MID-FREQUENCY APERTURE ARRAY

Element and array beam pattern measurements by an UAV system

Giuseppe Pupillo (IRA-INAF)

INAF **CNR-IEIIT** **POLITECNICO DI TORINO**

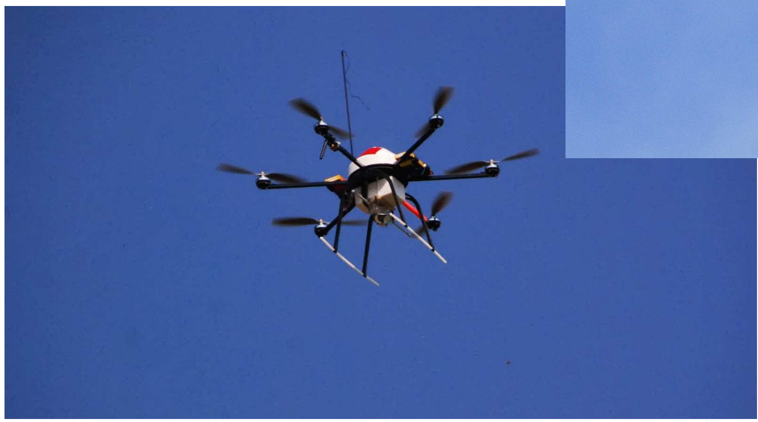
Dwingeloo – MIDPREP Workshop 31 March – 01 April 2014

Outline

- Description of the UAV – Hexacopter
- Isolated and Embedded Antenna Pattern Measurements
- Array Instrumental Calibration
- Array Beam Measurement
- Possible extension to AAMID

Unmanned Aerial Vehicle - 1

Unmanned Aerial Vehicle (UAV) is an aircraft without a human pilot aboard, which flight is controlled by onboard computer or by a remote control



Unmanned Aerial Vehicle - 2

Our UAV is a hexacopter (Mikrokopter KGPS v1.0) is a custom product based on commercial components, with engines and some electronic parts modified.

The hexacopter has been equipped with a continuous wave TX (RF generator + Antenna) having the following specs:

- **Frequency range from 5 MHz to 4.4 GHz (tested from 70 to 450 MHz)**
- **Minimum resolution 2.5 kHz**
- **Tx power 8 dBm (5 dBm with freq. divider)**
- **Linear polarization**

Unmanned Aerial Vehicle – 3

The UAV is a fully controlled artificial source in far-field able to perform measurements of antennas and arrays in real operative conditions

The hexacopter has further advantages:

- **low cost (< 2500 €)**
- **transportability**
- **no runways are required**
- **vertical and standing flight are allowed**

and some limitations:

- **flight time limited to 5 - 15 mins**
- **maximum height ~150 m**
- **no autonomous Take Off / Landing**

The measurement setup

UAV

↓

Array/Antenna Under Test

↓

Infrastructure and receiving system

↓

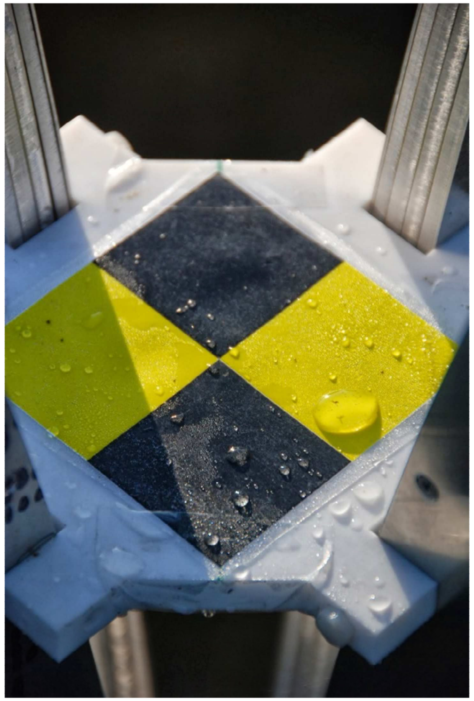
Data analysis software

Aerial Array Topography

The UAV is a very flexible, multipurpose and modular system

The Hexacopter can be equipped with a High-Res photo-camera

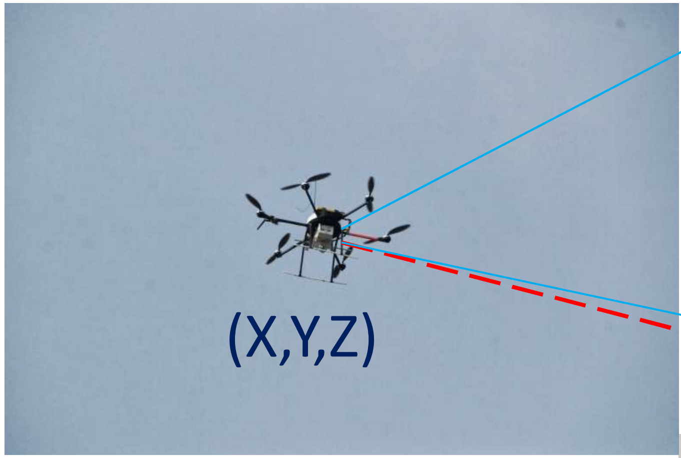
Optical markers placed on the antennas allow to reach sub-cm accuracy in the position measurement

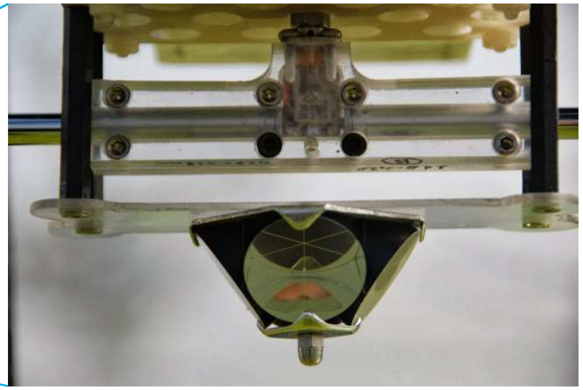


- **Antenna positioning / orientating**
- **Array maintenance (antenna displacement or structure damages)**

UAV trajectory measurement

In order to define the absolute position of the UAV vs. time, a topographic tracking has been performed using a motorized total station (MTS). It was possible thanks to a retro-reflector installed on the bottom part of the UAV.





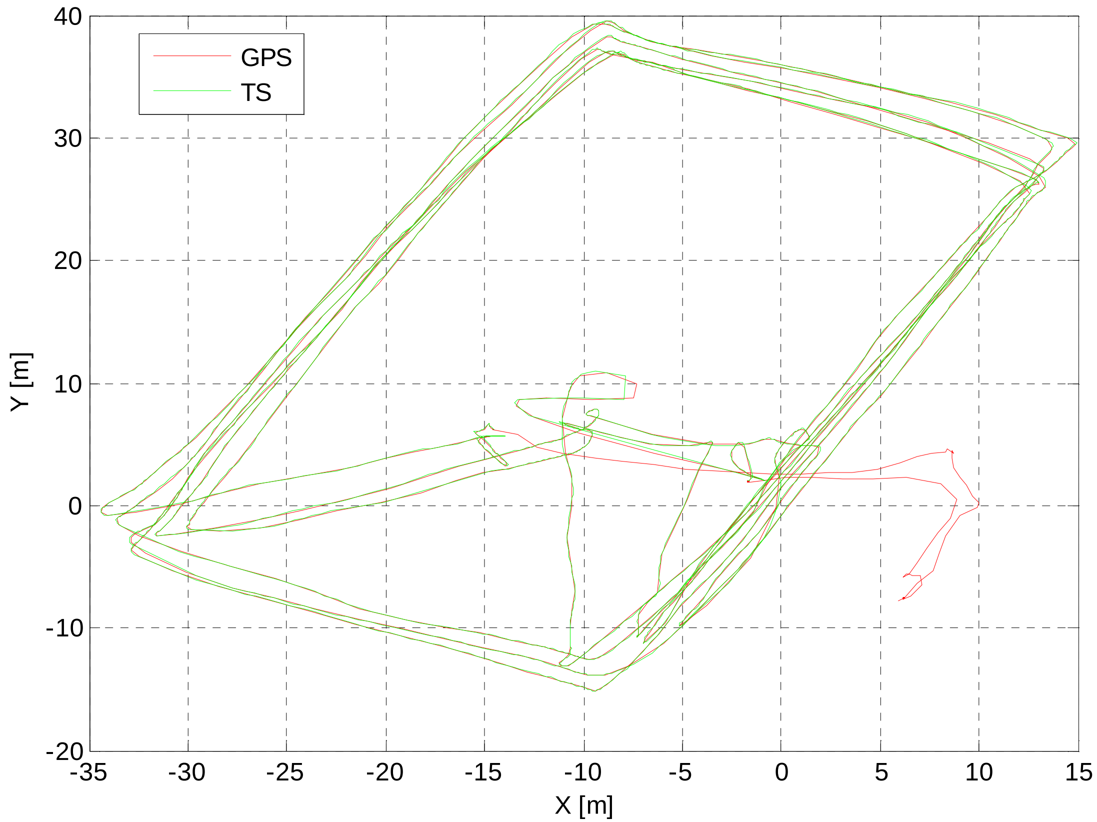
The UAV position is determined by the MTS at about 5 Hz rate

Performances of the MTS within 1 km of operative distance:

- **Angular resolution: 1 arcsec**
- **Range accuracy: 3 mm**

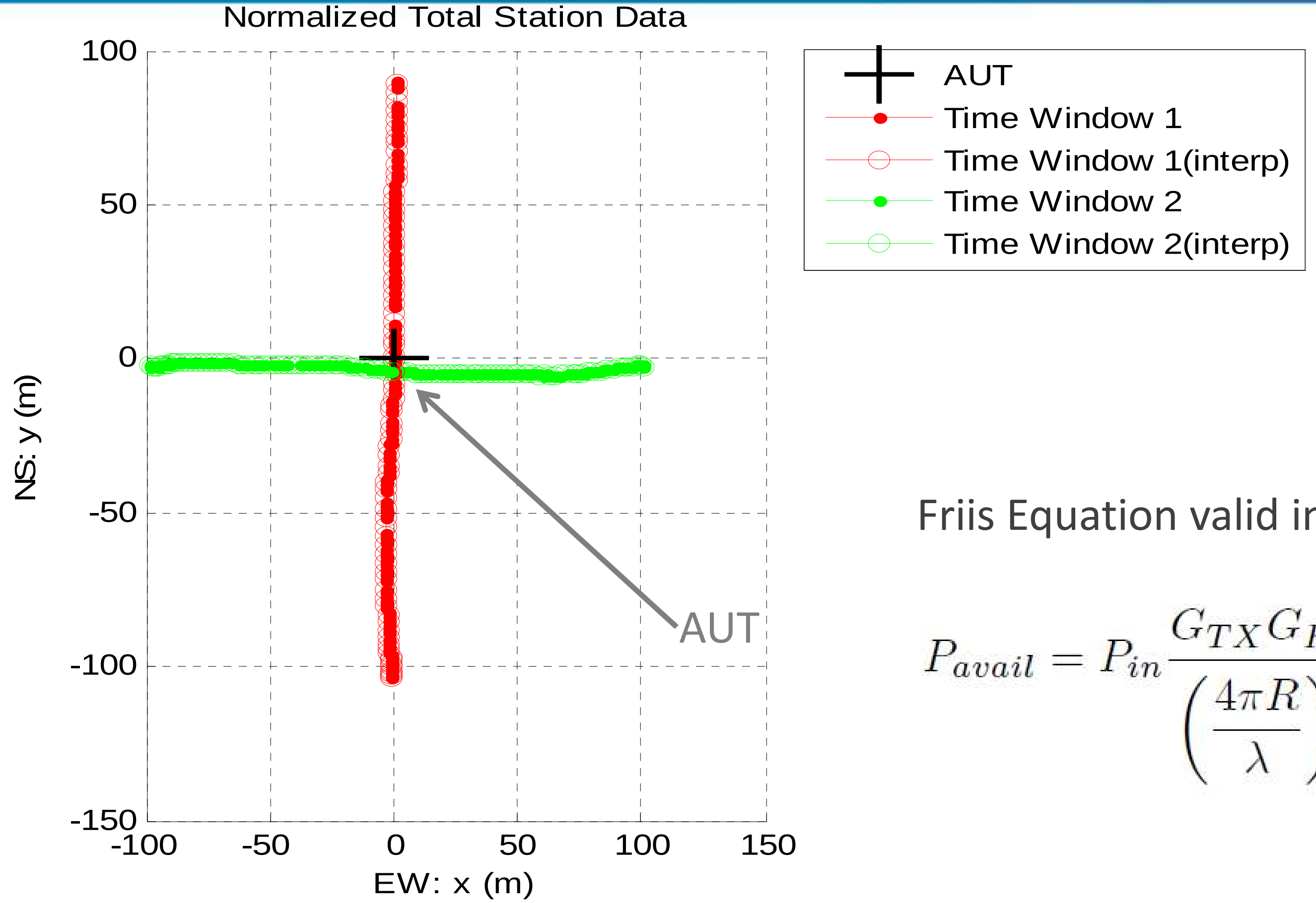
UAV position by differential GPS

Maximum error is 2-3 cm



The Total Station is no longer necessary

Flight Strategies

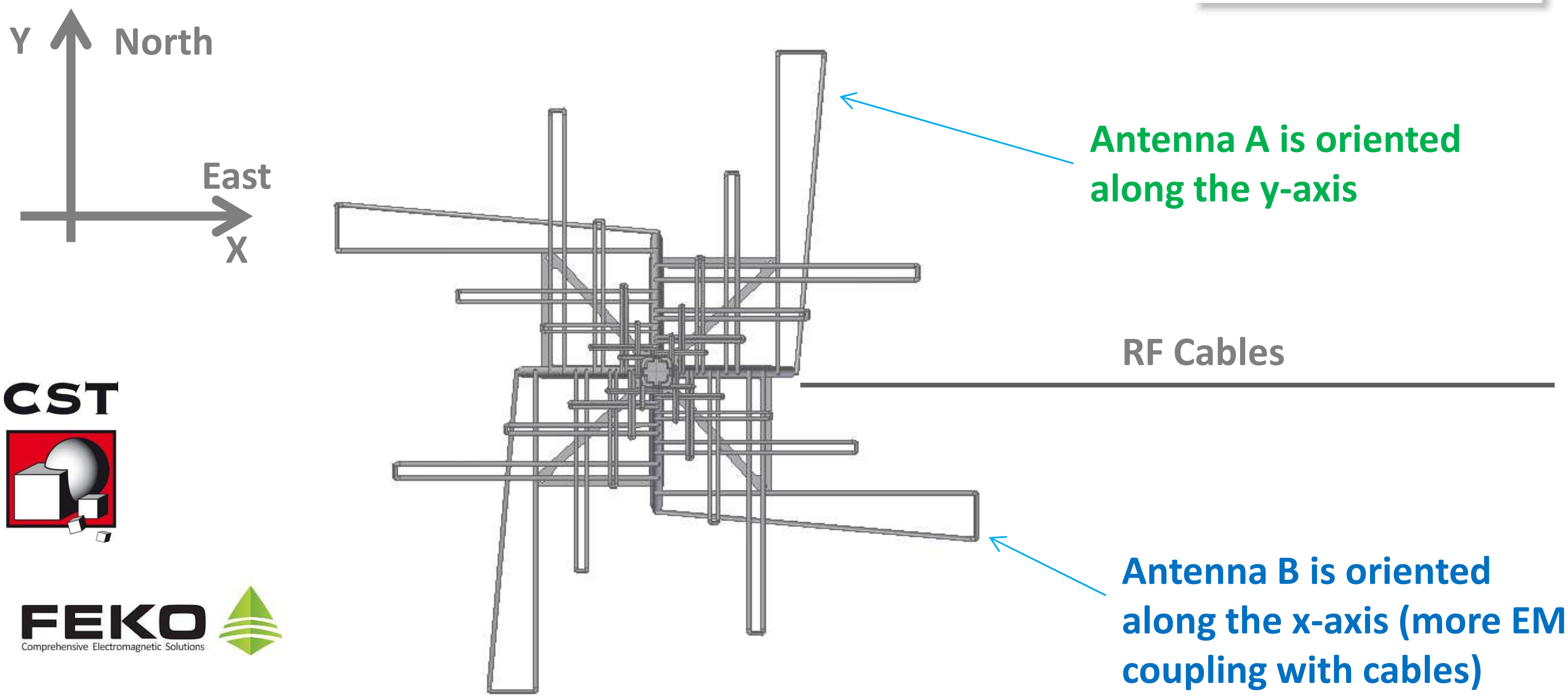


Friis Equation valid in FF conditions

$$P_{avail} = P_{in} \frac{G_{TX} G_{RX}}{\left(\frac{4\pi R}{\lambda}\right)^2} \left|\hat{\mathbf{p}}_{TX} \cdot \hat{\mathbf{p}}_{RX}\right|^2$$

Through two scans, it is possibile measuring both co- and cross-polar pattern of a dual polarized antenna in two main planes.

(Isolated) Antenna Pattern SKALA

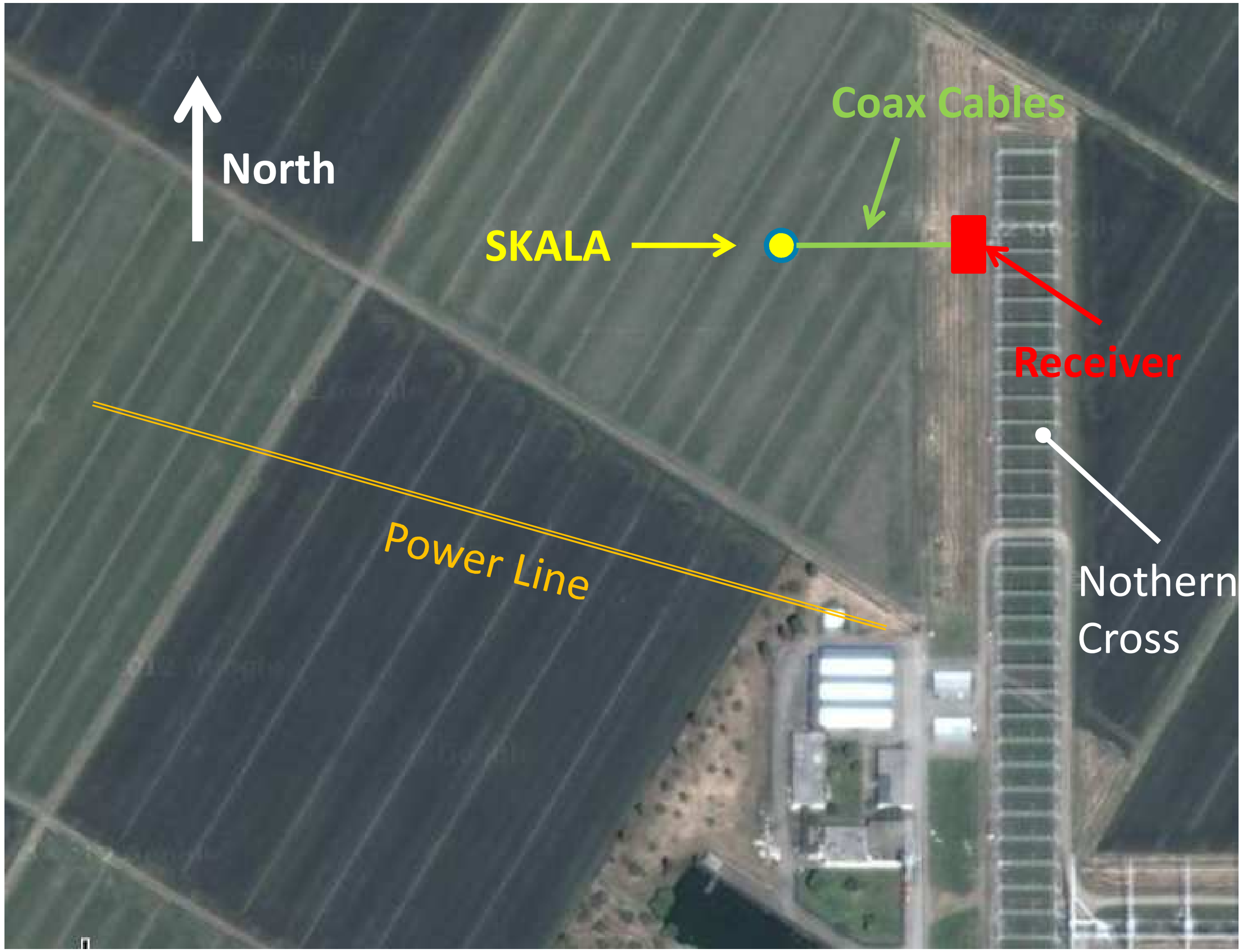


CST

FEKO
Comprehensive Electromagnetic Solutions

- Simulations on SKALA over “Soil C” carried out with CST MS and FEKO

Location and Environment



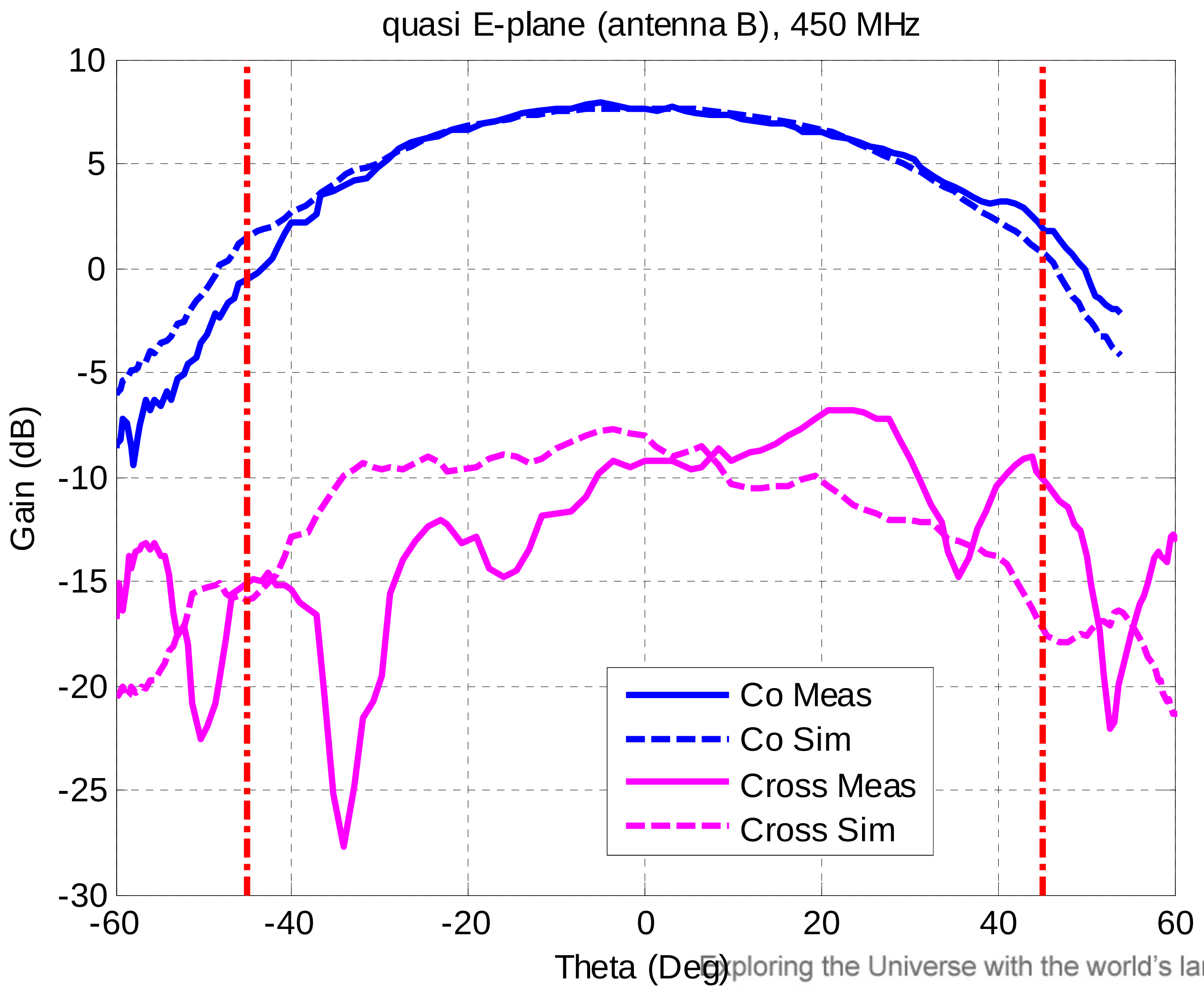
The SKALA has been measured in 4 h.
Measurements consist of:

- Co-polar and cross-polar patterns
- E-plane and H-plane
- 4 frequencies:
  70, 150, 300, 450 MHz.
- With and w/o metallic mesh

Distance from the Northern Cross and the Power Line is about 100 m

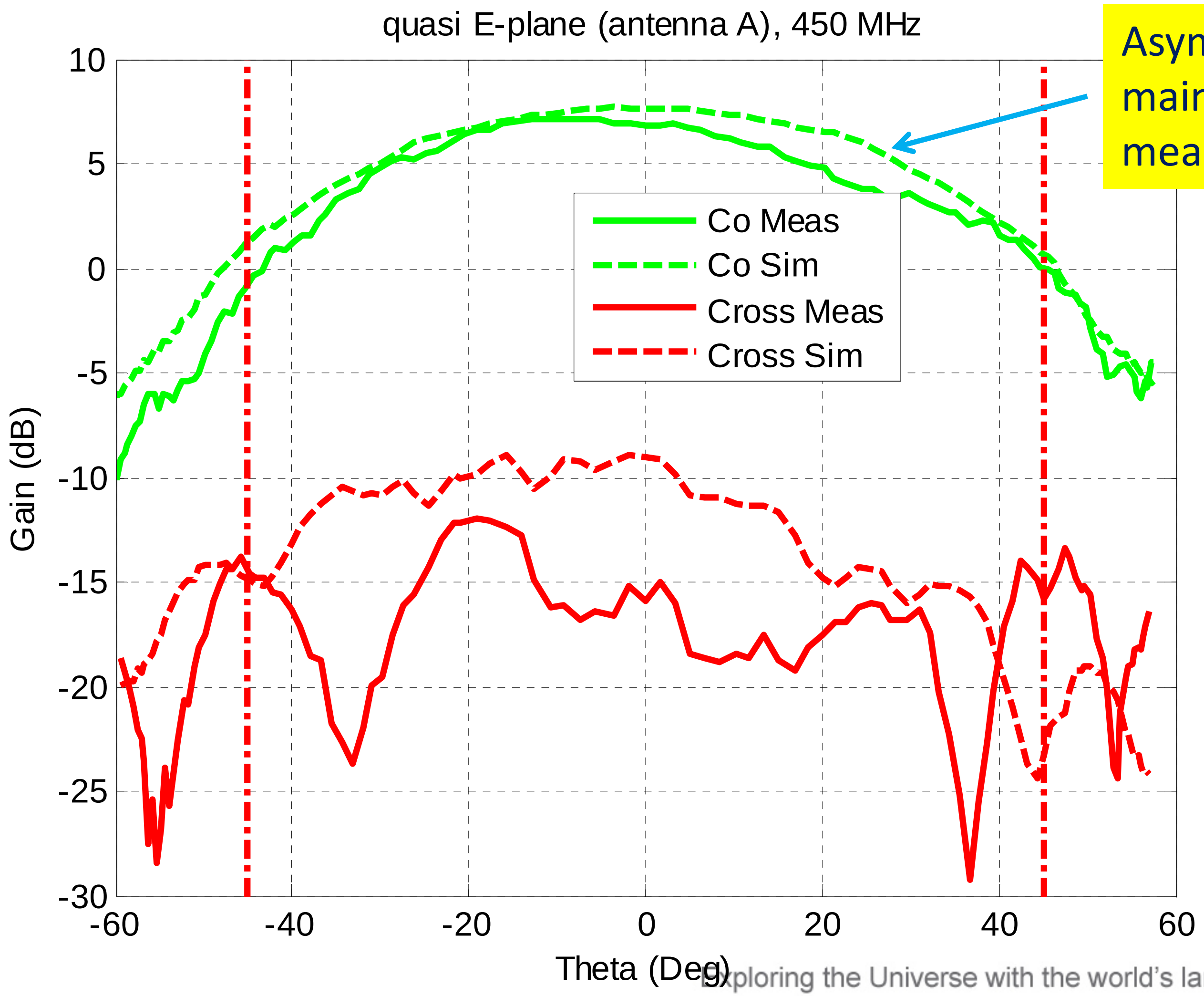
Antenna B: Quasi E-plane cut at 450 MHz

De-embedded Measurements



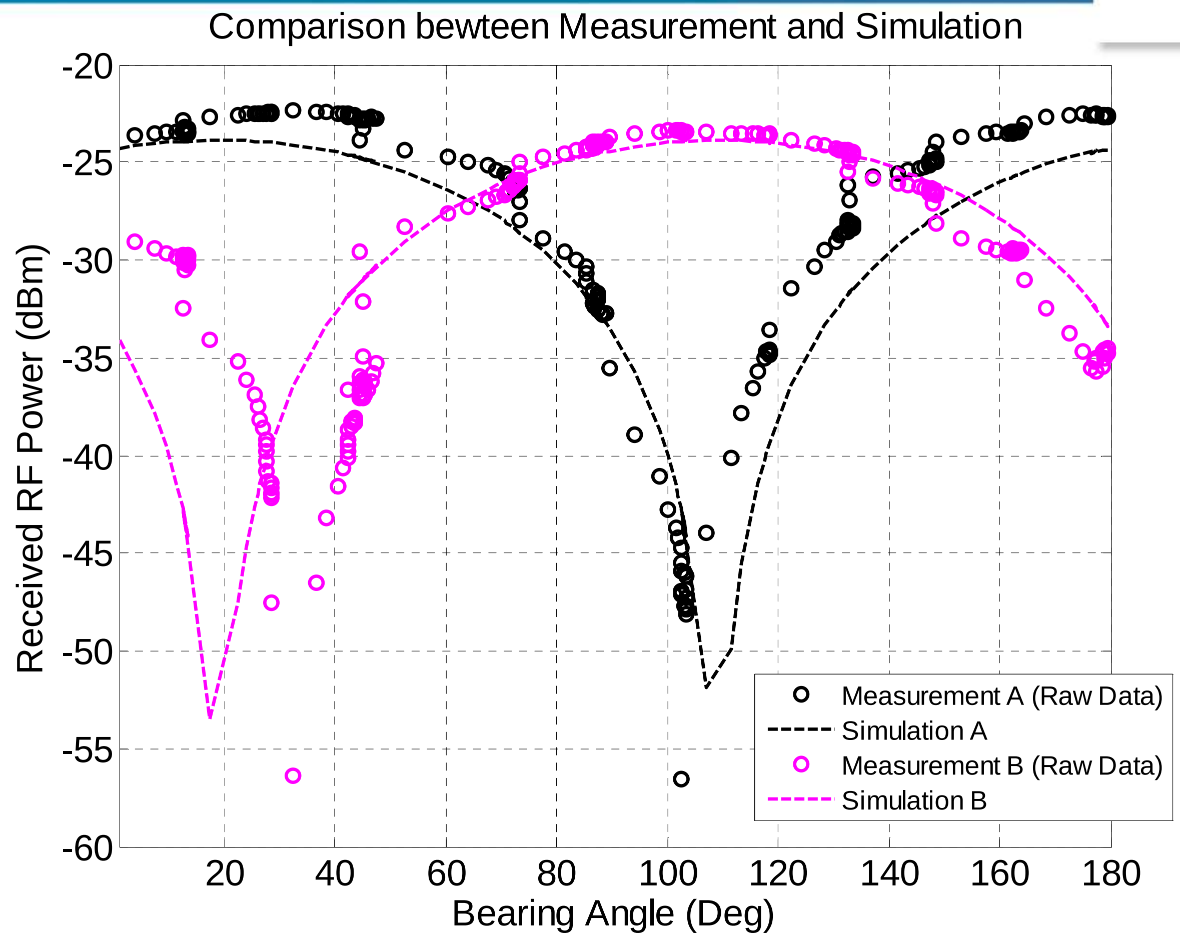
Antenna A: Quasi E-plane cut at 450 MHz

De-embedded Measurements



Asymmetries are mainly due to measurement field

Spin Flight at 70 MHz



At this frequency the two antenna polarization planes are not perfectly aligned

Embedded Element Pattern
(inside the array)

The antenna pattern can be significantly influenced by the local environment conditions (coax cables, proximity of large metallic structures and power lines, ground, …)

But inside the array the things are more complicated.

The Mutual coupling between antennas affects the antenna pattern depending also on the

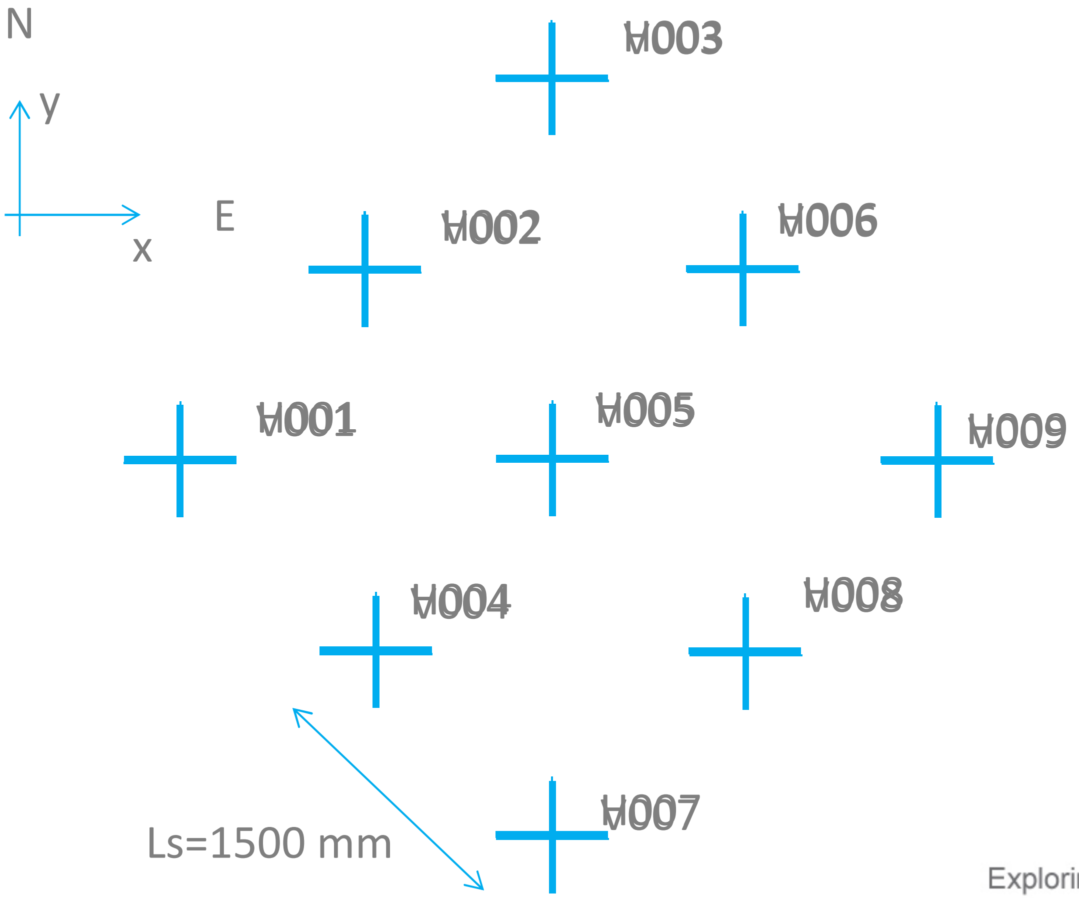
- Array configuration

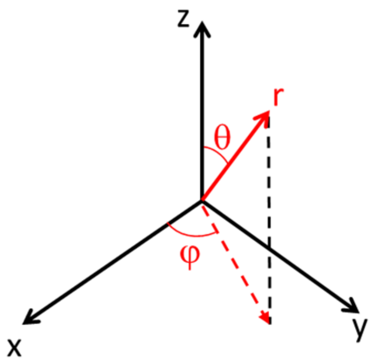
- Antenna position within the array

Medicina Array Demonstrator (MAD)

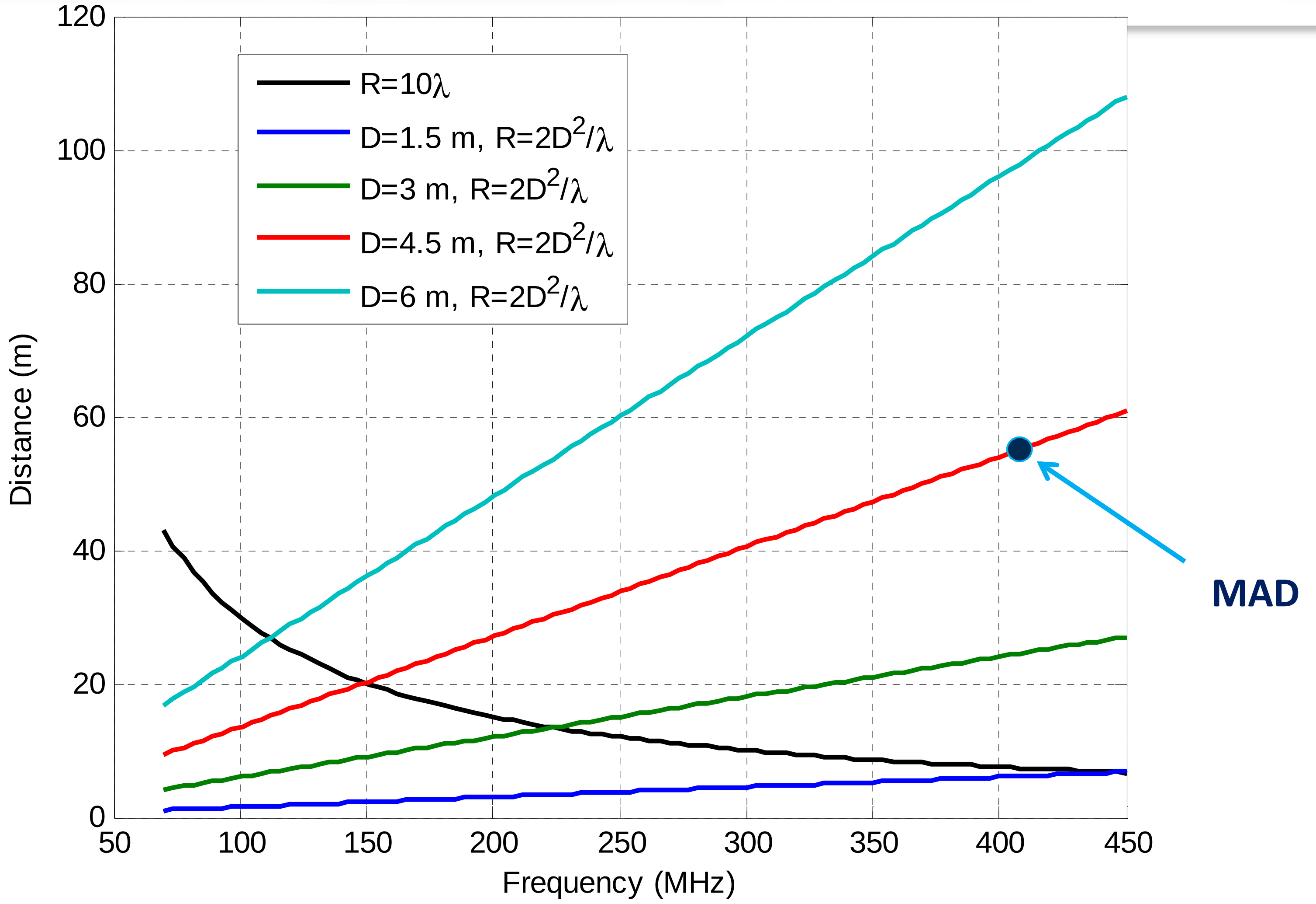
Array Configuration

MAD is a 3 x 3 regularly spaced antenna array, arranged in a rhomboidal configuration positioned at the same location of the SKALA test



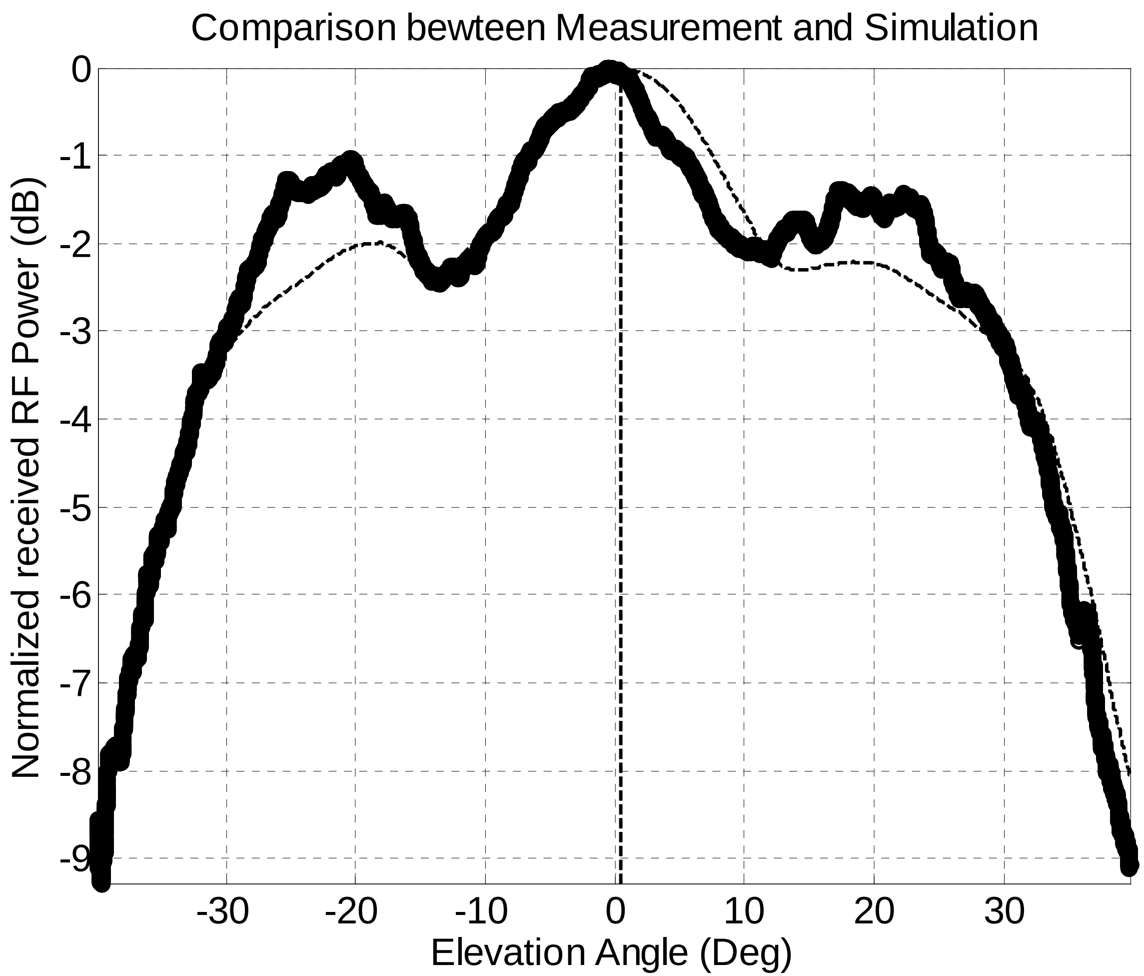


Far-field requirement in LFAA



Central Embedded Element Pattern @ 408 MHz

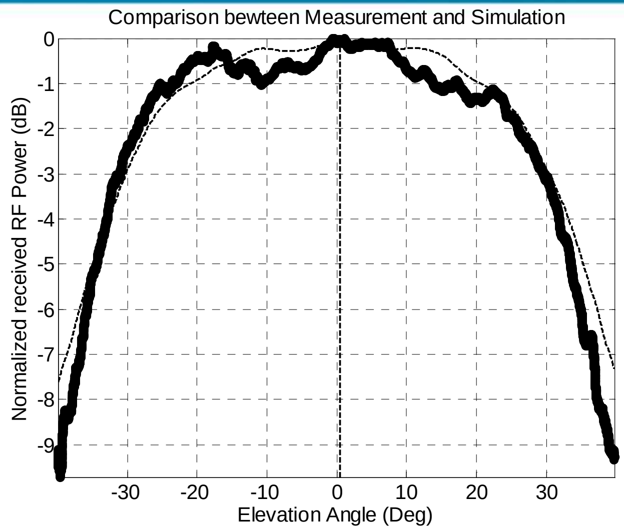
E-plane copolar



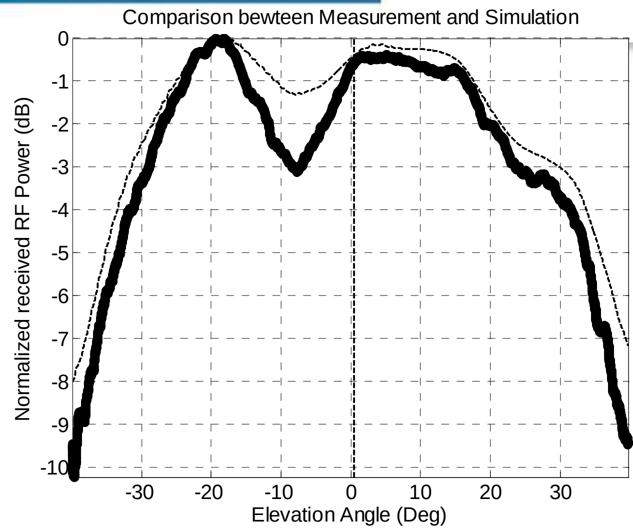
No De-Embedding has been performed

Embedded 1 - 4 Element Patterns

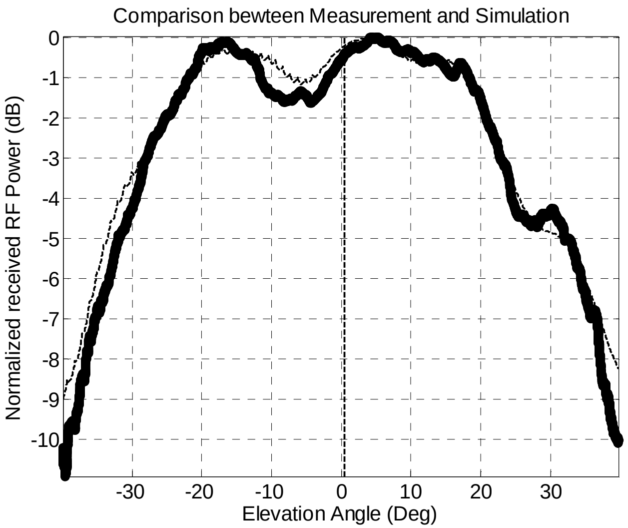
V1



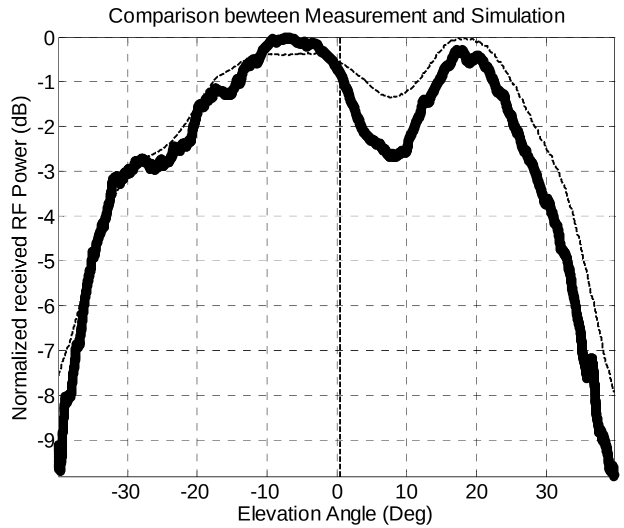
V2



V3



V4



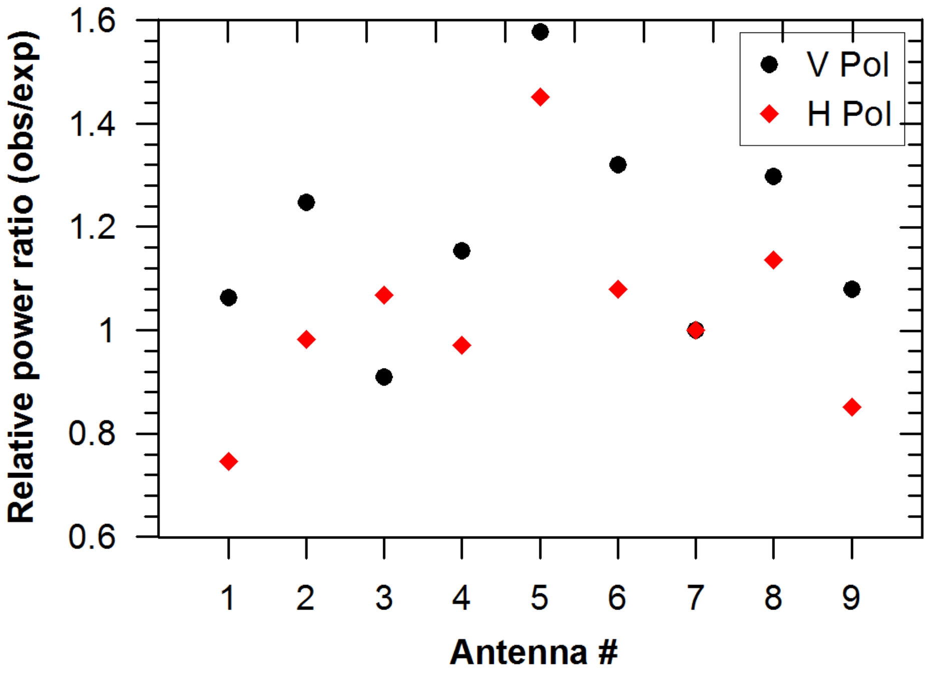
No De-Embedding has been performed

Amplitude coefficient calibration

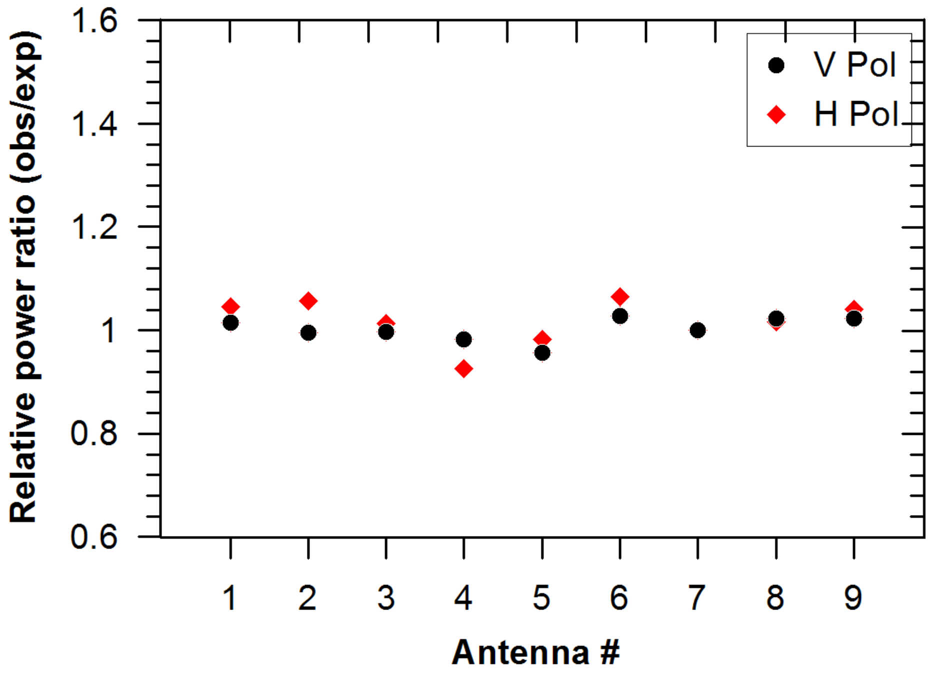
The amplitude of each complex coefficient was calculated by an algorithm based on the matching between the signal power ratios observed and simulated.

The procedure takes into account:

- antenna pattern for each array element obtained by e.m. simulations
- UAV trajectory
- Transmitting antenna pattern (from anechoic chamber measurements)



Before amplitude calibration

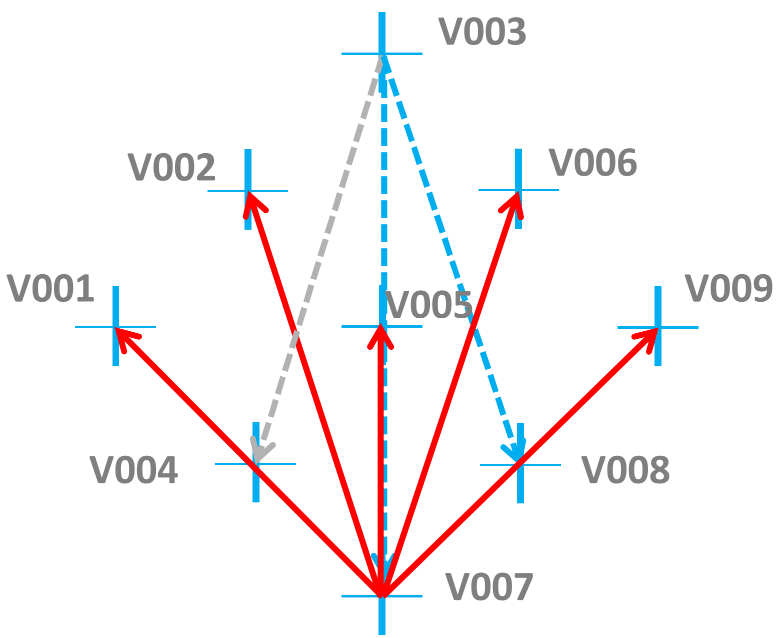


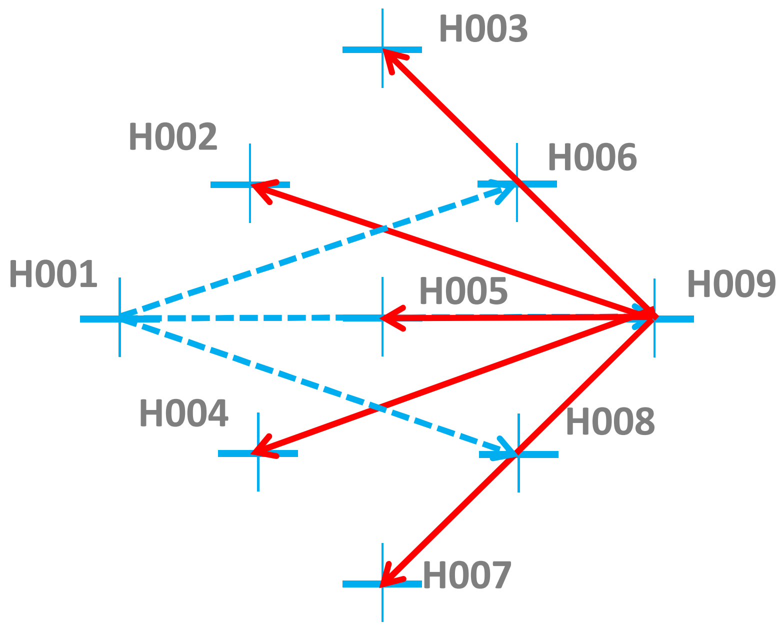
After amplitude calibration

Phase coefficient calibration

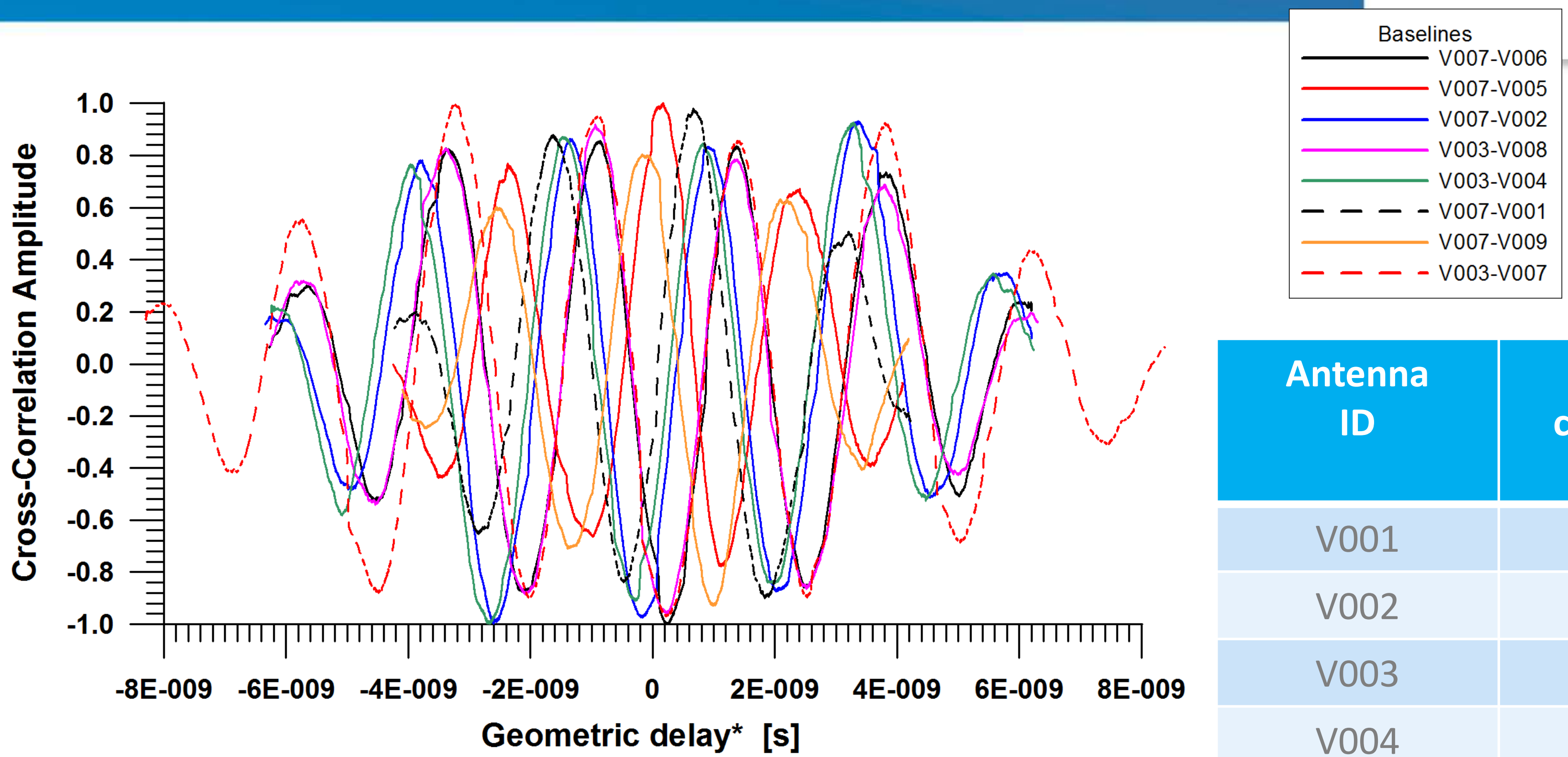
The phase coefficients were determined by means of a multiparametric fitting between simulated and observed fringe patterns.

For each polarization, fringes were obtained cross correlating the signals from an appropriate subset of (N-1) baselines, among a total number of independent baselines of N(N-1)/2, where N is the number of the array elements





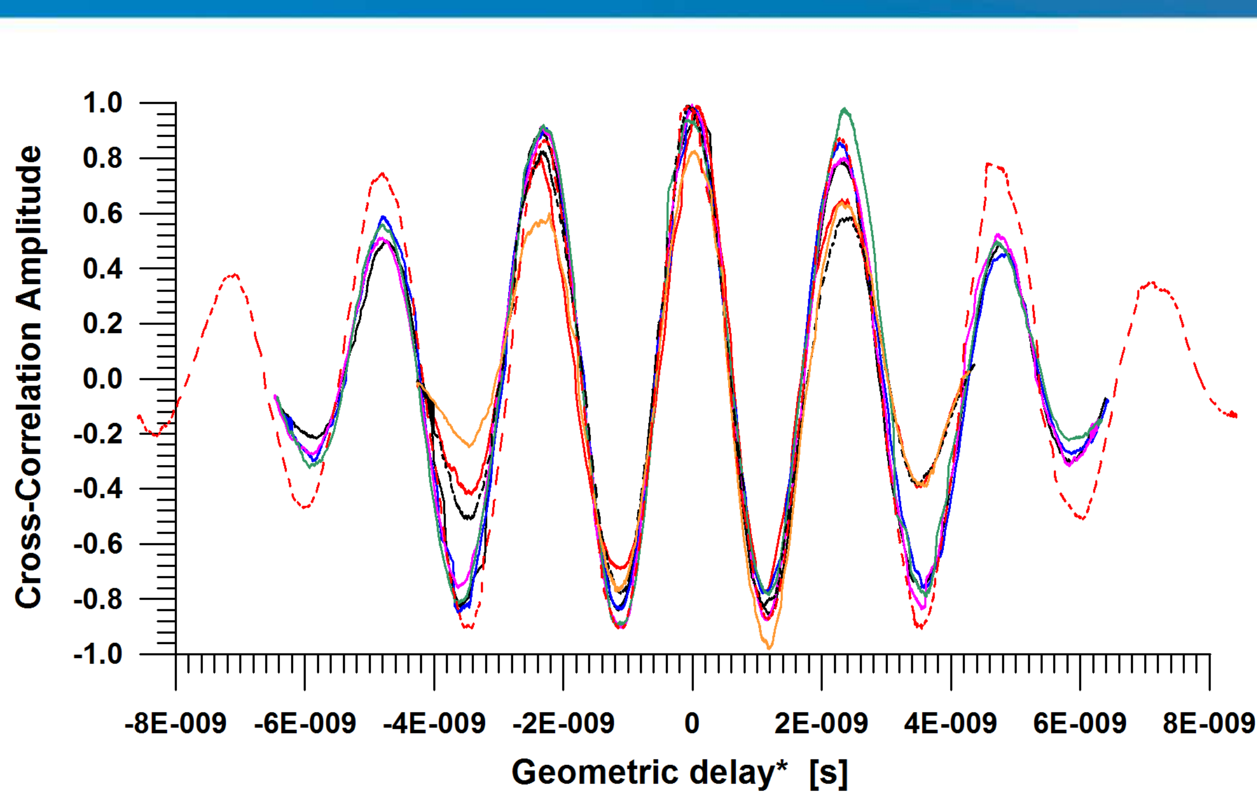
Cross correlations before the phase calibration



Antenna ID	Phase correction [deg]
V001	109.26
V002	148.68
V003	140.98
V004	270.49
V005	8.11
V006	215.07
V007	0.00
V008	353.91
V009	332.95

Phase reference antenna

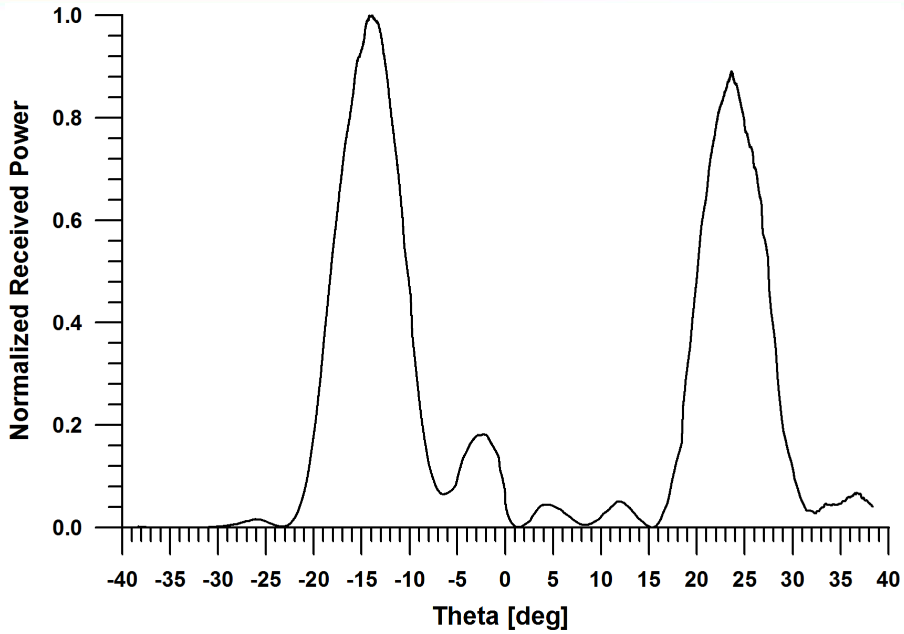
Cross correlations after the phase calibration

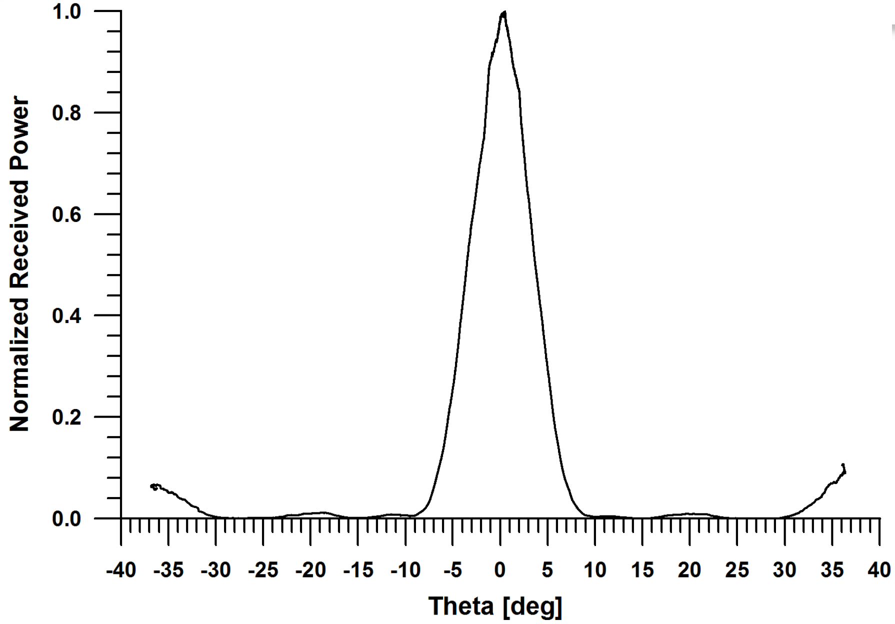


Antenna ID	Residual phase error [deg]
V001	1.85
V002	0.90
V003	0.60
V004	1.12
V005	-0.19
V006	-0.04
V007	0.00
V008	-0.69
V009	0.04

Phase reference antenna

Verification of the Array Beam before and after calibration

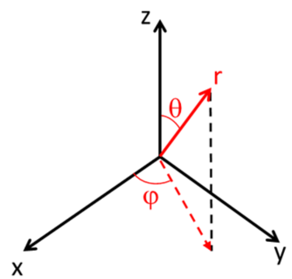




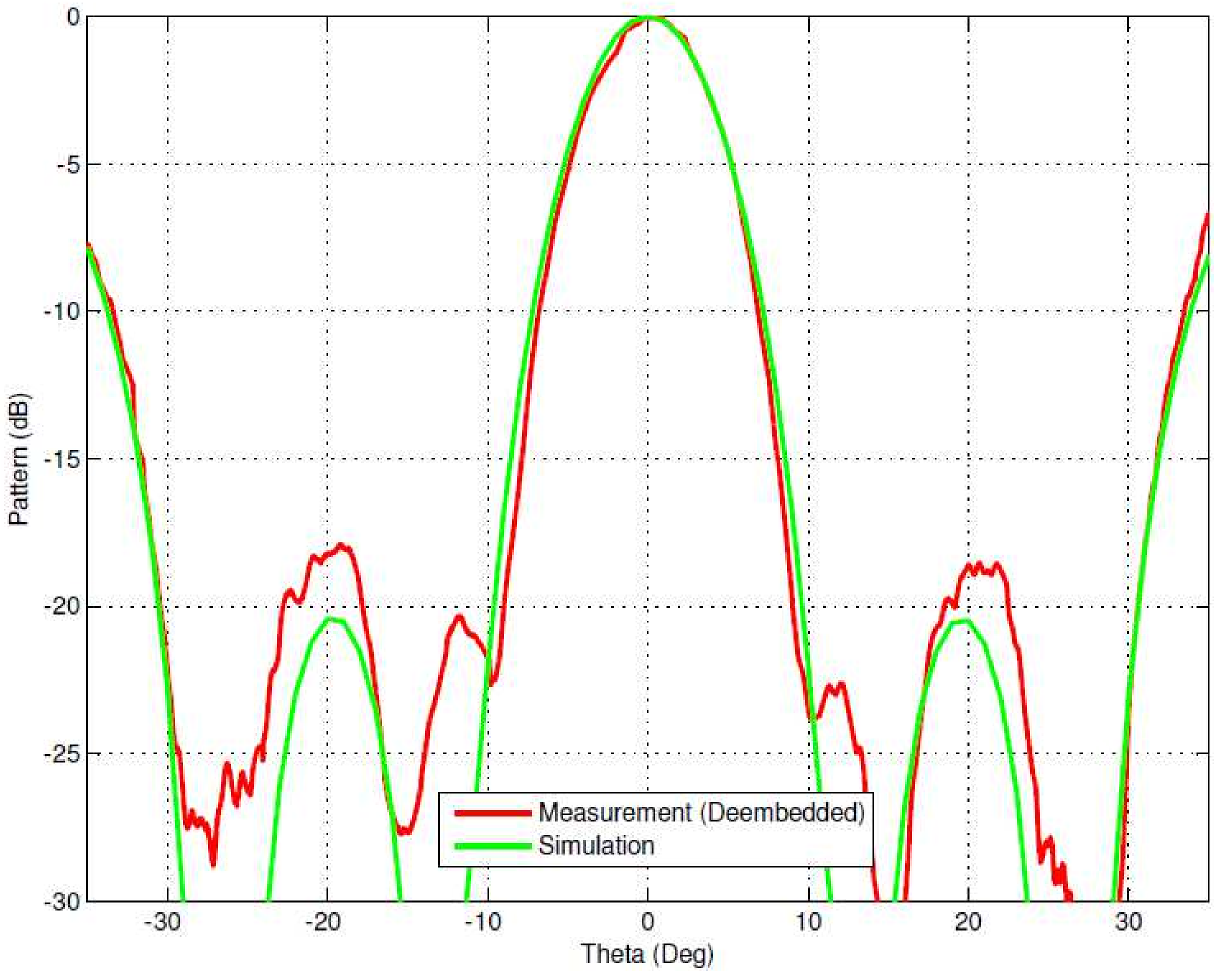
Before calibration

After calibration

- The beamformer was set to point the beam at zenith
- The measured pattern shows that, after the array calibration, the beam was correctly oriented

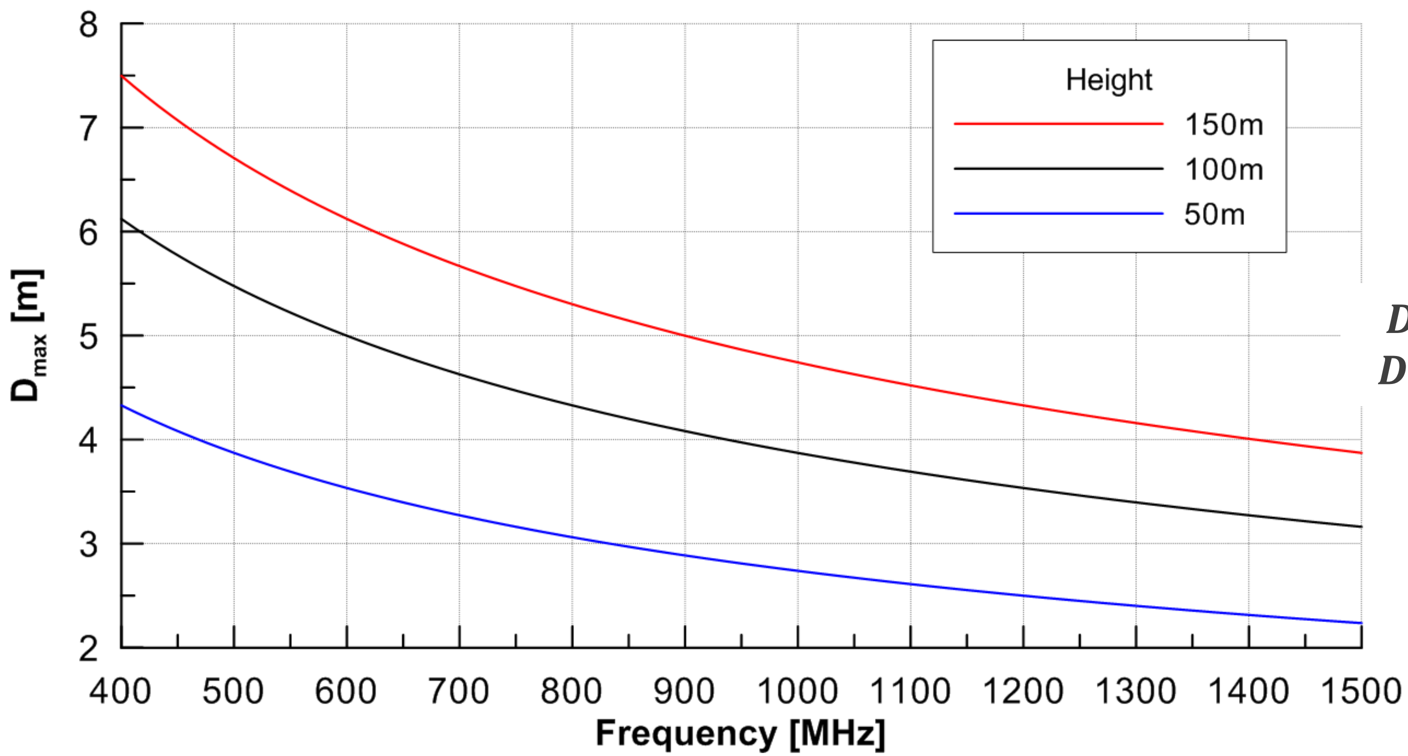


MAD Array Beam Radiation Pattern



AAMID – embedded patterns

These techniques developed in SKA-Lo could be transferred to SKA-Mid



$$D_{max}(450\ MHz) \cong 7\ m$$
$$D_{max}(1450\ MHz) \cong 4\ m$$

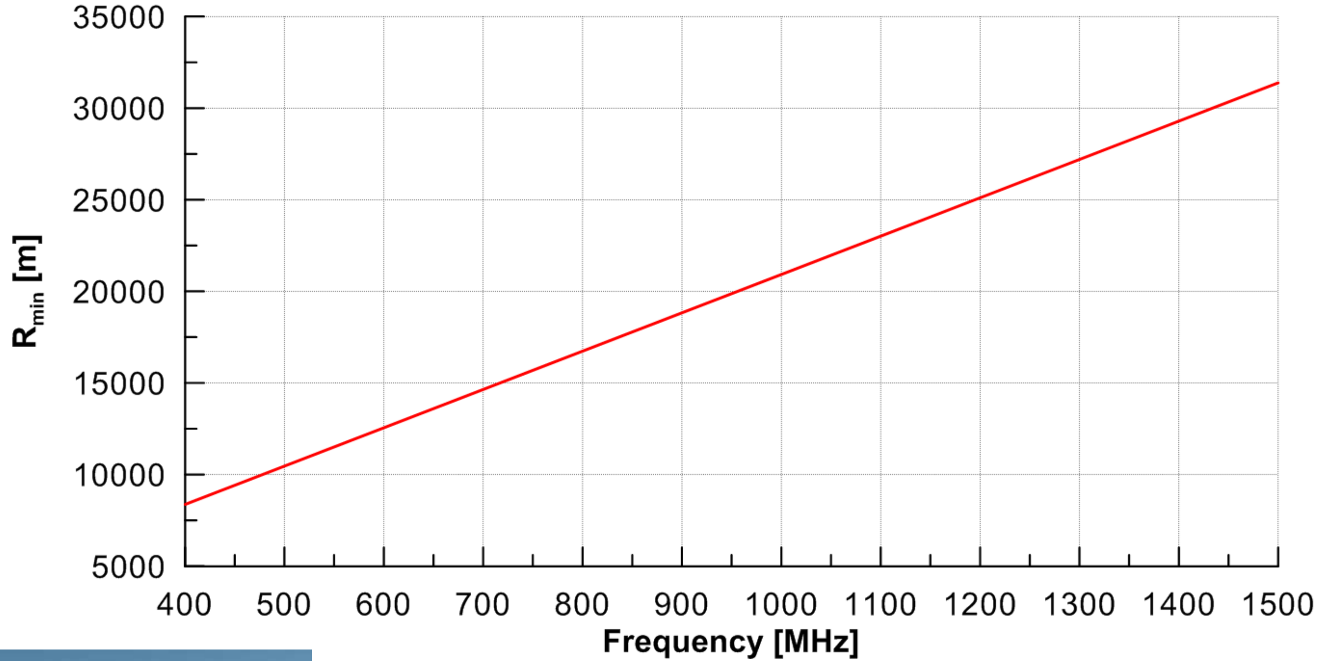
Embedded patterns for the antenna element up to a maximum sized sub-arrays (tile, tileset, …) can be measured by UAV in FF conditions

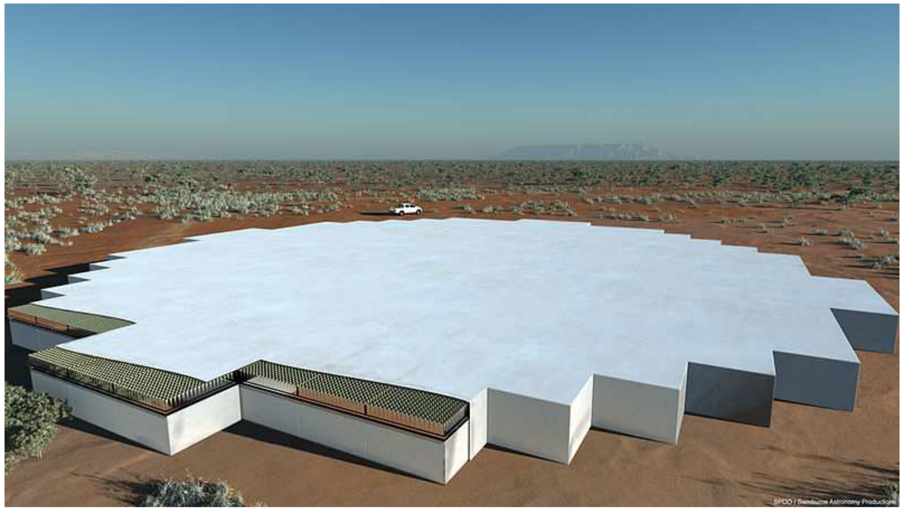
AAMID Station beam - 1

Station Diameter: 56 m

Operative Frequency:

450 MHz – 1450 MHz





Due to the too high distance necessary to operate in FF, the UAV-based AAMID Station Beam measurement is not feasible

However…

AAMID Station beam - 2

$$\boldsymbol{D_{max}(450\ MHz) \cong 7\ m}$$
$$\boldsymbol{D_{max}(1450\ MHz) \cong 4\ m}$$

The beam Station could be obtained from the sub-arrays embedded patterns and their relative phases measured in FF by UAV

$$P_{beam}(\theta,\varphi) = \left| \sum_{k=1}^{N} w_k \sqrt{P_k(\theta,\varphi)}\, e^{-i\phi_k} \right|^2$$

$P_{beam}(\theta,\varphi) = \text{station beam pattern}$

$P_k(\theta,\varphi) = \text{beam pattern of } k_{th} \text{ sub} - \text{array}$

Future works / improvements

- Implement of the differential GPS aboard UAV (ongoing)
- Third test campaign on the MAD Array (19 – 23 May)
- Repeat SKALA measurements (next 14 April)
  - in a more suitable field (without scatterers)
  - with optical fibers instead of copper cables
- Test the new improved SKALA antenna (isolated and in array)
- Verify the Inertial Measurement Unit (IMU) i.e. compass, roll, pitch
- Automate take-off and landing
- Test UAV on larger arrays LFAA (i.e. AAVS1)
- Acquire/Assemble an UAV dedicated to radio astronomy
- …

Conclusion

- It has been demonstrated that UAV system allows to operate on antennas and arrays in their real operative condition for:
  - Isolated and embedded antenna pattern measurement
  - Array topography
  - Instrumental array calibration
  - Array beam pattern measurement
- UAV-based techniques could be transferred to AAMID for what concern the measurement of antenna / tile embedded radiation patterns
- The AAMID array beam pattern (at level station) cannot be directly determined, but it can be calculated from the measured sub-array embedded patterns

Thanks for your attention

References

[1] G. Virone et al. - “Antenna Pattern Verification System Based on a Micro Unmanned Aerial Vehicle (UAV)”, IEEE, Antennas and Wireless Propagation Letters, vol. 13

[2] F. Chiabrando et al. – ”Direct Photogrammetry Using UAV: Tests and First Results” - ISPRS Archives, vol. XL

[3] G. Virone et al. – ”UAV-based Radiation Pattern Verification for a Small Low-Frequency Array” – IEEE International Symposium on Antennas and Propagation, USNC-URSI National Radio Science Meeting 2014, Jul 6-12, Memphis, USA.

Appendix

Description of the Simulation

- Full-wave Simulation of the TX antenna
- Full-wave Simulation of the AUT
- Combination of the data using the **Friis equation**

$$P_{avail} = P_{in} \frac{G_{TX} G_{RX}}{\left(\frac{4\pi R}{\lambda}\right)^2} \left| \hat{\mathbf{p}}_{TX} \cdot \hat{\mathbf{p}}_{RX} \right|^2$$

Polarization vectors

34