Computing embedded element patterns for SKA-Low prototype stations AAVS2 and AAVS3

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ICRAR

International Centre for Radio Astronomy Research

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THE UNIVERSITY OF WESTERN AUSTRALIA

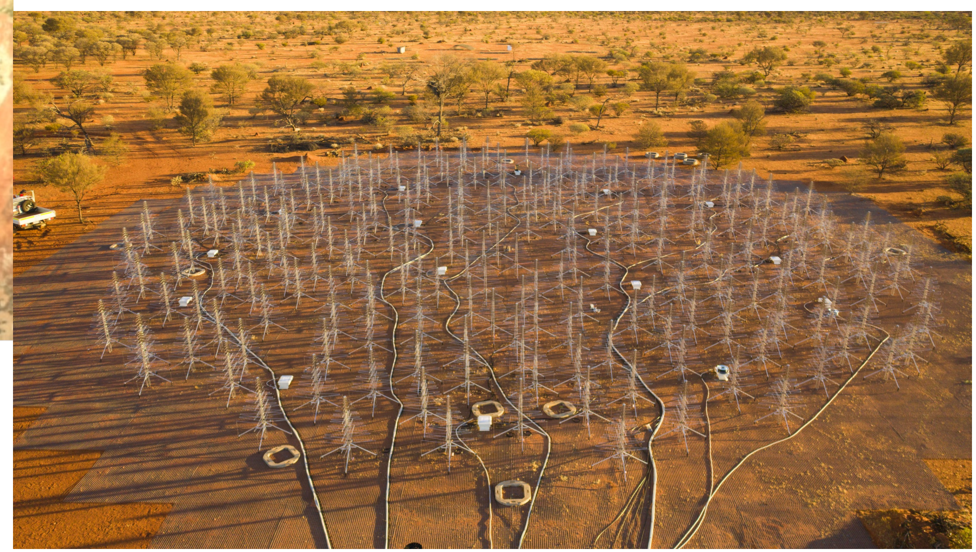
Government of Western Australia
Department of the Premier and Cabinet
Office of Science

Overview of talk

Acknowledge work of many engineers from the SKA project from around the world.

- **SKA-Low prototypes: SKA-Low prototype Aperture Array Verification System 2 (AAVS2) using SKALA4.1 antennas.**
- **Primary beam modelling using CEM.**
- **Visualisation of element beams (EEPs) and station beams.**
- **New station layouts under consideration for AAVS3.**
- **Leads directly into next talk on station calibration.**

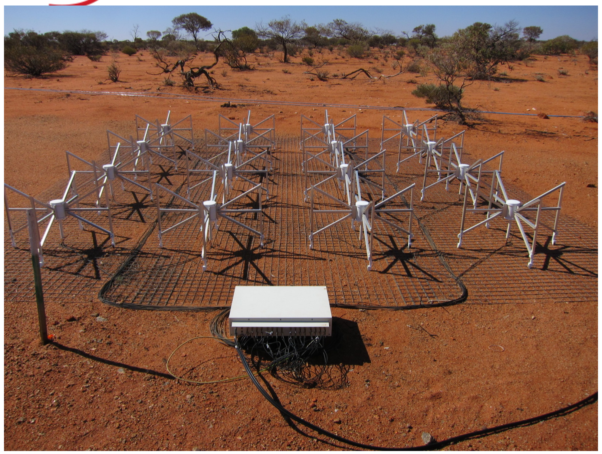
SKA-LOW

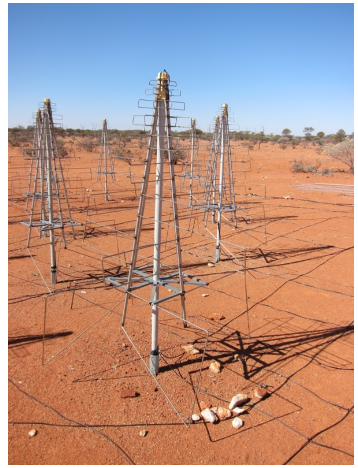


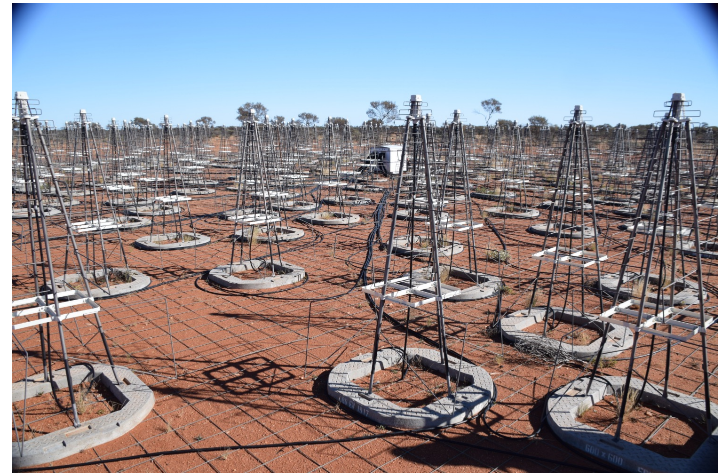
The MRO in WA – 600km NE of Perth. Murchison approx. size of NL – population ±100.

AAVS2.0 – 2019 prototype

SKA-LOW precursor and prototypes: MWA; Aperture Array Verification System 0.5 & 1.0; EDA2







Clockwise:
MWA tile (2012)

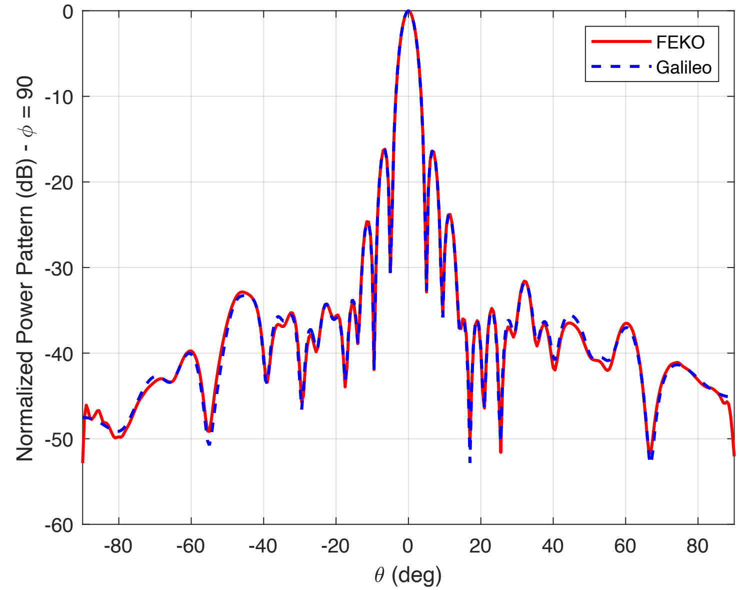
AAVS0.5: 16 SKALA elements (2014)

AAVS1.0: 256 element SKALA2 elements (2016)

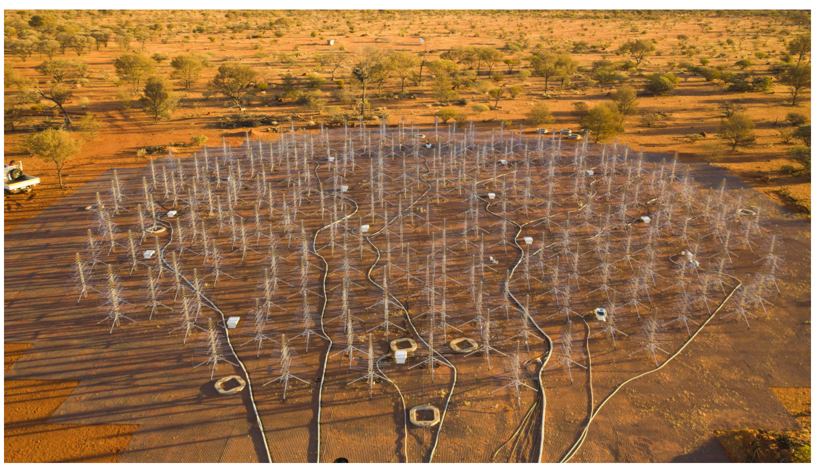
EDA2 256 MWA dipoles (2018)

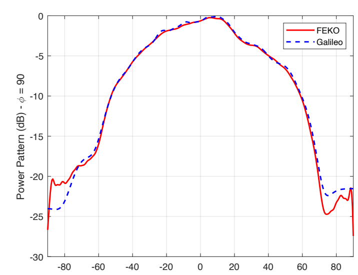
Current SKA-LOW prototype: AAVS2

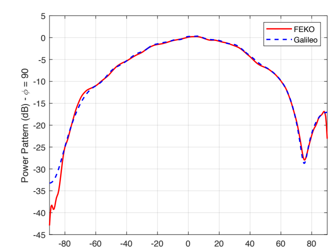
AAVS2.0 construction - 2019 (Credits: ICRAR/INAF).



Below: ”Embedded” (individual) element patterns at 110 MHz. Above: “Synthesised” beam (N-S arm, E plane).

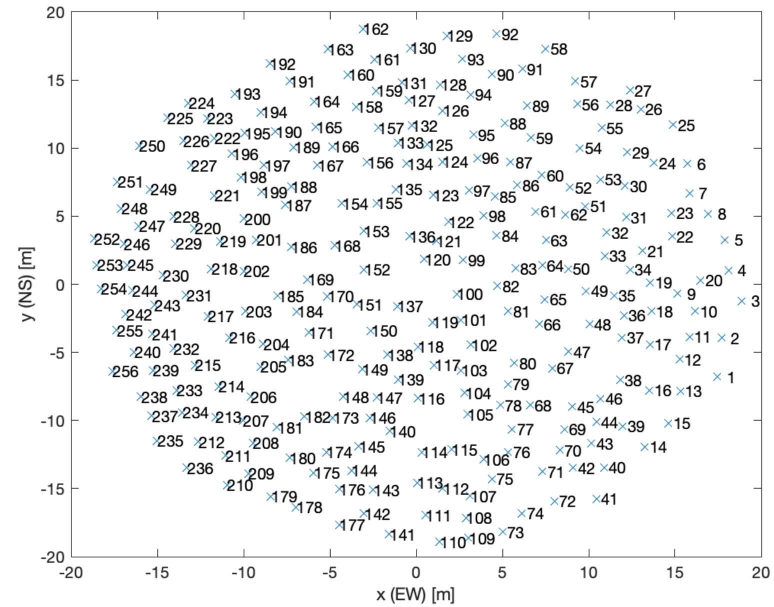






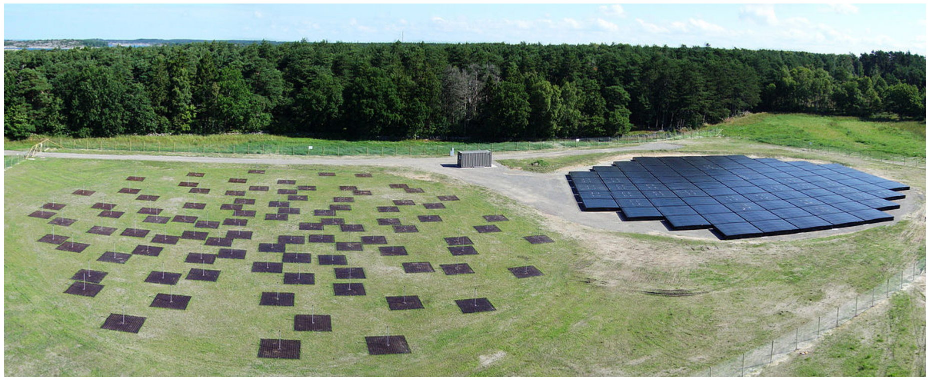
SKAO baseline design envisages 512 such stations on the MRO and beyond.

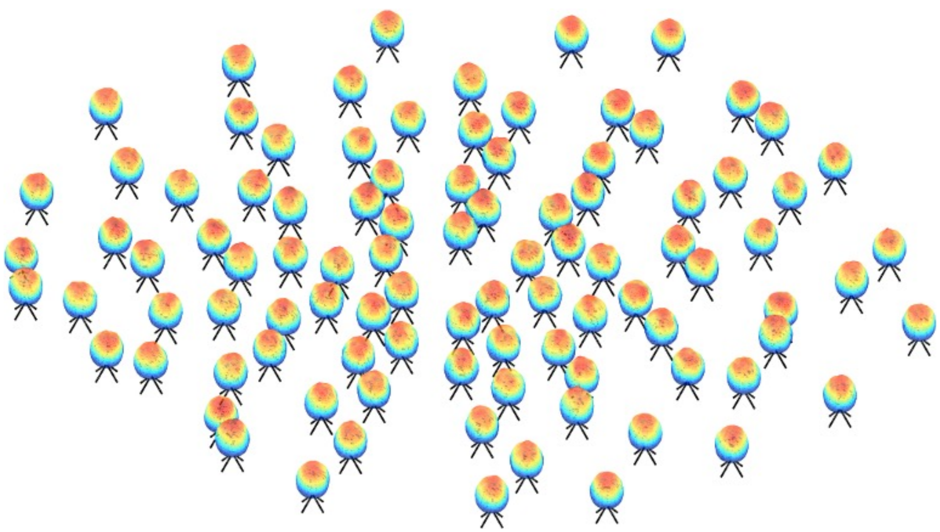
SKALA4.1 and array layout



(Left top and bottom) The SKALA4.1 antenna, with SKAO staff member making adjustments.

Beam modelling





- **Knowing what the antenna "beams" look like is increasingly important to get high-res images.**
- **Traditional, expensive dishes, in a highly sparse array layout, can be modelled with one or two parameters.**
- **Aperture array elements have beams which are directional and differ between elements.**
- **Early work: LOFAR low-band array.**

A. Young, S. J. Wijnholds, T. Carozzi, R. Maaskant, M. V. Ivashina, and D. B. Davidson, "Efficient Correction for both Direction-Dependent and Baseline-Dependent Effects in interferometric Imaging: An A-Stacking Framework", Astronomy and Astrophysics, May 2015.

Simulating element beams with Computational Electromagnetics

Simulation aims

- **Compute *Embedded Element Patterns* for all elements: 256 for AAVS2 x2 (X & Y pols.)**
- **EEPs computed one at a time (other ports terminated in matched load).**
- **Row or column of *array mutual impedance matrix* Z_A computed at same time.**
- **Simulation method used: *Method of Moments.***
- **Computations done at ICRAR-Curtin (D Ung & D Davidson) and INAF/IDS (P Bolli & M Bercigli).**

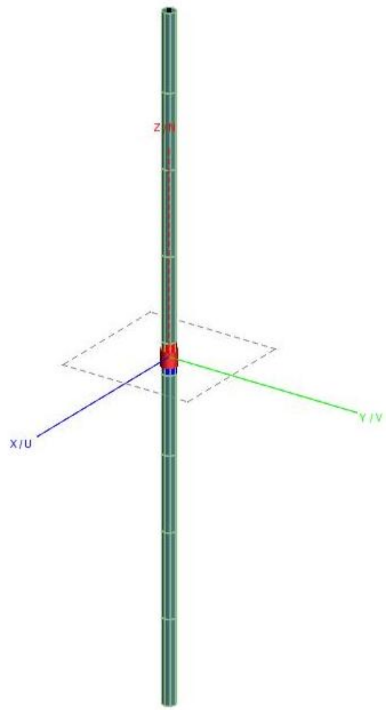
Basics of the Method of Moments

- **Thin-wire formulation: based on integral eqn:**

$$E_z^{inc}(z) = \frac{1}{j\omega\varepsilon_0}\int_L \left[\frac{\partial^2\psi(z,z')}{\partial z^2} + k^2\psi(z,z')\right] I_z(z')dz$$

$$\psi(z,z') = \frac{e^{-jkR}}{4\pi R}$$

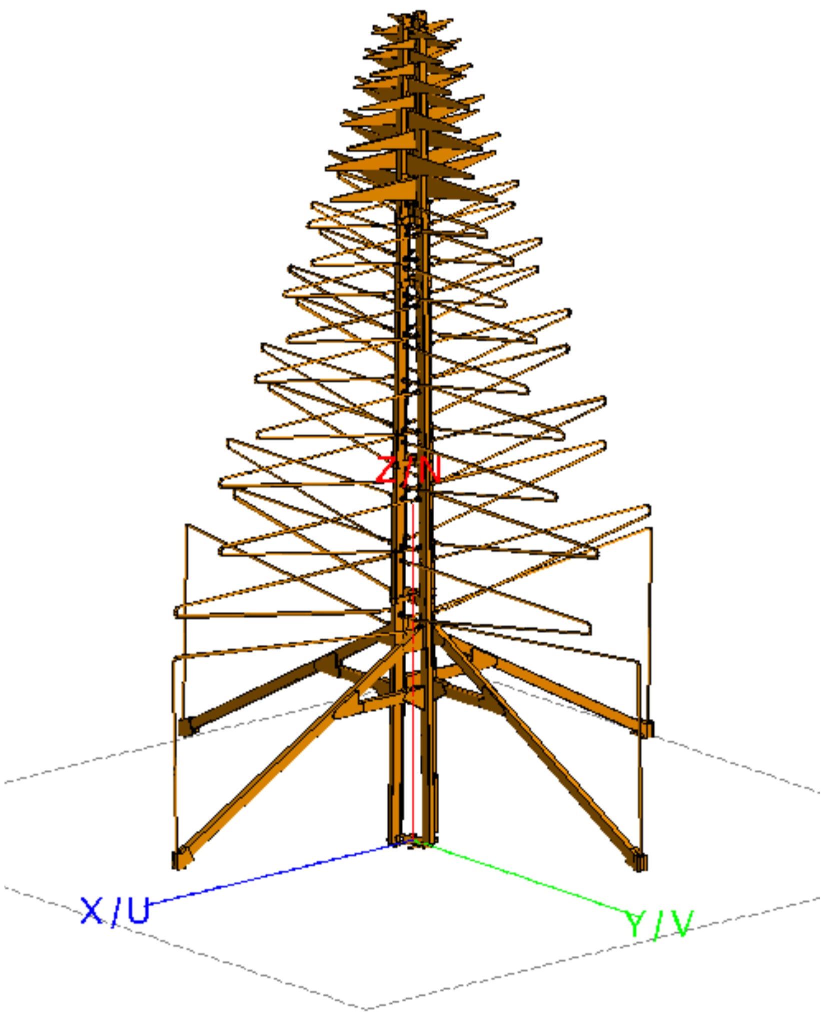
- **Solves for current on structure by breaking wires into short *segments* and solving for current (degrees of freedom – d.o.f.s) on each by enforcing boundary conditions.**
- **Around 10 d.o.f.s per wavelength needed to resolve phase of current adequately.**
- **Surfaces meshed with triangular elements ("RWG" elements).**



- **Generates full, complex-valued interaction matrix:**
  - **$O(N^2)$ memory to save.**
  - **$O(N^3)$ asymptotic computational cost to solve.**

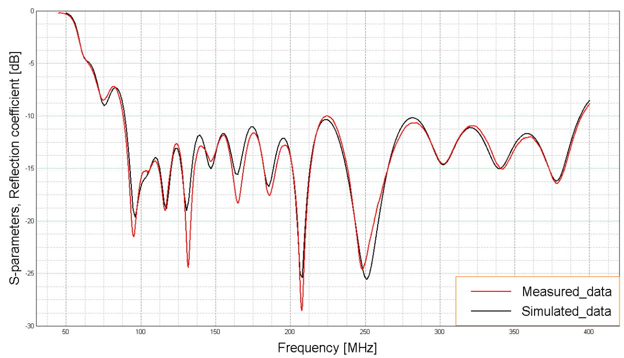
Simulation work

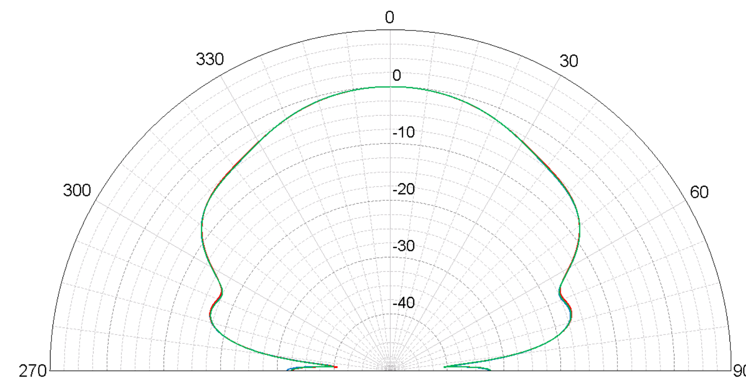
- **Simulations used FEKO (ICRAR) and Galileo (INAF via IDS)**
- **SKALA4.1 is latest reference design.**
- **Usable FEKO model of SKALA4.1 obtained ~ 12 000 dofs per antenna (instead of 29 000 from CAD).**
- **IDS model ~ 9 000 dofs per antenna.**

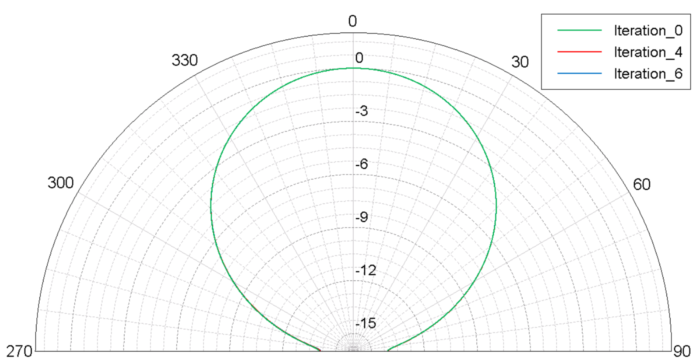


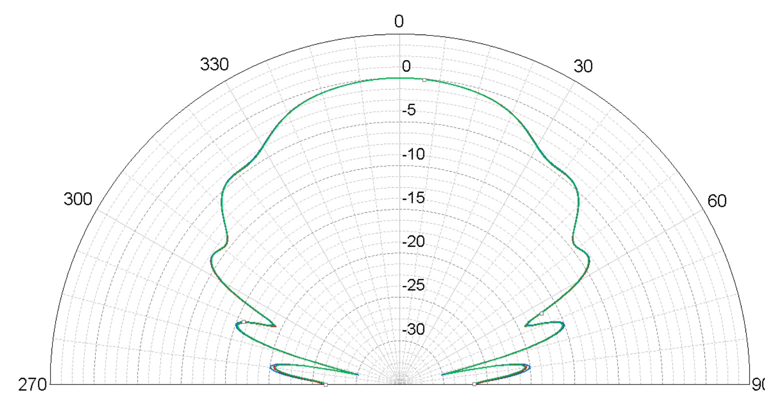
Simulation work contd.

FEKO model benchmarked against measured data (S11) and full FEKO model (patterns).





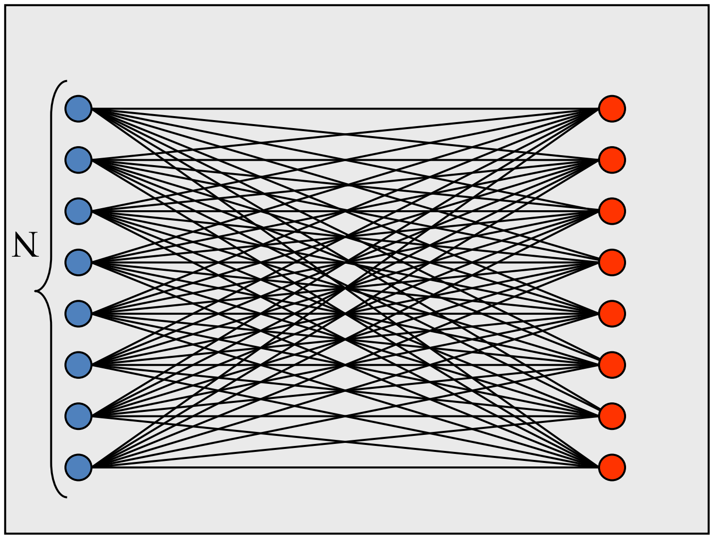




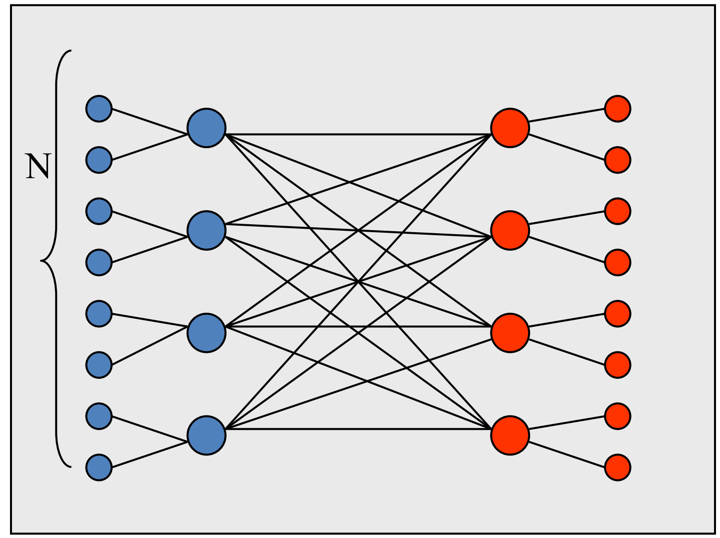
Simulation considerations

- **These are large computational models: 256 antennas times 12 000: 2~3 million unknowns.**
- **Use parallel Multi-Level Fast Multipole Method (MLFMM) approximation.**
- **MLFMM is an iterative method, not guaranteed to converge. Issues encountered at 50 and 70 MHz.**
- **Typical run-times for a full 256 element station vary from days to weeks, depending on convergence of MLFMM.**
- **Overall, thousands of CPU-hours expended in Perth and Pisa.**
- **Work currently in progress on DUG and Pawsey HPC systems in Perth.**

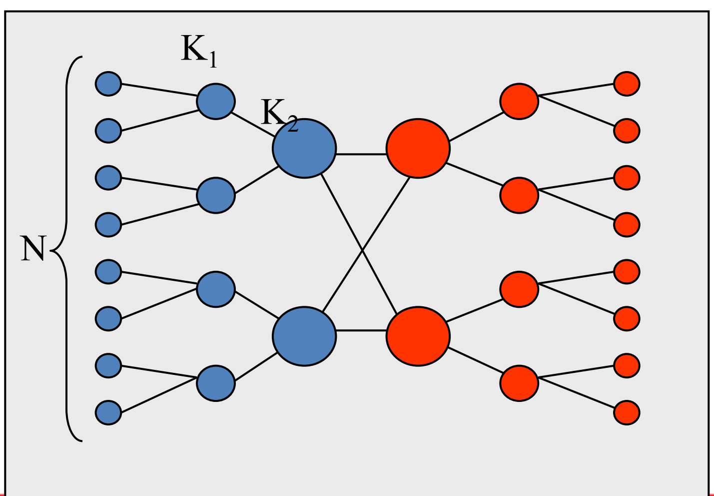
Multilevel Fast Multipole Method (MLFMM)



one level



two levels



Multiple levels in the limit:

Memory requirement: $O\,(N \log N)$
Run-time: $O\,(N \log^2 N)$
(per iteration)

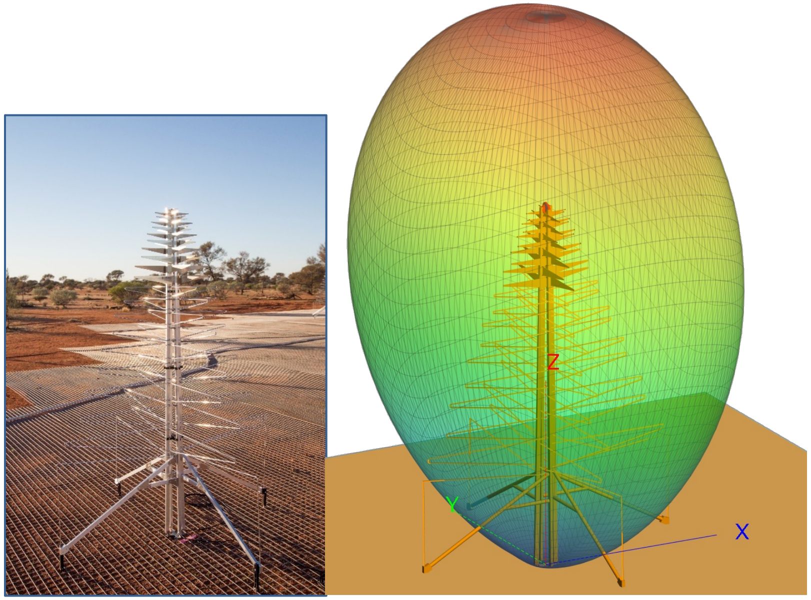
Credits: FEKO (Altair)

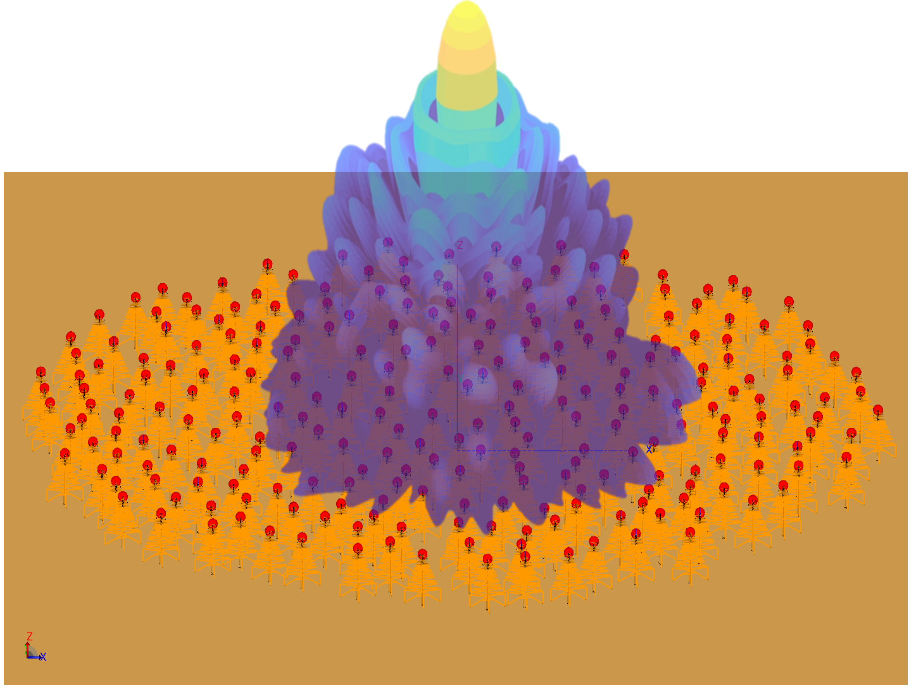
AAVS2 beams (and a sneak peek at AAVS3)

Video (play externally)

https://vimeo.com/657724198

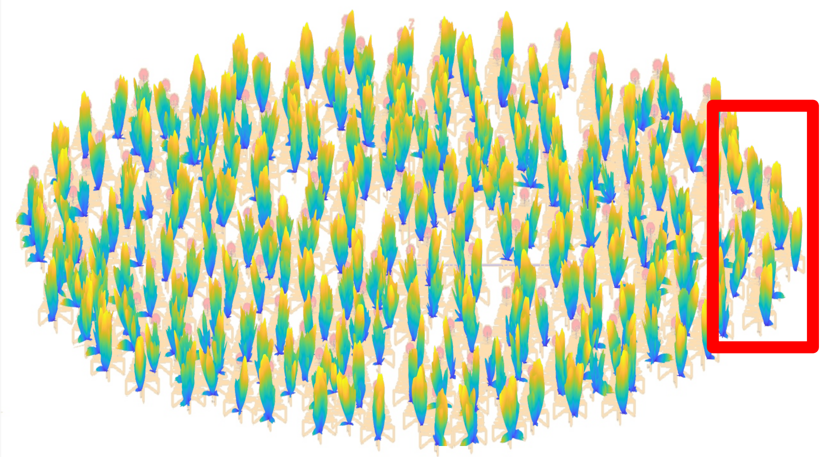
Beam Pattern Simulation



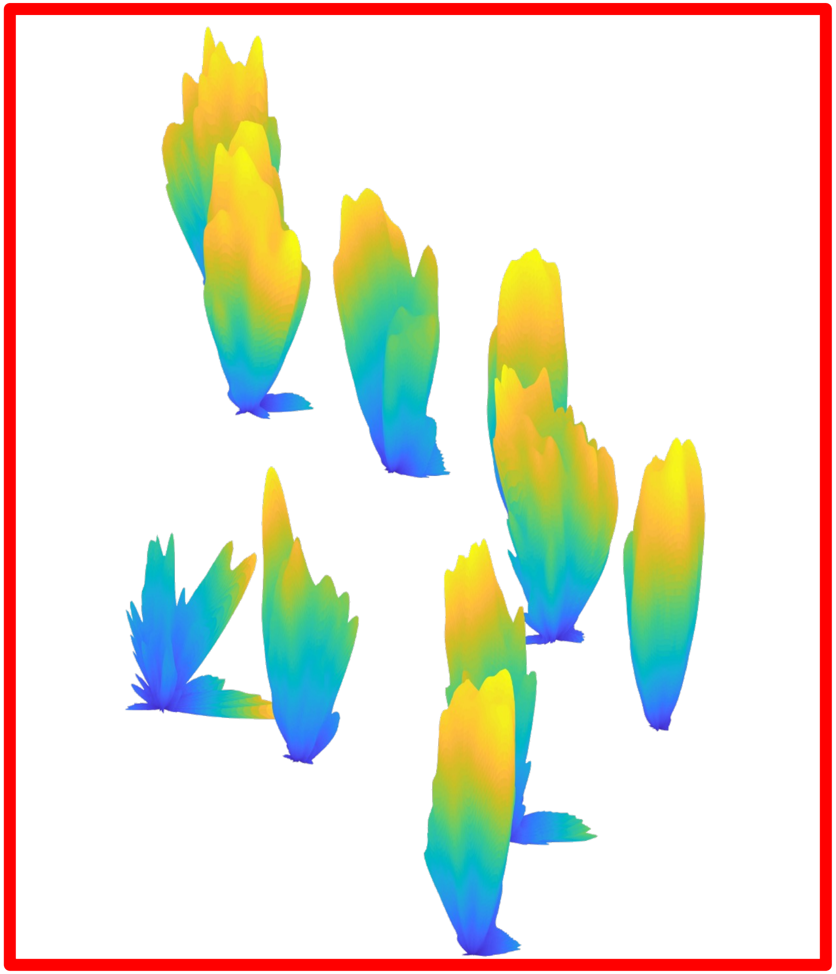


Credit: D. Ung, ICRAR

Beam Patterns (contd.)



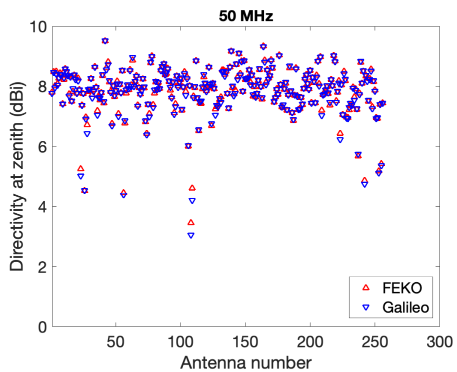
70 MHz: note how dissimilar beam patterns on eastern rim are.

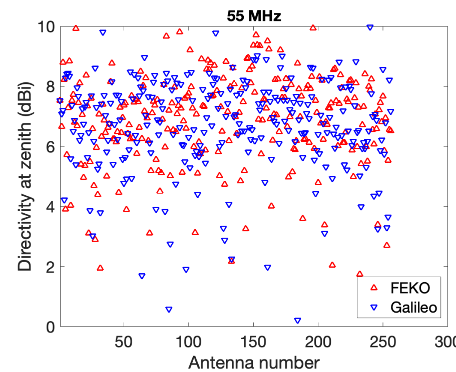


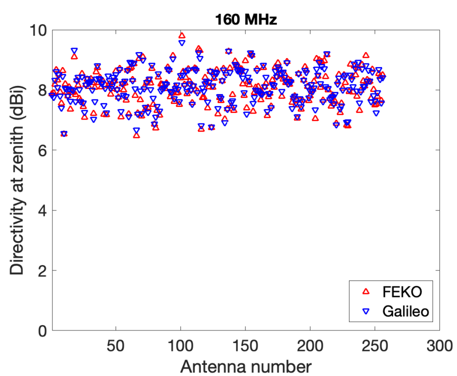
Credit: D. Ung, ICRAR

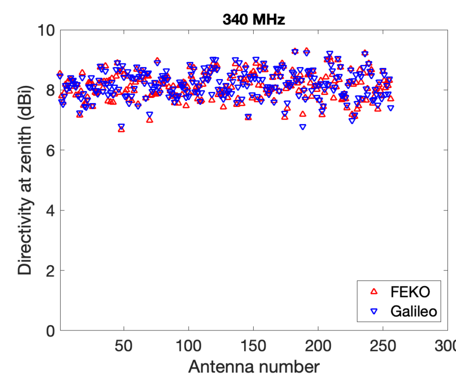
Verification: FEKO vs IDS Galileo

Two different commercial Method of Moments, with different model meshes. Plots show gains in EEPs at zenith. Generally excellent agreement – but a few problem frequencies!



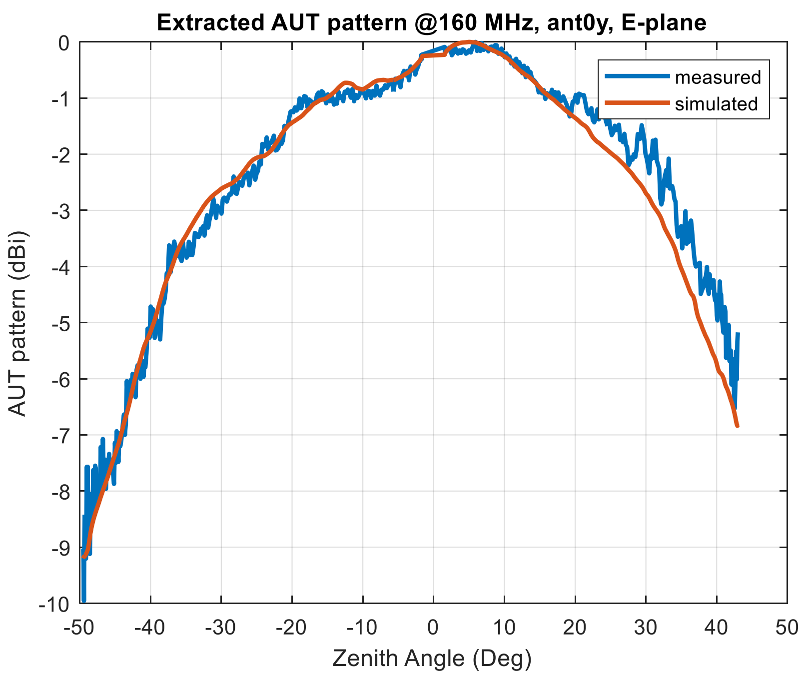


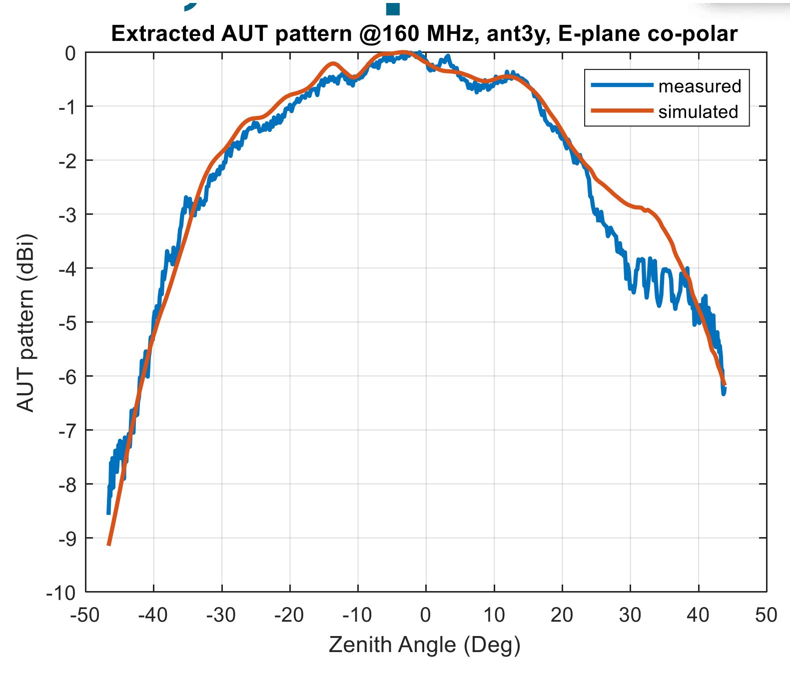




- Computing EEPs for AAVS2&3

Validation: Comparison with on-site drone measurements

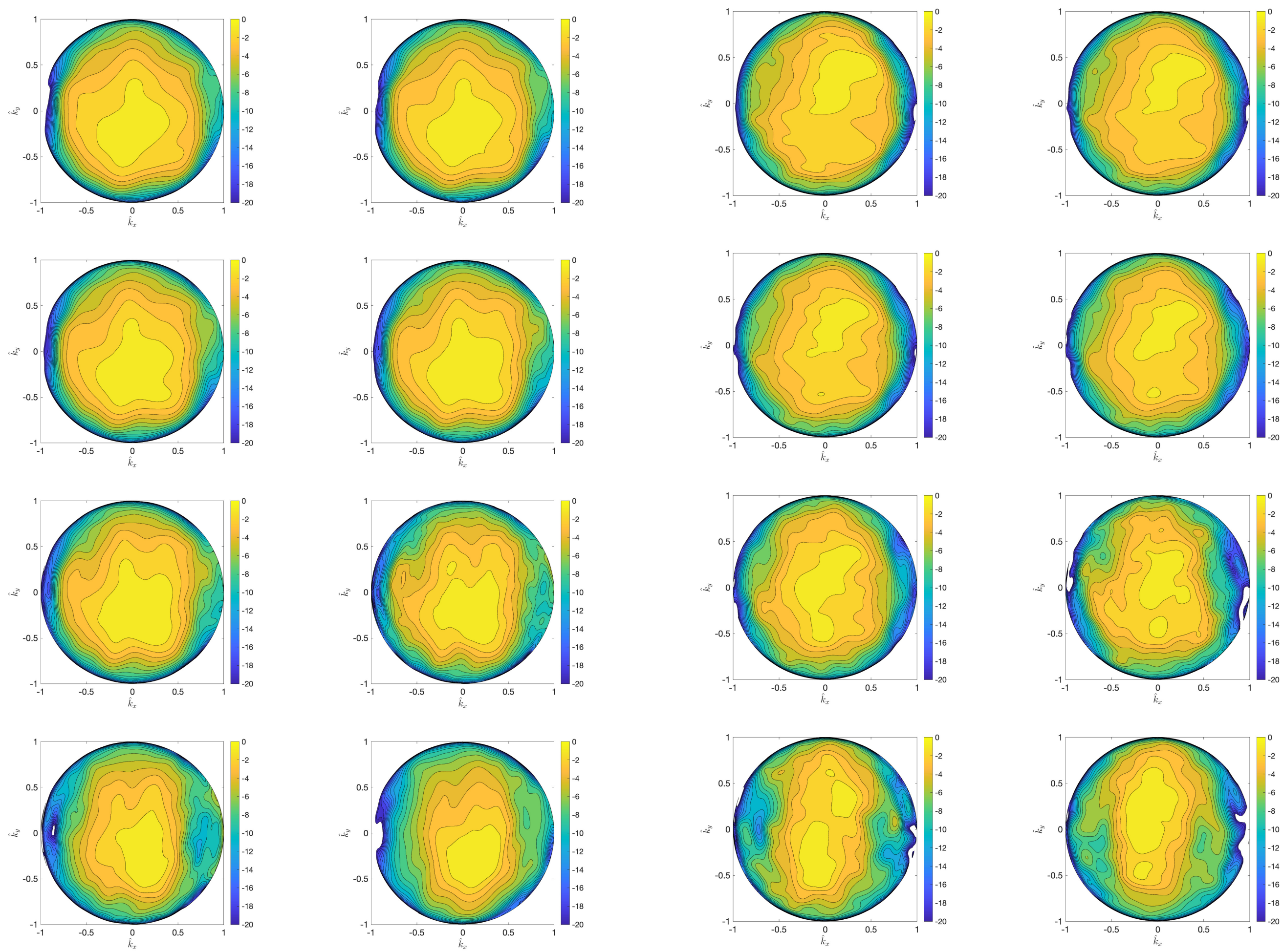




Credits: Virone et al., INAF

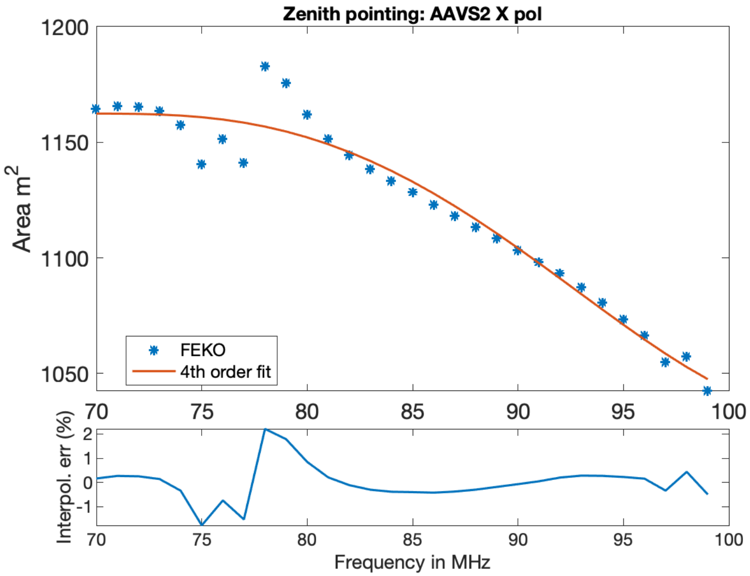
160MHz – two different antenna positions in AAVS1.5 (initial 48 antenna deployment, autumn 2019).

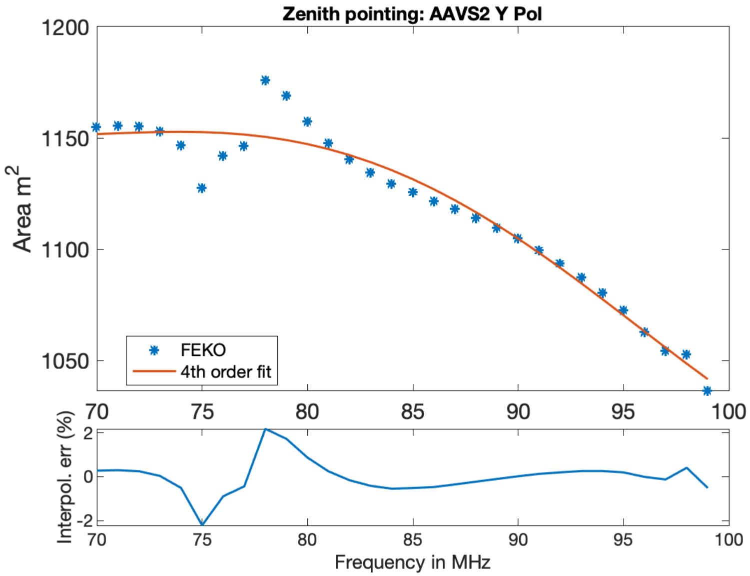
How spectrally smooth are the EEPs?



EEPs for: Left, antenna 1 (peripheral location); right, antenna 100 (central location). Orthographic projection. Rows from top: 70 &71 MHz, 72 &73 MHz, 74 &75 MHz and 76 &77 MHz.

How spectrally smooth is the station beam?





Station beam effective area vs frequency for X (EW) and Y pol (NS dipoles), comparing FEKO to a 4th order fit over a wider bandwidth. Lower plot shows error in 4th order interpolant.

Roll-off in area is due to being on the dense/sparse boundary.

Why is this an issue?

- *Once calibrated,* the station beam (weighted sum of EEPs) is generally well-behaved, aside from some spot frequencies (as shown – note that ~78 MHz is ~ Cosmic Dawn).
- To calibrate the station, it is treated as an interferometric array in its own right.
- The complex amplitude corrections are computed over frequency.
- The EEPs introduce *directional dependence,* which are also freq. dependent.

Bowman et al, *An absorption profile centred at 78 megahertz in the sky-averaged spectrum,* Nature 555 2018.

Using the EEPs

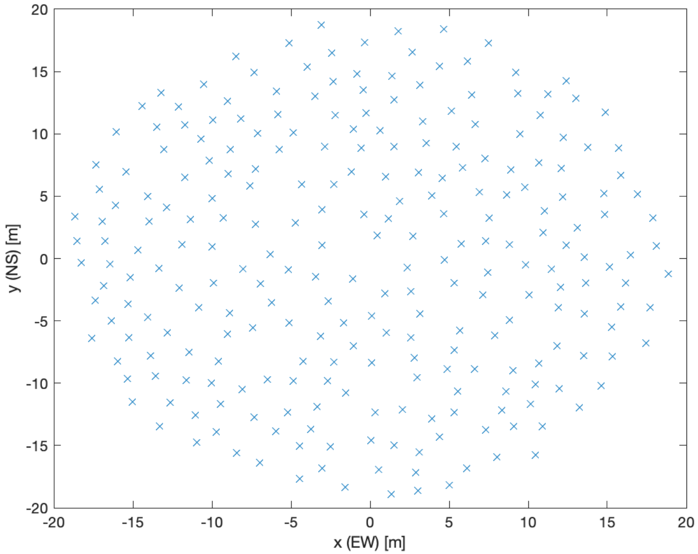
- **The EEPs provide the direction dependent *voltage gain* terms E_p & E_q in the interferometric integral for dissimilar element patterns:**

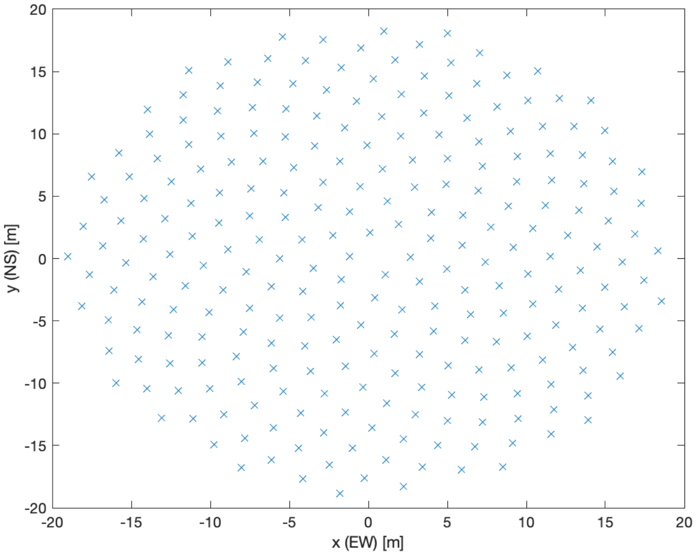
$$V(u,v) \approx \iint_{-\infty}^{\infty} B(l,m)\alpha_p E_p(l,m)\alpha_q^* E_q^*(l,m)e^{-j2\pi(ul+vm)}dl\,dm$$

- **NB! these are field (i.e. voltage, not power) gains – complex valued.**
- **Calibration solves for unknown gains α.**
- **Transform is frequency-dependent. Rapidly varying EEPs will pose a significant computational load.**

A new SKA-Low station layout?

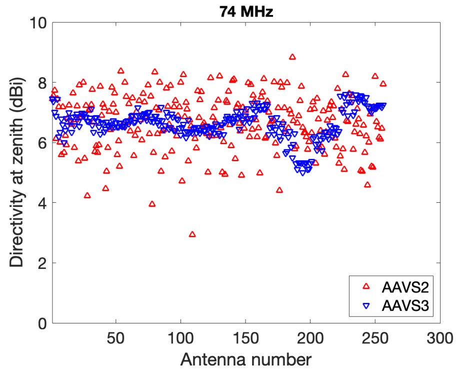
AAVS2 (left): quasi-random.
AAVS3 (right): Proposed “Vogel” pattern (sunflower- inspired).

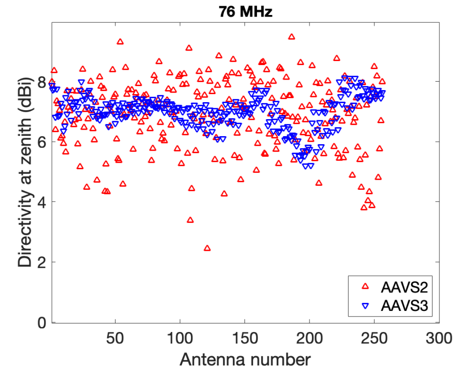


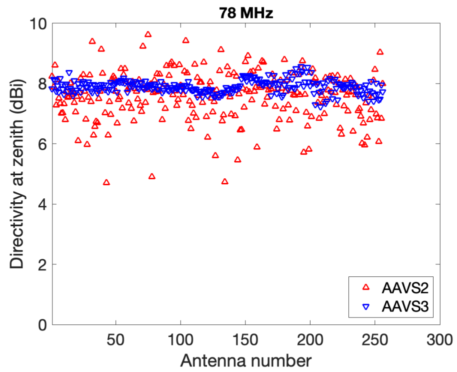


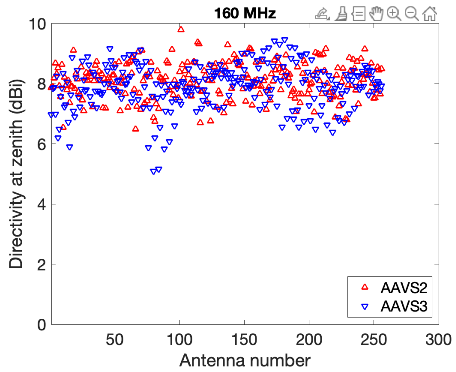
Vogel (AAVS3) vs. AAVS2

Plots show gains in EEPs at zenith, comparing the proposed AAVS3 (Vogel) to existing AAVS2 (quasi-random). Show improvement around 76-78 MHz, but poorer performance in mid-band.





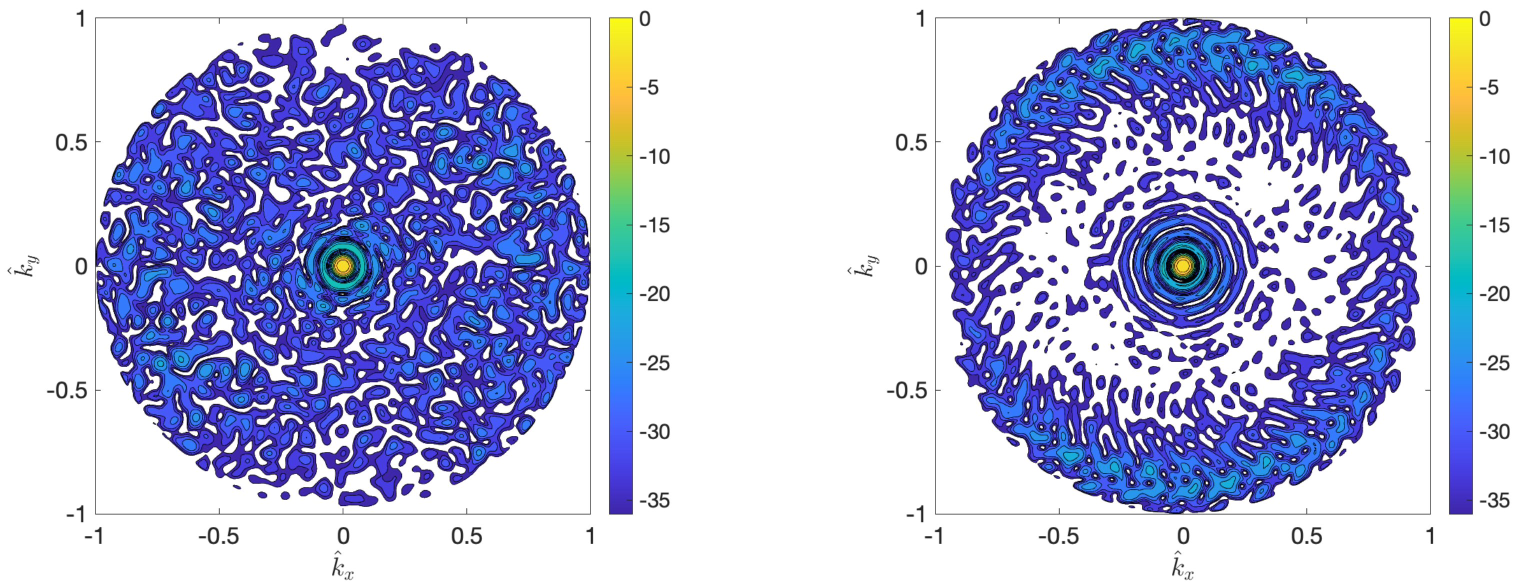




- Computing EEPs for AAVS2&3

AAVS2 & AAVS3 station beams

AAVS2 (left): quasi-random.
AAVS3 (right): Proposed “Vogel” pattern (sunflower- inspired).
Orthographic (uv) projection, 160 MHz, X pol.
Decibel (10 log) scale; white space on plots implies value below bottom of scale (-35dB).



AAVS3 layout has better defined inner sidelobes, and lower sidelobe level over much SKA-Low field of view (cone 45 deg from zenith) but structured sidelobes towards horizon.

Conclusions – CEM & SKA-Low

- **Large quasi-randomly configured aperture arrays pose *major* challenges to CEM tools.**
- **SKA-Low is *just* tractable with commercial CEM tools, using MLFMM.**
- **HPC very useful for production runs.**
- **Other fast methods hold promise - but are TBD in commercial codes.**
- **Results from CEM simulations are impacting on calibration and commissioning of these new arrays.**
- **Looking ahead, including such tools early in the design optimization loop could improve performance further in future upgrades or new-builds.**

Acknowledgments

- I acknowledge a large number of engineers from the SKA project from around the world.
- The Murchison Radio-astronomy Observatory is operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.
- Picture credits: ICRAR.