Towards SKA

Multi-beam concepts and technology

SKA meeting
Meudon Observatory, 16 June 2009

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Square Kilometre Array:

Next giant radiotelescope (~2020) at decimetre and centimetre wavelengths

- **Collecting area:** $10^6 \text{ m}^2$
  
  line observation: sensitivity up to 100 $\times$ current designs
  
  continuum observation: sensitivity up to 1000 $\times$ current designs (large bandwidth)

- **frequency range:** 70 MHz – 25 GHz ($\lambda$ 3 m - 1 cm)

- **Field of view:** 200 deg$^2$ @ f<0.3 GHz 50 deg$^2$ @ 1 GHz

- **Nb of FoV:** 1 to 4

- **Baseline length:** up to 3000 km

- **Wideband, wide field of view, multi beam**

- **total construction cost** $\sim 1.5 \cdot 10^9$ EUR
SKA will be a very high sensitivity instrument

=> need of a very large collecting area

  • Very large number of small dishes (~10m Ø)

and

SKA will be a general purpose instrument optimized for large surveys

=> need of large FoV

  • Very large number of small dishes
  • Multi beam operating mode
    and / or
  • Large area of aperture array
Multi-beam concepts for synthesis of independent beams:

- Tied array mode with single pixel feed on dishes
  ATA (0.5 – 11 GHz) …

- Phased Array Feed on dishes
  APERTIF (0.7 – 1.8 GHz), ASKAP …

- Aperture arrays using quasi omnidirectional antenna elements
  LOFAR (30 – 240 MHz), EMBRACE (0.5 – 1.5 GHz) …

Multi-beam concept for synthesis of grid of beams:

- Spatial fourier transform from each antenna signal

Multi beam with cluster of feeds on a dish:

- Cluster of corrugated horns (Parkes, 13, Arecibo, 7)
SKA will have a large frequency range and a wide instantaneous bandwidth:

- Single pixel feeds can cope with large frequency range, but are not multi-beam friendly

- Phased Array Feeds and aperture arrays can deliver multiple independent beams, but can’t cover large frequency range

=> SKA will use a hybrid design with

- Small to medium dishes with single pixel feeds, or (preferably) with phased array feeds
- Aperture arrays
SKA reference design (1)

Core:
200,000 m² of phased array - tiles

Station:
parabolas with Phased Array Feed
SKA reference design (2)

Numbers of dishes (2000-3000) depends on whether Phased Array Feeds and/or Aperture Arrays are used in the SKA.

P. Picard  SKA meeting Meudon 16/06/2009
Tied array mode and multi-beam for single pixel feeds

Dish Ø d (10m)
HPBW ~ \( \frac{\lambda}{d} \)
1.72° @ 1 GHz
FoV 3 sq deg

Plane wavefronts A, B, C

Max FoV limited by dish diameter
Multi-beam mode with Phased Array Feeds:

HPBW of each beam: $\approx \lambda/d$

For $d=12$ m
FoV one beam $\approx 1$ sq deg @ 1.4 GHz

Array of $\approx 10 \times 10$ small elements with 20 beams: FoV 20 sq deg

All beams can be set independently

Phased array feeds allow access to a FoV larger than the dish FoV
Aperture array:

Tiles of ~1 to a few m², 8 x 8 up to 16 x 16 dual polarized antenna elements
RF analog beamforming + digital beamforming (EMBRACE demonstrator)
All digital beamforming (2-PAD demonstrator)
Aperture Array

Engineering test of an EMBRACE tile (Nançay lab)
Amplitude and phase calibration

Beam steering computation

Digital beamforming

Digital phase shift: multiply by a complex value

Phase shift ≈ true time delay only in narrow bandwidth

Apply phase shift beam forming on subbands
Technology and operation challenges:

Small dishes with single pixel feed:
- mature technology to be optimized for low cost
- Front end cooling system

Phased array feed and aperture arrays:
- System noise ? (no use of cooled front ends)
- Very high digital bandwidth for digital signal processing (Tb/s)
- Very high power requirement

Output data flow from such a system:
- Tera bytes of data / hour...
- Availability of raw data? (10 min., 1 hour, 3 days?)
- Data archive
Ongoing developments under SKADS (E.C. FP6) and PrepSKA (E.C. FP7):

- Antenna elements for aperture arrays and phased array feeds
- LNA (Cmos, SiGe, AsGa)
- Low cost front ends (aperture array tiles)
- Cooling system for phased array feeds
- RF beamforming: Beamformer chip
- Digital beamforming
- Array layout
- Signal transport
- Calibration
SKA Pathfinders and Precursors:

**ATA (USA) - Pathfinder**

- Up to 350 dishes, Ø 6m
- Feed: Wideband single pixel
- Frequency range: 0.5 to 11 Ghz

Max. baseline: a few km
Operation: ATA 42 since end of 2007 – future enlargement?

**MeerKAT (South Africa)**

- Up to 80 dishes, Ø12m
- Feed: 2:1 corrugated horns + wideband feeds
- Frequency range: 0.7 to 10 GHz
- Instantaneous bandwidth: 1 GHz

Max. baseline: 8 km ; with flexible beam size (6-60 arcsec)
Fully operational by 2013

KAT-7: 7 antennas on site by the end of 2009
ASKAP (Australia)

Array of 36 dishes Ø12m with Phased Array Feed

- Frequency range 0.7 to 1.8 GHz
- Instantaneous bandwidth 300 MHz
- $T_{sys}$ 50 K after beamforming
- 30 independent beams of 1 sq deg each @ 1.4 GHz
- Cross correlation on a per beam basis
- FoV: 30 sq deg @ 1.4 GHz
- Max. baseline 6 km (optimized for beam size of 30 arcsec)

Western Australia site (Murchison Radio Observatory),
very low RFI environment

Digital beamforming per antenna: ~100 dual pol elements
After sub-banding, beamforming in each subband by a weighted sum of all elements, up to 30 beams in each subband.
Cross correlation of all same beams for all antennas

Beta phase of six antennas by 2011
Fully operational by 2013
### ASKAP survey speed and sensitivity:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>10&quot;</th>
<th>18&quot;</th>
<th>30&quot;</th>
<th>90&quot;</th>
<th>180&quot;</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum survey speed (300 MHz, 100uJy)</td>
<td>220</td>
<td>361</td>
<td>267</td>
<td>54</td>
<td>17</td>
<td>sq deg/hr</td>
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<tr>
<td>Line survey speed (100kHz, 5mJy)</td>
<td>184</td>
<td>301</td>
<td>223</td>
<td>45</td>
<td>14</td>
<td>sq deg/hr</td>
</tr>
<tr>
<td>Surface brightness survey speed (5 kHz, 1K)</td>
<td>-</td>
<td>-</td>
<td>1.1</td>
<td>18</td>
<td>94</td>
<td>sq deg/hr</td>
</tr>
</tbody>
</table>

Survey speeds for different angular resolutions under the assumption of a 50 K system temperature and an aperture efficiency of 0.8.

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<th>units</th>
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</thead>
<tbody>
<tr>
<td>Continuum sensitivity (300 MHz)</td>
<td>37</td>
<td>29</td>
<td>34</td>
<td>74</td>
<td>132</td>
<td>µJy/bm</td>
</tr>
<tr>
<td>Line sensitivity (100 kHz)</td>
<td>2.1</td>
<td>1.6</td>
<td>1.9</td>
<td>4.1</td>
<td>7.3</td>
<td>mJy/bm</td>
</tr>
<tr>
<td>Surface brightness sensitivity (5kHz)</td>
<td>51</td>
<td>12</td>
<td>5.2</td>
<td>1.3</td>
<td>0.56</td>
<td>K</td>
</tr>
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</table>
Square Kilometre Array

Within a week,

SKA could deliver information equivalent to...

All the words ever spoken by human beings