SKA1 beam models

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Overview

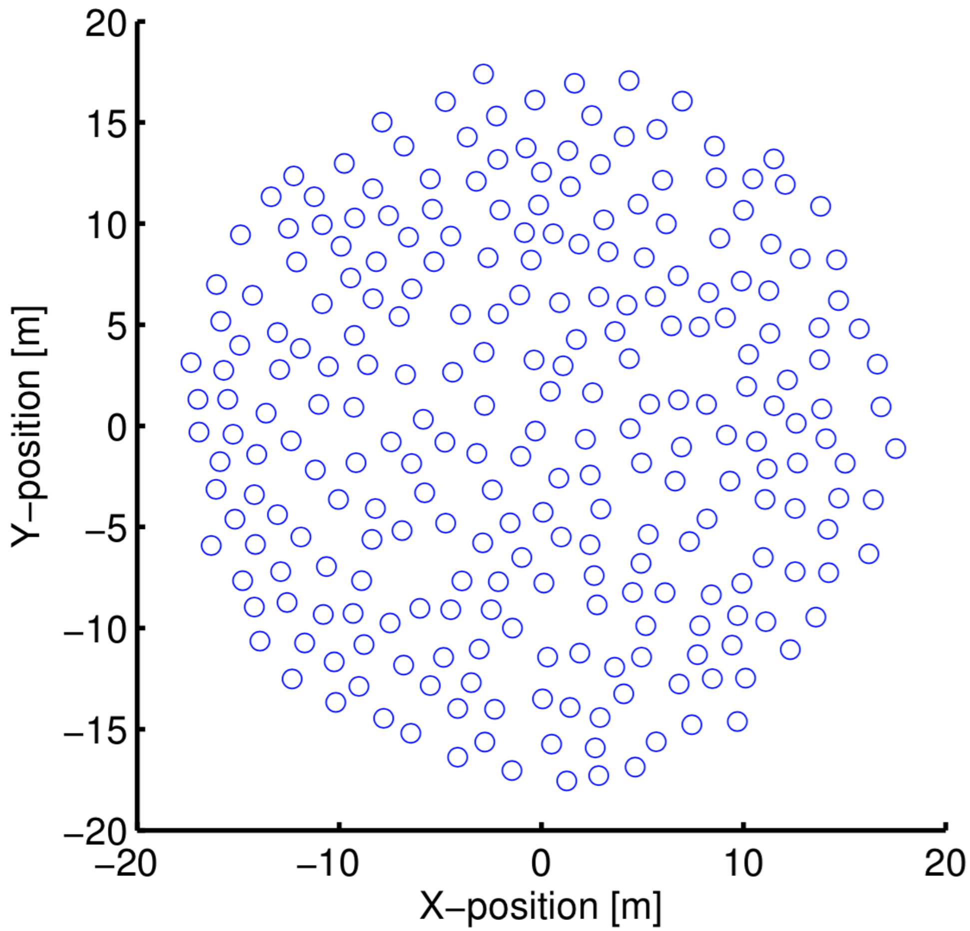
- Introduction
- SKA EM simulation framework
- Discussion

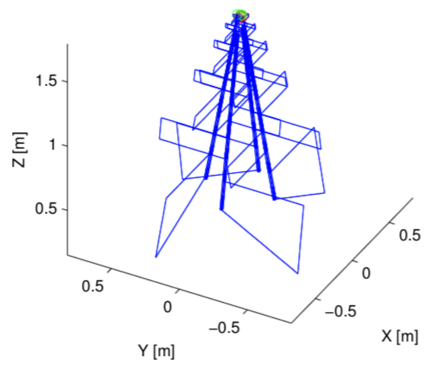
Introduction

- Parameterized SKA station beam models are products that LFAA have to deliver to TM/SDP.
- Here we present the status of the current EM simulation framework.
- Discussion is needed about future steps.

The SKA EM simulation framework

SKA station





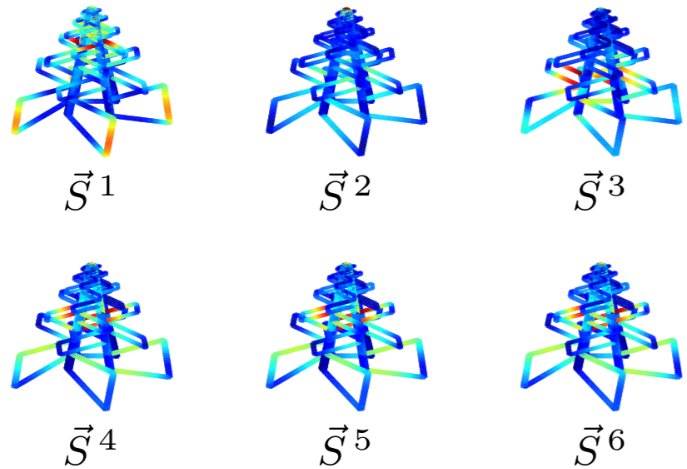
- 256 SKALAs
- Diameter of 35 m
- 50 – 350 MHz

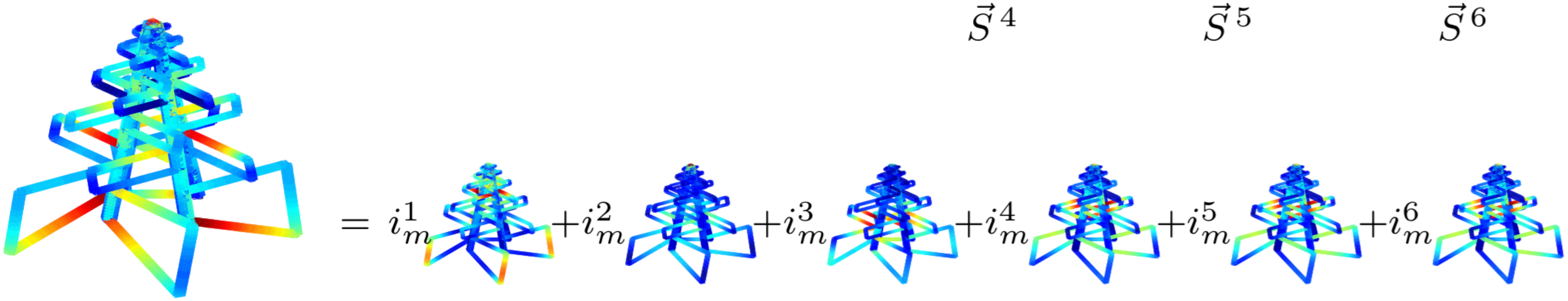
E. de Lera Acedo, “SKALA: A log-periodic antenna for the SKA,” (ICEAA), 2012.

The SKA EM simulation framework

MBF are current distributions on a sub-domain written as an aggregation of elementary basis functions.

$$\vec{S}^{\,k}(\vec{r}\,') = \sum_{j=1}^{B} \alpha_j^k \vec{f}_j(\vec{r}\,')$$





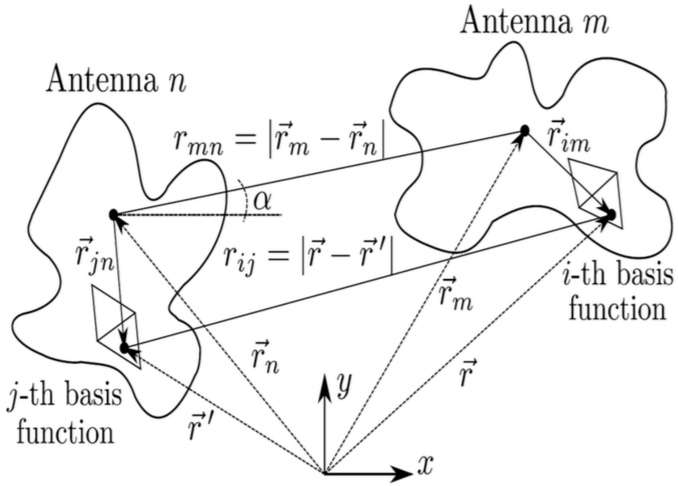
Current distribution on each antenna in the array as a sum of a few MBFs.

The SKA EM simulation framework

Interpolatory Approach:

$$G(\vec{r},\vec{r}') \approx \frac{1}{4\pi} e^{-jkr_{mn}} e^{-jk\hat{\alpha}\vec{r}_{im}} e^{jk\hat{\alpha}\vec{r}_{jn}}$$

$$Z_{TS}^{app} \approx -j\omega\mu \vec{F}_{T,m}^{-,0} . \vec{F}_{S,n}^{+,0} \frac{e^{-jkr_{mn}}}{4\pi r_{mn}}$$



Ref.[1]

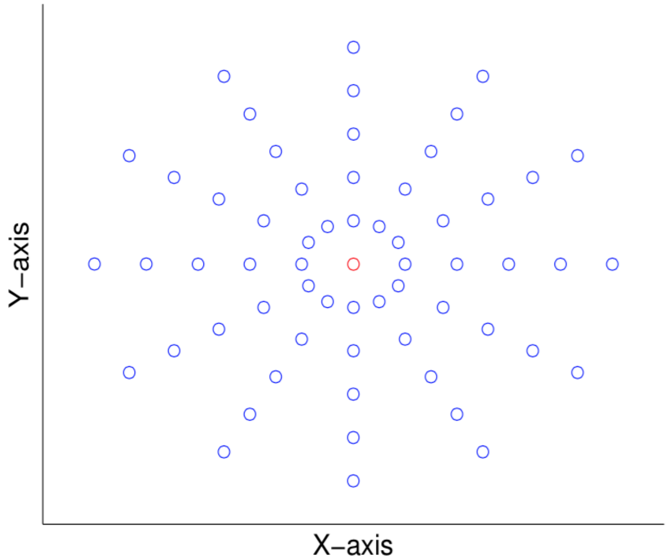
Idea: interaction between antennas are approximated as far-field interaction.

➡ **Model the difference**

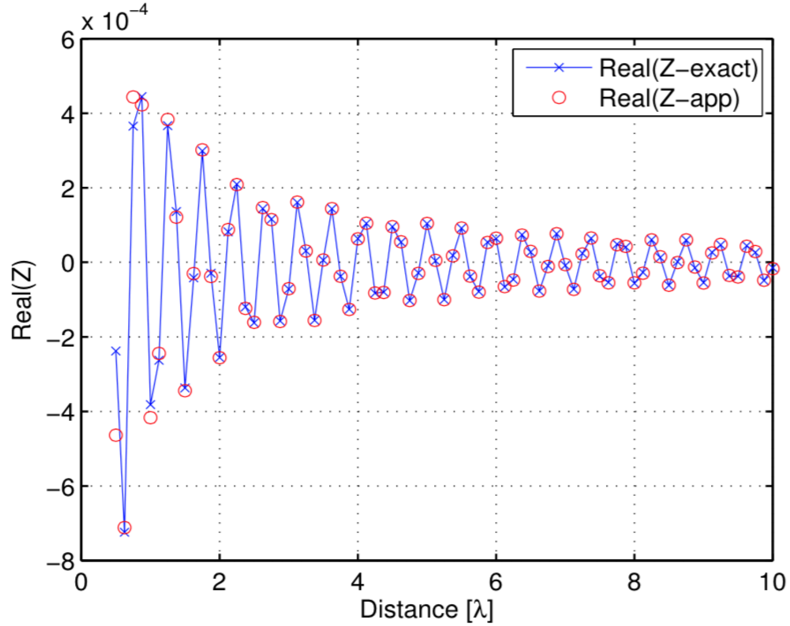
[1] D. Gonzalez-Ovejero and C. Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic arrays," *TAP*, 2011.

The SKA EM simulation framework

Far-field approximation



Pre-defined grid: red circle for the source antenna, blue circle for testing position.

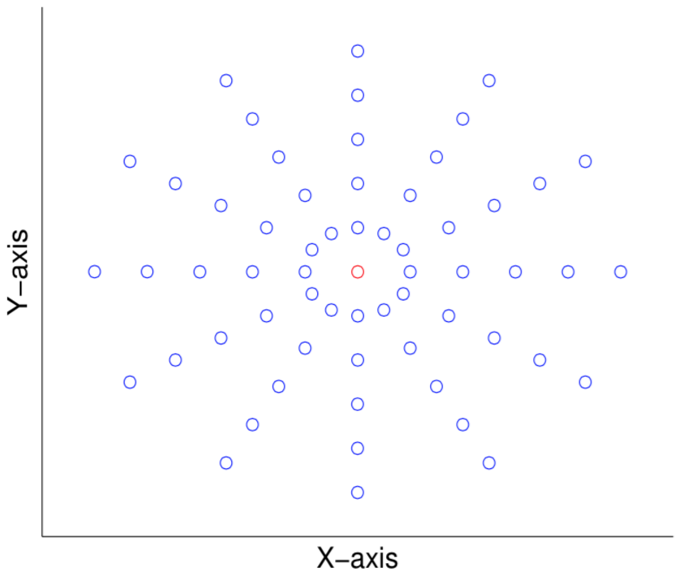


Z_{TS}^{ext} vs. Z_{TS}^{app}.

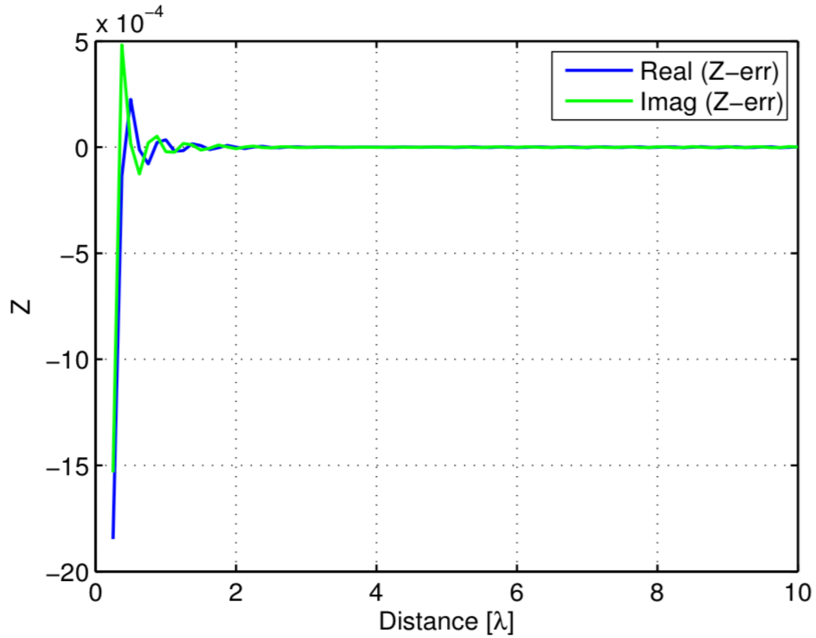
[1] D. Gonzalez-Ovejero and C. Craeye, “Interpolatory Macro Basis Functions Analysis of Non-Periodic arrays,” *TAP*, 2011.

The SKA EM simulation framework

Far-field subtraction $Z_{\text{TS}}^{\text{ext}}(r,\hat{\alpha}) - Z_{\text{TS}}^{\text{app}}(r,\hat{\alpha})$



Pre-defined grid: red circle for the source antenna, blue circle for testing position.

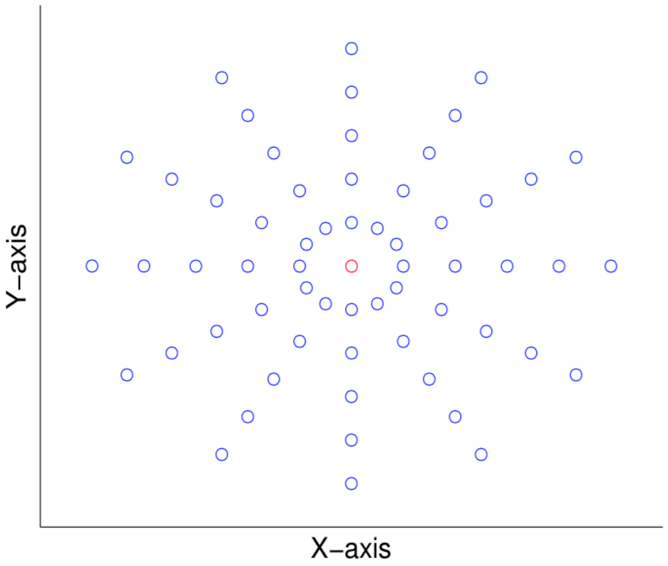


$Z_{\text{TS}}^{\text{ext}} - Z_{\text{TS}}^{\text{app}}$.

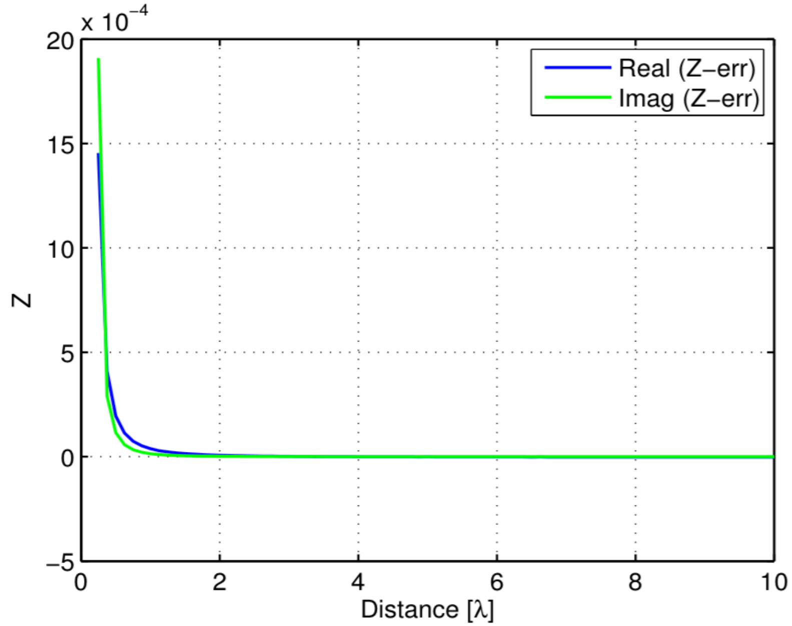
[1] D. Gonzalez-Ovejero and C. Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic arrays," *TAP*, 2011.

The SKA EM simulation framework

Phase Correction $\frac{Z^{ext}_{\mathrm{TS}}(r,\hat{\alpha})-Z^{app}_{\mathrm{TS}}(r,\hat{\alpha})}{e^{-jkr_{mn}}}$



Pre-defined grid.

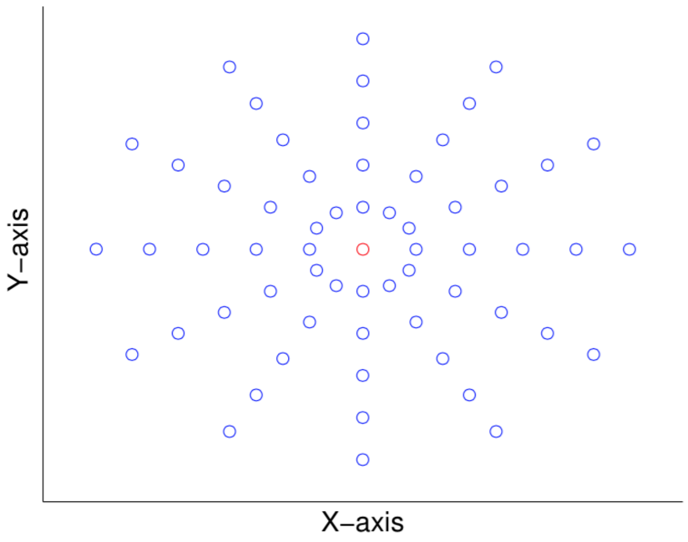


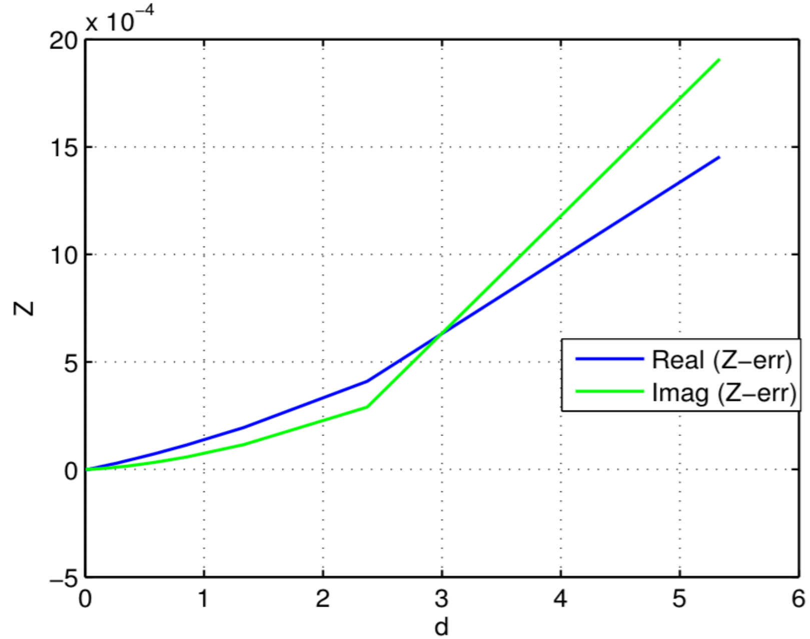
$$\frac{Z^{\mathrm{ext}}_{\mathrm{TS}}(r,\hat{\alpha})-Z^{\mathrm{app}}_{\mathrm{TS}}(r,\hat{\alpha})}{e^{-jkr_{mn}}}.$$

[1] D. Gonzalez-Ovejero and C. Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic arrays," *TAP*, 2011.

The SKA EM simulation framework

Change variables $d = \frac{1}{r}$





HARmonic Polynomial ((HARP)) Representation

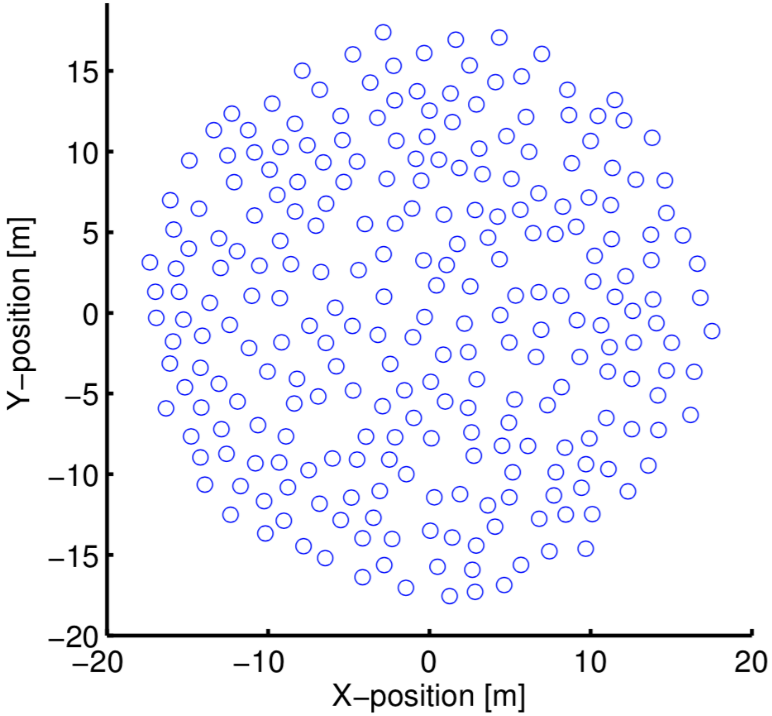
$$B_{\text{TS}}(r, \hat{\alpha}) \quad = \sum_{p=-P}^{P} e^{jp\phi} \sum_{q=0}^{Q} c_{pq} \, (kr)^{-q}$$

$$Z_{\text{TS}}(r, \hat{\alpha}) \quad \approx Z_{\text{TS}}^{\text{far}}(r, \hat{\alpha}) + B_{\text{TS}}(r, \hat{\alpha})$$

[1] D. Gonzalez-Ovejero and C. Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic arrays," TAP, 2011.

Current work: Validation

- A station of 256 SKALAs
- Simulated at 110 MHz
- SKALA discretized by 1218 basis functions
- 20 MBFs
- Validated with CST and WIPL-D

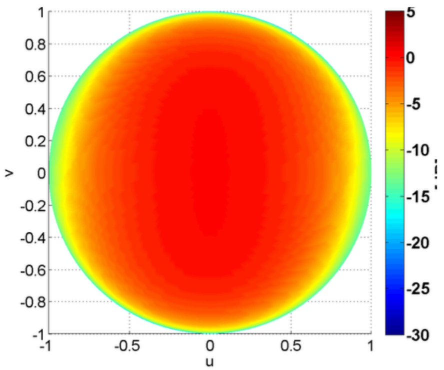


Error defined as:

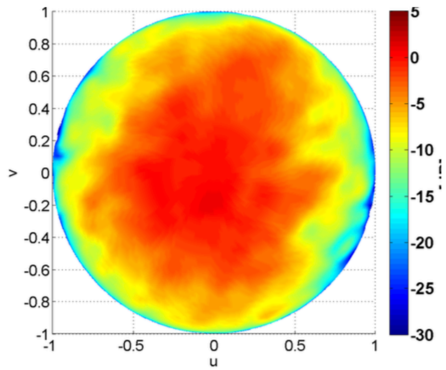
$$e = 10\log_{10}\left(\frac{\left|\vec{E}_{\mathrm{BF}}(\theta,\phi) - \vec{E}_{\mathrm{HARP}}(\theta,\phi)\right|^2}{\max\left|\vec{E}_{\mathrm{BF}}(\theta,\phi)\right|^2}\right)$$

Current work: Validation

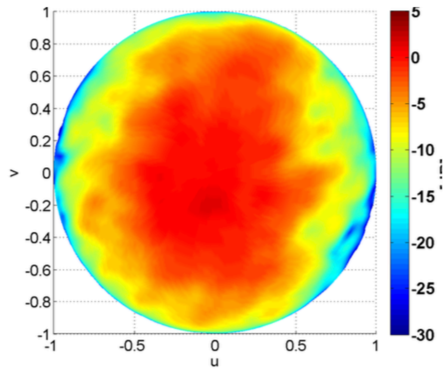
Embedded Element Patterns:



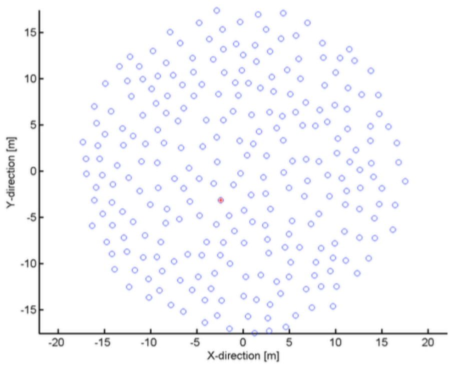
Isolated



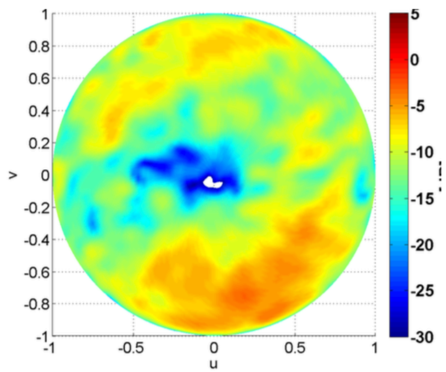
CST



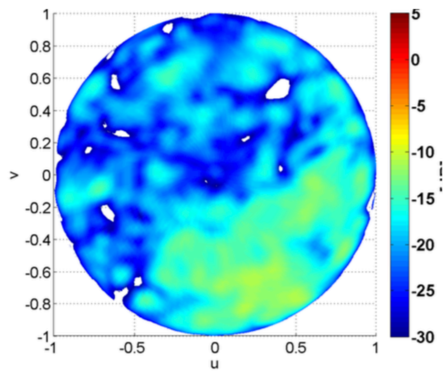
HARP



Position



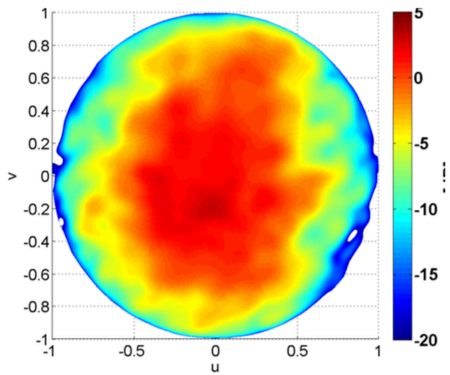
CST - Isolated



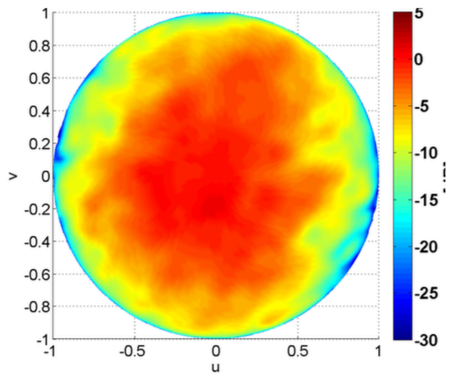
CST - HARP

Current work: Validation

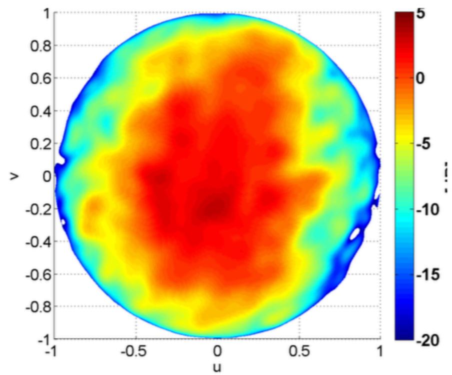
Embedded Element Patterns:



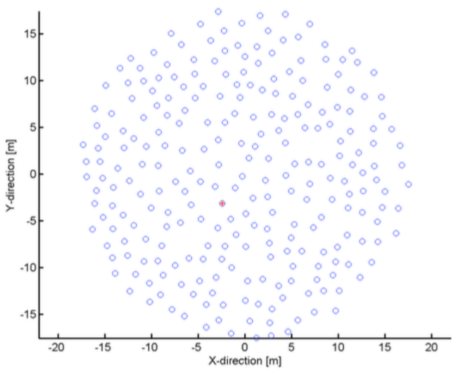
HARP



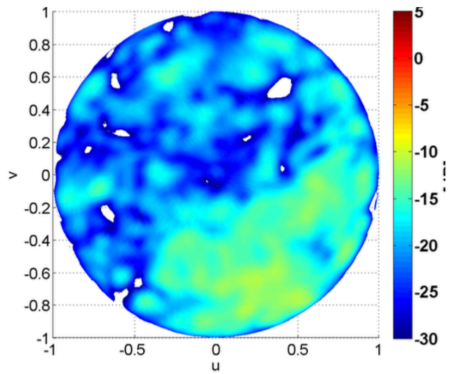
CST



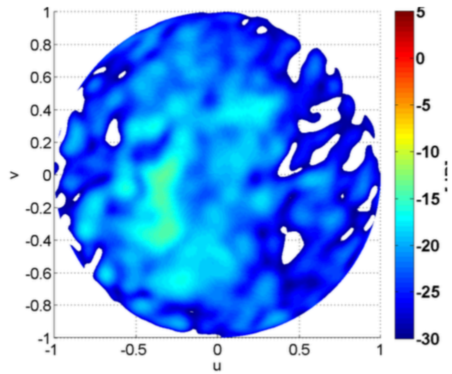
WIPL-D



Position

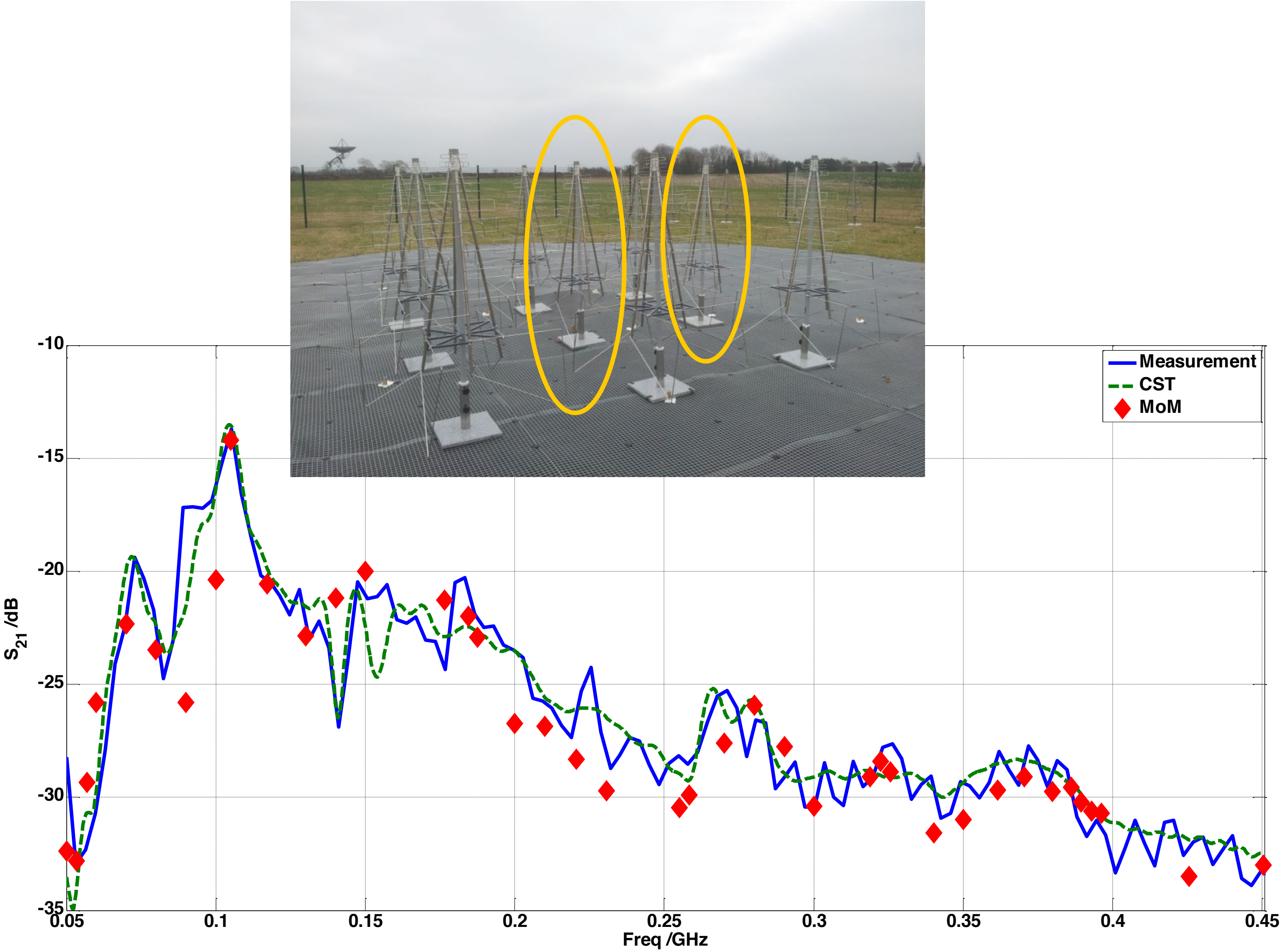


CST-HARP



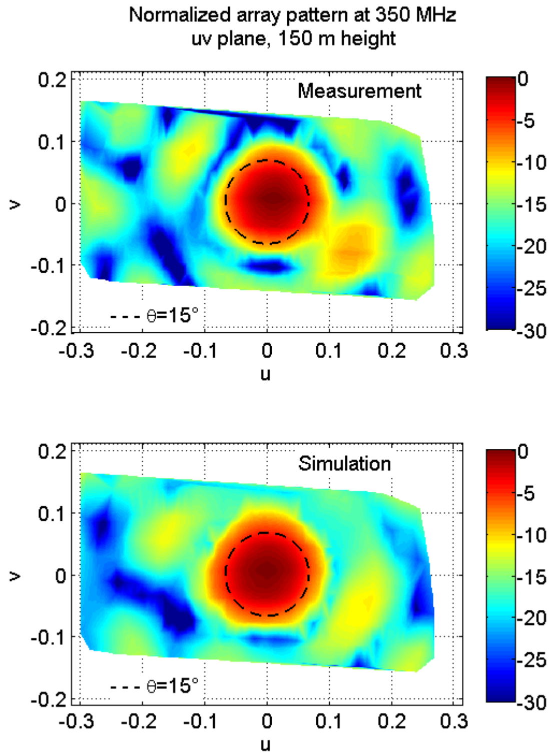
WIPLD - HARP

Current work: Validation



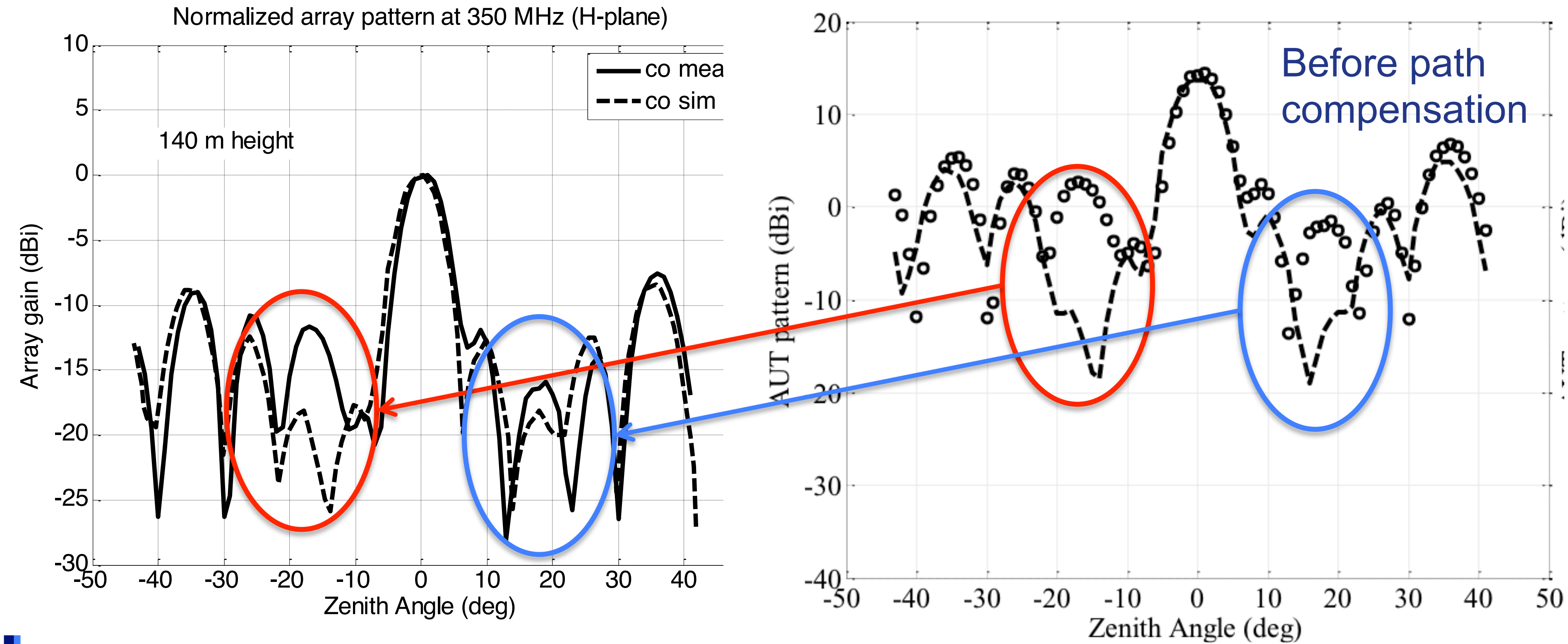
Beam measurement

- AAVS0 @ Lord's Bridge
- Hexacopter beam test



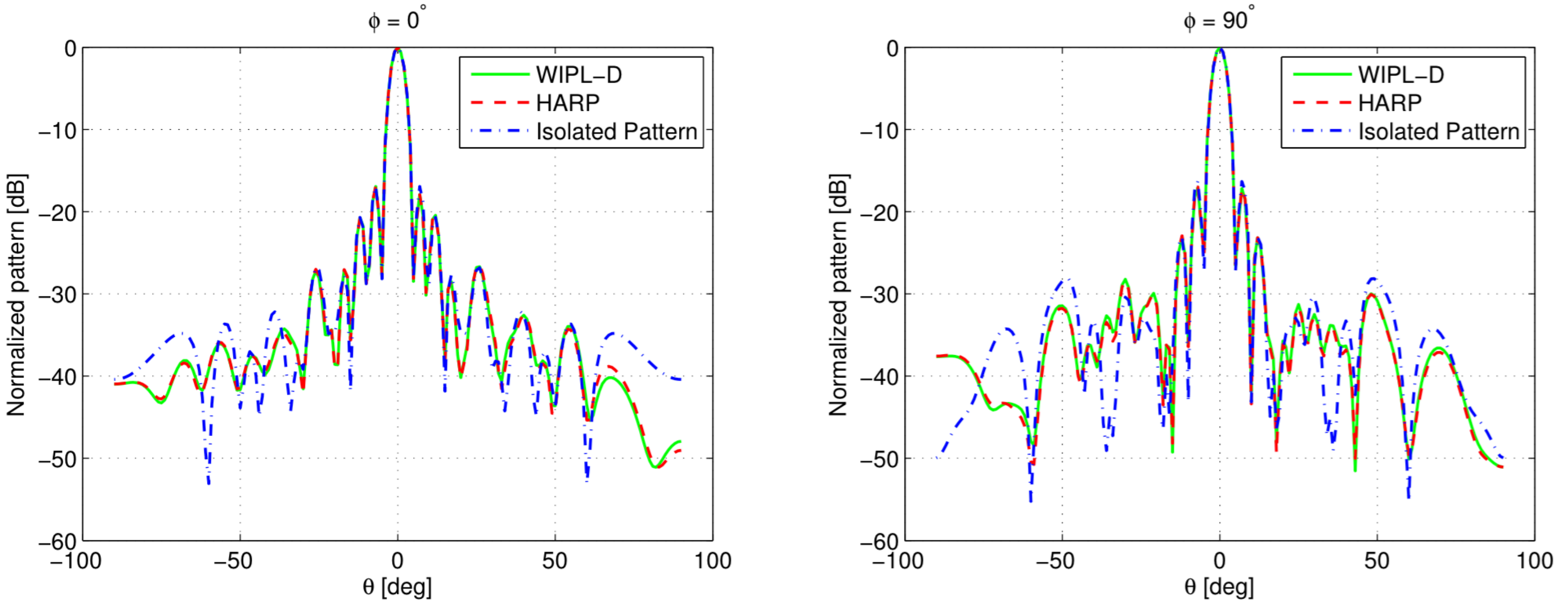
***In preparation for IEEE TAP**

Beam measurements



Current work: AAVS1 simulations

Uniformly excited array: 1^{st} polarization



Current work

*In preparation for IEEE TAP

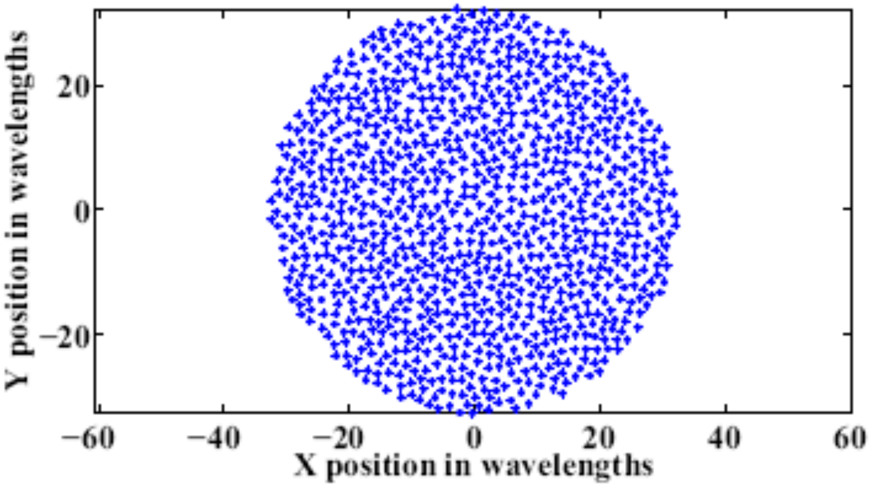
Performance on a SKA station for 1 frequency

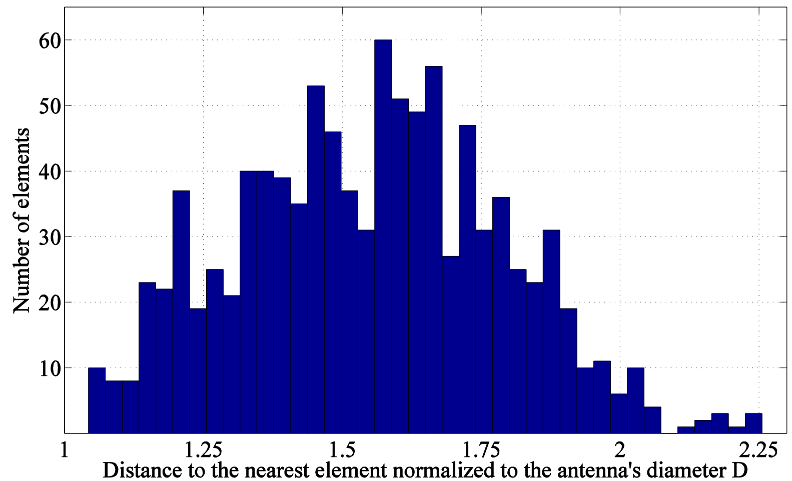
	CST[1]	WIPL-D[2]	HARP[3]
Preparation	–	–	3 hours
Simulation	96 hours	97 hours	1 mins

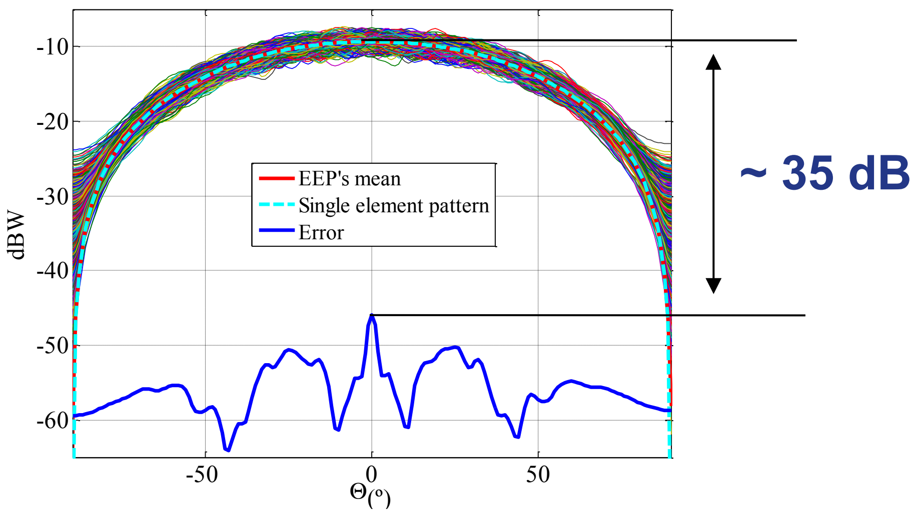
NB: The preparation for HARP has been done once and for all, for each frequency, regardless the array configurations.

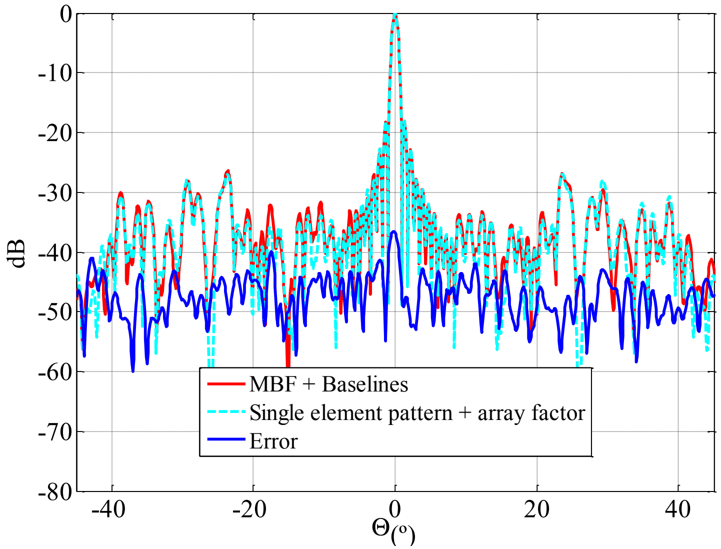
[1] On a sever with 384 GB of RAM at University of Cambridge
[2] On the Windows Server with 125GB of RAM at ASTRON, The Netherlands
[3] On a desktop with 16GB of RAM at Université catholique de Louvain

Antenna Arrays: Mutual coupling



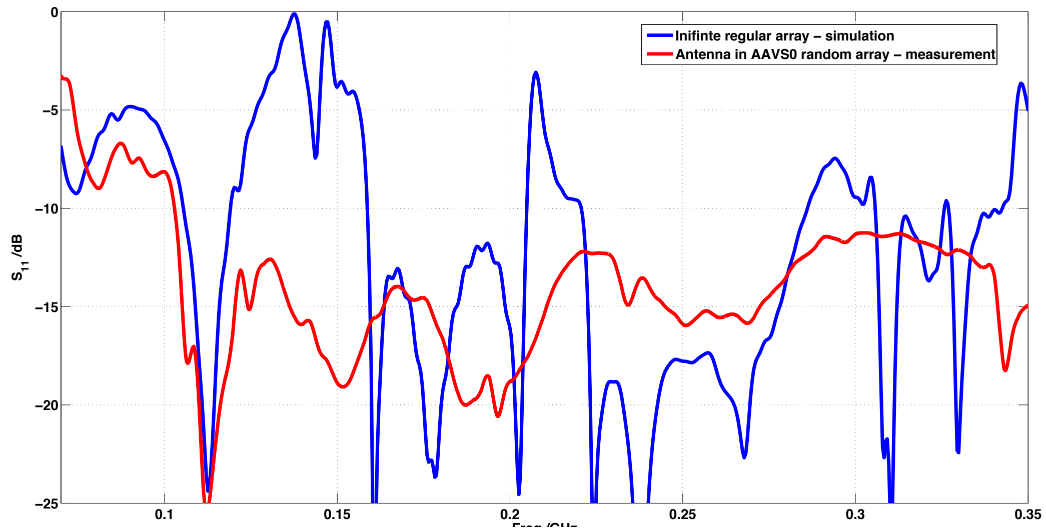


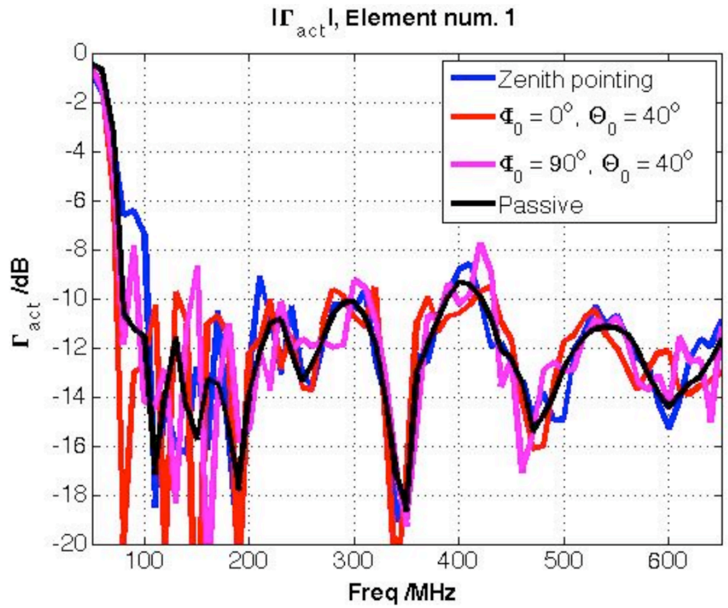




IEEE APS 2011, *Gonzalez et al.

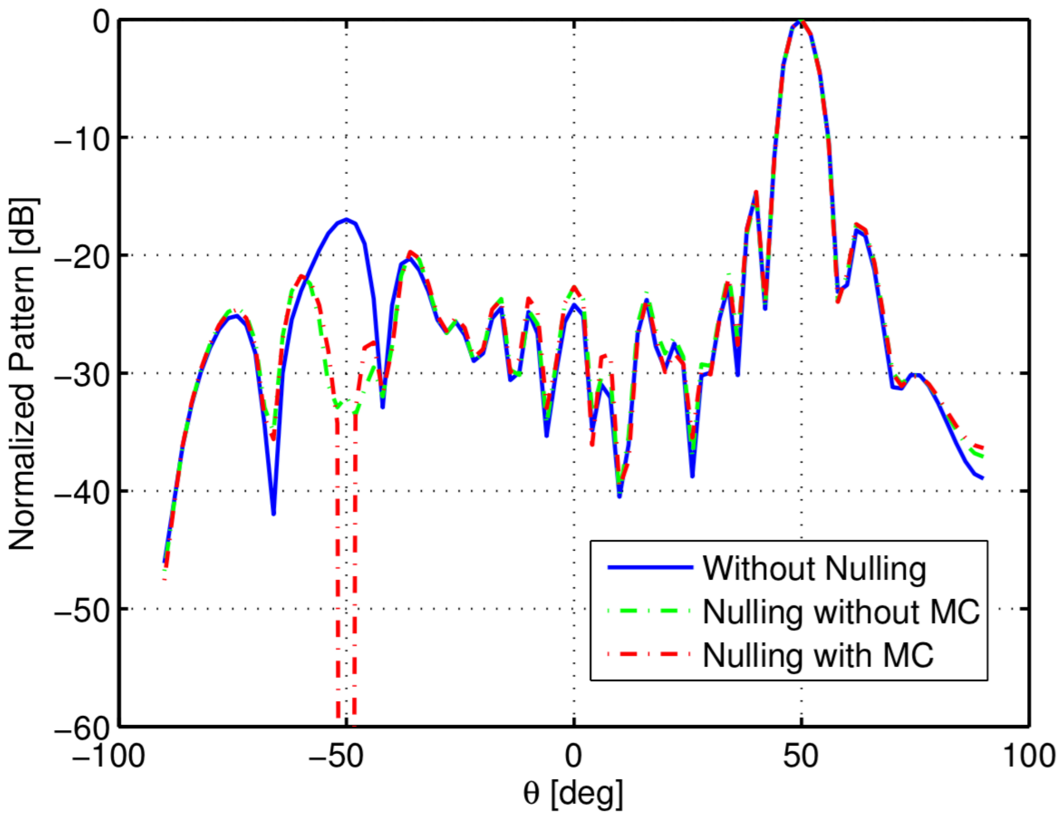
Antenna Arrays: Mutual coupling





Nulling and interference rejection

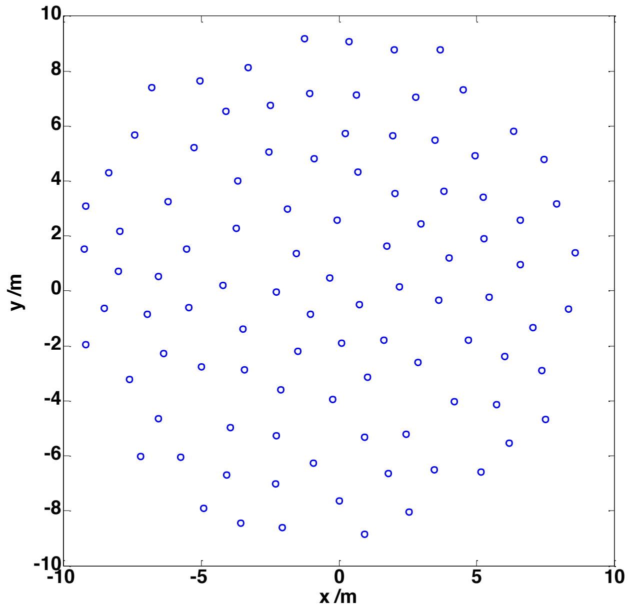
SKA station scanned 50°

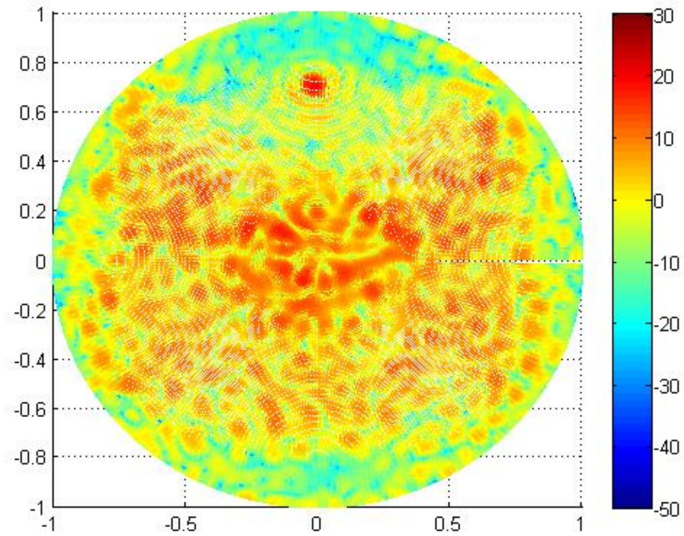


***In preparation, 2016**

Parametrized beams

- For calibration and image formation, models of the beam are necessary.
- Required:
  - Few coefficients (for few measurement points)
  - Quick access
  - Low storage requirements





Low order beam models

Zernike representation of deficiencies in the pattern including mutual coupling

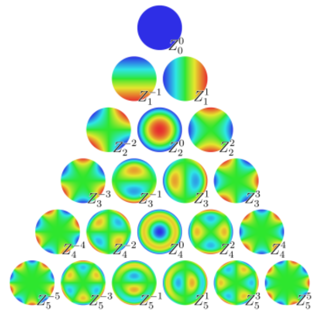
$$\overline{F_{rec}}(\theta,\phi) = \sum_{m=1}^{t} \alpha_m \sum_{i=1}^{n} \overline{f}_i(\theta,\phi) e^{-j\left(\varphi_i-\varphi_{i,0}\right)} Z_m$$

- 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.

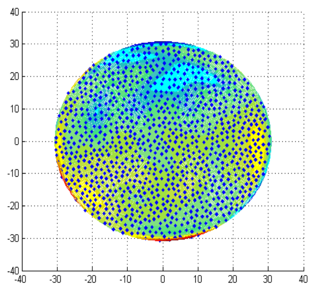
*de Lera et al., ICEAA 2013

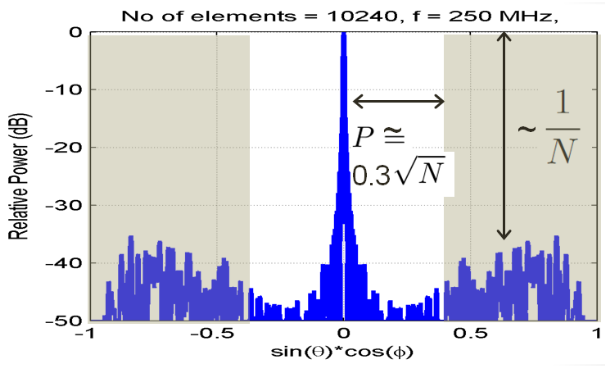
Zernike polynomials

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



- 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

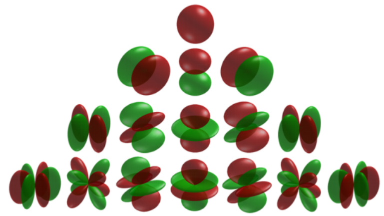
Similar to theory of ~circular apertures:
Y. Rahmat-Samii and V. Galindo-Israel, "Shaped reflector antenna analysis using the Jacobi-Bessel series," IEEE Trans. Antennas Propagat., Vol. 28, no.4, pp. 425-435, Jul. 1980.

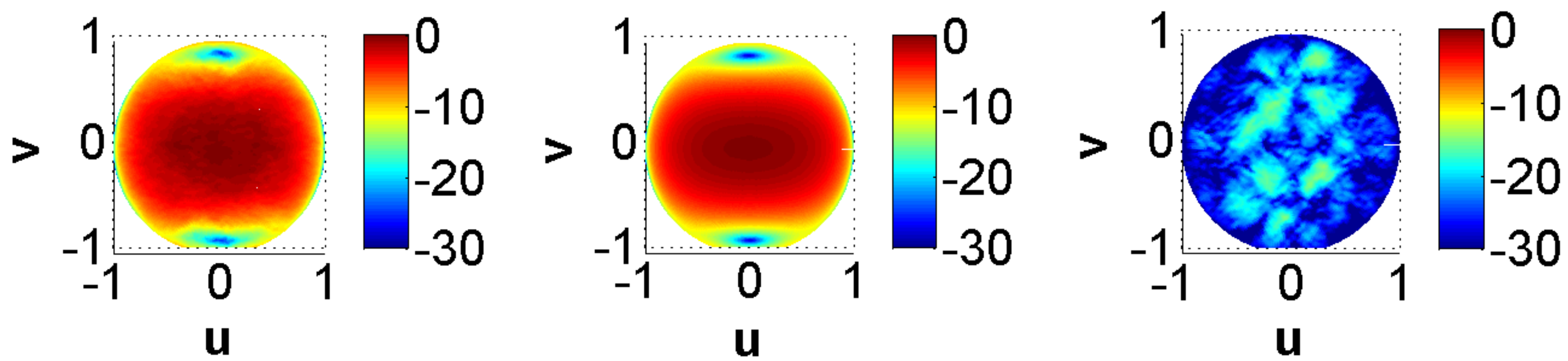
Pre-computed smooth EEPs

- 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.

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

Spherical Harmonics



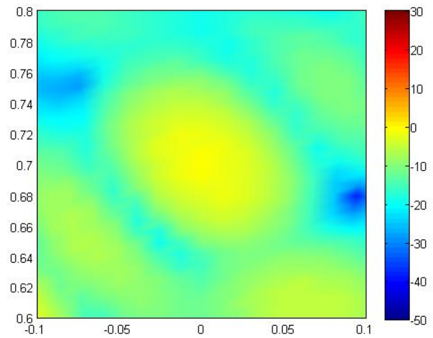


*de Lera et al., ICEAA 2011

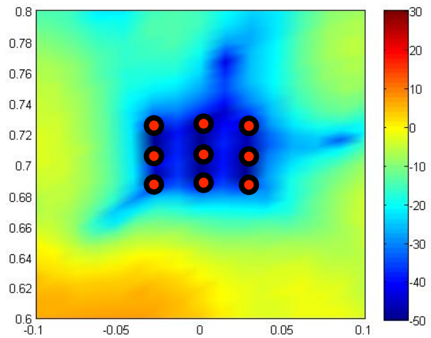
Pattern reconstruction

- Study of the effect of the distribution of the sources and the number of them.

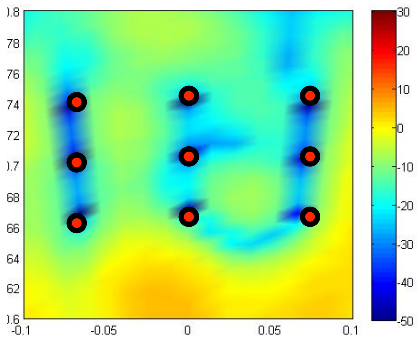
Scan:
Θ = 45 deg.
Φ = 90 deg.



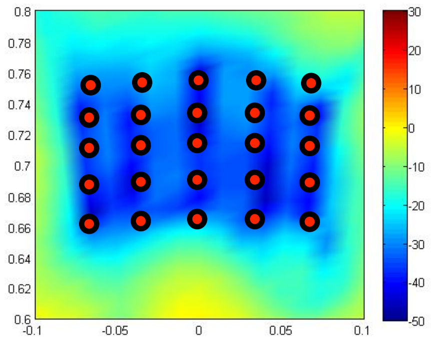
Error Rec. - Actual



t = 28, *w* = 9



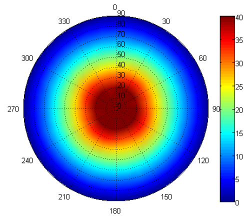
t = 28, *w* = 9



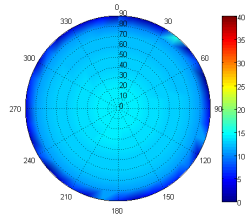
t = 28, *w* = 25

Summary

– Up to now, EM simulations used for:
  - Array and element design
  - Tolerance analysis
  - Analysis of environmental effects



PEC gnd



Soil

– In future, beam models needed for optimal calibration and high dynamic range imaging.
  - Example: Mitra, Makhathini, Foster, Smirnov, Perley, "Incorporation of antenna primary beam patterns in radio-interferometric data reduction to produce wide-field, high-dynamic-range images", ICEAA 2015.

Conclusions

- EM simulation framework for SKA up and running
- Parameterized beam models exist. Accuracy is understood.
- Discussion needed for the next steps:
  - What is the correct parameterization?
  - How do we further validate these models (AAVS1 and beyond)
  - How do they fit in the SKA pipeline
  - Etc.