MFAA System Engineering

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What is AA-mid for?

Survey HI to z ~3

AA-mid

fulfills the *original* concept of

SKA!

MID-FREQUENCY APERTURE ARRAY

Benefits of aperture arrays

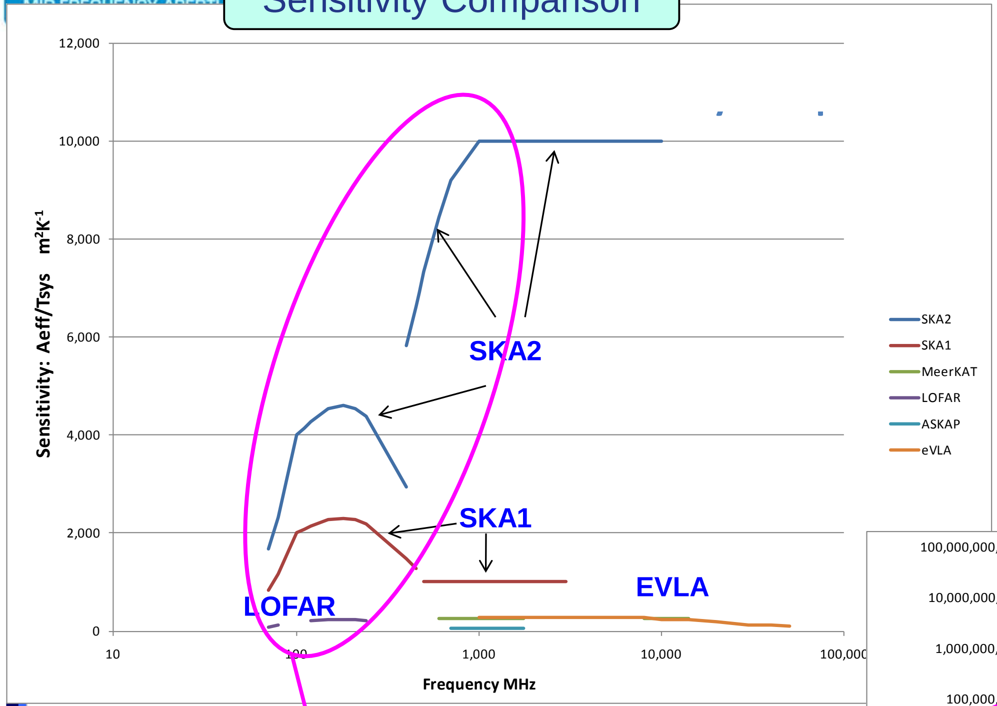
- At lowest frequencies, <~300MHz, the only realistic way of building sufficient collecting area
- Unsurpassed ability to create Field of View through multiple beams
- Extremely flexible in observation parameters e.g. Sky area vs. bandwidth
- Can run multiple experiments concurrently
- Using a large amount of up front processing they mitigate the back-end processing load
- Can tune imaging coverage, beam size, post-processing load etc.

Survey Speed!

Processor based AAs provide new opportunities

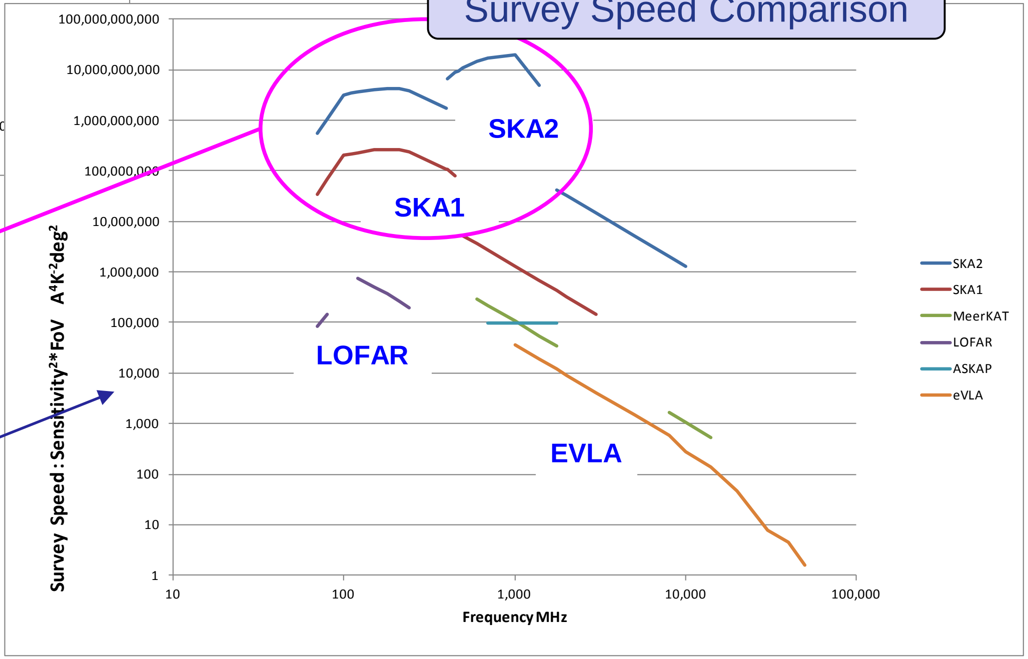
Rough SKA performance comparison

Sensitivity Comparison



SKA$_1$ & SKA$_2$ will have very high sensitivity & survey speeds

Survey Speed Comparison



Aperture Arrays

Note: log scale!

Tough Dynamic Range requirements…

- AA is operating at low frequency **?** Tricky
- Physical stability (wind etc.)
- Unblocked aperture
- Smaller beams are better
- Narrow band is important

- Calibration capability
- Trade DR for sensitivity

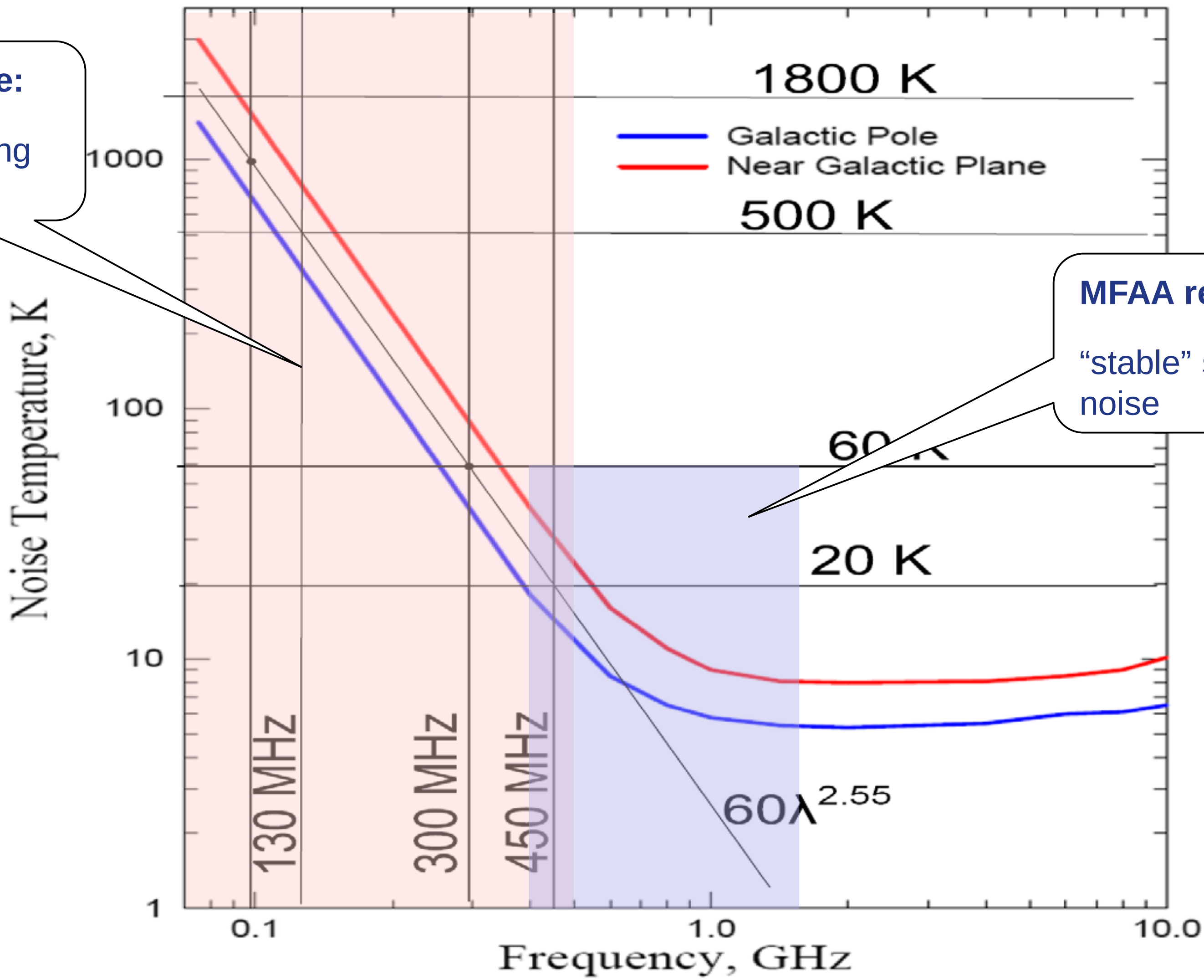
Tough Dynamic Range requirements…

• AA is operating at low frequency	? Tricky
• Physical stability (wind etc.)	✓ Good, study details
• Unblocked aperture	✓Inherent
• Smaller beams are better	✓~56m collectors (AA-mid)
• Narrow band is important	✓AA is Wide Band *but* many channels
• Calibration capability	✓Excellent, by channel
• Trade DR for sensitivity	✓AA v. flexible

Array choice vs. Sky noise

LFAA regime:

High and rising sky noise



MFAA regime:

“stable” sky noise

From:
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Consider a SKADS-SKA....

Freq. Range	Collector	Sensitivity	Number / size	Distribution
70 MHz to 450 MHz	Sparse Aperture array (AA-lo)	4,000 m^2/K at 100 MHz	250 arrays, Diameter 180 m	66% within core 5 km diameter, rest along 5 spiral arms out to 180 km radius
400 MHz to 1.4 GHz	Dense Aperture array (AA-hi)	10,000 m^2/K at 800 MHz	250 arrays, Diameter 56 m	
1.2 GHz to 10 GHz	Dishes with single pixel feed	5,000 m^2/K at 1 GHz	**1,200** dishes Diameter 15 m	50% within core 5 km diameter, 25% between the core and 180 km, 25% between 180 km and **500 km** radius.

Major surveys are <1.4 GHz: below HI line

Is 10,000 m^2/K essential at all frequencies?

AA-mid likely principal specifications

Parameter	AIP: Adv. Inst. Package	SKA Phase 1	SKA Phase 2	Comments
Frequency range	400-1450 MHz	-	400-1450 MHz	Want to get to rest HI line
Max. Instantaneous Bandwidth	~300 MHz	-	1050 MHz	Ability to get full bandwidth
Max scan angle	±45°	-	±45°	Or wider with reduced sensitivity
Field of view	>2 beams	-	200 deg^2	Many beams are used
Sensitivity (@ 800 MHz)		-	10,000 m^2K^{-1}	
T_{sys} @ 1000MHz	<50 K	-	< 50K	Ideally reduced T_{sys} of <40 K for SKA_2
Polarisation separation	Tbd	-	30-40dB	Same as LFAA
Imaging dynamic range *capability*	Tbd	-	74 dB	The capability requirement for high dynamic range is very challenging
Array output data rate	<1 Tb/s	-	16 Tb/s	Data rate defines performance
Array diameter	~15 m	-	56 m	AIP has a number of arrays for test
No. of arrays	TBD	-	250	Or maybe the same as LFAA - 1024
Configuration	Small array	-	66% >5 km	
Max. Sensitive Baseline	~5 km	-	180 km	TBD

Performance questions

- Survey speed requirement as a function of frequency
- Point source sensitivity as a function of frequency
- Polarisation performance
- Scan angle sensitivity as a function of frequency
- Maximum baseline requirements

Opportunity Questions

- Ability to have transient buffers
- Independence of stations (e.g. ability to “watch” pulsars continuously)
- Alternative post processing algorithms

LFAA knowledge *(will be useful!)*…

- Design of a very large array
- Performance capabilities of a (very) sparse array
- Station beamforming techniques
- Use of a flexible data network for signal transmission and steering
- RFoF analogue transmission capabilities
- Calibration techniques
- Defining alternative station sizes, apodisation approaches etc.

Some SKA AA-mid challenges.....

Highest frequency, ideally:	1,450 MHz
Close spaced elements (if dense):	~15cm pitch
Low T_{sys} at ambient temperature:	≤40K

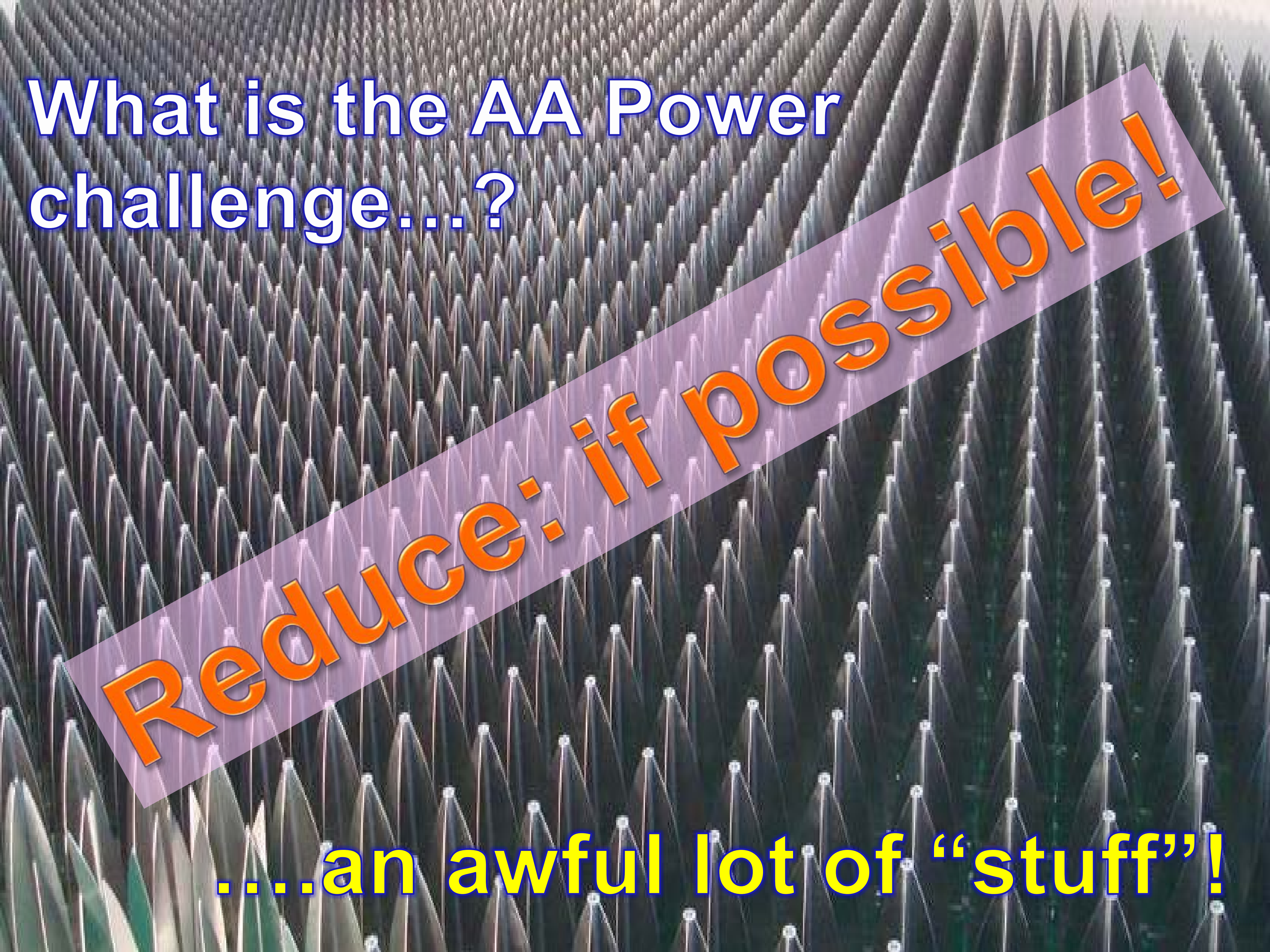
Very large number of components

Constraining **power** and cost

Manufacturability and reliability

Calibration…

Constant antenna pitch across a station


What is the AA Power challenge…?
Reduce: if possible!
….an awful lot of "stuff"!

AA-mid technology trends

- **High volume IT system:** mass manufacture is understood
- Processing is getting cheaper, it is **~10years** before deployment
- Exascale developments are of direct benefit to MFAA:
  - Processing architectures
  - Power
  - Internal communication networks
  - Integration
- Digital always overtakes analogue for size/cost/performance eventually
- Communications gets faster for cost/power with time

Major benefits for MFAA

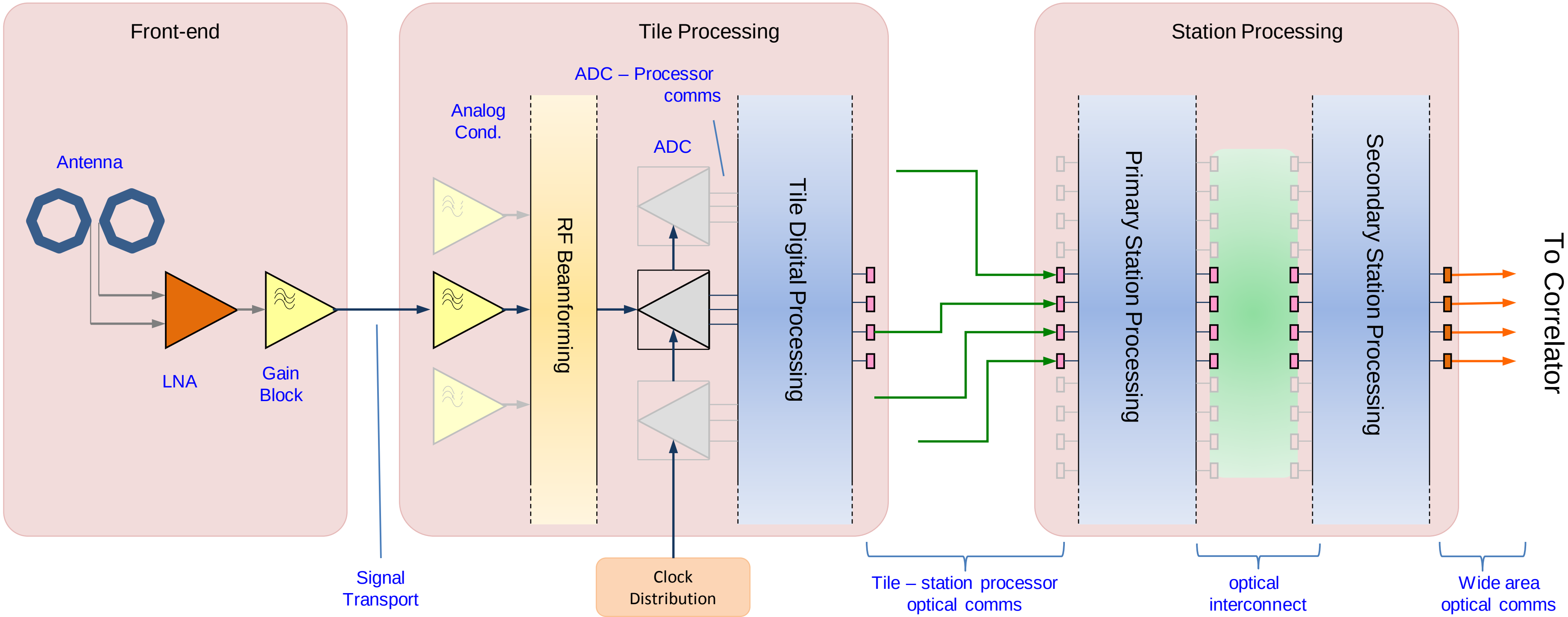
AA-mid paradigms to challenge...

For example:

- Science :
  - How can the sensitivity/survey speed vary with frequency?
  - Trade-off beams and sensitivity for survey speed

- Technology
  - Could the array be random, sparse…?
  - Why can't we have 5:1, 7:1 or more frequency range?

Generic AA-mid signal path

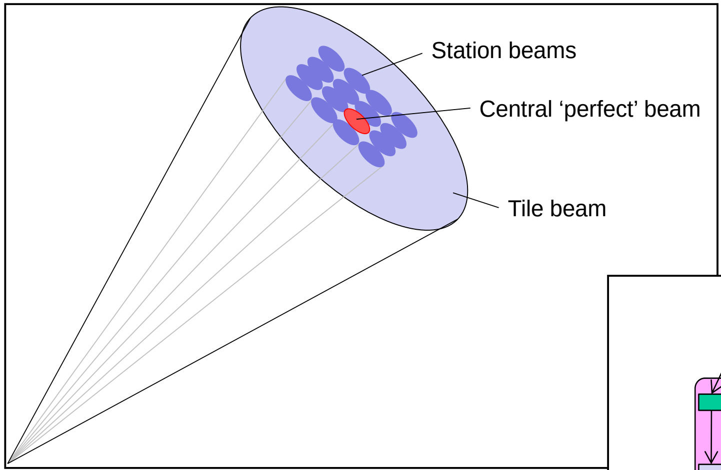


Antenna design, Dense/sparse?	How much, if any, RF Beamforming?	Tile processing Location and scale	Complexity of Station processing?

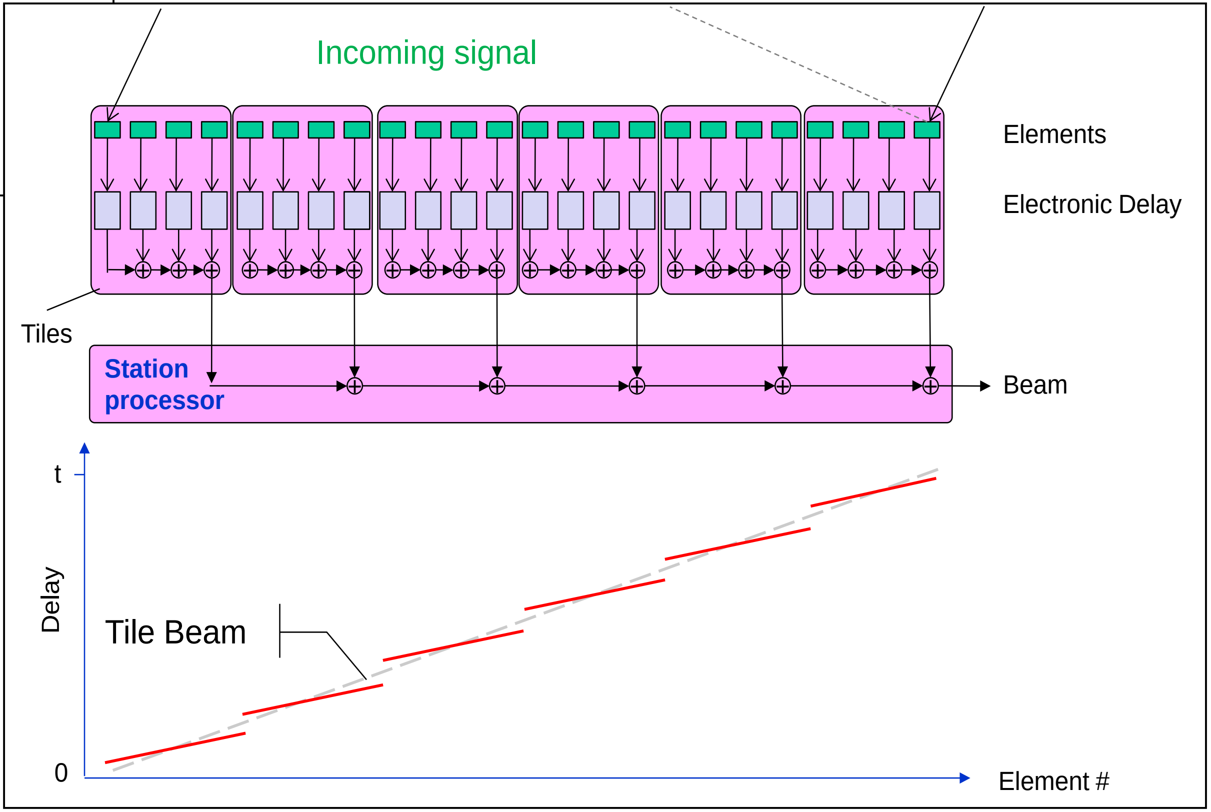
1st stage Beamforming technology

Tech.	Technique	Benefits	Disadvantages	Comments
Analogue		Cheap – at present	Each beam has own hardware Limited calibration ability Stability over time & temp	Analogue systems require more hardware for more performance
	Phase shift	Integrated on chip	Limited bandwidth	Useful technology today and in AAVS1
	True time delay	Full bandwidth	Large, hard to integrate. Harder for low freq.	There are early trials of integrated TTD
Digital		Very flexible Can create many beams	Power and cost high?	Digital better and cheaper over time.
	Frequency Domain	Excise some RFI immediately Good calibration and flatten bandpass Can extract just the desired bands	Requires digitisation and processing resources.	Very flexible, requires Poly Phase filter per channel which is expensive. More FoV is cheap
	Time domain	Time resolution Reduced processing load	No RFI excision Harder to calibrate Interpolation precision	No PFF per channel, but keeps full bandwidth for B/F

Two stage beamforming



Filling "Tile beams" with station beams leads to discontinuities in the beamforming for off-centre beams



Can be resolved with higher data rate Tile to station processor

Station processing

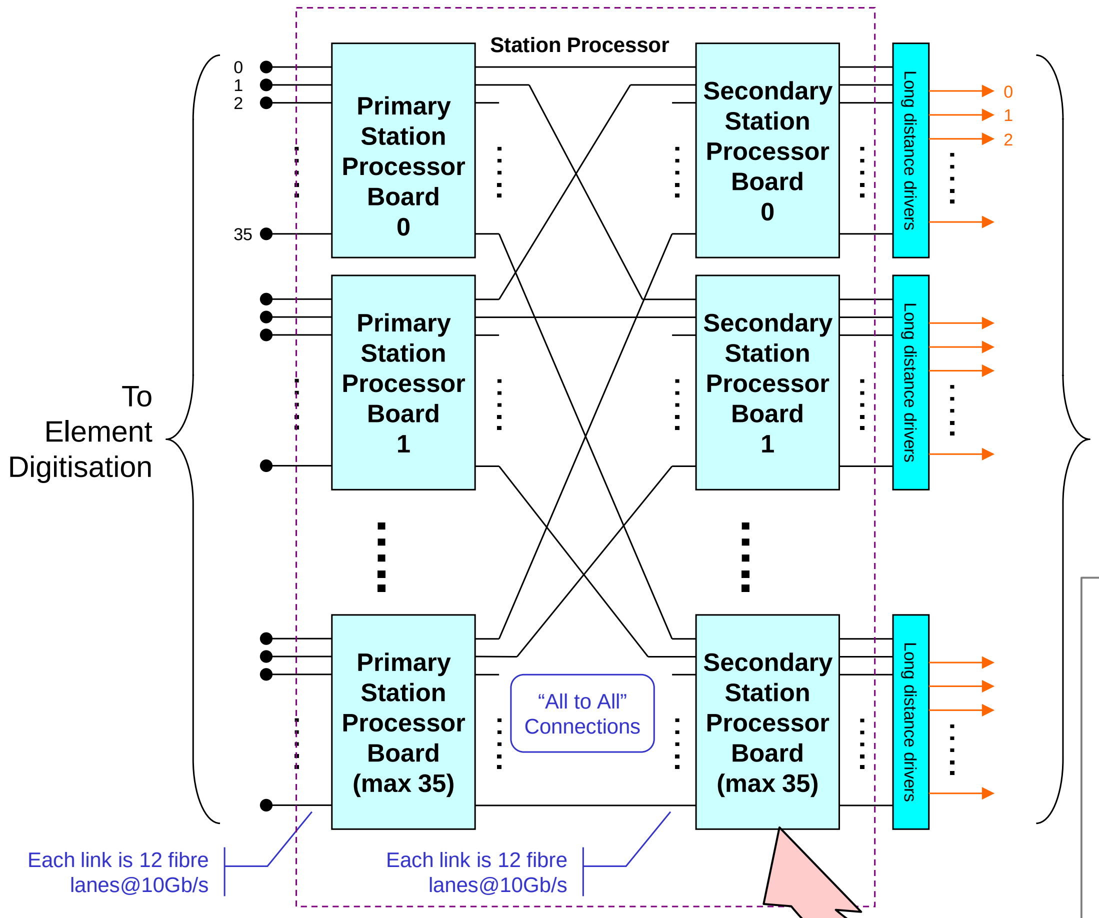
Similar for AA-low and AA-mid:

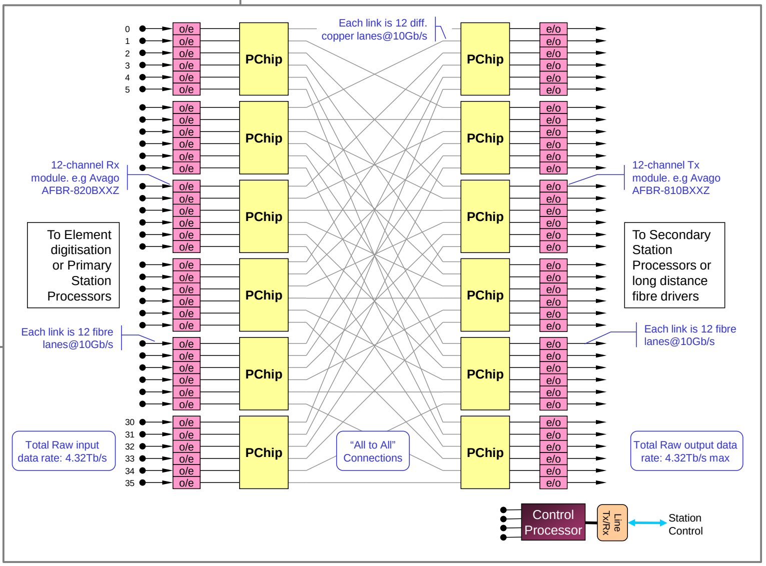
- Station level beamforming on all the tiles
- Distributes the clock information for all the tiles
- Station calibration calculations and corrections (using the tile processors)
- Transmits observation beams to the correlator
- Station monitoring and control functions

Station processor

Requirements:

- High bandwidth in
- **High bandwidth out**
- Largely cross connected
- Scaleable at various levels
- Programmable beamforming





Output data rate & array performance

- The output data rate defines the performance of the array
- A better measure than "beams" since it considers flexible use of data between bandwidth and direction.
- Front end analogue beamforming restricts areas of sky that can be observed concurrently
- Changing the number of bits/sample for different observation types maximises performance
- Not a problem for the correlator which only "sees" total data rate
- Post-processor needs to interpret blocks of data

Build flexibility into Station processing

Finally….

AA-mid is **THE** most exciting instrument in SKA2!

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

We have the opportunity to realise a great design