SKA-low array simulations and beam modelling for calibration

University of Cambridge
Eloy de Lera Acedo, Nima Razavi-Ghods, Edgar Colin-Beltran

University of Oxford
Fred Dulwich
Benjamin Mort

Univeriste catholique de Louvain
Christophe Craeye, David Gonzalez-Ovejero (now JPL), Quentin Gueuning, Christopher Raucy, Remi Sarkis

University of Manchester
Keith Grainge

ASTRON
Michel Arts
Benedetta Fiorelli (now ESA)
Overview

- Introduction
- Physical effects
- EM simulations of SKA antennas and stations
  - Validation
- Low-order beam models for calibration
- Full SKA simulations (OSKAR)
- Conclusions and Future Work
SKA-low technical description

**Antenna:** Log Periodic

**No. of ant.:** 131,072 \((2^{17})\)

**Ant. Spacing, min:** 1.5m (av. ~1.9m)

**Station size:** 256 antennas
35m dia.

**No. of stations:** 512

**Frequency:** 50MHz – 350MHz
(or 650MHz…)

**Scan angle:** >45°

**Sensitivity:** 500m²/K (110–350MHz)

**Polarisation:** Dual (of good quality)

**Beam size:** >5° (no beam stitching)

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**Why sparse?**

**Why random?**
Sparse arrays (AA-low)

Num. antennas: 10,000,000
Int. time: 1,000 hr
Velocity resolution: Km/s

Sparse arrays (AA-Mid)

Num. antennas: 10,000,000
Int. time: 1,000 hr
Velocity resolution: Km/s
SKA-low technical description

- Early and relevant papers:


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Physical effects

- Effects with slow changing cycles:
  - Mutual Coupling (change with “dead antennas”, etc.)

\[ \text{~35 dB} \]
Physical effects II

- Effects with slow changing cycles:
  - Cabling
  - Ground plane/soil (small effect on Stokes I sensitivity, strong in polarization)

PEC ground 50 MHz

Desert ground:
- 10 % moisture content
- Relative permittivity: 6.31
- Conductivity: 22 mS/m
Physical effects III

- Effects with slow changing cycles:
  - Misalignments

- Effects with fast changing cycles:
  - Electronics (LNA impedance, noise), RFoF. Do we need to re-compute the patterns or just tune the parametrized models?
SKA-low signal chain

Antenna & LNA

Receiver

Signal Processing

Antenna structure

RFoF

Tile Processing module, TPM

Spectral filters

Tile Beamforming

Part Station beamforming

Network

Data out

Antenna

Processing Facility

ADC

Tile Processing module, TPM

Spectral filters

Tile Beamforming

Part Station beamforming

Network

Data out
• More about gain and phase effects in SKA Memo 153 (Sinclair et al.)
• But SKA-low is an all digital array! We can correlate all elements and we can try to correct for this.
• SKA-AAMid: analogue beam forming?
EM simulations of SKA-Low1

- Simulated SKA-Low1 sensitivity (before RBS)
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EM simulations of SKA stations

• Antenna simulations
  • CST, MoM in house

• Prototype arrays in Cambridge and WA (16 elements)
  • CST, FEKO, WIPL-D, MoM in house

• Stations and core (256+ elements)
  • CST, FEKO, WIPL-D, MoM in house

• Beam models for calibration
  • Based on MoM in house (MBF based: D. Gonzalez-Ovejero, C. Craeye 2011)
EM simulations of SKA stations

• What can we simulate?
  • Full stations and larger (stations within the core) inc. mutual coupling.
  • Include effects of misalignments/tolerances, electronics (LNA impedance), ground plane/soil, cabling, station boxes, etc.

• Computing requirements
  • 100s GB of RAM required (depending on detail and accuracy required)
  • ~4-24 hours per frequency (depending on assumptions and software package)
  • Once pre-computed, the solutions above can be reduced (smoothed, decomposed in spherical harmonics) to be stored.

• What are we working on?
  • Improve accuracy (~30 dB below max. of beam currently)
  • Reduce complexity (easier to store)
  • Reduce computation time
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Coupling: AAVS0 array

![Image of AAVS0 array]

- Frequency (GHz)
- S21 (dB)

- Measurement
- CST
- MoM

Graph showing the comparison of measurement, CST, and MoM for AAVS0 array coupling.
Hexacopter (AAVS0 array)
AAVS0.5

- 16 antennas connected to MWA back-end
- Hydra A
  - AAVS – MWA
  - 112 sec, 32MHz, around 119MHz
- Good initial verification of scalable LFAA design tools
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Introduction: What is the problem?

- Required:
  - Capture DDEs
  - High accuracy
  - Few coefficients (for few measurement points)
  - Quick access
  - Low storage requirements

[Graph and diagram showing data points and a color scale representing values.]
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.

Low Order Beam Models for Calibration

Zernike representation of deficiencies in the pattern including mutual coupling

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

• 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): \( AP = \sum_{k} AF_k xMBF_k \)
Use of pre-computed EEPs

\[ \overline{F}_{rec}(\theta, \phi) = \sum_{m=1}^{n} \alpha_m \sum_{i=1}^{n} \overline{f}_i(\theta, \phi) e^{-j(\phi_i - \phi_{i,0})} Z_m \]

- They can be pre-computed accurately.
- They are smooth and can be stored with low resolution. Better simulated EEPs mean less Zernike polynomials needed.

Spherical Harmonics
Use of Zernike polynomials

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

- 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.

Related work: C. Craeye et al. (2012), R. Maaskant, M. Ivashina, et al. (2012), etc.

Similar to theory of circular apertures:
Tests: Pointing error (2 deg.) – scanning
Also possible: dead elements, etc.

Scan:
\( \Theta = 45 \text{ deg.} \)
\( \Phi = 90 \text{ deg.} \)

Error Rec. - Actual

\( t = 36, w = 81 \)

\( t = 15, w = 16 \)

*\( t \): number of Zernike polynomials / *\( w \): number of measured points.
Summary

- Use of spherical harmonics to map the smooth pre-computed EEPs or even the Macro Basis Function (MBF) patterns that define the EEPs.
- Use the Zernike polynomials to map the aperture like pattern including mutual coupling.
- We can either use the EEPs or use the MBF patterns directly to calculate the full array response.
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Interferometric Simulations

- We carried out a study using OSKAR simulation software to assess Far-Sidelobe Confusion Noise (FSCN) as a function of frequency
- Using CASA to do the imaging
- Computed at spot frequencies:
  - 50, 70, 110, 170, 250, 350, 450, 550, 650 MHz
- Simulating essentially the core of SKA1-LOW (979 stations in original baseline design)
- All stations with different randomised configurations
- The simulated pattern of SKALA was included
- Sky model: VLSS catalogue (brightest sources removed)
Telescope model

- Model has the same density in the core as the baseline design.
- 1024 stations out to 41 km from the centre, 979 within 3 km radius.
- Element patterns simulated at 9 frequencies from 50 to 650 MHz.
Antenna and station beams
Sky model

- Sky model based on VLSSr (~92k sources)
  - Applied a ‘perfect’ demixing of sources > 15 Jy/beam by searching for groups of source components with peak fluxes > 15 Jy/beam at 74 MHz.
  - This removed 598 components from 424 sources.
- A spectral index value for each component was then randomly generated using the mean and standard deviation for the 388 sources listed in Helmboldt et al. (2008). The mean spectral index was -0.92, and the standard deviation was 0.22.
- Emulation of CLEAN procedure for sources out to the edge of the first side-lobe.
  - Removed sources based on apparent flux > 5-sigma noise level for a 6 hour observation.
- E.g. 4000 sources removed at 50 MHz
- Apparent fluxes were approximated from the simulated cross-power beam, and noise levels were based on the simulated element level effective area and system noise temperatures.
- 6 pointing directions were randomly generated with a minimum elevation of 75 degrees at transit to avoid bias due to certain directions in the sky model.
FSCN Simulations

- 6h observation showing average FSCN (over 6 blank fields)
- Trend line is shown
- Dashed lines show theoretical image thermal noise 1 sigma level
- This is still being analysed but it shows lower frequency imaging to be more challenging.
Polarization with OSKAR

Figure 1: Percentage difference in measured Stokes I source flux for a randomly polarised source at the phase centre.
Conclusions and Future Work

• Several years of work modelling UWB random sparse arrays. We keep including more effects on the full EM simulations of SKA stations (ground, electronics, etc.). Validation is critical but not easy.
• Zernike based models mixed with spherical harmonics and EM simulations can help us map the fully polarimetric station beams accurately with just a few coefficients.
• Include Mutual coupling in OSKAR.
• Next big chance to validate/test: AAVS1.
AAVS1 (end of 2015)

- 4 stations
- 400 elements
- At the MRO
- Hosted by MWA
Thank you!

• Questions?