SKA AA High Level System Description

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High level description

- Overview of AA designs for SKA_1 and SKA_2
- System view consistent with SKA_1 and SKA_2
- These are concept designs and reasons for choices
- Potential designs – not formed in concrete
- Considers technical flow-down from sub-system dev.
- Highlights some likely issues

This is a discussion on AA Station designs

Why aperture arrays?

- At lowest frequencies, <~300MHz, the only way of building sufficient collecting area
- Unsurpassed ability to create Field of View through multiple beams
- Extremely flexible in observational 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.

Processor based AAs provide new opportunities

Dynamic Range requirements

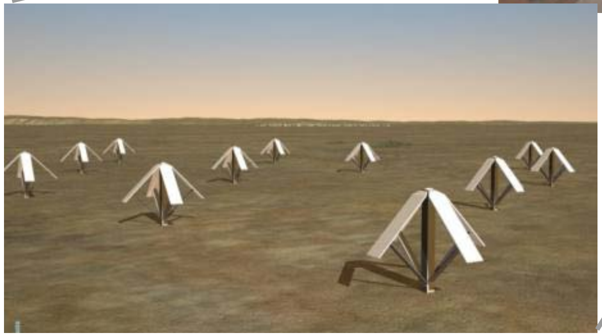
• AA is operating at low frequency	? Tricky
• Physical stability (wind etc.)	✓ Good, study details
• Unblocked aperture	✓Inherent
• Smaller beams are better	✓~56m collectors (AA-mid)
• Narrow band is important	✓AA is Wide Band *but* many channels
• Calibration capability	✓Excellent, by channel
• Trade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

SKA$_1$ Receptor Technologies

~300 Dishes

One Core reserved for SKA$_2$ use.

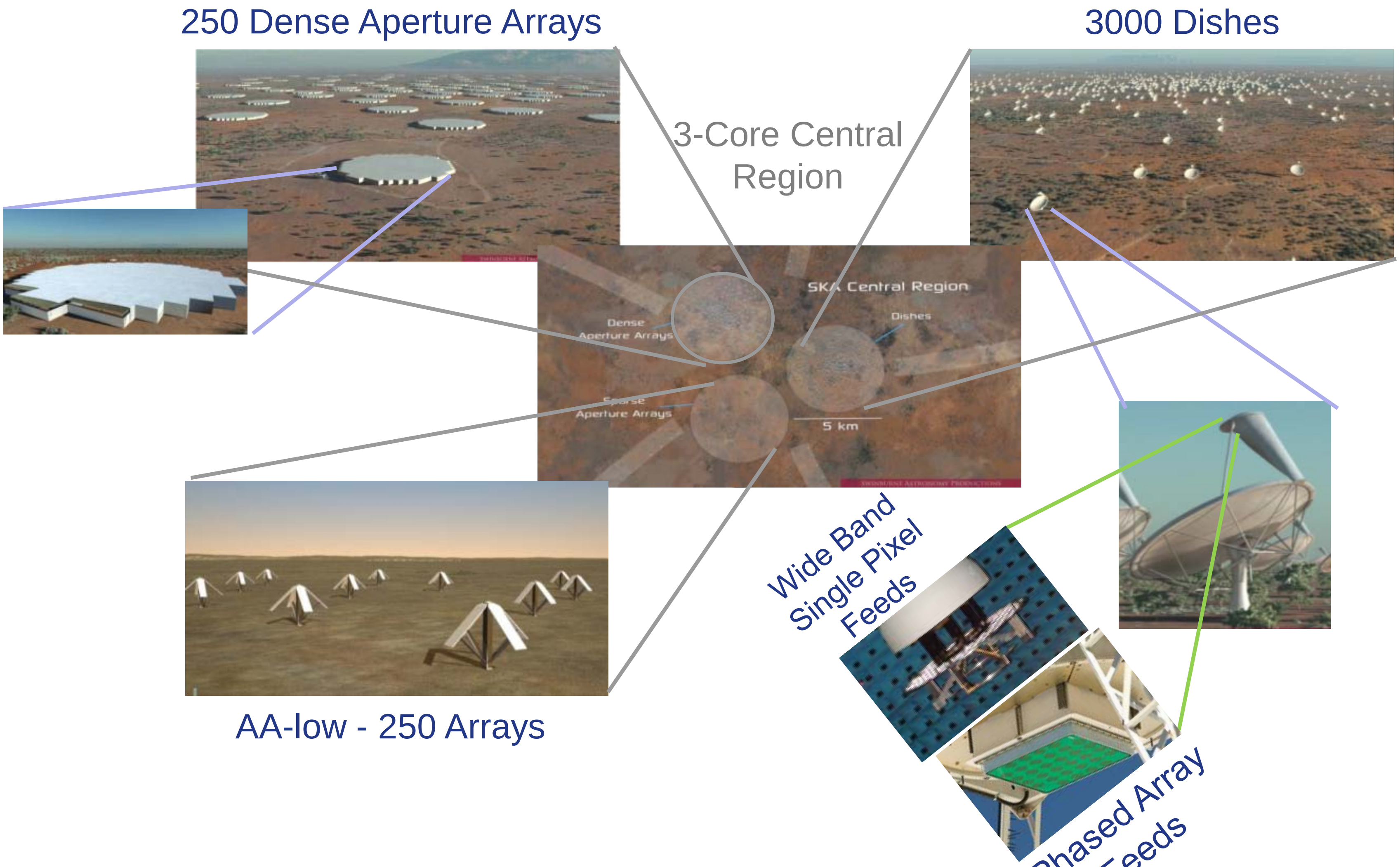
2-Core Central Region



AA-low - 50 arrays

Artists' Renditions from Swinburne Astronomy Productions

SKA$_2$ including AIP technologies



Artist renditions from Swinburne Astronomy Productions

An SKA collector summary

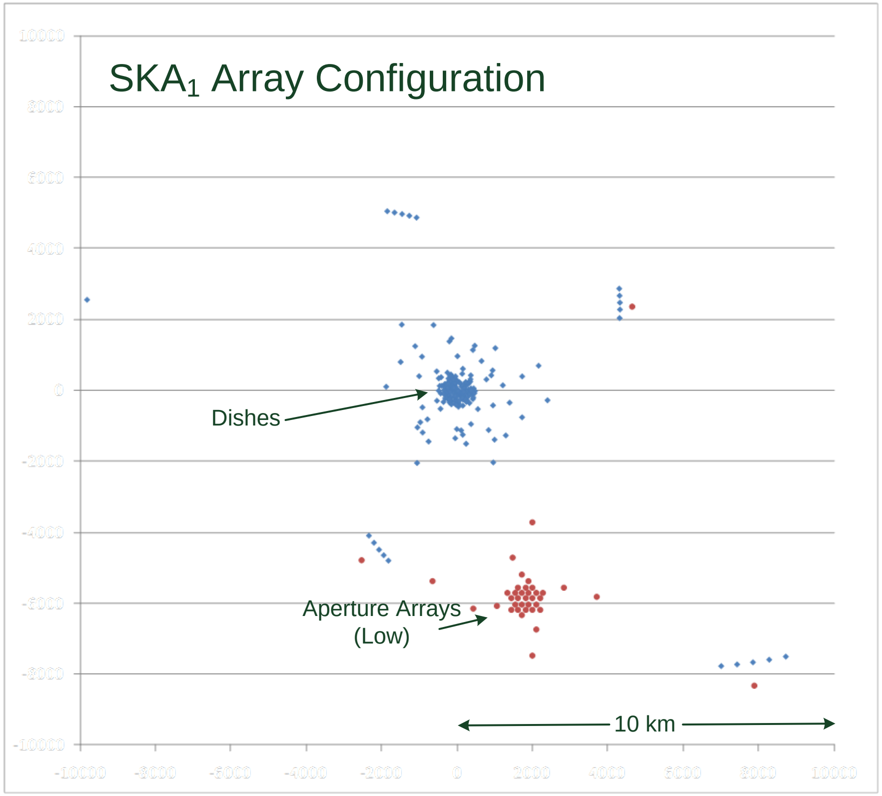
SKA_1

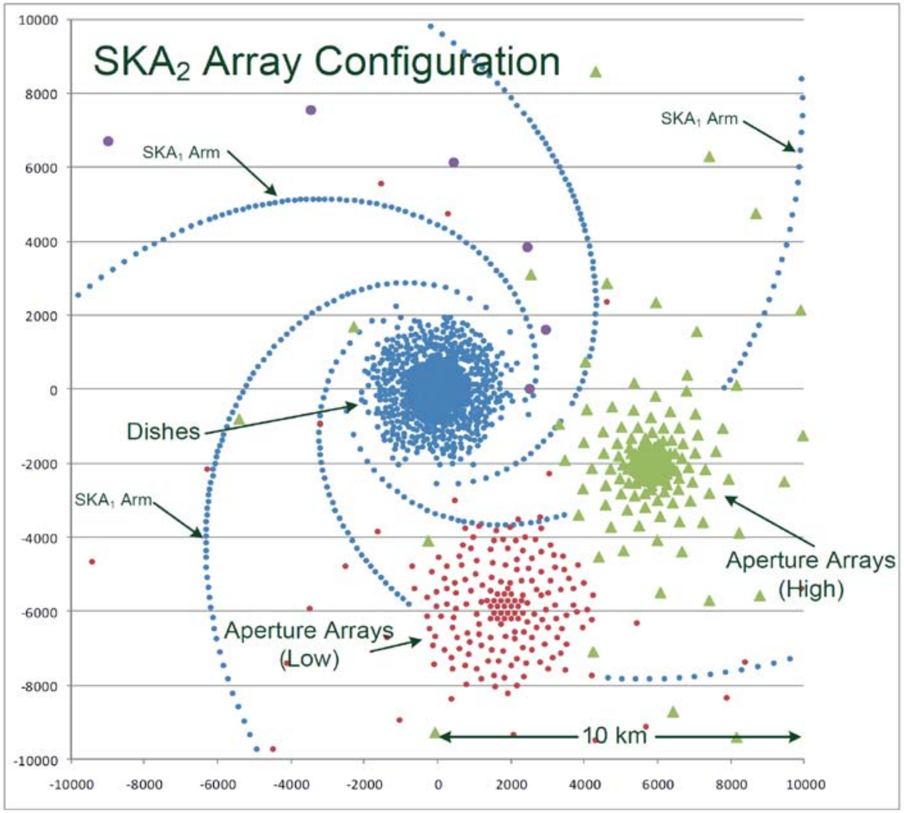
Freq. Range	Collector	Sensitivity	Number / size	Distribution
70 MHz to 450 MHz	**AA-low** Sparse AA	1,000 m^2/K at 100 MHz	50 arrays, Diameter 180 m	70% within 5 km dia., 30 % along 3 spiral arms out to 100 km radius
300 MHz to 3 GHz	Dishes with single pixel feed	1,000 m^2/K at 1.4 GHz	250 dishes Diameter 15 m	

SKA_2

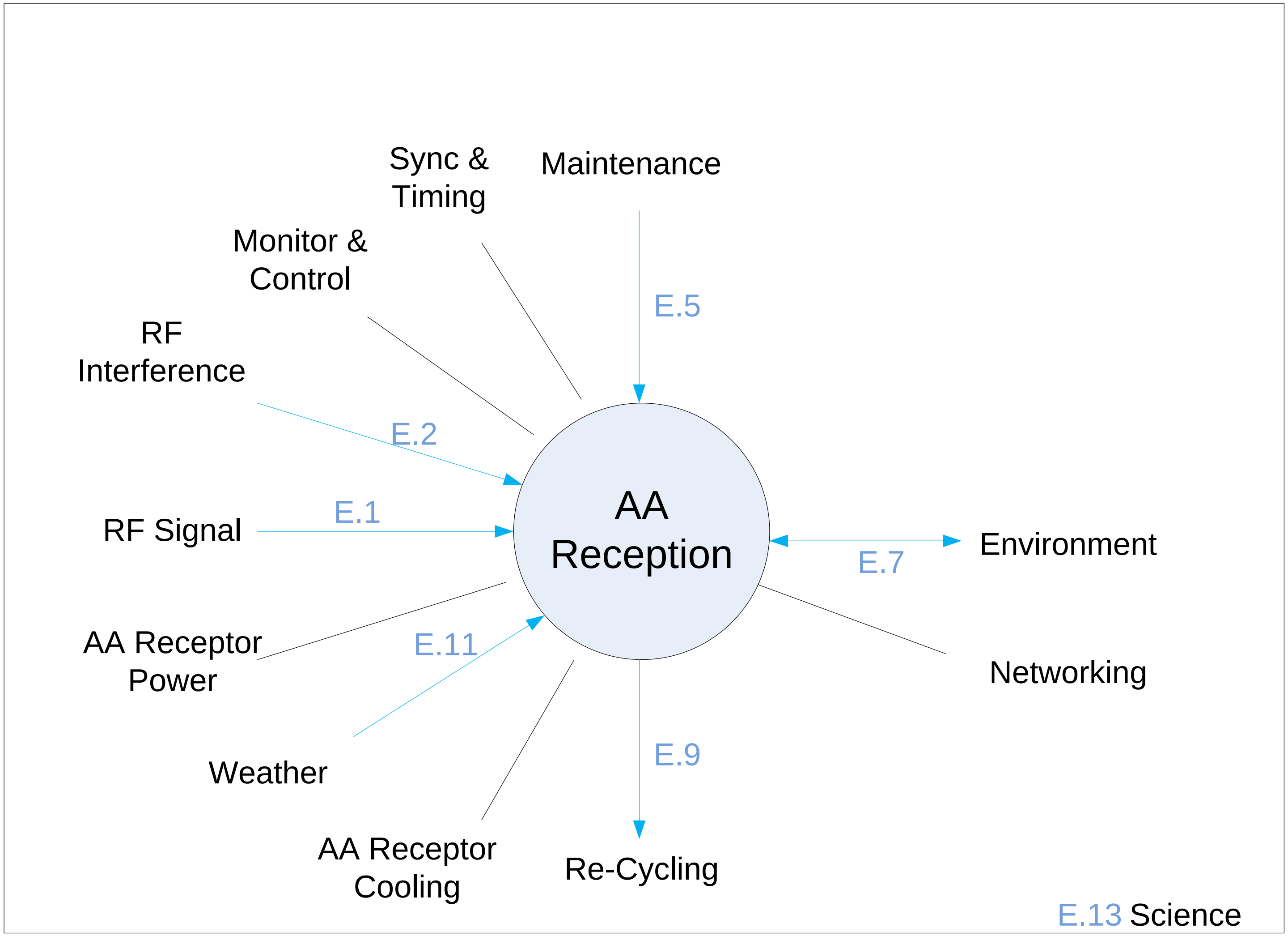
Freq. Range	Collector	Sensitivity	Number / size	Distribution
70 MHz to 450 MHz	**AA-low** Sparse AA	4,000 m^2/K at 100 MHz	250 arrays, Diameter 180 m	66% within 5 km dia., 34% along 5 spiral arms out to 180 km radius
400 MHz to 1.45 GHz	**AA-mid** Dense AA	10,000 m^2/K at 800 MHz	250 arrays, Diameter 56 m	
300/1000 MHz to 10 GHz	Dishes with single pixel feed + PAF	10,000 m^2/K at 1.4 GHz	2000 – 3000 dishes Diameter 15 m	50% within 5 km dia, 30% 5km - 180 km 20% 180 km-3,000 km.

SKA configurations





AA context diagram



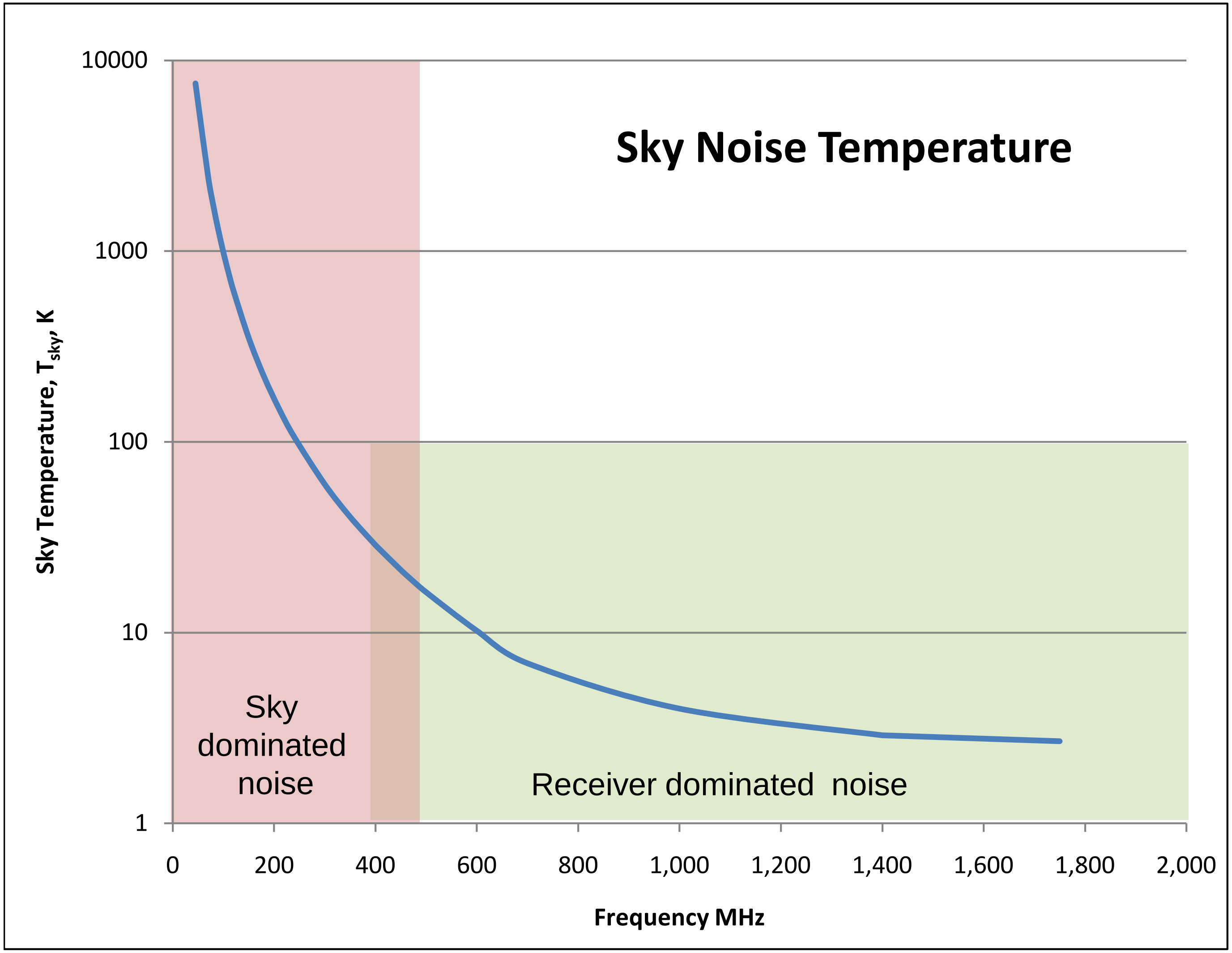
AA-low principal specifications

Parameter	AIP: Advanced Inst. Package	SKA Phase 1	SKA Phase 2	Comments
Frequency range	-	70 – 450 MHz	70 – 450 MHz	
Max. Instantaneous Bandwidth	-	380 MHz	380 MHz	
Nyquist frequency	-	~100 MHz	~100 MHz	λ/2 antenna spacing (min.)
Max scan angle	-	±45°	±45°	
Field of view	-	20 deg^2	200 deg^2	Defined by output data rate
Sensitivity (@ 100 MHz)	-	>1000 m^2K^{-1}	$10^4 m^2K^{-1}$	Total system sensitivity. Target of 2000 m^2K^{-1} for SKA_1
T_{sys} @ 100MHz	-	1100 K	1100 K	T_{sky} 1000K, T_{rec} 100K
Polarisation	-	Tbd	Tbd	After calibration
Imaging dynamic range *capability*	-	Tbd	74 dB	
Array output data rate	-	1 Tb/s	16 Tb/s	
Array diameter	-	180m	180m	
No. of arrays	-	50	250	
Configuration	-	70% >5 km	66% >5 km	
Max. Sensitive Baseline	-	100 km	180 km	Core to furthest station

AA-mid principal specifications

Parameter	AIP: Adv. Inst. Package	SKA Phase 1	SKA Phase 2	Comments
Frequency range	400-1450 MHz	-	400-1450 MHz	
Max. Instantaneous Bandwidth	>500 MHz	-	1050 MHz	
Nyquist frequency	1000 MHz	-	1000 MHz	Defines dense-sparse antenna array transition
Max scan angle	±45°	-	±45°	
Field of view	>2 beams	-	200 deg^2	
Sensitivity (@ 1000 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	-	Tbd	
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	
Array diameter	~15 m	-	56 m	AIP has a number of arrays for test
No. of arrays	12-16	-	250	
Configuration	Small array	-	66% >5 km	
Max. Sensitive Baseline	~5 km	-	180 km	AIP baseline TBD

Sparse and Dense regimes



Sparse or Dense….

Dense:

Element spacing ≤ λ/2	**Constant A_{eff}**
Fully sampled wavefront	Excellent side lobe control
Regular layout pattern	Beam performance equiv to the best dish design

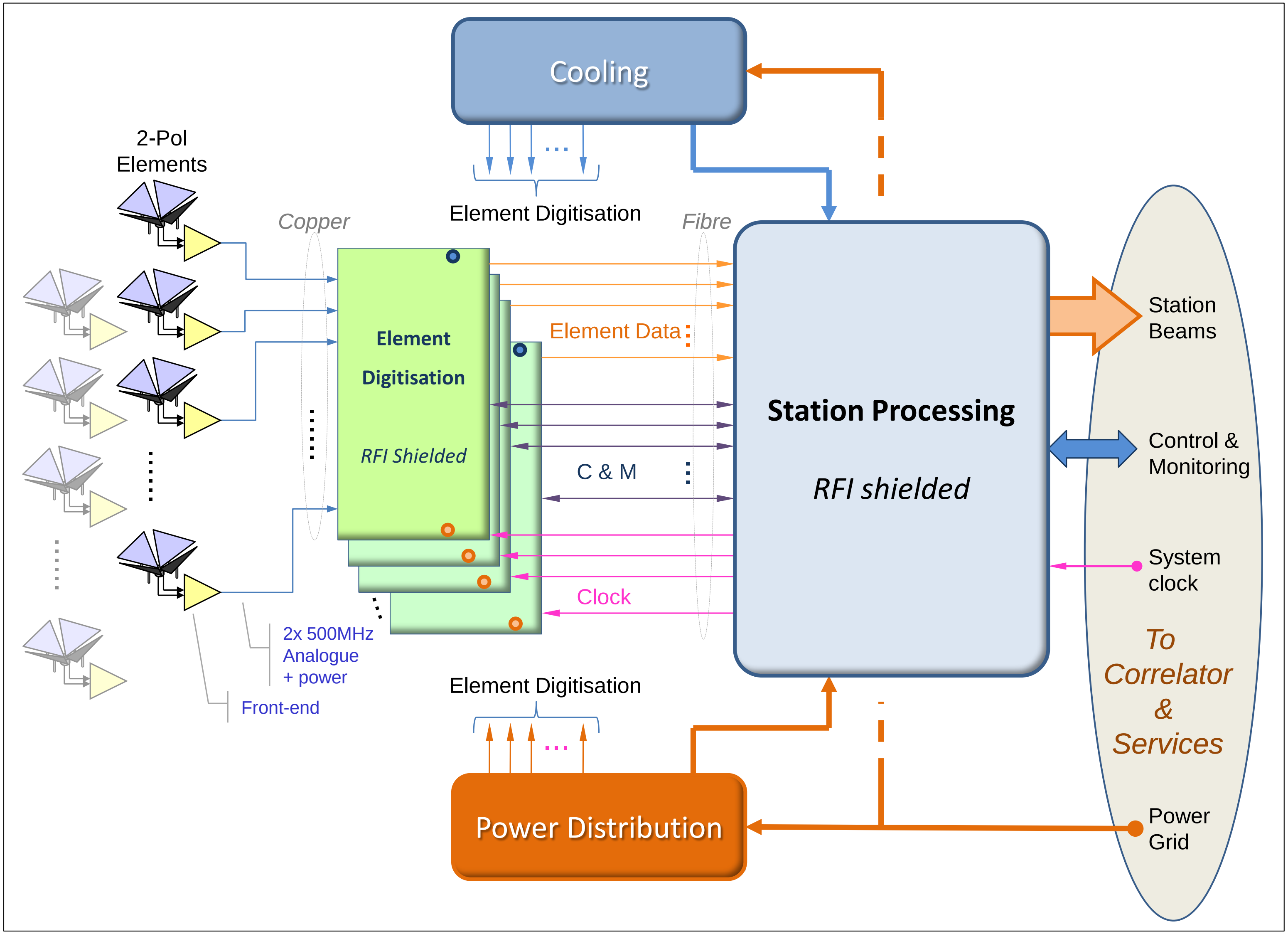
Sparse:

Element spacing >λ/2	**A_{eff} increases as λ^2** (~ $\lambda^2/4$)
Layout irregular to control grating lobes	Increased skynoise from grating lobes
	Possible dynamic range issues

Array trade offs

		Regular	Irregular
	Sidelobes	Lowered by gain taper	Lowered by space taper
Dense	Grating lobes	No	
	Receiver temp	Lower, smooth (angle, freq)	
	Effective area	Constant over frequency, smooth over angle	
	Element patterns	Depend on position	
	Field of View	Large	
Sparse	Grating lobes	Few high ones	Many low ones
	Receiver temp	Higher, not smooth (angle, freq)	Higher, smooth (angle, freq)
	Effective area	Steep decrease with wavelength Not smooth (angle, freq)	Steep decrease with wavelength Smooth (angle, freq)
	Element patterns	Constant for most elements	Depend on position
	Field of View	Smaller	

An AA-low station layout



Some SKA AA-low challenges.....

Frequency range: 70-450 MHz or 6.4:1

Filling factor -

assuming dense ≤100MHz: 100% - 5%

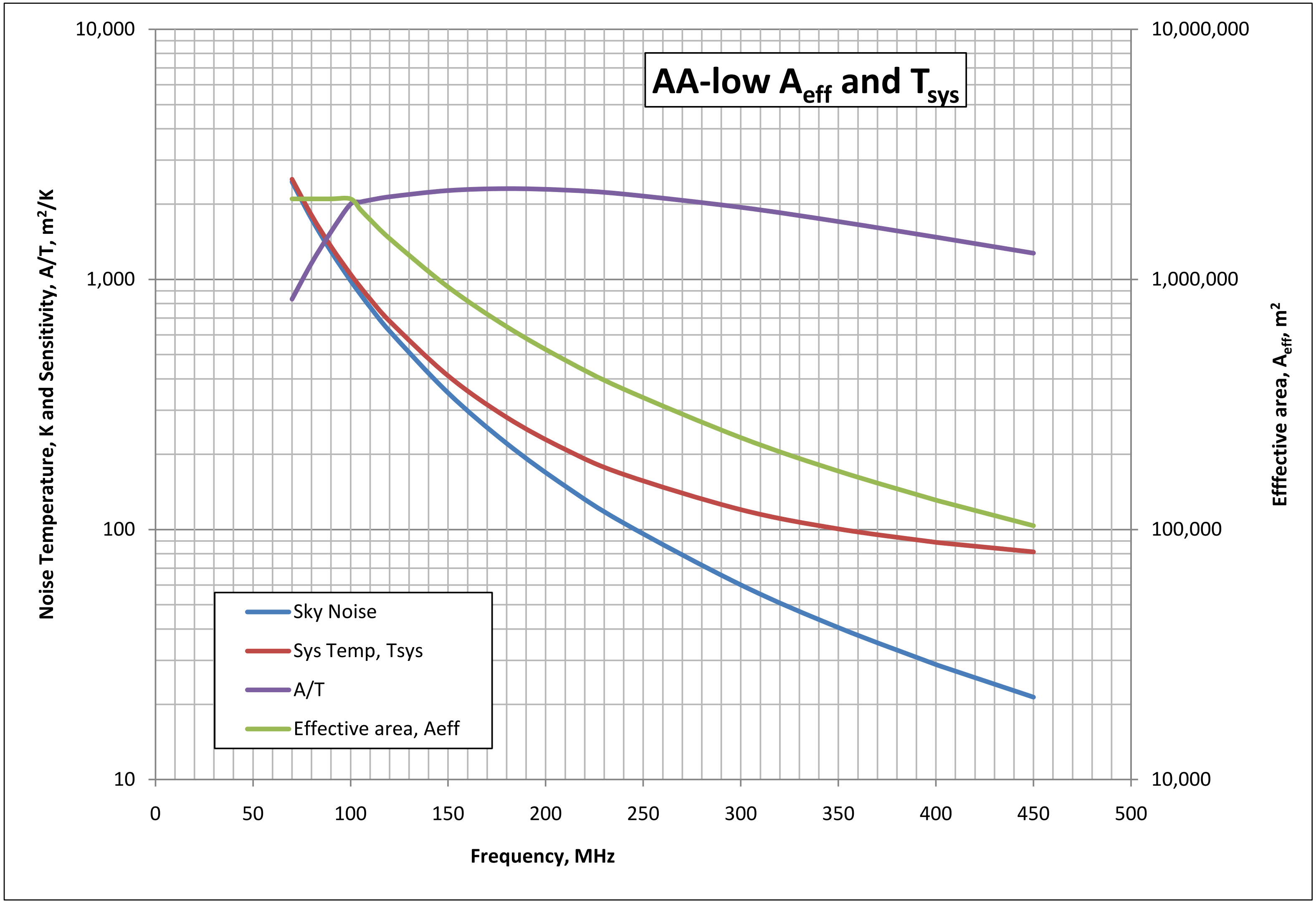
Low grating lobes, avoid sky “hotspots”

Ability to fill the core with flexible arrays

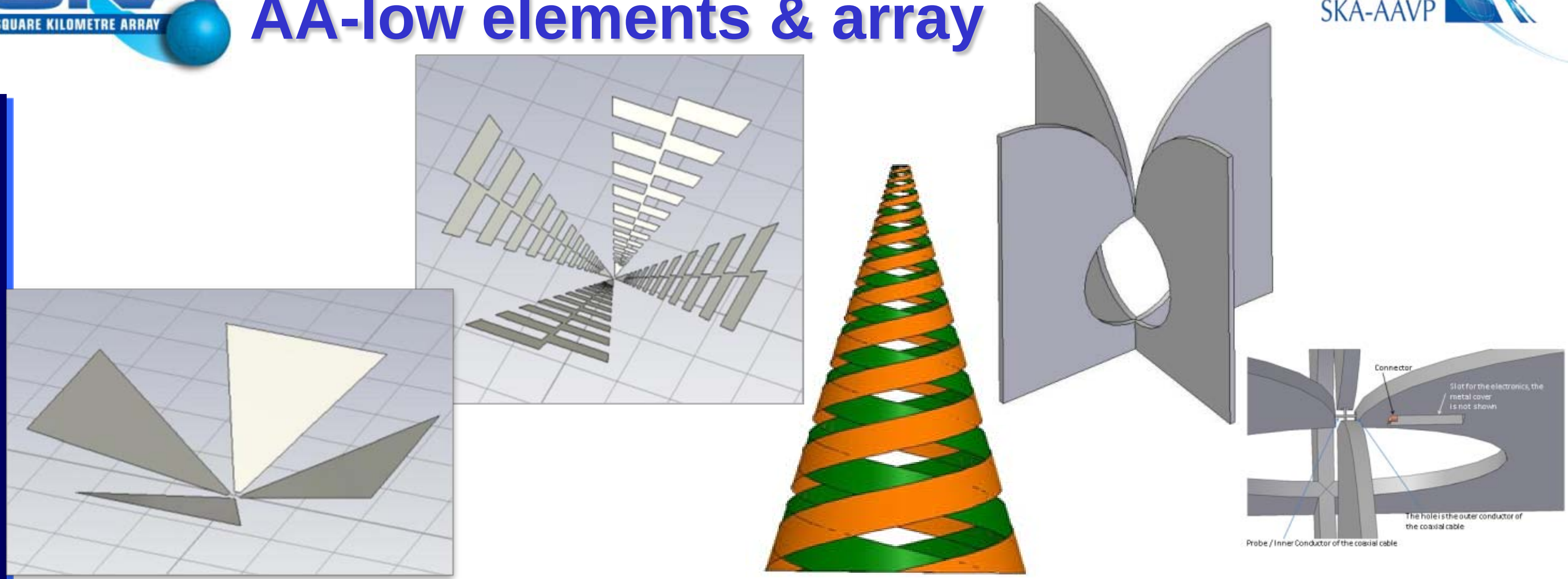
Calibration capable of reaching 70dB

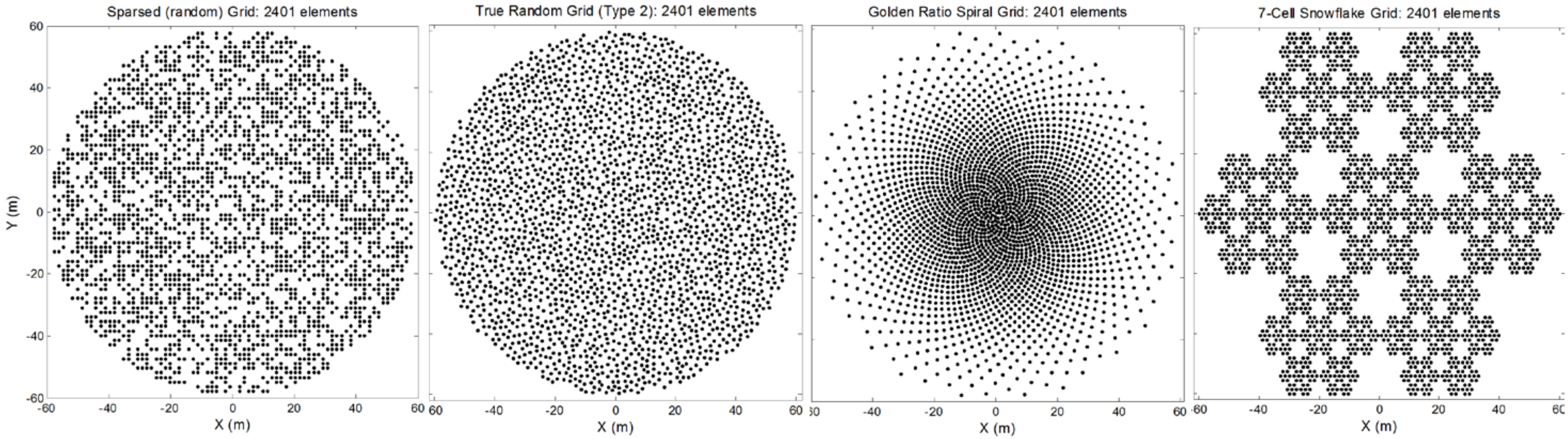
Easy deployment of elements

Simple variation of A/T with frequency



AA-low elements & array





Array design trade-offs

- Individual elements or Tiles of elements
  - More flexible design with standalone elements
  - Tiles: less work on site, transport costs may be increased
- More randomisation
  - Sidelobes/Grating lobes and system temperature may be reduced
  - Best with individual elements, rather than tiles of elements
  - Beamforming more difficult
  - Likely to be more expensive
- Totally random
  - Tessellating the stations – core design
  - Potential for selecting station size in the core

See Jan Geralt’s talk....

Single or dual?

Characteristic	1. Single element	2. Dual: separate arrays	3. Dual: shared arrays
Element – LNA matching	Difficult due to wide frequency range	Easier due to two narrower frequency ranges	As 2.
Filling factor, station	Reducing filling factor at high frequencies.	Each array has lower frequency range, increased the FF is at high frequencies.	As 2.
Filling factor, core	The core filling factor will be the same or similar to a station. (see above)	With two AA-low cores, the FF will be the same or similar to the stations at the same frequencies.	The core filling factor is substantially reduced due to there being unused arrays present at any specific frequency.
Land area usage	Minimum. The high frequencies are completely integrated in a single array.	Higher due to there being two completely distinct arrays.	Likely to be the same or potentially higher than 2. Could be increased by use of distinct stations in the core.
Beam predictability	All elements are identical at specific frequencies leading to a well predicted beam.	Each frequency has a specific homogenous array, so well predictable beams.	As 2.
Sensitivity over frequency	Determined by the fixed element count and if the array is still in the sparse regime.	The high and low frequency sensitivity is set in two bands dependant on element count.	As 2.
Processing reqts: System	A single array with high bandwidth connections.	The core will consist of two distinct arrays, each handled in a similar way to 1.	Stations will consist of two adjacent arrays probably using one station processing system.
Processing reqts: Spectral filter.	The spectral filter will have to handle the full bandwidth of the array.	More spectral filters due to the increased no. of elements –each only handles the bandwidth of the element.	There are only as many spectral filters as elements in the biggest array. This will probably be similar to 1.
Processing reqts: Specific survey speed.	High survey speeds at high frequencies will be expensive in beamforming &data transport.	The size of the beams is kept higher due to each array minimising the under-sampling of elements.	As 2.
Cost (will need to be reviewed as a system)	Single element may be more expensive than 2 dual elements. One high performance processing system. Only one cabling network. Minimum deployment costs.	There are two network systems, two processing systems. Each may be cheaper than in 1. However, it is likely that the total will be more expensive. Each element should be low cost Deployment costs are high.	The processing system should be cheaper than 1. or 2. but less capable in terms of instantaneous bandwidth. Element costs as 2. Deployment cost is high with two arrays and interconnect.

Single or Dual: Philosophy

Dual: probably too expensive/will get cut to a single array

Single: may not work well over the full band

So:

1. Meet SRS for performance of single element array over crucial science: 70-~200MHz;
2. Maximise performance over 200-450MHz, there is good science;
3. Simulate/measure actual performance achieved at the high frequencies;
4. If not to SRS, then evaluate with scientists to determine if acceptable;
5. If yes: go ahead. If not revert to dual system.

In a cost constrained system, may not meet SRS at all with dual array

Station size

- For a given total A_{eff} the collector cost is **roughly constant**
  - Increasing overhead with many smaller stations
  - Possibly increasing station processor complexity with large arrays
- Total data rate to correlator for a fixed survey speed remains constant whatever number of stations

BUT

- Correlator and central processor demands become more challenging

Station size largely determined by central processing costs

Core Design

Core for SKA_1 AA-low becomes virtually fully filled.

More so for SKA_2.

⇨

Core "stations" are not separated – there is a "sea" of elements

Design options/considerations to be made:

- Non-circular "stations" easier? e.g. Square or hexagonal?
- Maximising the sensitivity from each element:
  - overlapping "stations"?
  - smaller "stations" (how small) with more correlation?
- Apodising element density within areas of the core:
  - Benefit? Save money?

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Implies interconnected "station processing", especially for SKA_2

Correlation goes up as n^2, but incoming data rate is constant

Where to digitise?

	At element	At processor
RFI	Maximised	Minimised
Phase stability	LNA & Filters + Clock distribution	LNA + Filters + Second stage Gain + Cables
Data transport	Digital possibly over fibre	RF over copper
Power	At element or over copper	Over RF cable or at element
Lightning protection	Can be good if link is fibre	Can be challenging if link is copper
Bandpass	Very good	Equalization after transport
Cross talk	Minimised between elements and polarizations	Dependent on screening and design of RF boards

Where to digitise?

	At element	At processor
RFI	Maximised	Minimis[illegible]d
Phase stability	LNA & Filters + Clock distribution	L[illegible] Filters + [illegible]econd stage Gain + C[illegible]bles
Data transport	[illegible]	[illegible]ver copper
Power	[illegible]	[illegible] RF cable or at [illegible]ent
Lightning protection	[illegible]	[illegible]be challenging if [illegible]s copper
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Relatively safe option

Likely to require distributed digitisation around station. (Cable cost and range)

Requires good, stable analogue design

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More stable

Requires: low power, quiet digitisers. Low cost short range optical drivers.

Likely, requires custom chips

No option to upgrade digitisers.

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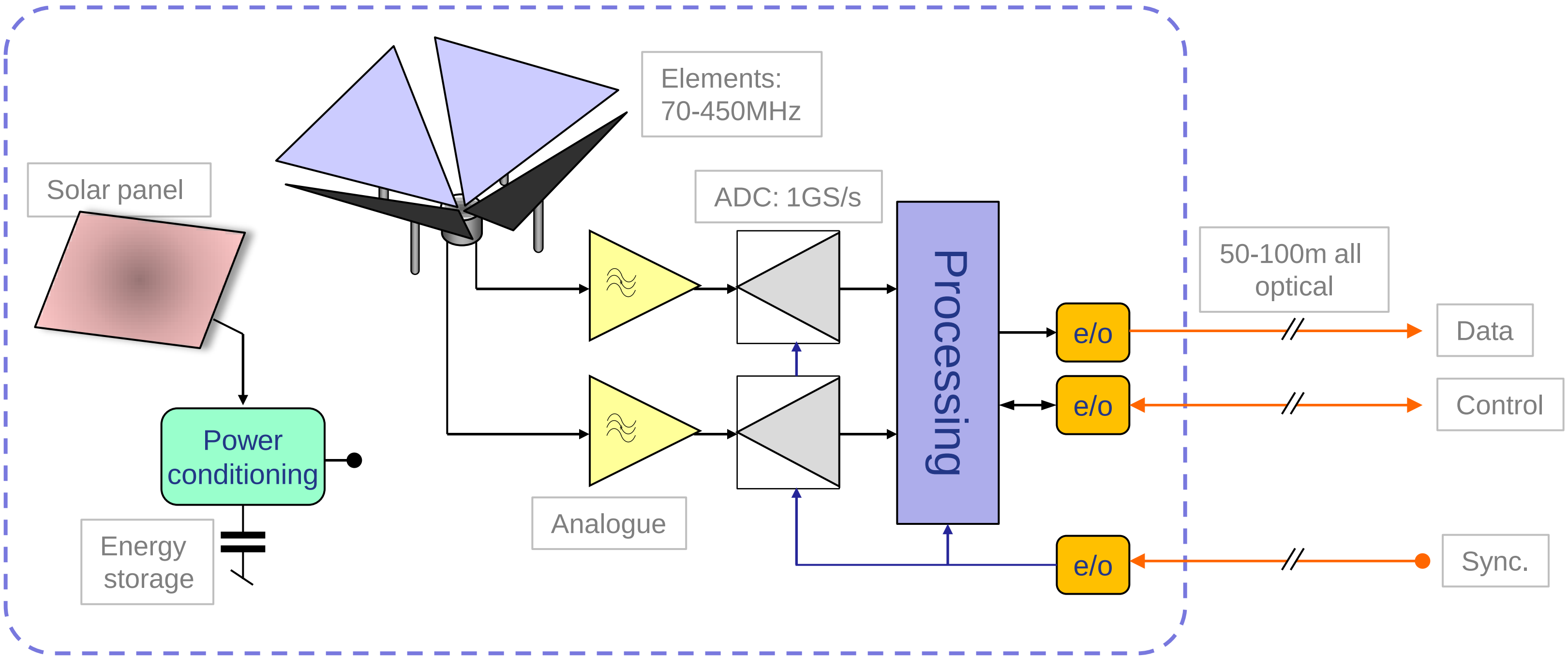
Standalone SKA-low element (option)



Benefits:

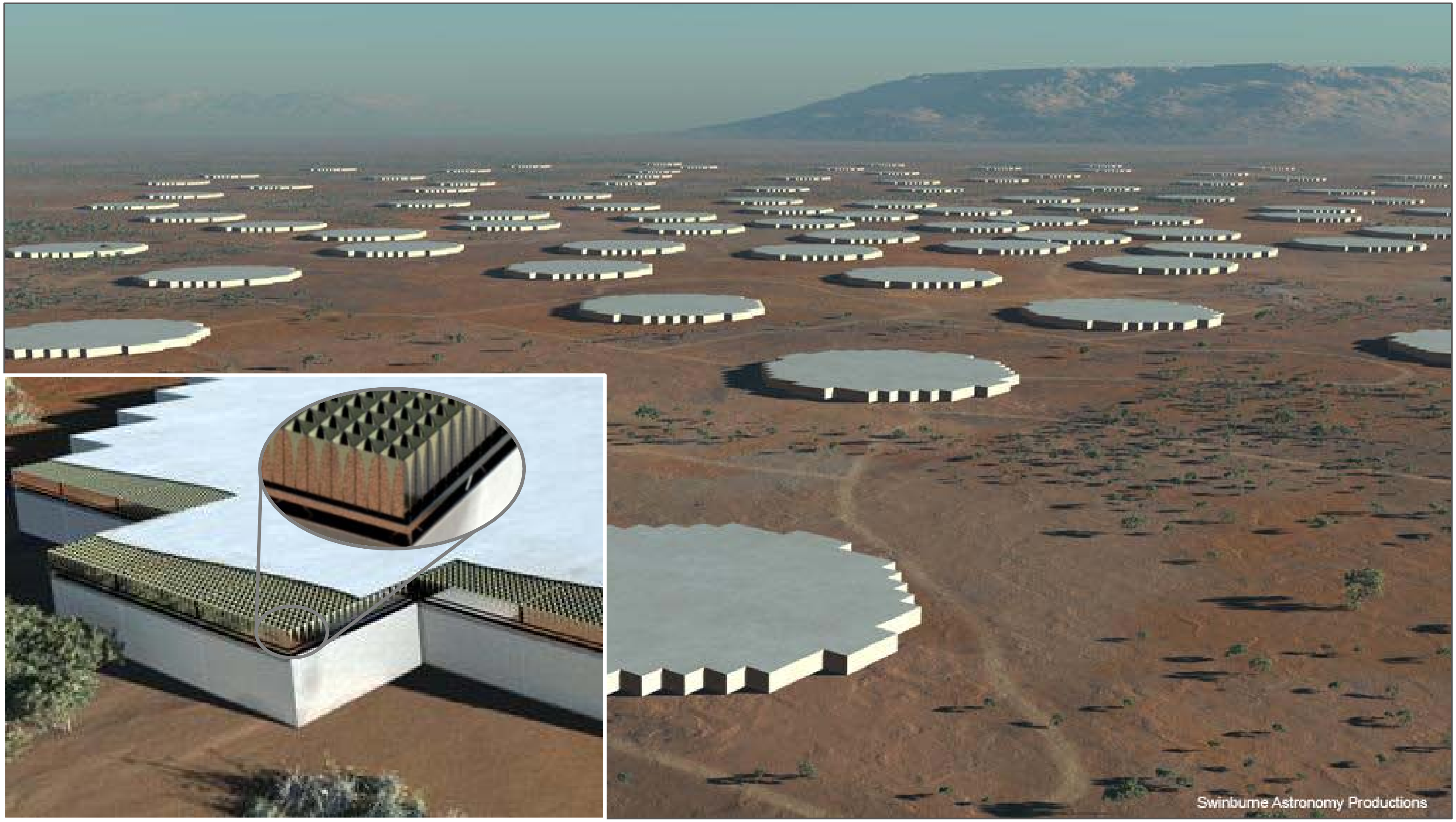
Integrated single unit
No copper connection
Easy to deploy
Minimum RFI
Lightning "immunity"

Challenges:

Low total power
Integration
Manufacturability
Packaging

No need for digitisation boxes

AA-mid Array



Some SKA AA-mid challenges.....

Highest frequency: 1,450 MHz

Close spaced elements: ~15cm pitch

Low T_{sys} at ambient temperature: ≤40K

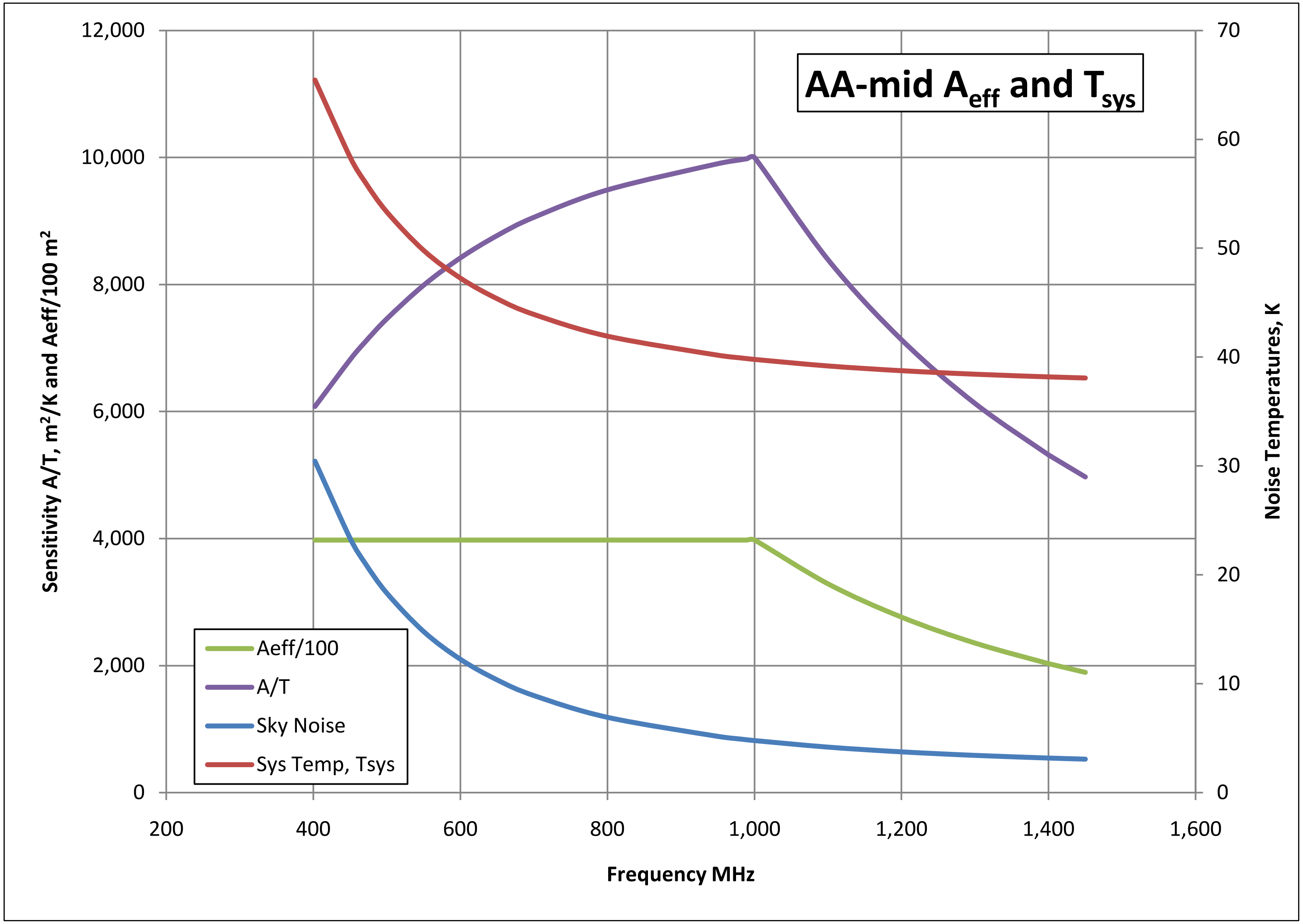
Very large number of components

Constraining power and cost

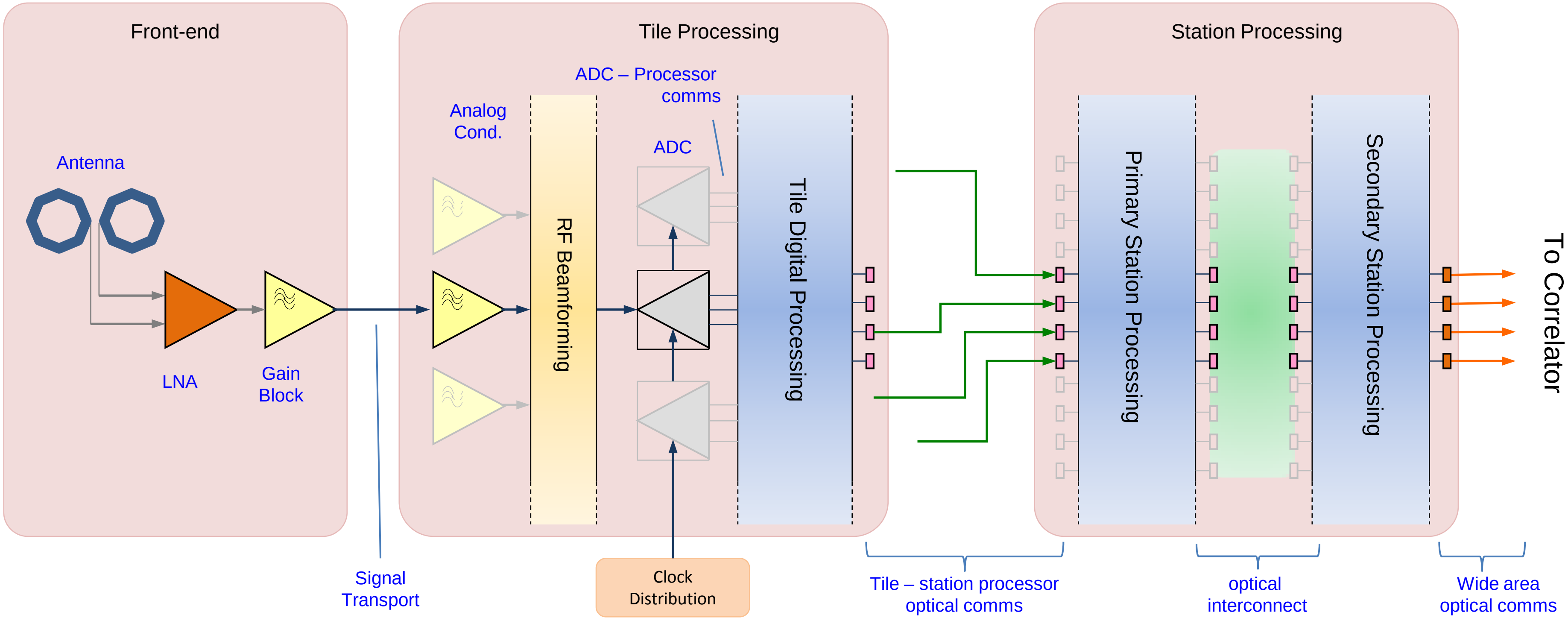
Manufacturability and reliability

Maintaining constant element pitch

Simple AA-mid sensitivity



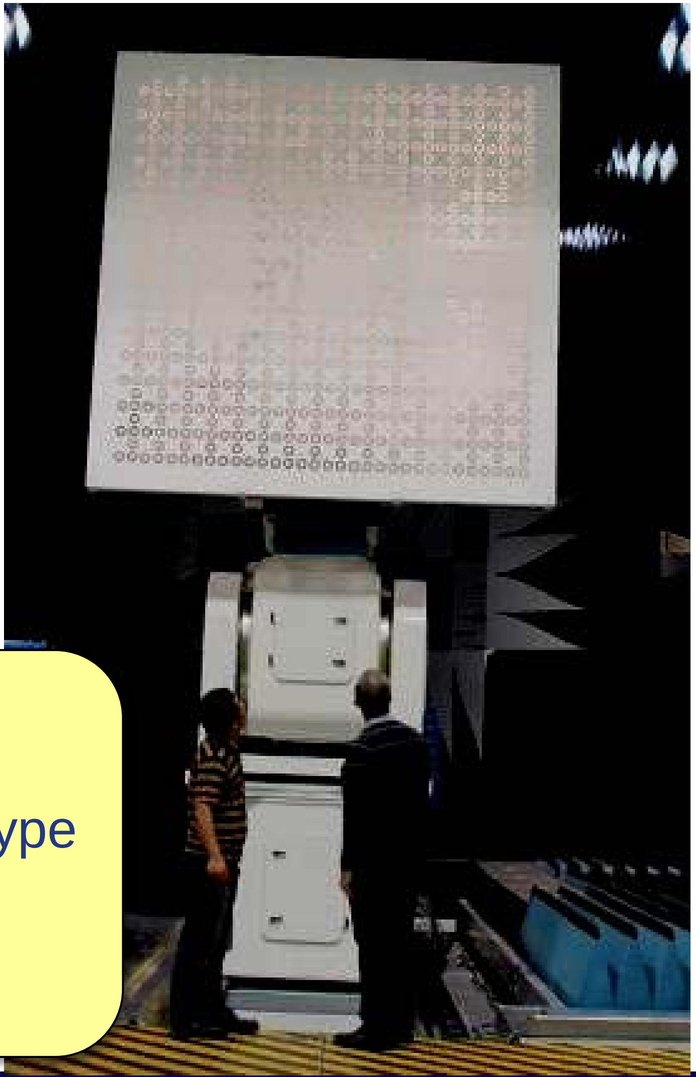
AA-mid signal path



AA-mid elements and array

Vivaldi array - EMBRACE

ORA array - SKADS



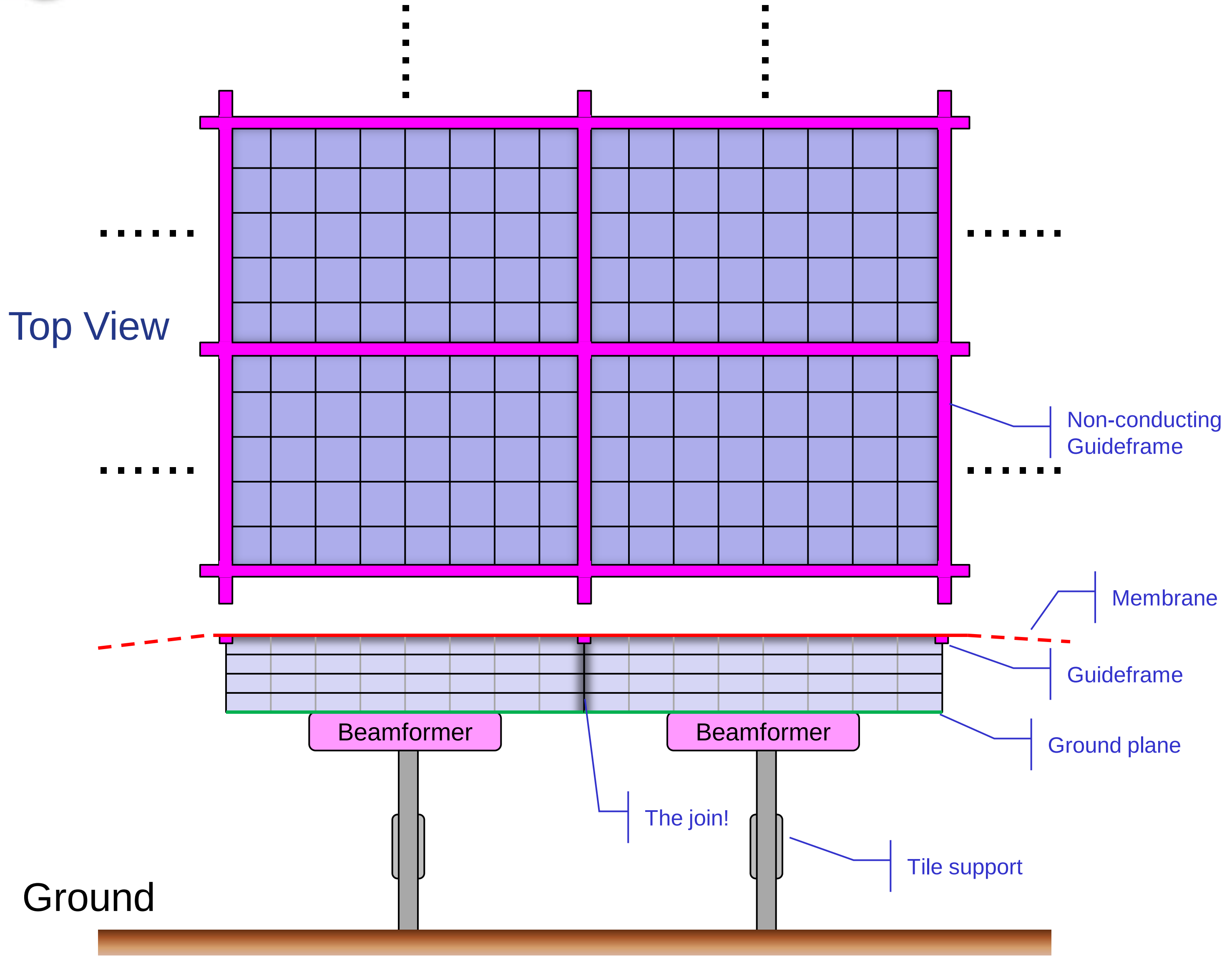
Dense array design, largely decided, select:

- Element pitch for frequency range & element type
- Element type and construction technique
- LNA: differential or single ended

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

Possible AA-mid construction

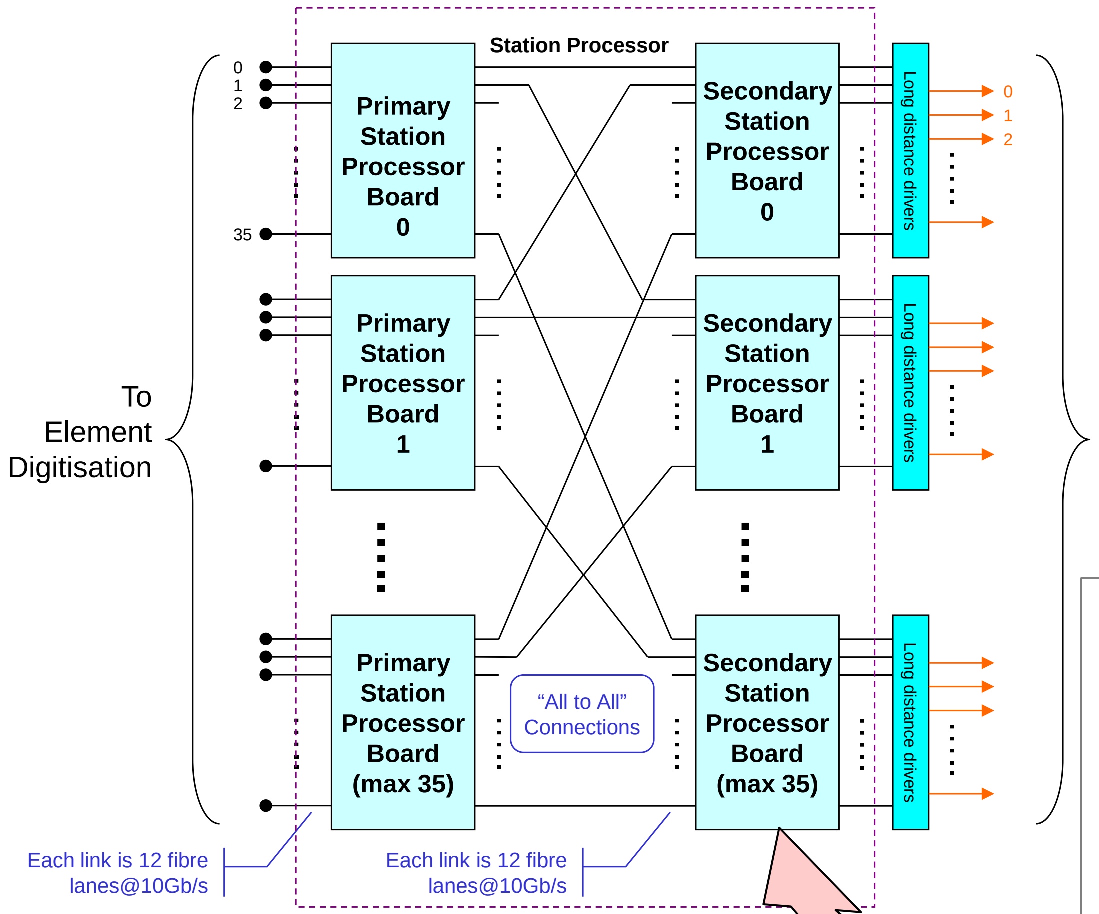


Station processing

Similar for AA-low and AA-mid:

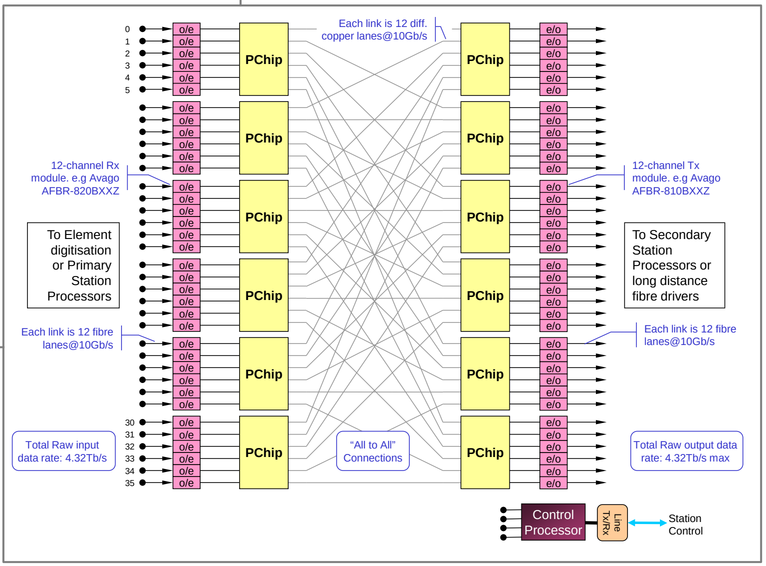
- Station level beamforming on all the tiles
- Distributes the clock information for all the tiles
- Station calibration calculations and corrections (using the tile processors)
- Transmits observation beams to the correlator
- Station monitoring and control functions

Station processor

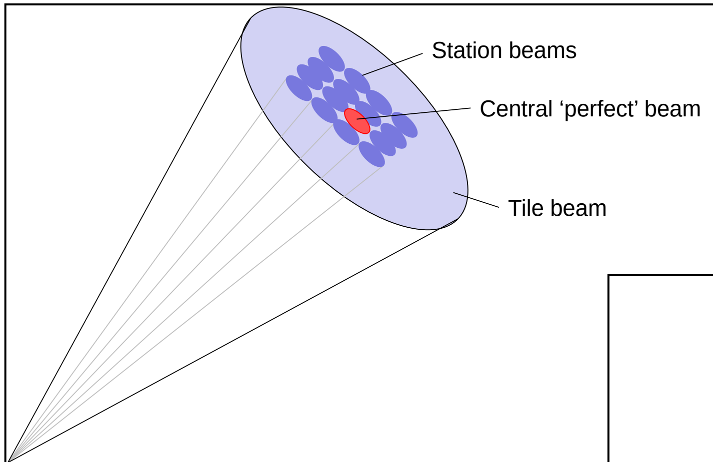


Requirements:

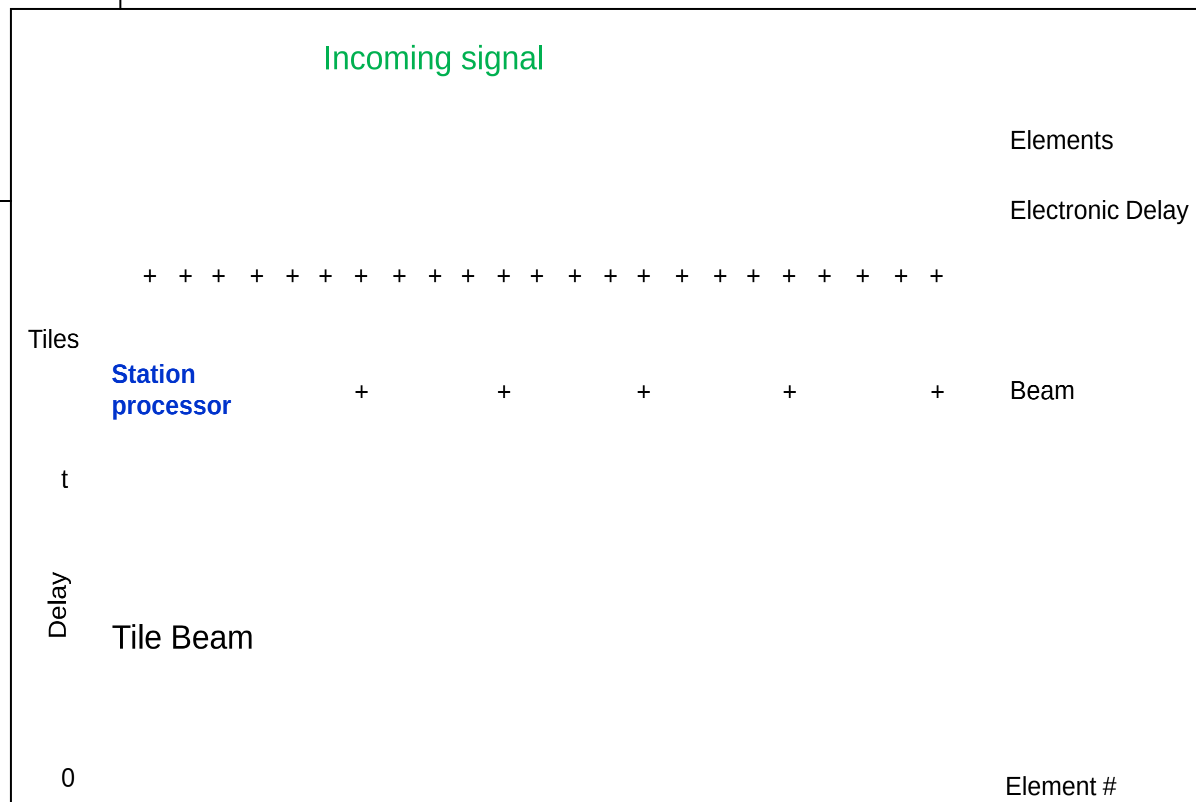
- High bandwidth in
- High bandwidth out
- Largely cross connected
- Scaleable at various levels
- Programmable beamforming



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

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
- No a problem for correlator which only “sees” total data rate
- Post-processor needs to interpret blocks of data

Build flexibility into the Station processor

Decisions, decisions....

Most sub-systems: "just" design for the specification

AA-low

- Front-end
  - Single/dual element array
  - Array layout design
  - Element type
  - Regular tiles or individual elements
- Signal processing
  - Any analogue beamforming?
  - Location of digitisation
  - Beamform in clusters?

AA-mid

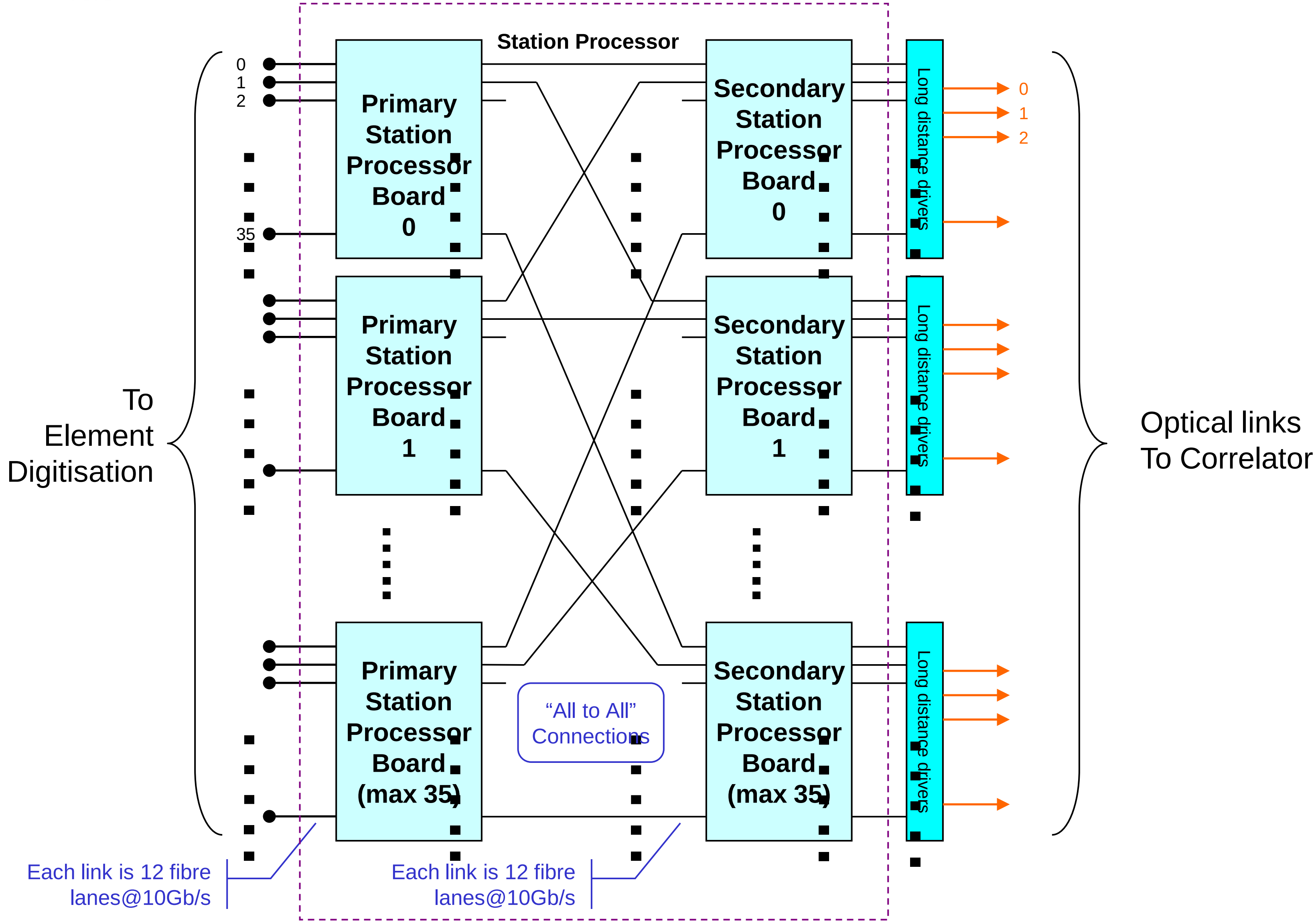
- Front-end
  - Element type
  - Element pitch
  - Single ended or differential LNA
- Signal processing
  - Amount of analogue beamforming
  - Data rate from Tile beamformer to Station Processor

See Implementation talk....

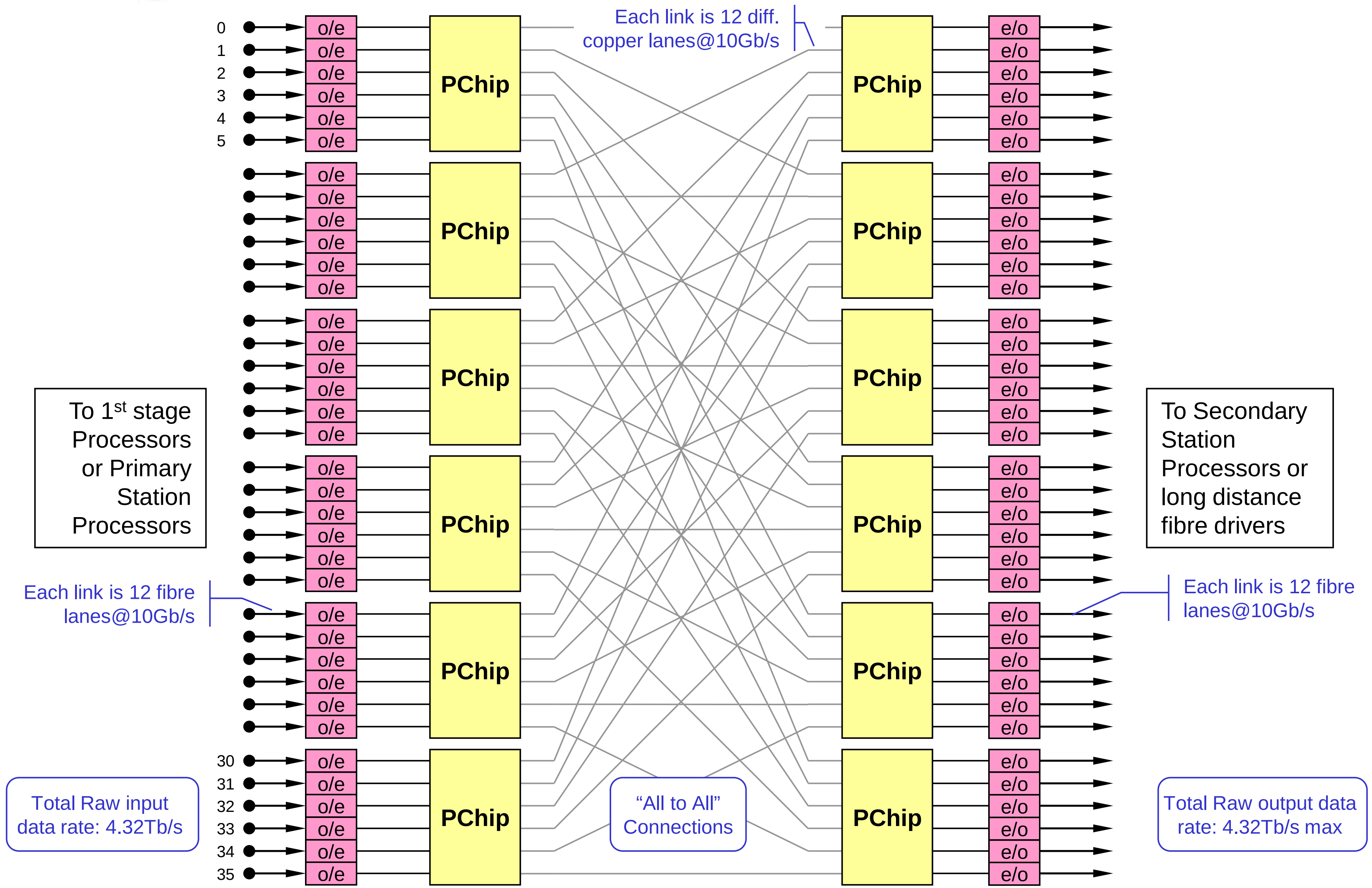
AA-low Core

- Very high general filling factor
- Probably a “sea of elements”
- Placing the processing Bunkers may put in discontinuities, this will need to be simulated
- May well be necessary to have specified array sizes – including overlapping for short baselines

Station processor



Station Processor Board



One or two elements?

	One element	Two elements
Cost	Minimised	Higher Doubles # RF chains, ground planes and interconnects
Element performance	Some compromise across band	Less compromise across band
Station design	Forces highly sparse design at top-end of band	Reduces sparcity while maintaining sensitivity
Power	Minimises power	Increases power
Filling factor	Good filling factor at low *f*	Poor filling factor unless multiple cores
Matching	Challenging	Easier

Beam

analo

digita

Characteristic	RF Beamforming	Digital Beamforming	Remarks/Timeline
Implementation	Integrated into analogue chips. Each chip produces multiple beams from each block of input channels.	Each analogue signal is digitized. The signals are split into multiple channels and beamformed in narrow channels.	The analogue system "easy" to implement in current technology. Digital is relatively complex, is mostly on chips.
Beam generation	Each beam is formed by phase shifting each input and then summed for each chip. True time delay technology integrated onto chips is not currently proven, external delays become to large for practical implementation on a dense high frequency array. Each beam operates as a single frequency channel. This will restrict the number of tile beams that may be produced independently.	Beams are produced by phase shifting a narrow frequency band. Each channel may be calibrated for amplitude. Polarisation may be corrected as a function of frequency. Each channel may be considered to be a sub-beam. More beams may be produced by repeating the beamforming functions after spectral separation. The output data rate determines the overall performance of the beamformer, assuming that there is sufficient processing available to produce the beams.	The analogue system is relatively simple and cheap to implement for restricted numbers of beams. The digital solution is more complex to implement the basic system, but is very flexible for providing more beams of arbitrary bandwidth.
Multiple beams	Each Tile beam needs to be produced via specific hardware within the beamformer chip. The configuration is fixed by the architecture design.	As discussed above the beams are made up of multiple sub-beams from specific frequency dependant coefficients. These can make up beams in any format required within the constraints of output data rates and processing.	The digital beamformer is very flexible for output data requirements. The analogue beamformer has its macro parameters determined at build time.
Bandwidth	Assuming that the beamformer is using phase shifting for time delays, or a frequency dependent time delay then the bandwidth will be restricted to some fraction of the operating frequency for each beam. Wider bandwidths can be constructed using multiple beams. If true time delay can be produced then wider bandwidths up to the operational range of the elements and analogue system can be produced.	The digital system can operate over the full bandwidth available from the elements and analogue conditioning. This is because each of the sub-beams can be treated as a narrow independent beam.	There are significant constraints on the analogue system. The digital system is able to operate over the bandwidth available from the front end system.
Bandpass corrections	The bandpass corrections for each element need to be made in an overall fashion. It is unlikely that they can be adjusted for changing conditions. The corrections made will be identical for each beam.	The analogue system up to the ADC has to be flat enough for effective digitization to take place. Additional flexibility can be achieved through further digitisation resolution although this has cost and power implications. The bandpass can be corrected as a function of frequency and if necessary by beam; each sub-band can be independently changed.	The analogue chain is likely to be subject to variation due to temperature and ageing effects; using relatively low cost components is liable to result in ripples in the bandpass. These can only be taken out in a gross sense with RF beamforming, but can be corrected in detail by the digital system.
Calibration	The analogue beamformer can provide element level amplitude and approximate time delay calibration; neither of these are as a function of frequency. It is unlikely to be able to provide element level polarisation calibration since this is highly frequency and direction dependant.	The digital system can provide frequency and direction dependant calibration per beam. The calibration can be high resolution amplitude, phase and polarisation corrections for each sub-beam. Since many beams can be formed it is viable to dedicate a number of sub-beams to observe calibrated sources during observations to refine	The calibration of the AAs is critical to providing high dynamic range beams, of know characteristics. If the ability to calibrate at the element level then a digital system is probably essential, however, if the AA can be calibrated at the Tile level, then an analogue beamformer can be used.

Beam

analo

digita

Characteristic	RF Beamforming	Digital Beamforming	Remarks/Timeline
Implementation	Integrated into analogue chips. Each chip produces multiple beams from each block of input channels.	Each analogue signal is digitized. The signals are split into multiple channels and beamformed in narrow channels.	The analogue system "easy" to implement in current technology. Digital is relatively complex, is mostly on chips.
Beam generation	Each beam is formed by phase shifting each input and then summed for each chip. True time delay technology integrated onto chips is not currently proven, external delays become to large for practical implementation on a dense high frequency array. Each beam operates as a single frequency channel. This will restrict the number of tile beams that may be produced independently.	Beams are produced by phase shifting a narrow frequency band. Each channel may be calibrated for amplitude. Polarisation may be corrected as a function of frequency. Each channel may be considered to be a sub-beam. More beams may be produced by repeating the beamforming functions after spectral separation. The output data rate determines the overall performance of the beamformer, assuming that there is sufficient processing available to produce the beams.	The analogue system is relatively simple and cheap to implement for restricted numbers of beams. The digital solution is more complex to implement the basic system, but is very flexible for providing more beams of arbitrary bandwidth.
Multiple beams	Each Tile beam needs to be produced via specific hardware within the beamformer chip. The configuration is fixed by the architecture design.	As discussed above the beams are made up of multiple sub-beams from specific frequency dependant coefficients. These can make up beams in any format required within the constraints of output data rates and processing.	The digital beamformer is very flexible for output data requirements. The analogue beamformer has its macro parameters determined at build time.
Bandwidth	Assuming that the beamformer is using phase shifting for time delays, or a frequency dependent time delay then the bandwidth will be restricted to some fraction of the operating frequency for each beam. Wider bandwidths can be constructed using multiple beams. If true time delay can be produced then wider bandwidths up to the operational range of the elements and analogue system can be produced.	The digital system can operate over the full bandwidth available from the elements and analogue conditioning. This is because each of the sub-beams can be treated as a narrow independent beam.	There are significant constraints on the analogue system. The digital system is able to operate over the bandwidth available from the front end system.
Bandpass corrections	The bandpass corrections for each element need to be made in an overall fashion. It is unlikely that they can be adjusted for changing conditions. The corrections made will be identical for each beam.	The analogue system up to the ADC has to be flat enough for effective digitization to take place. Additional flexibility can be achieved through further digitisation resolution although this has cost and power implications. The bandpass can be corrected as a function of frequency and if necessary by beam; each sub-band can be independently changed.	The analogue chain is likely to be subject to variation due to temperature and ageing effects; using relatively low cost components is liable to result in ripples in the bandpass. These can only be taken out in a gross sense with RF beamforming, but can be corrected in detail by the digital system.
Calibration	The analogue beamformer can provide element level amplitude and approximate time delay calibration; neither of these are as a function of frequency. It is unlikely to be able to provide element level polarisation calibration since this is highly frequency and direction dependant.	The digital system can provide frequency and direction dependant calibration per beam. The calibration can be high resolution amplitude, phase and polarisation corrections for each sub-beam. Since many beams can be formed it is viable to dedicate a number of sub-beams to observe calibrated sources during observations to refine	The calibration of the AAs is critical to providing high dynamic range beams, of know characteristics. If the ability to calibrate at the element level then a digital system is probably essential, however, if the AA can be calibrated at the Tile level, then an analogue beamformer can be used.

Array choice vs. Sky noise