Development and Calibration of a Low-cost AESA Module for Weather Sensing at X-band

Update on the active front-end project WRADph2

20 March 2025

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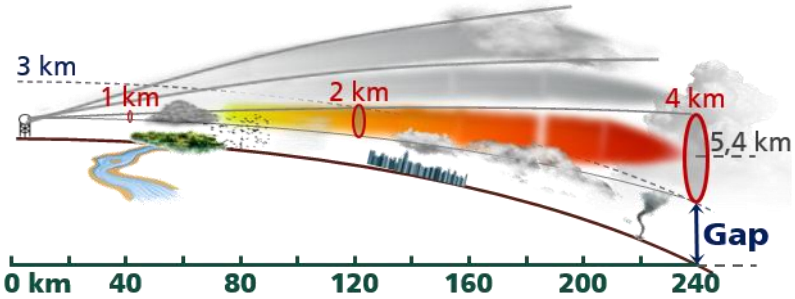
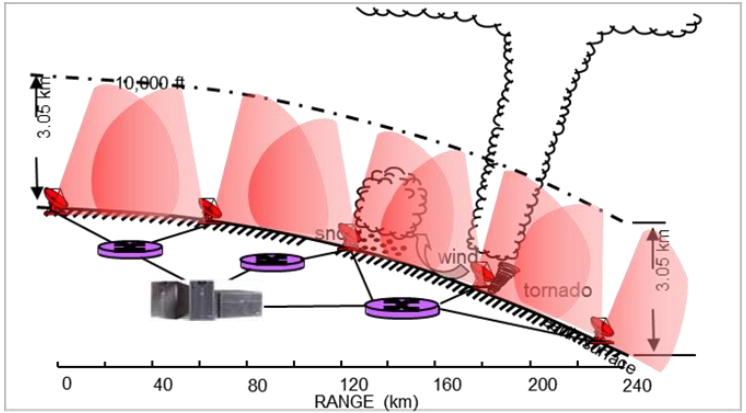
Densely networked weather radars!



- **About 70% of the troposphere below 1 km cannot be observed by radar means.** Being limited by the Earth curvature, traditional long range weather radars (up to about 200 Km range) are unable to provide coverage of the lower part of the atmosphere

- **A networked approach** generates high resolution composite maps of short-range units with a typical refresh rate of one minute and **improves monitoring of the lower troposphere.**



"There is insufficient knowledge about what is actually happening (or is likely to happen) at the Earth's surface where people live", U.S. National Academy of Sciences,1998.

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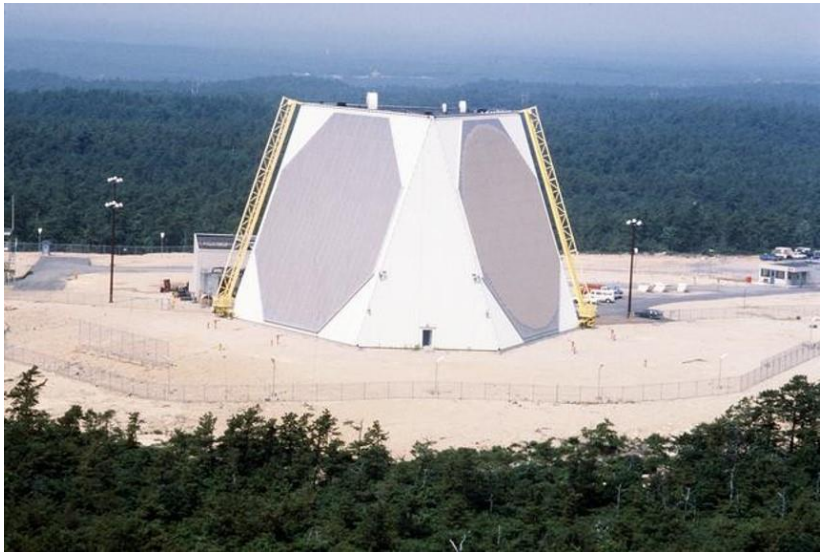
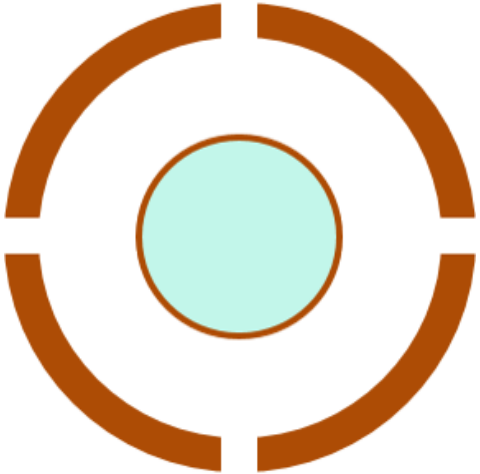
Agile beam repositioning to decrease volumetric sounding time

AESA radar for military applications



Air Force Space Command radar system PAVE Phased Array Warning System (PAWS)
1792 active elements @ 325 W, 583 KW peak power

AESA radar for civilian applications



Concept low-cost
AESA micro-radar

- 1 KW radiated power
- 0.5 m^2 array panel area
- 4 panels

AESA radar for civilian applications

Concept low-cost
AESA micro-radar

- ¼ KW radiated power
- 0.5 m^2 array panel area
- 1 panels

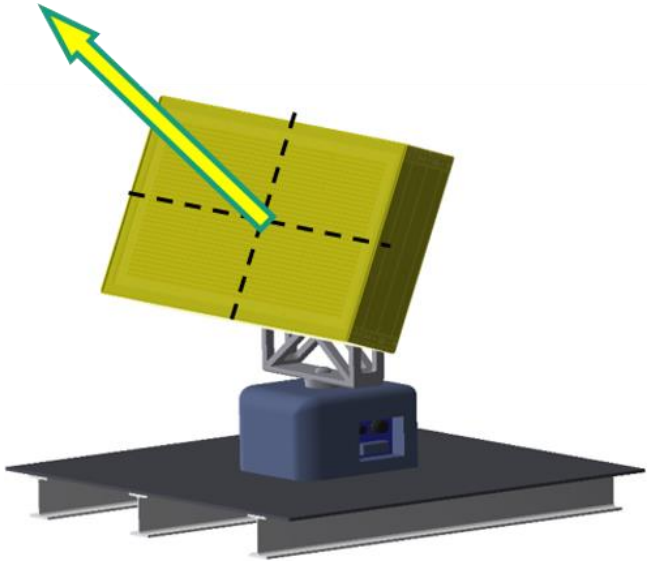
Micro-radar concept
Mechanical assembly

Rotor

- Horizontal working position
- 250 kgm^2 moment of inertia (max)
- 5.5 rpm (max)
- Ø 410 mm, tabletop
- Absolute encoder
- Integrated slip-ring
- Up to 200 kg load
- Remotely controllable
- Abound 15 K$ unitary cost

Rotor

Antenna concept
Mechanical assembly



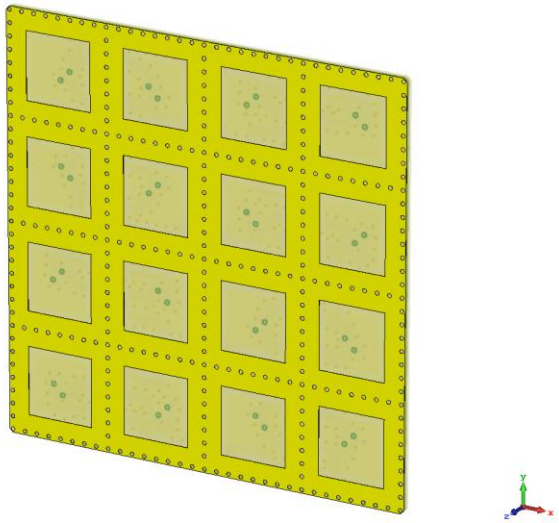
Concept rendering mock-up, front

- **Flat aperture**
  - 0.5 meter^2 array panel (1 m x 0.5 m)
  - electronically steered in elevation
  - antenna aperture turned by a rotor for mechanical azimuth scanning
  - mechanically adjustable elevation tilts
  - receiver over-elevation
  - distributed power generation

Flat aperture

Antenna concept

Sub-array

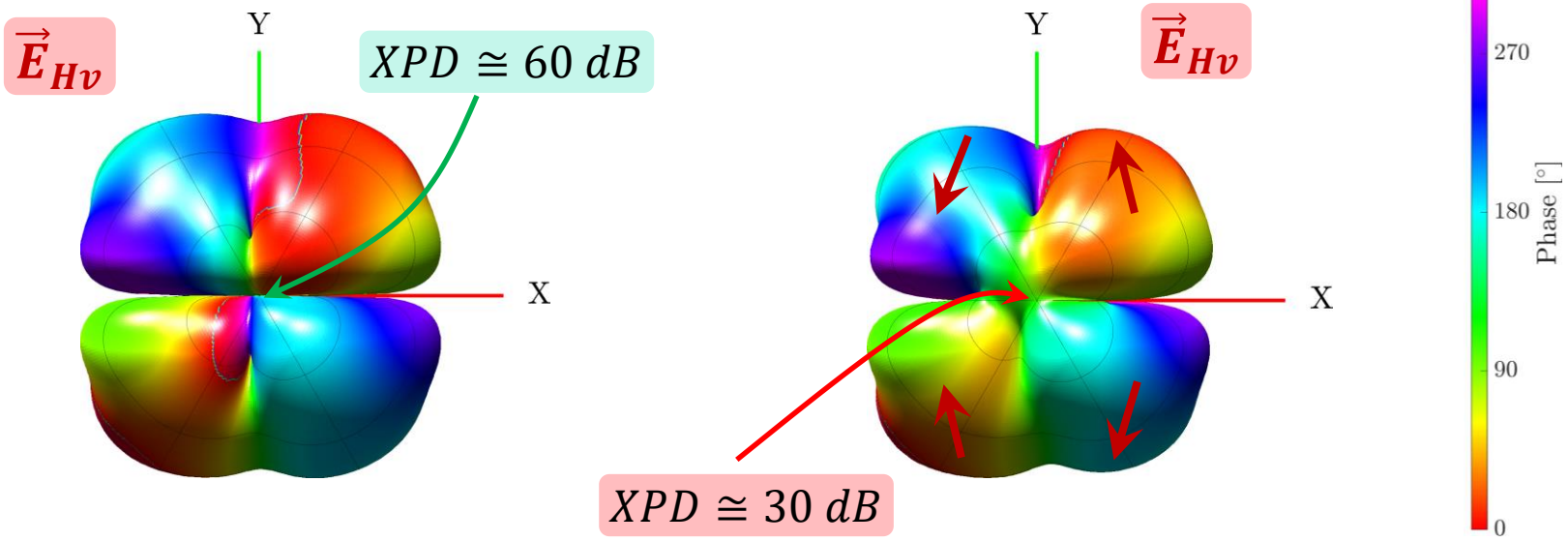


Subarray, 4x4, front

- Modular antenna design
  - built on aggregation of subarrays
  - based on printed antenna elements
  - flat-panel, compact design
  - cost-effective, simplified manufacturing
  - low-weight

Front-end, subarray

Low-cost printed antennas exhibit XPD degradation

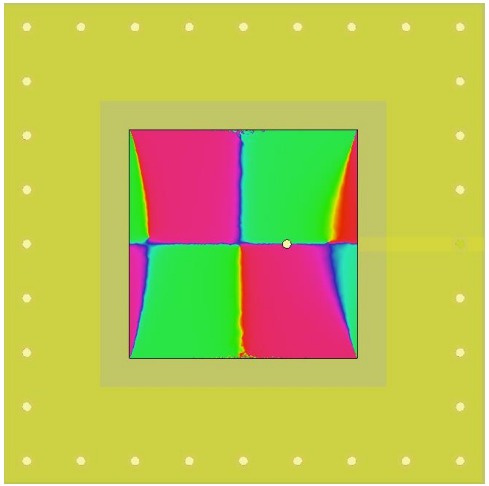


Mono-pol Patch Antenna

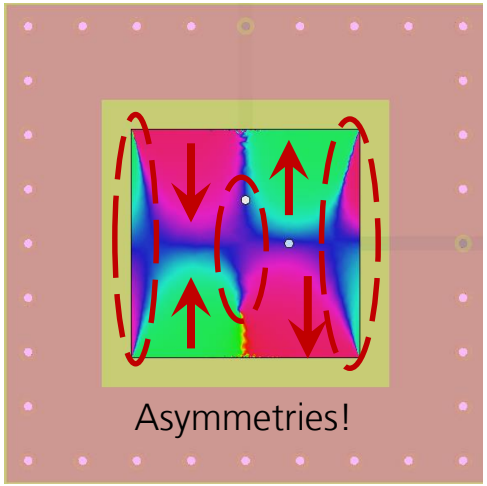
Dual-pol Patch Antenna

Front-end, subarray

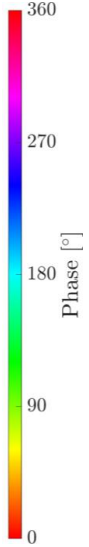
Surface current phase asymmetries found as main cause



Mono-pol Patch Antenna

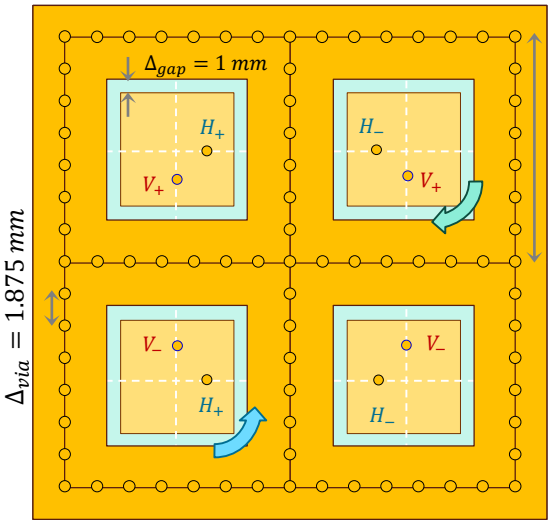


Dual-pol Patch Antenna



Front-end, subarray

In-depth investigation leads to a cost-effective solution

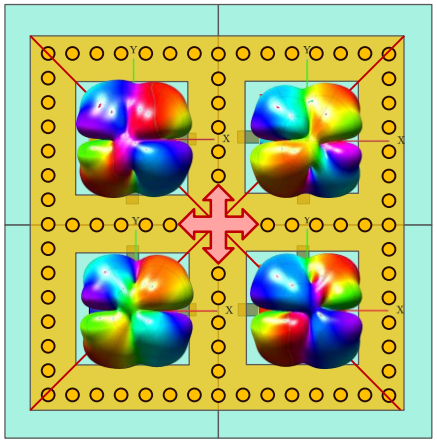


2x2 subarray with rotated probe feeding and frontal ground

- Feed rotation [1] (XPD ↑)
  - Physics-based cancellation of cross-polarization terms in the main planes
  - Increased feed-net complexity
- Frontal ground (XPI ↑)
  - Reduced mutual coupling
  - No major effect on radiation performance (matching, cross-polarization,…)

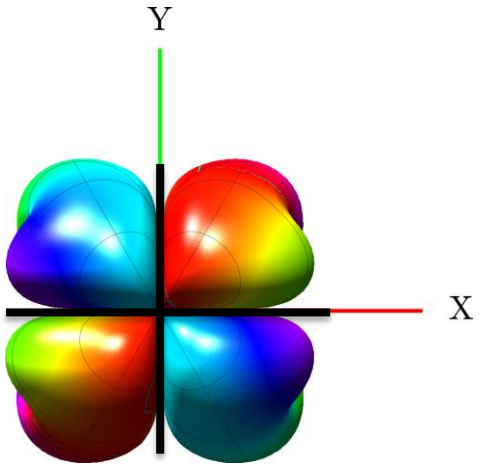
Front-end, subarray

Excellent theoretical cross-polarization suppression

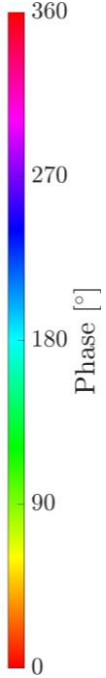


Odd symmetry
($\Delta\varphi \approx 180°$)

Theoretical
field combination
(without coupling)



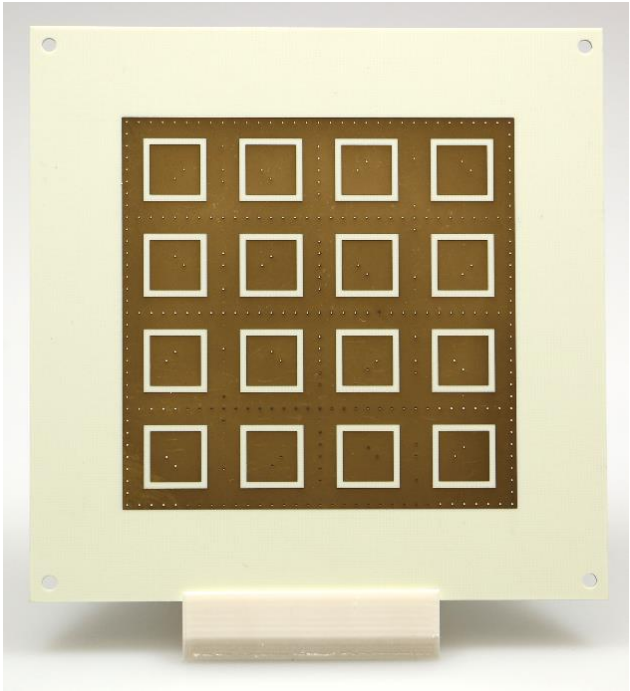
$XPD \cong 60\ dB$



Front-end

Sub-array

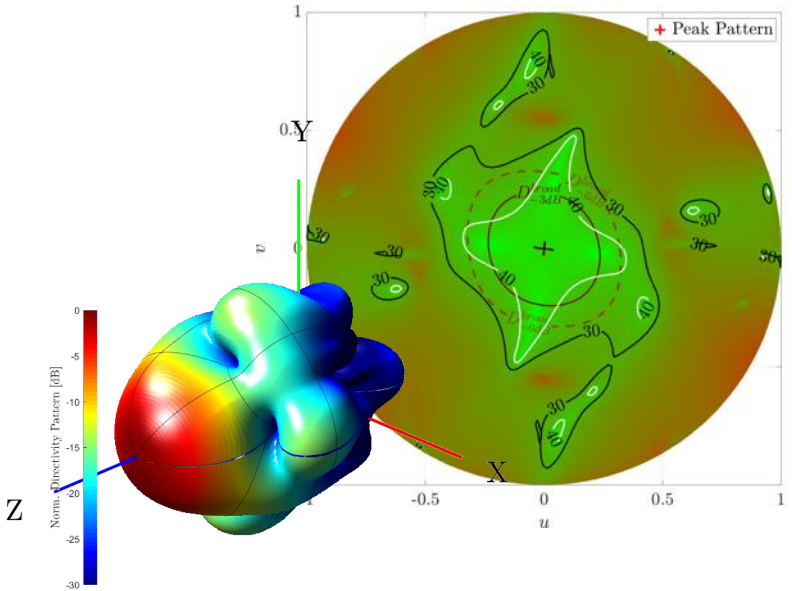
- Probe feed rotation and optimized feeding network design for improved cross-polarization
- Manufacturing of a 4x4 planar sub-array for validation
- Simulation and measurements in anechoic chamber for comparison



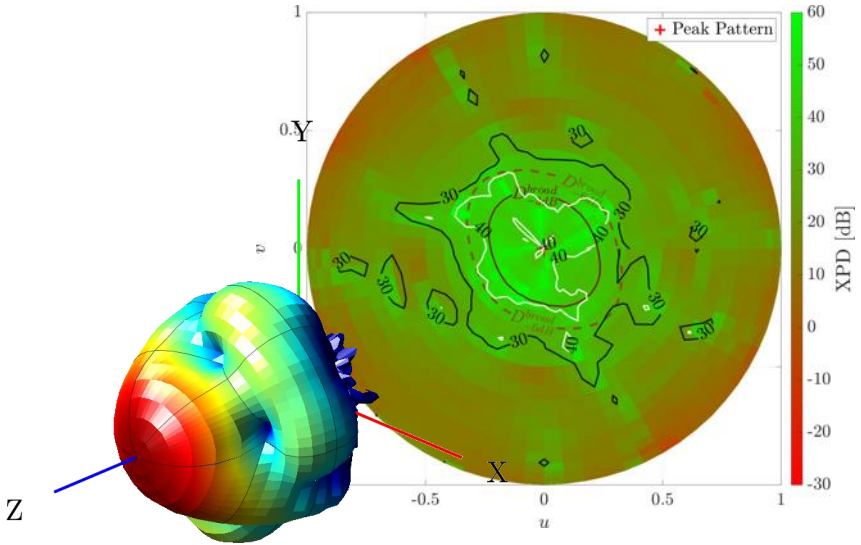
prototype

Front-end

Sub-array, pattern and XPD, broadside



simulation

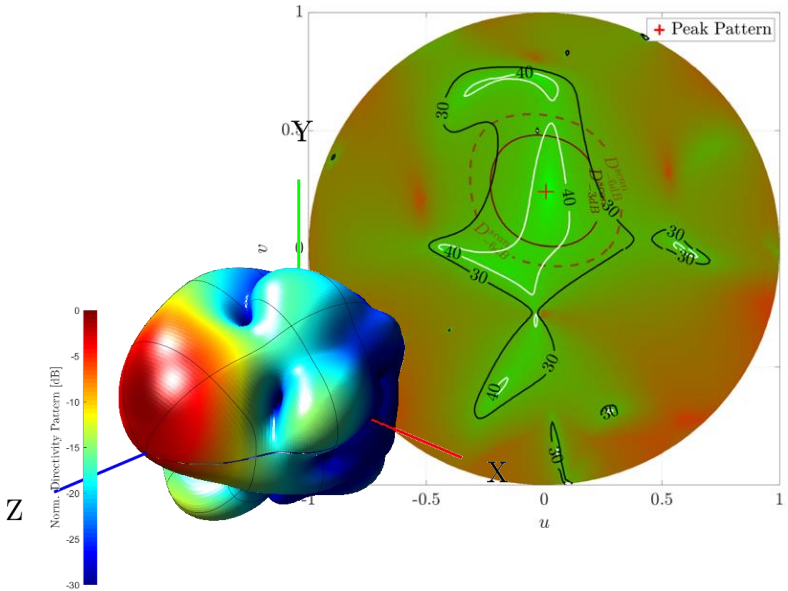


measurements, 5° resolution,
>40 dB XPD

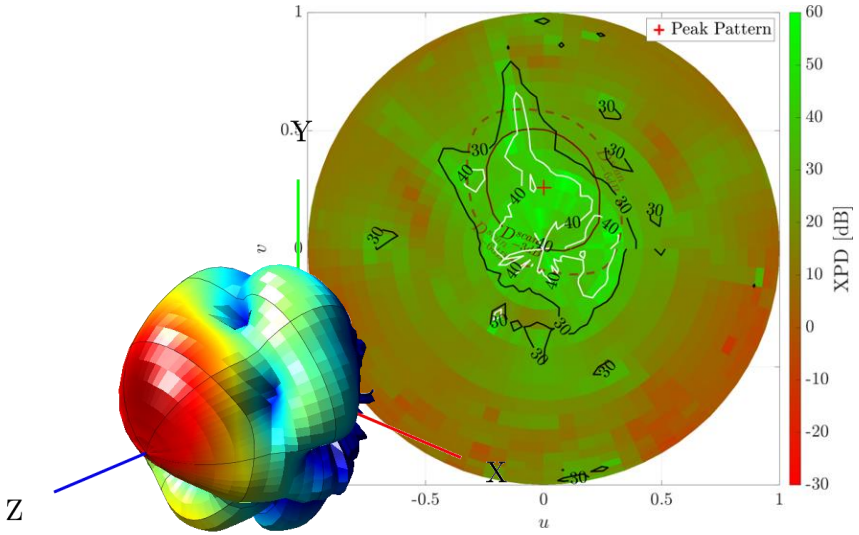
Fraunhofer FHR

Front-end

Sub-array, pattern and XPD, 15° scan



simulation

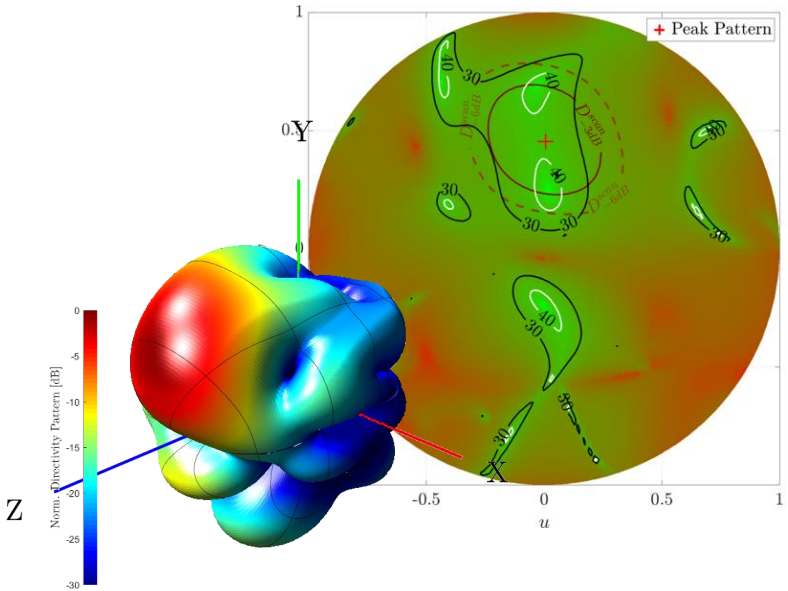


measurements, 5° resolution,
>40 dB XPD

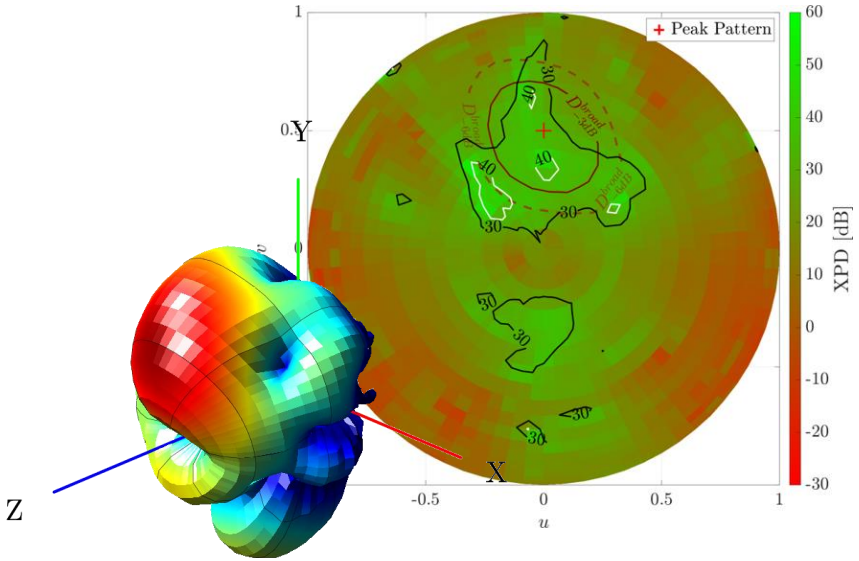
Fraunhofer FHR

Front-end

Sub-array, pattern and XPD, 30° scan



simulation

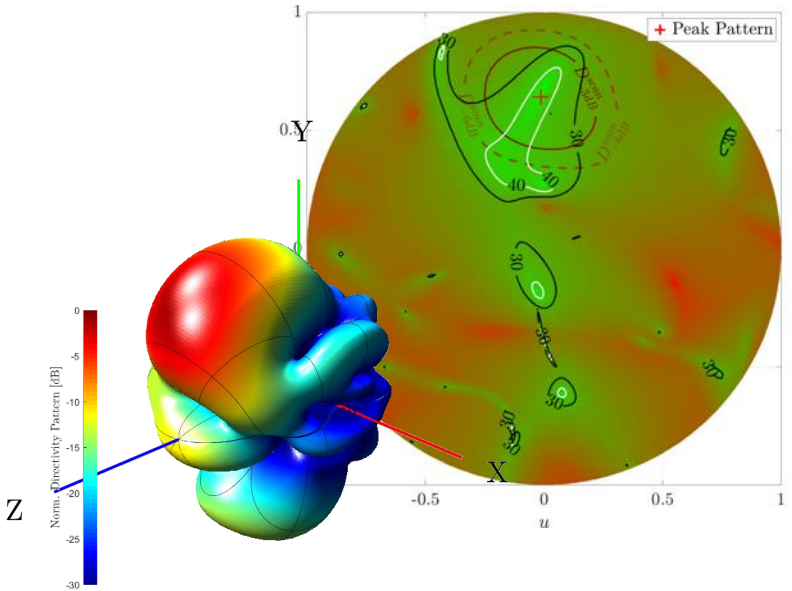


measurements, 5° resolution,
>40 dB XPD

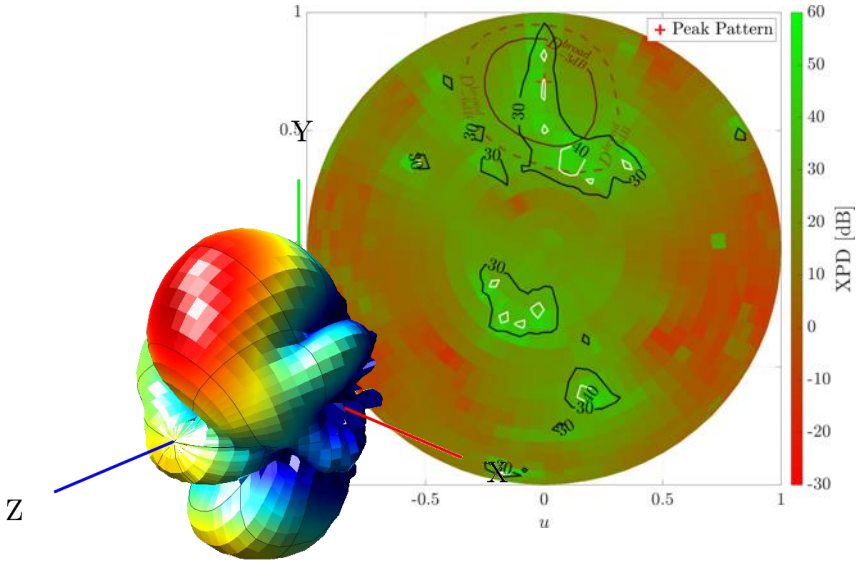
Fraunhofer FHR

Front-end

Sub-array, pattern and XPD, 45° scan



simulation

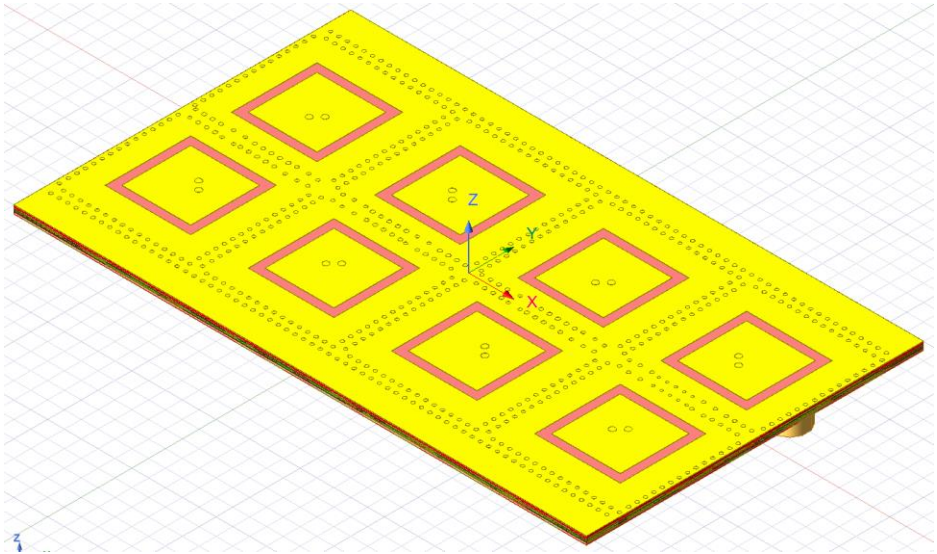


measurements, 5° resolution,
>30 dB XPD

Fraunhofer FHR

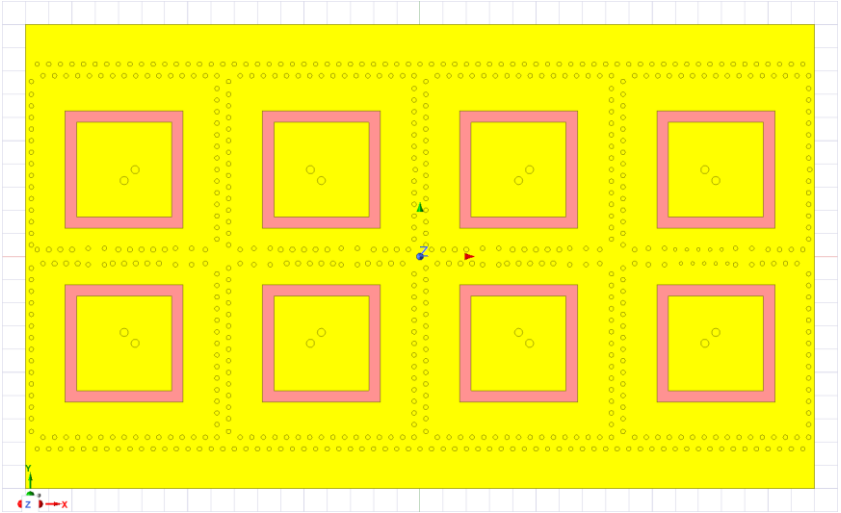
Front-end

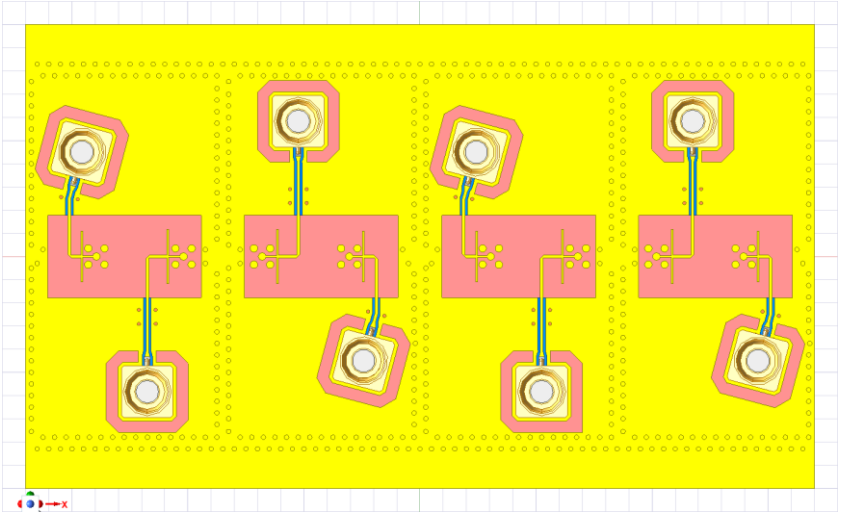
Sub-array 4x2



Front-end

Sub-array 4x2



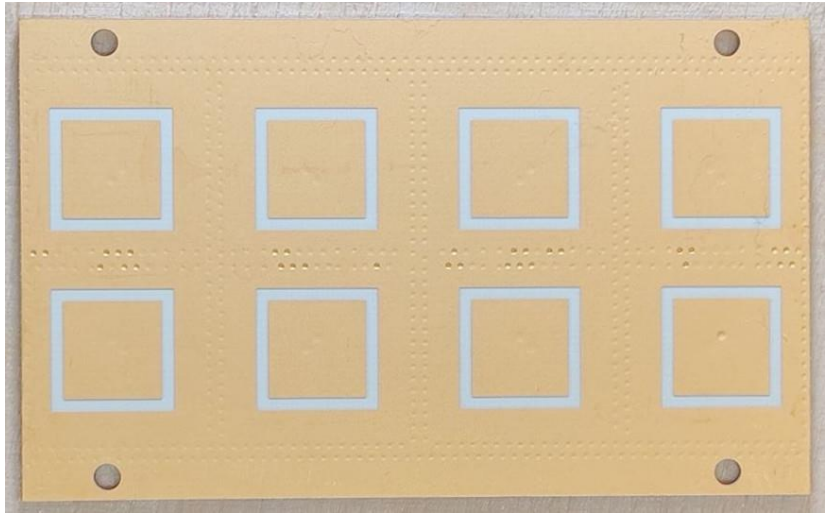


Fully-passive variant

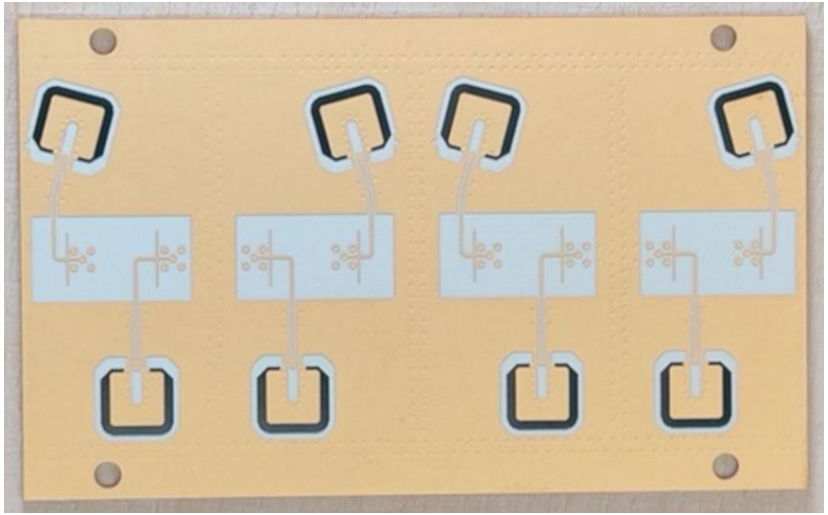
Design and simulation by Carlos G. Salzburg

Front-end

Sub-array 4x2



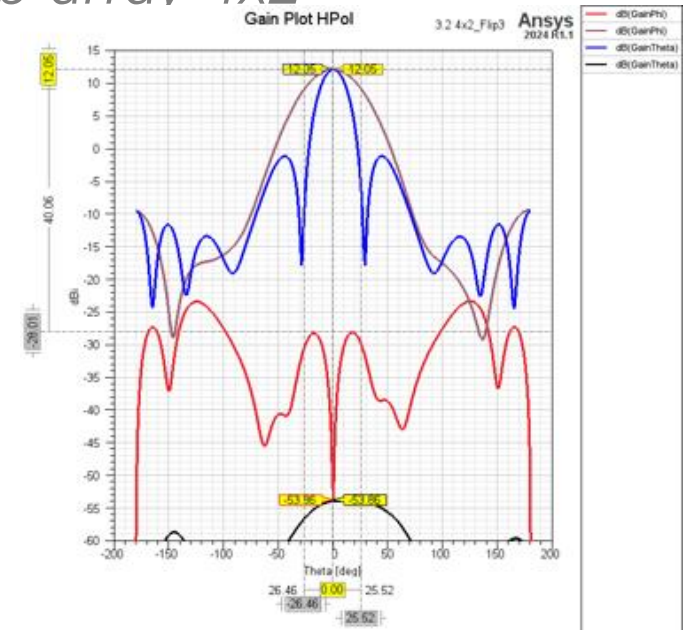
Fully-passive variant



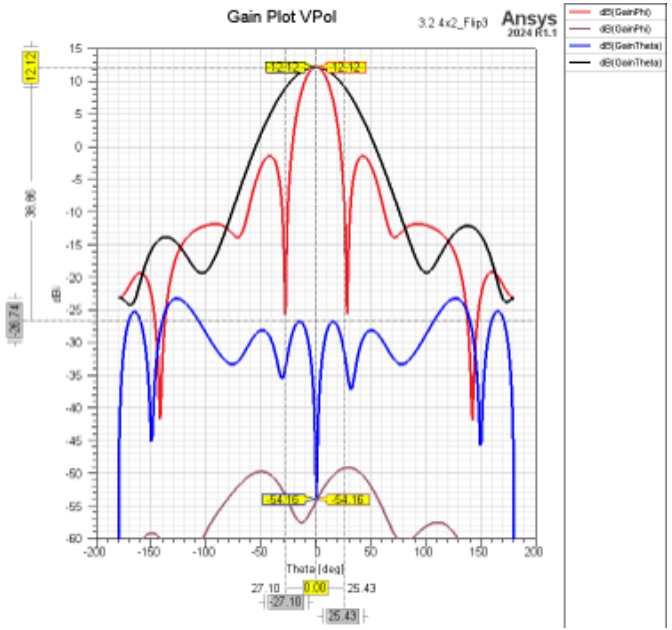
Prototype

Front-end

Sub-arrav 4x2



Gain, H pol
XPD ~ 40 dB @ broadside

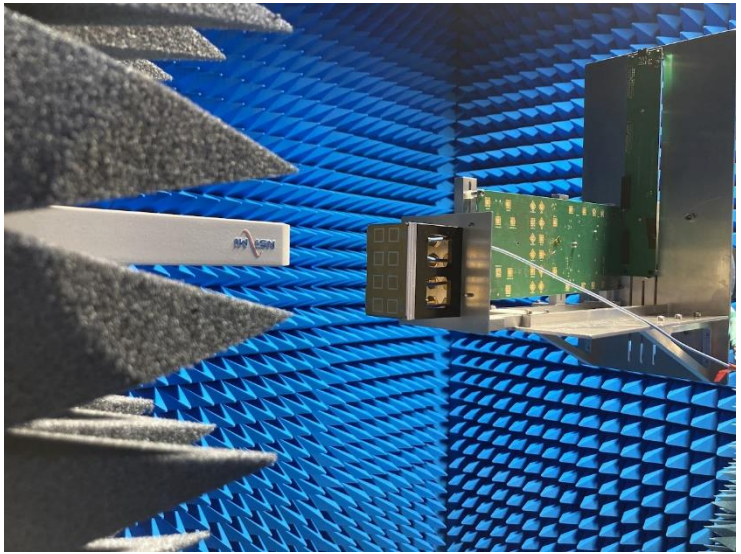


V pol
XPD ~ 41 dB

Fraunhofer FHR

Front-end

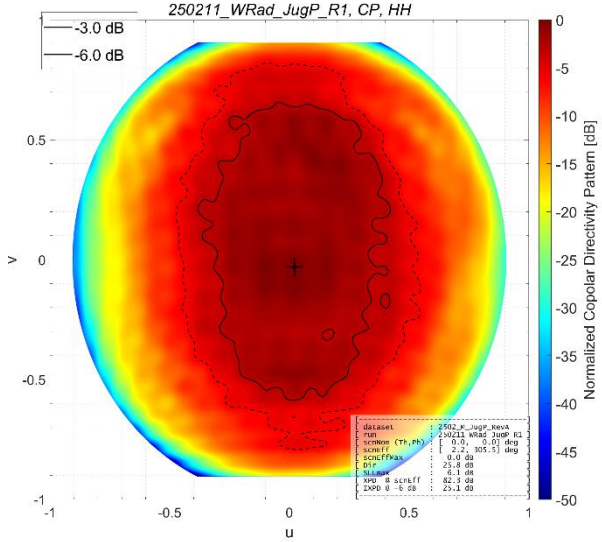
Sub-array 4x2



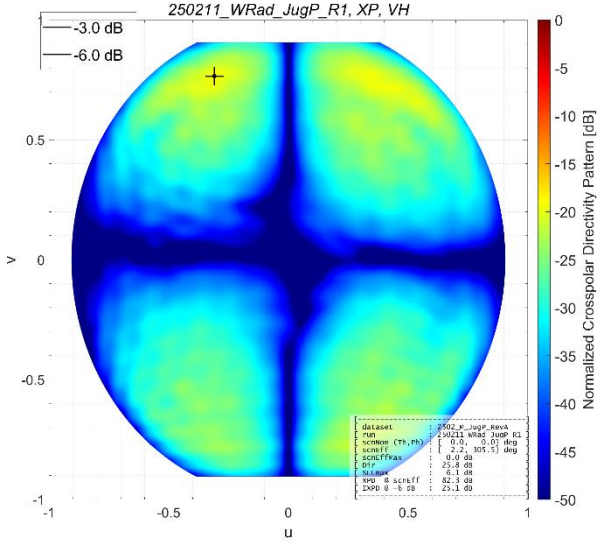
Experimental validation in anechoic chamber
Planar near-field scanner

Front-end

Sub-array 4x2



Co-polar component,
H pol, row 1

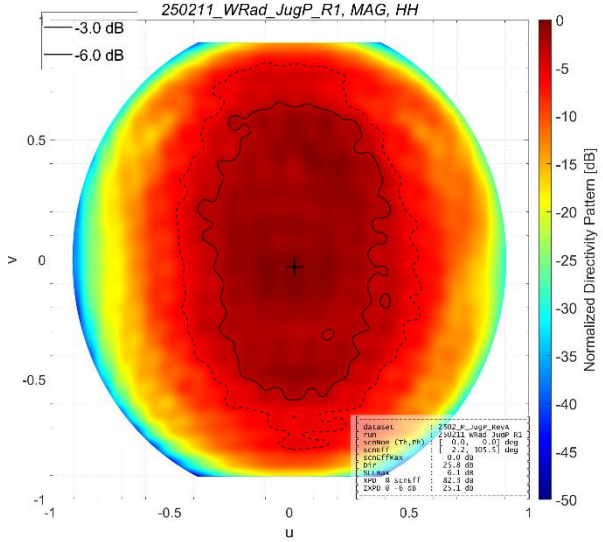


Cross-polar component,
H pol, Row 1

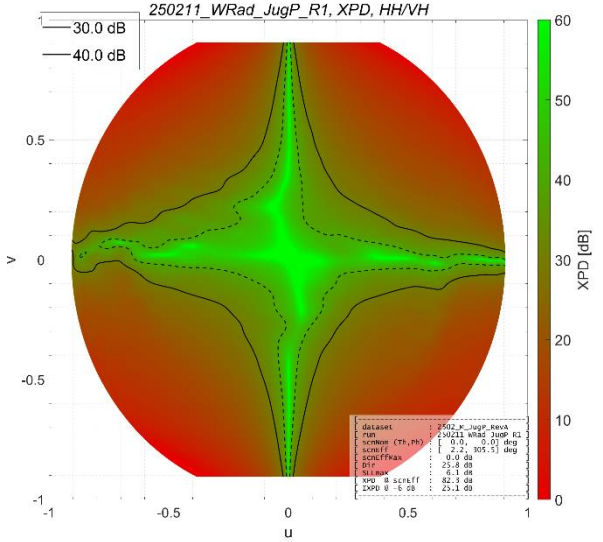
Fraunhofer FHR

Front-end

Sub-array 4x2



Magnitude,
H pol, **row 1**

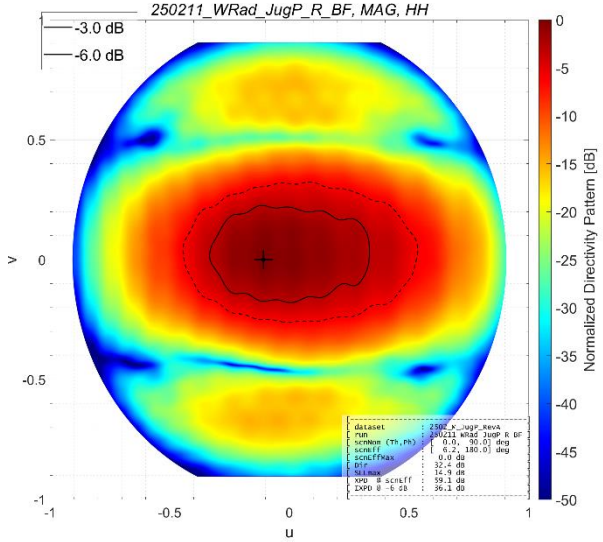


Cross-polar discrimination,
H pol, Row 1

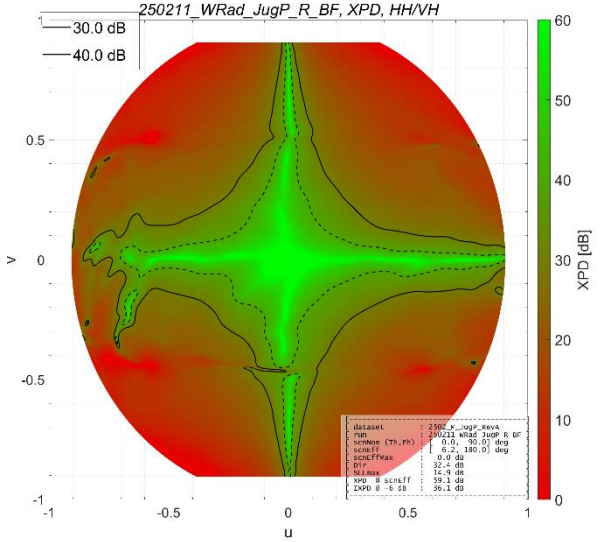
Fraunhofer FHR

Front-end

Sub-array 4x2



Beamformed, magnitude, **broadside**
H pol, rows 1 to 4

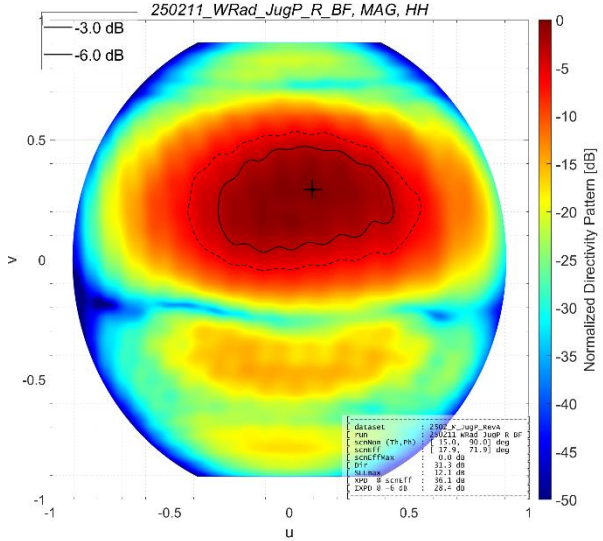


Beamformed, XPD, broadside
H pol, rows 1 to 4

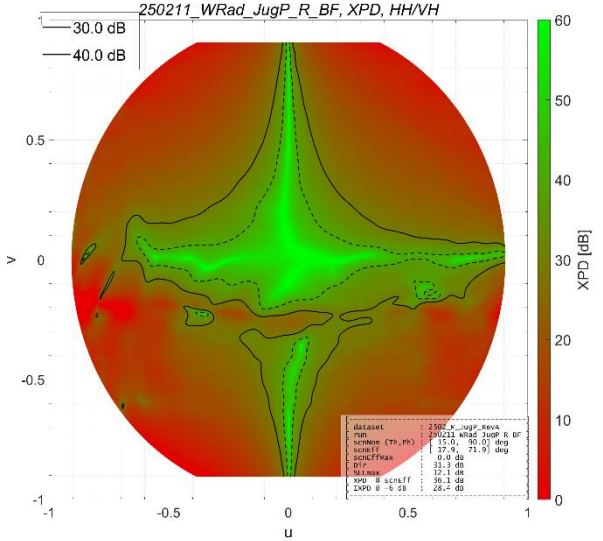
Fraunhofer FHR

Front-end

Sub-array 4x2



Beamformed, magnitude, **15° scan**
H pol, rows 1 to 4

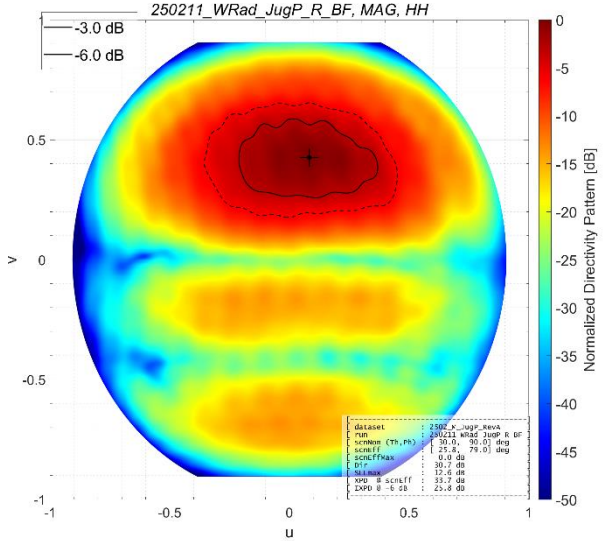


Beamformed, XPD, 15° scan
H pol, rows 1 to 4

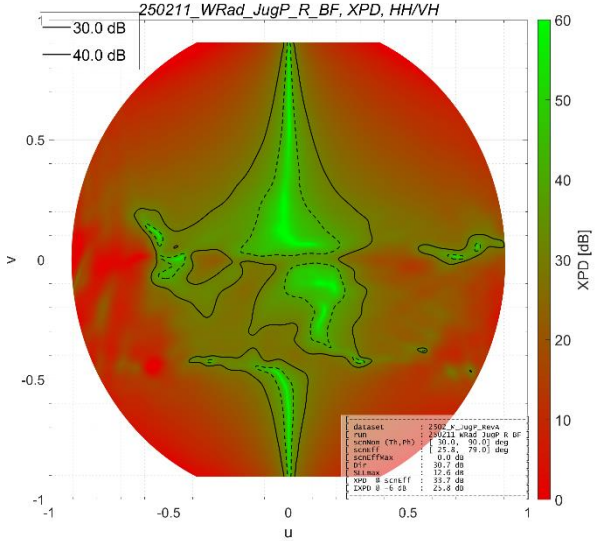
Fraunhofer FHR

Front-end

Sub-array 4x2



Beamformed, magnitude, **30° scan**
H pol, rows 1 to 4

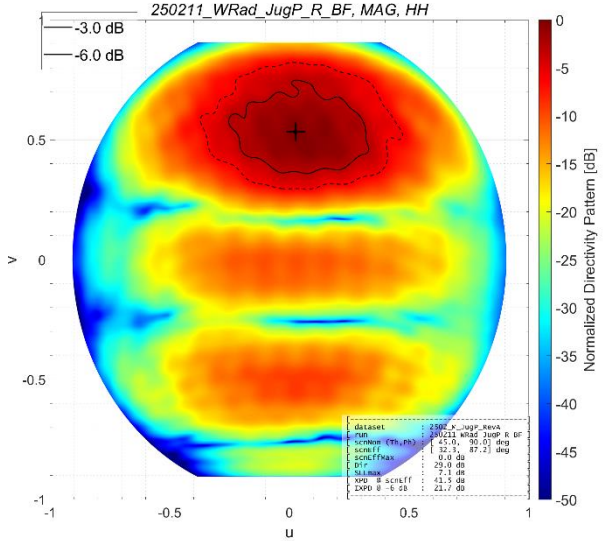


Beamformed, XPD, 30° scan
H pol, rows 1 to 4

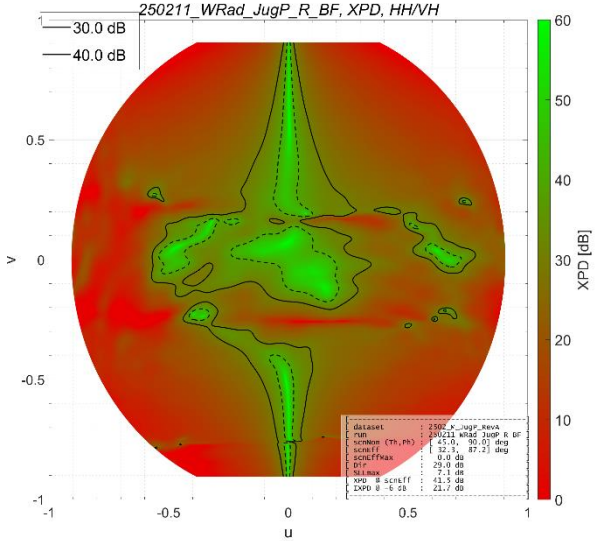
Fraunhofer FHR

Front-end

Sub-array 4x2



Beamformed, magnitude, **45° scan**
H pol, rows 1 to 4

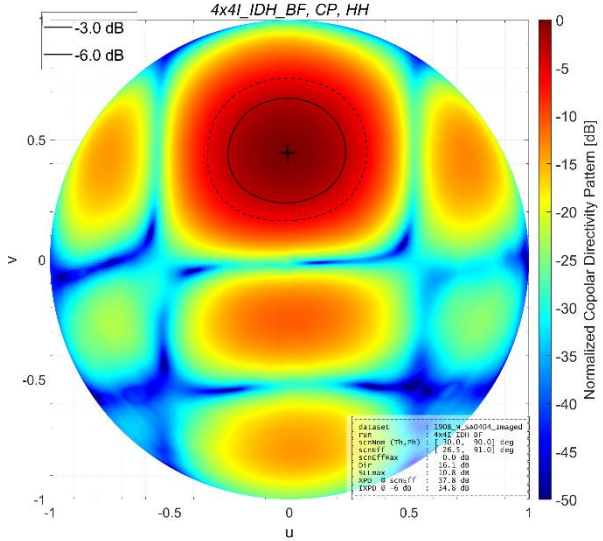


Beamformed, XPD, 45° scan
H pol, rows 1 to 4

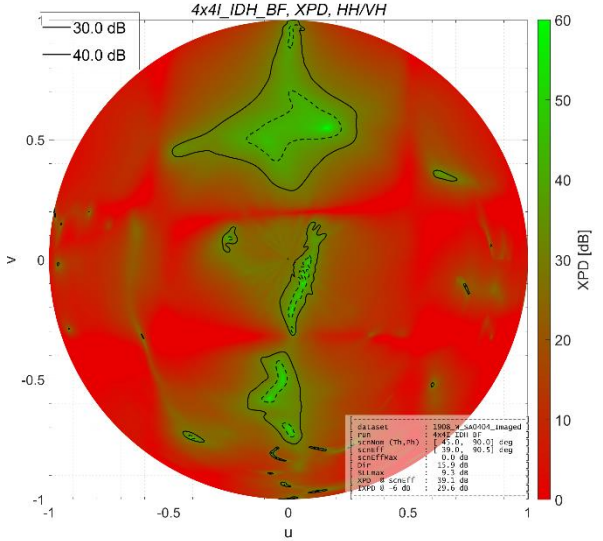
Fraunhofer FHR

Front-end

Sub-array 4x4



Beamformed, magnitude, 30° scan, **4x4 feed rotation**
H pol, rows 1 to 4

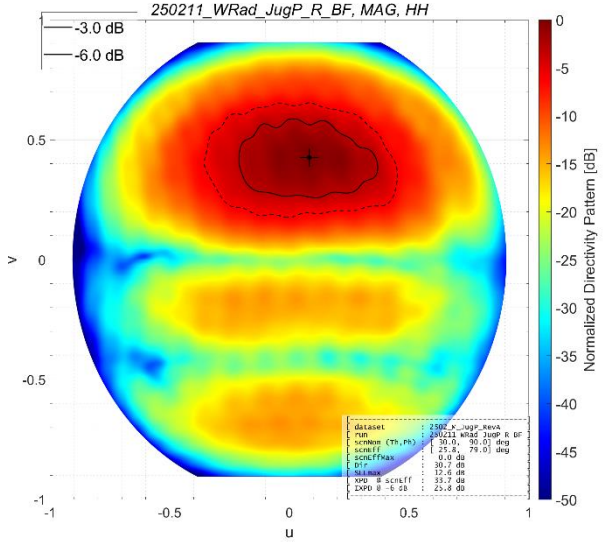


Beamformed, XPD, 30° scan, 30° scan, 4x4 feed rotation
H pol, rows 1 to 4

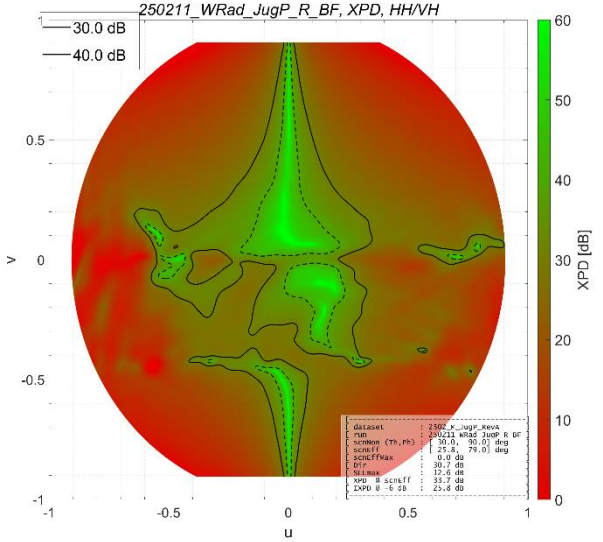
Fraunhofer FHR

Front-end

Sub-array 4x2



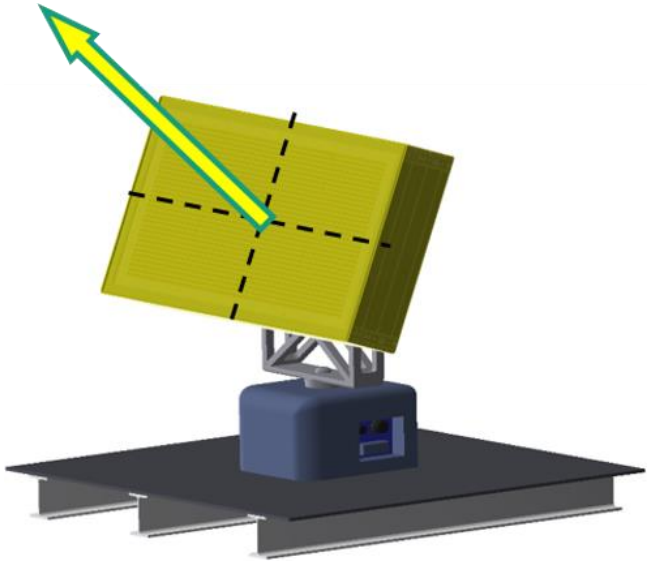
Beamformed, magnitude, 30° scan, **4x2 feed rotation r2**
H pol, rows 1 to 4



Beamformed, XPD, 30° scan, 4x2 feed rotation r2
H pol, rows 1 to 4

Fraunhofer FHR

Antenna concept
Mechanical assembly



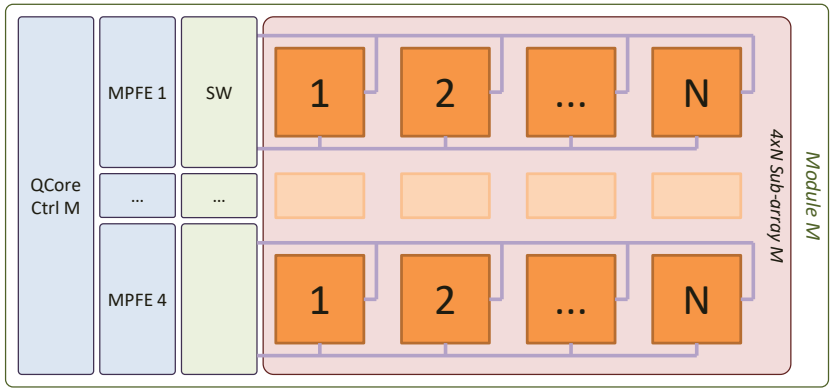
Concept rendering mock-up, front

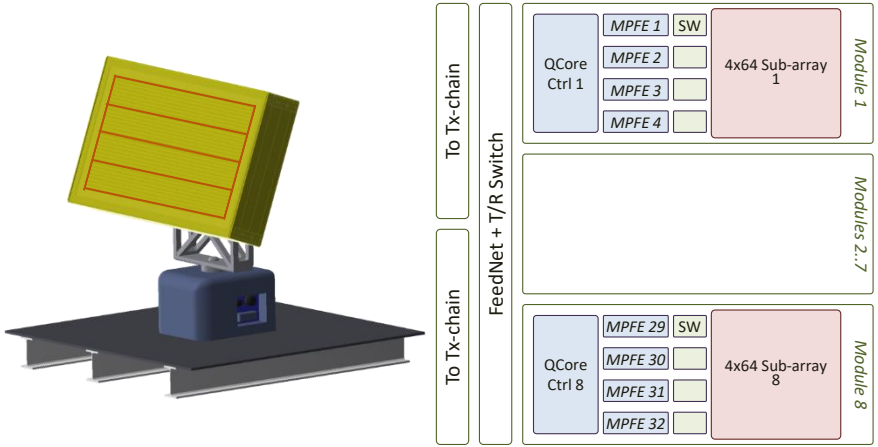
- **Flat aperture**
  - 0.5 meter^2 array panel (1 m x 0.5 m)
  - electronically steered in elevation
  - antenna aperture turned by a rotor for mechanical azimuth scanning
  - mechanically adjustable elevation tilts
  - receiver over-elevation
  - distributed power generation

Flat aperture

Front-end concept

- **Active Row Module**, based on an integrated AESA controller driving 4 Medium Power Front Ends. Each MPFE feeds a row array of N patches through a polarization switch. 4 radiating rows are grouped as a 4xN sub-array.





- **AESA panel**, based on 8 Active Row Modules stacked vertically, modular design. Total radiating surface of about 960 x 480 mm. Main beam steered electronically in elevation and mechanically in azimuth.

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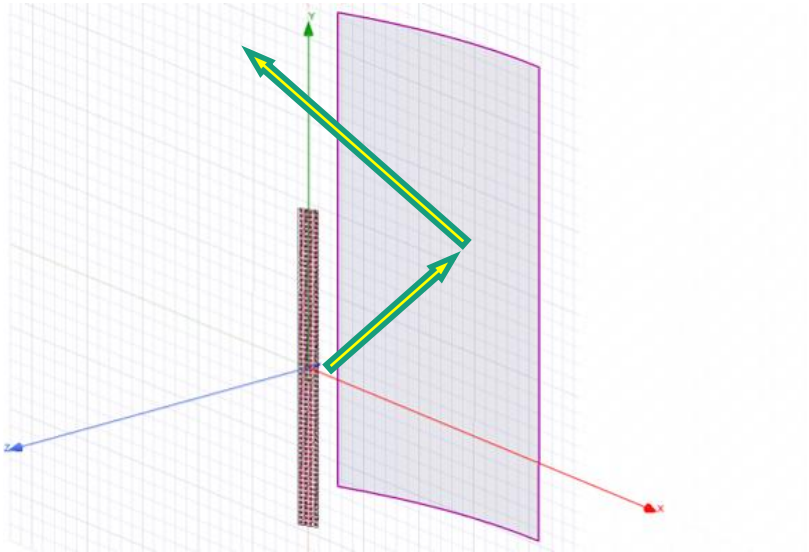
Front-end concept (b)

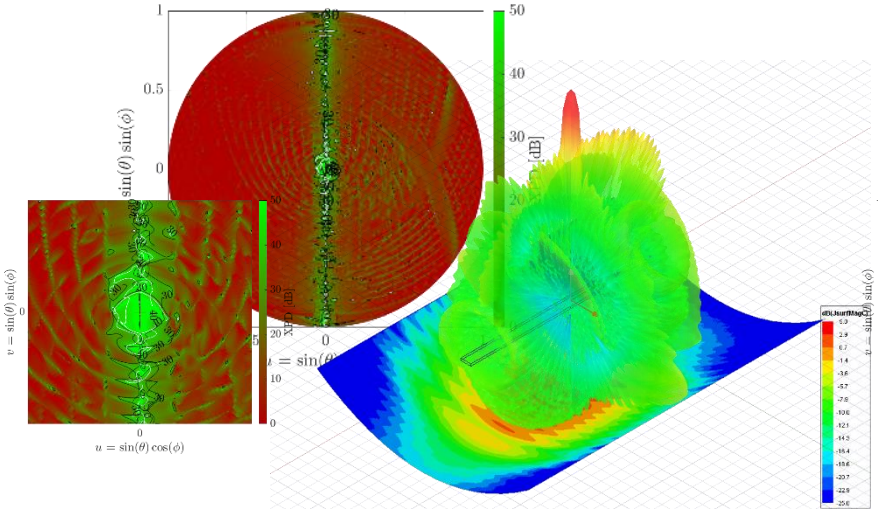


Novel active antenna approach

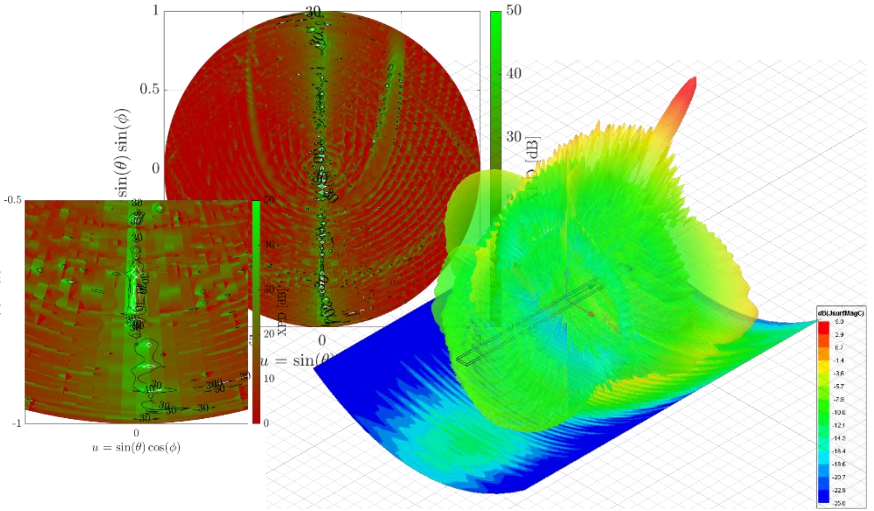
- A new approach to AESA apertures for weather radars
  - An active linear phased-array feed is placed in the focal line of a parabolic cylinder with optional offset configuration.
  - The linear feed generates an asymmetric fan beam which can be electronically steered in elevation. Such beam is specularly reflected along the planar section of the reflector (vertical plane) to cover an interval of scanning angles

Reflector design

Assembly 220.40, reflector XPD



Radiation patter and surface current density of the axial reflector at broadside.



Radiation patter and surface current density of the axial reflector at 45° beam steering.

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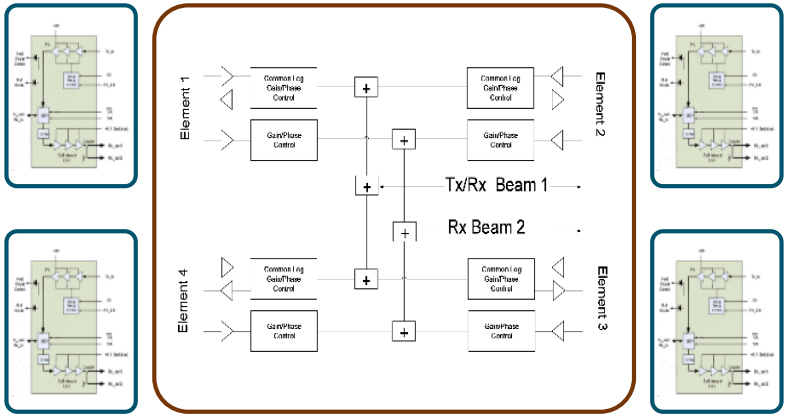
Front-end design

Recent technology advancements

COTS quad-core beam forming MMIC

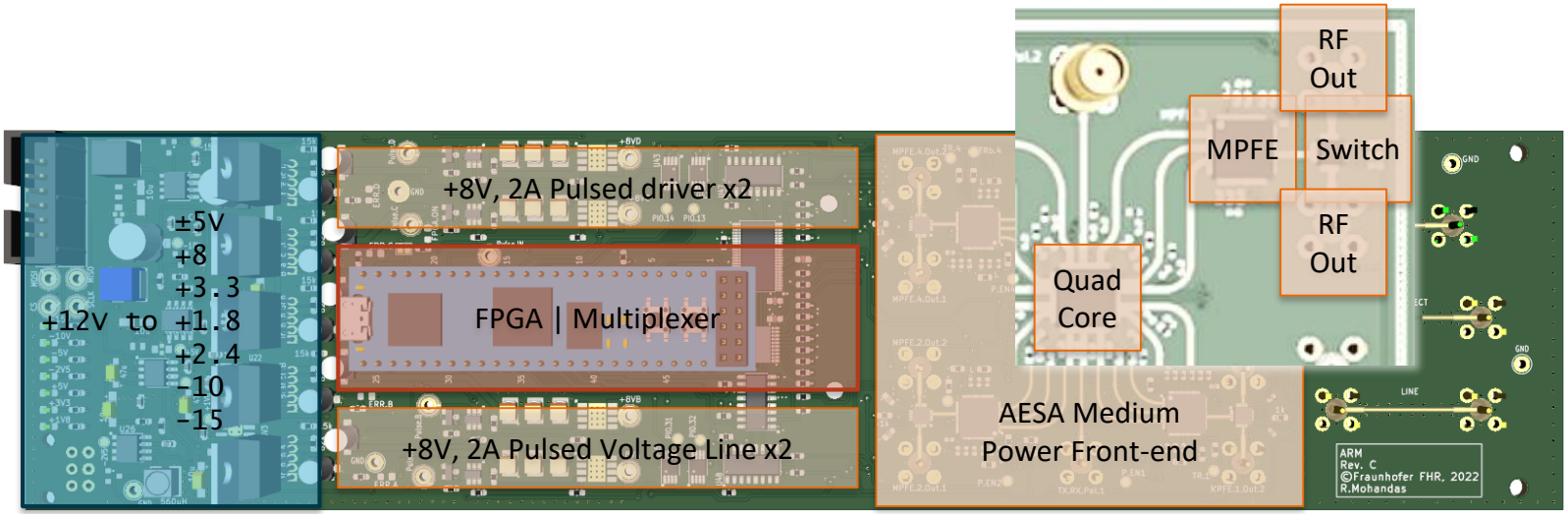


Quad-core controller driving four RF transceivers

- COTS quad-core MMIC supporting four independent radiating branches each offering integrated on chip
  - high linearity dual Rx channel
  - single Tx channel
  - output power telemetry
  - temperature compensation

ARM – Active Row Module

Rev.C



Block diagram, detail

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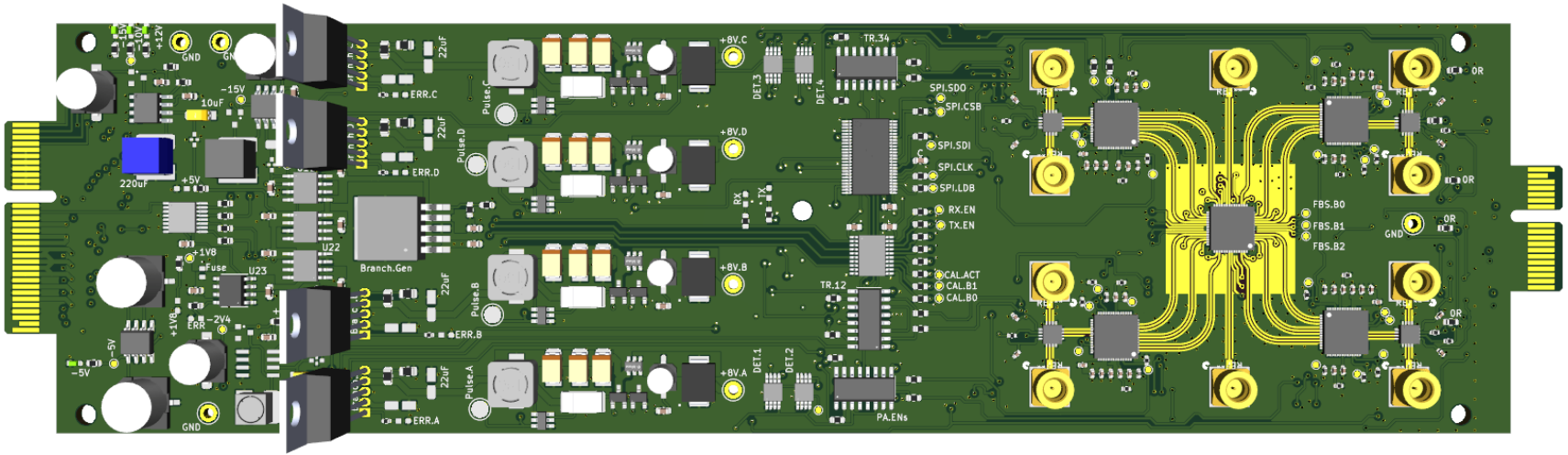
ARM – Active Row Module

Rev.D

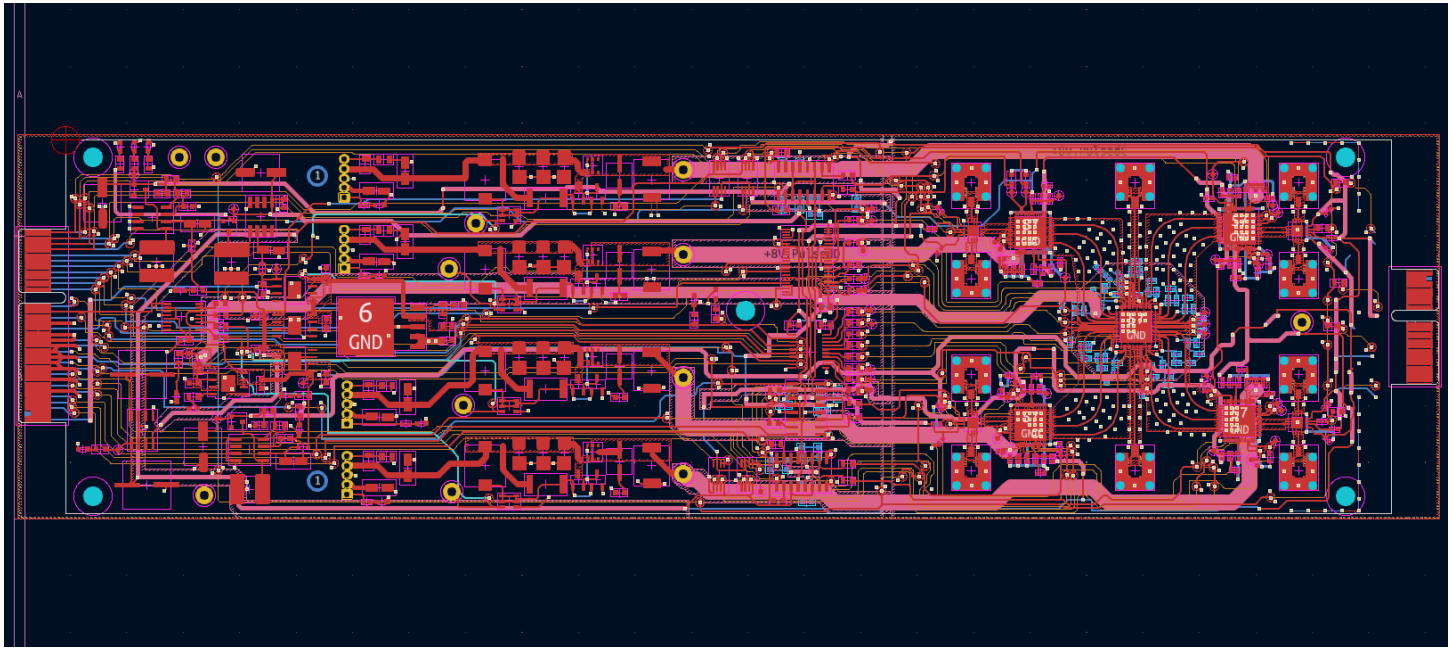


Top layer
RF core

Fraunhofer FHR

ARM – Active Row Module

Rev.D

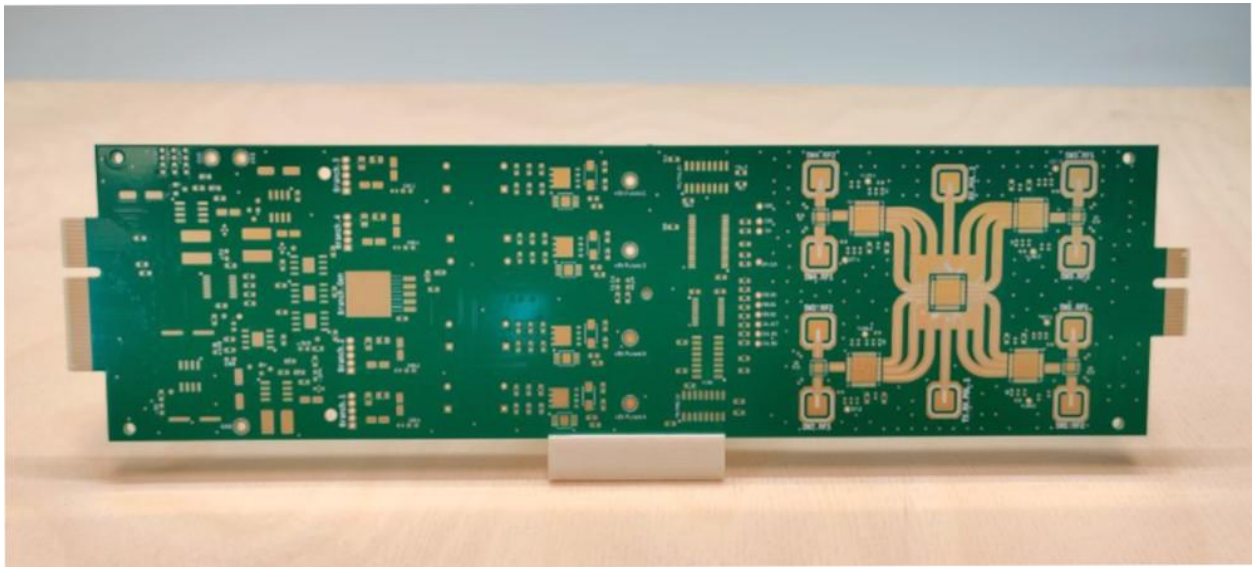


Top layer
RF core, switches on sub-array

Fraunhofer FHR

ARM – Active Row Module

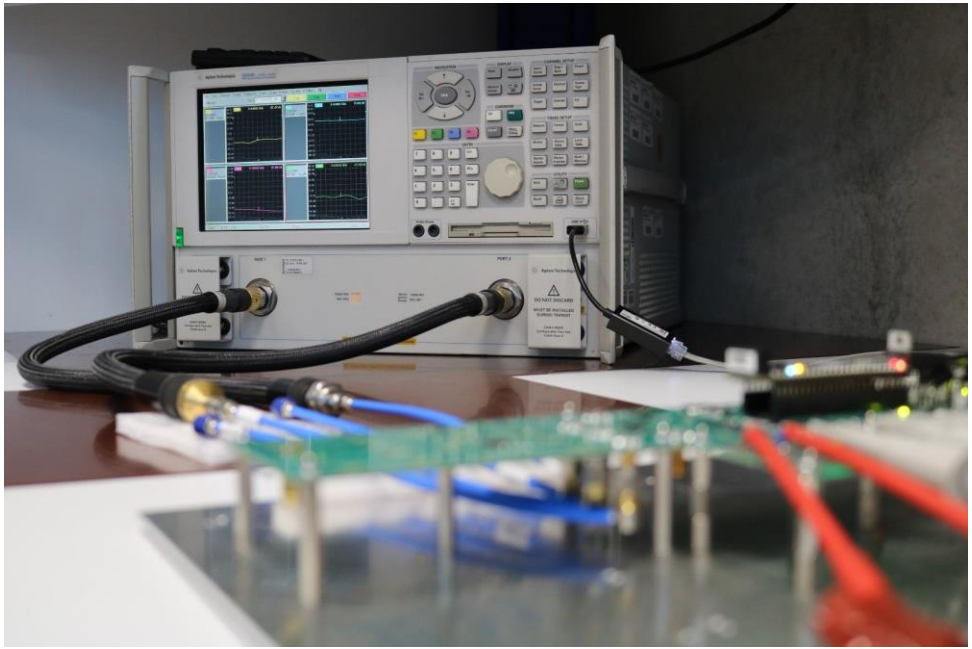
Rev.D



Top layer
RF core

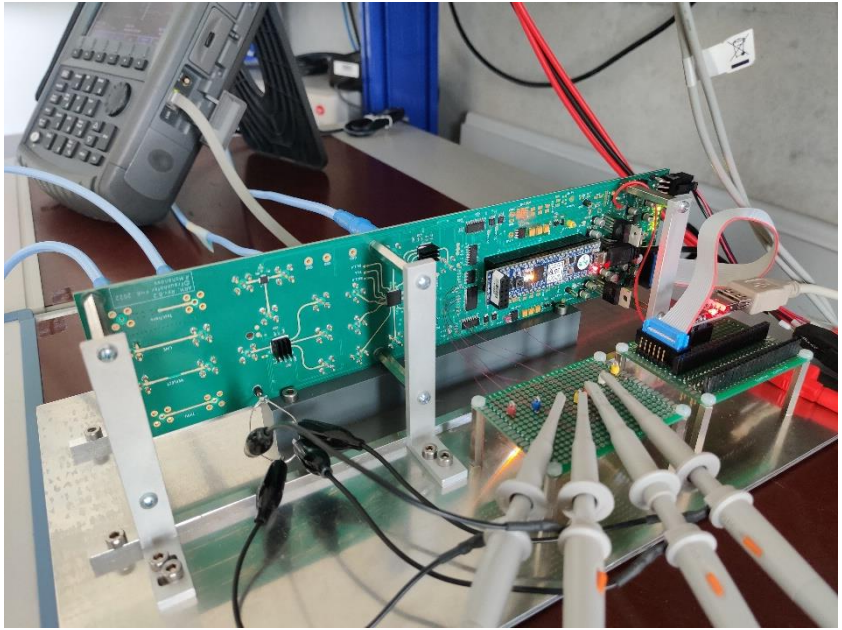
Fraunhofer FHR

Beamforming and calibration



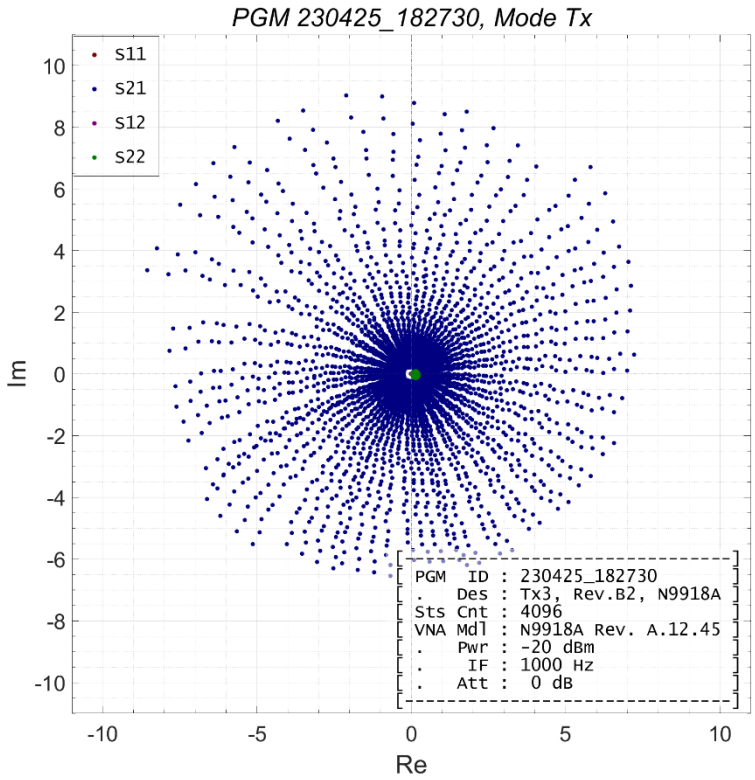
Measurement setup

Rev.B2

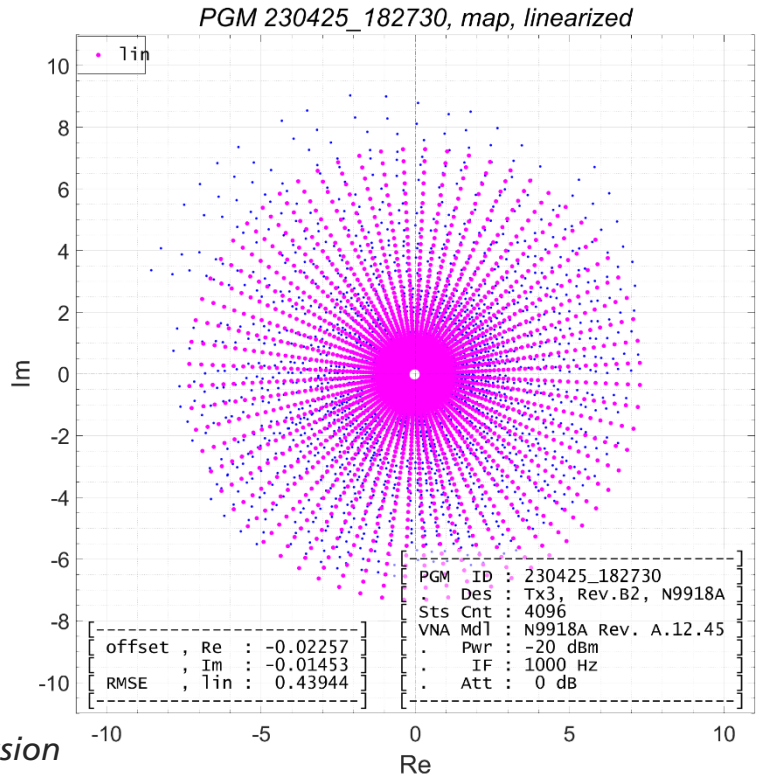


Fraunhofer FHR

Beamforming



Beamforming



dual dimensional linear regression

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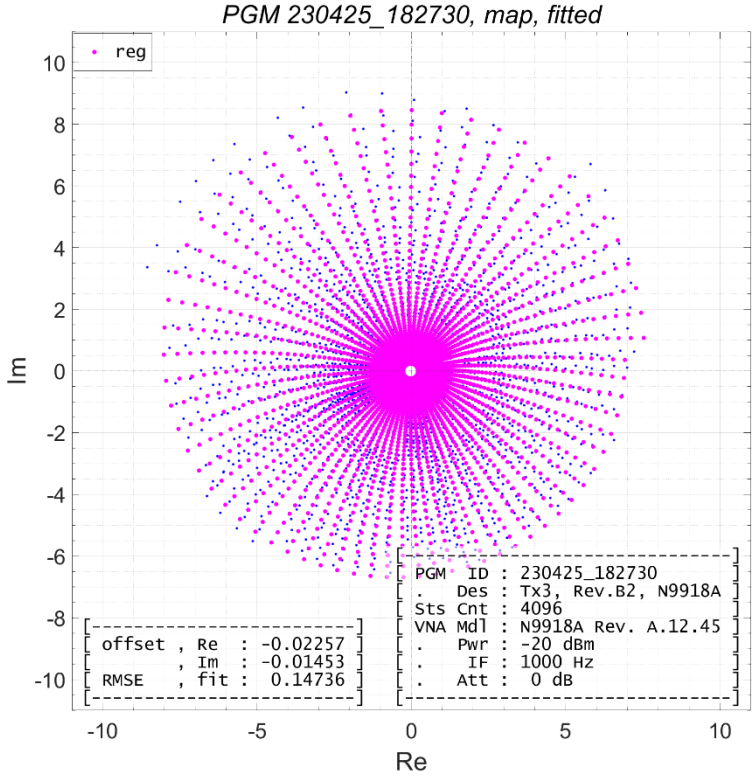
Beamforming

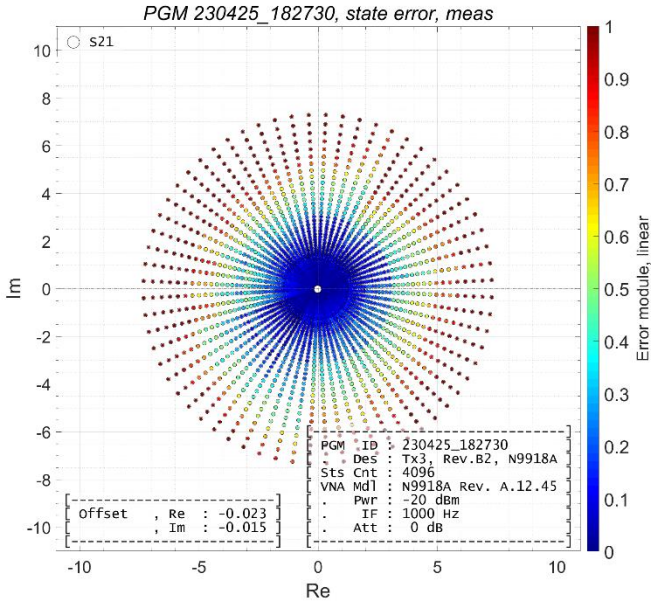


surface regularization

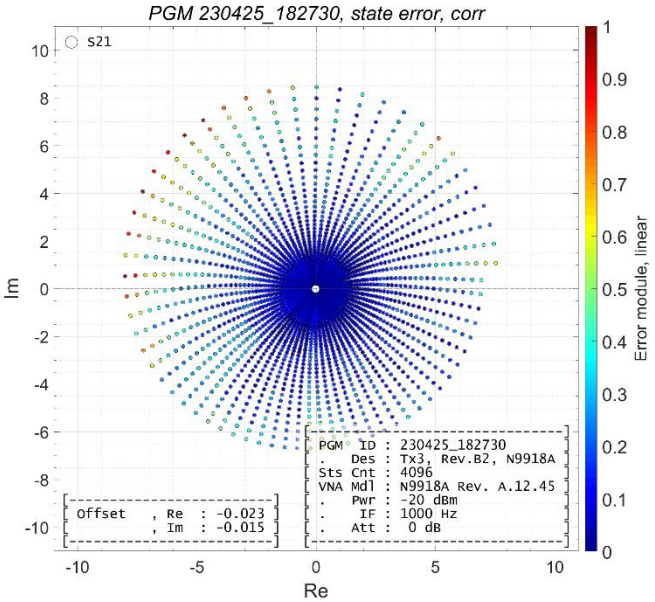
Fraunhofer FHR

Beamforming

Rev.B2



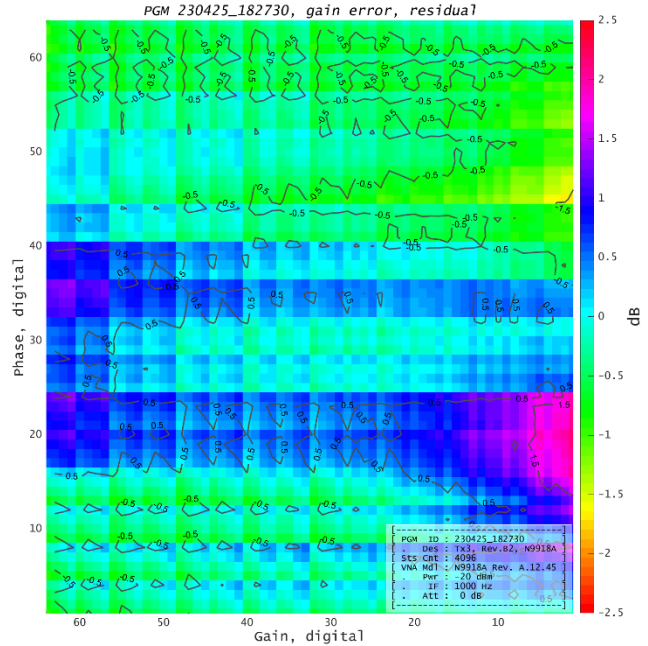
Error module, linearization



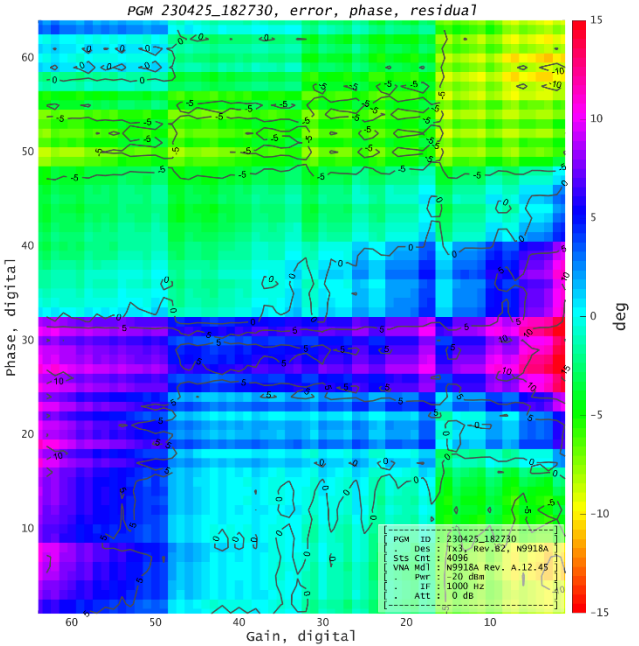
regularization

Beamforming

ARM PCB Rev.B2
Measured



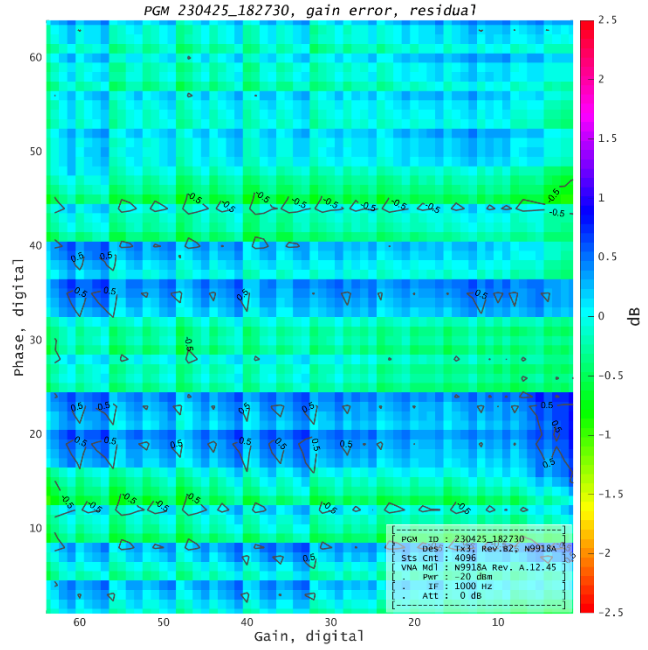
gain error



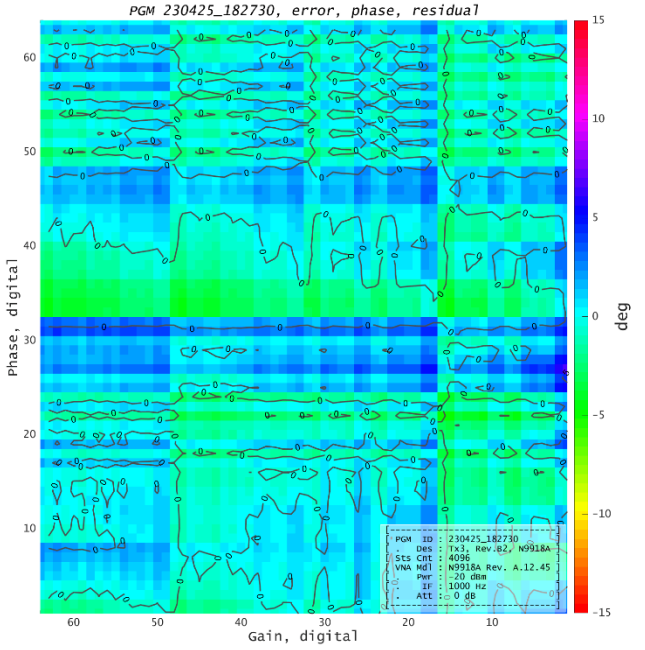
phase error

Beamforming

ARM PCB Rev.B2
Corrected

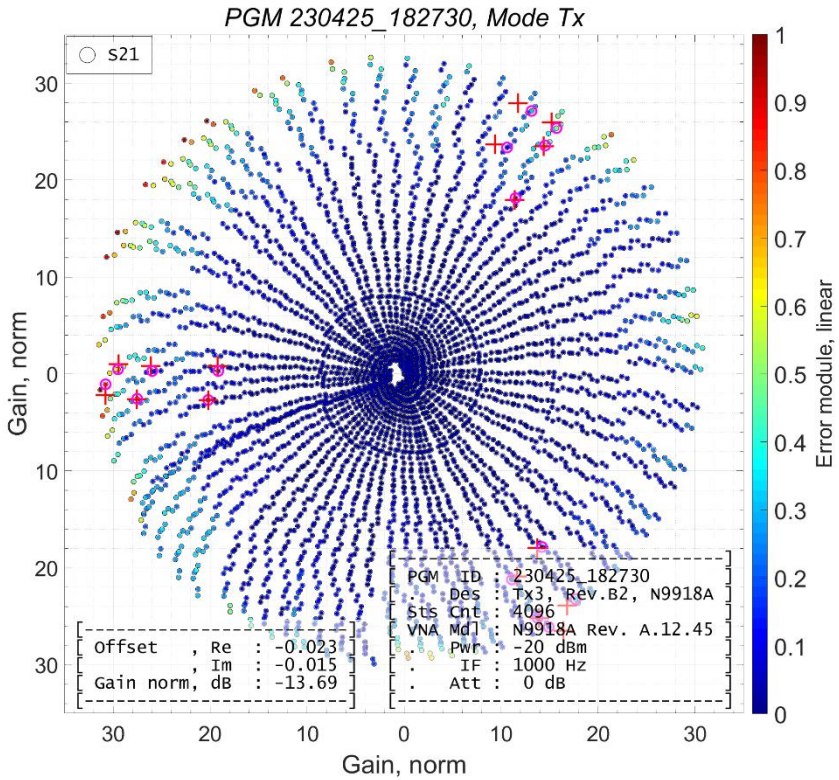


gain error



phase error

Beamforming



States selection

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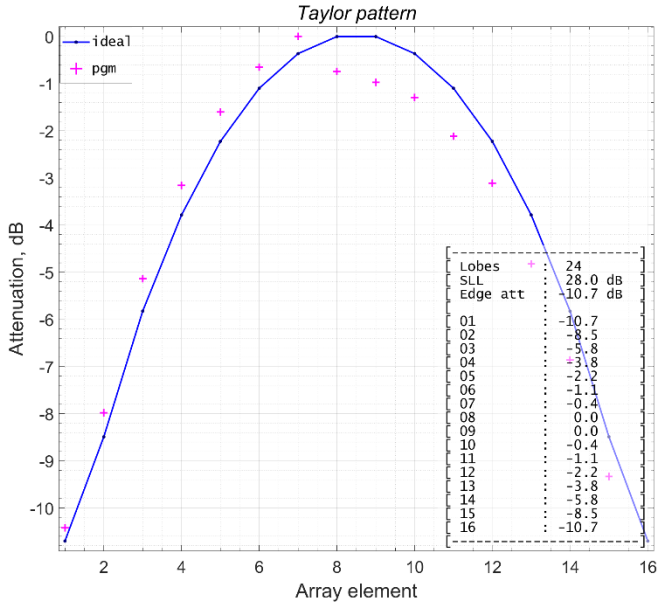
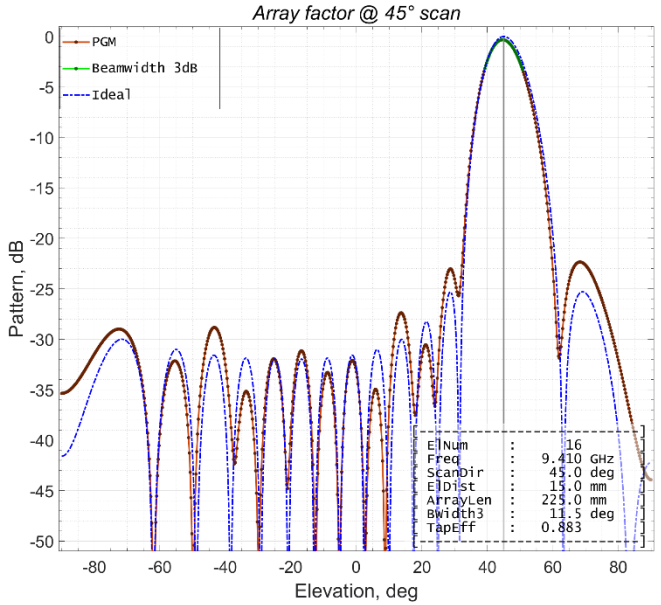
Beamforming



Tapering
ideal and synthesized



Array factor
16 elements

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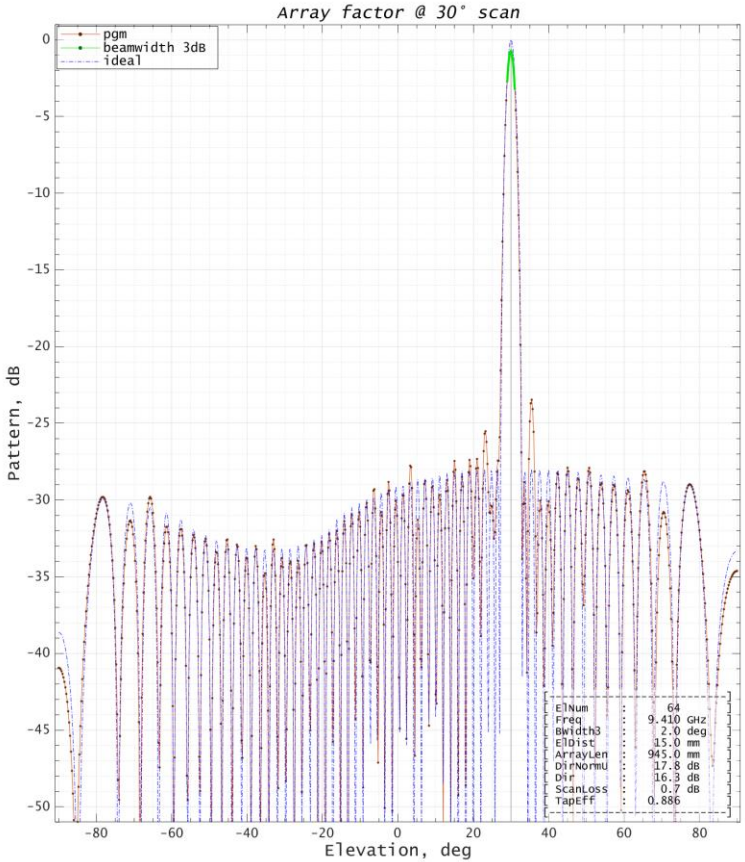
Beamforming



array factor, 64 elements steered, beamformed

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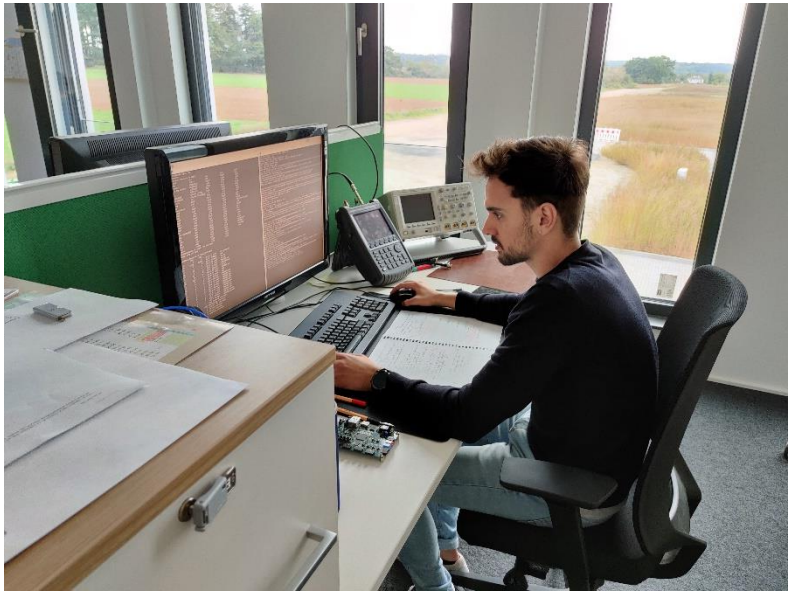
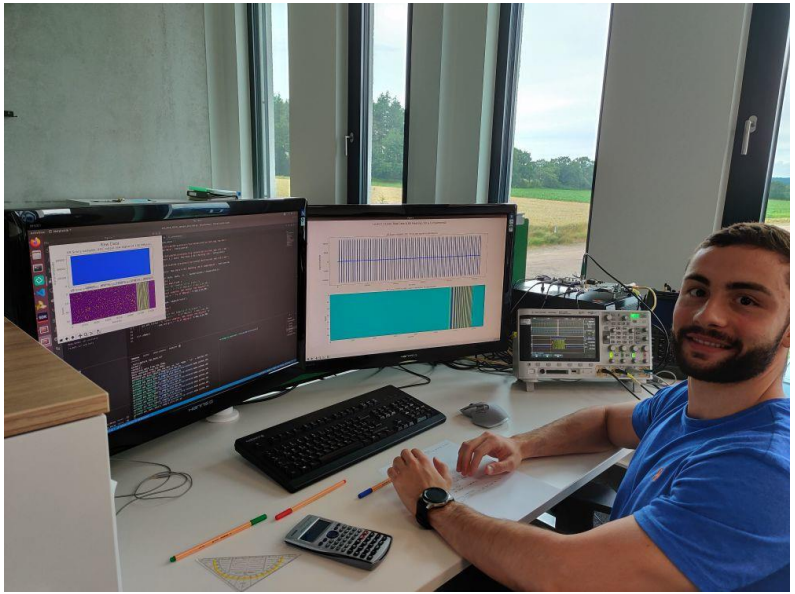
Students on back-end…
by Tobias ands Florian, 2022

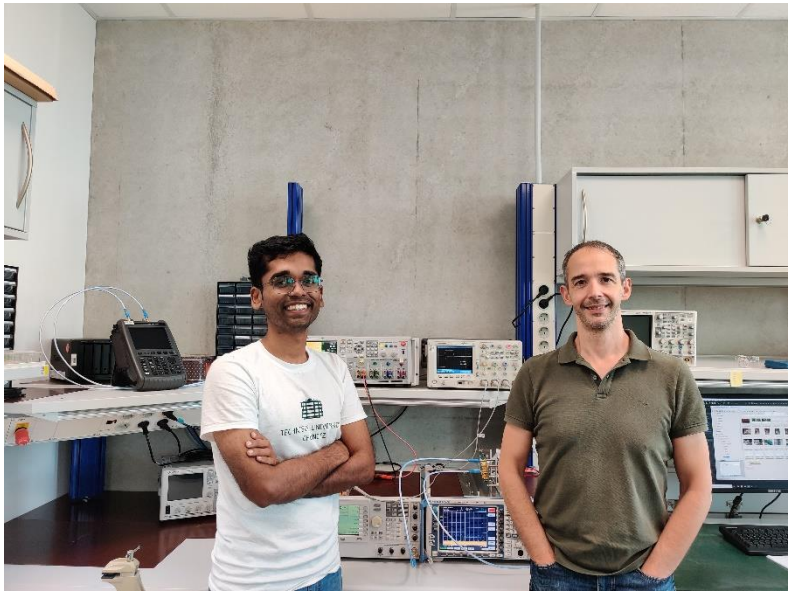


… radar signal processor …
by Alejandro, 2022

The Weather Radar Lab @ Fraunhofer FHR



… radar core engine…
by Miguel, 2023



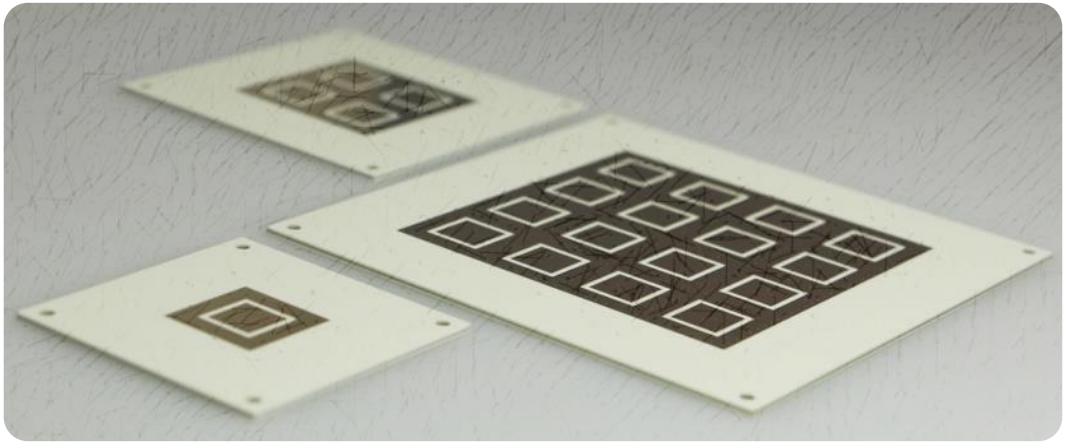
… and all the rest!
by Rohan and me ;)

Thank you for your attention!

The team!

Thank you for your attention!

Questions?



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