Phased Array Technology
Aperture Arrays
Type of AA selection

- Sparse AA-low
- Fully sampled AA-mid
- Becoming sparse

Frequency (MHz)

Sky Brightness Temperature (K)

$A_{\text{eff}}$, $T_{\text{sky}}$

$A_{\text{eff}}/T_{\text{sys}}$ (m$^2$/K)

AA frequency overlap

Dish operation

Sparse

Dense
SKA Phase 1 Implementation: 2016 - 2019

Southern Africa

- 250 15m dia. Dishes
- 0.4-3GHz

Australia

- ~280 80m dia. sparse Aperture Array Stations
- 50-450MHz

Survey: 90 Dishes
- 0.7-1.7GHz
SKA Phase 2 Implementation:
2020 on

~2700 15m dia. Dishes
0.4 – 10GHz

~250 60m dia. dense Aperture Array Stations
400-1400MHz

~280 180m dia. sparse Aperture Array Stations
50-450MHz
**Sensitivity Comparison**

**Survey Speed Comparison**

SKA\(_1\) & SKA\(_2\) will have much higher sensitivity & survey speed than existing instruments.

**Aperture Arrays**

Note: log scale!
LOFAR station
### AA-low outline specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SKA1</th>
<th>SKA2</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of array</td>
<td>Single element</td>
<td>Single element</td>
<td>Sparse array using a single wide-band element</td>
</tr>
<tr>
<td>No. of elements /station</td>
<td>300-1750</td>
<td>300-11,000</td>
<td></td>
</tr>
<tr>
<td>No. of elements total</td>
<td>250-500,000</td>
<td>3,000,000</td>
<td>Approximately</td>
</tr>
<tr>
<td>Approx. Size of elements</td>
<td>1x1x2 m</td>
<td>1x1x2 m</td>
<td>Must be small enough for the pitch</td>
</tr>
<tr>
<td>No. of polarisations</td>
<td>2</td>
<td>2</td>
<td>Each element has two receiver chains</td>
</tr>
<tr>
<td>Diameter of station</td>
<td>30 - 80m</td>
<td>30 - 180m</td>
<td>Variable in the core – tuned to experiment</td>
</tr>
<tr>
<td>Number of stations</td>
<td>280-1000</td>
<td>280-1000+</td>
<td>Anticipated number SKA “Stations”</td>
</tr>
<tr>
<td>Element communication</td>
<td>Analogue fibre</td>
<td>Analogue fibre</td>
<td>Requires copper for power</td>
</tr>
<tr>
<td>Layout</td>
<td>pseudo-random</td>
<td>pseudo-random</td>
<td>The most flexible design is as individual elements.</td>
</tr>
<tr>
<td>Frequency range</td>
<td>50-350 MHz</td>
<td>50-450 MHz</td>
<td>Under discussion maybe up to 650MHz</td>
</tr>
<tr>
<td>Digitisation rate</td>
<td>1 - 2GS/s</td>
<td>1 - 2GS/s</td>
<td>There is no frequency conversion, covers frequency range in 1 or 2 with guard bands</td>
</tr>
<tr>
<td>Digitisation depth</td>
<td>6 or 8-bit</td>
<td>6 or 8-bit</td>
<td>Required for RFI environment at these frequencies</td>
</tr>
<tr>
<td>Max instantaneous bandwidth</td>
<td>400 MHz</td>
<td>400 MHz</td>
<td>Covers operating band of array</td>
</tr>
<tr>
<td>Data rate into correlator</td>
<td>10Tb/s</td>
<td>2.2Pb/s</td>
<td>Peta = $10^{15}$</td>
</tr>
</tbody>
</table>
Challenges: low frequency AA

- Power
- Cost
- Reliability
- Technical Readiness
- Design/implementation time
- Flexibility
- Speed of deployment
- Maintainability
- Upgradability

SKA Phase1 Deployment 2017-2019
Test system in Cambridge...
... and in Western Australia

- 16 elements on “SKA site”
- Collaboration Cambridge, ASTRON & ICRAR
- Site testing
- Test bed for AAVS1 (~256 elements in 2014/5)
- Important Demonstrator
SKA1 300-1,750 Elements

AA-low Station

SKA2 300-11,000 Elements

Element power distribution

Analogue Fibre

AA-low Digitisation & Station Processing

RFI shielded

Station Beams

Control & Monitoring

System clock

Correlator & Services

Power Grid

Cooling

Element power distribution

Single or dual fibres

Power over copper

Power conditioning

LNA, filter, gain

500MHz LO

Mixer

500 MHz

Pol 2

Pol 1

Data Pol 1 & 2

Pol 2

Pol 1

Power over copper

Elements: 50-450MHz

March 2013

Phased Array Technology

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SKA_1 AA-low Station Processing

RF over Fibre from Elements

ADCs
1-2GS/s
8 bit

Spectral filters
1st Beamforming

Station beamforming

Data to Central Processing System

RFI shield

16Gb/s per element

2 x 50-450MHz

March 2013
Andrew Faulkner
Uniboard 1: Early Implementation

Shelf:
- 4 Processors
- 8 ADC interfaces
- 64 inputs (32 elements)
**Processing and digitisation**

<table>
<thead>
<tr>
<th>Technology</th>
<th>FPGA (TMAC/s)</th>
<th>Board (TMAC/s)</th>
<th># per station*</th>
<th>Power/Board, inc ADC (W)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNIBOARD 1</td>
<td>0.5</td>
<td>4</td>
<td>200</td>
<td>400</td>
<td>80kW</td>
</tr>
<tr>
<td>UNIBOARD 2</td>
<td>~4.0</td>
<td>32</td>
<td>25</td>
<td>500</td>
<td>12.5kW</td>
</tr>
<tr>
<td>SKA1 processing</td>
<td>10 est.</td>
<td>80</td>
<td>10</td>
<td>700</td>
<td>7kW</td>
</tr>
</tbody>
</table>

*allowance made for inefficiency

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**Processing requirement**

**Spectral filter:**
- Polyphase filter into 1024 channels: 10^5 MACs
- PFF rate at 1GS/s: 10^6 /s
- Processing rate per element: 2*10^11 MAC/s
- Total spectral filter proc. (1750 el.): 3.5*10^14 = 350TMAC/s

**Beamforming:**
- Each element 40GS/s (>160Gb/s): 8*10^10 MAC/s
- Total processing/station (1750 el.): 1.4*10^14 = 140TMACs
- Total station processing: ~500TMAC/s

**Analogue and Comms Power**

**Element power**
- LNA: 50mW, 100mW
- Gain chain and mux: 50mW, 100mW
- Optical Transmission: 100mw, 150mW
- Total Element power: 350mW
- All elements: <1000W

**Communications etc. power**
- Transmission: 3*56Gb/s, 100W
- Internal comms: 30*56Gb/s, 300W
- Misc.: 1000W
- Total Station: 2.5kW

**Total AA-low station power** ~10kW

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Phased Array Technology

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Technologies for SKA-low....

...we have a good starting point

<table>
<thead>
<tr>
<th>Technology</th>
<th>For...</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design for manufacture &amp; deployment, low cost</td>
<td>Antenna elements, dual polarisation</td>
<td>SKA₁: 250k – 500k</td>
</tr>
<tr>
<td>Solar power</td>
<td>Individual element power</td>
<td>1/element</td>
</tr>
<tr>
<td>Low power low noise front end:</td>
<td></td>
<td>2/element</td>
</tr>
<tr>
<td>Differential LNA T&lt;sub&gt;rx&lt;/sub&gt; 20 - 30K</td>
<td>Matched amplifier to element, gain &amp; optical drive</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td></td>
<td>2/element</td>
</tr>
<tr>
<td>RF over fibre, max 1km 1GHz</td>
<td>Analogue signal transport to processing</td>
<td></td>
</tr>
<tr>
<td>Low power digitisation 8-bit</td>
<td>Digitising each signal, 1 or 2 GS/s</td>
<td>1 or 2/element</td>
</tr>
<tr>
<td>Programmable signal processing 1-2W/channel</td>
<td>Channelisation, beamforming and correlation at station</td>
<td>Systems per station</td>
</tr>
<tr>
<td>Calibration Algorithms</td>
<td>Ensuring performance</td>
<td>--</td>
</tr>
</tbody>
</table>

Volume is the name of the game!
AA-mid Array – SKA$_2$

Development is for volume 2020 on
This is the AA-mid Power challenge...

....an awful lot of “stuff”!
## AA-mid design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of array</td>
<td>Single element</td>
<td>Dense array using Vivaldi or ORA.</td>
</tr>
<tr>
<td>Number of elements</td>
<td><strong>110,000</strong></td>
<td></td>
</tr>
<tr>
<td>Pitch of elements</td>
<td>15 cm</td>
<td>$\lambda/2$ at 1000MHz</td>
</tr>
<tr>
<td>No. of polarisations</td>
<td>2</td>
<td>Each element has two receiver chains</td>
</tr>
<tr>
<td>Diameter of station</td>
<td>56m</td>
<td></td>
</tr>
<tr>
<td>Cluster size</td>
<td>4 elements</td>
<td>Uses true time delay beamforming</td>
</tr>
<tr>
<td>Tile size</td>
<td>16 x 16 elements</td>
<td>Built out of 4 x 4 clusters</td>
</tr>
<tr>
<td>No. of Tiles</td>
<td>430</td>
<td>Each tile is ~2.4m square</td>
</tr>
<tr>
<td>Number of stations SKA₂</td>
<td>250</td>
<td>Anticipated number of Phase 2 SKA Stations</td>
</tr>
<tr>
<td>Layout</td>
<td>Dense rectangular</td>
<td>Regularly spaced</td>
</tr>
<tr>
<td>Frequency range</td>
<td>400-1450 MHz</td>
<td>Top freq at rest HI and overlap with AA-low at bottom</td>
</tr>
<tr>
<td>Digitisation rate</td>
<td>3GSamples/s</td>
<td>There is no frequency conversion,</td>
</tr>
<tr>
<td>Digitisation depth</td>
<td>6/8-bit</td>
<td>Required for RFI environment at these frequencies</td>
</tr>
<tr>
<td>Beamforming technology</td>
<td>Digital</td>
<td>Using after element cluster outputs</td>
</tr>
<tr>
<td>Max inst. bandwidth</td>
<td>1000 MHz</td>
<td>Covers operating band of array</td>
</tr>
<tr>
<td>Max output data rate</td>
<td>16Tb/s</td>
<td>Organised as 4+4bit complex data</td>
</tr>
</tbody>
</table>
AA-mid elements

Vivaldi

FLOTT: (a)(d)
BECA: (b)(e)
ORA: (c)(f)
SKA₂ AA Station processor

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

Each link is 12 fibre lanes@10Gb/s

To Element Digitisation

Primary Station Processor Board (max 35)

Secondary Station Processor Board (max 35)

Station Processor

Long distance drivers

Optical links

To Correlator

PChip

12-channel Rx module, e.g. Avago AFBR-820BxxZ

12-channel Tx module, e.g. Avago AFBR-810BxxZ

Total raw input data rate: 4.32Tb/s

Total raw output data rate: 4.32Tb/s max

"All to All" Connections

Each link is 12 fibre lanes@10Gb/s

25 watt
Possible AA-mid construction

Top View

Ground

Non-conducting Guideframe
Membrane
Guideframe
Ground plane
Beamformer
Beamformer
The join!
Tile support
### Technologies SKA-mid....

**...very demanding requirements**

<table>
<thead>
<tr>
<th>Technology</th>
<th>For...</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated Design for simple manufacture, very low cost</td>
<td>Antenna elements, dual polarisation</td>
<td>SKA₂: 20m – 30m</td>
</tr>
<tr>
<td>Even element spacing across array</td>
<td>High quality beams</td>
<td>--</td>
</tr>
<tr>
<td>Low power, low noise front end:</td>
<td>Integrated LNA with element</td>
<td>2/element</td>
</tr>
<tr>
<td>Differential LNA $T_{rx} &lt; 20K$</td>
<td>Digitising each signal, 3GS/s</td>
<td>2/element or cluster</td>
</tr>
<tr>
<td>Power $&lt;100mW$</td>
<td>Channelisation, beamforming and correlation at station</td>
<td>Systems per station</td>
</tr>
<tr>
<td>Low power digitisation 6-8-bit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Programmable signal processing $&lt;500mW/$channel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;20$TMAC/chip</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration Algorithms</td>
<td>Ensuring performance</td>
<td>--</td>
</tr>
</tbody>
</table>

**Low Power and integration are critical**