SKA1: Current Baseline Design

Local HI Assessment WS
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Sept 23, 2013
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.

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.”
- …
Science Case, DRM, Requirements, and Baseline Design

Science Case
Lays out overarching goals, full suite of science

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

Baseline Design!

SCI-SYSR-0010
SCI-SYSR-0020
...
SCI-S-REQ-0110
SCI-S-REQ-0120
SCI-S-REQ-0130
SCI-S-REQ-0140
SCI-S-REQ-0150
...
OPS-REQ-0010

Baseline Design!

Requirements Document
Input from science, but from other areas as well
Approx. Design Process up to PDR

- Full SKA Science Case
- Design Reference Mission: Primary Science
- Derived Science Requirements
- System Technical Requirements
- Sub-systems (Consortia)
  1st Order Design, Costing, Interface Definition
- Science Assessment Workshops
- System Cost Analysis
  => Cost Cap
- New Baseline
  (More Detailed)
- System-level Models; Sub-system refinements
- PDR

Eventual Technical Specifications

Traceability

~1 yr
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)

<table>
<thead>
<tr>
<th></th>
<th>JVLA</th>
<th>MeerKAT</th>
<th>SKA-mid</th>
<th>ASKAP</th>
<th>SKA1-survey</th>
<th>LOFAR</th>
<th>SKA1-low</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Ae} / \text{Tsys}$</td>
<td>$m^2/K$</td>
<td>265</td>
<td>321</td>
<td>1630</td>
<td>65</td>
<td>391</td>
<td>61</td>
</tr>
<tr>
<td>$\text{FoV}$</td>
<td>$\text{deg}^2$</td>
<td>0.25</td>
<td>0.86</td>
<td>0.49</td>
<td>30</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>$\text{Survey Speed FoM}$</td>
<td>$\text{deg}^2 \text{m}^4 \text{K}^{-2}$</td>
<td>$1.76 \times 10^4$</td>
<td>$8.86 \times 10^4$</td>
<td>$1.30 \times 10^6$</td>
<td>$1.27 \times 10^5$</td>
<td>$2.75 \times 10^6$</td>
<td>$5.21 \times 10^4$</td>
</tr>
<tr>
<td>$\text{Resolution}$</td>
<td>arcsec</td>
<td>1.4 - 44</td>
<td>11</td>
<td>0.22</td>
<td>7</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>

| $\text{Ae}/\text{Tsys}$     | 6.2 x JVLA | 74x    |
| $\text{Survey Speed FoM}$   | 6.0 x ASKAP | 22x    |
|                             | 16 x LOFAR | 520x   |
Sky Noise: Fundamental System Noise Regime

- 1800 K
- 500 K
- 60 K
- 20 K
- $60\lambda^{2.55}$

Frequency, GHz

Noise Temperature, K
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 0.350 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 m²/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).
    • 256,000 channels => more than 1 km-s⁻¹ velocity resolution across all bands, except Band 1 (~3 km-s⁻¹).
  − 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
<table>
<thead>
<tr>
<th>Band</th>
<th>Sky Freq.</th>
<th>Sampled Bands</th>
<th>Potential Feed Type</th>
<th>Streams x bits</th>
<th>Total per Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>350 – 1050 MHz</td>
<td>1 x 1 GHz</td>
<td>3:1 Quad-Ridge</td>
<td>2 x 8</td>
<td>48 Gbit s⁻¹</td>
</tr>
<tr>
<td>Band 2</td>
<td>0.95 – 1.76 GHz</td>
<td>1 x 1 GHz</td>
<td>1.8:1 Corrugated Horn</td>
<td>2 x 8</td>
<td>48</td>
</tr>
<tr>
<td>Band 3</td>
<td>1.65 – 3.05 GHz</td>
<td>1 x 2.5 GHz</td>
<td>1.8:1 Corrugated Horn</td>
<td>2 x 8</td>
<td>120</td>
</tr>
<tr>
<td>Band 4</td>
<td>2.80 – 5.18 GHz</td>
<td>1 x 2.5 GHz</td>
<td>1.8:1 Corrugated Horn</td>
<td>2 x 4</td>
<td>60</td>
</tr>
<tr>
<td>Band 5</td>
<td>4.6 – 13.8 GHz</td>
<td>2 x 2.5 GHz</td>
<td>3:1 wide-band feed</td>
<td>4 x 4</td>
<td>120</td>
</tr>
</tbody>
</table>

No MeerKAT coverage
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

Array Configurations
MeerKAT and SKA2

10 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.

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**Graph: Log Noise Power vs. Log Effective Integration Time**
- Noise follows $t^{-1/2}$
- We can quickly find this one.
- Oh-Oh! What causes this?
- Disaster! May take years.
- Target $t \sim 1000$ hr
- Target Noise Level
• 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-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 deg² (36 beams at the highest frequency).
  – Survey Speed Figure-of-Merit (SSFoM)
     • ~10⁶ m⁴ K⁻² deg².

• **Signal and Image Processing**
  – Central signal processing building for PAF beamforming, channelisation, cross-correlation.
  – 256,000 channels => selected to 1 km-s-1 velocity resolution in PAF Band 2.
  – Output transported to the science data processing centre.
SKA1-Low & SKA1-survey BD Array Configurations

SKA-survey and SKA-low Spiral Arms

100 km
The large number of channels presents technical/cost issues in some areas:
- Not a major problem to produce them in the correlator.
- Data transport from correlator to the science data processor could be very expensive, depending on the distance.
- Image processing of a large number of channels is expensive.
  - See Cornwell’s talk.

Blind searches for narrow lines across wide bands may be very important.
- If so, perhaps more detailed arguments may be necessary at some stage.
- This does not mean that the baseline will change pre-maturely.
End