MidPrep Workshop
20th April 2015 – Aveiro, Portugal

SKA-low array simulations and beam modelling for calibration

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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…)

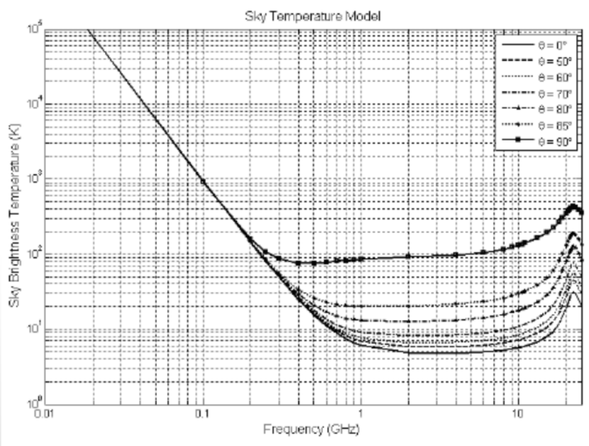
Scan angle: >45°

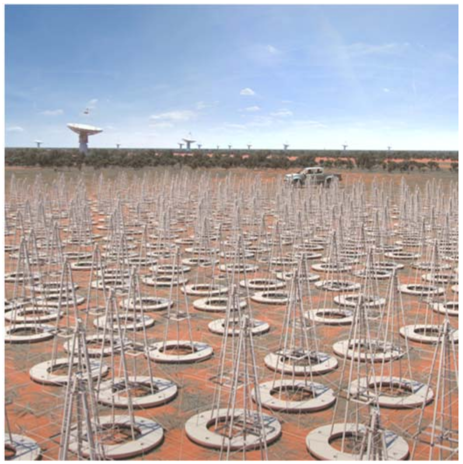
Sensitivity : 500m^2/K (110–350MHz)

Polarisation: Dual (of good quality)

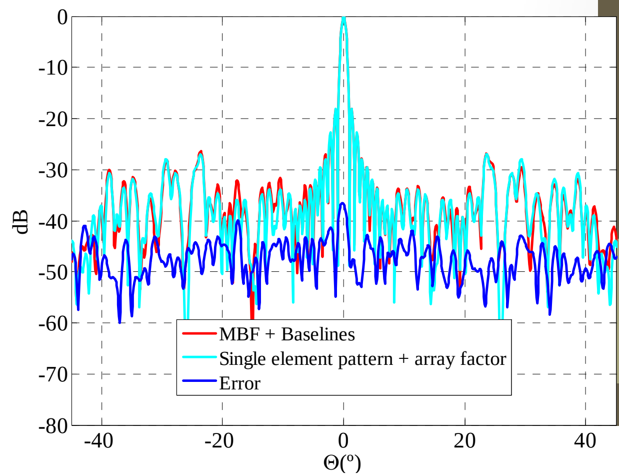
Beam size: >5° (no beam stitching)

Why sparse?

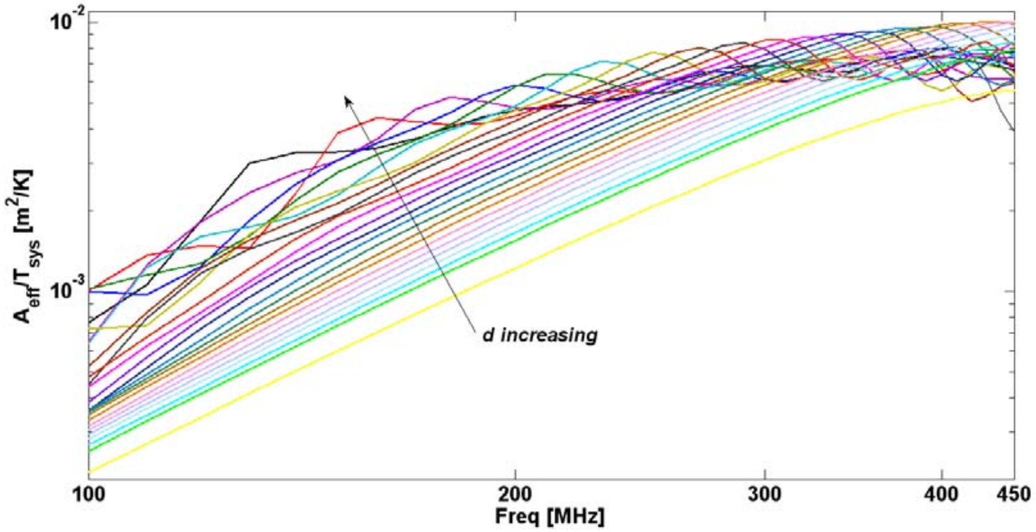




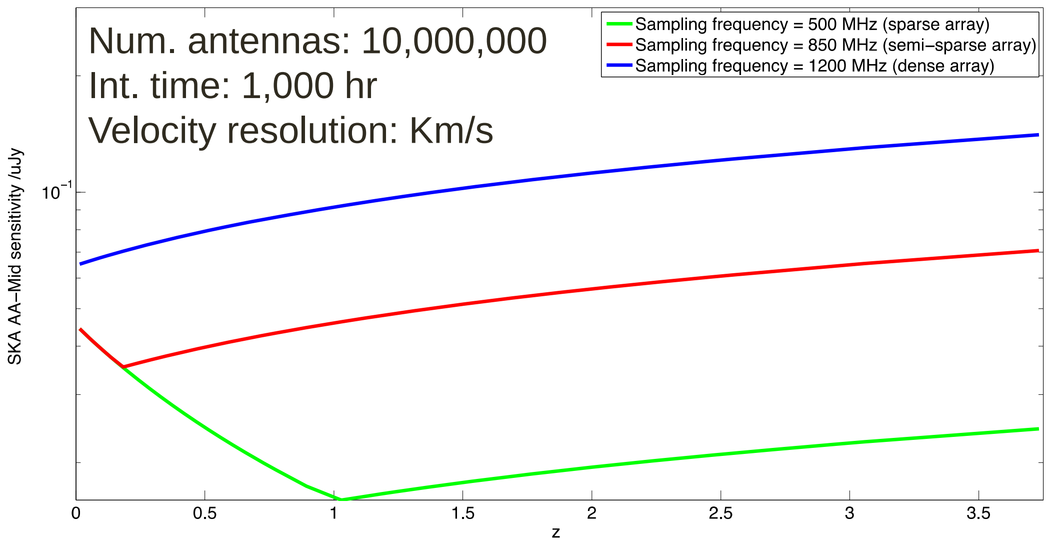
Why random?



Sparse arrays (AA-low)



Sparse arrays (AA-Mid)



SKA-low technical description

- Early and relevant papers:

Dense vs Sparse: [1] R. Brown & W. van Cappellen, SKA Memo 87: Aperture Arrays for the SKA: Dense or Sparse?, 11/06.

Randomization effects: [1] D. González-Ovejero, E. de Lera Acedo, N. Razavi-Ghods, C. Craeye, E. García, Non-periodic arrays for radio-astronomy applications, APS-URSI 2011, Washington, USA, July 2011.

Effect on side lobes: [2] N. Razavi-Ghods, E. De Lera Acedo, A. El-Makadema, P. Alexander, A. Brown, Analysis of Sky Contributions to System Temperature for Low Frequency SKA Aperture Array Geometries, *Experimental Astronomy*, Vol. 33, Issue 1, pp.141-155, 2011.

Mutual coupling and randomization: [3] E. de Lera Acedo, N. Razavi-Ghods, D. González-Ovejero, R. Sarkis, C. Craeye, Compact representation of the effects of mutual coupling in non-regular arrays devoted to the SKA telescope, International Conference on Electromagnetics in Advanced Applications (ICEAA 2011), Torino, Italy, September 2011.

Why are we using random-sparse for SKA-low?: [4] E. de Lera Acedo, N. Razavi-Ghods, N. Troop, N. Drought, A.J. Faulkner, SKALA, a log-periodic array antenna for the SKA-low instrument: design, simulations, tests and system considerations, *Experimental Astronomy*, DOI 10.1007/s10686-015-9439-0.

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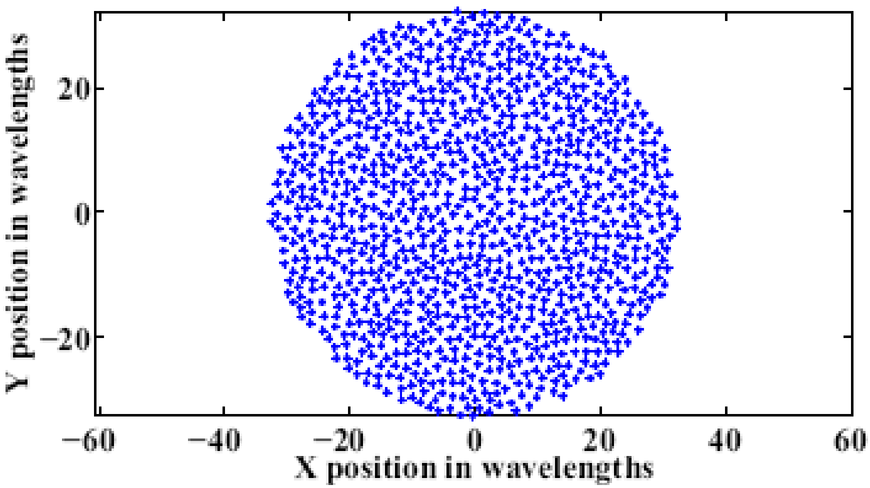
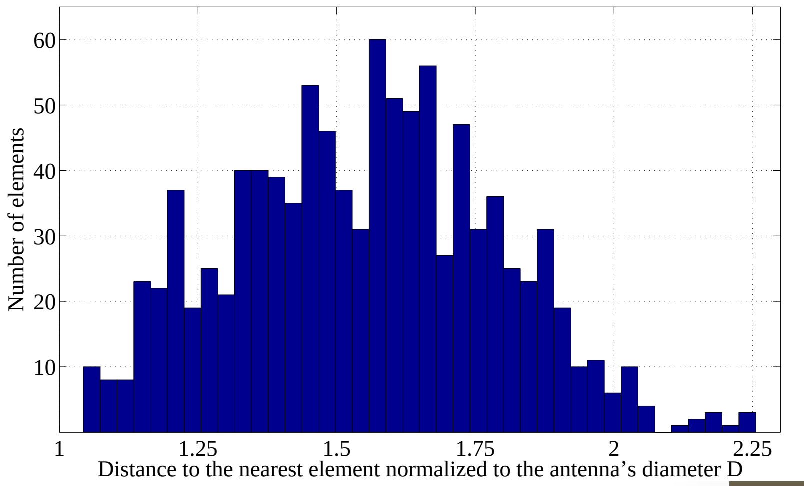
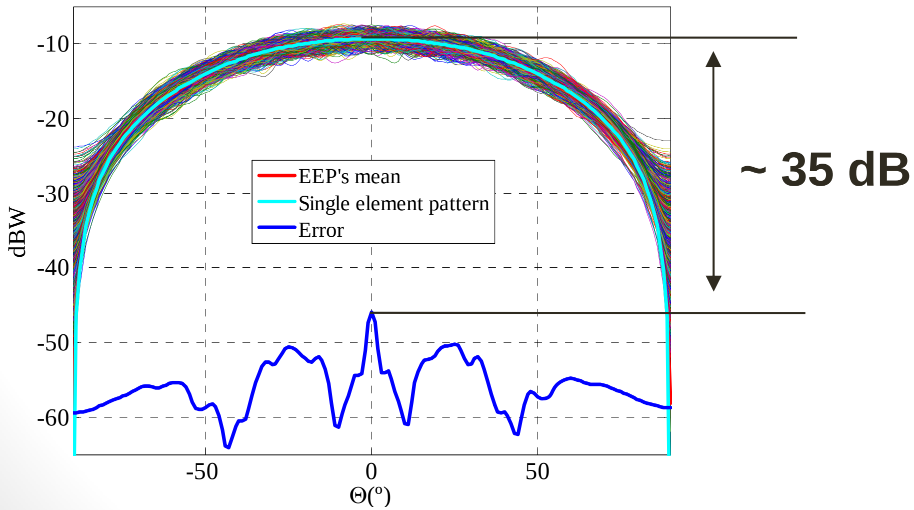
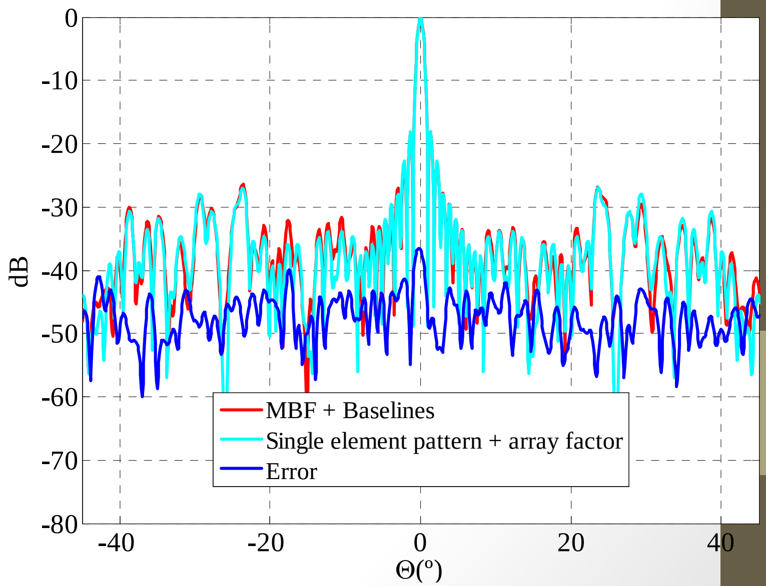
Physical effects

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









Physical effects II

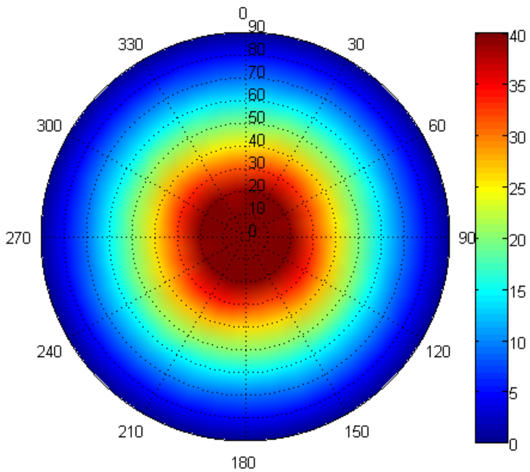
- Effects with slow changing cycles:
  - Cabling
  - Ground plane/soil (small effect on Stokes I sensitivity, strong in polarization)

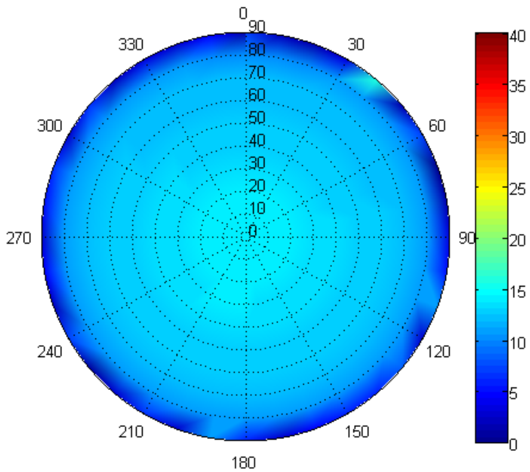
PEC ground

50 MHz

Desert ground:

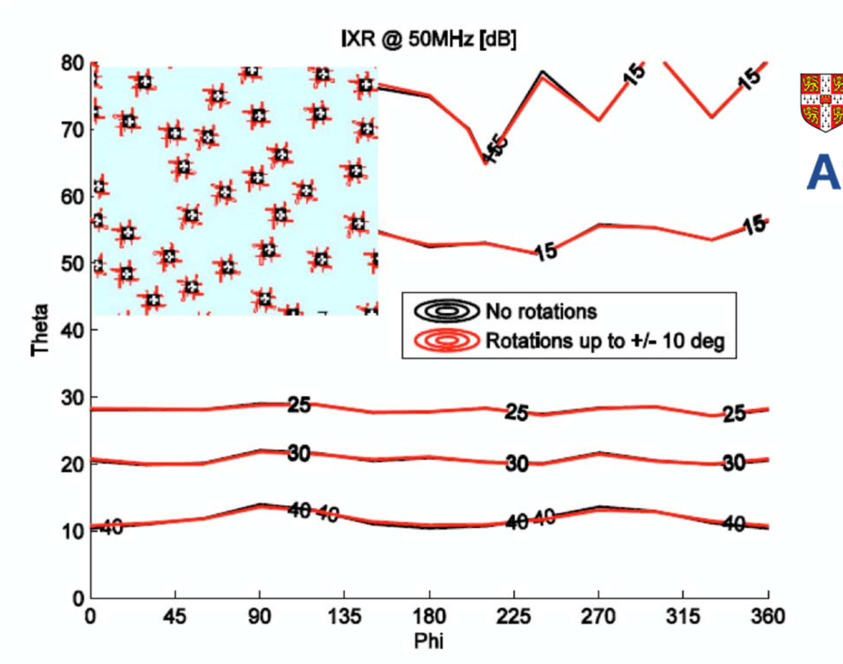
- 10 % moisture content
- Relative permittivity: 6.31
- Conductivity: 22 mS/m





Physical effects III

- Effects with slow changing cycles:
  - Misalignments



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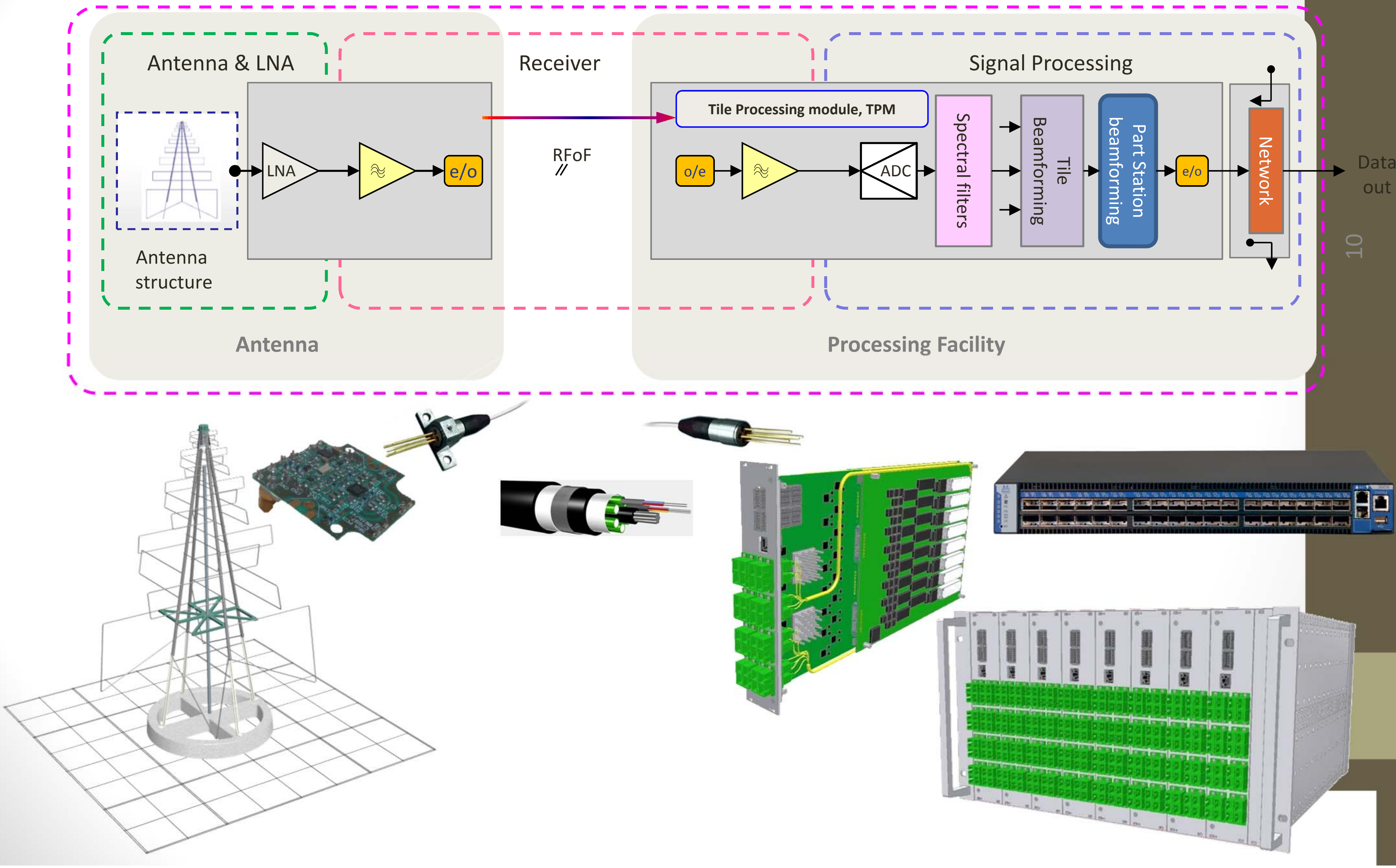
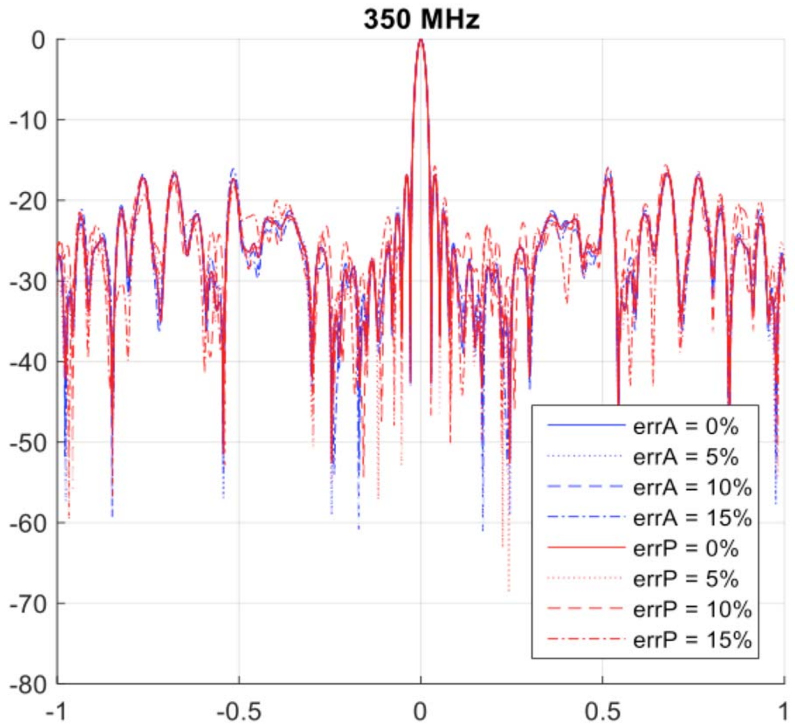
- Effects with fast changing cycles:
  - Electronics (LNA impedance, noise), RFoF. Do we need to re-compute the patterns or just tune the parametrizsed models?

SKA-low signal chain



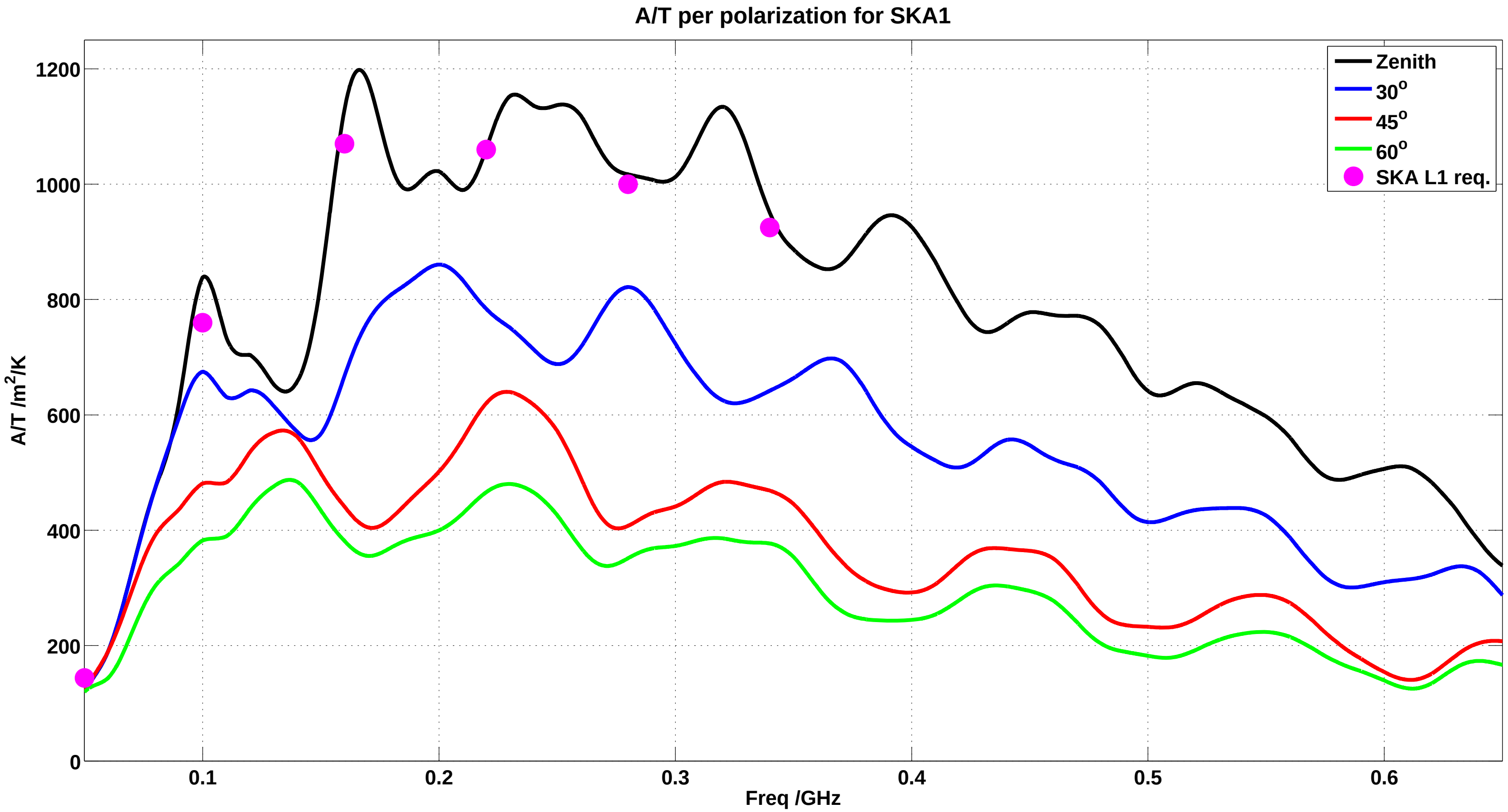
Physical effects IV



- 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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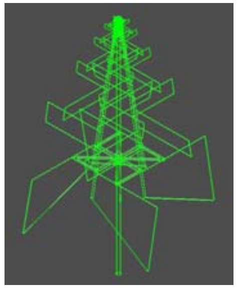
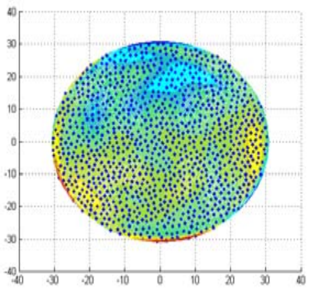
EM simulations of SKA stations

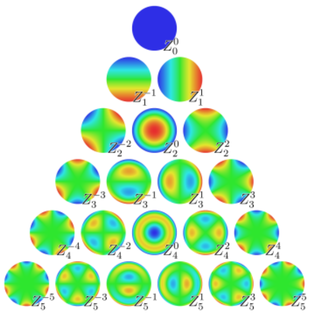
- Antenna simulations
  - CST, MoM in house



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

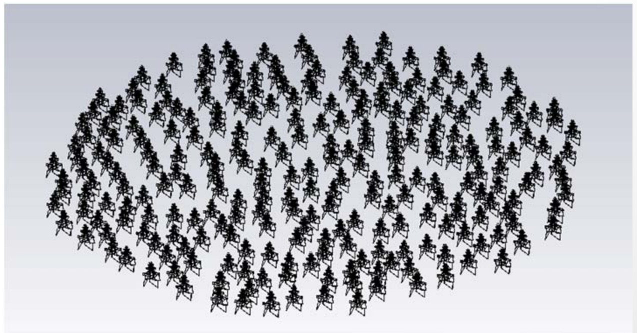
- Stations and core (256+ elements)
  - CST, FEKO, WIPL-D, MoM in house
- Beam models for calibration
  - Based on MoM in house (MBF based: D. Gonzalez-Ovejero, C. Craeye 2011)





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 o 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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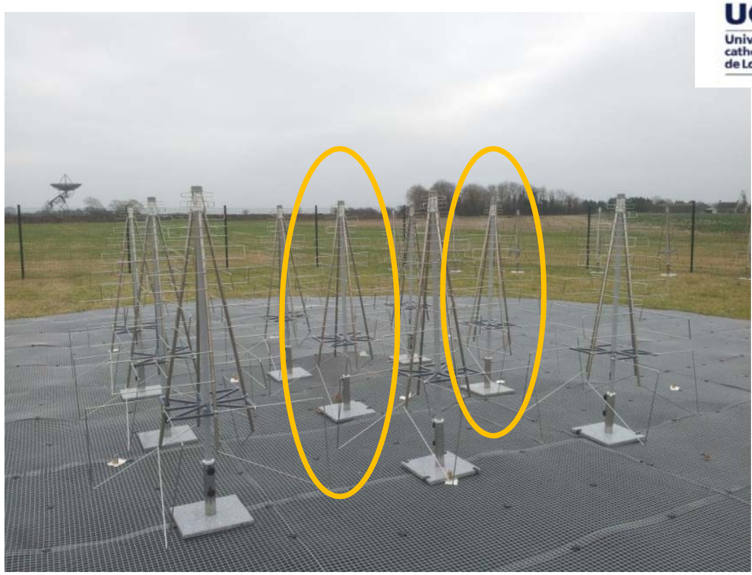
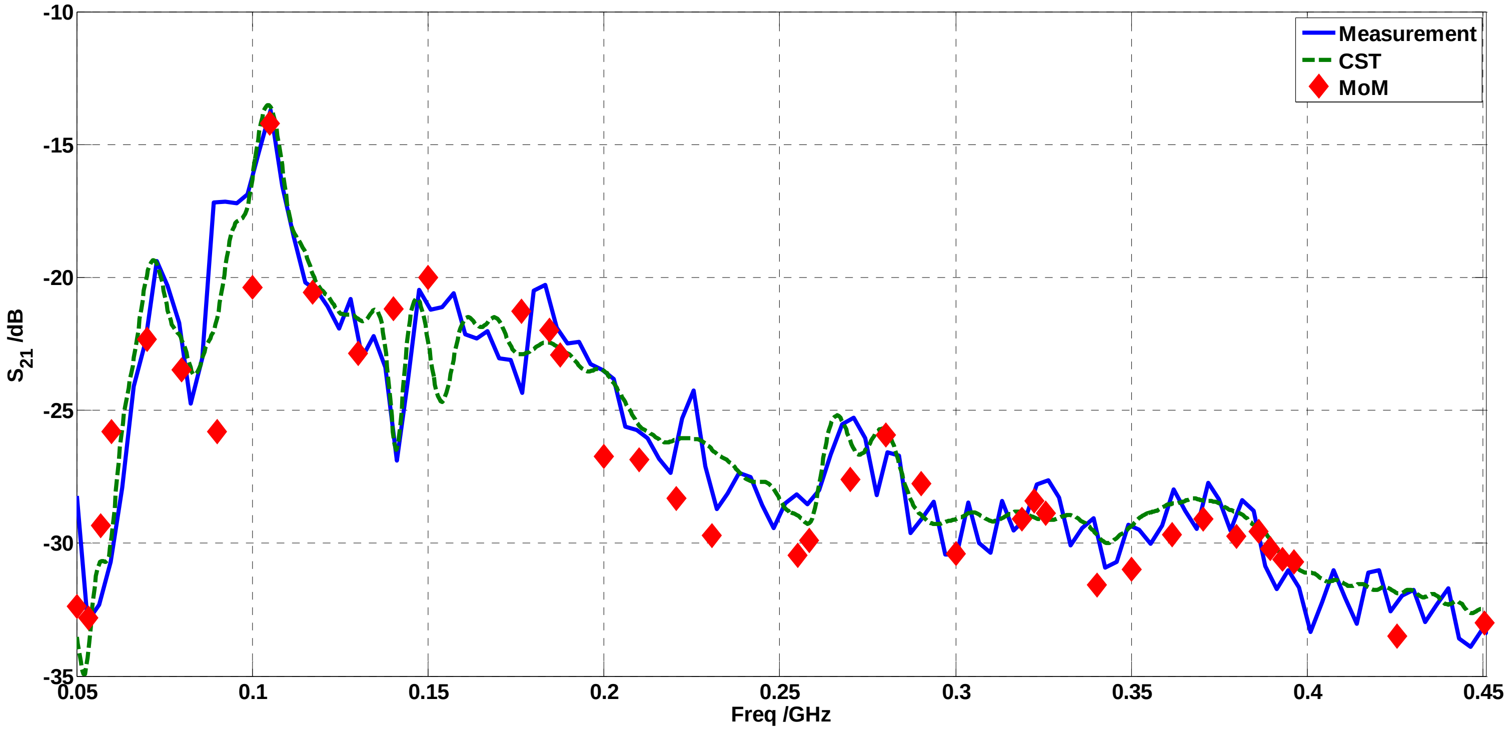
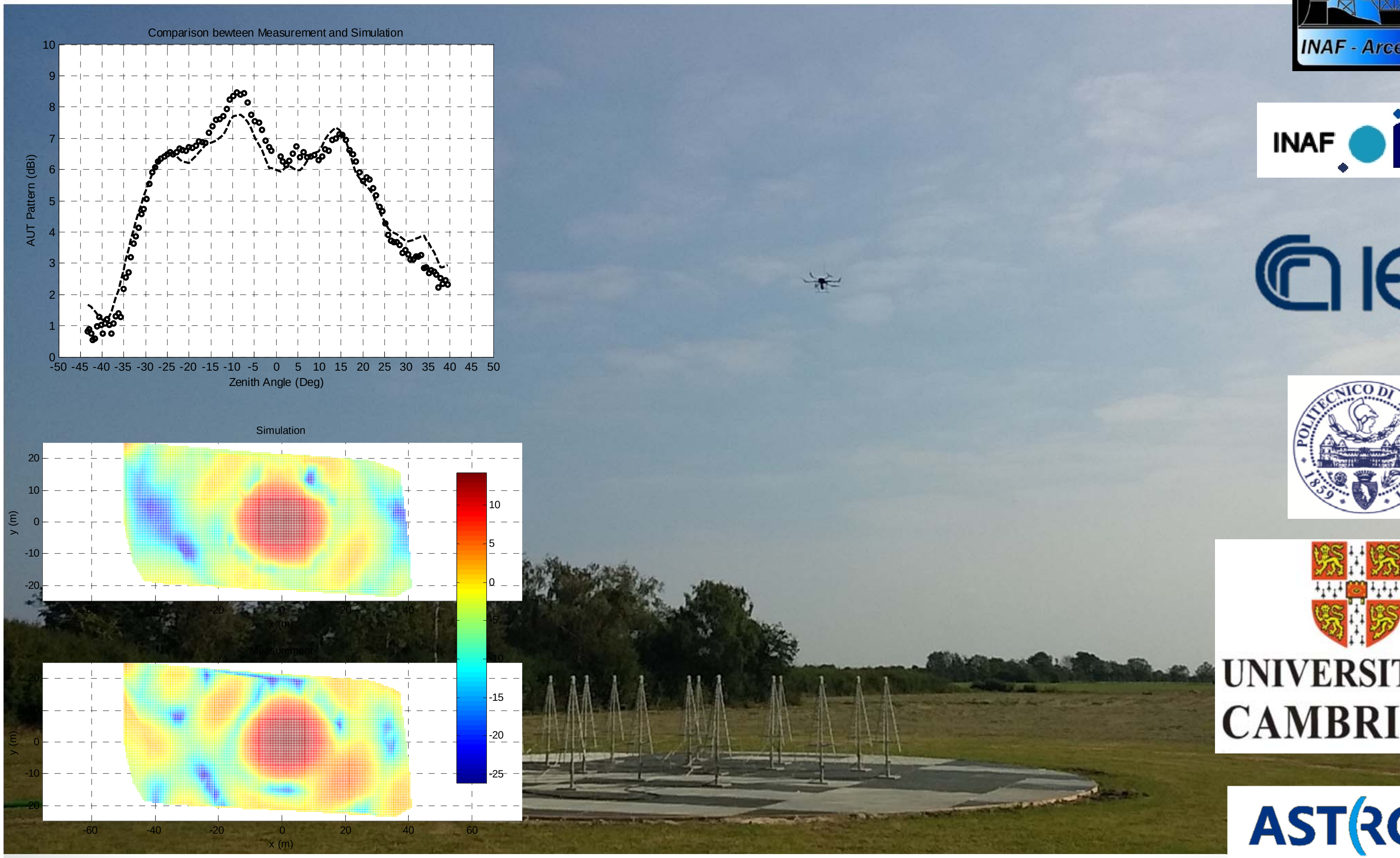
Coupling: AAVS0 array





Hexacopter (AAVS0 array)



INAF - Arcetri

INAF ira

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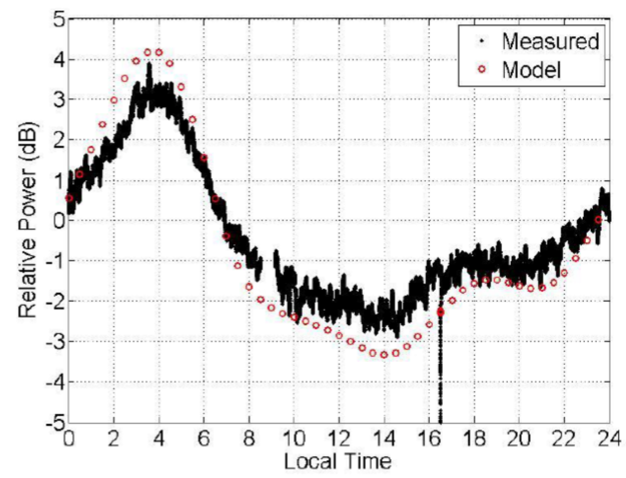
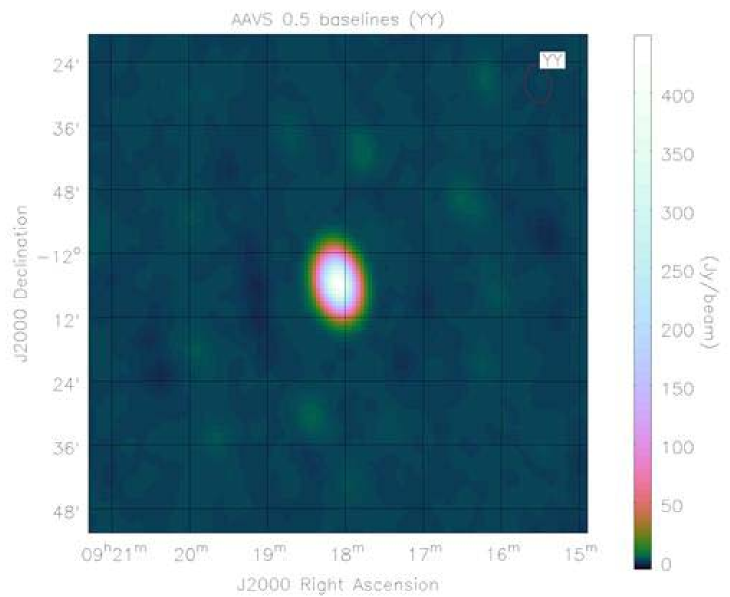
AAVS0.5

- 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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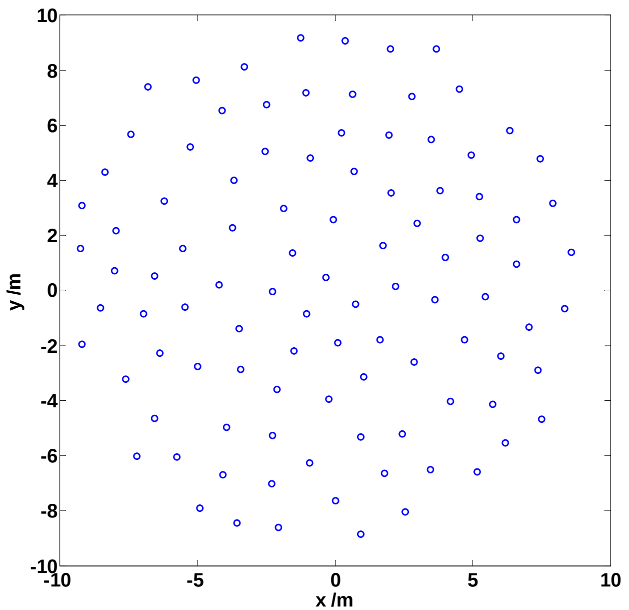
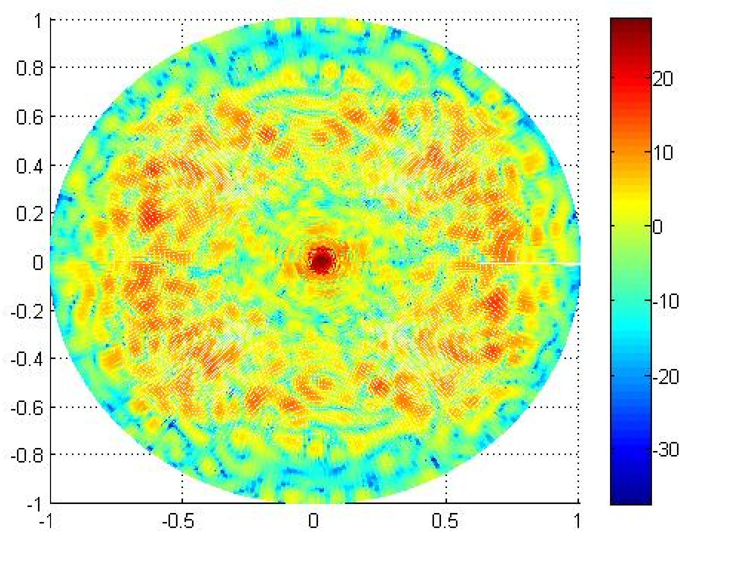
Introduction: What is the problem?

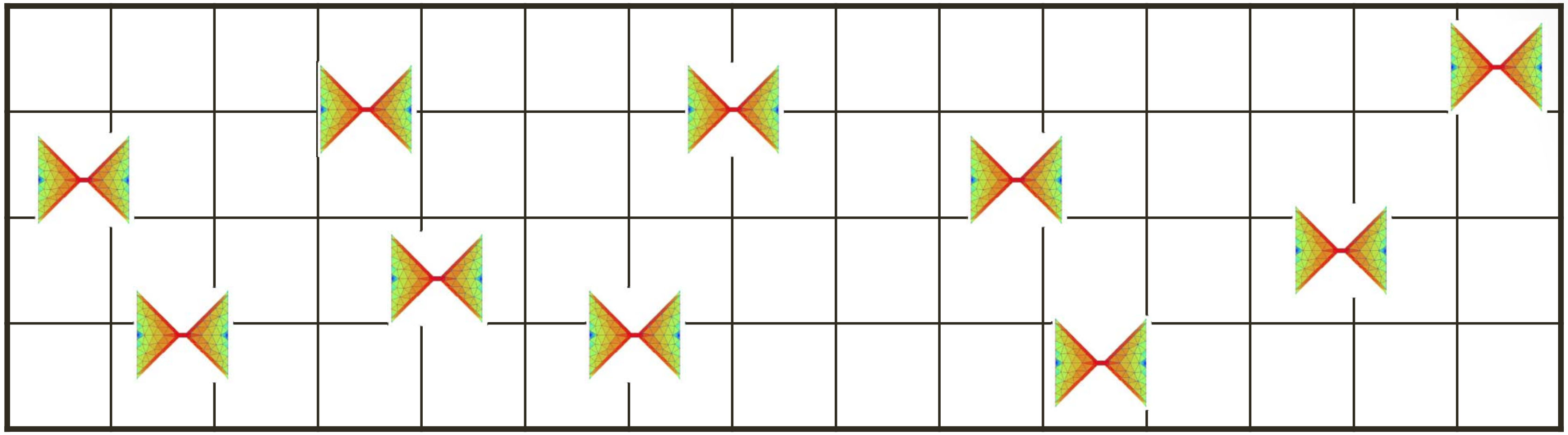
- Required:
  - Capture DDEs
  - High accuracy
  - Few coefficients (for few measurement points)
  - Quick access
  - Low storage requirements



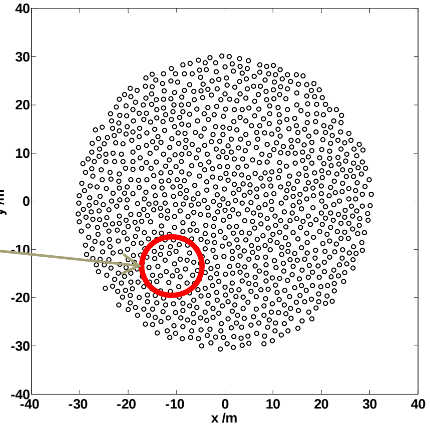


MoM-MBF simulations of large irregular arrays

- 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**.



Radius of Influence



[1] David Gonzalez-Ovejero, Christophe Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic Arrays," IEEE Trans. Antennas Propag., vol.59, no.8, pp.3117,3122, Aug. 2011

Low Order Beam Models for Calibration

Zernike representation of deficiencies in the pattern including mutual coupling

$$\overline{F_{rec}}(\theta,\phi) = \sum_{m=1}^{t} \alpha_m \sum_{i=1}^{n} \overline{f}_i(\theta,\phi) e^{-j\left(\varphi_i-\varphi_{i,0}\right)} Z_m$$

- 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.

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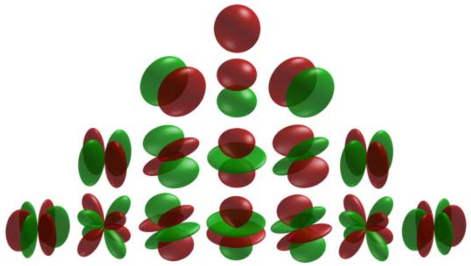
*Before: C. Craeye et al. (2012): $\mathrm{AP} = \sum_k AF_k x MBF_k$

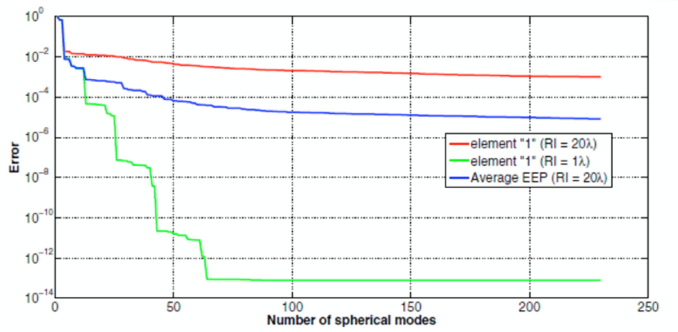
Use of pre-computed EEPs

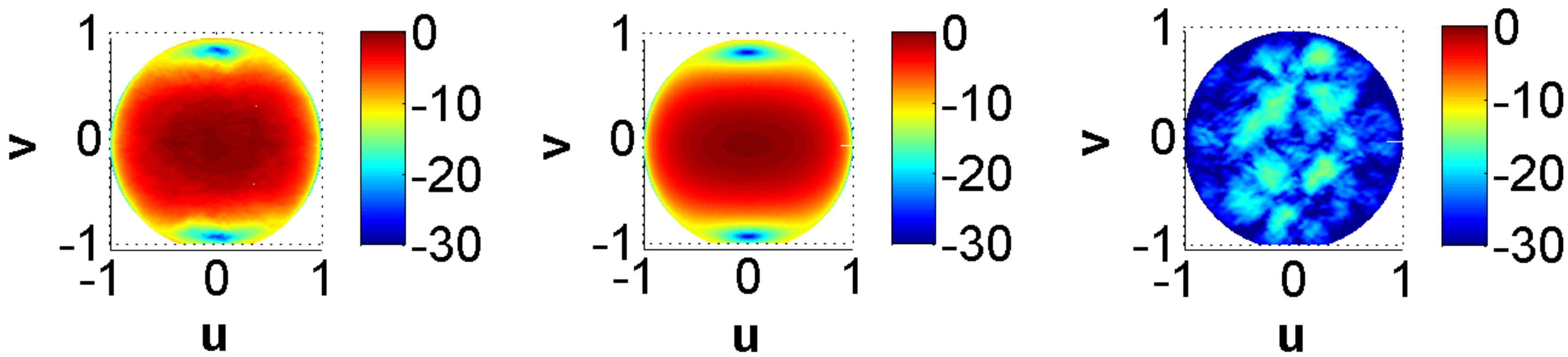
$$\overline{F_{rec}}(\theta,\phi) = \sum_{m=1}^{t} \alpha_m \sum_{i=1}^{n} \overline{f}_i(\theta,\phi) e^{-j(\varphi_i - \varphi_{i,0})} Z_m$$

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

Spherical Harmonics

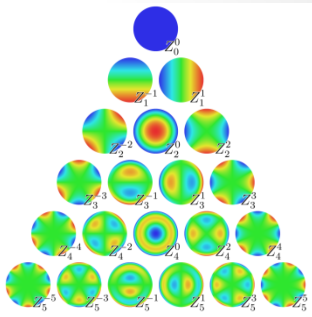




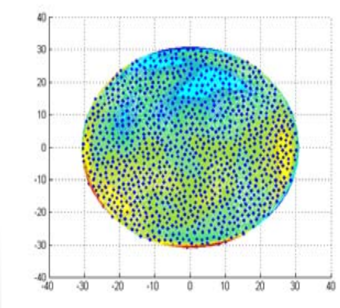


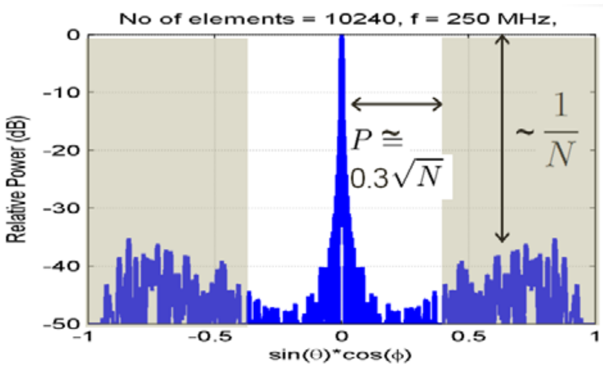
Use of Zernike polynomials

$$\overline{F_{rec}}(\theta,\phi) = \sum_{m=1}^{t} \alpha_m \sum_{i=1}^{n} \bar{f}_i(\theta,\phi) e^{-j(\varphi_i - \varphi_{i,0})} Z_m$$



- 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.





Continuous aperture regime

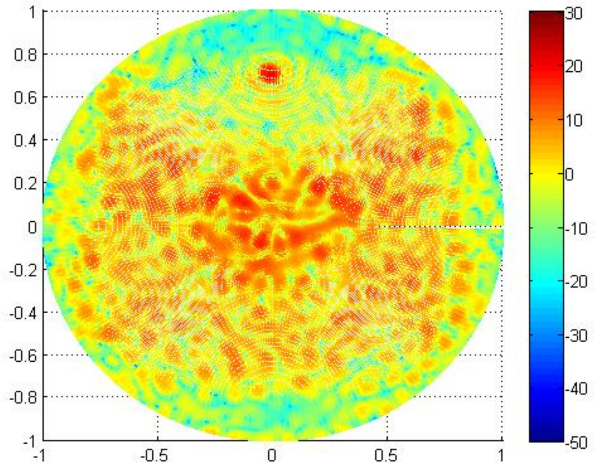
Similar to theory of ~circular apertures:
Y. Rahmat-Samii and V. Galindo-Israel, “Shaped reflector antenna analysis using the Jacobi-Bessel series,” IEEE Trans. Antennas Propagat., Vol. 28, no.4, pp. 425-435, Jul. 1980.

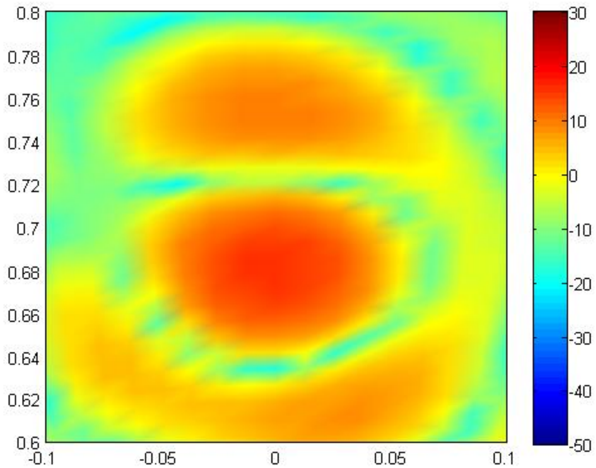
Related work: C. Craeye et al. (2012), R. Maaskant, M. Ivashina, et al. (2012), etc.

Tests: Pointing error (2 deg.) – scanning

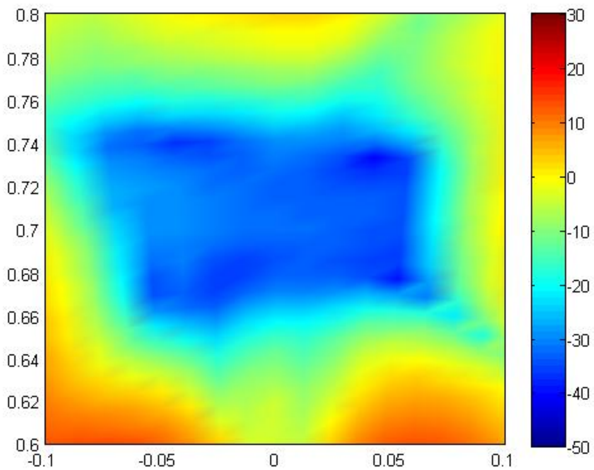
Also possible: dead elements, etc.

Scan:
Θ = 45 deg.
Φ = 90 deg.

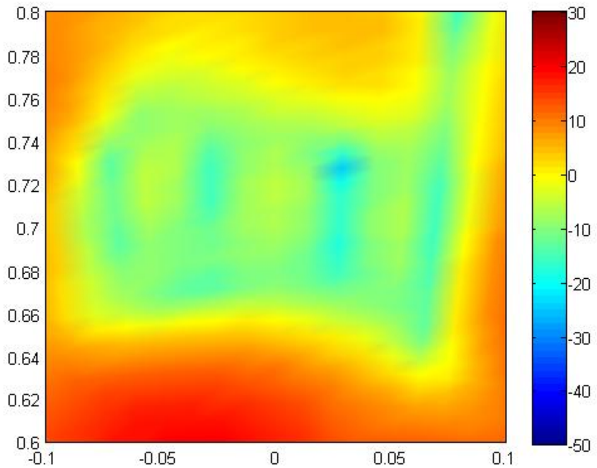




Error Rec. - Actual



t = 36, *w* = 81



t = 15, *w* = 16

**t* : number of Zernike polynomials / *w* : number of measured points.

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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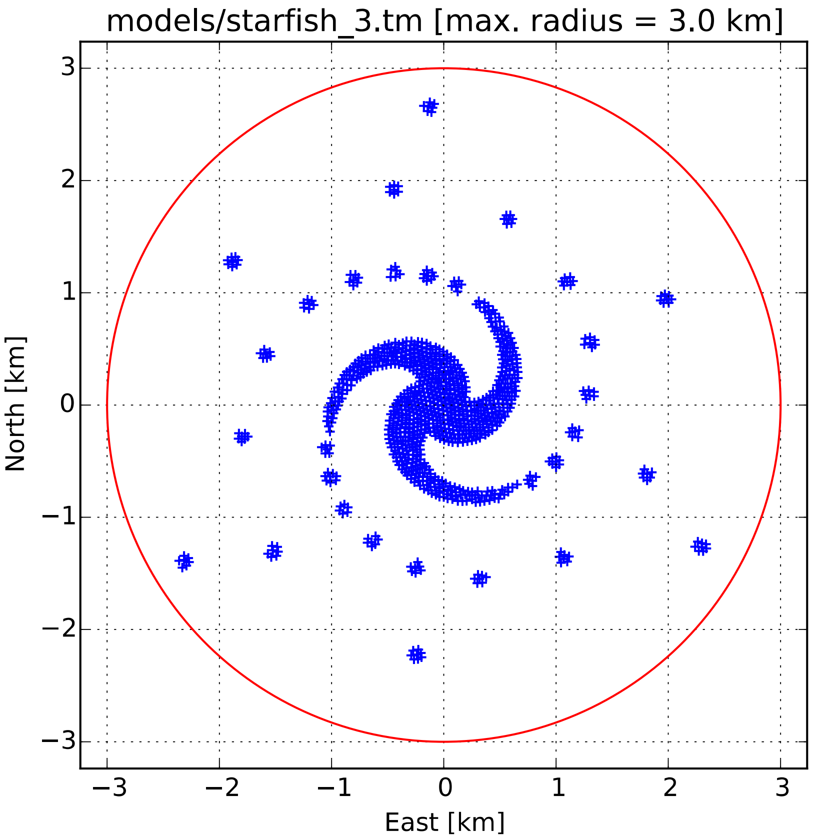
Interferometric Simulations

- 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:

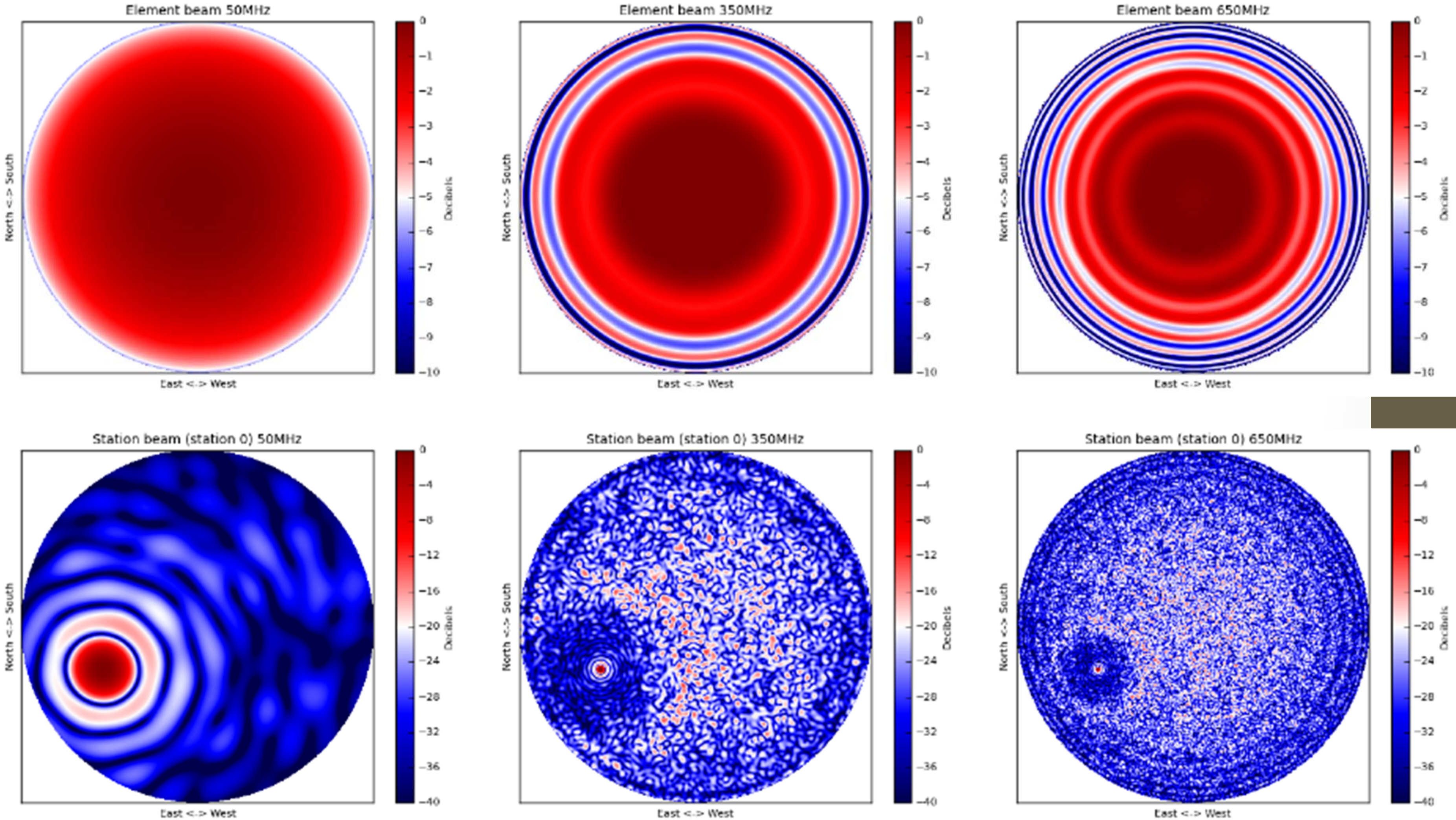
  50, 70, 110, 170, 250, 350, 450, 550, 650 MHz
- Simulating essentially the core of SKA1-LOW (979 stations in original baseline design)
- All stations with different randomised configurations
- The simulated pattern of SKALA was included
- Sky model: VLSS catalogue (brightest sources removed)

Telescope model

- Model has the same density i
  the core as the baseline desig
- 1024 stations out to 41 km fr
  the centre, 979 within 3km
  radius.
- Element patterns simulated a
  frequencies from 50 to 650 M



Antenna and station beams

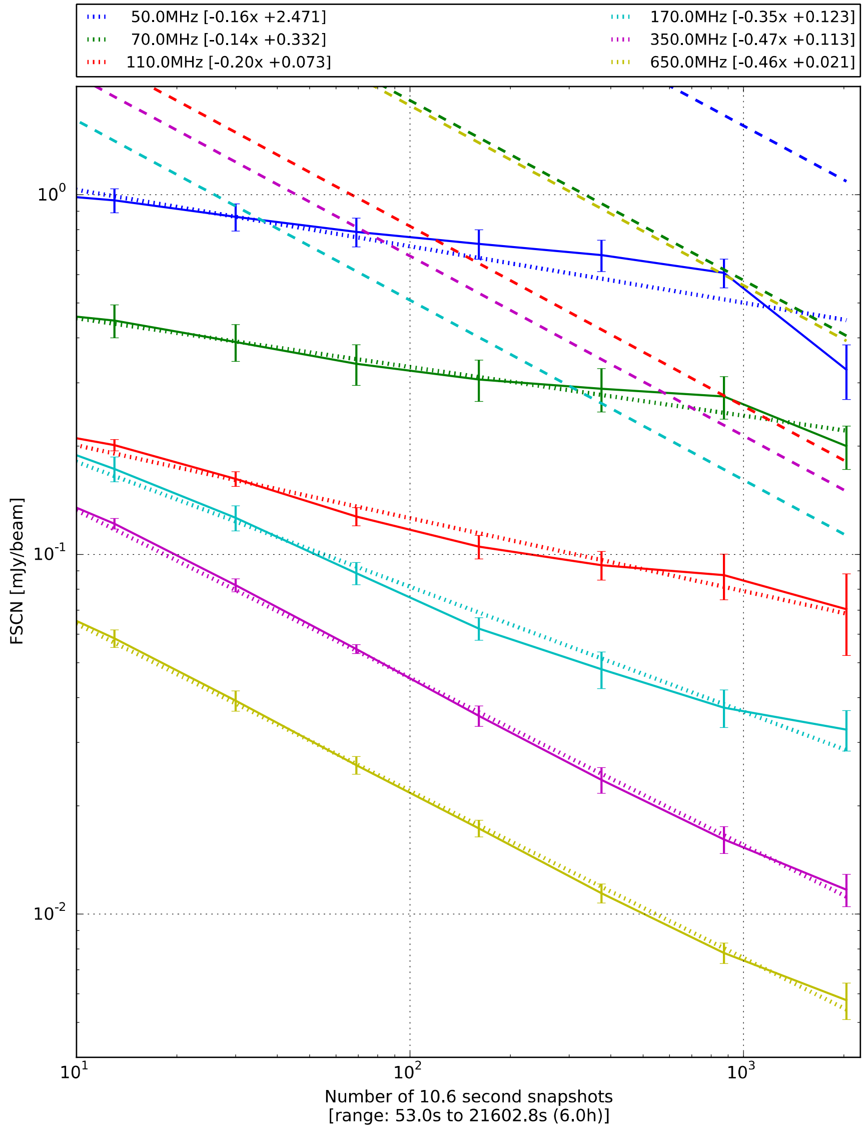


Sky model

- 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

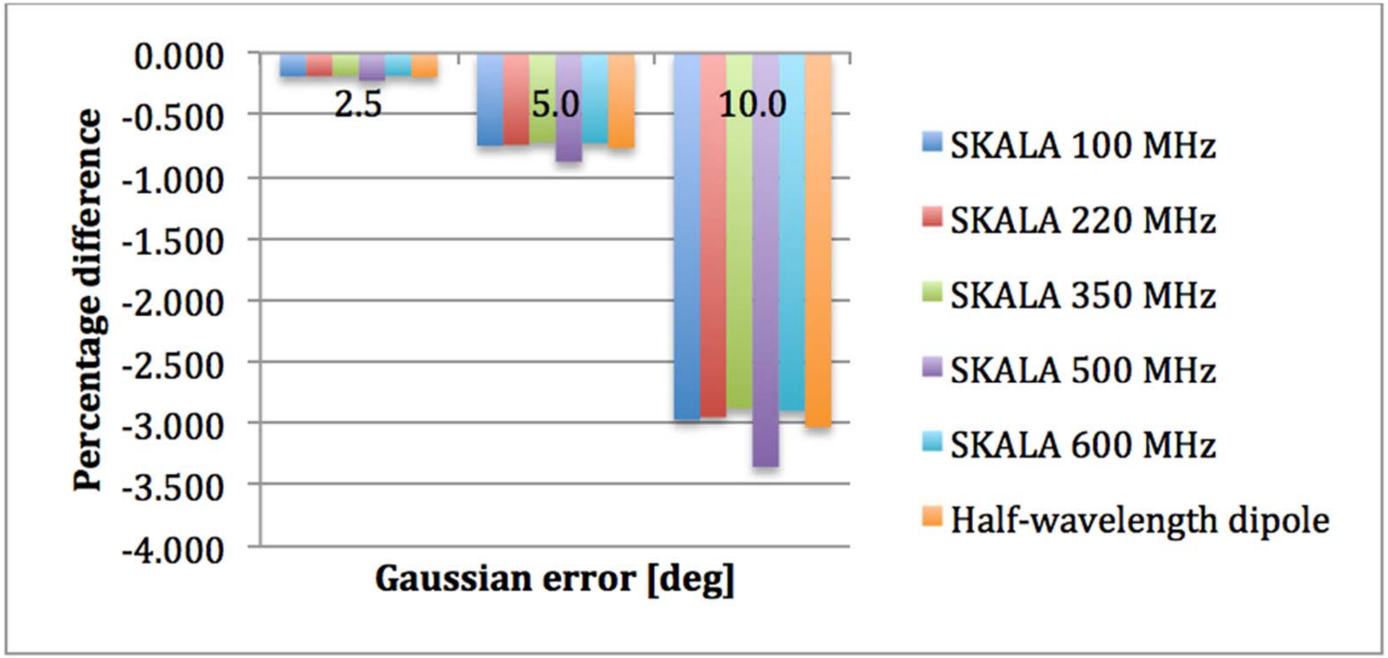


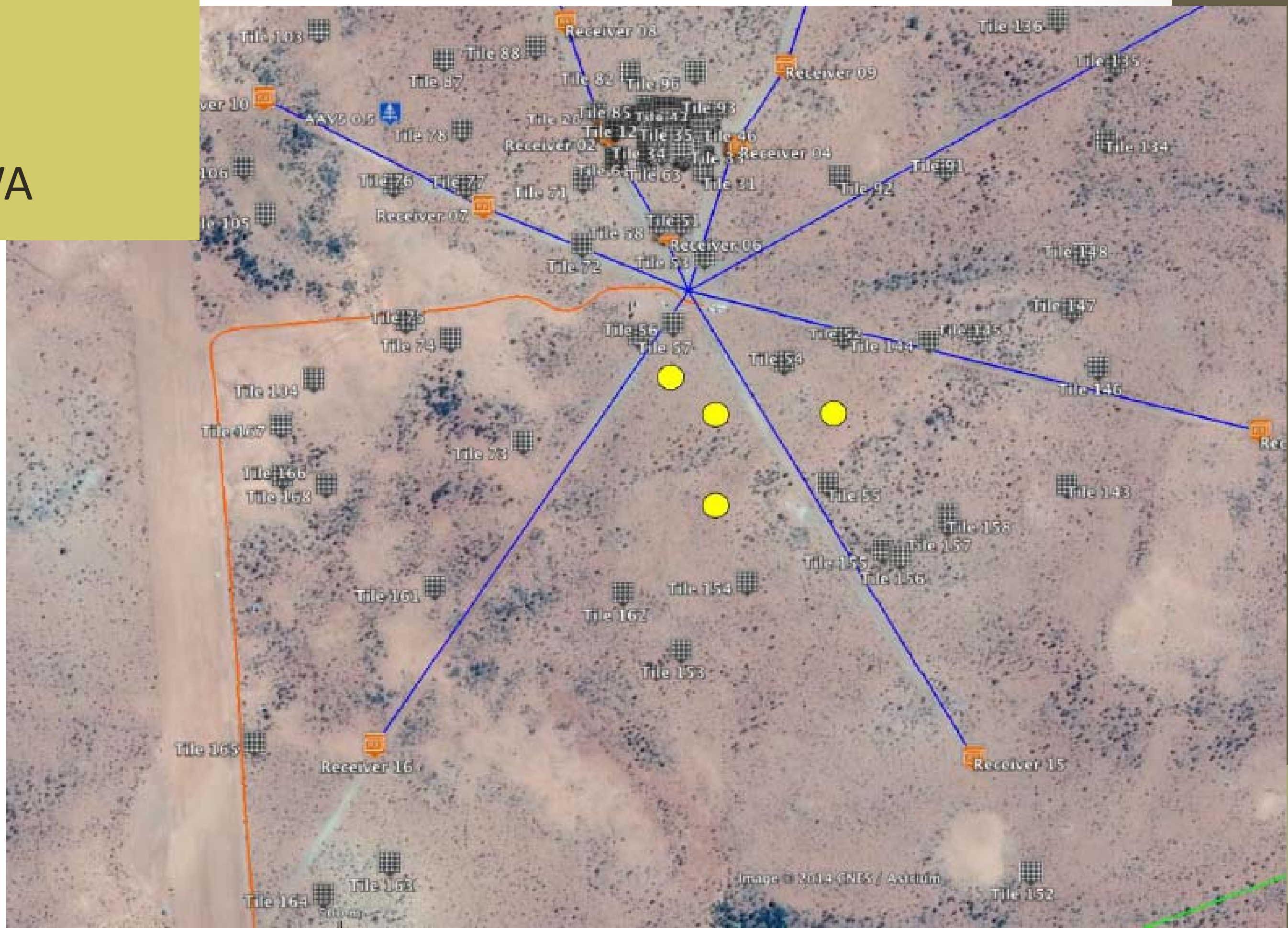
Figure 1: Percentage difference in measured Stokes I source flux for a randomly polarised source at the phase centre.

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?