



SKA1-low Baseline Design: Lowest Frequency Aspects & EoR Science

1st Science Assessment WS, Jodrell Bank

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Intent of the Baseline Design



- Basic architecture: 3-telescope, 2-system model
 - SKA1-low, SKA-survey (Australia); SKA1-mid (South Africa).
- Produce a design that:
 - Emphasises capability to do key science.
 - Otherwise preserves flexibility for all types of observations
 - Architecturally bounded without being overly constrained.
- Appropriate “hooks” to permit extension to the full SKA.
 - Where feasible and within cost.
- Not the final design. Controlled changes permissible as a result of:
 - science assessments,
 - responses to the RfPs,
 - design work by the consortia during preconstruction.
- Major design changes will have to be extremely well motivated.
 - No immediate changes are contemplated.
- The final design based on cost analysis and these inputs.
 - well considered trade-offs.

SKA1-low Science Input



- The primary science consideration for the design was EoR.
- The primary source document is Design Reference Mission (DRM).
- Guidance from EoR ‘White Paper’
 - “Reionization and the Cosmic Dawn with the Square Kilometre Array”, Mellema et al., (European SKA EoR Working Group).
- Secondary, but important considerations:
 - HI-line absorption (evolution of galaxies at high z)
 - Requires more emphasis on higher frequencies (~ 100 - 300 MHz).
 - Continuity of frequency coverage across the entire ‘SKA range’.
 - Transition to dish frequency range.

SKA1-Low

Key Performance Characteristics



- Frequency Range
 - Of greatest interest between 54 and 215 MHz ($z = \sim 25$ and 5.5)
 - Note that the legislation in Australia, the location of this instrument, provides legal protection only as low as 70 MHz. This means that usage of frequencies below this limit is at some risk of interference from legitimate users in the protected region.
 - Since AAs cannot be built with flat frequency response, a frequency of ~ 110 MHz has been selected for maximum sensitivity.
 - Upper frequency range to be 350 MHz
 - $\sim 6:1$ frequency ratio
 - Provides continuous frequency coverage across the SKA suite of telescopes.

SKA1-Low

Key Performance Characteristics



- Sensitivity:
 - EoR sensitivity requirements expressed as a brightness temperature
 - At ~110 MHz, rms noise of ~1 mK on scales of ~5 arcmin is required to detect the signal, which is expected to be $\sim\pm 10$ mK peak deviation from a spectral baseline.
 - AA sensitivity falls off with zenith angle as $\cos(Z)$ in the ‘dense regime’ (at lowest frequencies).
 - Zenith angle coverage is to some extent tradable.
 - The array configuration and the frequency range are “coupled”.
 - Filling factor determined by the lowest frequency.
 - Can’t squeeze the array for higher frequencies or change the configuration.
 - The total number of antennas determines the array collecting area.
 - For a given element gain.
 - Both dense and sparse regimes.
 - Sky noise is the other factor for most of the frequency range.

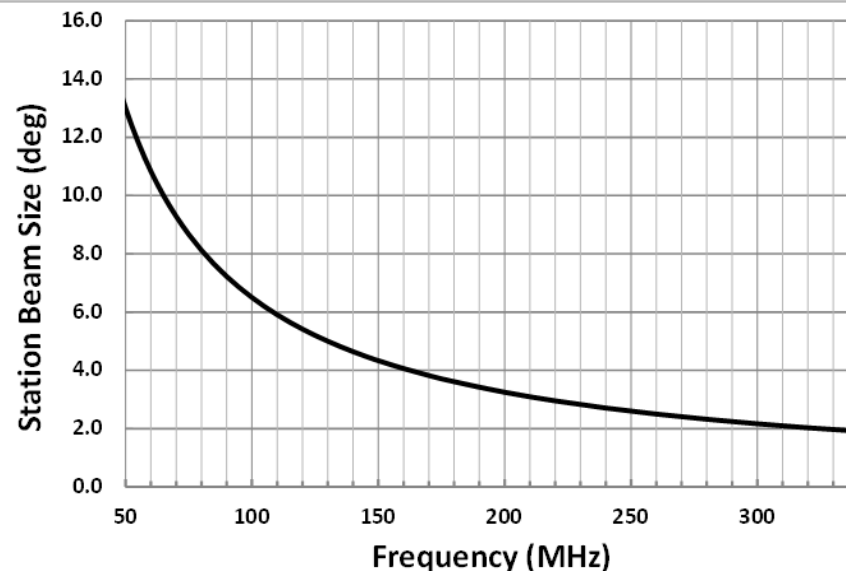
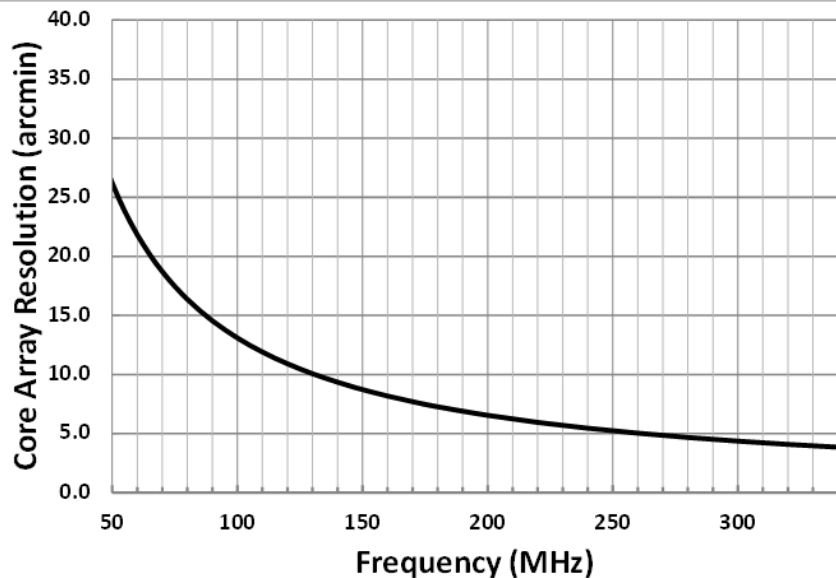
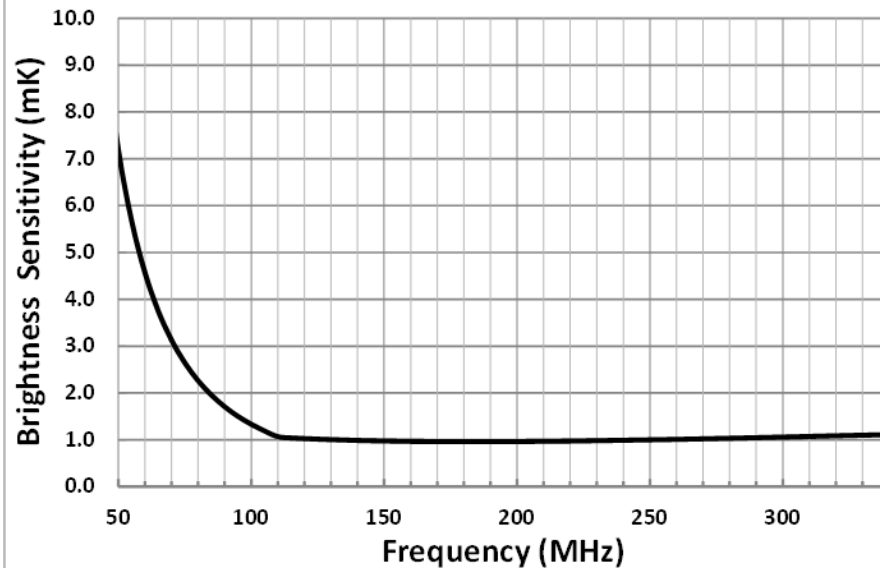
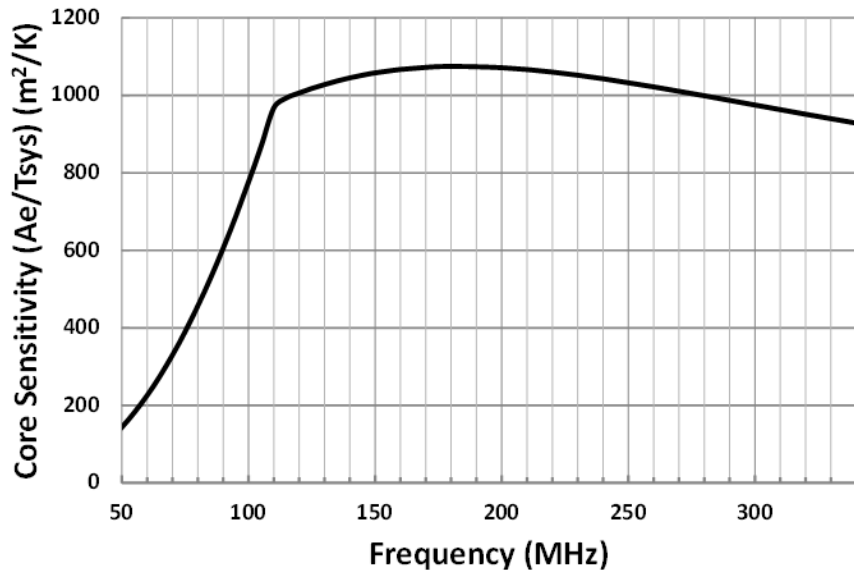
SKA1-Low

Key Performance Characteristics



- Station Beamsize/FoV:
 - EoR observations will be very sensitive to spatial fluctuations on angular scales from ~ 5 - 10 arcmin to several degrees.
 - Translates to a calibration requirement of <1 mK in fields where typical emission is ~ 10 K (ie, $10^4:1$).
 - Especially no residuals with frequency structure similar to expected signal.
 - Synthesising a field-of-view by stitching multiple beams entails a high risk of exceeding this requirement.
 - To minimise this risk, the angular size of a station beam at ~ 110 MHz is specified as >5 degrees at zenith.

SKA1-Low Core Sensitivity, Resolution, FoV

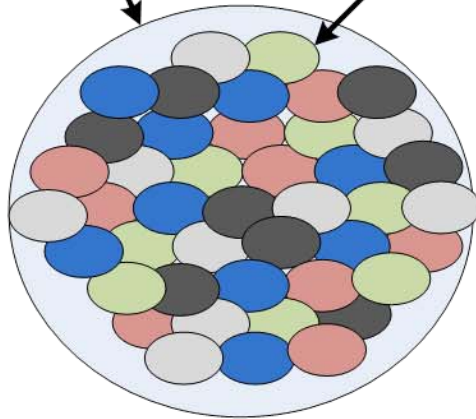


Artefacts

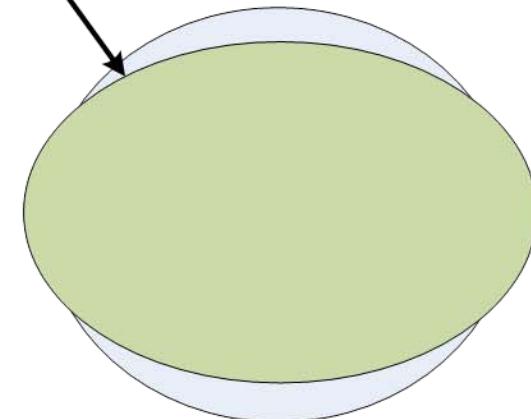
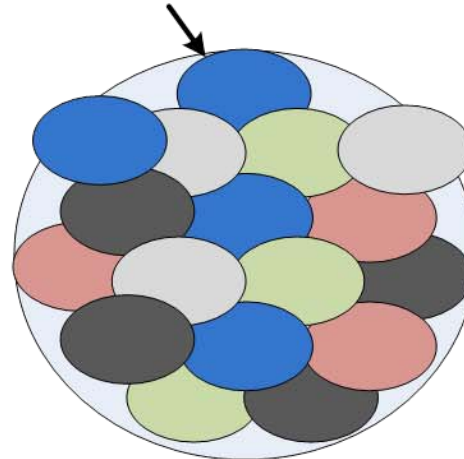


Science FoV

Large
Station Beam



~35-m
Station Beam



Not to Scale

● Synthesised Beam

- Station beamshape
 - Scales with frequency
 - Changes with HA
 - Pol'n changes with freq., HA.
 - All to be calibrated, assuming that errors are multiplicative only (complex gain).
- Q1: In which case are the FT of residual errors most likely to be similar to the signal?
 - The repetition interval of any stitching artefacts will produce an error signal in the FT plane.
- Q2: With similar types of errors for the small-station beam, do the errors manifest themselves in the same way?

SKA1-Low

Key Performance Characteristics



- Sky Coverage
 - Assumption is that a small number of fields (~10) will be observed
 - These will be selected to be a reasonably high zenith angles at transit.
 - ZA of $> \sim 30$ degrees will be much less sensitive.
 - Sky coverage has a lower priority than sensitivity, array configuration.
 - This priority will have an impact on antenna element selection.

SKA1-Low

Key Performance Characteristics



- **Polarisation Capability:**

- Dual polarization capability is required, mainly to remove continuum ‘foreground emission’.
- Polarised diffuse background probably much brighter than signal.
 - Source distribution
 - Faraday rotation
- Instrumental polarisation intrinsic to low-frequency antennas
 - Direction and frequency dependent in main station beams.
 - Complex instrumental polarisation in sidelobes.
 - Must not be too time dependent or calibration will be difficult.
 - Probably needs to be characterised to 1 part in 10^{-4-5} .
- otherwise generate results that mimic the signature of HI-line emission/absorption.

SKA1-Low

Key Performance Characteristics



- **Three-dimensional smoothness**
 - Lowest possible high-order derivatives
 - No sharp features.
 - **Spatial (angular), spectral, temporal (could be 4-D if you count 2 angular dimensions)**
 - **Examples:**
 - Sharp spectral features resulting from resonances in the system
 - Likely to be very temperature dependent, hence also time dependent.
 - Strongly chromatic sidelobes (more than simple frequency scaling).
 - Multiple reflections or scattering effects that may be affected by mechanical stability.
 - Probably be more apparent in far-out sidelobes.
 - Sharp changes in instrumental polarisation
 - In spatial and frequency dimensions.
 - **Temporal smoothness**
 - Same as system stability.
 - Intervals between calibrations depends upon stability of the parameter being calibrated.

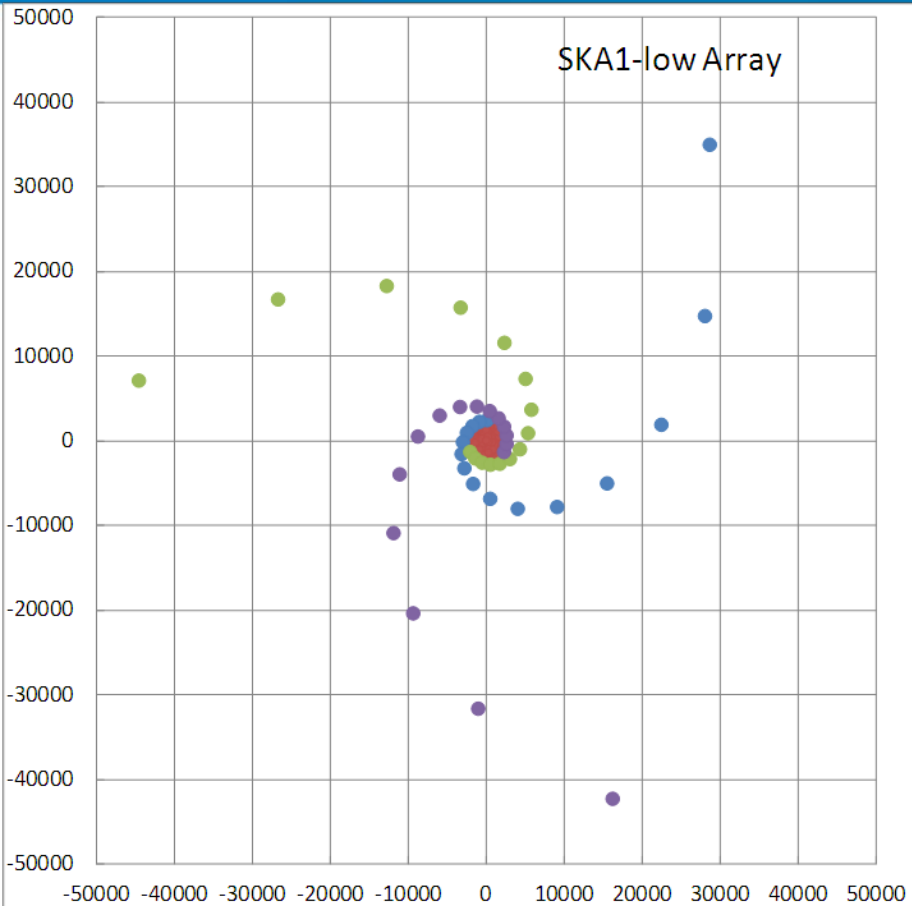
SKA1-Low

Key Performance Characteristics

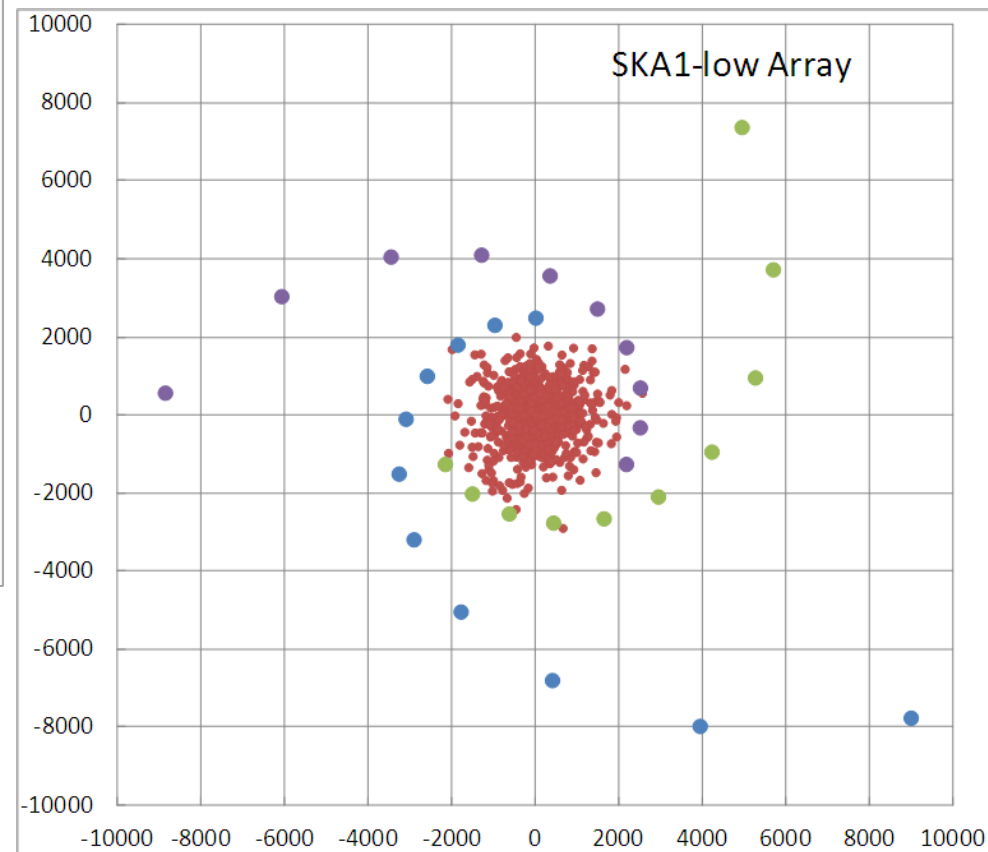


- Array Configuration:
 - Array is as compact as possible to achieve BT sensitivity.
 - Only 5-10 arcmin array resolution from core.
 - Synthesized beamsizes are taken as a second priority to BT sensitivity.
 - High resolution spiral configuration added to achieve 100 km maximum baselines.
 - Subtraction of “foreground” continuum sources.
 - Do we really need the long baselines?
 - Expensive
 - How long?
 - What is confusion limit at ~50 MHz?
 - LOFAR should be able to provide evidence.

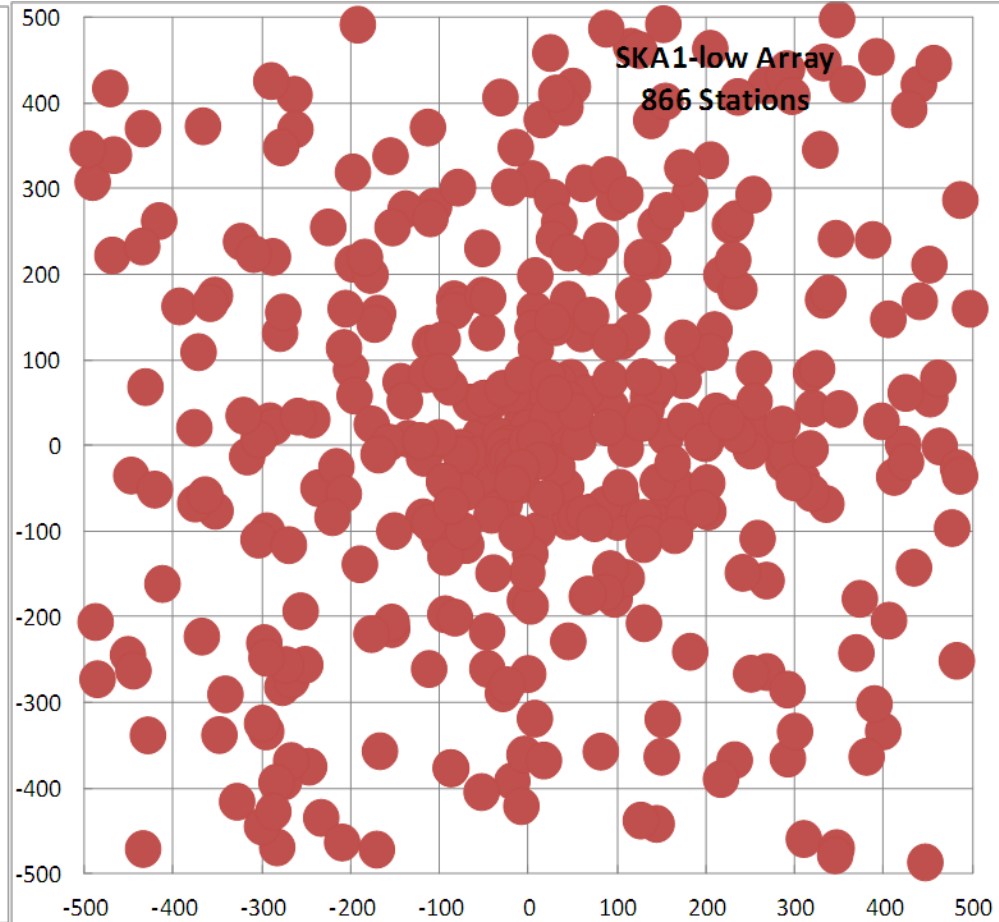
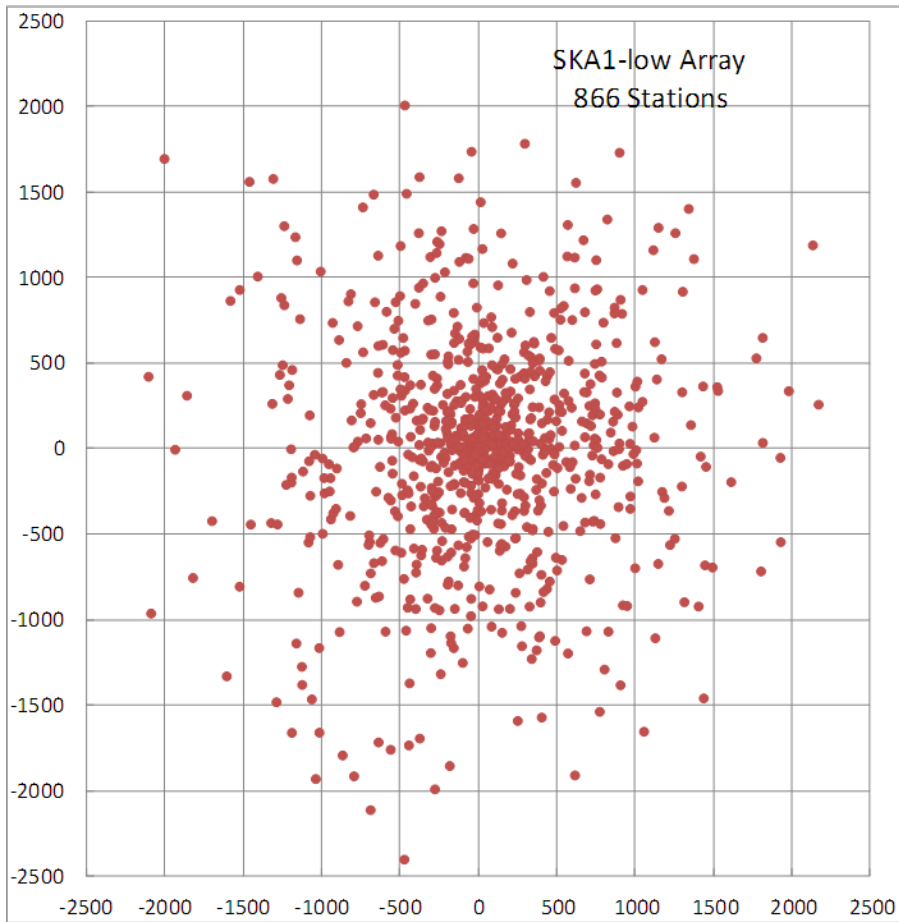
Array Configuration



Dimensions in meters



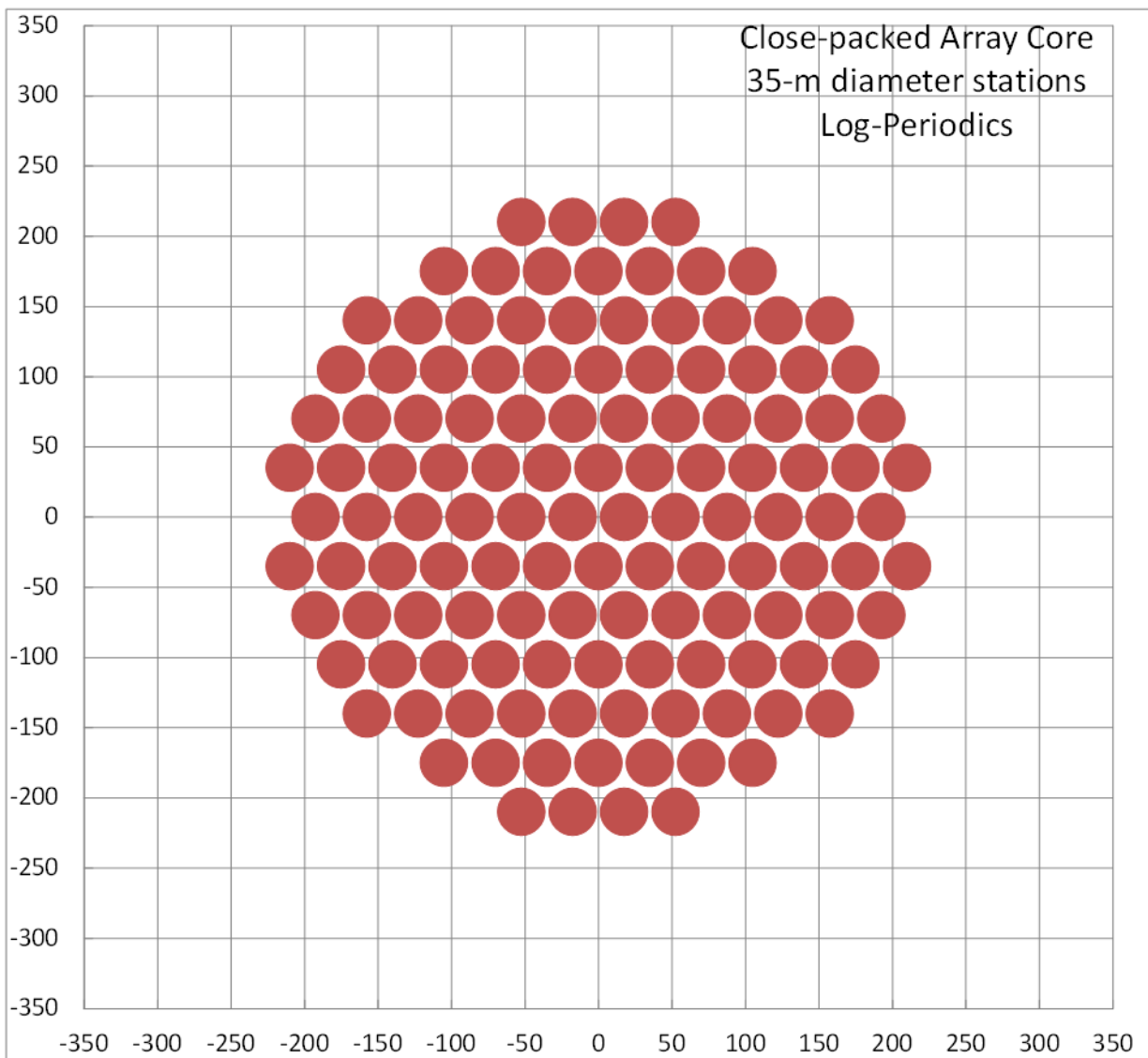
Central Array Configuration



Dimensions in meters

Array Configuration

Maximum Central Packing Density

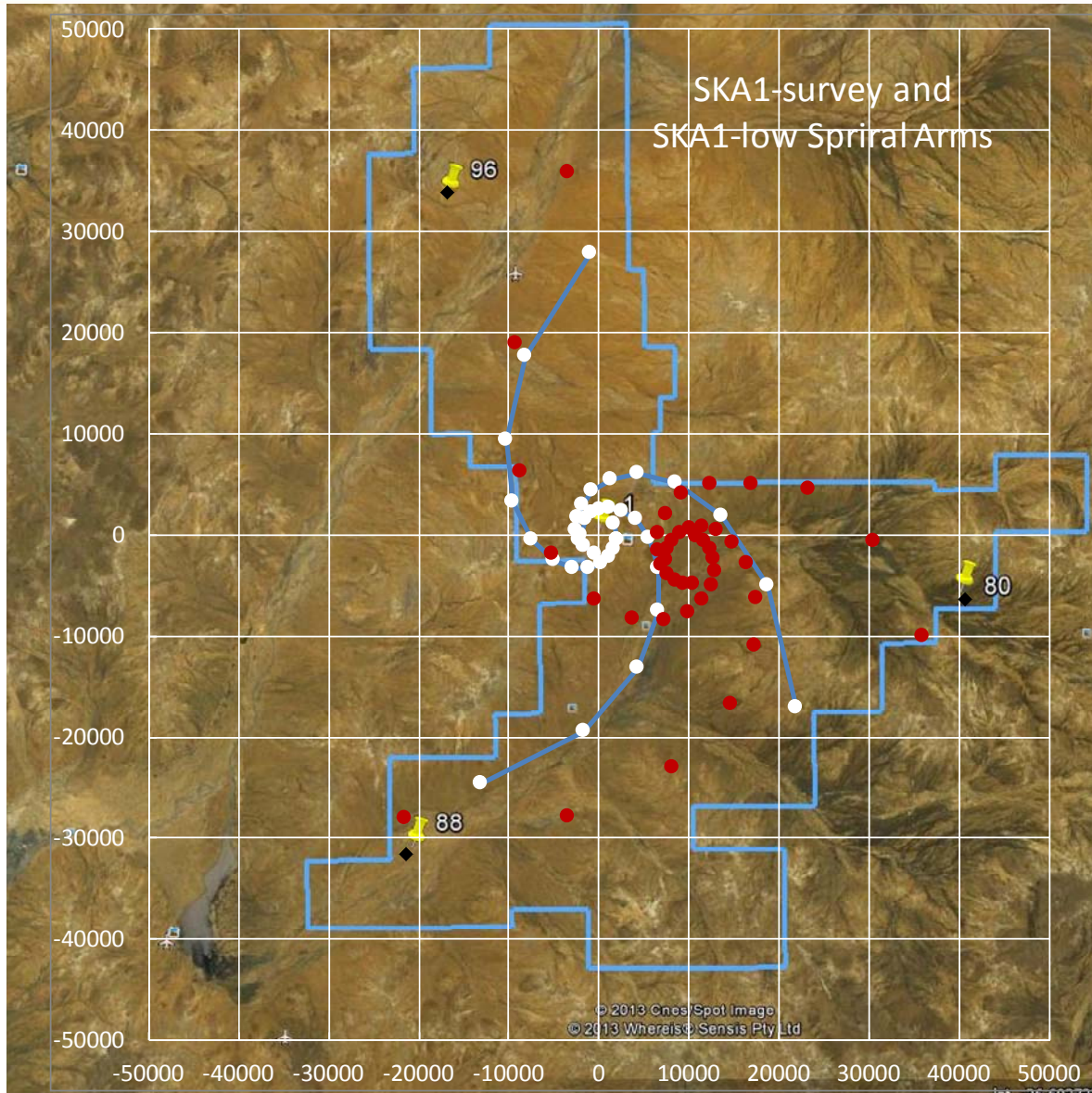


SKA1-Low: Discussion Point

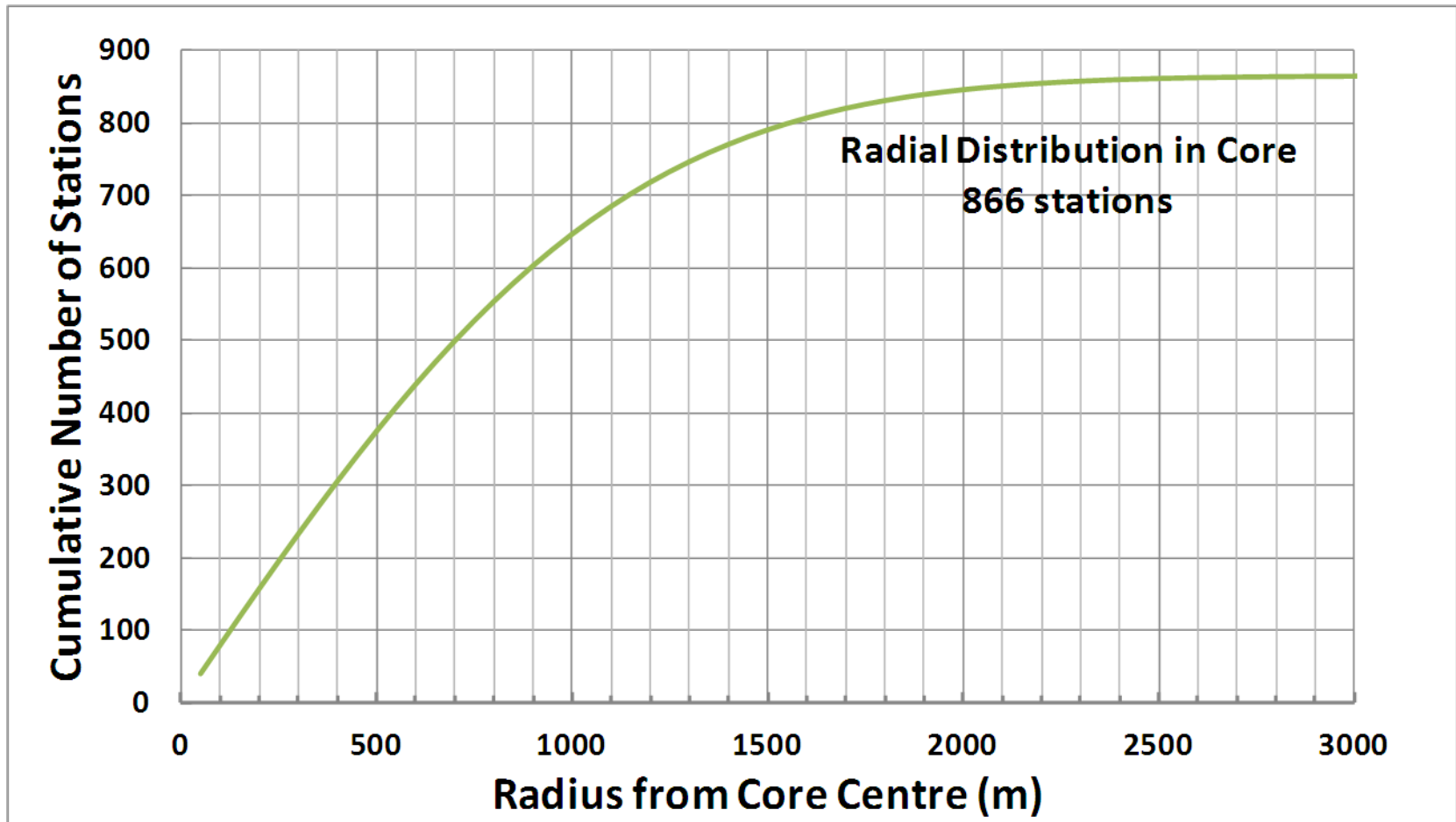


- McCool has recently considered opportunities for signal/data transport from elements => beamformers.
- Beamformers will be housed in enclosures.
 - ‘Reach’ of the element-to-enclosure link is the key performance aspect.
 - Determines the number inputs available for beam-forming.
- Number of enclosures
 - Minimum is one large enclosure (building) for all stations in/near ‘core’.
 - *Permits elements to be shared among adjacent stations.*
 - Potentially permits ‘virtual stations’ within the area served.
 - Maximum is one enclosure per station.
 - Does not provide possibility of sharing elements, or flexibility in beam size.
- Questions:
 - Is there a science advantage to extending the reach of enclosures from a single station?
 - What is the optimum reach or when is it no longer important?
 - Note: Cannot reach the entire array, but could reach the core.

SKA1-Low & SKA1-survey Potential Array Configurations



SKA1-Low Parameter Selection



SKA1-Low Parameter Selection



$$T_{b_min} = \frac{4\pi 60 \lambda^{4.55}}{\eta \eta_s L_e^2 \theta_{res}^2 N_{el_total} \sqrt{2\Delta \nu \tau}}$$

Dense regime

$$T_{b_min} = \frac{4\pi 60 \lambda^{2.55}}{\eta \eta_s D_{element} \theta_{res}^2 N_{el_total} \sqrt{2\Delta \nu \tau}}$$

Sparse regime

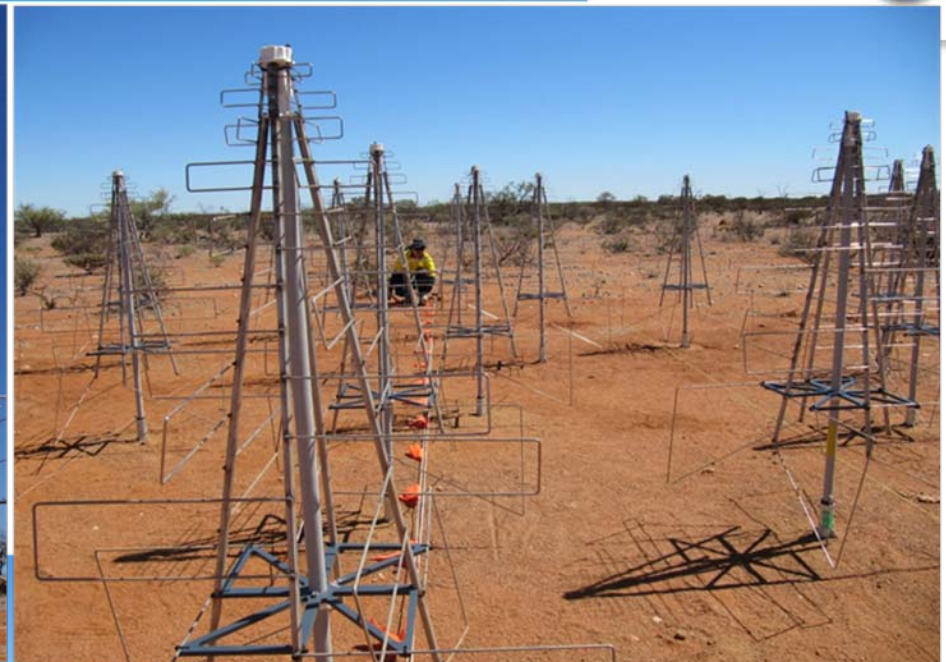
SKA1-Low

Antenna Element Selection



- Antenna technology choices
 - Arrays of low-gain antennas (droopy dipoles, LOFAR style)
 - Frequency range may require two arrays, but only one has been included so far.
 - Mature technology – LOFAR in operation for some time.
 - Higher-gain antenna elements (log-periodic).
 - Higher gain => fewer elements, lower cost.
 - *Potential issue: Smooth frequency and spatial response.*
 - Less sky coverage.
 - Better frequency coverage individually.
 - Array will be very sparse at high frequencies.
 - Less sky coverage.
 - Better frequency coverage.
 - 8 dBi gain chosen => ~250,000 antenna elements.

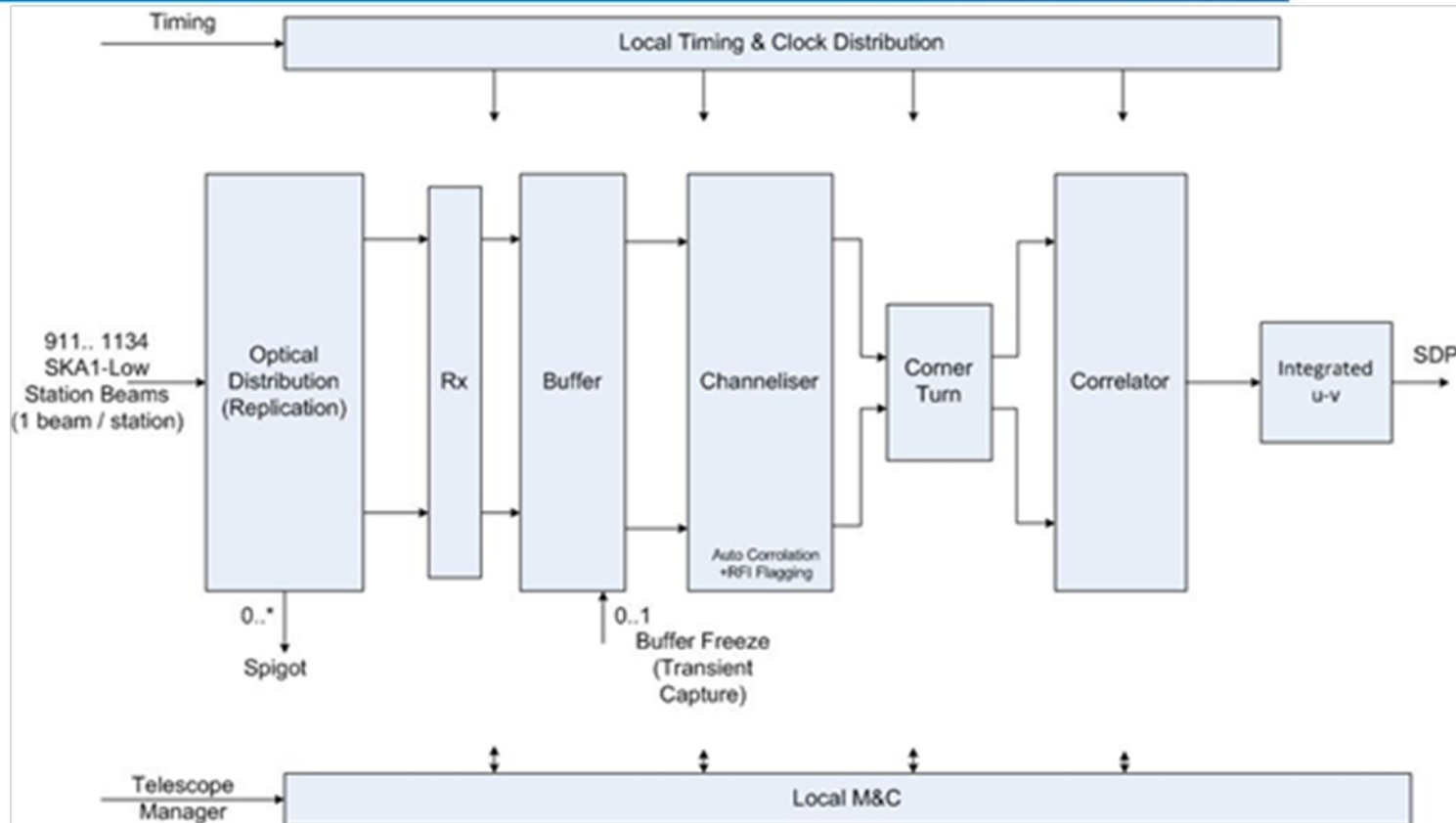
Log-Periodic Test Array



Cambridge-ASTRON-ICRAR & industrial partners

- 16 log periodic dipole antenna array
- Configured as an MWA station

Correlator System Sizing



Channeliser processing load**	60 T Mult/s	
Correlator load	1660 T mult/s	Total channeliser + correlator = 1720 T mult/s
Number of cabinets	~ 10.8	80 kW*

Performance at $f > \sim 200$ MHz



- A_e/T_{sys} maintained as noise decreases faster than A decreases.
- Sparseness increases dramatically because element effective area decreases as f^{-2} , while filling factor is constant.
 - Grating lobes (or similar) develop as a result of undersampling.
 - Less of an issue for high-z HI-line absorption observations, although subtraction of continuum could be an issue.
 - Pulsar observations, if applicable, also should be feasible.
- LNAs will have to be designed for low noise at the high frequencies.

Issues



- Backing out instrumental polarisation.
- Length of long baselines and confusion.
- Station size.
- Frequency range.
- Smoothness (spatial, frequency, time).
- Cost issues.

Design Alternatives



- All require motivation
 - Evidence-based.
- Long baselines
 - Clearer motivation needed.
- Larger stations
 - Number of stations may be reduced
- Station configuration optimisation
 - Adjustment of element positions.
 - More compact?
 - Less compact?
- Element type
 - If log-periodic elements exhibit unexpected issues.

Expansion to SKA2



- Assume that the boundaries of the Boolardy site are not a constraint for SKA2.
- Few topological barriers to expansion of the array configuration.
- SKA-survey core may limit to expansion in some directions.
- Two alternatives (at least):
 - An expansion of the SKA1 array.
 - EoR “signature” detected but not imaged => EoR higher resolution imaging.
 - Higher resolution.
 - A second array operating at higher frequencies.
 - Better coverage from ~200 – ~400 MHz.
 - HI-line in emission, $z = 2.5 - 6$.
 - Better brightness temperature sensitivity and/or higher resolution.

End