SKA-low array

Eloy de Lera Acedo
Cambridge University
Overview

• The SKA-low array system
• SKA-low front-end technology development
• Simulations and calibration for SKA-low
• Future work and conclusions
The SKA-low array system
A central bunker will integrate the LFAA beamforming/correlation, signal transport, Maser clock and local monitoring and control.
LFAA signal flow

SKA MidPrep workshop, ASTRON, NL, 31st March 2014
LFAA consortium

✓ Project Leader: Jan Geralt bij de Vaate (ASTRON)
✓ Project Engineer: Andy Faulkner (Cambridge)
✓ Project Scientist: Carol Jackson (ICRAR)
✓ Project manager: Andre van Es (ASTRON)

Work Packages:
- Engineering management (Jan Geralt bij de Vaate - ASTRON)
- System Engineering (Andy Faulkner - UCam)
- Antenna and low noise amplifier (Eloy de Lera Acedo - UCam)
- Receiver (Jader Monari – INAF)
- Signal Processing (Kris Zarb Adami – Oxford)
- Array Prototypes (Adrian Sutinjo – ICRAR)
- Local Infrastructure (Tom Booler – ICRAR)
- Local Monitoring and Control (Pieter Benthem - ASTRON)
<table>
<thead>
<tr>
<th>Component</th>
<th>Includes</th>
<th>Budget cost for SKA1 (each antenna sub-system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna Mechanical components</td>
<td>Radiating arms, Support structure including base, Electronics housing, Ground plane (if required), Mechanical shielding, Fixings</td>
<td>€60</td>
</tr>
<tr>
<td>Signal Chain Electronic systems</td>
<td>Low noise amplifier, Matching components, Amplifiers and filters, Laser driver, Laser control, Local power regulation, Connectors, Circuit boards, Shielding mounted on board</td>
<td>€40</td>
</tr>
<tr>
<td>Solar power unit</td>
<td>Solar cells, Control electronics, Battery/super-capacitor, Enclosure and fixings, Cable connections and connectors</td>
<td>€50</td>
</tr>
<tr>
<td>Deployment</td>
<td>Antenna sub-system assembly, Transport from site receiving area to antenna placement site, Deployment at site including final assembly, Accurate positioning and alignment, Connection to fibre links, Local installation test and identification</td>
<td>€30</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>€180</td>
</tr>
<tr>
<td>Week</td>
<td>Date</td>
<td>Event</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>T0</td>
<td>1 Nov. 2013</td>
<td>Official start of the consortium work. Also, the initial release of the &quot;Level 1&quot; requirements for the SKA1.</td>
</tr>
<tr>
<td>T0+12</td>
<td>1 March 2014</td>
<td>Release of detailed “Level 1” requirements</td>
</tr>
<tr>
<td>T0+34</td>
<td>1 July 2014</td>
<td>Preliminary installation plan (including demonstration plan).</td>
</tr>
<tr>
<td>T0+46</td>
<td>14 Sept. 2014</td>
<td>System Requirements Review (documents only)</td>
</tr>
<tr>
<td>T0+50</td>
<td>Oct. 2014</td>
<td>Preliminary Design Review</td>
</tr>
<tr>
<td>T0+72</td>
<td>1 April 2015</td>
<td>AAVS1 Detailed design Review</td>
</tr>
<tr>
<td>T0+85</td>
<td>1 July 2015</td>
<td>Completed installation plan including demonstration</td>
</tr>
<tr>
<td>T0+112</td>
<td>31 Dec. 2015</td>
<td>Installation and commissioning of AAVS1 completed</td>
</tr>
<tr>
<td>T0+140</td>
<td>1 July 2016</td>
<td>Submit test and evaluation report for AAVS1</td>
</tr>
<tr>
<td>T0+148</td>
<td>1 Sept. 2016</td>
<td>Critical Design Review for LFAA, including submission of manufacturing documentation</td>
</tr>
<tr>
<td>T0+156</td>
<td>1 Nov. 2016</td>
<td>Closure of Pre-construction Phase</td>
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</tbody>
</table>
Introduction
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- $2^{18}$ antennas
- $D_{\text{station}} = 35$ m
- 256 antennas/station
- $D_{\text{average}} = 1.93$ m
LFAA Sensitivity

\[
\frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{2}{\pi} \frac{\sqrt{G}}{\sqrt[4]{T_A}} \left(1 + \frac{T_0 + T_{\text{rec}}}{1 - G^2}\right)
\]
LFAA Sensitivity

\[ T_{sky} = 60 \times l^{2.55} \]

<table>
<thead>
<tr>
<th>Frequency /MHz</th>
<th>Min /m2/K</th>
<th>Typical /m2/K</th>
<th>Max /m2/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>108.5</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>760</td>
<td>842</td>
<td>925</td>
</tr>
<tr>
<td>160</td>
<td>1025</td>
<td>1140</td>
<td>1255</td>
</tr>
<tr>
<td>220</td>
<td>975</td>
<td>1081</td>
<td>1190</td>
</tr>
<tr>
<td>280</td>
<td>941</td>
<td>1046</td>
<td>1150</td>
</tr>
<tr>
<td>340</td>
<td>887</td>
<td>986</td>
<td>1084</td>
</tr>
</tbody>
</table>
LFAA Sensitivity (extended band)

A/T per polarization for SKA

Freq /GHz
A/T /m²/K

LFAA
Dishes
LFAA at 30°
LFAA at 45°
LFAA at 60°
LFAA polarization

\[ IXR_J = \left( \frac{\kappa(J) + 1}{\kappa(J) - 1} \right)^2 \]

➢ Credit: “IXR SKALA with GP vs Vivaldi V2 with Soil C”, 08/10/2012 – B. Fiorelli.
SKA-low front-end technology development
SKALA: Design

• **SKALA: SKA Log-periodic Antenna**
  - Good Impedance
  - Pattern width controllable (7:1 band!)
  - Low back lobe at high frequencies

• Dual polarization

• 9 wide dipoles: top 2 are not resonant in band

• Maximizing A/T in the +/- 45 deg. Region

\[
\frac{A_{\text{eff}}}{T_{\text{sys}}} = \frac{\lambda^2}{4\pi} \cdot G_{\theta,\phi} \cdot \left( \eta_{\text{rad}} \cdot T_A + \left(1 - \eta_{\text{rad}}\right) \cdot T_0 \right) + T_{\text{rec}}
\]

  - Distance to ground plane
  - Opening angle (trade off: A_{\text{eff}} and XP): 10°
  - Antenna size/footprint
  - Growing factor

Antenna + LNA: 90€/element
SKALA: Design

- Ideally; differentially fed for lowest noise.
- Feeding at the top for practical reasons:
  - Avoid Damage in case of flooding
  - LNA and electronics (RFOF, etc.) could be integrated at the top of the antenna.
SKALA-2

Credit: MIT
Measurements: Pattern

150 MHz 300 MHz 450 MHz

Hplane Co Polarised

-200 -150 -100 -50 0 50 100 150 200

-45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20

Measurement CST Simm
Measurements: Pattern (with LOFAR)

NOAA 3 sat: 137 MHz

- Also: Beam forming with LOFAR HBA, cross-correlation, LNA stability over large periods of time, etc.
- Next: Correlation of LOFAR with SKALA array?
Measurements: Pattern (with Hexacopter - INAF)
Measurements: Near field patterns / Cross-polarization / IXR

Near Field Scanner does not give meaningful measurements.

Next step: Try with Celestial Sources (MWA, LOFAR).

Credit: B. Fiorelli, ASTRON.
Measurements: LNA

- 1st stage amplifier with Agilent noise analyser in reverberation chamber.

![Graph showing measured noise temperature across a range of frequencies and temperatures.]
Test arrays

- **AAVS0, and AAVS05:**
  16 dual-polarised SKALA elements.
- **Aim:** Test realistic SKA AA-low front-end technology in an array environment.
  - Cross check with simulations: mutual coupling, embedded element patterns and noise.
- **Tests:**
  - Mutual coupling.
  - Patterns (using near field probe, micro-copter, 2 element interferometer (alt-az mount), etc.).
  - Noise: Hot/cold pointing of the array.
  - RFI & satellites.
  - Imaging experiment.
  - Further tests to check software, calibration strategies, cross-polarization, cross-talk, tolerances, lightning modelling environmental, etc.
AAVS0 test array at Lords Bridge
Test arrays

- Mutual coupling
AAVSO

- Used so far for impedance and coupling measurements in an array environment.
- Full receiver system to be deployed soon to carry out pattern, noise and polarisation measurements.
- To be used in conjunction with an alt/az mount for measuring antenna patterns using strong sources such as Cas-A and Cyg-A.
- Will allow testing of RFoF system in the field.
- Allow development of some early calibration strategies.

SKA MidPrep workshop, ASTRON, NL, 31st March 2014
AAVS0.5 test array at MRO, Western Australia
AAVS0.5: RFI Testing

- Credit: A. Sutinjo, F. Schlagenhauber
AAVS0.5: 24 hour drift-scan

• Credit: A. Sutinjo, P. Hall

SKA MidPrep workshop, ASTRON, NL, 31st March 2014
AAVS0.5: Correlation with MWA (first image)

- 2 minute integration, wide-field snapshot, centred on 3C444
- AAVS 0.5 baselines only (but calibrated using whole MWA)
RFoF: 2\textsuperscript{nd} prototype

Credit: Nima Razavi
RFOF: 2nd prototype performance

- Design BW: 50-700 MHz, -60dBm input, <2dB Passband ripple
- 1310nm, single mode G. 652/G. 655 fibre, LC/UPC connector
- Pros: Good link performance across SKA LFAA band, small footprint (SFP), low power (Tx: 5V@30mA, Rx: 5V@95mA)
- Cons: Temperamental connectors (not angled)

Credit: Nima Razavi
How configuration affects astronomical measurements

Irregularity and in particular randomness are vital for under-sampled antenna arrays
Effects of mutual coupling in regular arrays
Simulations and Calibration for SKA-low
OSKAR2 simulations

Telescope Station layout (core)
X: East (metres)
Y: North (metres)

Comparison of VLSS (minus 50 brightest sources) with generated sky model (broken power law, 2M sources)

MoM-MBF simulation of large irregular arrays

- Based on Method of Moments + MBFs (CBFs) and the interpolation technique presented in [1], where the computation of interactions between MBFs is carried out by interpolating exact data obtained on a simple grid.

Mutual coupling in irregular arrays

\[ e = 10 \log_{10} \left( \frac{E_{\text{mean}}(\theta, \phi) - E_{\text{single}}(\theta, \phi)}{} \right)^2 \]

Random configuration

\[ \begin{align*}
&\begin{cases}
E_{\text{mean}}(\theta, \phi) = E_{\text{single}}(\theta, \phi)
\end{cases} \\
&\begin{cases}
E_{\text{mean}}(\theta, \phi) = E_{\text{single}}(\theta, \phi)
\end{cases}
\end{align*} \]

\[-\frac{50}{0} 50\]

\[-60\]

\[-50\]

\[-40\]

\[-30\]

\[-20\]

\[-10\]

\[\Theta^{(\circ)}\]

\[\text{E-plane}\]

\[\text{H-plane}\]

\[\sim 35 \text{ dB}\]
Station_Beam = Array_Factor \times \text{Average\_EEP}
Beam Models for pattern prediction/calibration (inspired by Jan Noordam and the 3GC workshops)
Spherical Harmonics
Zernike functions

$$e^{jn\alpha} F_{m}^{|n|} (r/b)$$

Picture from Wikipedia
Array factorisation

\[ \mathbf{J}_{ns} \approx \sum_{p=1}^{P} C_{nsp} \mathbf{J}_p^o \]

Antenna index

<table>
<thead>
<tr>
<th>MBF 1</th>
<th>MBF 2</th>
<th>( \cdots )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{111} )</td>
<td>( C_{211} )</td>
<td>( C_{311} )</td>
</tr>
<tr>
<td>( C_{112} )</td>
<td>( C_{212} )</td>
<td>( C_{322} )</td>
</tr>
</tbody>
</table>

Coefficients for IDENTICAL current distribution

\[ \mathbf{F}_s \approx \sum_{p=1}^{P} \sum_{n=1}^{N} \left( \sum_{s=1}^{N} A_s C_{nsp} \right) e^{jk\hat{u} \cdot \mathbf{r}_n} \mathbf{F}_p^o \]

\[ \mathbf{A}_p \]

\[ \mathbf{AF}_p \]
Zernike representation of deficiencies in the pattern including mutual coupling

\[
\overline{F_{rec}}(\theta, \phi) = \sum_{m=1}^{\infty} \alpha_m \sum_{i=1}^{n} \overline{f_i}(\theta, \phi) e^{-j(\varphi_i-\varphi_{i,0})} Z_m
\]

• Basis functions = EEPs.
  • They can be pre-computed accurately.
  • They are smooth and can be stored with low resolution.

• The variations wrt the simulated response are mapped using Zernike polynomials.
  • They are generic and flexible.
  • We can optimize the number of coefficients needed according to the number of sky sources available.

• The weights for the “predicted” pattern can be found from the combination of basis functions.
Low Order Beam Models for Calibration

Zernike representation of deficiencies in the pattern including mutual coupling

\[
F_{\text{rec}}(\theta, \phi) = \sum_{m=1}^{l} \sum_{i=1}^{n} \alpha_m \overline{f_i}(\theta, \phi) e^{-j(\varphi_i - \varphi_{i,0})} Z_m
\]

- The **Embedded Element Patterns** (EEPs) define the “expected” array pattern.
- The variations with respect to the simulated response are mapped using **Zernike polynomials**.
- The **weights** for the “reconstructed” pattern can be found from the combination of basis functions and a least squares estimation from a few measured points.

*Before: C. Craeye et al. (2012): AP = \[ \sum_k A F_k x M B F_k \]
Use of pre-computed EEPs

\[
\overline{F}_{rec}(\theta, \phi) = \sum_{m=1}^{n} \alpha_m \sum_{i=1}^{n} f_i(\theta, \phi) e^{-j(\varphi_i - \varphi_{i,0})} Z_m
\]

- They can be pre-computed accurately.
- They are smooth and can be stored with low resolution (enough for main beam and first few side-lobes). Better simulated EEPs mean less Zernike polynomials needed.
Use of Zernike polynomials

\[ \overline{F}_{rec}(\theta, \phi) = \sum_{m=1}^{\infty} \sum_{i=1}^{n} \alpha_m f_i(\theta, \phi) e^{-j(\varphi_i - \varphi_{i,0})} \]

- It is inspired from radiation from apertures, but including effects of mutual coupling. In here, the Zernike polynomials map the divergences in the main beam and first side-lobes!
- They are generic and flexible.
- We can optimize the number of coefficients needed according to the number of available measurement points.

Similar to theory of circular apertures:

Related work: C. Craeye et al. (2012), R. Maaskant, M. Ivashina, et al. (2012), etc.
The array pattern is modeled with (approximately) computed embedded element patterns. Each pattern is multiplied by a constant with smooth variation over the array (Zernike function). Zernike coefficients are estimated in least-squares sense based on observations.
Tests: Pointing error (2 deg.) – scanning

Scan:
Θ = 45 deg.
Φ = 90 deg.

Error Rec. - Actual

t = 36, w = 81

t = 15, w = 16

*t : number of Zernike polynomials / w : number of measured points.
Tests: Dead elements (10%)

Error Rec. - Actual

$t = 3$

$t = 10$

$t = 21$

$t = 36$

$t :$ number of Zernike polynomials / $w :$ number of measured points = 57.
Conclusions and Future Work

• The LFAA array will have a major demonstrator in Western Australia (AAVS1 with approx. 512 elements) by mid 2015. End of 2016 is the end of the pre-construction phase.

• Front-end technologies are being developed to meet the SKA budget and deployment/mechanical/environmental limits.

• Accurate beam models for calibration are essential and already exist. Use of UAV systems and demonstrator arrays are key for these developments.
Thank you