SKA-low array

Eloy de Lera Acedo

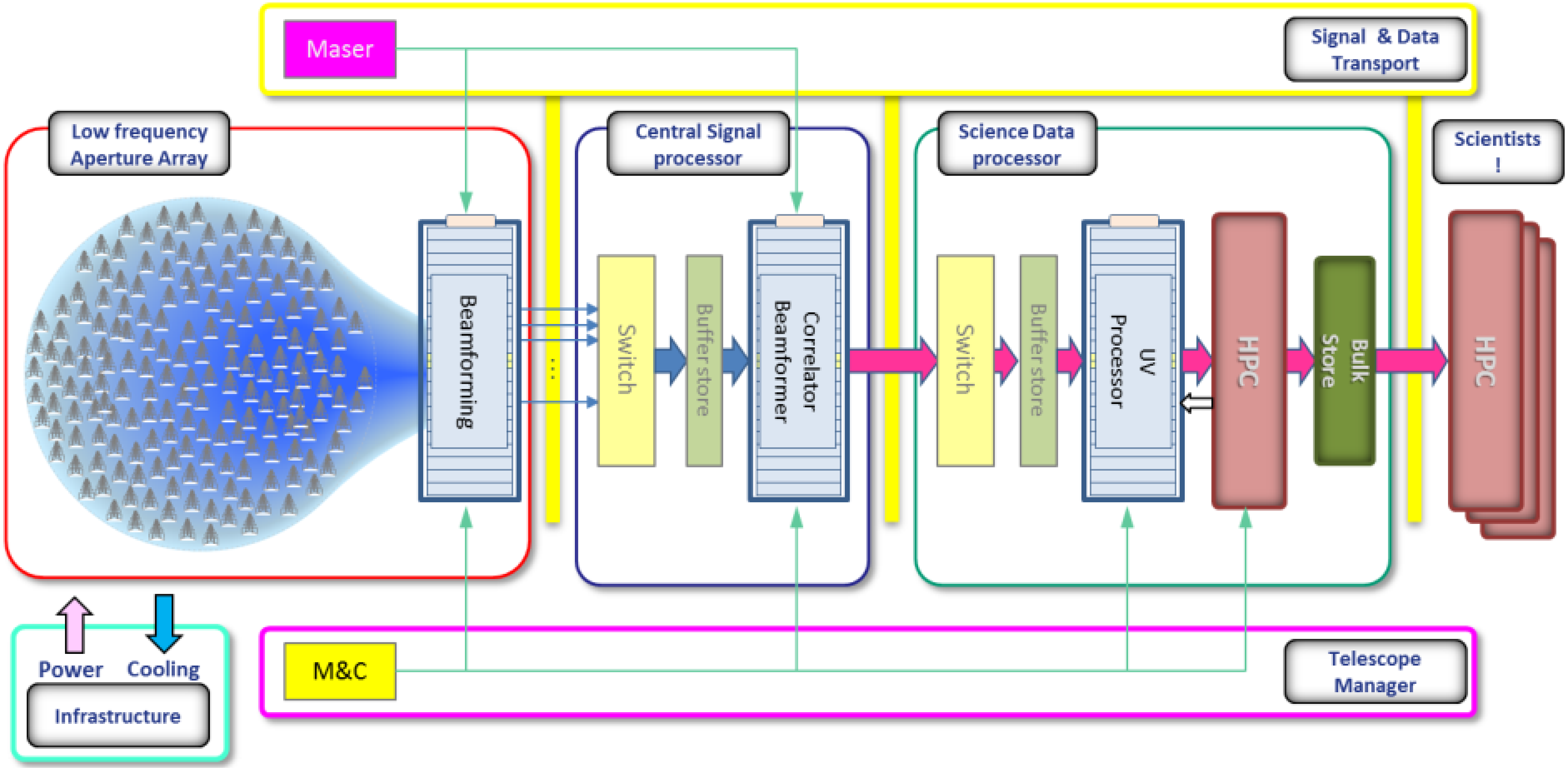
Cambridge University

Overview

- The SKA-low array system
- SKA-low front-end technology development
- Simulations and calibration for SKA-low
- Future work and conclusions

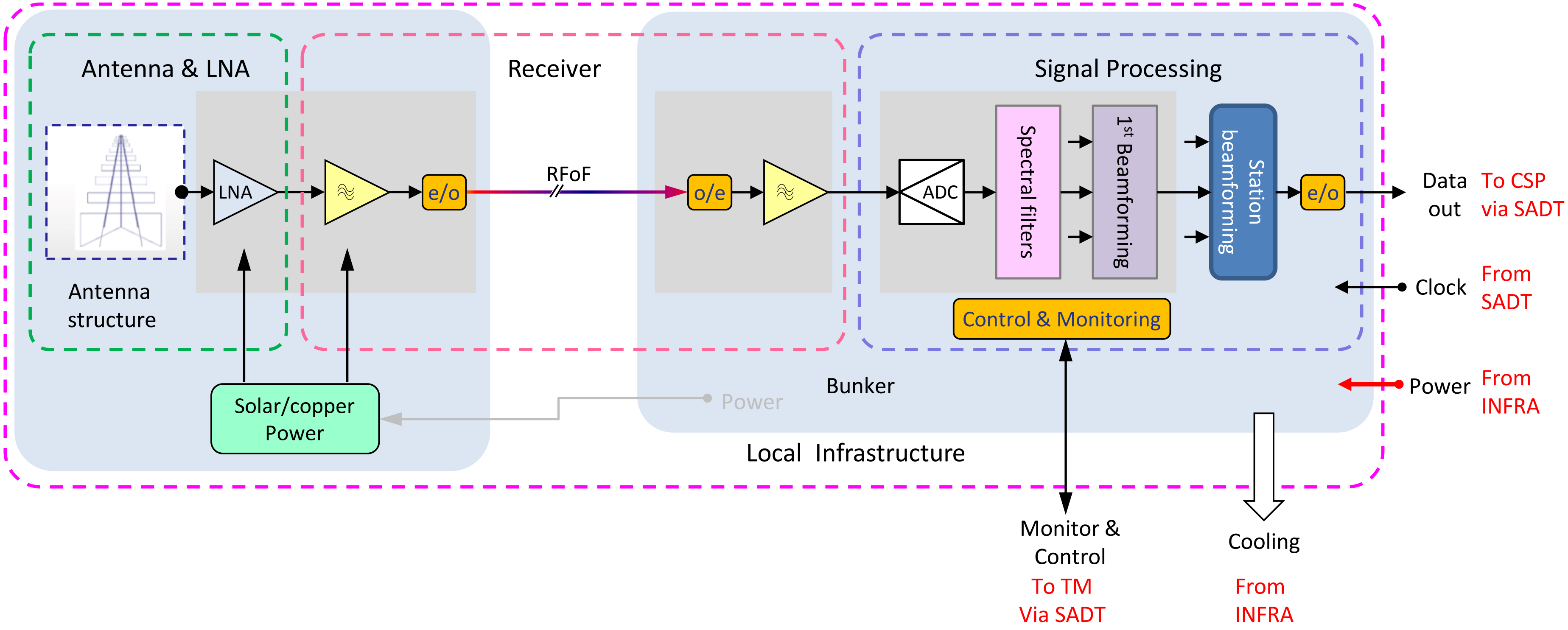
The SKA-low array system

SKA-low end-to-end system architecture



A central bunker will integrate the LFAA beamforming/correlation, signal transport, Maser clock and local monitoring and control

LFAA signal flow



LFAA consortium

- ✓ Project Leader: Jan Geralt bij de Vaate (ASTRON)
- ✓ Project Engineer: Andy Faulkner (Cambridge)
- ✓ Project Scientist: Carol Jackson (ICRAR)
- ✓ Project manager: Andre van Es (ASTRON)

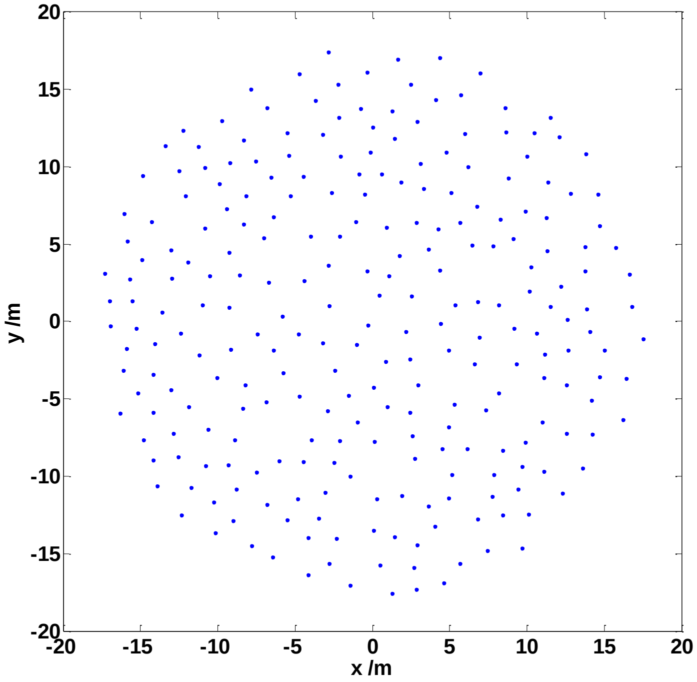
Work Packages:

- Engineering management (Jan Geralt bij de Vaate - ASTRON)
- System Engineering (Andy Faulkner - UCam)
- Antenna and low noise amplifier (Eloy de Lera Acedo - UCam)
- Receiver (Jader Monari – INAF)
- Signal Processing (Kris Zarb Adami – Oxford)
- Array Prototypes (Adrian Sutinjo – ICRAR)
- Local Infrastructure (Tom Booler – ICRAR)
- Local Monitoring and Control (Pieter Benthem - ASTRON)

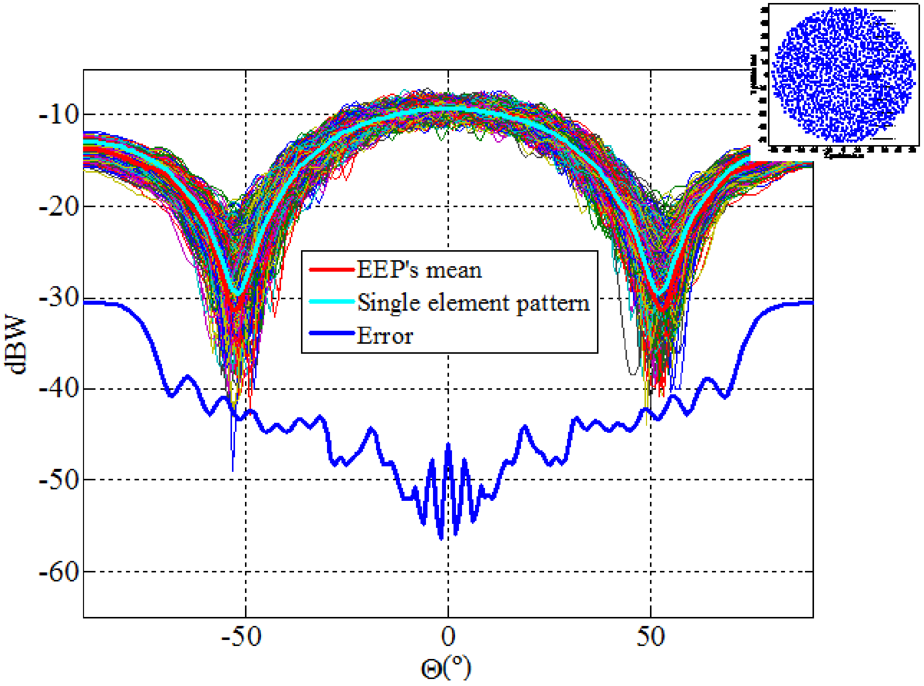
Component	Includes	Budget cost for SKA1 (each antenna sub-system)
Antenna Mechanical components	Radiating arms, Support structure including base, Electronics housing, Ground plane (if required), Mechanical shielding, Fixings	€60
Signal Chain Electronic systems	Low noise amplifier, Matching components, Amplifiers and filters, Laser driver , Laser control, Local power regulation, Connectors, Circuit boards, Shielding mounted on board	€40
Solar power unit	Solar cells, Control electronics, Battery/super-capacitor, Enclosure and fixings, Cable connections and connectors	€50
Deployment	Antenna sub-system assembly, Transport from site receiving area to antenna placement site, Deployment at site including final assembly, Accurate positioning and alignment, Connection to fibre links, Local installation test and identification	€30
Totals		€180

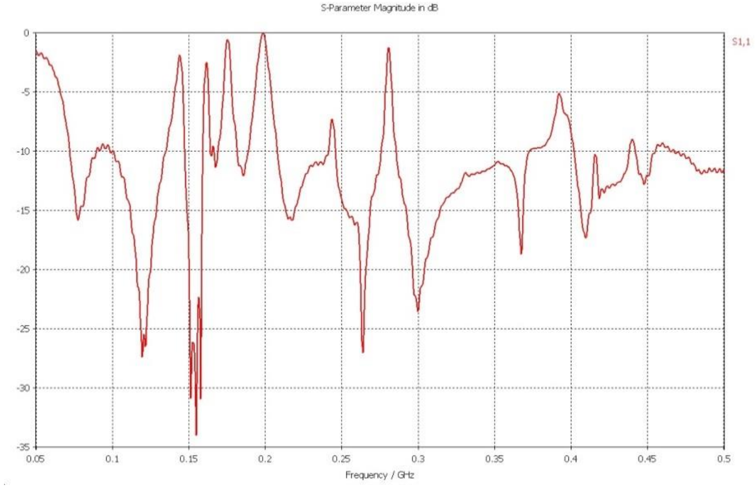
Week	Date	Event	Comments
T0	1 Nov. 2013	Official start of the consortium work. Also, the initial release of the “Level 1” requirements for the SKA1.	
T0+12	1 March 2014	Release of detailed “Level 1” requirements	
T0+34	1 July 2014	Preliminary installation plan (including demonstration plan).	This needs to show how the antenna sub-systems will be installed and how long it takes
T0+46	14 Sept. 2014	System Requirements Review (documents only)	Internal draft documentation that gets submitted to SKAO
T0+50	Oct. 2014	Preliminary Design Review	Documents and presentation on way forward
T0+72	1 April 2015	AAVS1 Detailed design Review	Decide on what actually gets built for the major demonstrator
T0+85	1 July 2015	Completed installation plan including demonstration	Need to show that the deployment of LFAA can be done as stated
T0+112	31 Dec. 2015	Installation and commissioning of AAVS1 completed	This should be a complete and working array
T0+140	1 July 2016	Submit test and evaluation report for AAVS1	
T0+148	1 Sept. 2016	Critical Design Review for LFAA, including submission of manufacturing documentation	The final big review
T0+156	1 Nov. 2016	Closure of Pre-construction Phase	End of project

Introduction



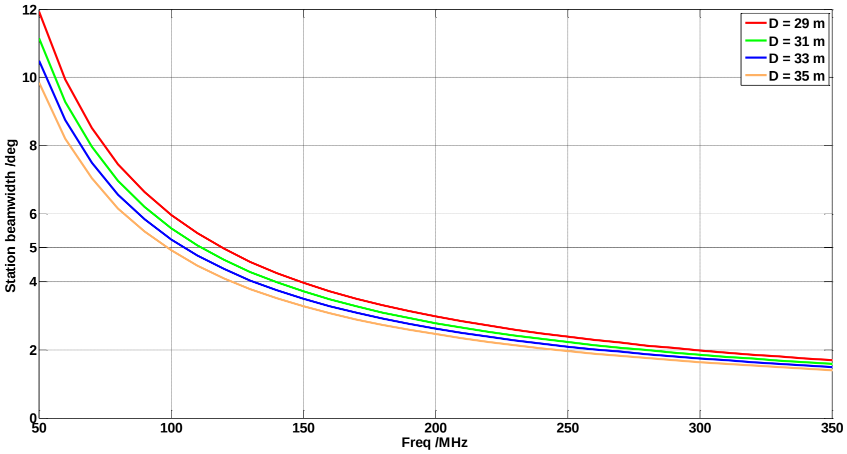
Introduction





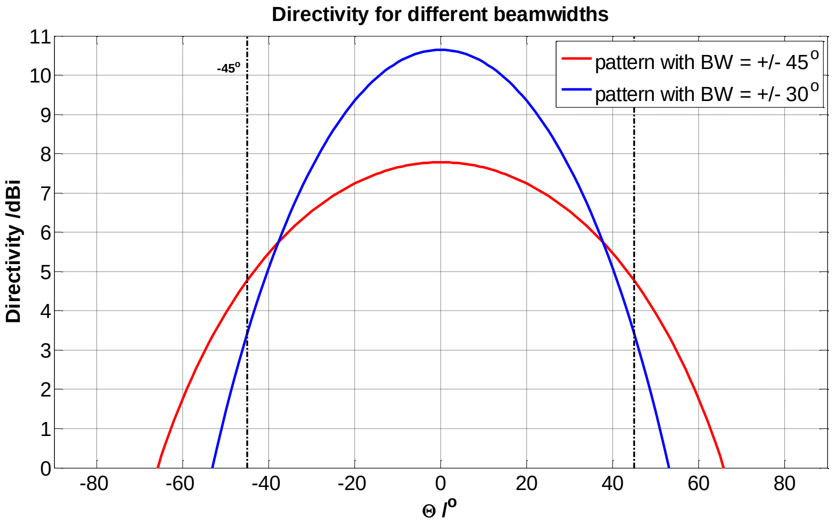
Introduction

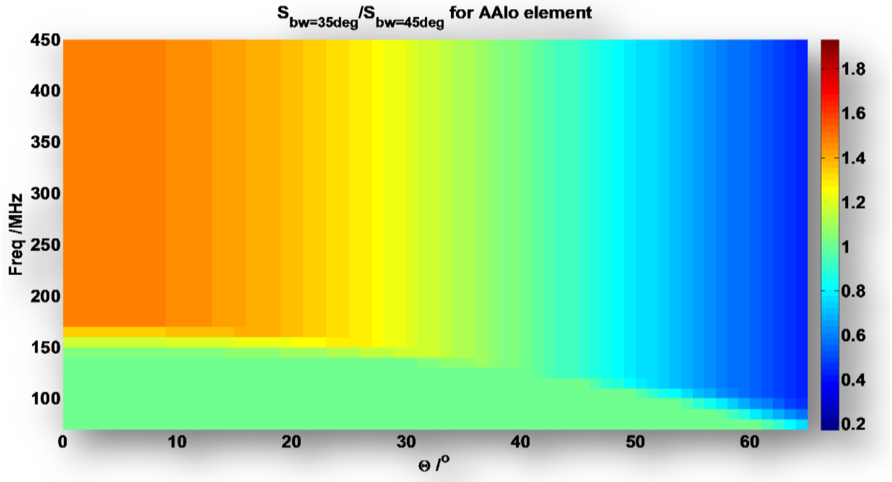
- 2^{18} antennas
- $D_{station}$ = 35 m
- 256 antennas/station
- $D_{average}$ = 1.93 m



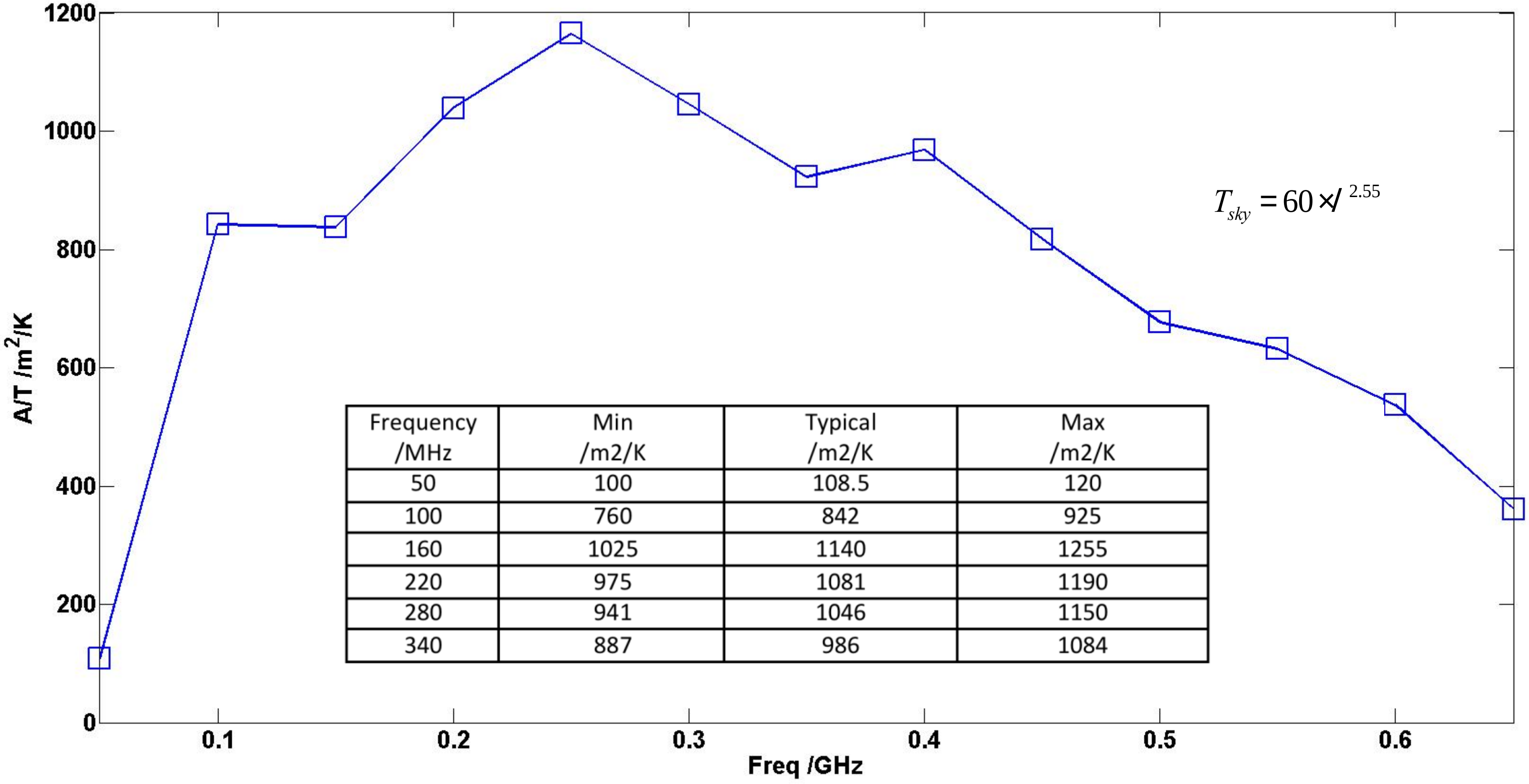
LFAA Sensitivity

$$\left.\frac{A_{\text{eff}}}{T_{\text{sys}}}\right|_{\theta,\varphi} = \frac{\lambda^2/4\pi \cdot G_{\theta,\varphi}}{\eta_{\text{rad}} \cdot T_{\text{A}} + \left(1-\eta_{\text{rad}}\right)\cdot T_0 + T_{\text{rec}}/(1-|\Gamma|^2)}$$





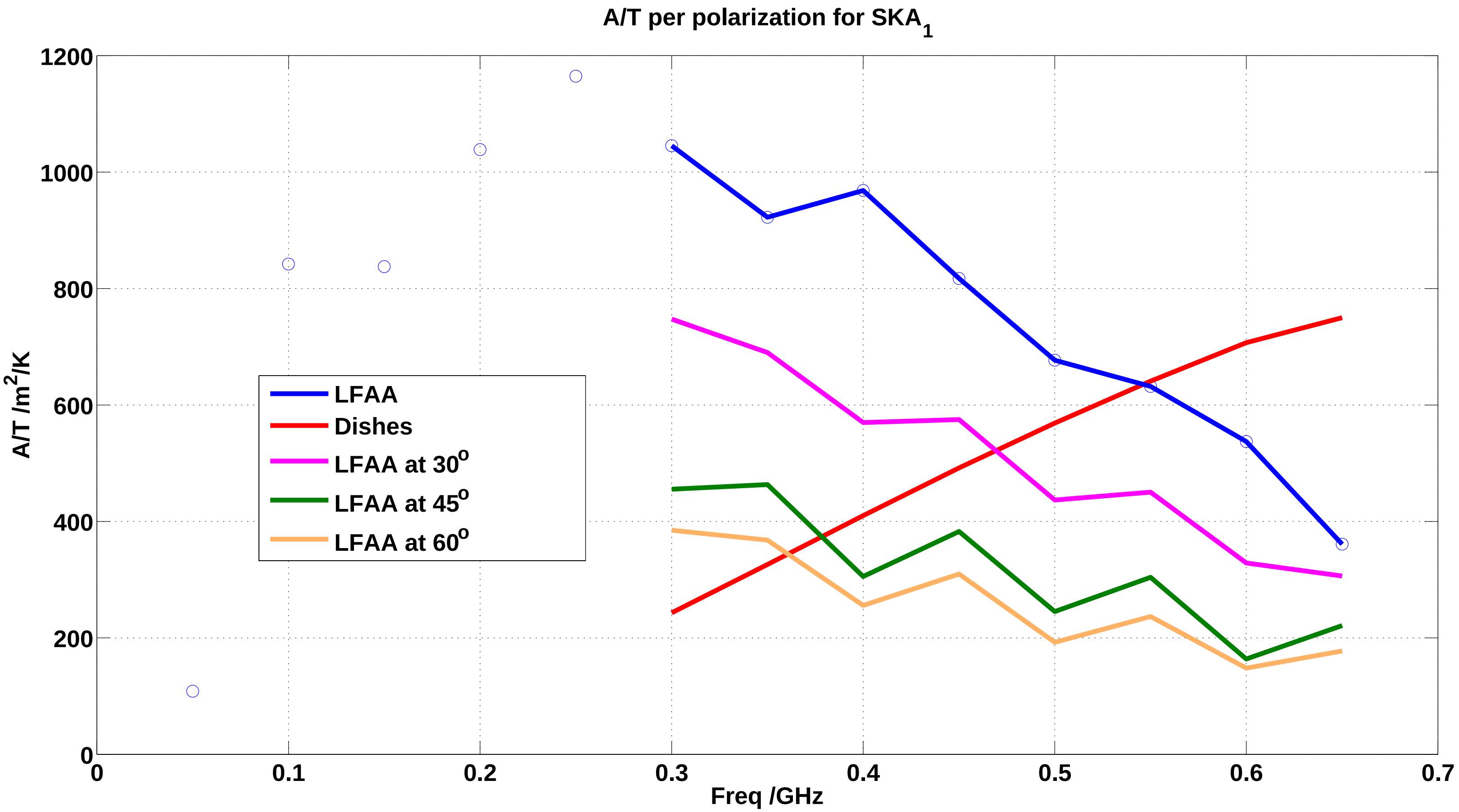
LFAA Sensitivity



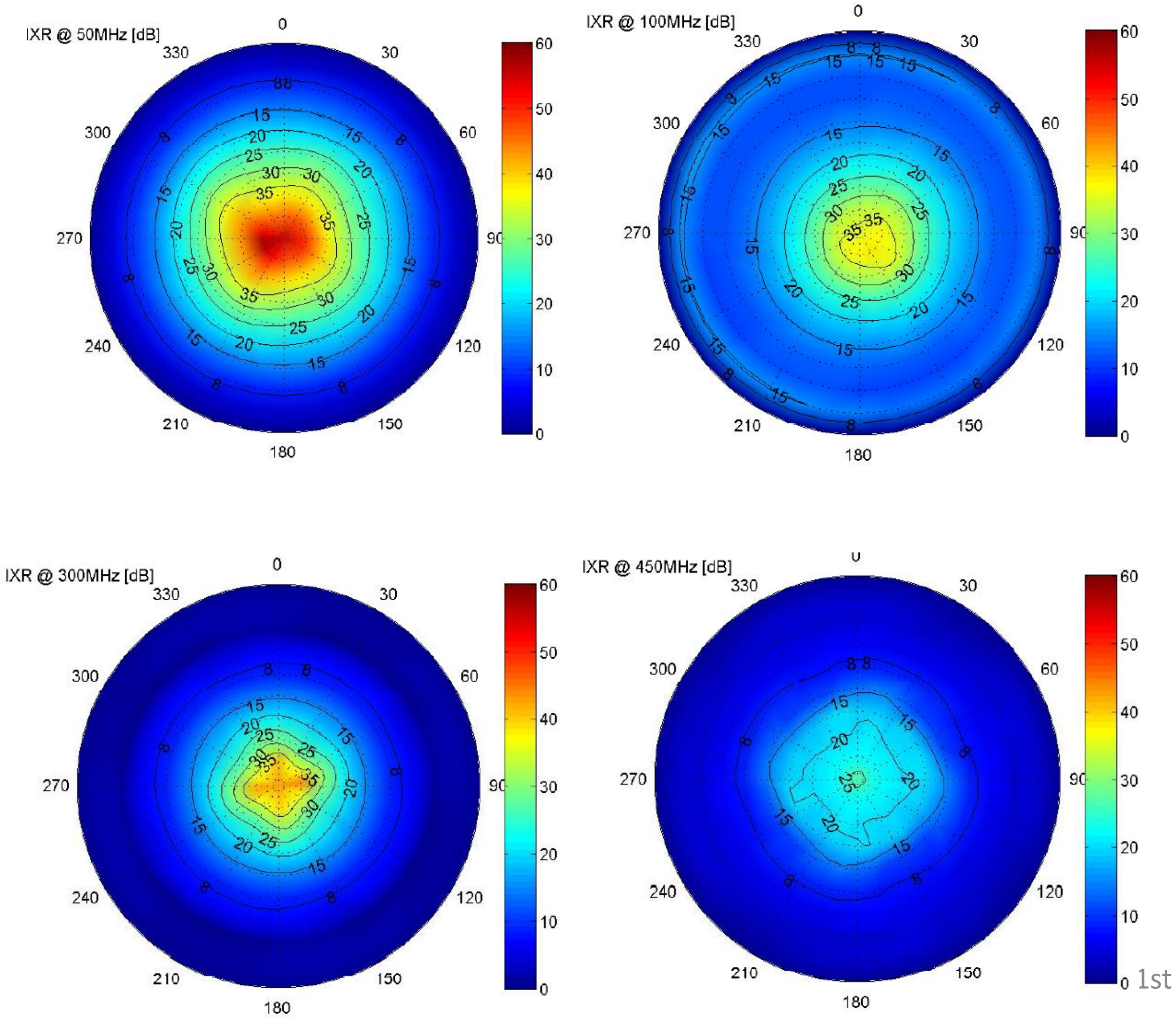
$T_{sky} = 60 \times \lambda^{2.55}$

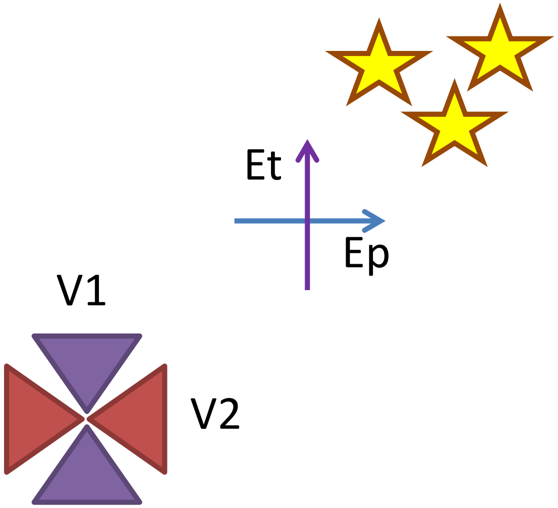
Frequency /MHz	Min /m2/K	Typical /m2/K	Max /m2/K
50	100	108.5	120
100	760	842	925
160	1025	1140	1255
220	975	1081	1190
280	941	1046	1150
340	887	986	1084

LFAA Sensitivity (extended band)



LFAA polarization





$$IXR_J = \left(\frac{\kappa(J)+1}{\kappa(J)-1}\right)^2$$

- Credit: "IXR SKALA with GP vs Vivaldi V2 with Soil C", 08/10/2012 – B. Fiorelli).

SKA-low front-end technology development

SKALA: Design

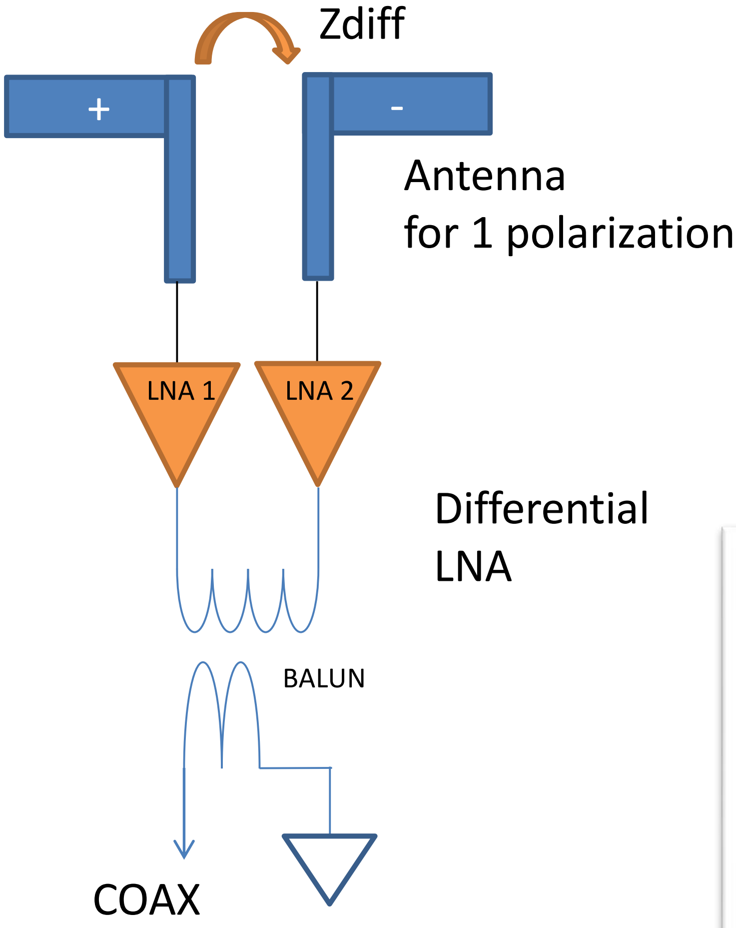
Antenna + LNA:
90€/element

- *SKALA*: *SKA L*og-periodic *A*ntenna
  - Good Impedance
  - Pattern width controllable (7:1 band!)
  - Low back lobe at high frequencies
- Dual polarization
- 9 wide dipoles: top 2 are not resonant in band
- Maximizing A/T in the +/- 45 deg. Region

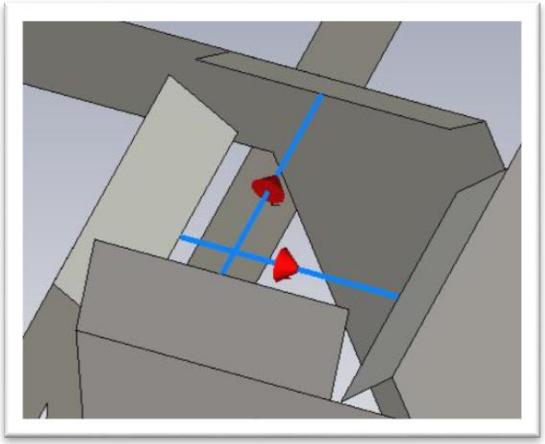
$$\left.\frac{A_{\mathrm{eff}}}{T_{\mathrm{sys}}}\right|_{\theta.\phi} = \frac{\lambda^2/4\pi \cdot G_{\theta.\phi}}{\eta_{\mathrm{rad}} \cdot T_{\mathrm{A}} + \left(1-\eta_{\mathrm{rad}}\right) \cdot T_0 + T_{\mathrm{rec}}}$$

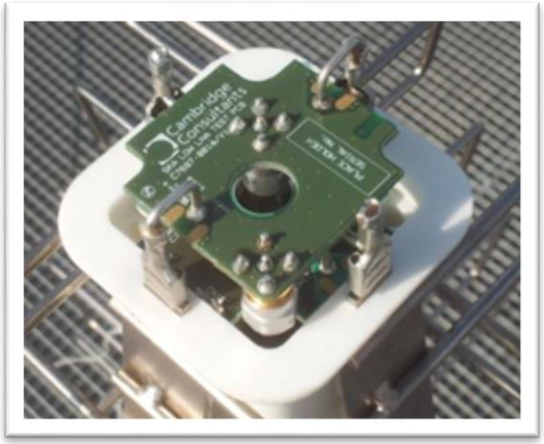
  - Distance to ground plane
  - Opening angle (trade off: Aeff and XP): 10°
  - Antenna size/footprint
  - Growing factor

SKALA: Design

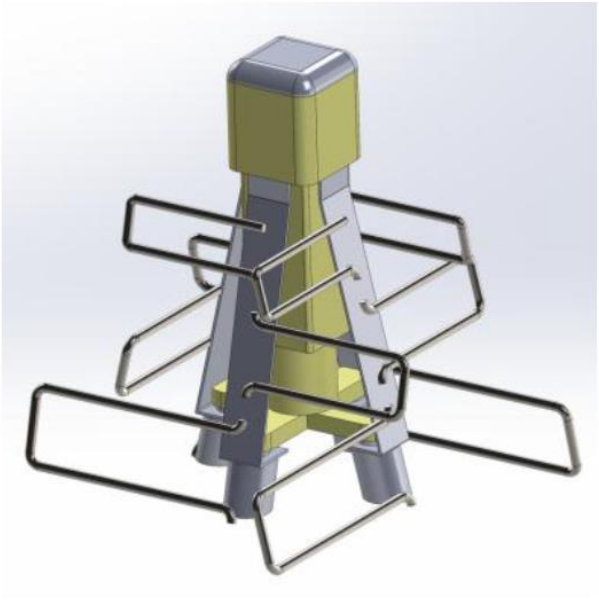


- Ideally; differentially fed for lowest noise.
- Feeding at the top for practical reasons:
  - Avoid Damage in case of flooding
  - LNA and electronics (RFoF, etc.) could be integrated at the top of the antenna.

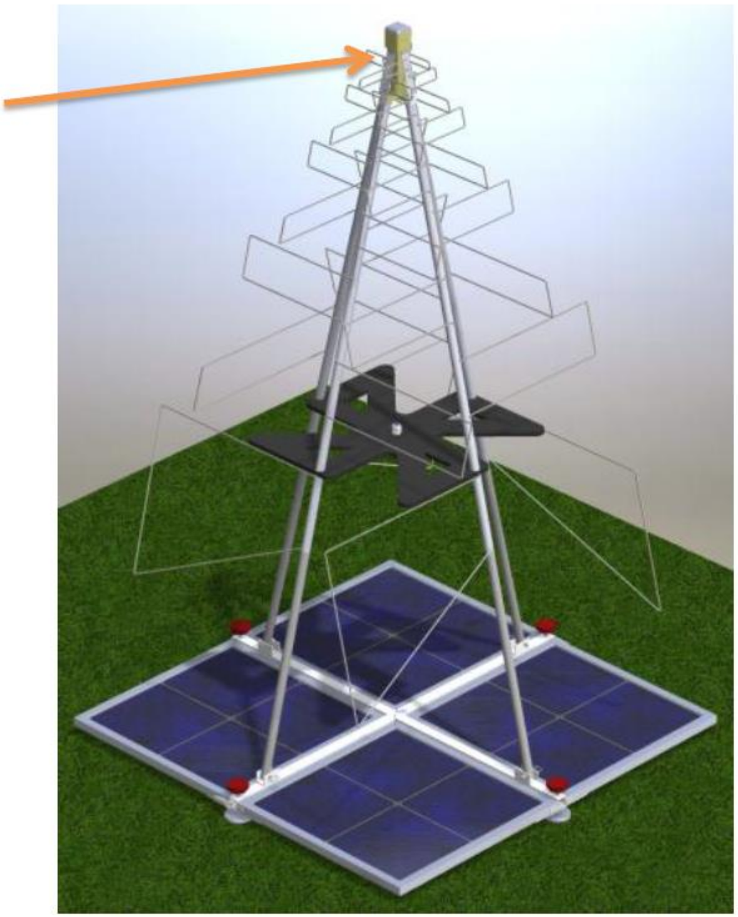




SKALA-2



Credit: MIT

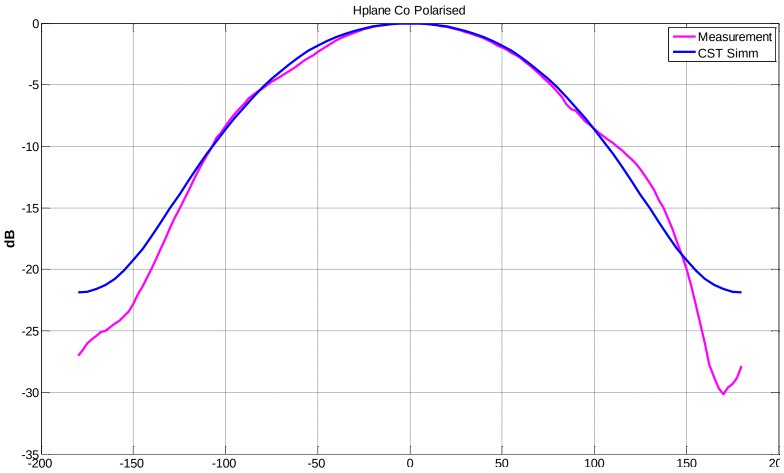


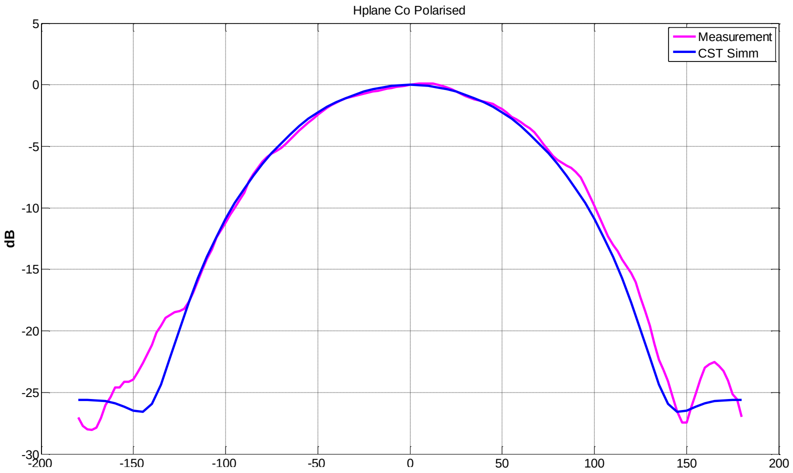
Measurements: Pattern

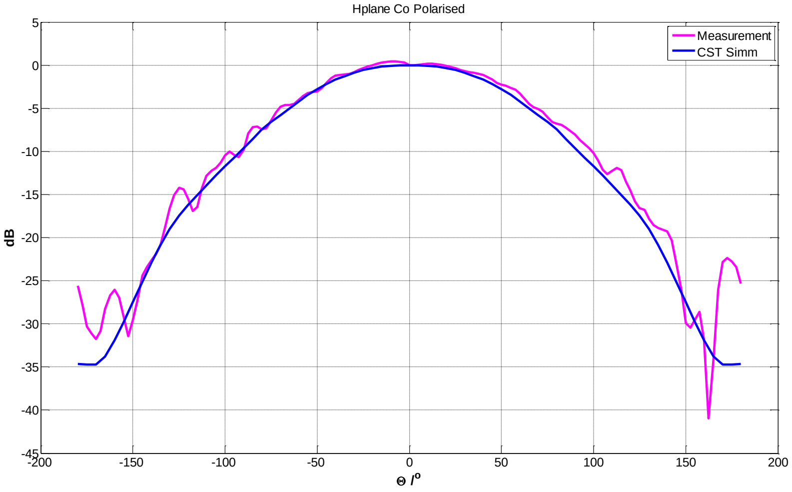
150 MHz 300 MHz

450 MHz

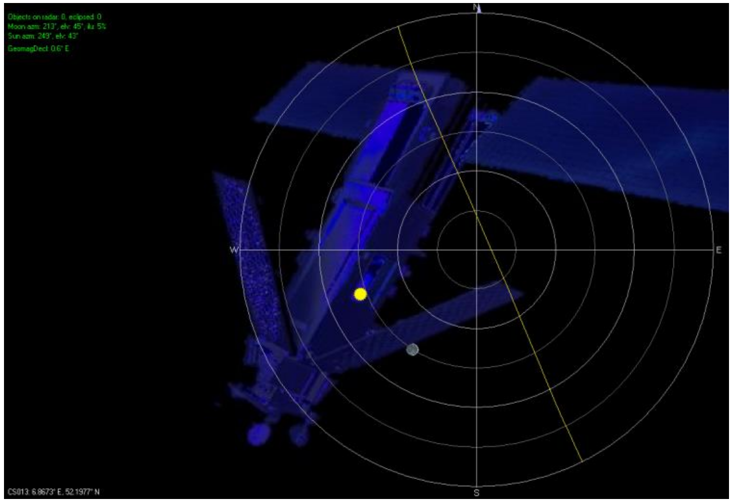
GEROTEK
TEST FACILITIES


Hplane Co Polarised

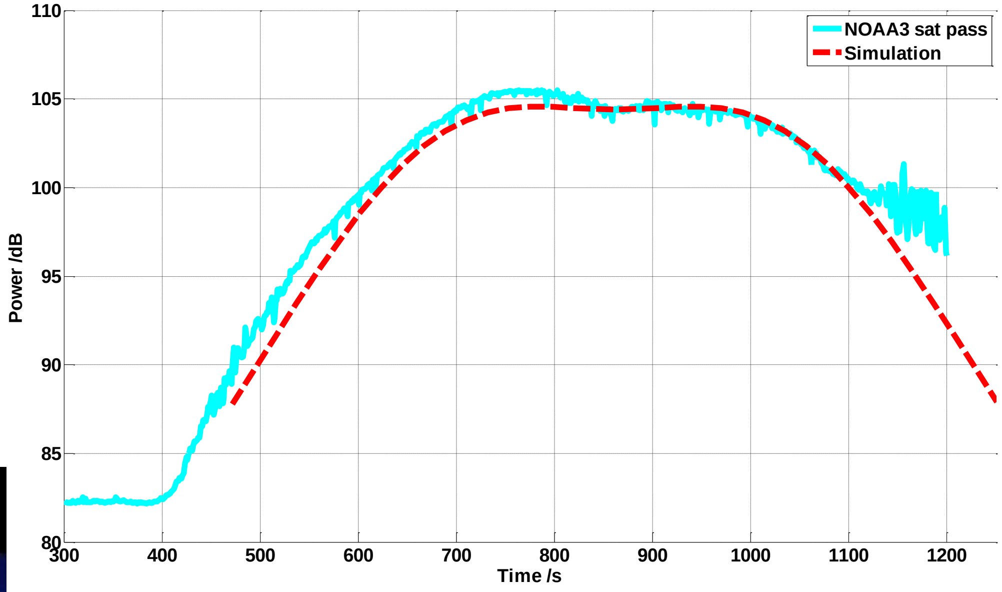

Hplane Co Polarised


Hplane Co Polarised

Measurements: Pattern (with LOFAR)



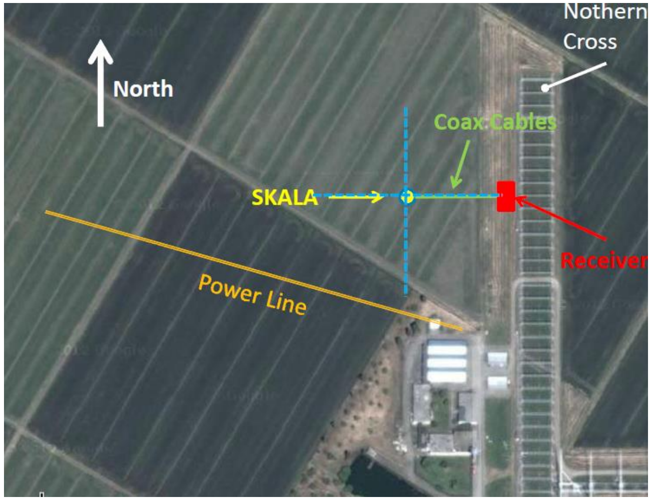
NOAA 3 sat: 137 MHz

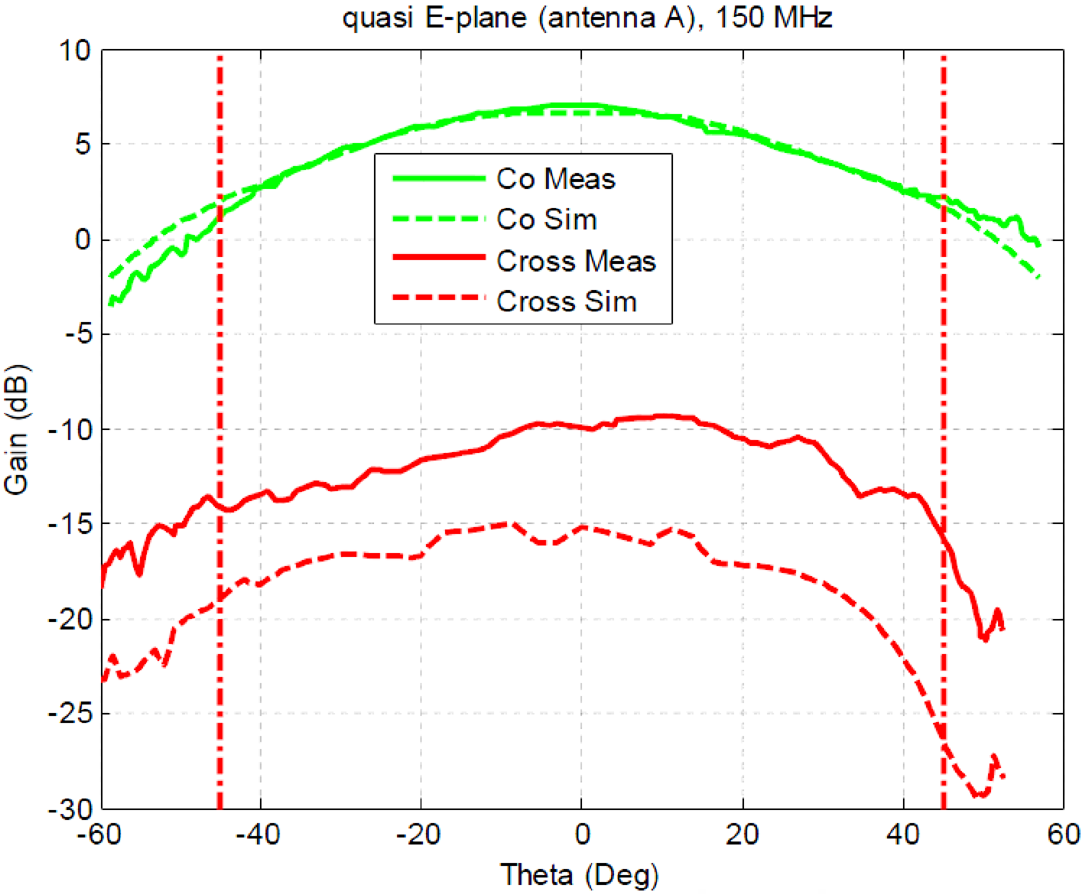


- Also: Beam forming with LOFAR HBA, cross-correlation, LNA stability over large periods of time, etc.

- Next: Correlation of LOFAR with SKALA array?

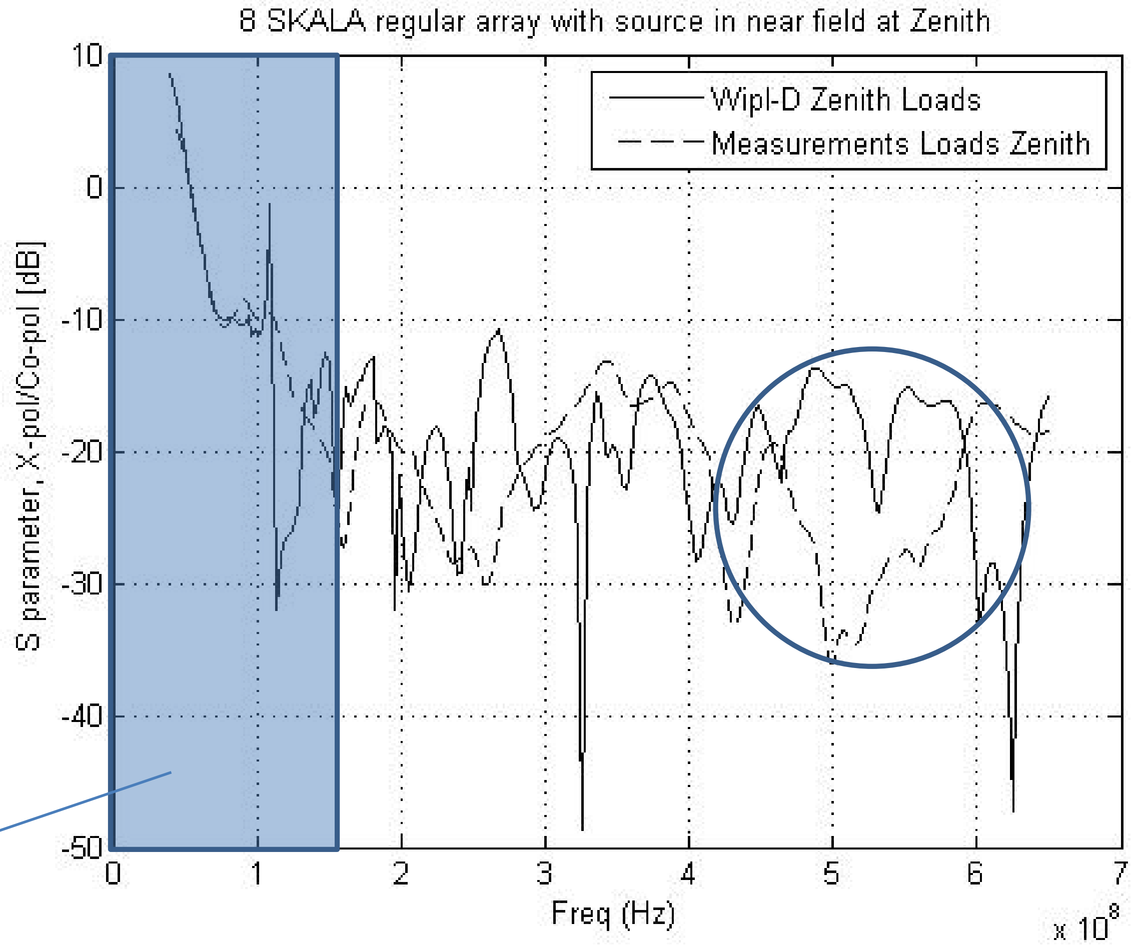
Measurements: Pattern (with Hexacopter - INAF)





Measurements: Near field patterns / Cross-polarization / IXR

Next step: Try with Celestial Sources (MWA, LOFAR).

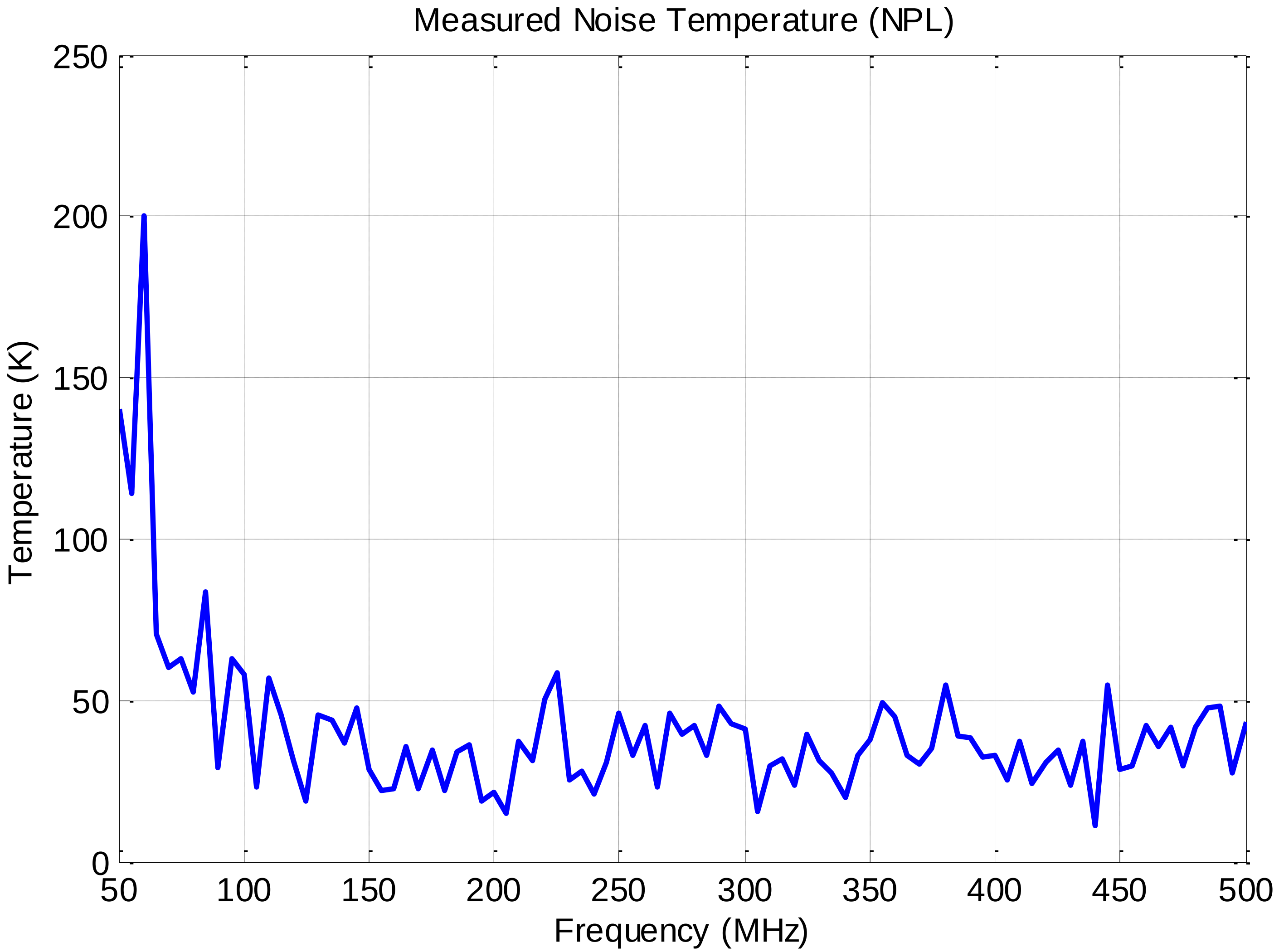


Near Field Scanner does not give meaningful measurements

Credit: B. Fiorelli, ASTRON.

Measurements: LNA

- 1st stage amplifier with Agilent noise analyser in reverberation chamber.

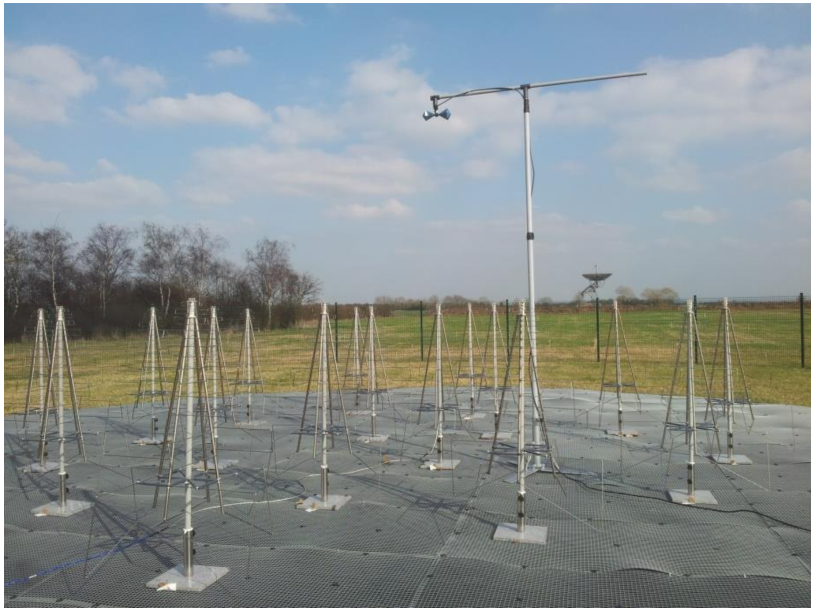


Test arrays

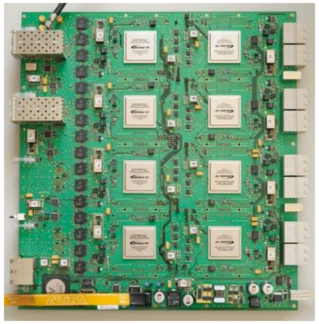
- AAVS0, and AAVS05:

16 dual-polarised SKALA elements.

- Aim: Test realistic SKA AA-low front-end technology in an array environment.
  - Cross check with simulations: mutual coupling, embedded element patterns and noise.
- Tests:
  - Mutual coupling.
  - Patterns (using near field probe, micro-copter, 2 element interferometer (alt-az mount), etc.).
  - Noise: Hot/cold pointing of the array.
  - RFI & satellites.
  - Imaging experiment.
  - Further tests to check software, calibration strategies, cross-polarization, cross-talk, tolerances, lightning modelling environmental, etc.



AAVS0 array under test

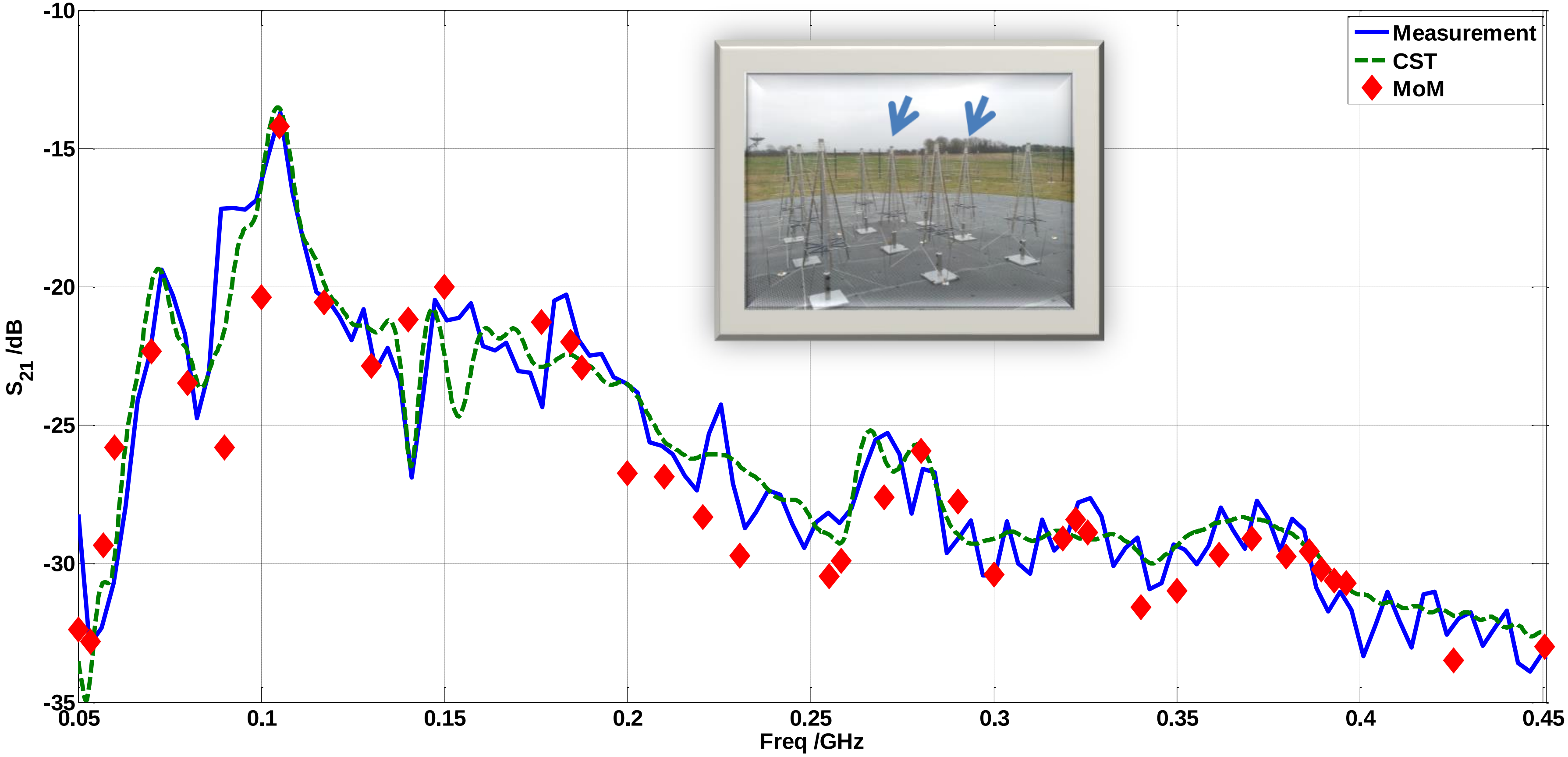


UNIBOARD back end

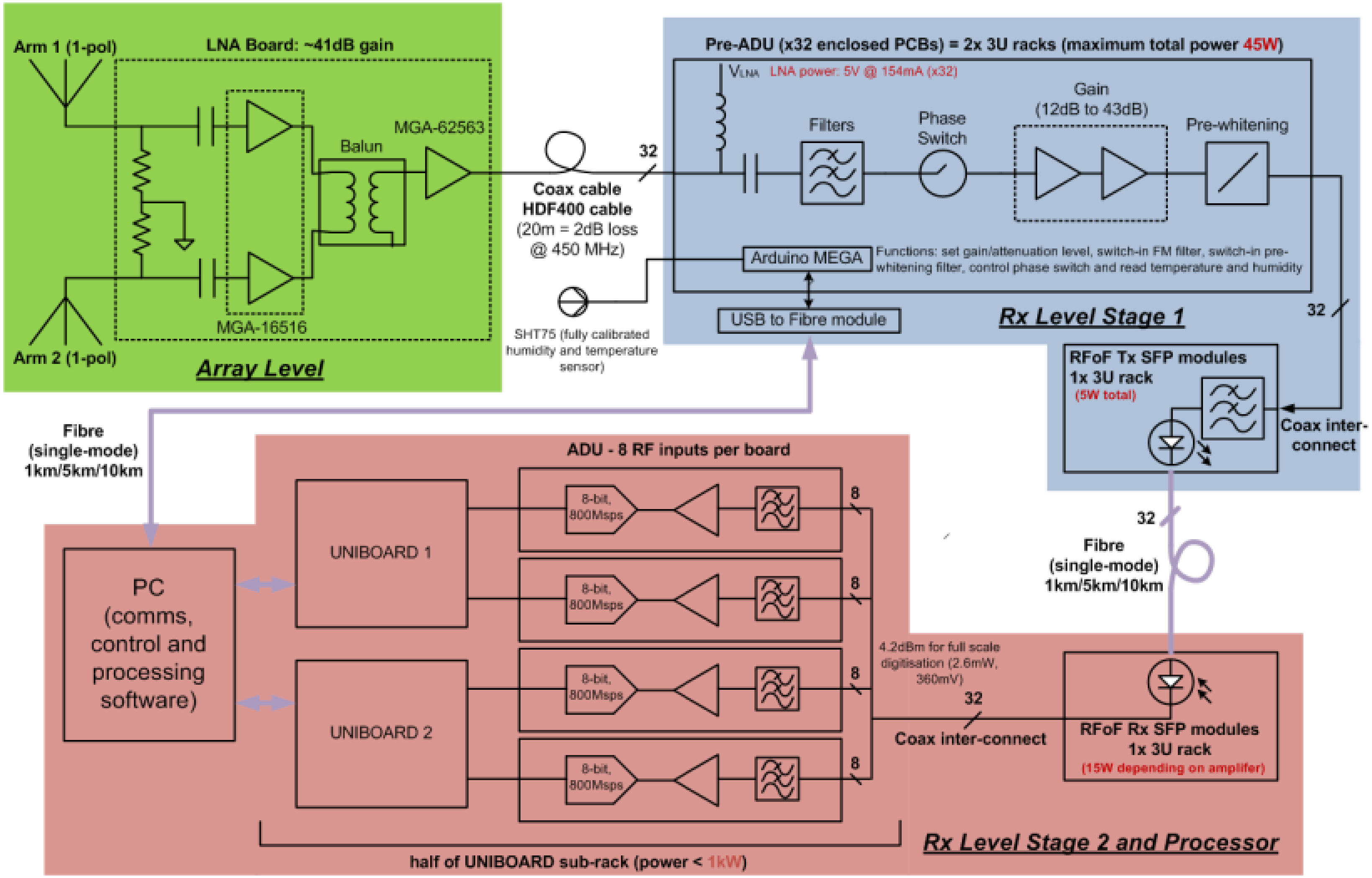
AAVS0 test array at Lords Bridge

Test arrays

- Mutual coupling



AAVS0



Array Level

Arm 1 (1-pol)

LNA Board: ~41dB gain

MGA-62563

Balun

MGA-16516

Arm 2 (1-pol)

Coax cable
HDF400 cable
(20m = 2dB loss
@ 450 MHz)

32

SHT75 (fully calibrated humidity and temperature sensor)

Pre-ADU (x32 enclosed PCBs) = 2x 3U racks (maximum total power 45W)

V_{LNA} LNA power: 5V @ 154mA (x32)

Filters

Phase Switch

Gain (12dB to 43dB)

Pre-whitening

Arduino MEGA

Functions: set gain/attenuation level, switch-in FM filter, switch-in pre-whitening filter, control phase switch and read temperature and humidity

USB to Fibre module

Rx Level Stage 1

32

RFoF Tx SFP modules
1x 3U rack
(5W total)

Coax inter-connect

Fibre
(single-mode)
1km/5km/10km

ADU - 8 RF inputs per board

8-bit, 800Msps

8

UNIBOARD 1

UNIBOARD 2

PC
(comms,
control and
processing
software)

32

Fibre
(single-mode)
1km/5km/10km

4.2dBm for full scale digitisation (2.6mW, 360mV)

32

Coax inter-connect

RFoF Rx SFP modules
1x 3U rack
(15W depending on amplifer)

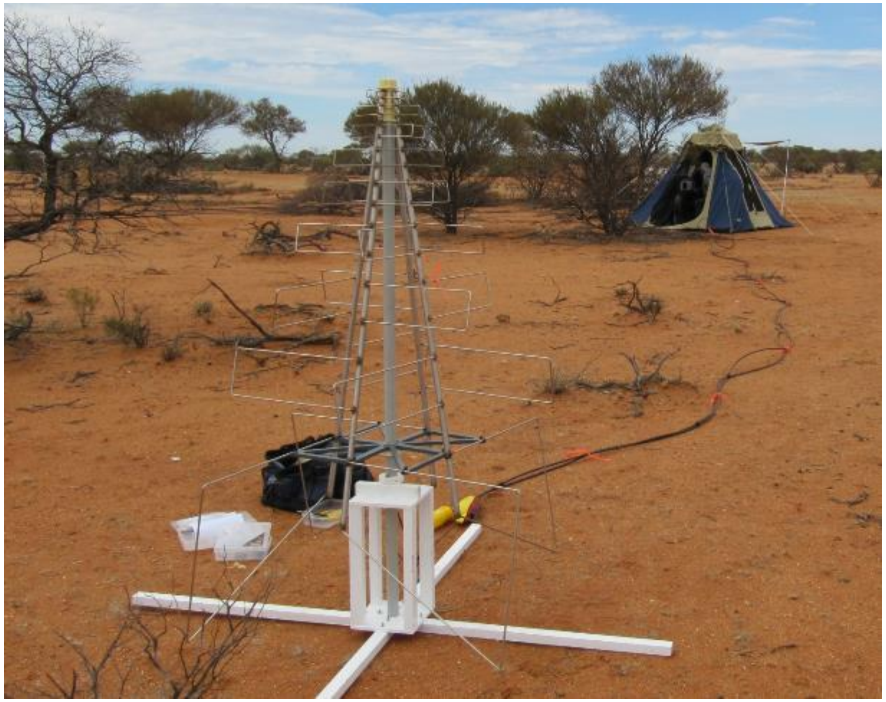
half of UNIBOARD sub-rack (power < 1kW)

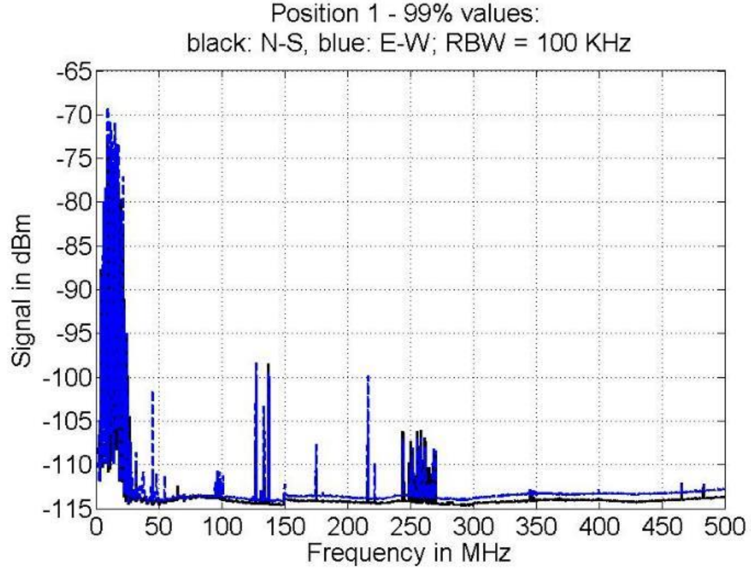
Rx Level Stage 2 and Processor

SKA MidPrep workshop, ASTRON, NL, 31st March 2014

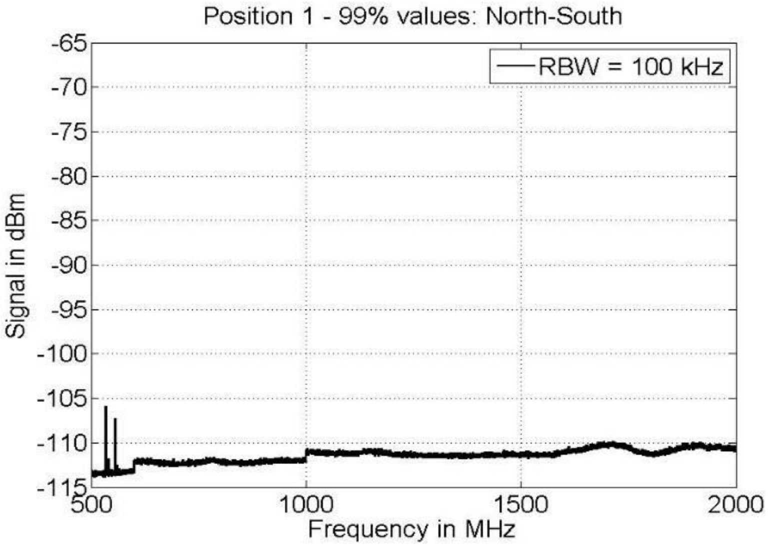
AAVS0.5 test array at MRO, Western Australia

AAVS0.5: RFI Testing





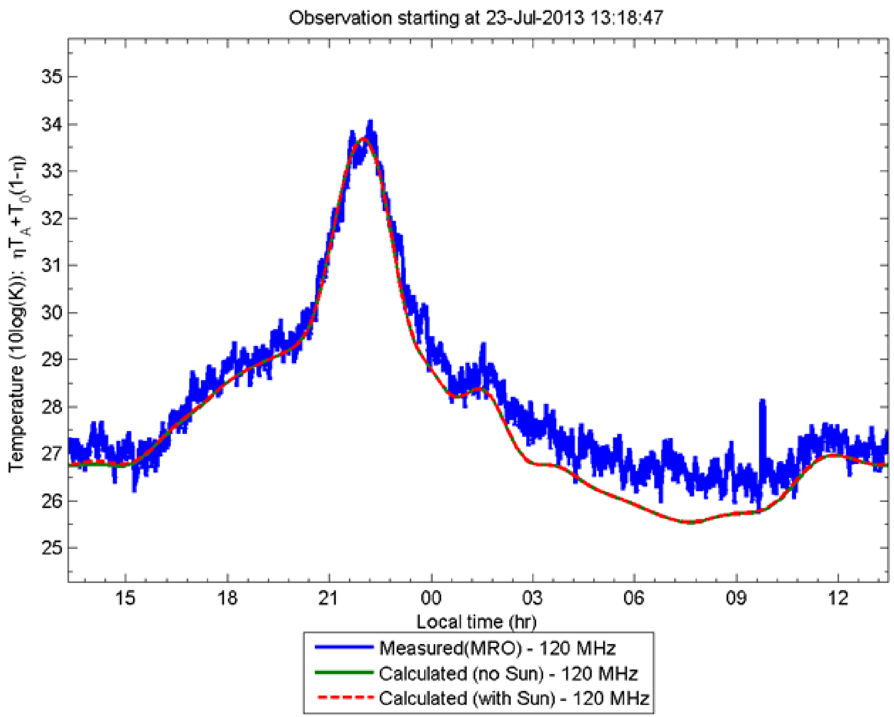
Position 1 - 99% values:
black: N-S, blue: E-W; RBW = 100 KHz

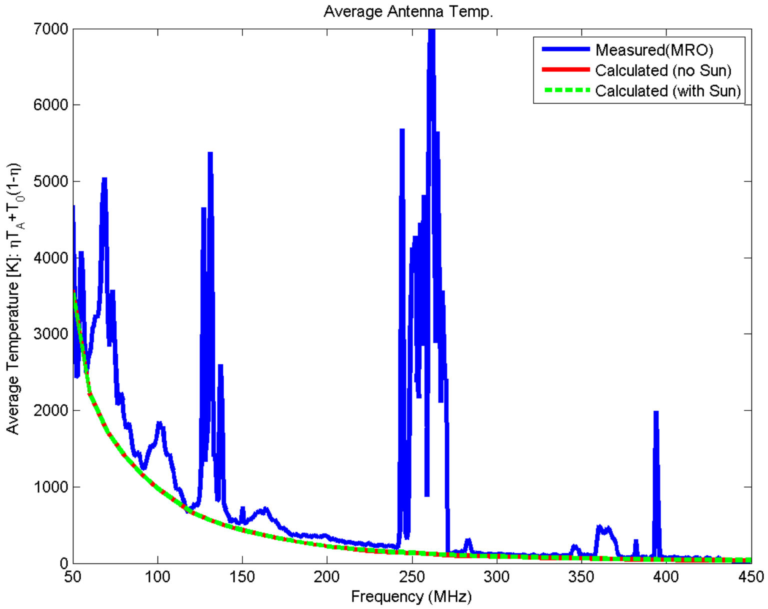


Position 1 - 99% values: North-South

- *Credit: A. Sutinjo, F. Schlagenhaufer*

AAVS0.5: 24 hour drift-scan

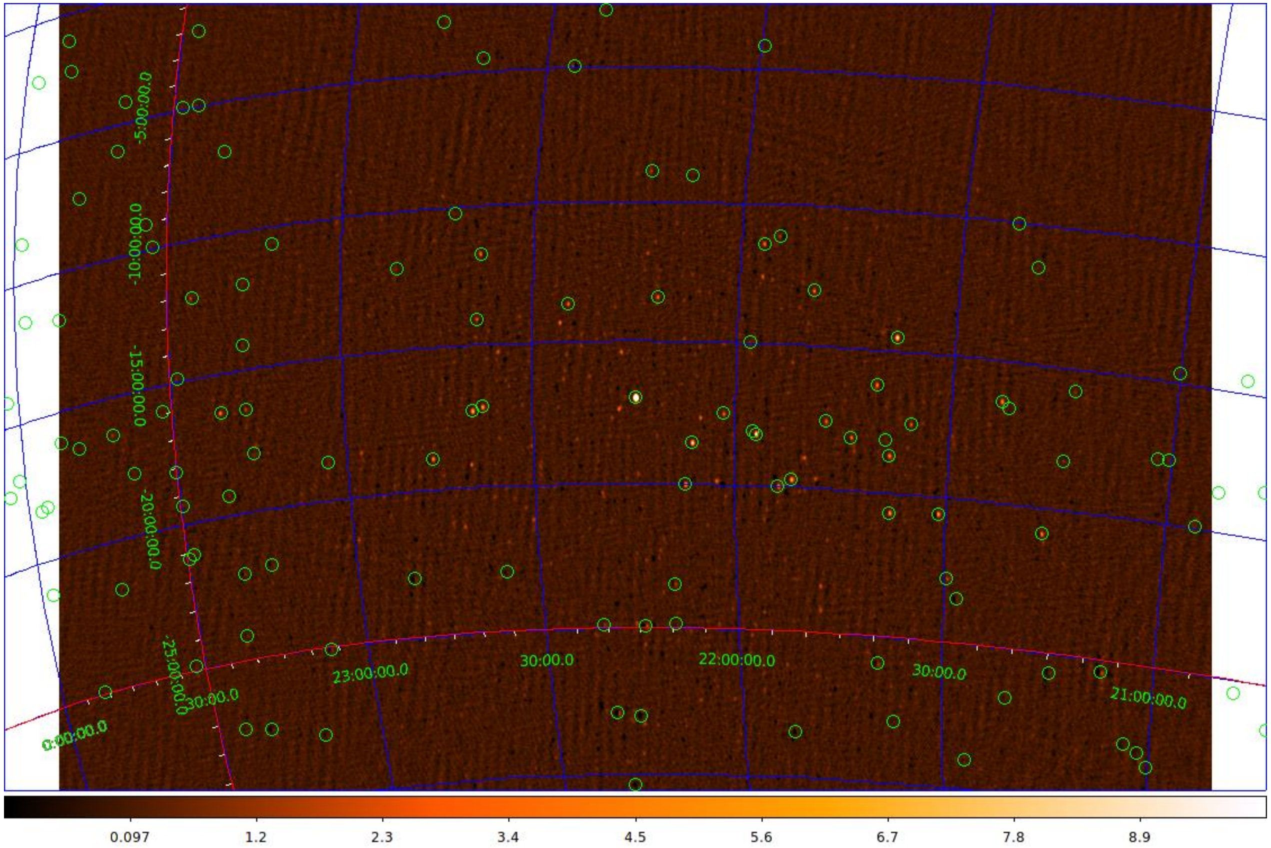




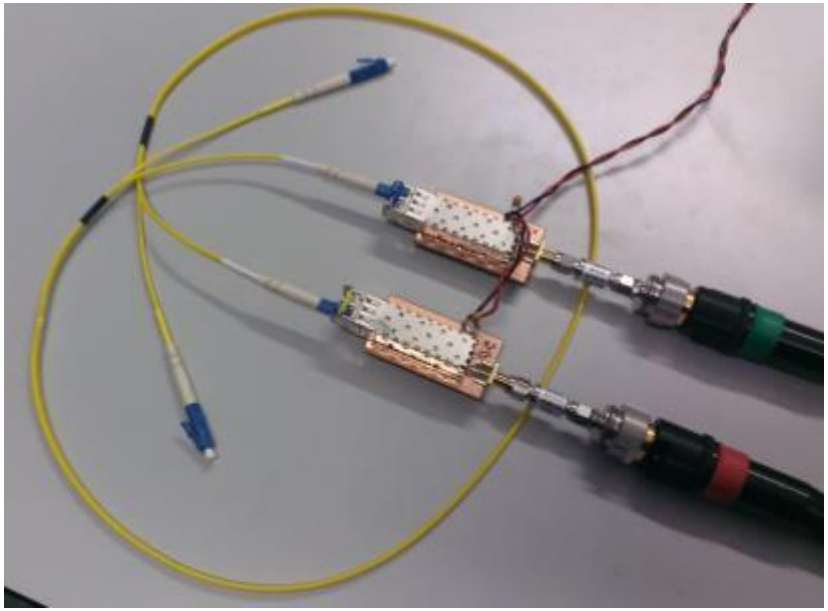
- *Credit: A. Sutinjo, P. Hall*

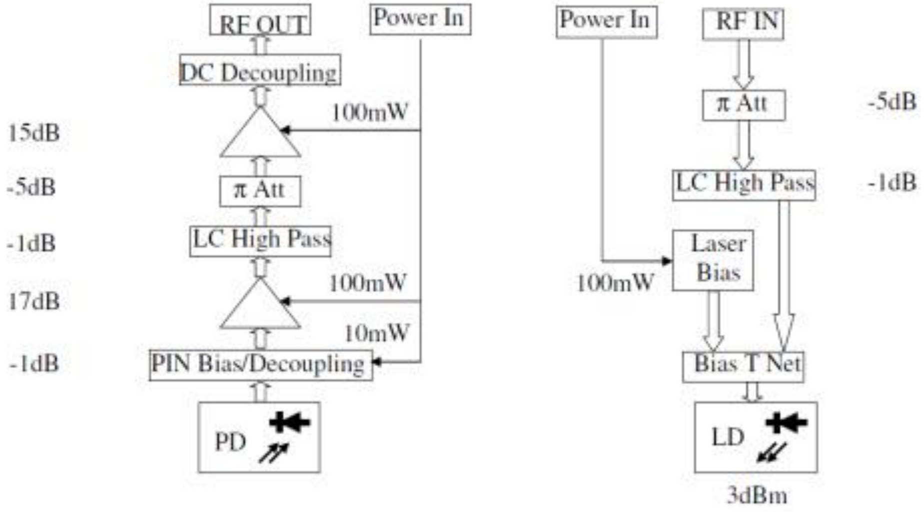
AAVS0.5: Correlation with MWA (first image)

- 2 minute integration, wide-field snapshot, centred on 3C444
- AAVS 0.5 baselines only (but calibrated using whole MWA)



RFoF: 2nd protoype

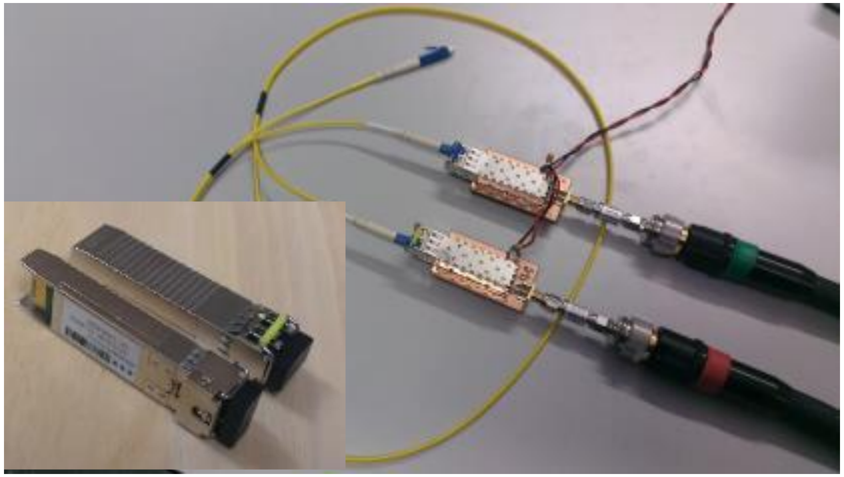


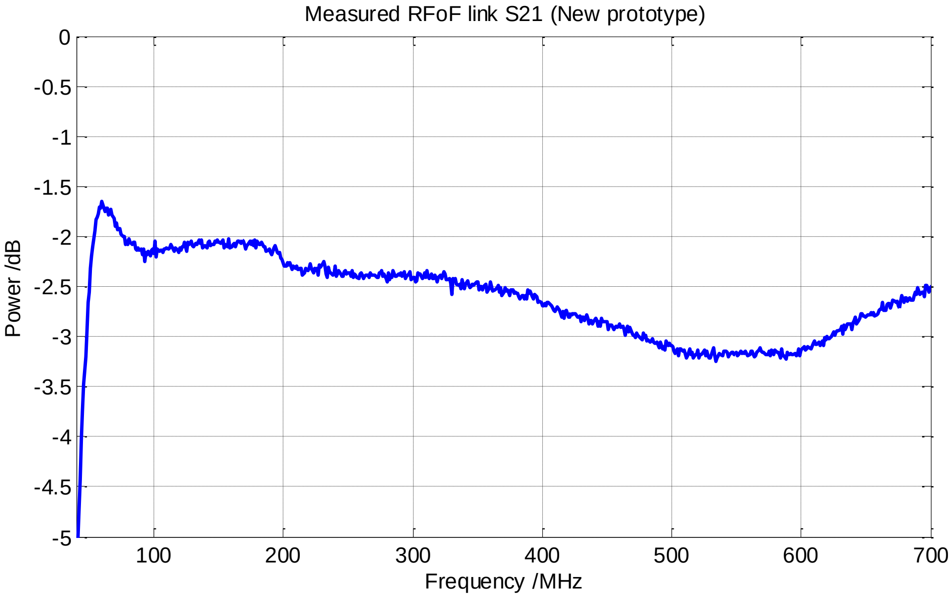


eblanaphotonics
precision light for advanced communications

Credit: Nima Razavi

RFoF: 2^{nd} ptototype performance

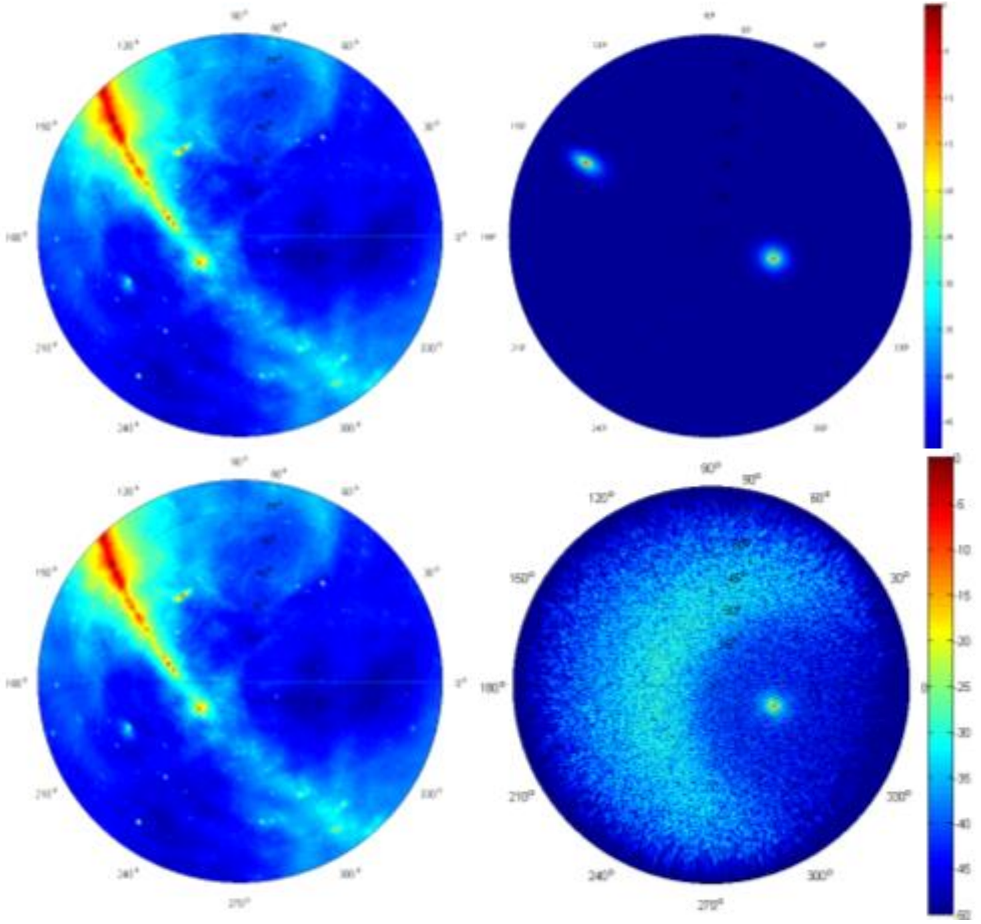




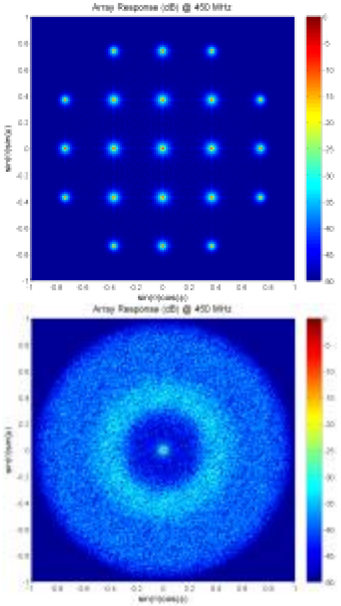
- Design BW: 50-700 MHz, -60dBm input, <2dB Passband ripple
- 1310nm, single mode G. 652/G. 655 fibre, LC/UPC connector
- Pros: Good link performance across SKA LFAA band, small footprint (SFP), low power (Tx: 5V@30mA, Rx: 5V@95mA)
- Cons: Temperamental connectors (not angled)

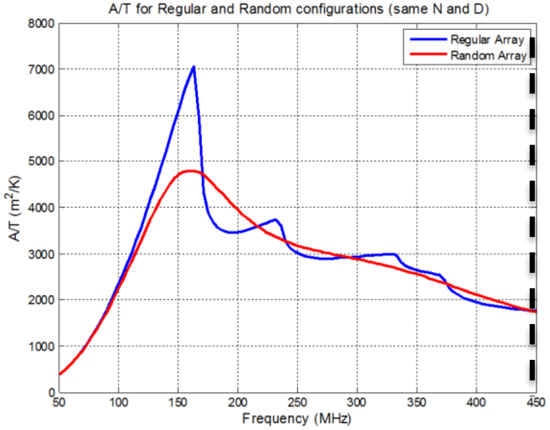
Credit: Nima Razavi

How configuration affects astronomical measurements

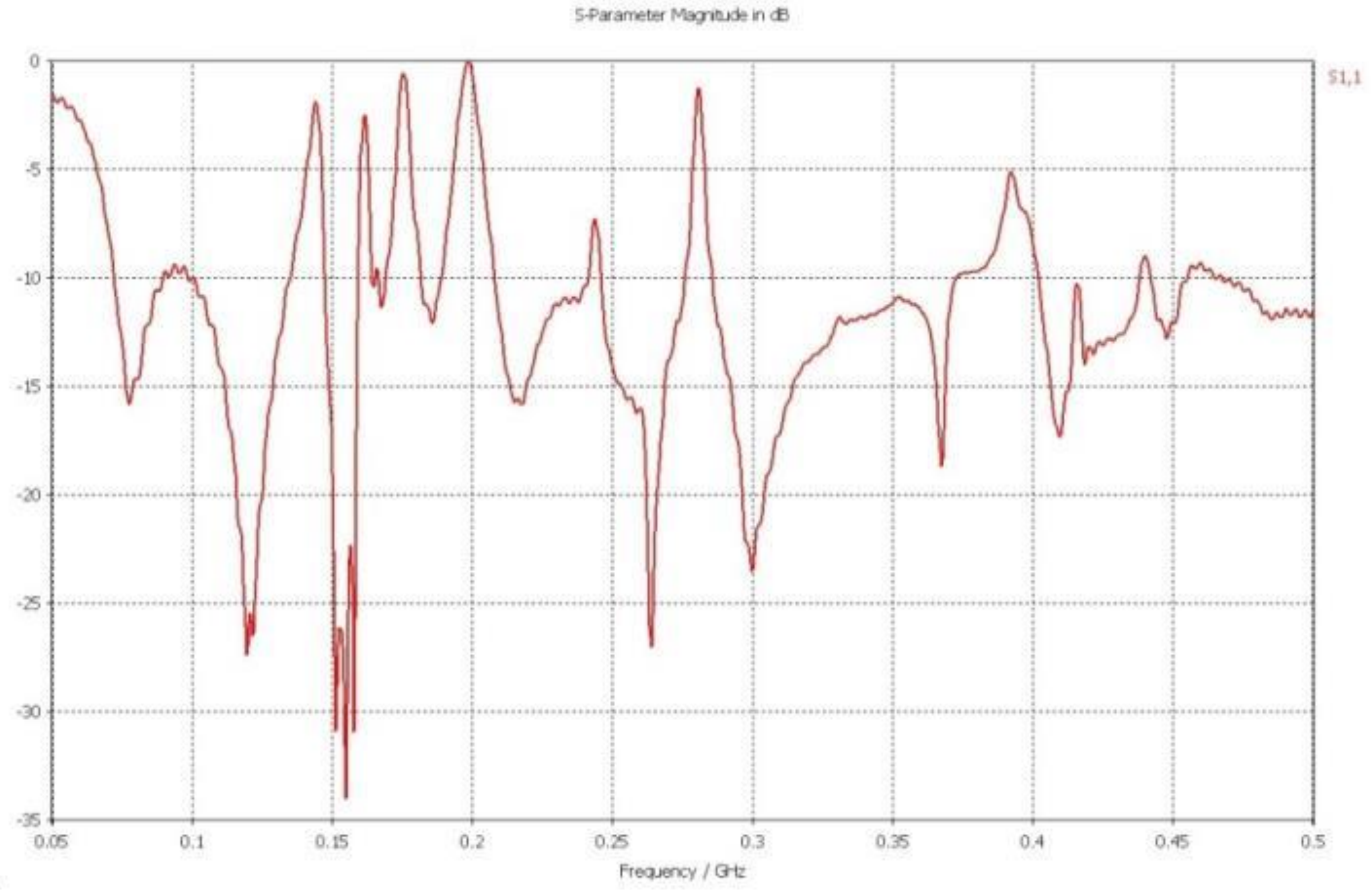


Irregularity and in particular randomness are vital for under-sampled antenna arrays



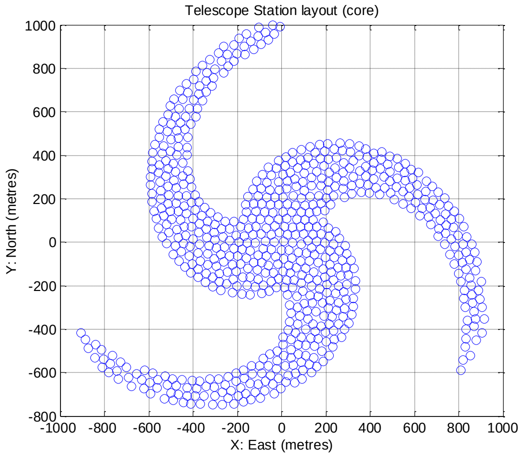


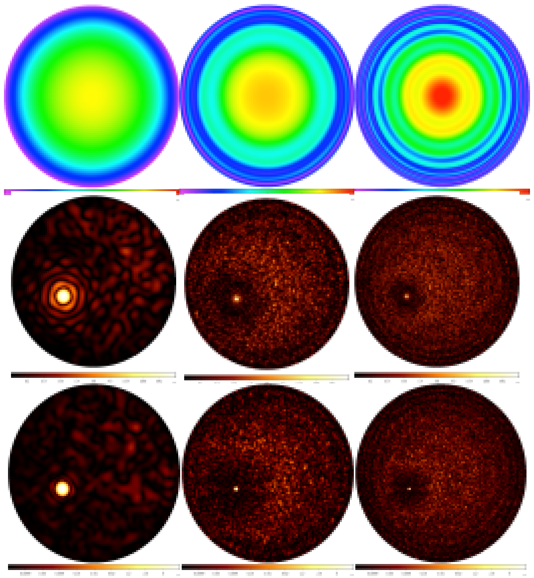
Effects of mutual coupling in regular arrays

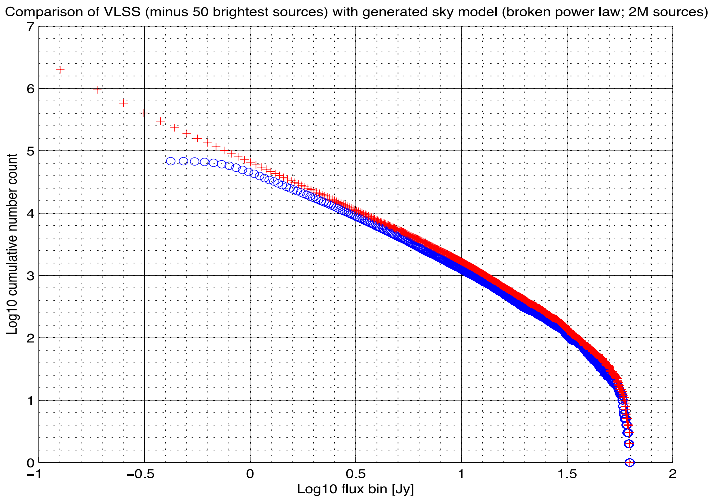


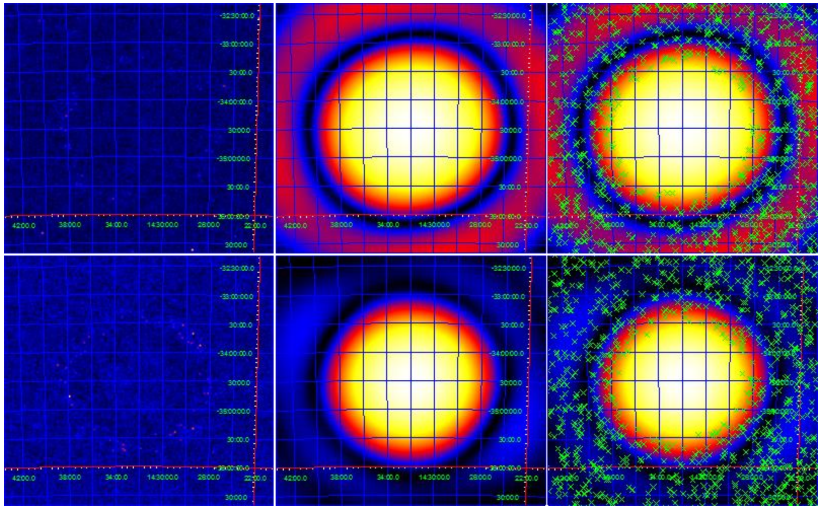
Simulations and Calibration for SKA-low

OSKAR2 simulations





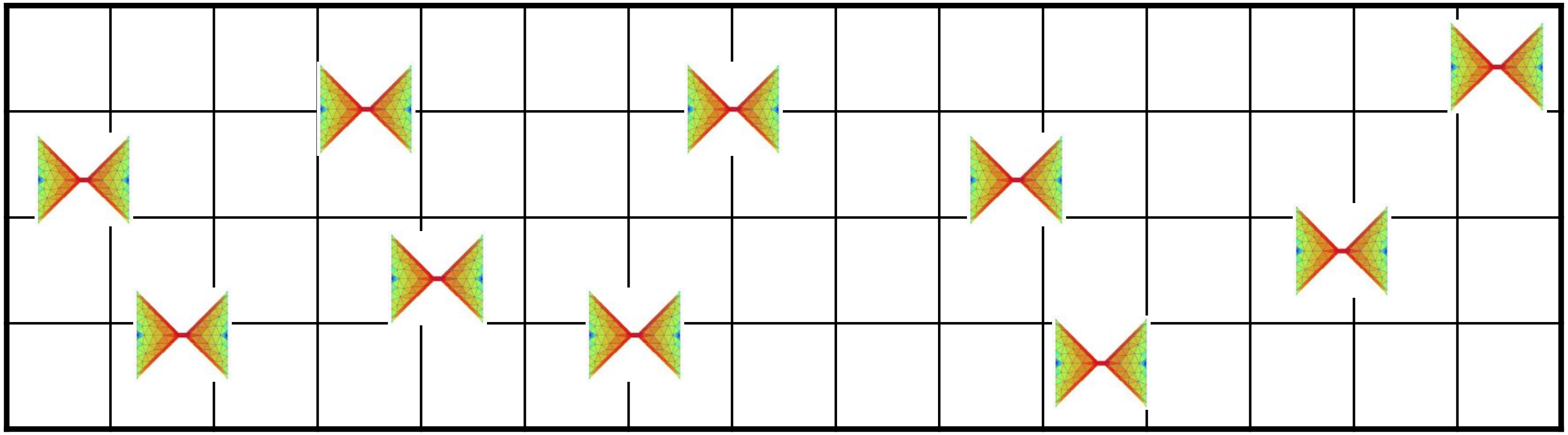




Credit: N. Razavi, B. Mort, F. Dulwich, E. de Lera, K. Grainge, R. Bolton, M. Jones and D. Sinclair.

MoM-MBF simulation 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**.



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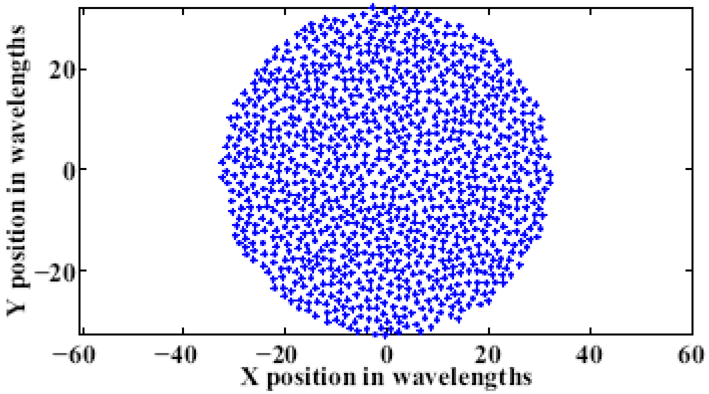
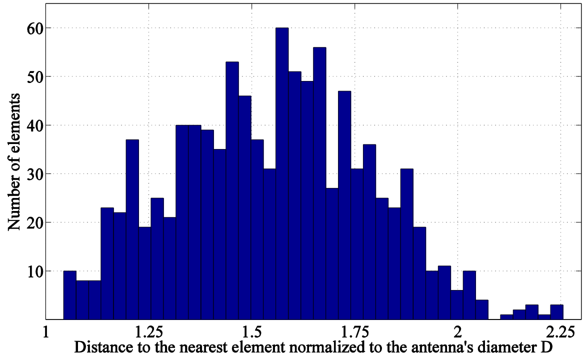
[1] David Gonzalez-Ovejero, Christophe Craeye, "Interpolatory Macro Basis Functions Analysis of Non-Periodic Arrays," IEEE Trans. Antennas Propag., vol.59, no.8, pp.3117,3122, Aug. 2011

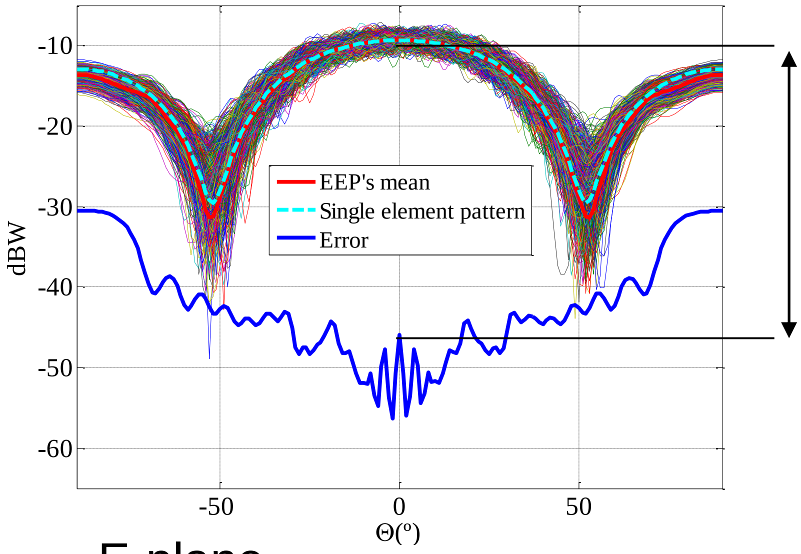
Mutual coupling in irregular arrays

$$e = 10\log_{10}\left(\left|\vec{E}_{mean}(\theta,\phi) - \vec{E}_{\sin gle}(\theta,\phi)\right|^{2}\right)$$

Random configuration

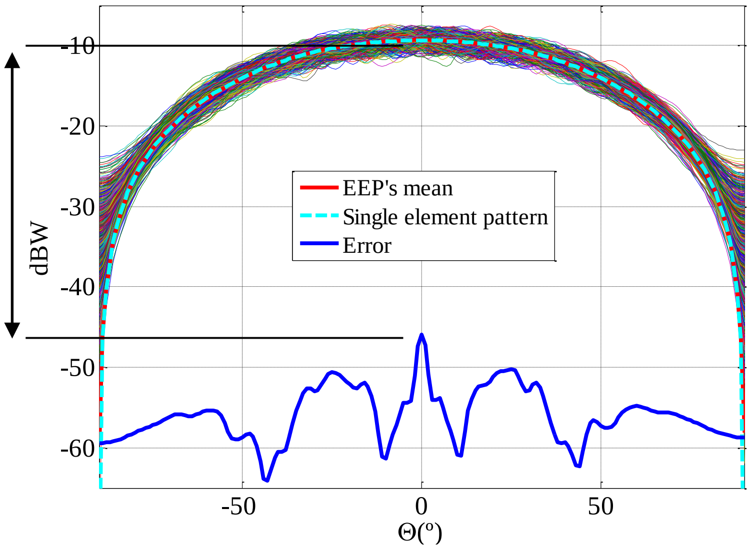






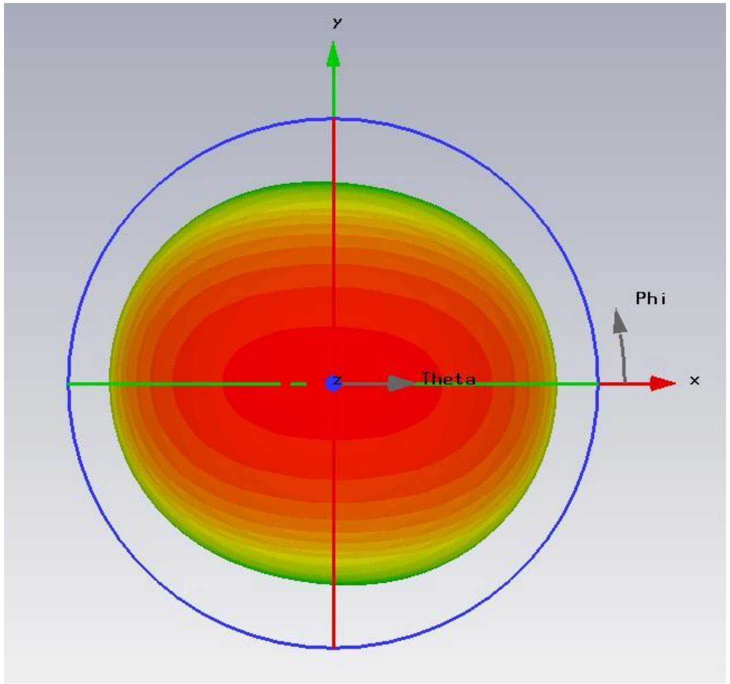
E-plane

~ 35 dB

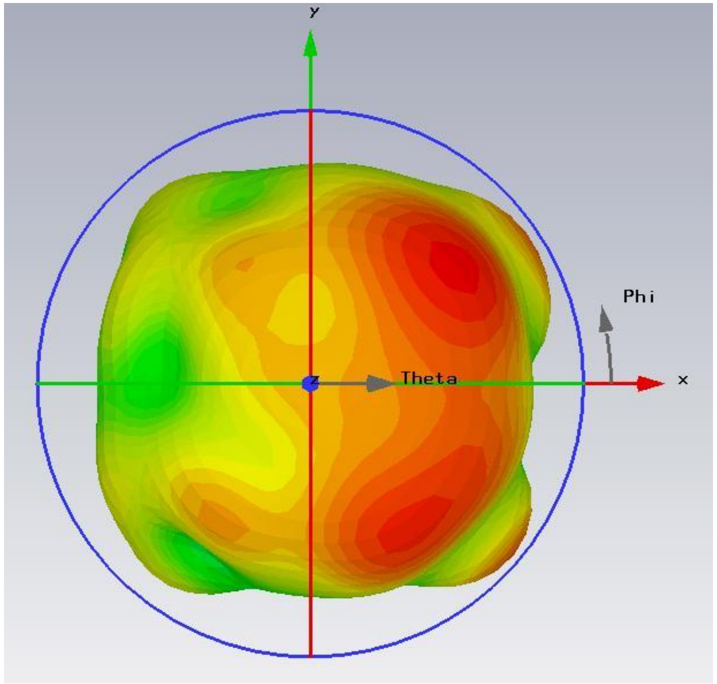


H-plane

Station_Beam = Array_Factor x Average_EEP

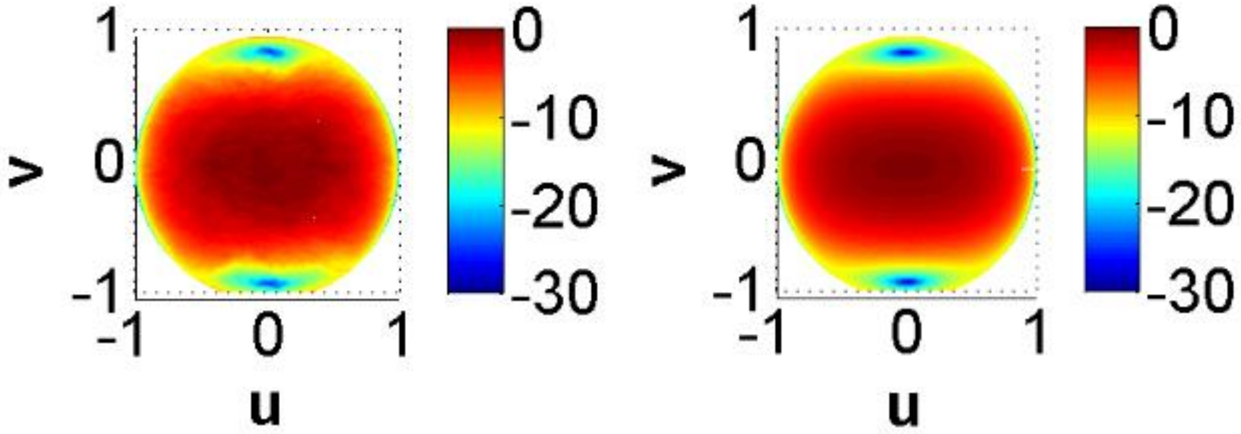


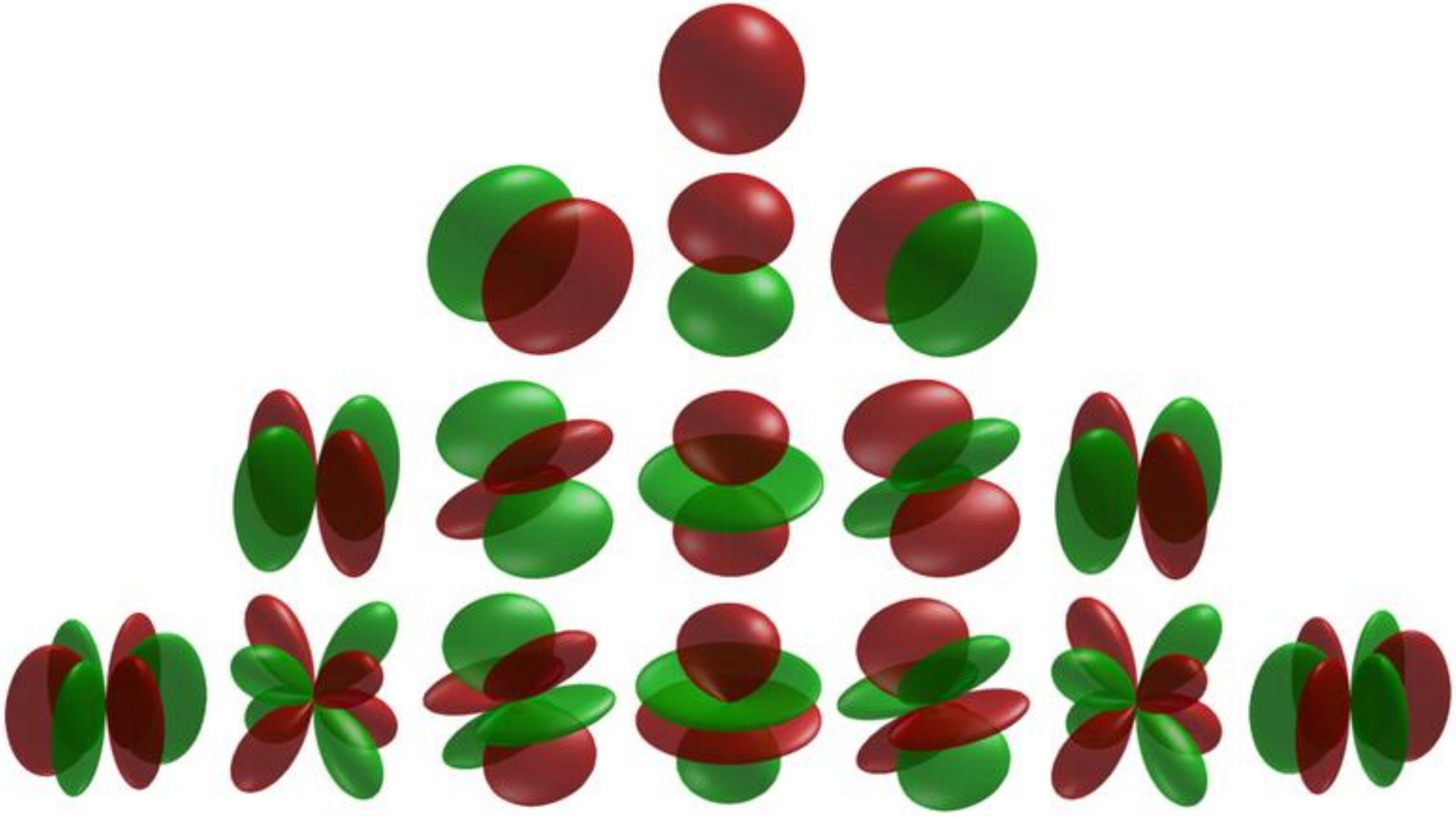
Average Embedded Element Pattern



Pattern of a given element

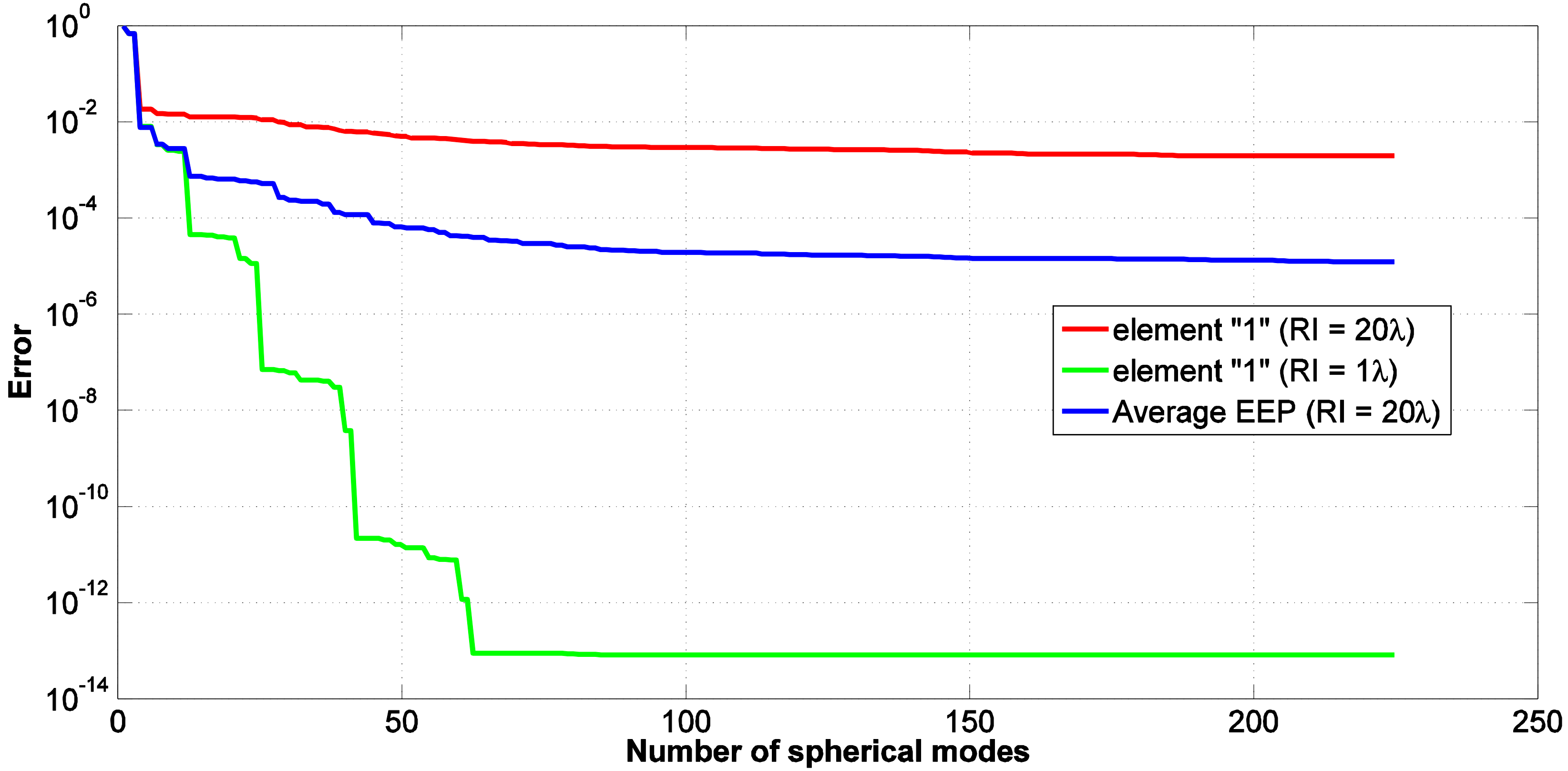
Beam Models for pattern prediction/calibration (inspired by Jan Noordam and the 3GC workshops)





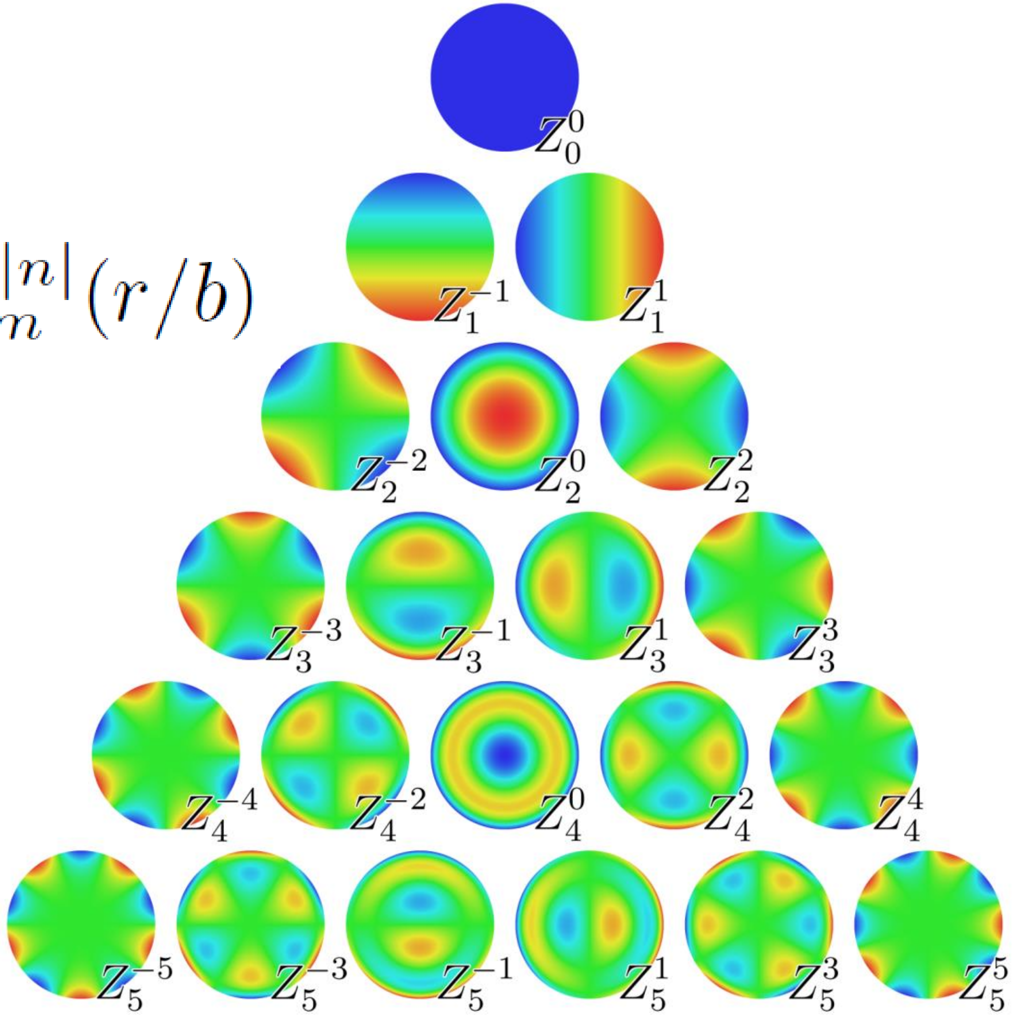
Spherical Harmonics

Average Embedded Element Pattern



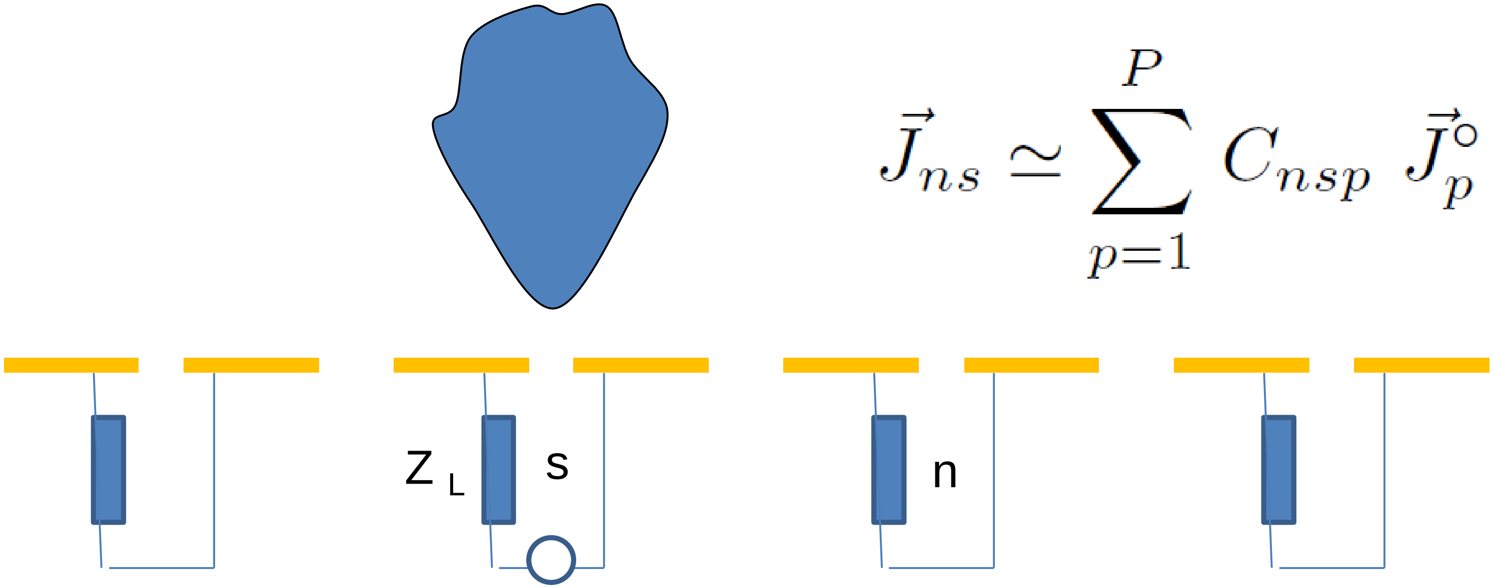
Zernike functions

$$e^{j\,n\,\alpha}\;F_m^{|n|}(r/b)$$



Picture from Wikipedia

Array factorisation



$$\vec{J}_{ns} \simeq \sum_{p=1}^{P} C_{nsp} \; \vec{J}^{\circ}_{p}$$

	Antenna index		
MBF 1	C_{111}	C_{211}	C_{311}
MBF 2	C_{112}	C_{212}	C_{322}
⋮			

Coefficients for **IDENTICAL** current distribution

$$\vec{F}_s \simeq \sum_{p=1}^{P} \underbrace{\sum_{n=1}^{N} \left(\overbrace{\sum_{s=1}^{N} A_s \, C_{nsp}}^{A'_p} \right) e^{j\,k\,\hat{u}.\vec{r}_n}}_{AF_p} \; \vec{F}^{\circ}_{p}$$

Zernike representation of deficiencies in the pattern including mutual coupling

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

- Basis functions = EEPs.
  - They can be pre-computed accurately.
  - They are smooth and can be stored with low resolution.
- The variations wrt the simulated response are mapped using Zernike polynomials.
  - They are generic and flexible.
  - We can optimize the number of coefficients needed according to the number of sky sources available.
- The weights for the “predicted” pattern can be found from the combination of basis functions.

Low Order Beam Models for Calibration

Zernike representation of deficiencies in the pattern including mutual coupling

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

- 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.

---

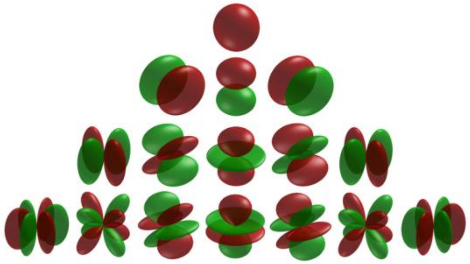
*Before: C. Craeye et al. (2012): $\mathrm{AP} = \sum_k AF_k x MBF_k$

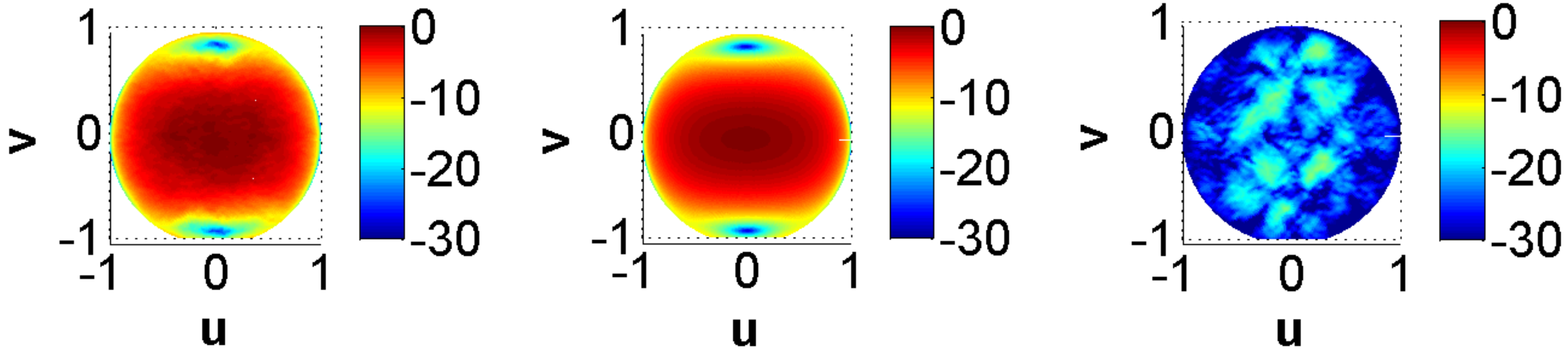
Use of pre-computed EEPs

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

- 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.

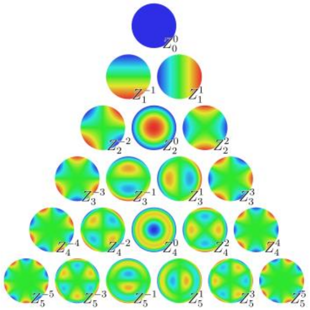
Spherical Harmonics



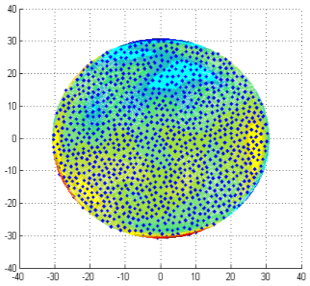


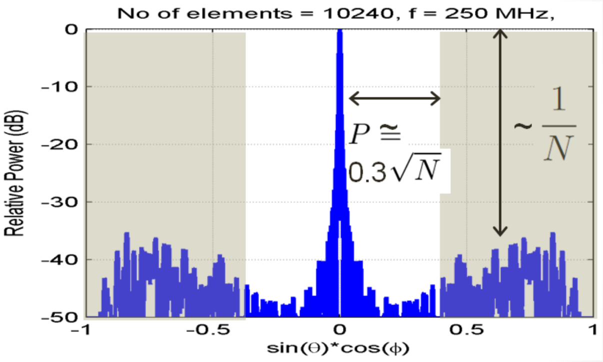
Use of Zernike polynomials

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



- 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.

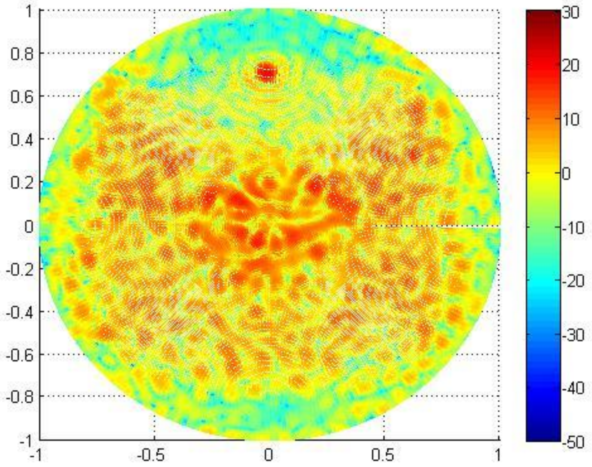
Related work: C. Craeye et al. (2012), R. Maaskant, M. Ivashina, et al. (2012), etc.

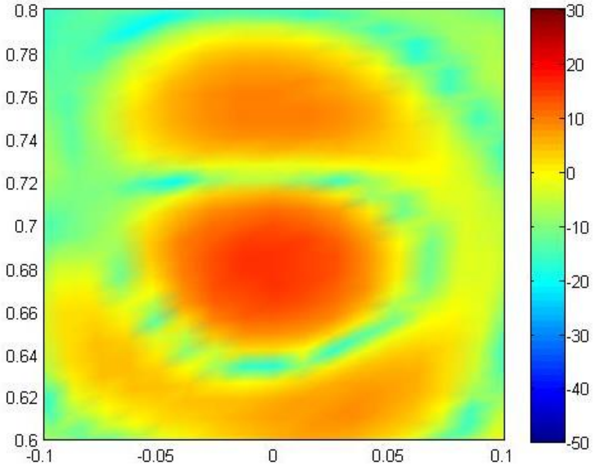
Summarizing…

- The array pattern is modeled with (approximately) computed embedded element patterns.
- Each pattern is multiplied by a constant with smooth variation over the array (Zernike function)
- Zernike coefficients are estimated in least-squares sense based on observations.

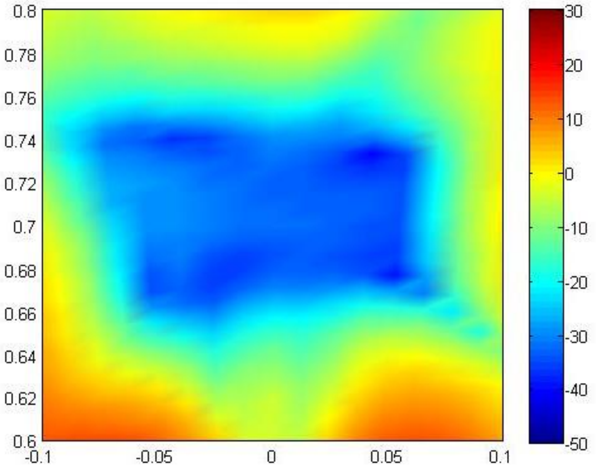
Tests: Pointing error (2 deg.) – scanning

Scan:
Θ = 45 deg.
Φ = 90 deg.

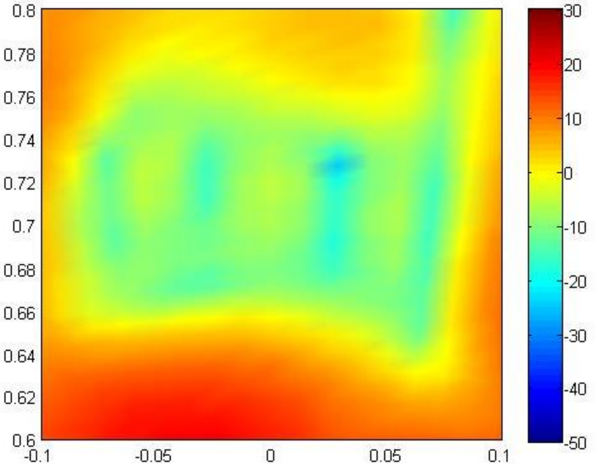




Error Rec. - Actual



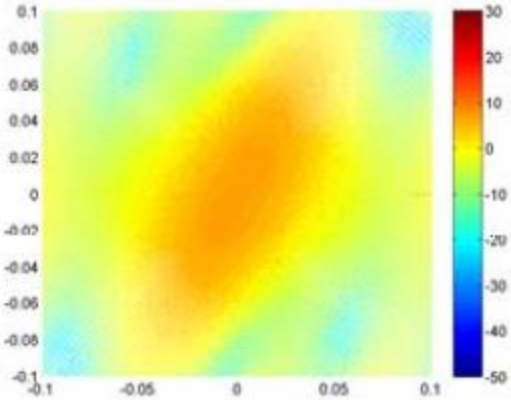
t = 36, *w* = 81



t = 15, *w* = 16

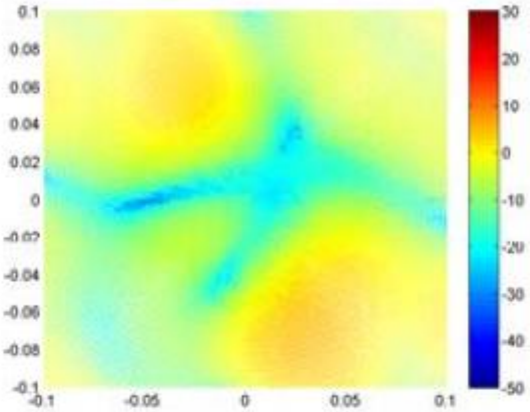
**t* : number of Zernike polynomials / *w* : number of measured points.

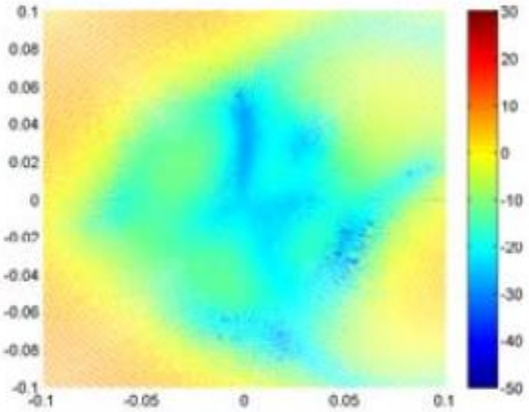
Tests: Dead elements (10%)



Error Rec. - Actual

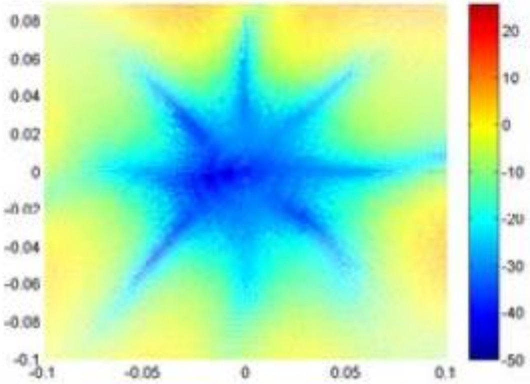
t = 3

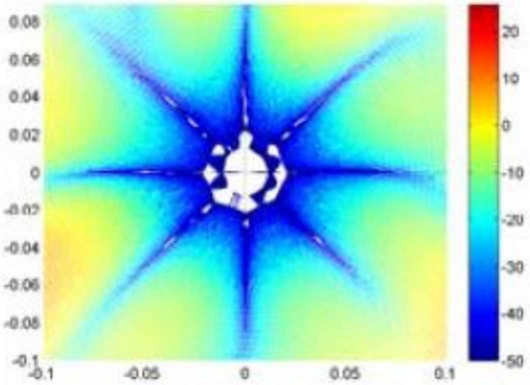




t = 10

t = 21





t = 36

**t* : number of Zernike polynomials / *w* : number of measured points = 57.

Conclusions and Future Work

- The LFAA array will have a major demonstrator in Western Australia (AAVS1 with approx. 512 elements) by mid 2015. End of 2016 is the end of the pre-construction phase.
- Front-end technologies are being developed to meet the SKA budget and deployment/mechanical/environmental limits.
- Accurate beam models for calibration are essential and already exist. Use of UAV systems and demonstrator arrays are key for these developments.

Thank you