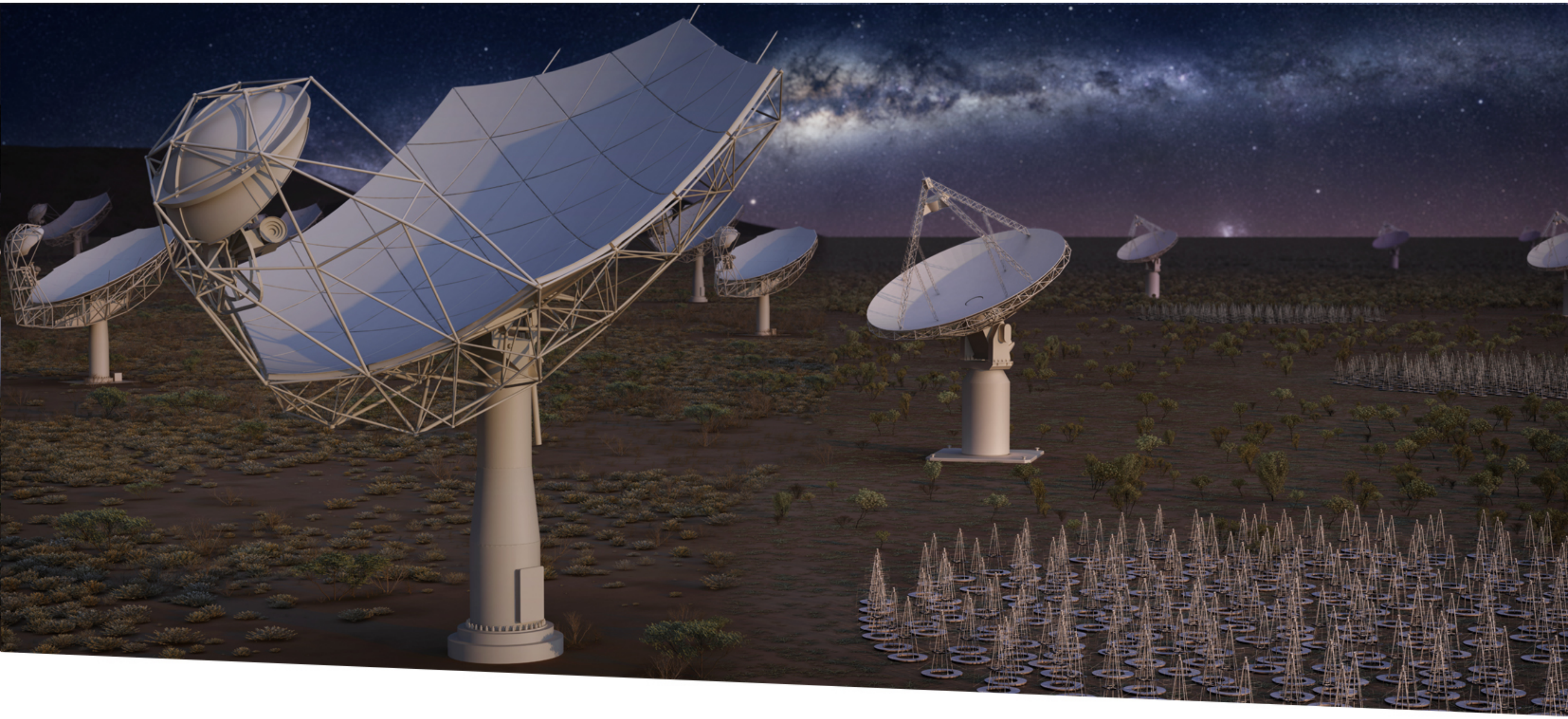
Electromagnetic modelling of the SKA-LOW AAVS2 prototype



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

David Davidson & Pietro Bolli et al

Sep 2020, URSI-GASS, Rome

Contributors

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- IEIIT, CNR *(Italy):* Giuseppe Virone
- *IDS (Italy):* Mirko Bercigli

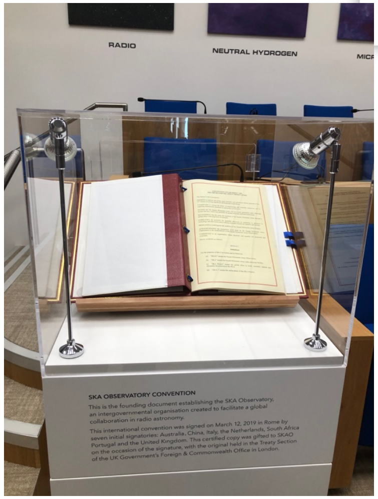
Also acknowledge former LFAA consortium members from ASTRON and Univ. of Cambridge, Oxford & Malta.

Outline

- SKA and SKA-LOW.
- SKA-LOW prototypes – history, AAVS1.5, AAVS2 and EDA2
- SKALA4 antenna
- Station level calibration
- CEM simulations (FEKO and Galileo)
- Work in progress.

The SKA project

- Square Kilometer Array is an international project to build the world’s largest radio telescope.
- Project has its genesis circa 1990: *Hydrogen Array*, a proposal to image neutral hydrogen dating back to early cosmic times.
- HI is still a major driver of SKA.
- IGO treaty currently being ratified in national parliaments.



SKA OBSERVATORY CONVENTION

This is the founding document establishing the SKA Observatory, an intergovernmental organisation created to facilitate a global collaboration in radio astronomy.

This international convention was signed on March 12, 2019 in Rome by seven initial signatories: Australia, China, Italy, the Netherlands, South Africa Portugal and the United Kingdom. This certified copy was gifted to SKAO on the occasion of the signature, with the original held in the Treaty Section of the UK Government’s Foreign & Commonwealth Office in London.

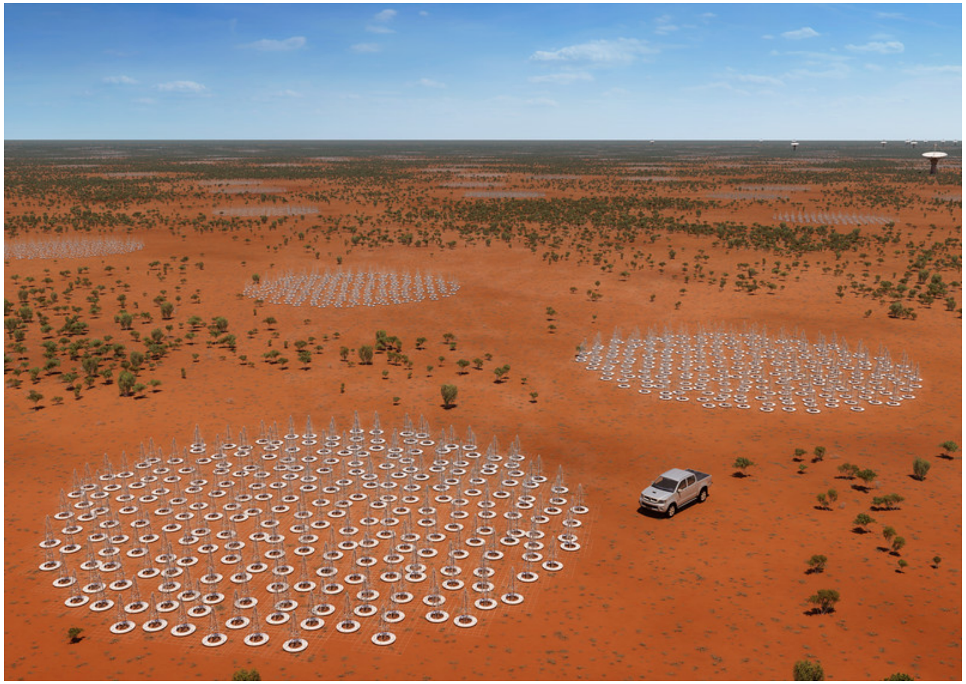
The SKA project – technical

Two main components in the field:

- SKA-MID
  - ± 200 15m dishes; Karoo (South Africa).
  - Planned to incorporate 64 dish MeerKAT.
- SKA-LOW
  - ± 130 000 array elements (512 stations of 256 antennas, ± 40 m station diameter); Murchison Radio-astronomy Observatory (Western Australia).
  - Co-located with (but does not include) ASKAP & MWA.

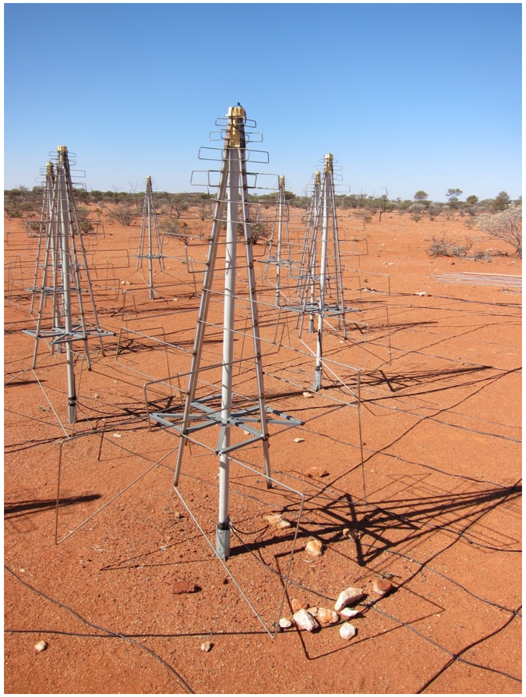
SKA-LOW

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



Artist's Image. Credit: SKAO.

SKA-LOW prototypes: Aperture Array Verification System 0.5 & 1.0



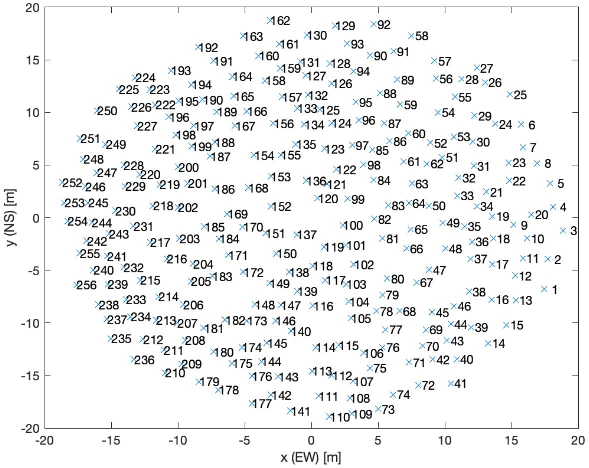
AAVS0.5: 16 SKALA elements

AAVS1.0: 256 element
SKALA2 elements

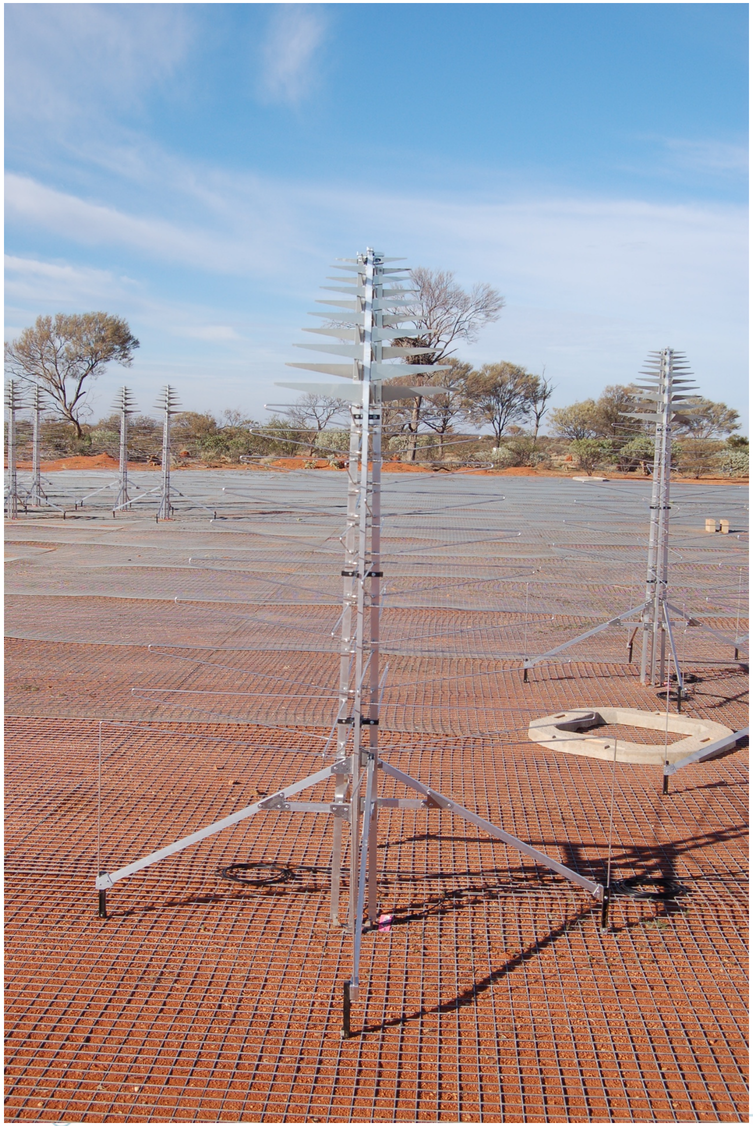
See also: Exp Astron (2018) 45:1–20, de Lera Acedo et al.

The current prototype AAVS2 (256elements) as built

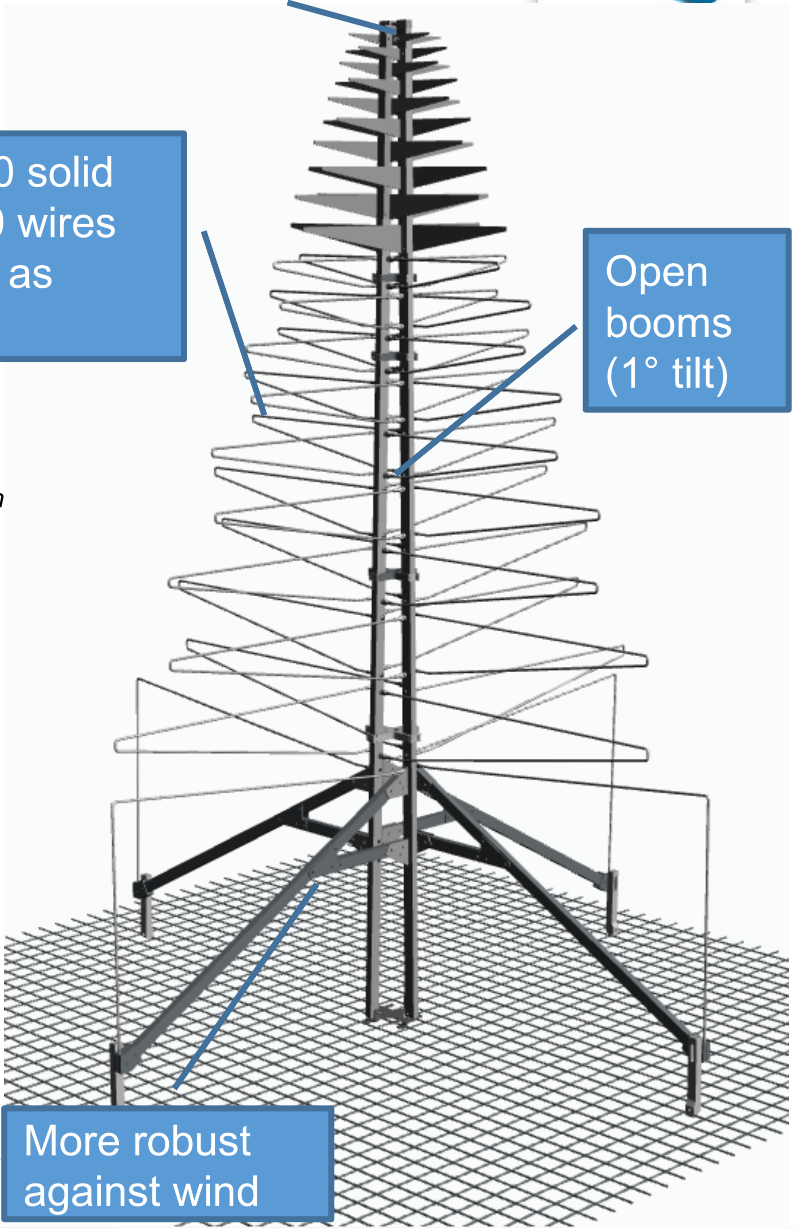
- Uses SKALA4.1-AL implementation of SKALA4 reference design.
- Same quasi-random distribution as AAVS1.0, scaled radially by 7.8%, with some other minor changes (walkways etc).
- Accommodates larger footprint of the SKALA4.1.
- Deployed in phase 1 (48 antennas) and now full phase 2 (all 256).



SKALA4.1-AL antenna



See Bolli et al, *Test-Driven Design of an Active Dual-Polarized Log-Periodic Antenna for the Square Kilometre Array*, IEEE OJAP, June 2020



New LNA connection to the antenna feed

20 dipoles: 10 solid dipole and 10 wires (same height as SKALA4-AL)

Open booms (1° tilt)

More robust against wind

Simulation aims

- Compute Embedded Element Patterns (a.k.a. active, or scan element patterns) for all 256 elements (x2 for opp. pol.)
- EEPs are computed one at a time, with all other elements terminated, with a rows or column of the array mutual impedance matrix Z_A computed at same time.
- EEPs are not unique – depend on termination of other elements.
- Most useful – loaded (often matched), and open-circuited.
- Transmit array beam is sum of OC EEPs.
- Receive array beam (with LNA loads taken into account) is sum of loaded EEPs.
- EEPs can be transformed mathematically between loading conditions (Warnick et al, CUP 2018 and Warnick, Davidson, provisionally accepted for IEEE Trans.AP).
- This does need Z_A.

Simulation considerations

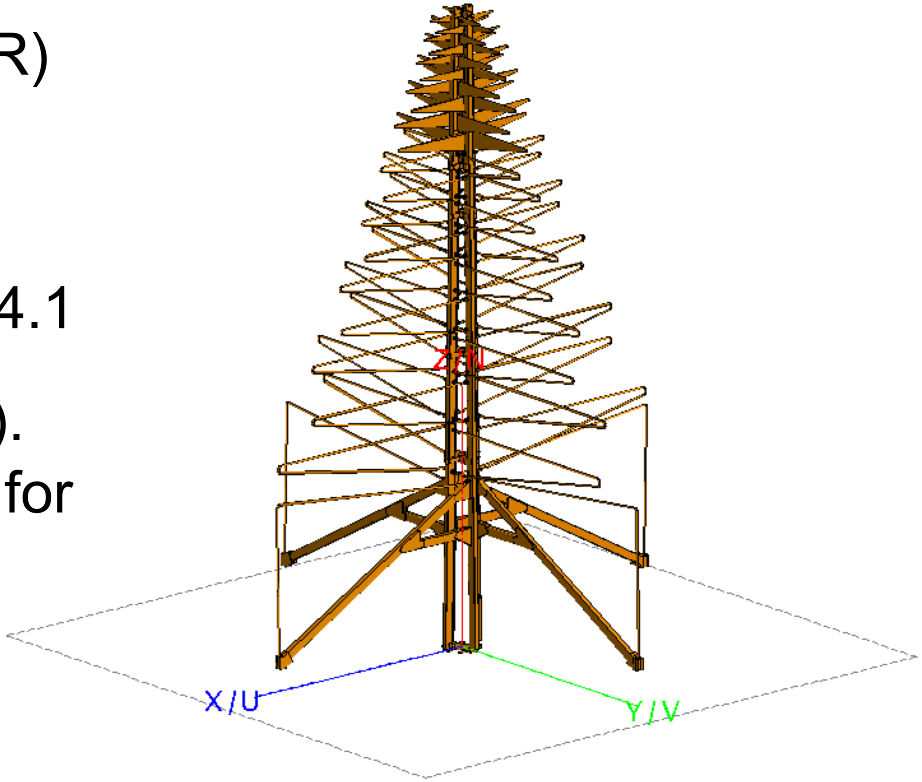
- These are large computational models.
- Cannot be solved using full Method of Moments (MoM).
- Use Multi-Level Fast Multiple Method (MLFMM) approximation.
- FEKO was first commercial code to offer this, circa 2000.
- Parallel MLFMM remains non-trivial.
- Special run-time parameter setting obtained from FEKO support to permit use of full 56 cores.
- MLFMM is an iterative method; iterations 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.

Limitations of MoM/MLFMM

- No obvious way of simulating a full station with a large, finite metallic ground plane (mesh) above a semi-infinite real ground (earth) using commercial codes.
- Investigations into finite grounds have addressed single elements (later in this presentation).
- SKALA4.1 is very complex when running station simulations with 256 elements – over 3 million dofs.

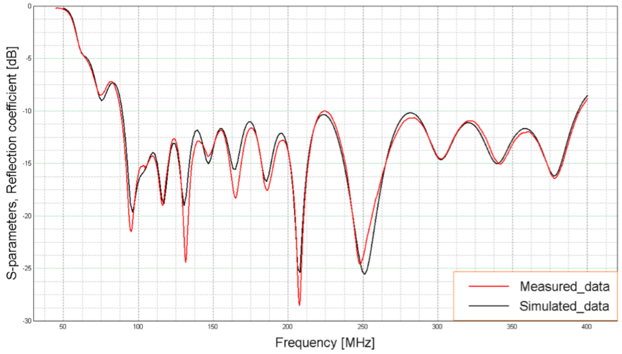
Simulation work

- Simulations used FEKO (ICRAR) and Galileo (INAF via IDS)
- SKALA4 is latest reference design.
- Usable FEKO model of SKALA4.1 obtained – approx. 12 000 dofs instead of 29 000 (per antenna).
- Large problem: ± 600 000 dofs for 48 antennas.
- IDS model uses around 9 000 dofs per antenna.
- ICRAR purchased Dell PowerEdge 740 server (56 cores, 1.5 TB RAM) for this work.
- Similar facilities at IDS.

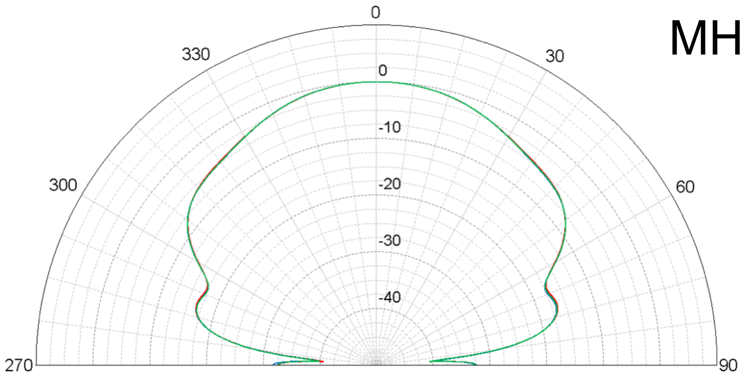


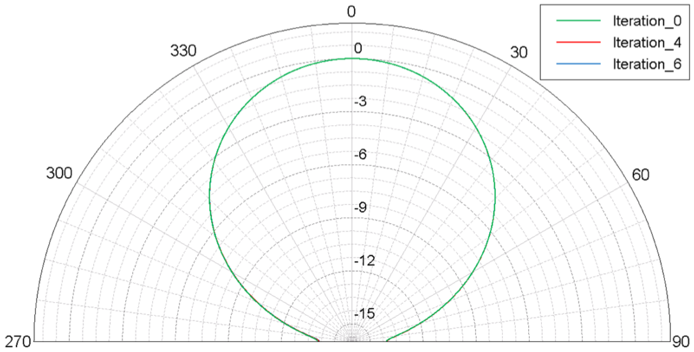
Simulation work contd.

- FEKO model benchmarked against measured data (S_{11}) and full FEKO model (patterns).

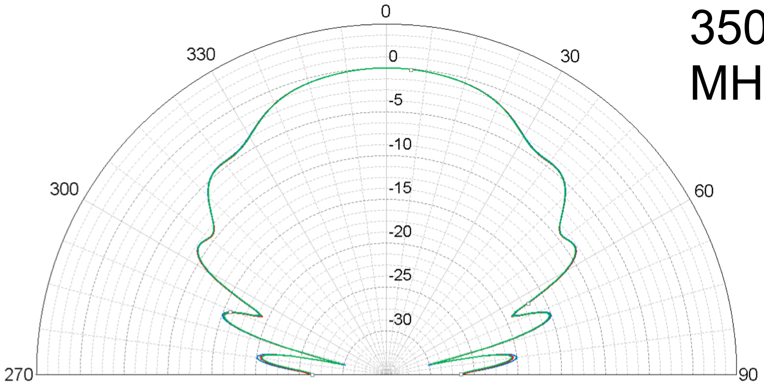


200 MHz





50 MHz

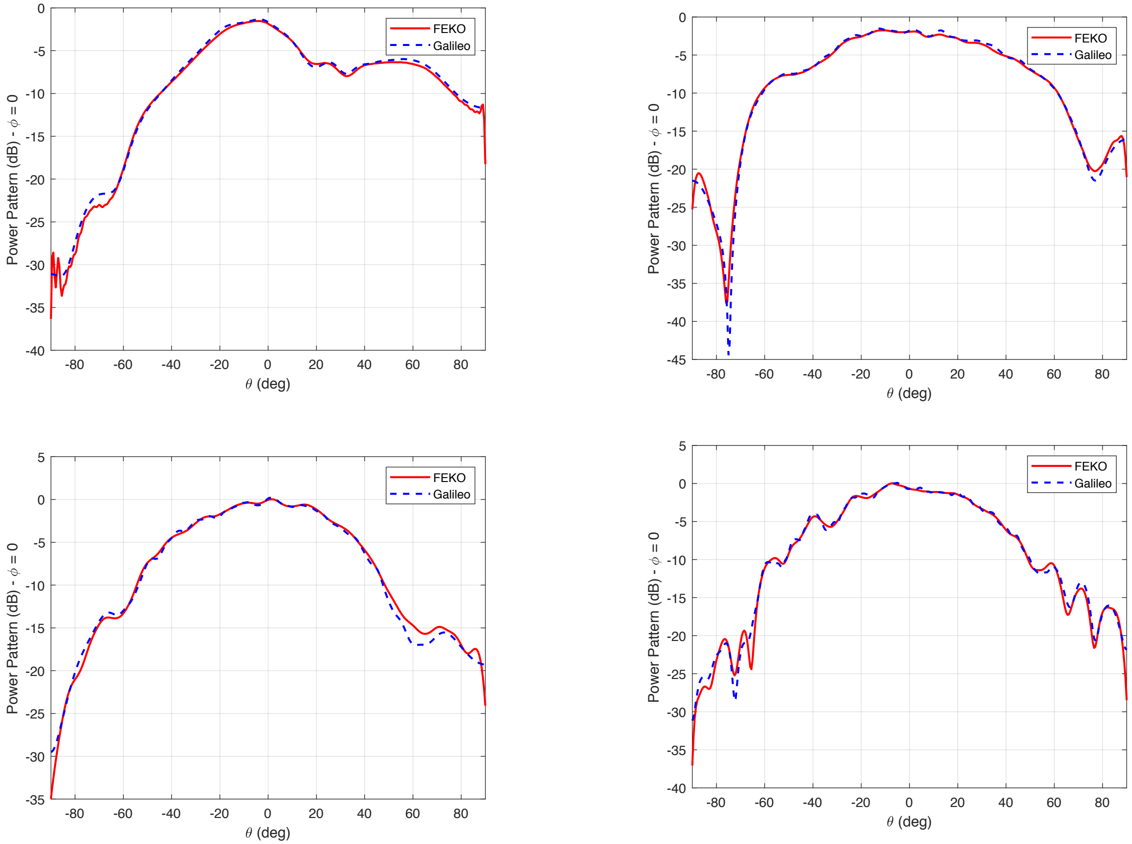


350 MHz

Other alternatives to MLFMM

- HARP (Craye, de Lera Acedo et al):
  - – Combination of primary and secondary CBFs (MBF) and a polynomial approximation of far-field coupling between MBFs.
  - – Not currently available in a commercial code.
- DGF (Ludick et al):
  - – Improves ∝ array approx (but not presently well suited to EEP work with only one driven antenna).
  - – Available in FEKO.
- Adaptive cross approximation (ACA) also in FEKO – does not work well on this problem.

Comparison of EEPs: FEKO & Galileo



Antenna 2. EW (X) pol.
Top left: 80 MHz Top right: 110MHz
Bot left: 160 MHz Bot right: 350MHz

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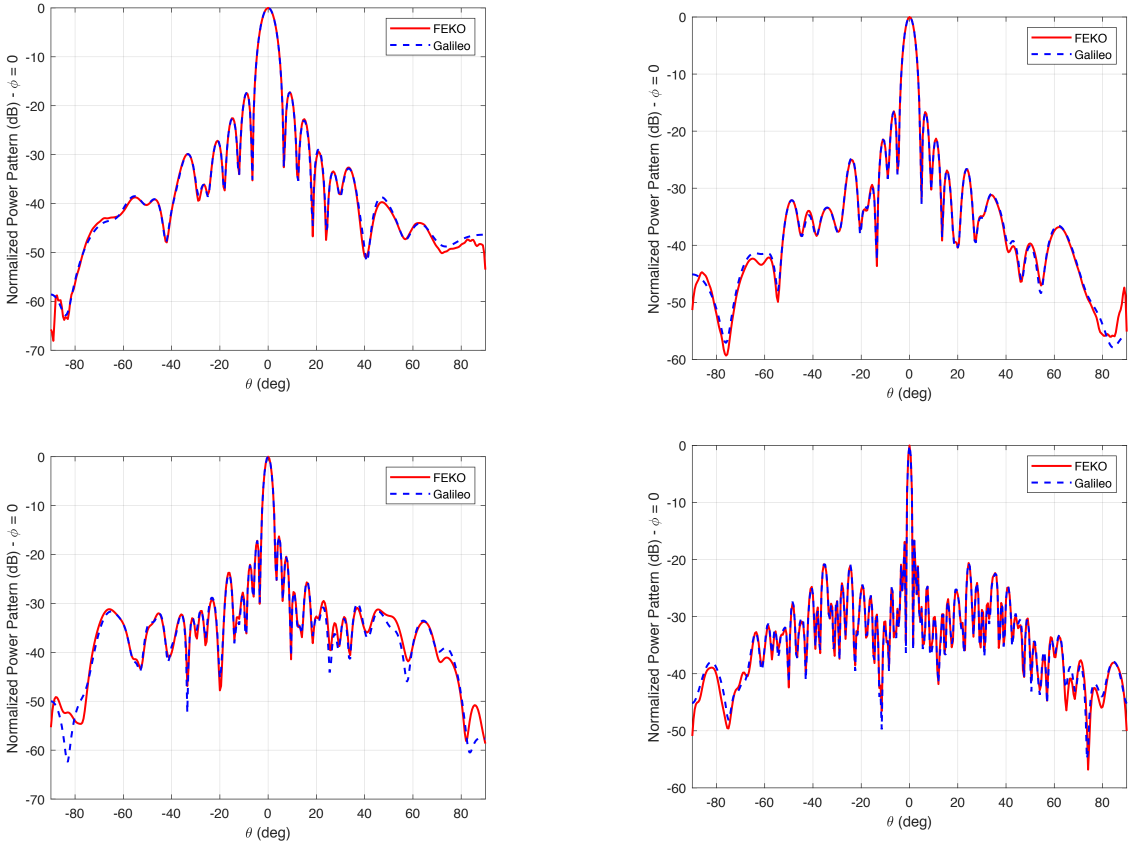
Zenith-pointing station beams from EEPs



Off-zenith pointings have a slight squint issue - see later presentation.

Antenna 2. EW (X) pol.
Top left: 80 MHz Top right: 110MHz
Bot left: 160 MHz Bot right: 350MHz

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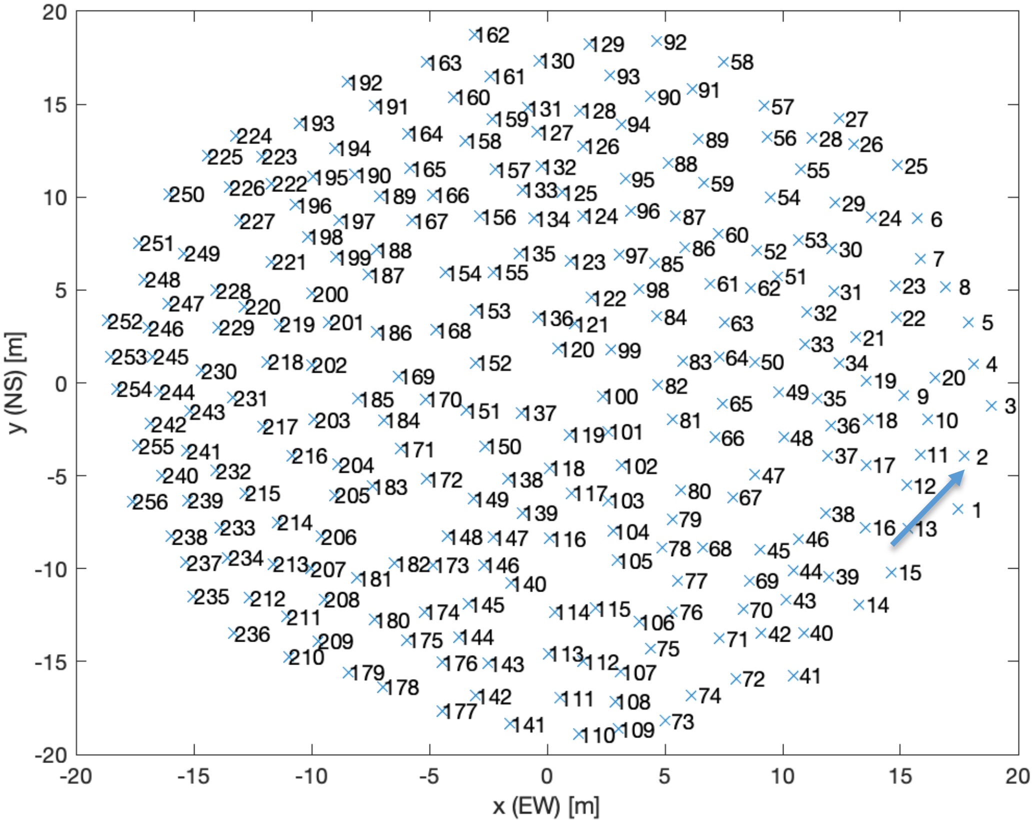
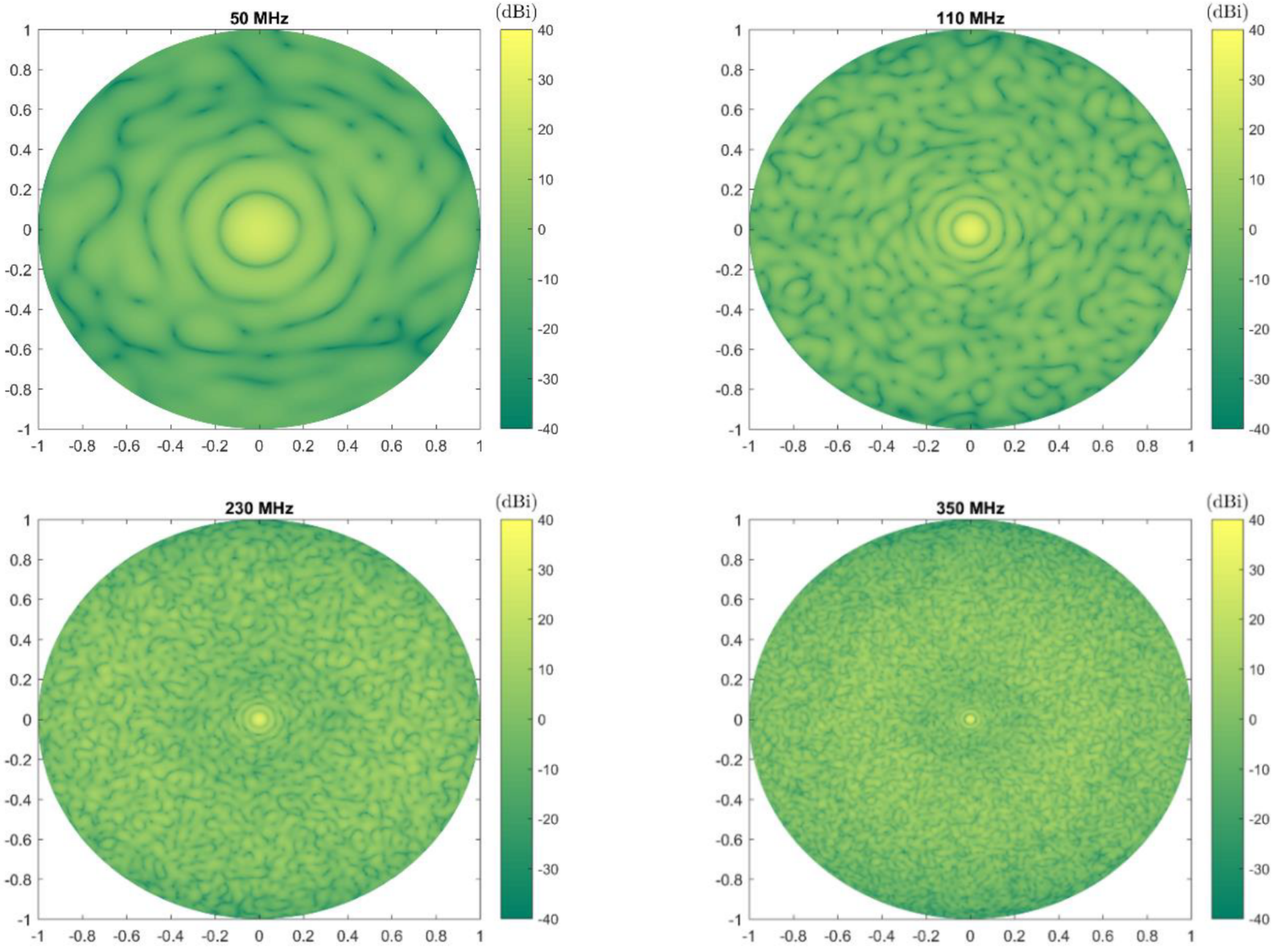
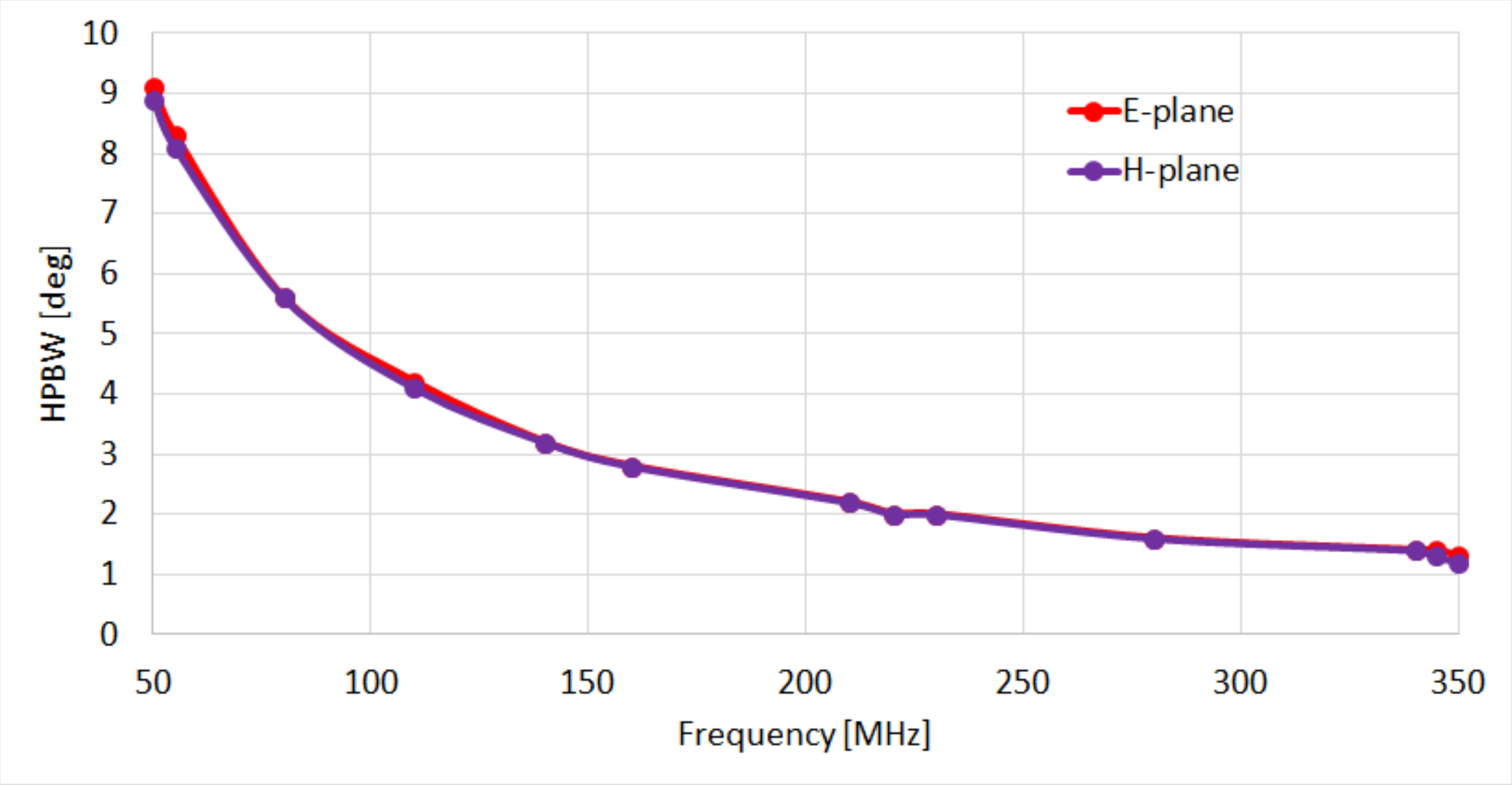
AAVS2 positions



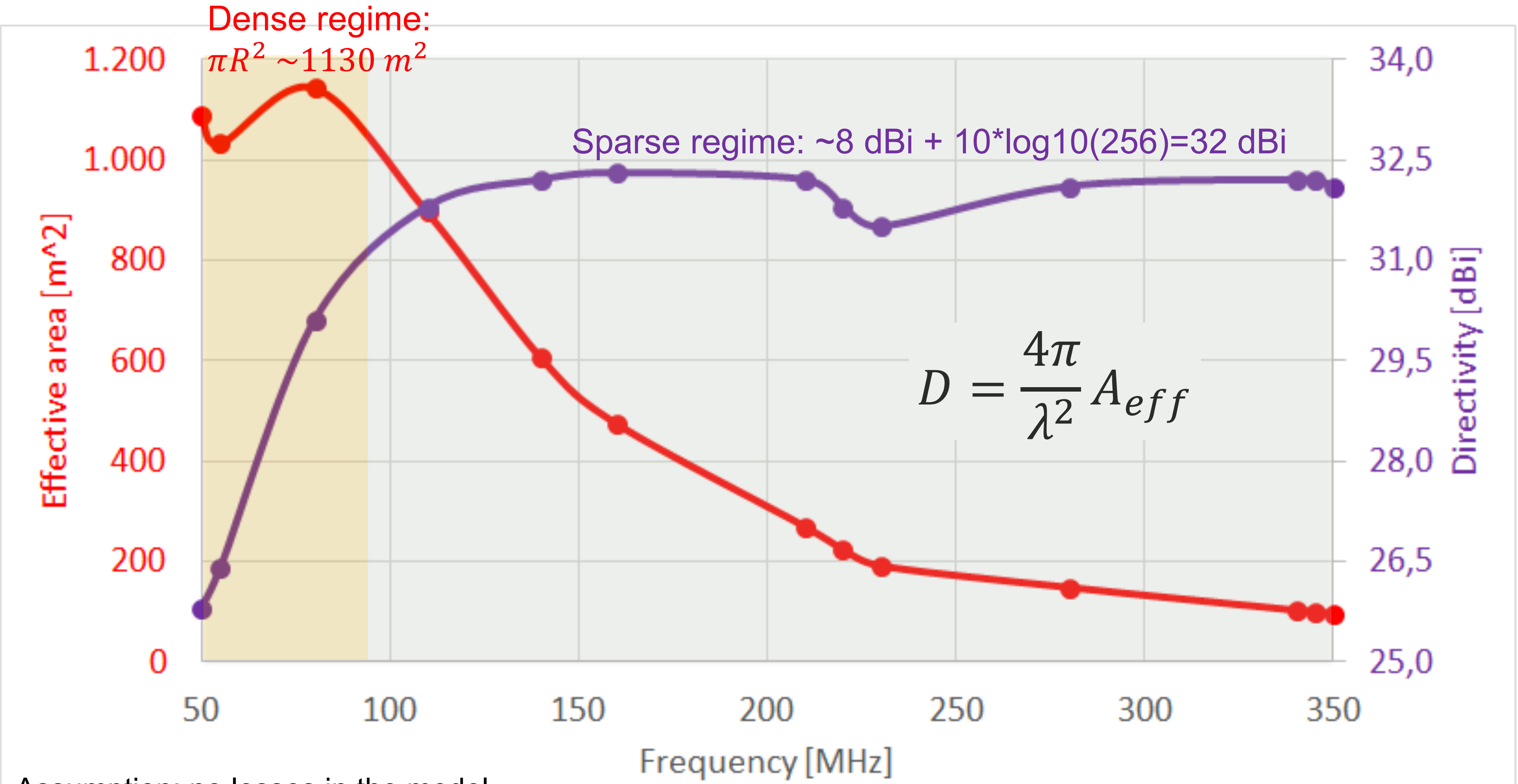
Array beam at zenith (from EEP)



Station beam HPBW at zenith

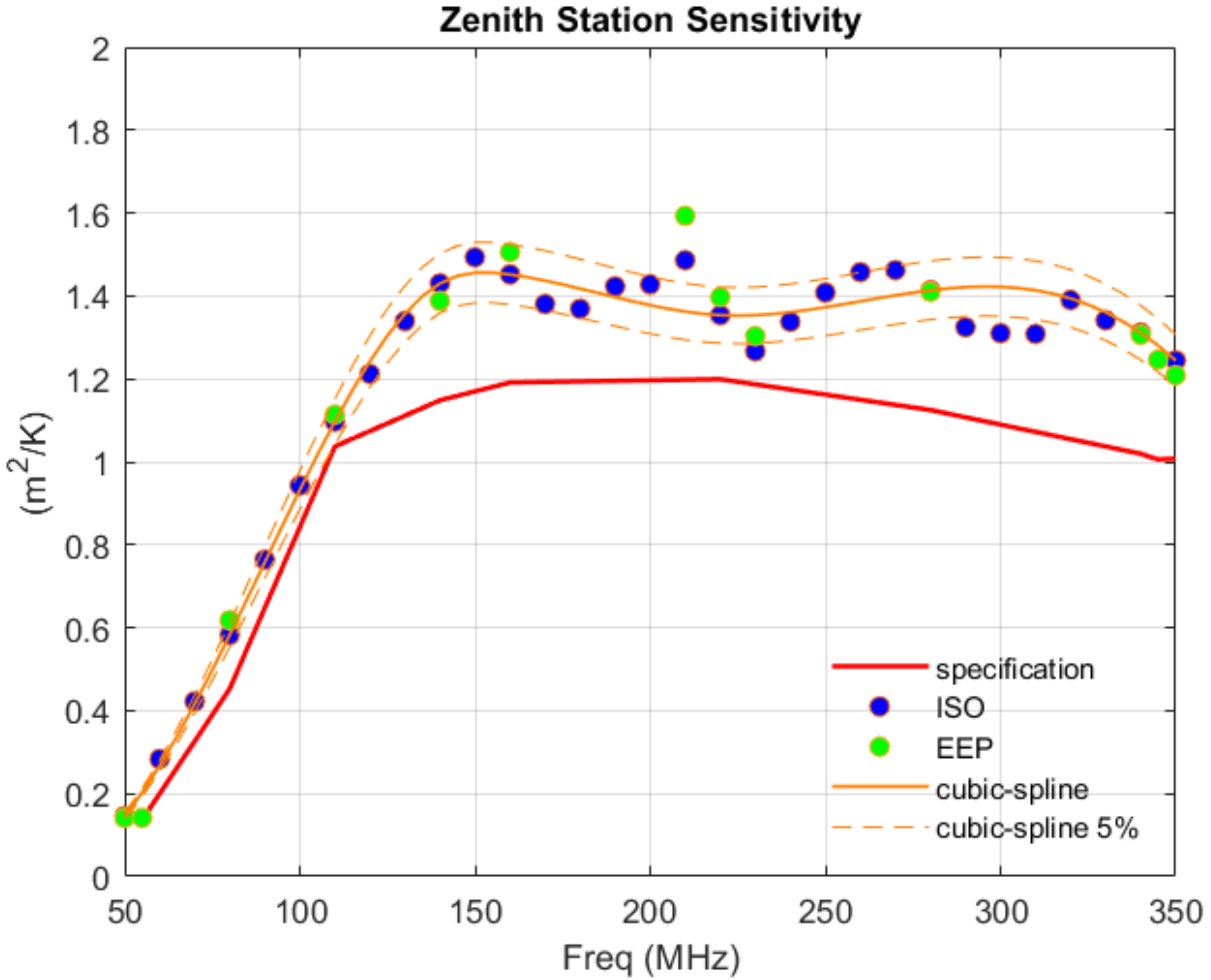


Station beam gain at zenith



$$D = \frac{4\pi}{\lambda^2} A_{eff}$$

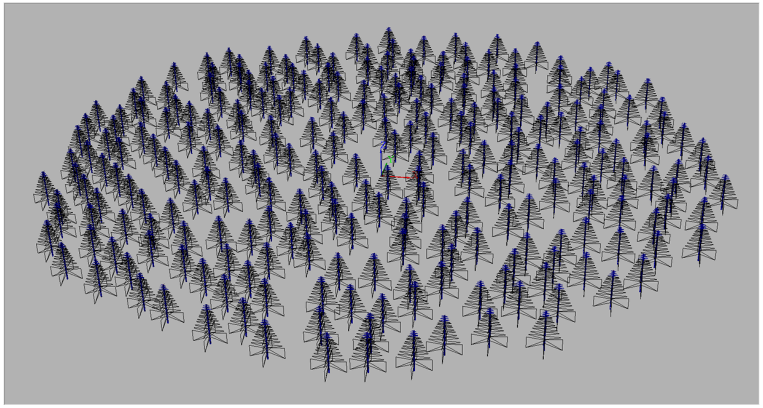
Assumption: no losses in the model



$$\mathit{Sensitivity}(\vartheta,\varphi) = \eta_{Dig}\frac{A_{eff}(\vartheta,\varphi)}{T_{sys}} = \eta_{Dig}\frac{\frac{\lambda^2}{4\pi}G(\vartheta,\varphi)}{\eta_L T_{ant} + (1-\eta_L)290 + \left[T_{LNA} + \frac{T_{rx}}{G_T}\right]}$$

Finite real ground

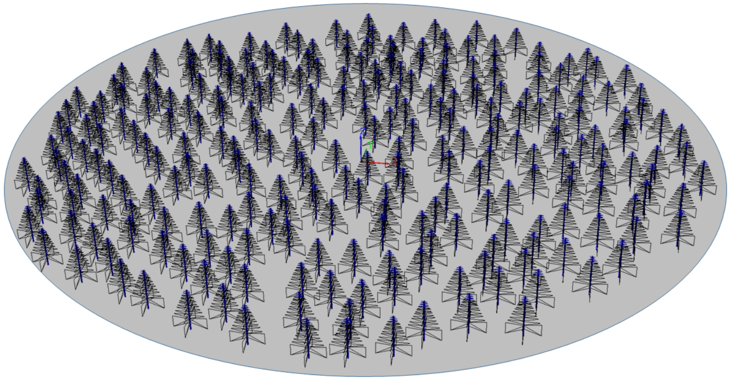
Infinite ground plane



Simplified approach which allows to use the reflection coefficient approximation adding a reflected component to the field, which is a very fast technique.

Finite ground plane

(42-m diameter)



More realistic scenario which allows to account for the truncation of the electrical currents induced in the ground plane and diffraction effects.

Technique for finite ground plane

Rather than using a full-wave technique, the problem of the finite ground plane is addressed through a simplified 3-step process:

1) computing with a full-wave approach the currents induced on the 256 antennas considering an infinite ground plane with reflection coefficient approximation;

2) starting from the currents of the previous point, the currents induced on a finite ground plane are computed with a full-wave approach;

3) the currents distributed in the antennas and in the finite ground plane are radiated applying the equivalence principle to obtain the scattered field.

More details in: P. Bolli, M. Bercigli, P. Di Ninni, M.G. Labate, G. Virone, "Preliminary Analysis of the Effects of the Ground Plane on the Element Patterns of SKA1-Low," *14th European Conference on Antennas and Propagation (EuCAP)*, (Copenhagen, Denmark), March 15-20, 2020.

Using EEPs for station calibration

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

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

- NB! It is very important to appreciate that these are field (i.e. voltage) gains – complex valued.
- This is NOT the usual antenna engineering usage, in which gain is a *power* based parameter.

Station calibration *contd. I*

- Direction dependent calibration is currently on the leading edge of radio astronomy practice.
- This aims to model the pattern using a simpler approximation, eg

$$E_p(l,m) \approx g_p A_p(l,m)$$

- Decompose into direction independent (DIEs) g_p (e.g. receiver gain) & direction dependent effects (DDE) $A_p(l,m)$ (element beam/EEPs; ionosphere).
- Approximate beam/EEP model:

$$A_p(l,m) = \sum_{i=1}^{M} \alpha_i P(l,m)$$

- Coefficients α_i are to be found; $P(l,m)$ could, for instance, be spherical harmonics, or characteristic pattern, etc.

Station calibration *contd. II*

- In principle, DIEs and DDEs can be solved during calibration, using measured visibilities & known sky map.
- However —- at station level there is too little information: a-priori model of element patterns is needed.
- LOFAR and MWA adopted empirical approach; actual parameters for dipole model are not solved for.
- Wide FoV pose challenges — sky model; inclusion of *w* term in interferometric integral.
- 256 SKALAs × 512 SKA-LOW stations produce 131 072 *different* EEPs — also very challenging!

Storing and using EEPs

- FEKO can store the EEPs as spherical harmonics or as a sampled radiation pattern.
- For efficiency when using SF, EEPs best phase-referenced to each individual antenna position, rather than array centre (dramatically reduces # harmonics – analogy with NF scans).
- Some post-processing is required to obtain the EEPs.
- Galileo stores sampled radiation patterns.
- If stored as a conventional radiation pattern, each set of EEPs is over one Gbyte of data at 0.5^o resolution.
- Data available for SKAO use.

Conclusions

- Embedded element patterns are central to contemporary phased array analysis.
- Previous results from different groups working on SKA have been difficult to compare.
- These EEP & beam results from ICRAR & INAF teams agree well.
- Essentially a verification – both groups have used (different) MoM codes with MLFMM acceleration; both assume infinite PEC ground planes for full-station models.
- Validation addressed via an on-site drone measurement campaign – not reported here.
- Progress in CEM has made full-wave modelling *just* tractable.
- Complicated EEPs make station beam calibration difficult:
  - Mutual coupling does *not* average out for individual EEPs
  - However, the EEPs *do* average out for the array pattern.
- Modelling large aperture arrays still challenges CEM tools — scope for further work on fast methods, and including finite ground planes.

- End of presentation.