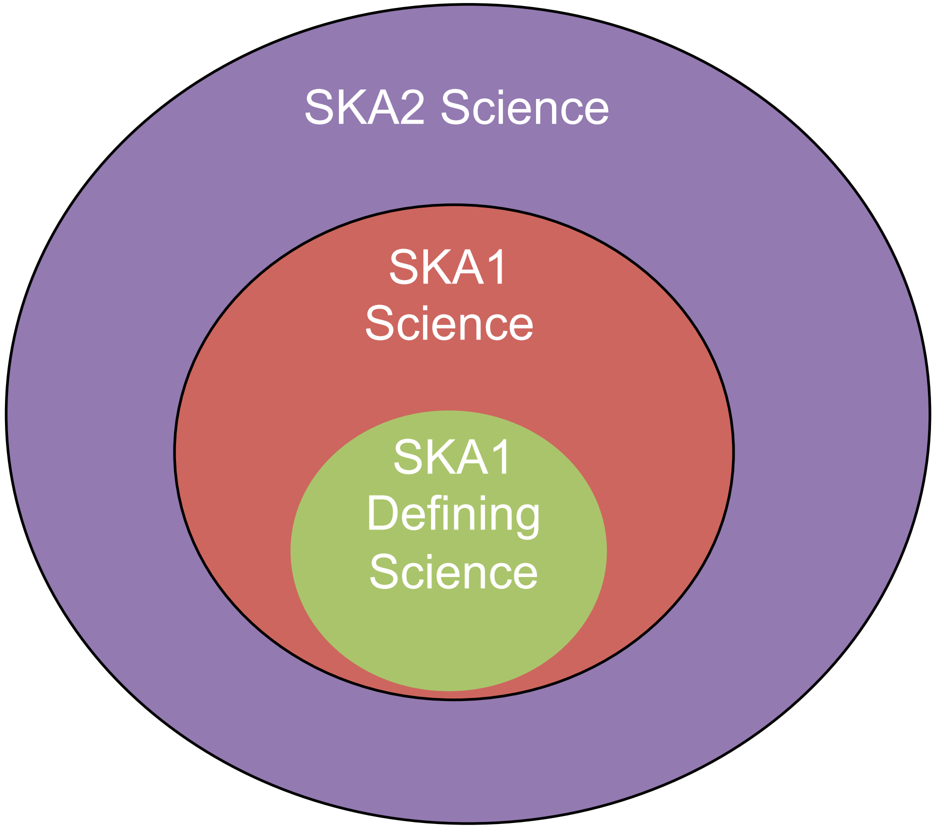
SKA1: Current Baseline Design

Continuum Assessment WS

P. Dewdney

Sept 10, 2013

SKA2 and SKA1



Other Constraints

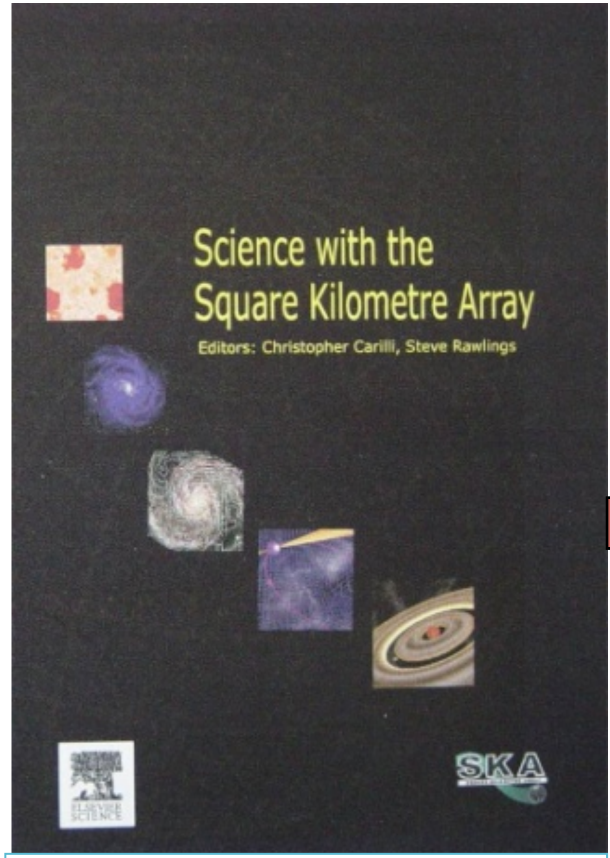
- Cost/Lifetime
  - 10 yr lifetime
- Location
- Forward compatibility
  - “[C]omponents of receptors used in SKA1 that are difficult or impossible to change will be […] SKA2 compliant.”
- …

SKA1 Defining Science

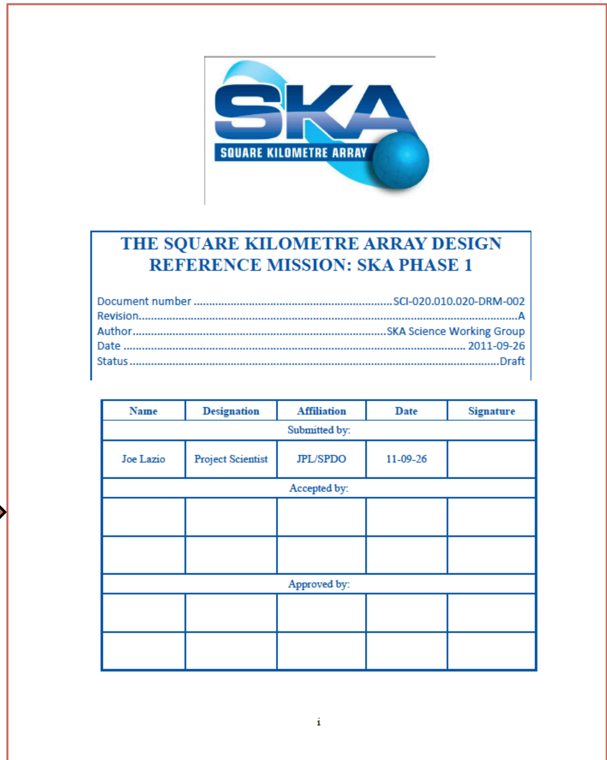
- Understanding the history and role of [H I] from the Dark Ages to the present-day, and
- Detecting and timing binary pulsars and spin-stable millisecond pulsars in order to test theories of gravity (…), to discover gravitational waves from cosmological sources, and to determine the equation of state of nuclear matter.
- Continuum added during Baseline Design process.

From Lazio

Science Case, DRM, Requirements, and Baseline Design



Science Case
Lays out **overarching** goals, full suite of science



THE SQUARE KILOMETRE ARRAY DESIGN REFERENCE MISSION: SKA PHASE 1

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Accepted by:				
Approved by:				

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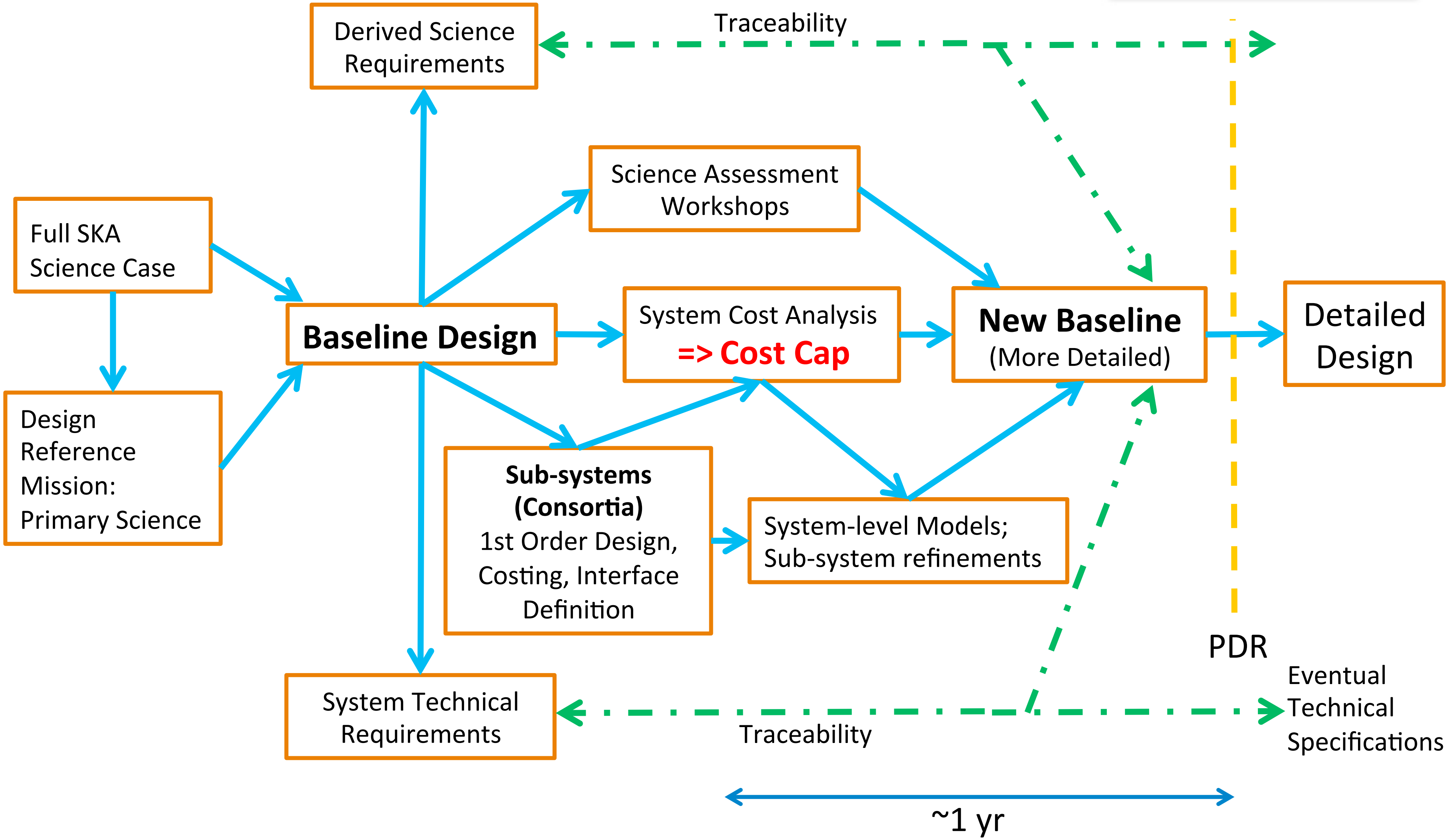
Design Reference Mission
Set of science observations to set **envelope** of science requirements

SCI-SYSR-0010
SCI-SYSR-0020
…
SCI-S-REQ-0110

Baseline Design!

Requirements Document
Input from science, but from other areas as well

Approx. Design Process up to PDR



Design Time-line

- 2013 start of preliminary design
- 2014 complete preliminary design
- 2016 complete detailed design
- 2017 initiate procurement/ pre-production runs.
- 2018 start construction.

Boundary Conditions for BD

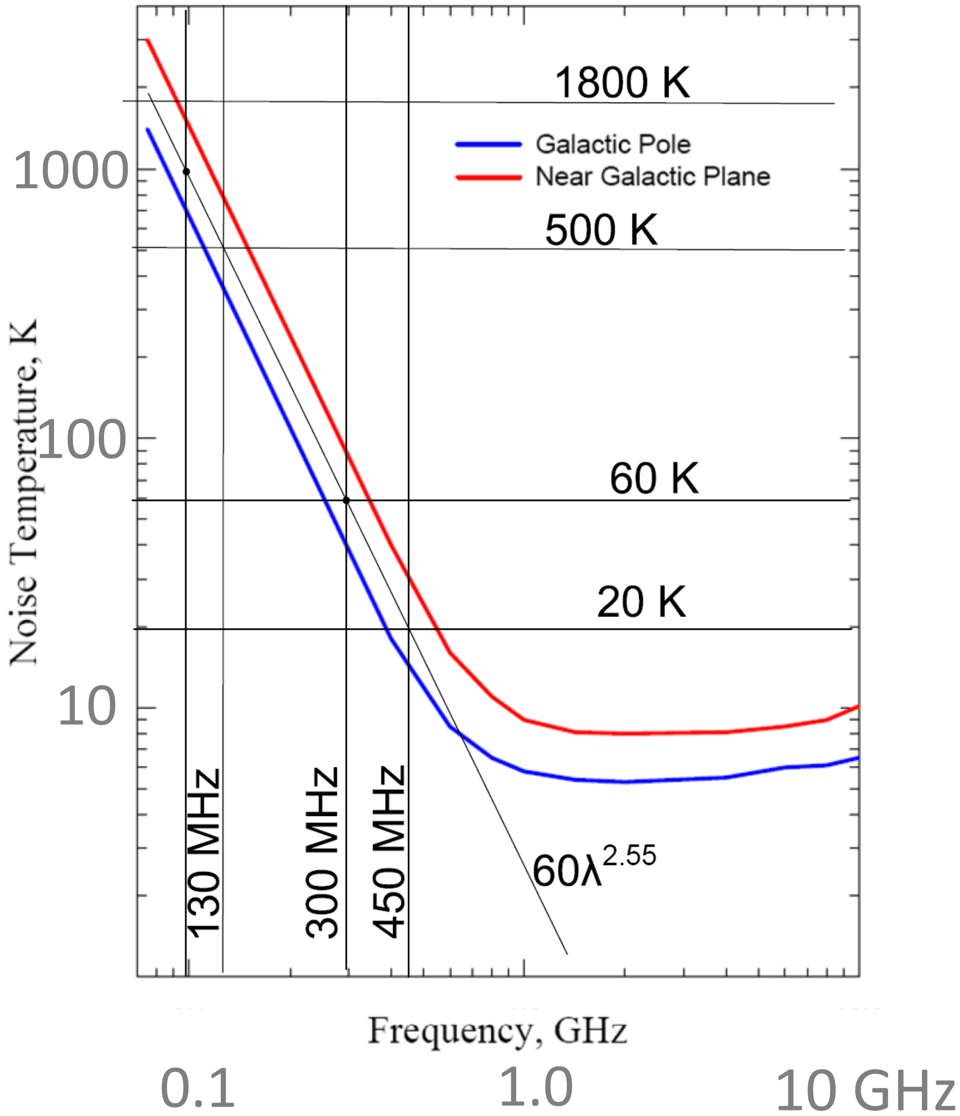
- Pre-selected sites in Australia and South Africa.
- Three broadly-defined telescopes
  - Boolardy site (Australia)
    - SKA1-low: Low frequency aperture array.
    - SKA1-survey: mid-frequency dish array equipped with Phased Array Feeds
  - Karoo site (South Africa)
    - SKA1-mid: mid-frequency dish array equipped with Single Pixel Feeds.
- Envelope of science and key science defined in the SKA1 Design Reference Mission.
- Incorporation of the Precursor telescopes, ASKAP and MeerKAT, into SKA1
  - so as to take advantage of as much of the investment in infrastructure and telescope equipment as possible,
  - based on a feasibility and cost-benefit analysis.
- Sufficient to enable a "motivated cost cap",
  - based on a cost analysis of a representative SKA1 system consistent with achievable science capabilities.
- Scope
  - as much specific information as needed to carry out the purpose
  - as little "arbitrary" information as possible, leaving as much freedom as possible for innovative solutions at the more detailed levels.
  - plausible estimate of performance for each telescope:
    - frequency coverage, sensitivity, resolution (distribution of collecting area), and processing in the spatial (images and maps), spectral (spectra) and temporal (pulsars, variables, transients) domains.
  - Outline of extensibility to SKA2.

Today's Comparable Telescopes (L-band)

		JVLA	MeerKAT	SKA-mid	ASKAP	SKA1-survey	LOFAR	SKA1-low
Aeff/Tsys	m^2/K	265	321	1630	65	391	61	1000
FoV	deg^2	0.25	0.86	0.49	30	18	14	27
Survey Speed FoM	$deg^2\ m^4\ K^{-2}$	1.76×10^4	8.86×10^4	1.30×10^6	1.27×10^5	2.75×10^6	5.21×10^4	2.70×10^7
Resolution	arcsec	1.4 - 44	11	0.22	7	0.9	5	11

Ae/Tsys	6.2 x JVLA	6.0 x ASKAP	16 x LOFAR
Survey Speed FoM	74x	22x	520x

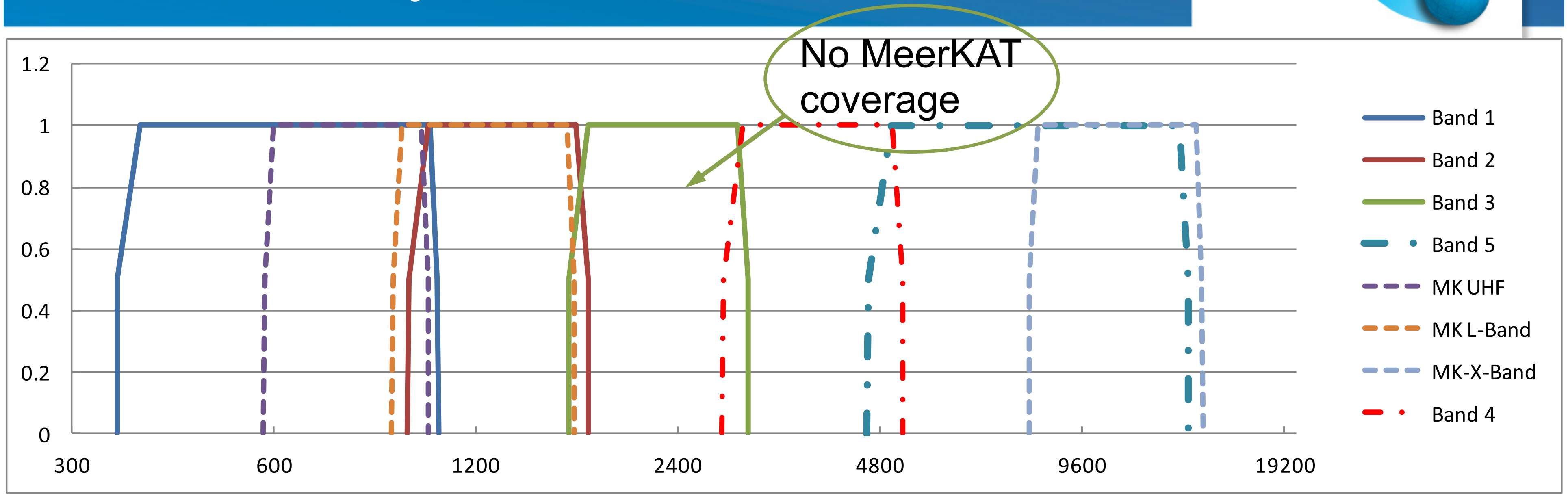
Sky Noise: Fundamental System Noise Regime



SKA1-mid in a Nutshell

- Headline Science
  - Radio pulsars and HI-line from local Universe, to moderate redshifts,
  - High sensitivity continuum.
    - Polarisation: magnetized plasmas, Galactic & Extragalactic,
    - potentially proto-planetary disks, if high frequency receivers enabled.
  - Other spectral lines (e.g. OH-lines).
  - Some classes of radio transients.
- Mixed Dish array
  - 190 15-m SKA1 dishes.
  - 64 13.5-m diameter dishes from the MeerKAT array.
  - Equipped with receivers from .350 to 3.0 GHz for SKA1 (dishes capable of 5 rcvr packages up to 20 GHz).
- Configuration
  - Compact core with a diameter of ~1 km, built on the MeerKAT array centre.
  - Further 2-D array of randomly placed dishes out to ~3 km radius, thinning at the edges.
  - Three spiral arms, a subset of the 5 equally spaced arms reserved for SKA2, extending to ~100 km from the centre.
  - Array to be expanded to a much larger SKA2 array (by "density matching").
- Sensitivity
  - SKA1 sensitivity: ~6.9 m^2/K.
  - System Equivalent Flux Density (SEFD): ~1.7 Jy. .
- Signals transported to a central signal processing building.
  - Channelisation, cross-correlation and array beam-forming (pulsars, VLBI).
  - Real-time pulsar search equipment (for frequencies ~800 – 1400 MHz).
  - candidates will be sent to the science data centre for further analysis.
  - Capability for detecting de-dispersed transients or bursts.
  - Outputs transported to the science data processing centre.
- Processing of the science data
  - include calibration, image-cube (i.e., spatial plus spectral) formation on various scales, and statistical analysis.
  - Pulsar candidate processing

SKA1-mid
Preliminary Dish Receiver Bands

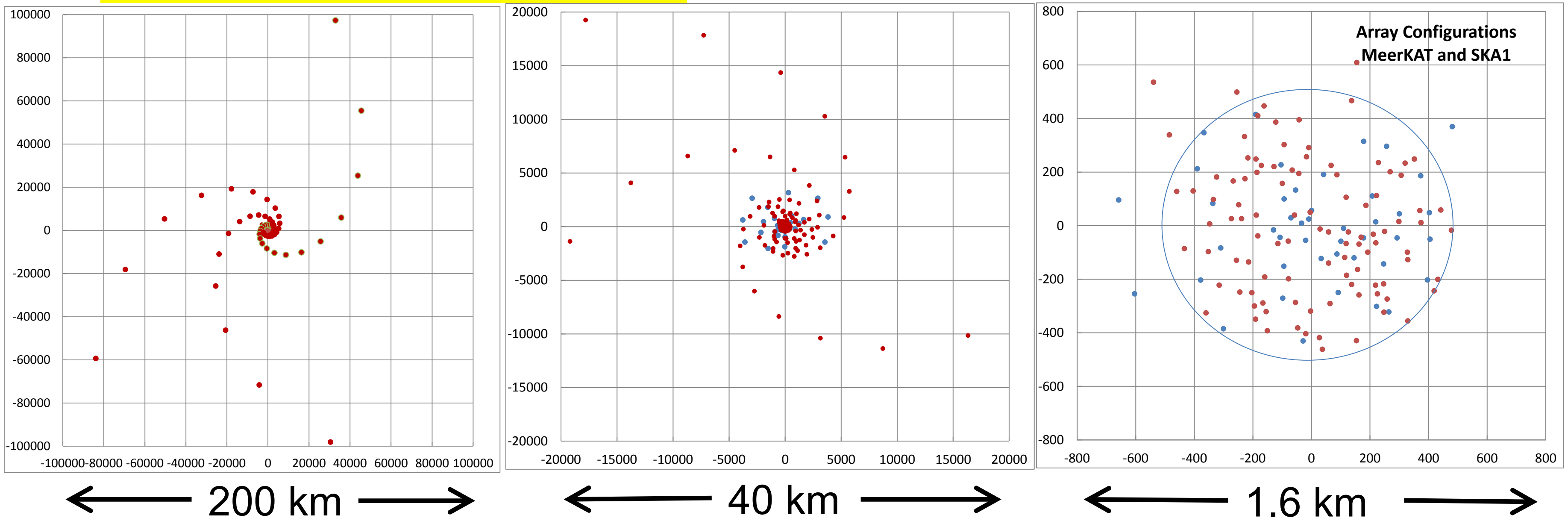


Band	Sky Freq.	Sampled Bands	Potential Feed Type	Streams x bits	Total per Antenna
Band 1	350 – 1050 MHz	1 x 1 GHz	3:1 Quad-Ridge	2 x 8	48 Gbit s^{-1} ←
Band 2	0.95 – 1.76 GHz	1 x 1 GHz	1.8:1 Corrugated Horn	2 x 8	48 ←
Band 3	1.65 – 3.05 GHz	1 x 2.5 GHz	1.8:1 Corrugated Horn	2 x 8	120 ←
Band 4	2.80 – 5.18 GHz	1 x 2.5 GHz	1.8:1 Corrugated Horn	2 x 4	60
Band 5	4.6 – 13.8 GHz	2 x 2.5 GHz	3:1 wide-band feed	4 x 4	120

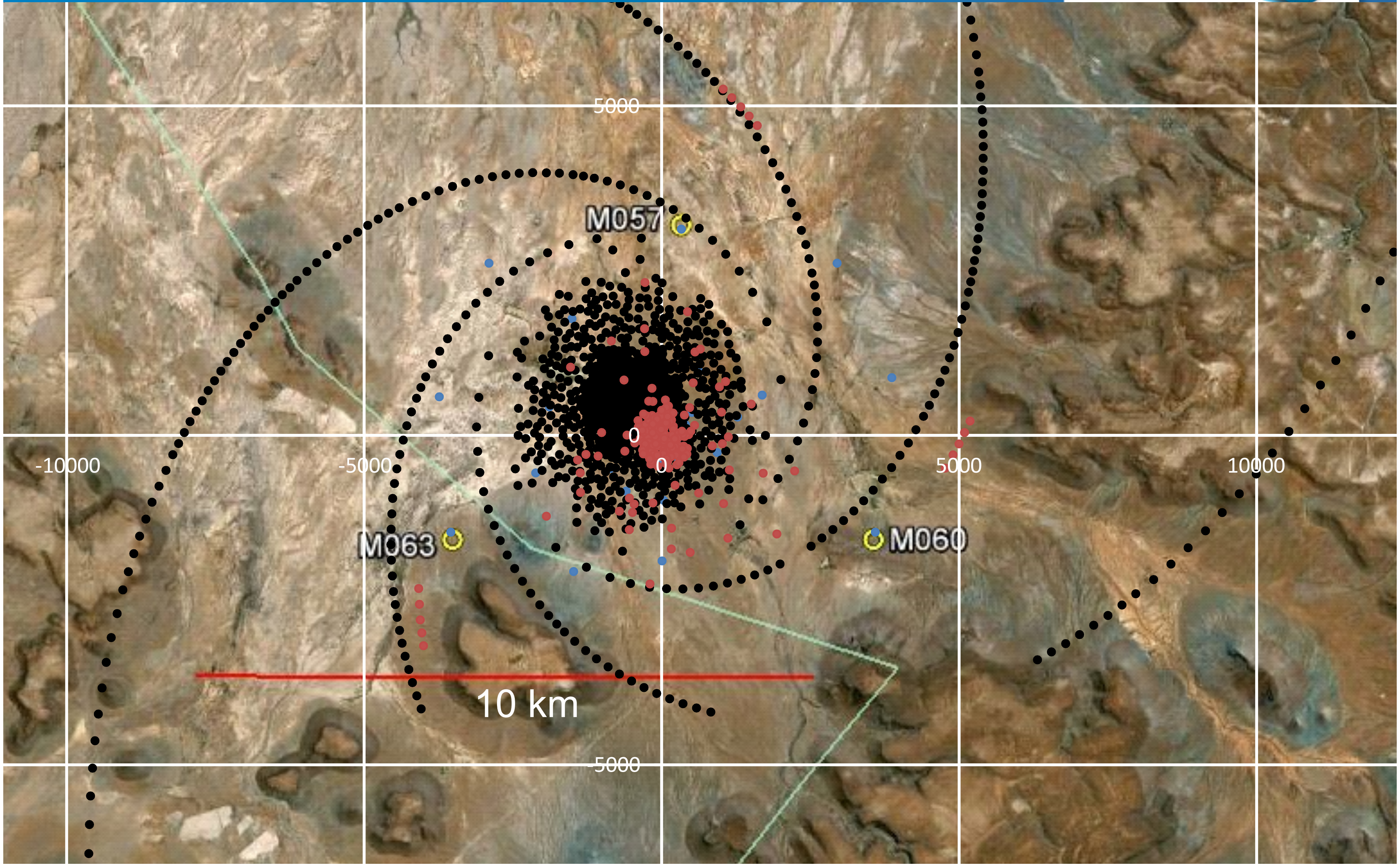
← SKA1

Array Configuration

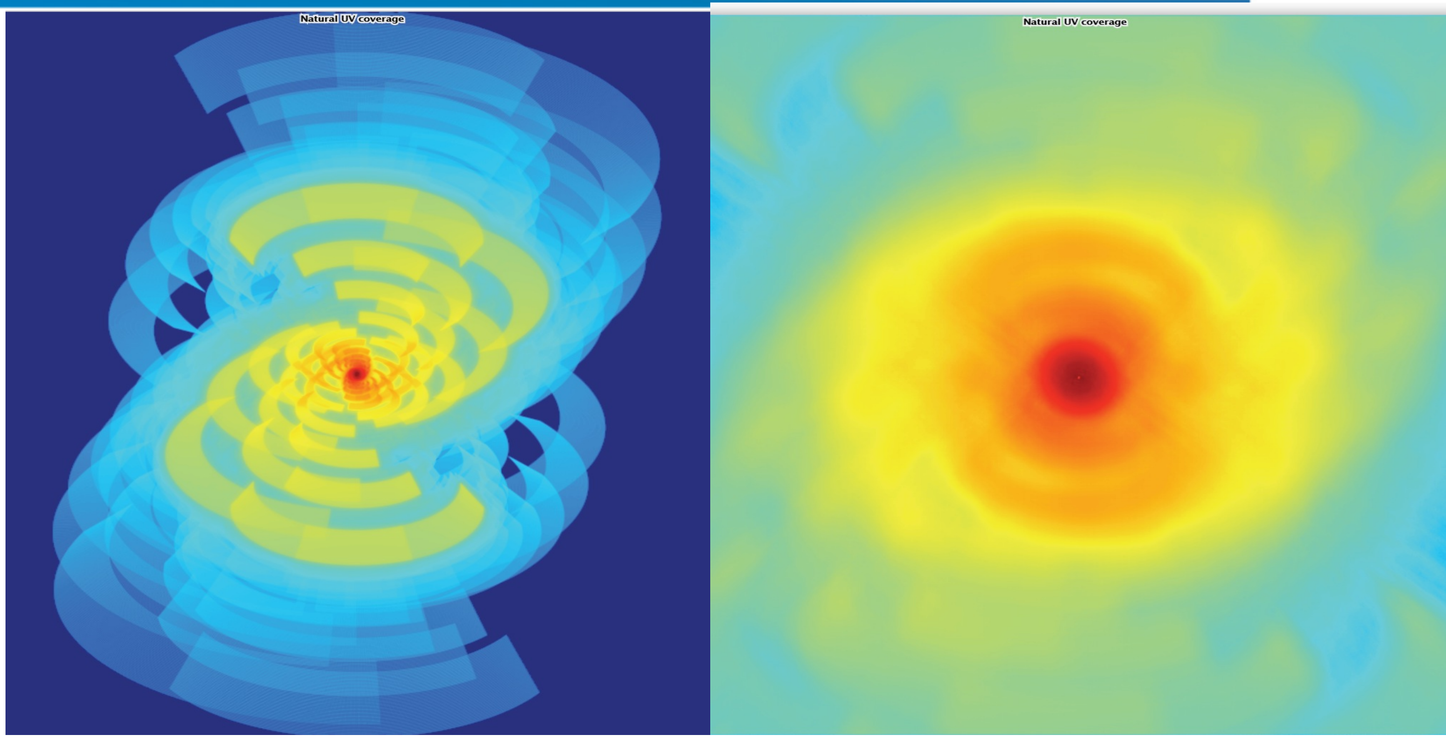
- Based on PreSKA working group configuration.
  - Dominant core for pulsar work.
    - 133 dishes in the core (~1 km diameter) + most MeerKAT dishes.
  - "Thinned" in the core to approx. compensate for MeerKAT dishes.
  - Three spiral arms as a subset of five planned for SKA2.
    - 19 dishes each arm.
  - Questions of confusion still?



Central SKA2 South Africa Core Site – Potential Dish



u-v Coverage SKA 1-mid

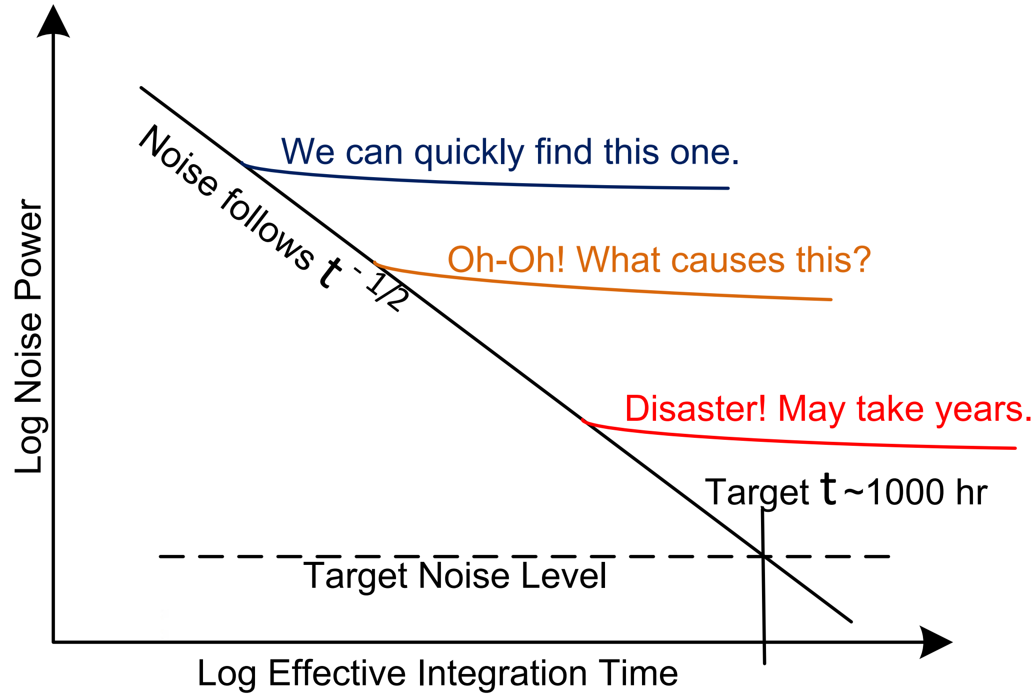


400 km | 320 km | 13 km | 12 km

- *u-v* coverage with a 20% fractional bandwidth in 8 hr observation.
  - Strong emphasis on core density enables sensitive pulsar survey but also generates patchy *u-v* coverage elsewhere. Bandwidth helps for continuum.
  - Right box shows excellent coverage at shorter spacings.

Challenge to Achieve Target Sensitivity

- With the SKA2, the telescope should be able to reach 10's of nJy in continuum with 1000 hr integration.
  - SKA2 system requirement, not just a receptor requirement.
  - Receptor performance is likely to play a limiting, if not dominant role.
- System-level systematic errors must be kept below the noise in the presence of sources ~$10^{7.3}$ times stronger in images.
  - Applies in L-band; not certain whether it should also apply at lower frequencies, where it will be more difficult.
  - Dishes for SKA1 must meet this standard if they are also to be used for SKA2.
  - Applies only after all calibration and algorithmic steps have been taken.
  - How to verify???
- Note that the SKA1 system must also be able to integrate for 1000 hr.
  - Separate SKA1 requirement.



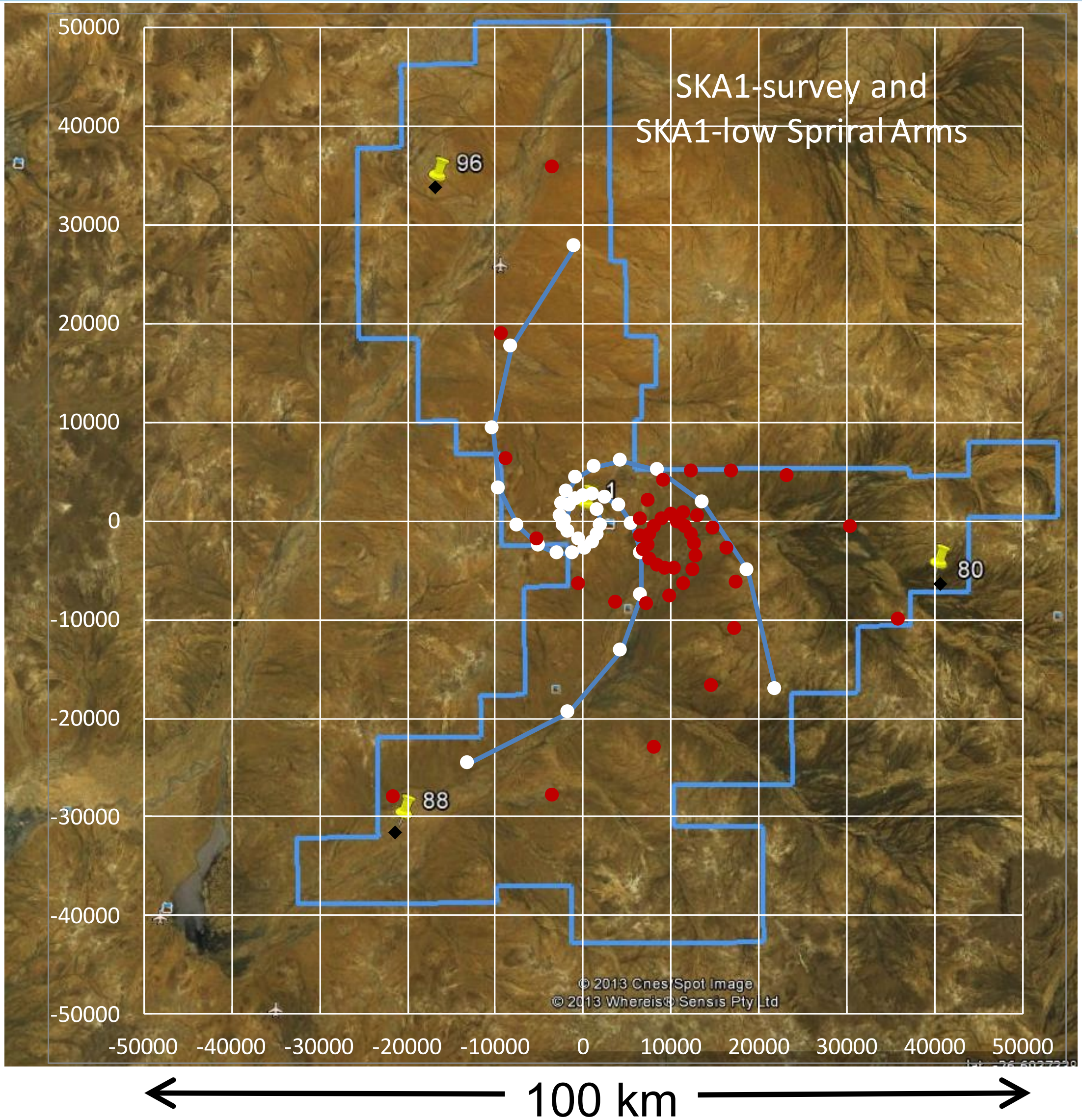
SKA1-mid Dish Qualitative Goals/ Requirements

- Optics
  - Clear-aperture, offset-Gregorian optics design.
- Receivers and frequency coverage
  - Capable of mounting five dual-pol, cryo-cooled receivers.
  - Capable of operations up to 20 GHz, although not equipped to cover this entire range for SKA1.
  - Capable of utilising PAFs.
  - Excellent performance down to ~450 MHz, good performance to 350 MHz.
  - Excellent performance to 15 GHz, good performance to 20 GHz.
  - SKA1: Continuous coverage from 350 MHz to 3 GHz in 3 receiver bands.
  - Lower frequency receivers will have a bandwidth of ~1 GHz and higher frequency receivers ~2.5 GHz in each polarisation.
- Sensitivity
  - Over majority of frequency range, optics and feeds to deliver aperture efficiency of 78%,
  - Spillover-plus-sky noise of ~6K at the zenith (L-band).
- Stability and Smoothness
  - Excellent stability of key parameters (beam shape, pointing, etc.).
  - Excellent pointing (repeatable).
  - Smoothness of response in spatial and spectral dimensions, as limited by fundamental physics (e.g. edge diffraction).
  - Minimised scattering (scattering objects tend to generate low-level resonances, which will have fine chromatic structure).
- Other
  - Very low sidelobes beyond the first one.
  - Excellent polarisation performance over beam to ~1/2 power point.
  - Beam circularity important, but not top priority.
- MeerKAT dishes equipped somewhat differently, but broadly compatible.

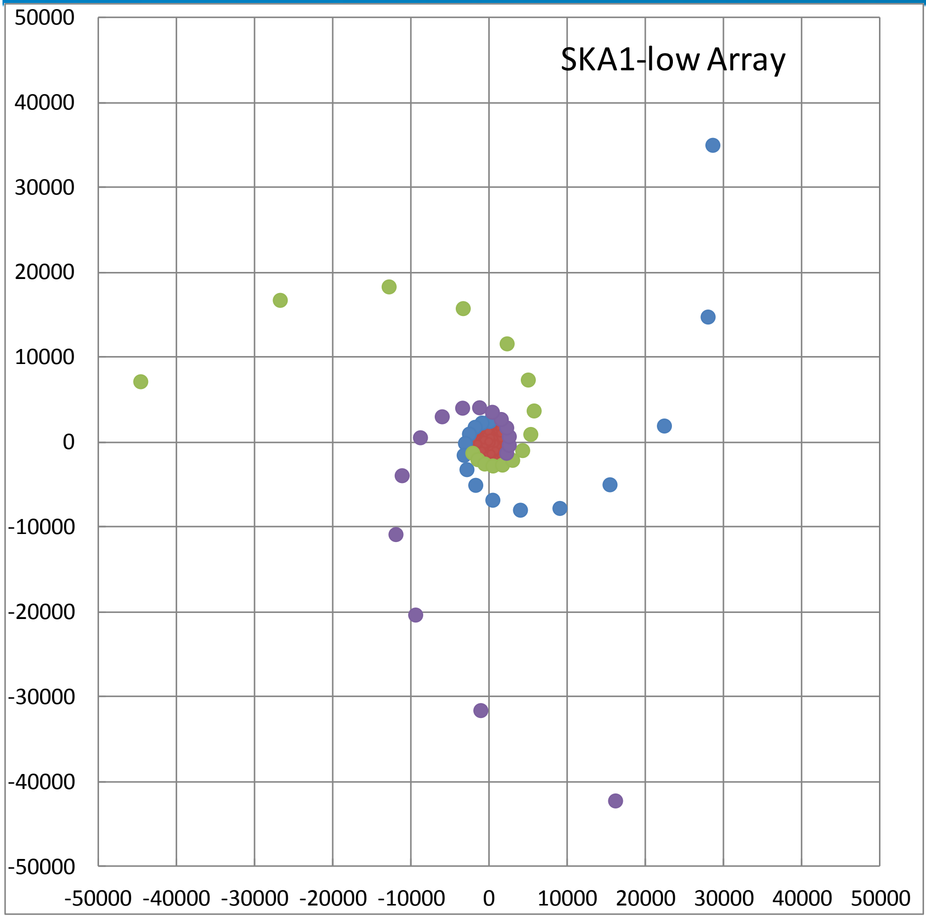
SKA1-low in a Nutshell

- Headline Science
  - Primarily address observations of the highly redshifted HI-line (emission & absorption) from the Epoch of Reionization and earlier.
  - High sensitivity continuum, potentially low-frequency pulsars, radio recomb lines, etc.
- Configuration (911 35-m diameter stations; 866 in “core”)
  - Consist of an array of ~250,000 log-periodic dual-polarised antenna elements.
  - 866 stations arranged in a very compact configuration (the ‘core’) with a diameter of ~1 km.
  - Outer stations configured in three spiral arms.
  - Radius of the configuration is ~45 km (max baseline ~80 km).
- Frequency range: 50 MHz to ~350 MHz.
- Sensitivity
  - ~1000 m^2 / K above 110 MHz at the zenith above transition frequency of ~110 MHz.
  - Brightness temperature sensitivity ~1 mK with core at the zenith above transition frequency.
- Beamforming
  - Elements will be coarse channelised and beam-formed to expose a field-of-view of ~20 deg^2 in a single smooth beam.
  - Possibilities exist for more elaborate beamformers in the core, if needed.
- Correlation & Processing
  - Signals from beamformers transported to a central signal processing building, for fine channelisation and cross-correlation.
  - Output from the correlator transported to the science data processing centre in Perth.

SKA1-Low & SKA1-survey Baseline Design Array Configurations



Array Configuration

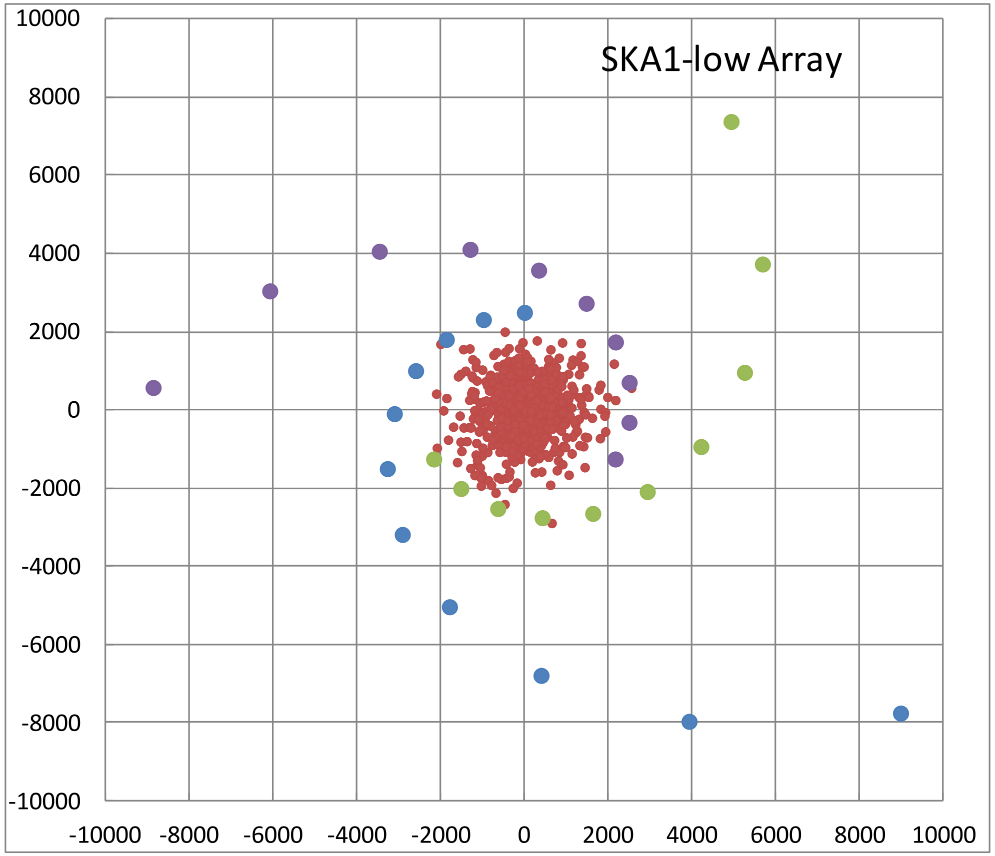


100 km

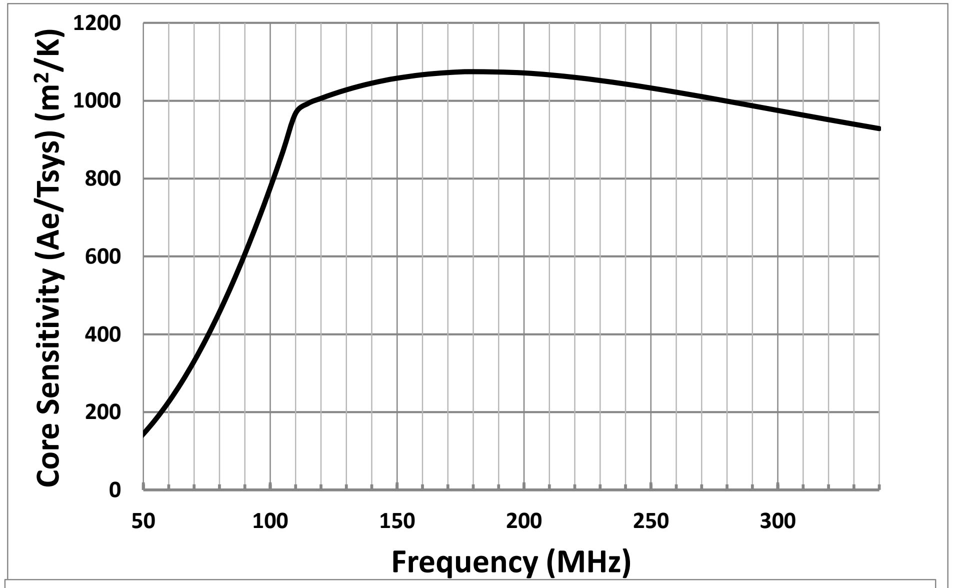
Dimensions in meters

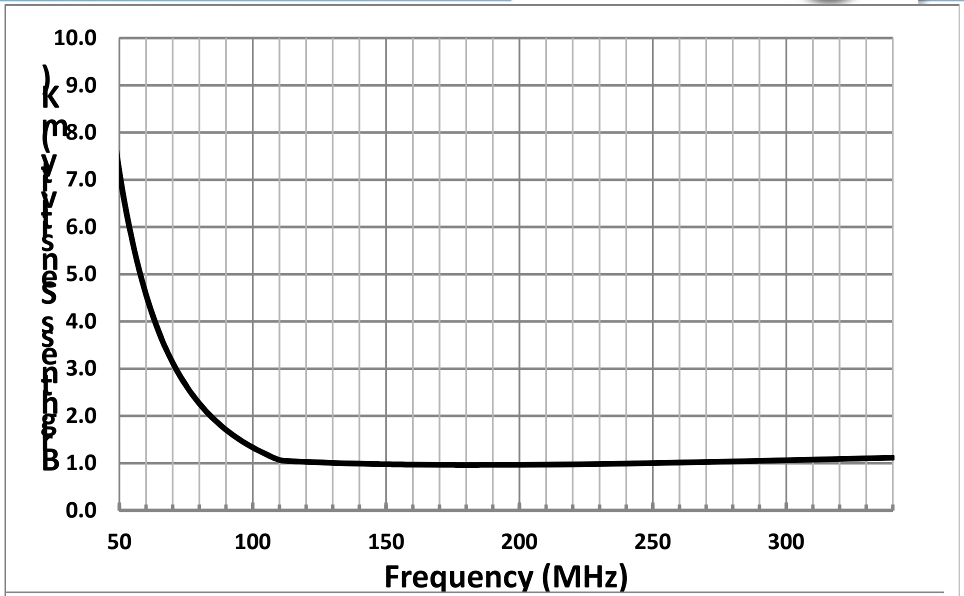
Full Extent

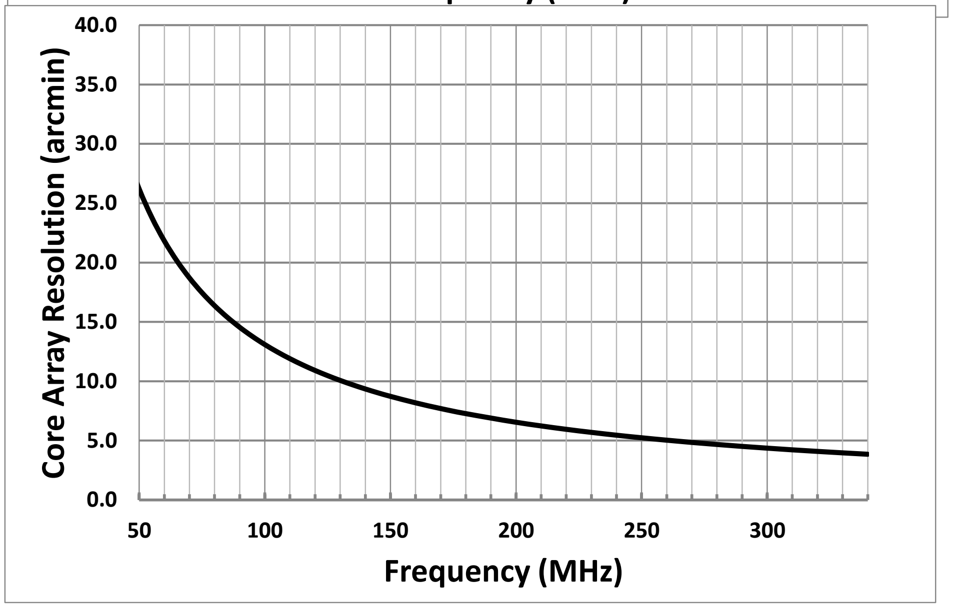
20 km

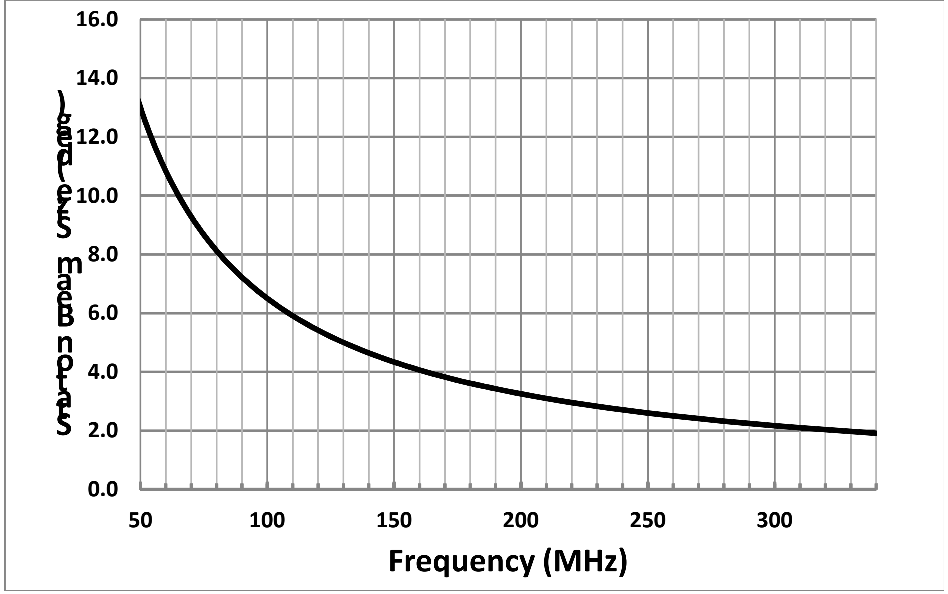


SKA1-Low
Core Sensitivity, Resolution, FoV









Performance at f>~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.

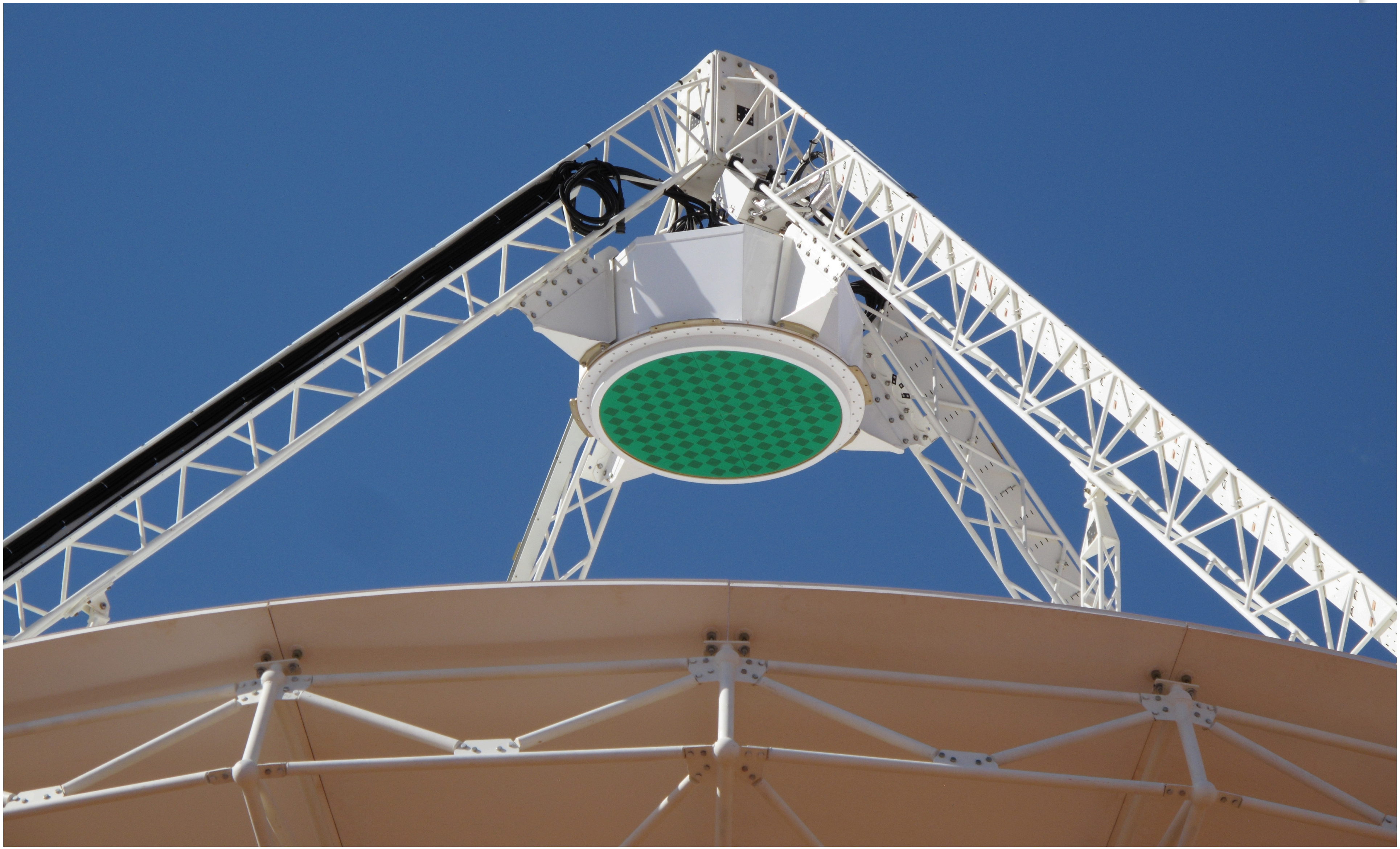
SKA1-Low
Antenna Element Selection

- 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.

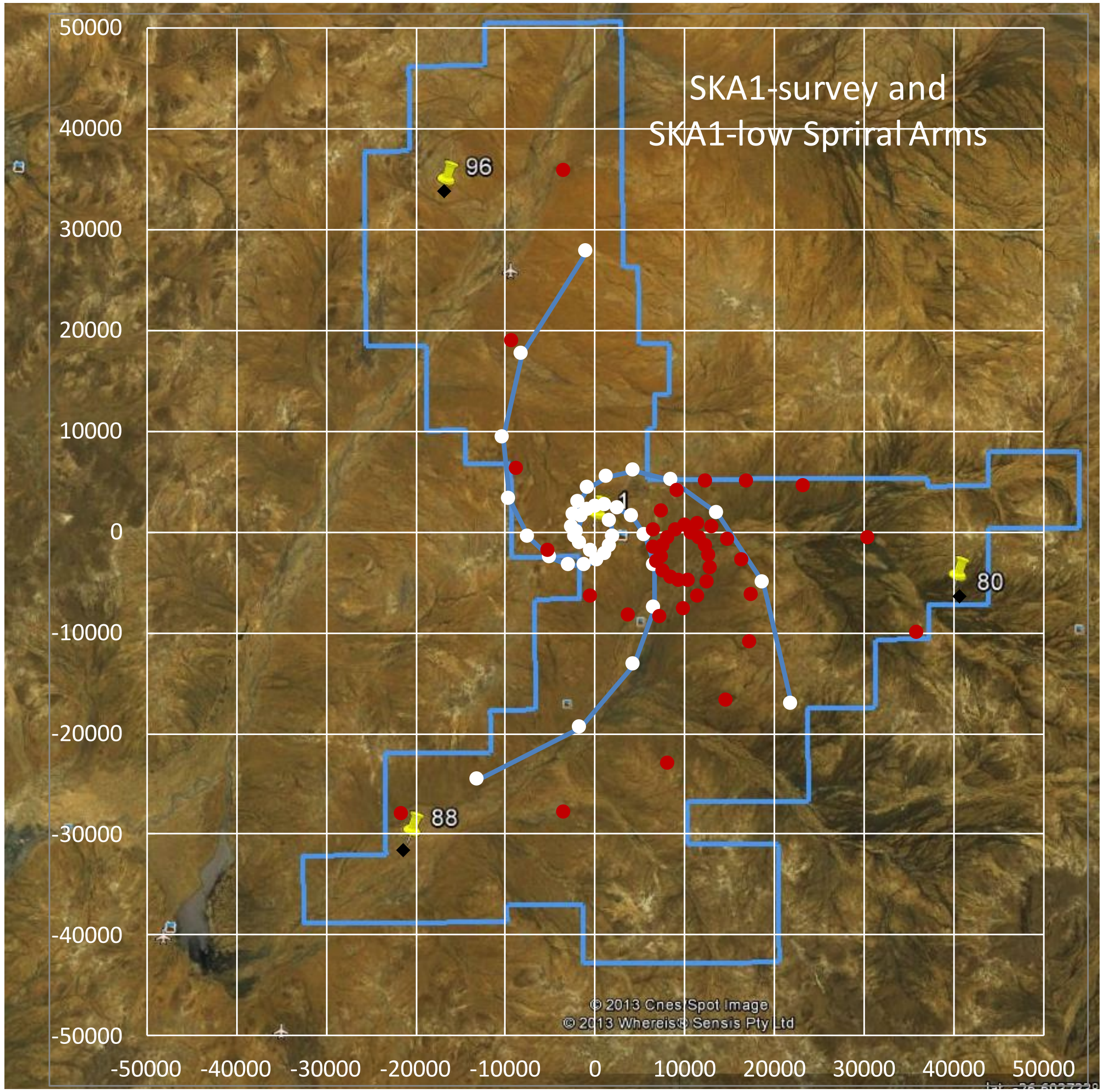
SKA1-survey in a Nutshell

- Headline Science
  - Surveys of large fractions of the sky.
  - Spectral line and continuum.
  - HI-line observations: Galaxy to moderate redshifts.
  - Continuum: total and polarised intensity.
- Mixed array
  - 60 15-m SKA1 dishes equipped with a PAF (room for 3 PAFs in 3 bands).
  - 36 12-m diameter dishes from the ASKAP array.
- Frequency coverage
  - 650 to 1670 MHz in a single dual-polarised PAF.
  - 500 MHz wide instantaneous bandwidth.
- Configuration
  - "Densified" ASKAP core with diameter ~2 km.
  - Three spiral arms to a radius of ~25 km from the centre.
- Sensitivity
  - aperture efficiency of ~80%.
  - system temperatures of ~30 K.
  - Constant Field-of-View with frequency:
    - ~18 deg^2 (36 beams at the highest frequency).
  - Survey Speed Figure-of-Merit (SSFoM)
    - $\sim 10^6\ m^4\ K^{-2}\ deg^2$.
- Signal and Image Processing
  - Central signal processing building for PAF beamforming, channelisation, cross-correlation.
  - Output transported to the science data processing centre.

ASKAP Phased Array Feed



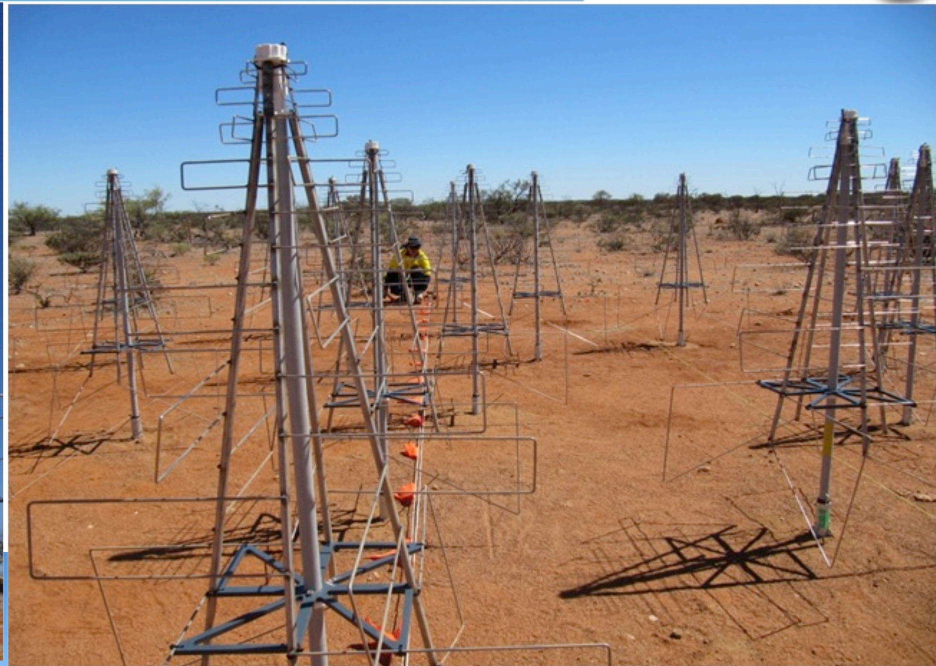
SKA1-Low & SKA1-survey BD Array Configurations

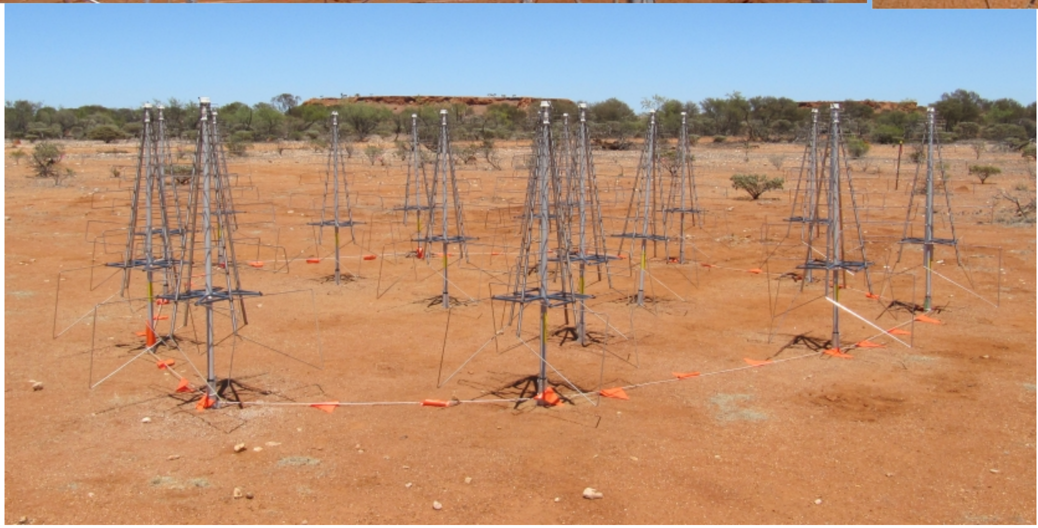


100 km

End

Log-Periodic Test Array in Australia





Cambridge-ASTRON-ICRAR & industrial partners

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

Technical Work Packages

- SKA.TEL.DSH Dish
- SKA.TEL.LFAA Low Frequency array
- SKA.TEL.SADT Signal and data transport
  - SKA.TEL.SADT.SAT Signal and data transport synchronization & timing
- SKA.TEL.CSP Central signal processor
- SKA.TEL.SDP science data processor

Signal Chain WPs

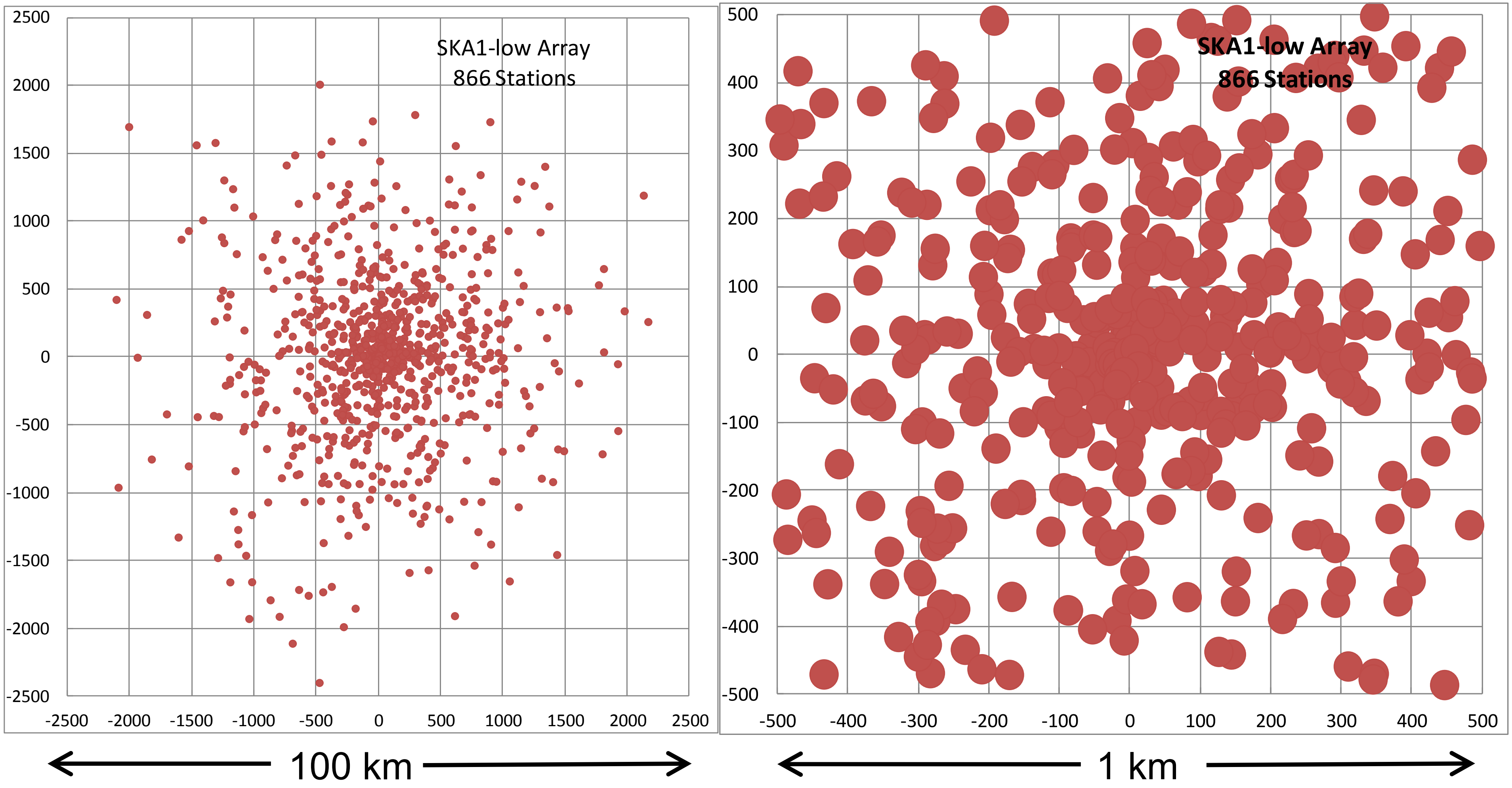
- SKA.TEL.SE system engineering
- SKA.TEL.MGR telescope manager
- SKA.TEL.INFRA Infrastructure
  - SKA.TEL.INFRA.POW Infrastructure power

System Wide WPs

- SKA.TEL.MFAA Mid frequency Aperture Array
- SKA.TEL.WBSPF Wideband single pixel feeds

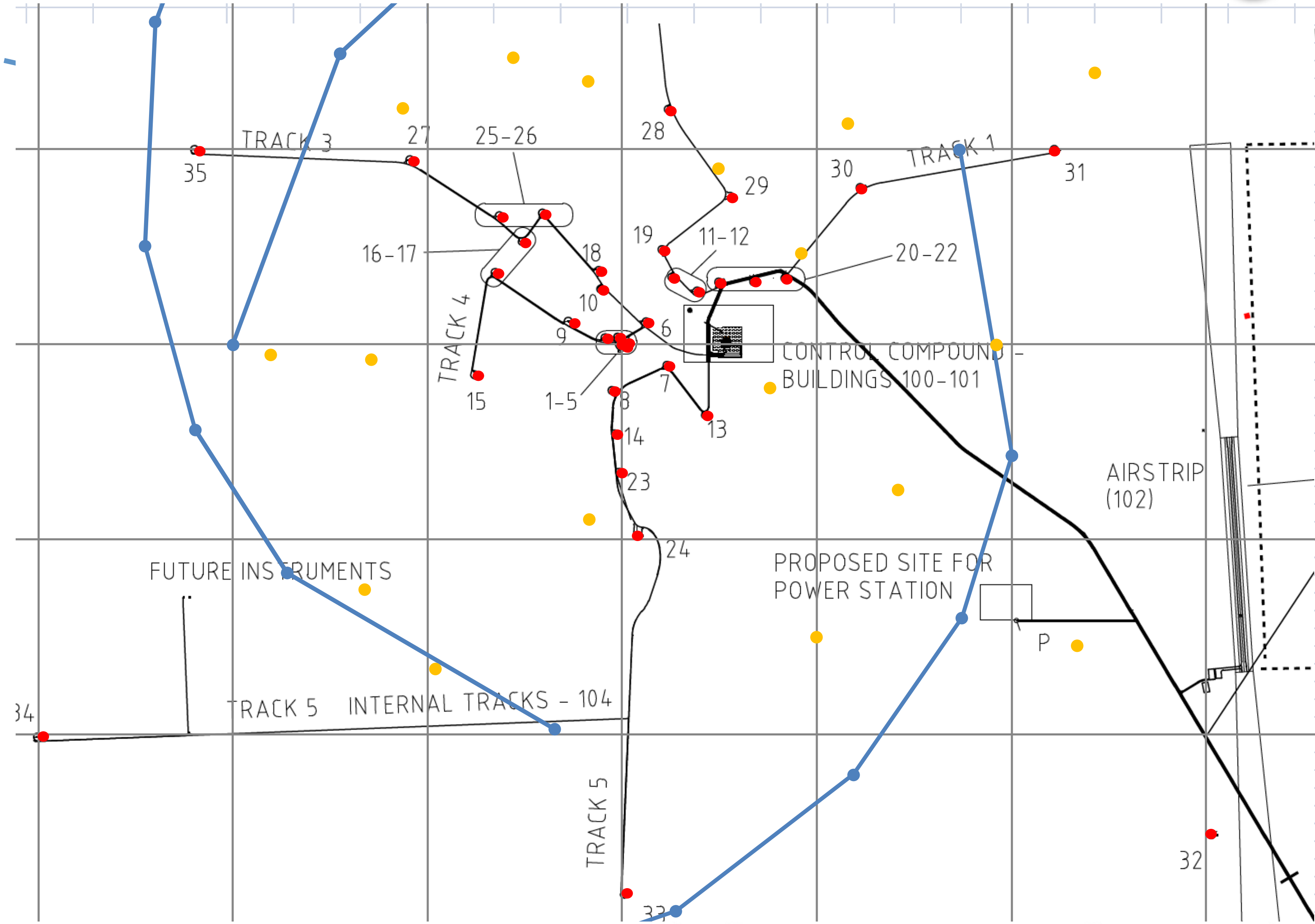
AIP WPs

Central Array Configuration

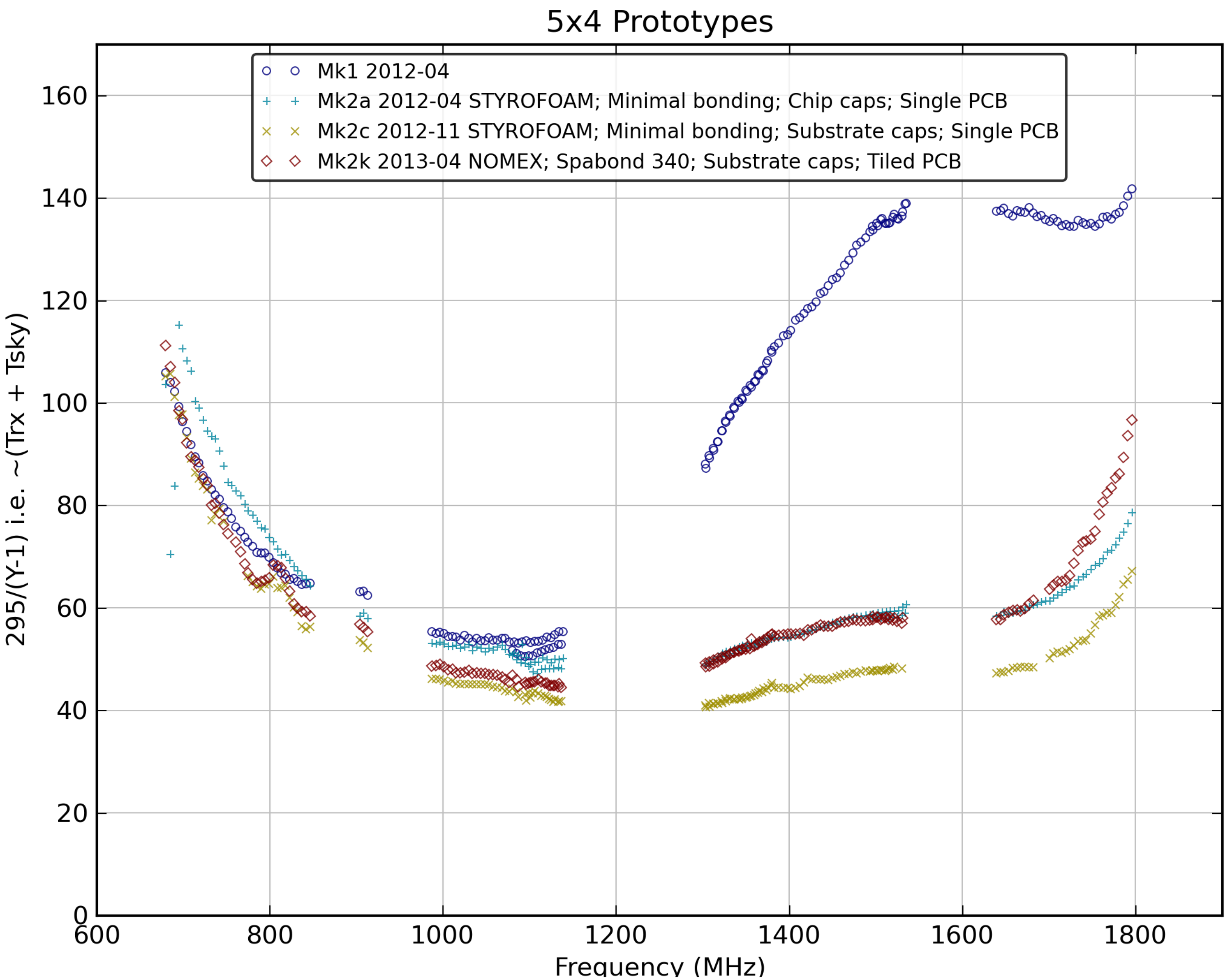


Boolardy (Aus) Inner Site

1000-m grid lines



ASKAP PAFs – Trcvr + Tsky



Measurements in aperture array mode.

Courtesy Schinckel, Hayman, Chippendale, Shaw, Forsythe (CSIRO)