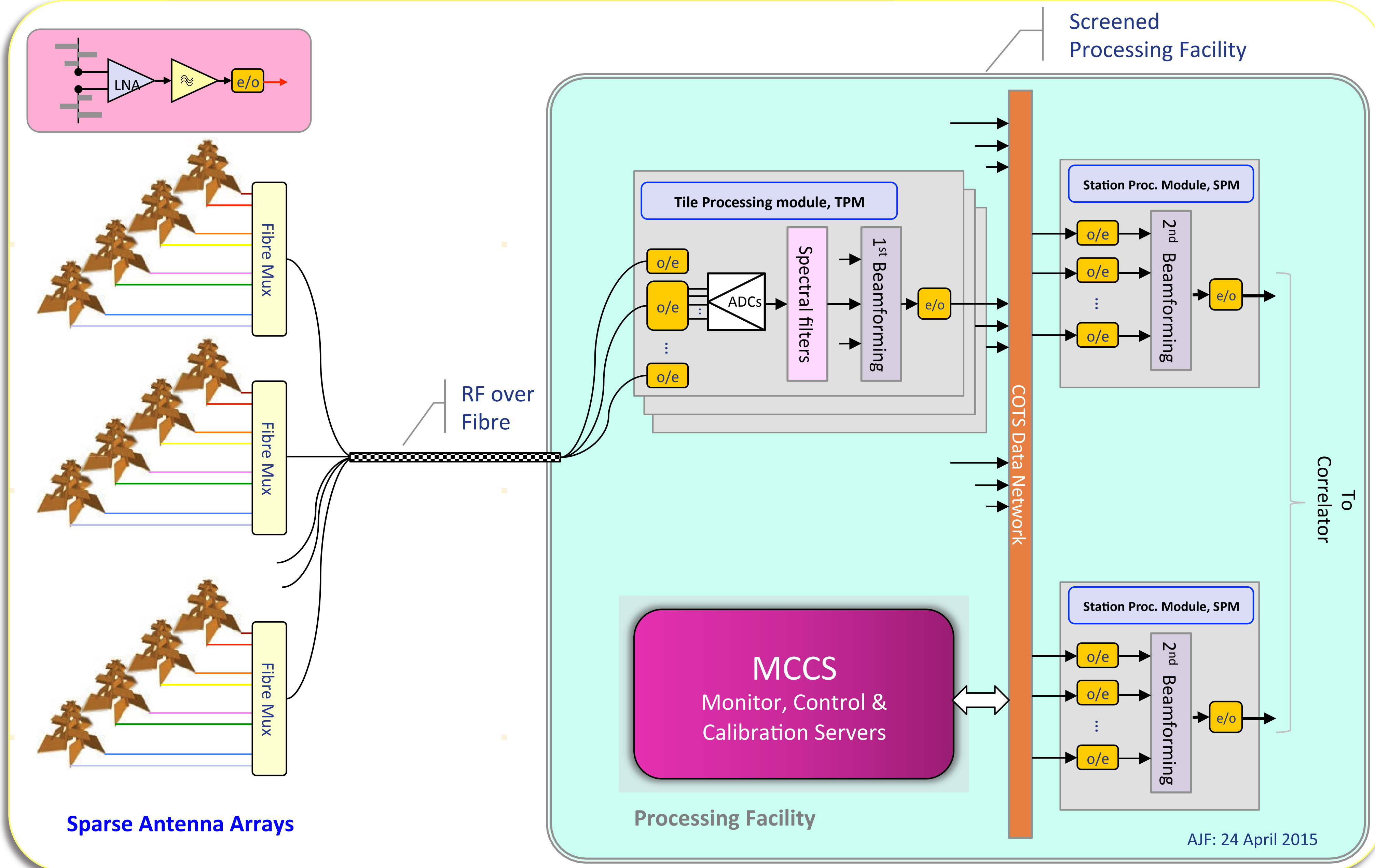
Implementation

- Minimise equipment in the field
- Very, very low RFI
  - 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)

System architecture (1)



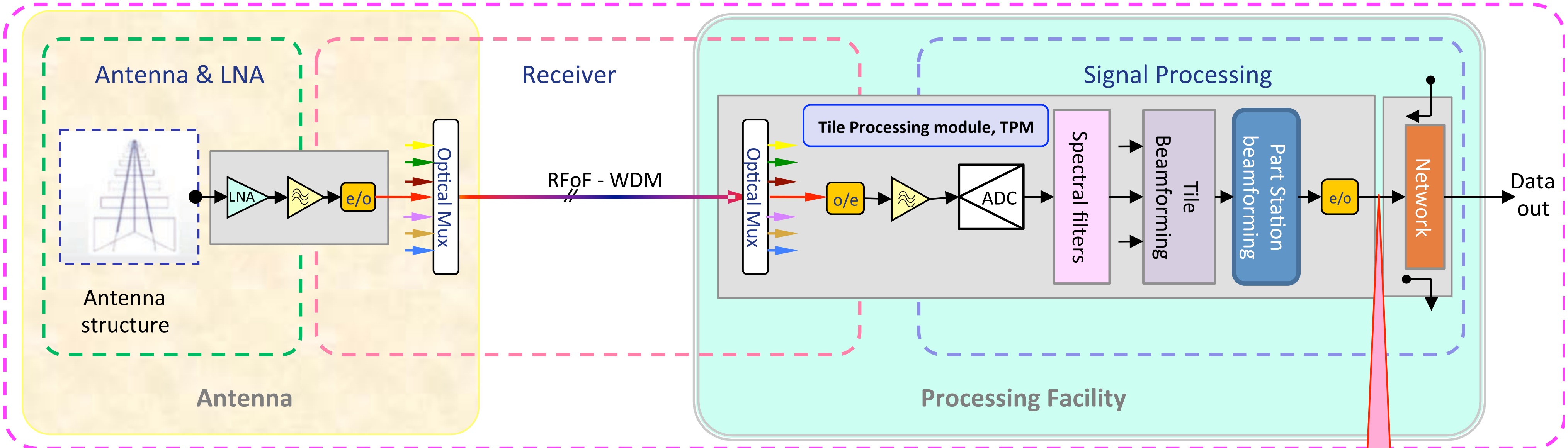
System architecture (2)



Beamforming

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

Signal path - sparse

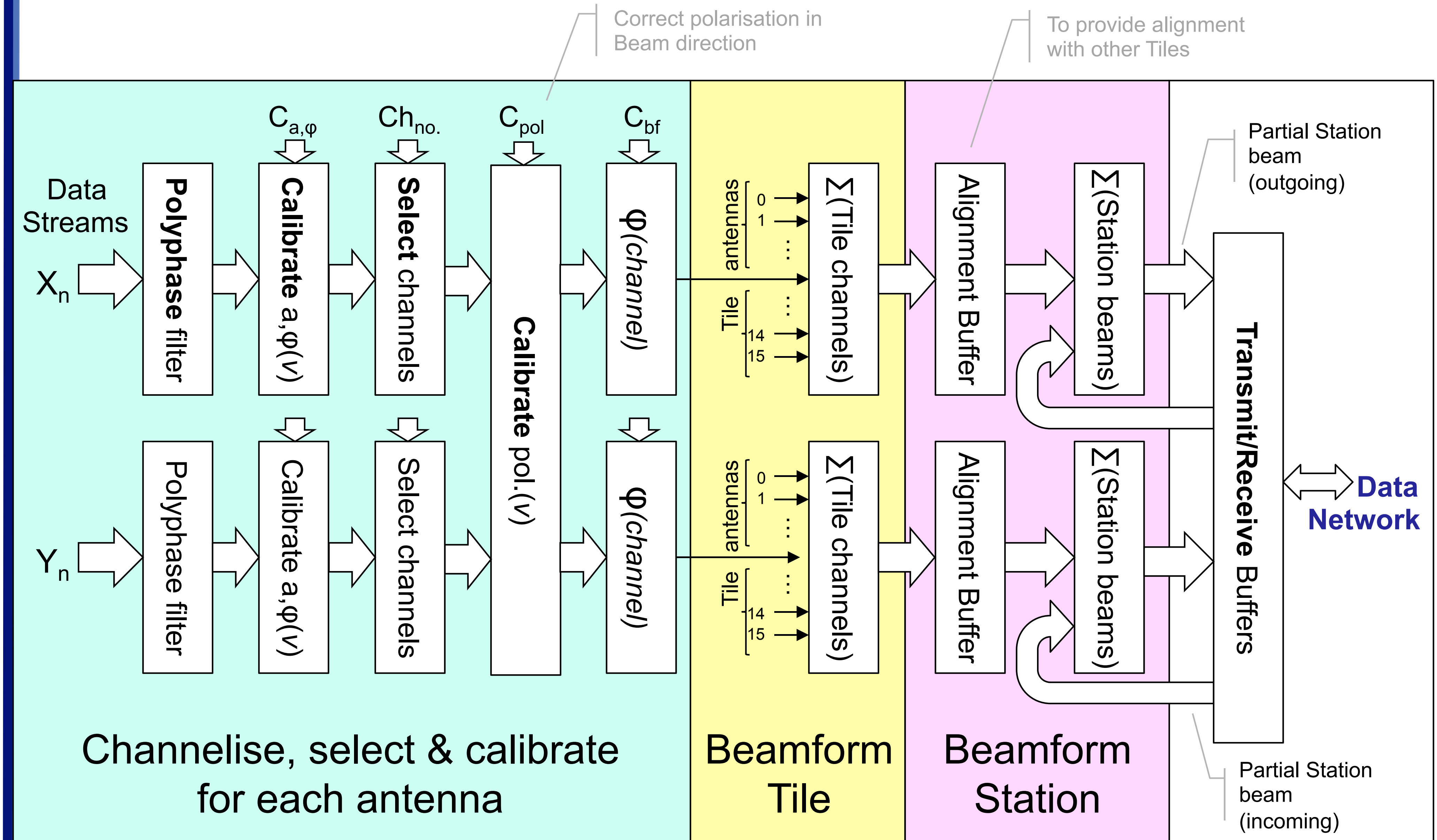


- Control data
- Calib. coefficients
- Partial beam in #x..
- Partial beam in #2
- Partial beam in #1

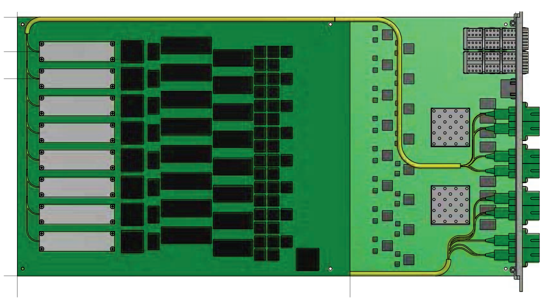
Data Network

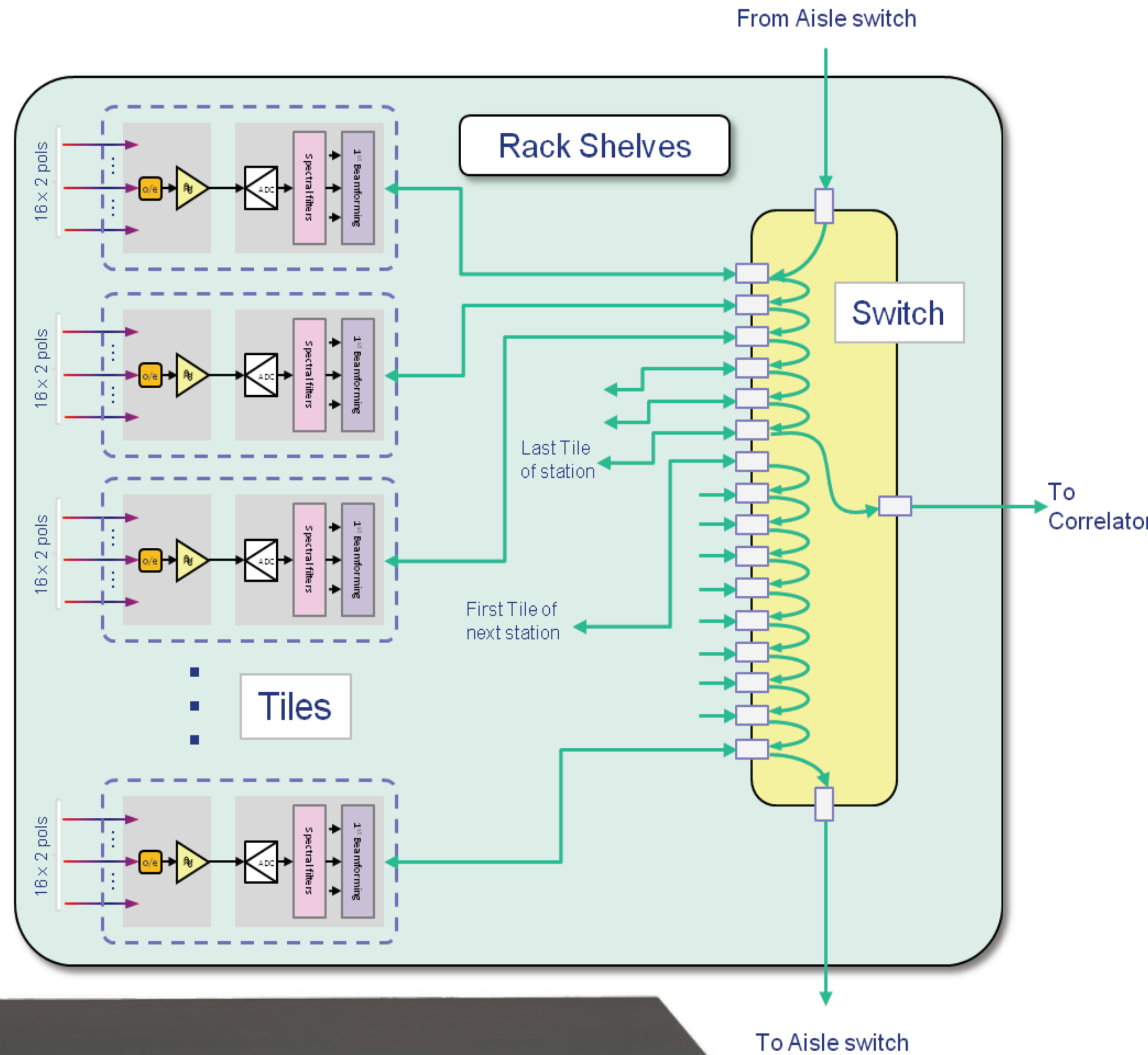
- Beam out #1 *(Partial)*
- Beam out #2 *(Partial)*
- Beam out #x.. *(Partial)*
- Data for calibration
- Tile monitoring data

Tile processing data flow



Beamforming thro' switched network

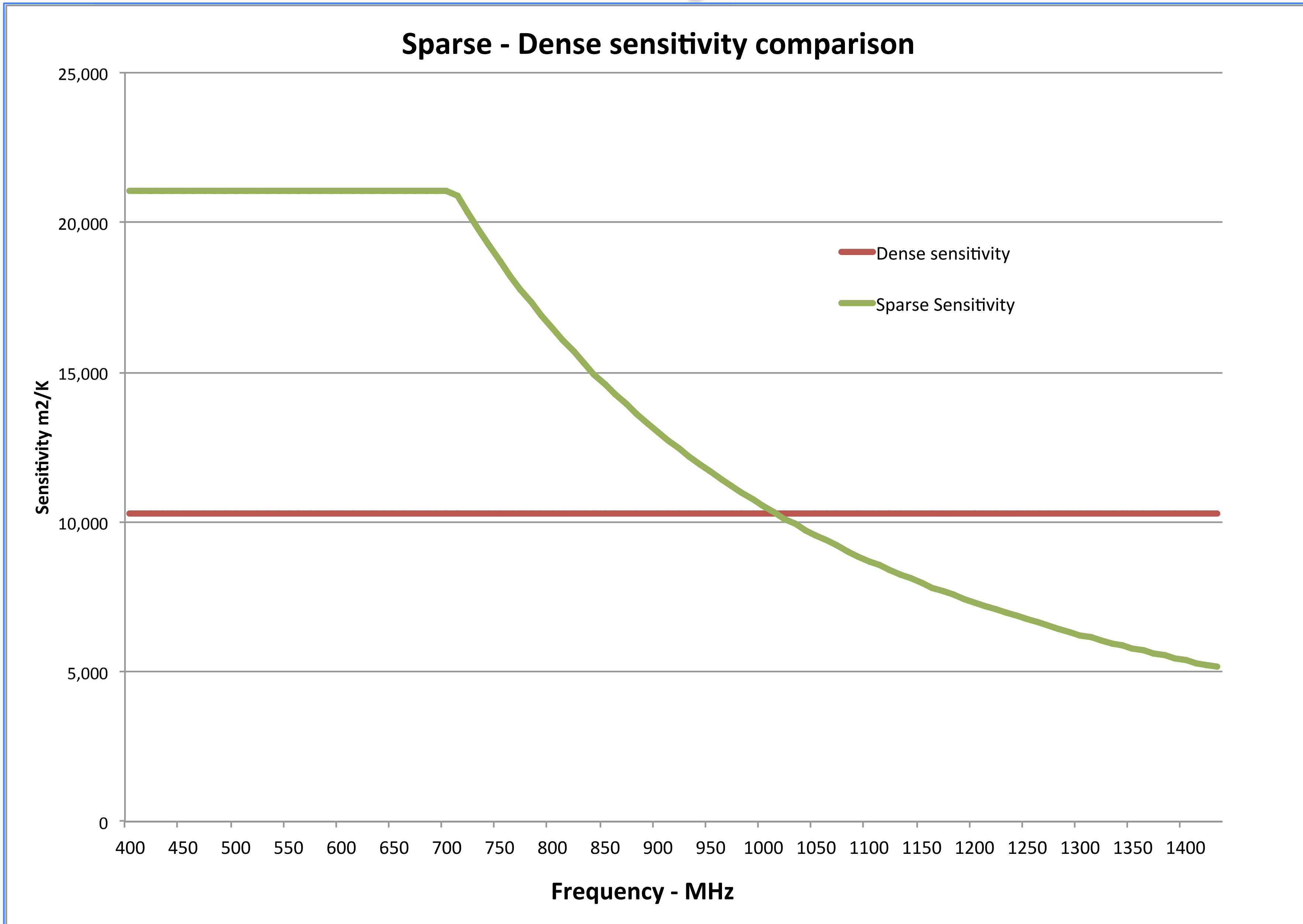




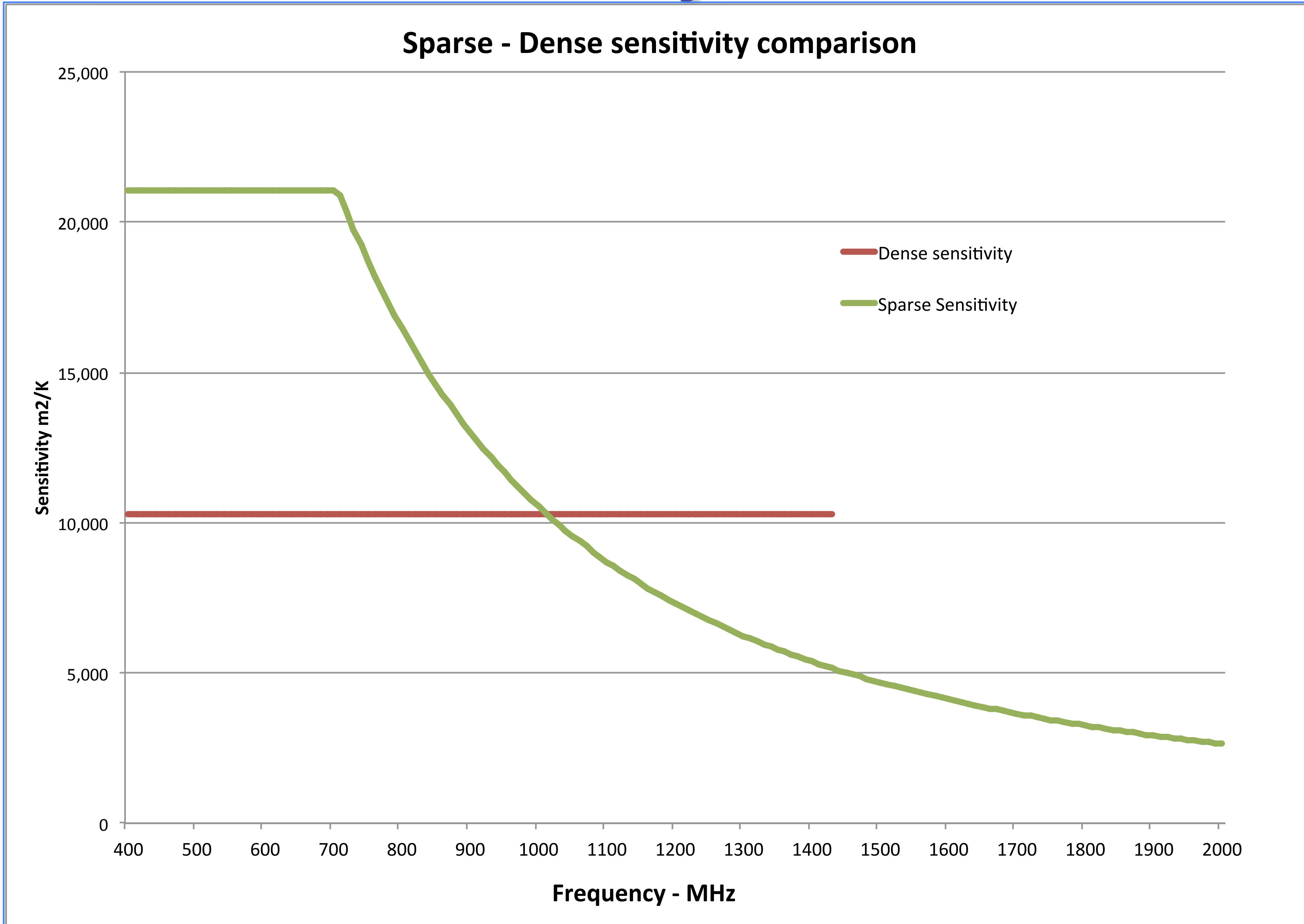
Sample array designs…

	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

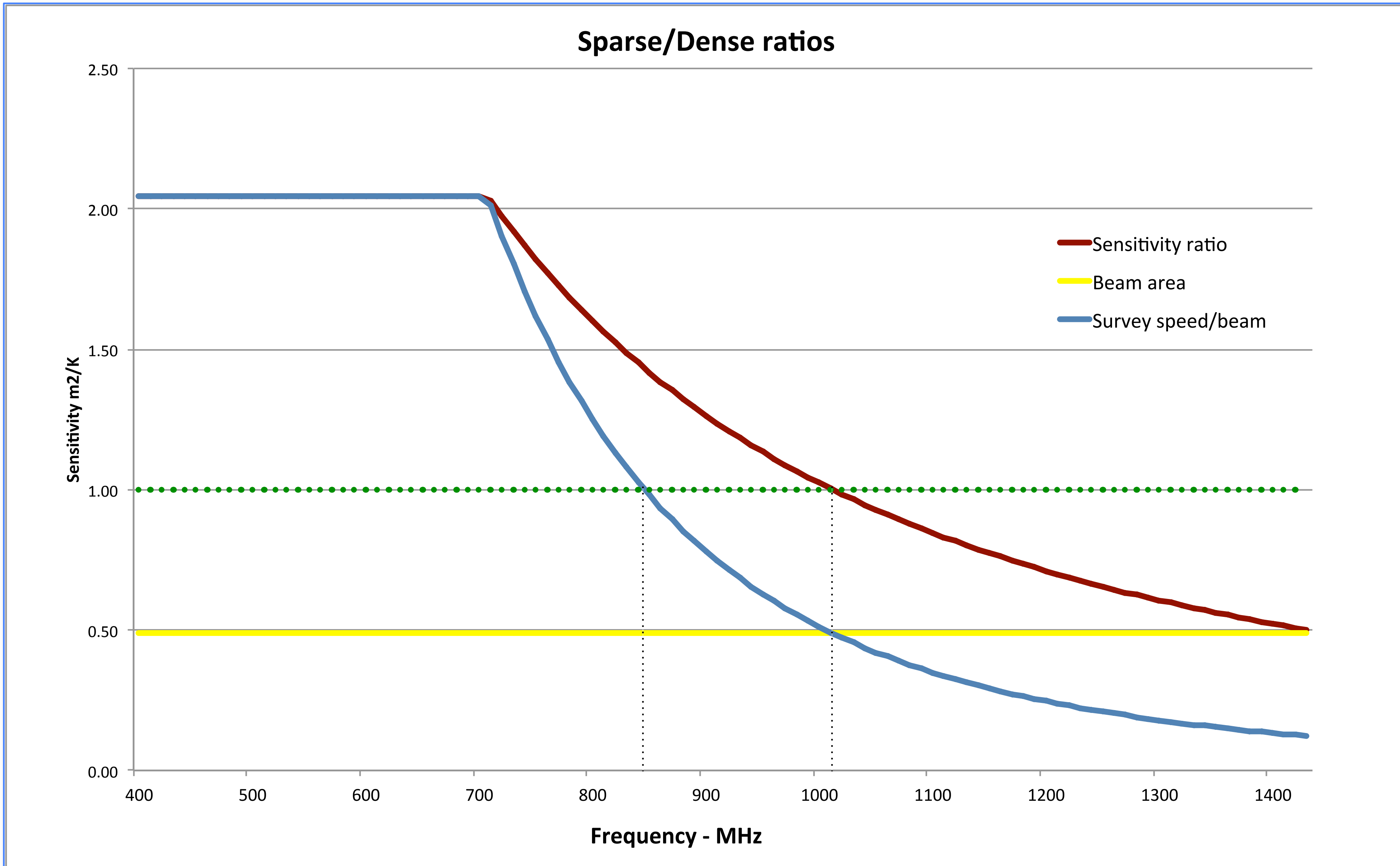
Charts - sensitivity



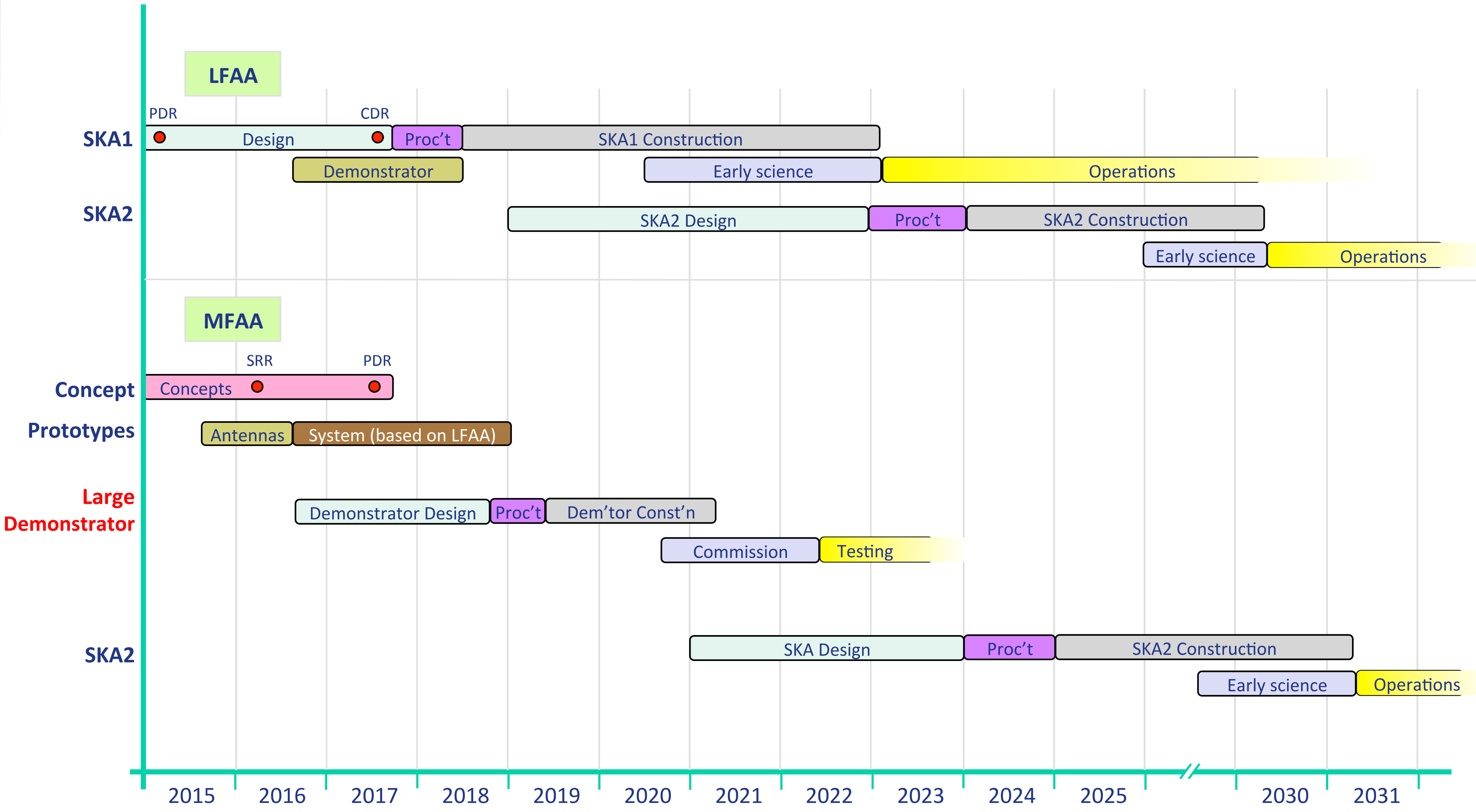
Charts - sensitivity



Charts - ratios



Timeline…



LFAA
SKA1
PDR
Design
CDR
Proc't
SKA1 Construction
Demonstrator
Early science
Operations
SKA2
SKA2 Design
Proc't
SKA2 Construction
Early science
Operations
MFAA
Concept
Concepts
SRR
PDR
Prototypes
Antennas
System (based on LFAA)
Large Demonstrator
Demonstrator Design
Proc't
Dem'tor Const'n
Commission
Testing
SKA2
SKA Design
Proc't
SKA2 Construction
Early science
Operations
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2030
2031

Some estimates for sparse…

Quantities		Power			Cost	
			Each	Total	Each	Total
2^{23} Antennas	2^{13} Ant/station	Antennas	1 W	8 MW	€30	€240M
2^{16} TPMs	2^{10} Station proc.	TPM	150 W	10 MW	€2500	€160M
2^{10} stations	2^{10} Racks	SPM	1 kW	1 MW	€10,000	€10M
2^{7} Ant./TPM	2^{6} TPMs/rack	Switches	250 W	0.5 MW	€5000	€10M
2^{5} Fibres/TPM	2^{2} Ant./fibre	Servers	1 kW	1 MW	€5000	€5M
2^{11} Data switches	2^{10} Servers	**Total** (+25% losses)		**25 MW**	(+30% for INFRA etc)	**€550M**

The finest receptor system ever….

All yours for €0.5Bn and ~25MW!