Preliminary Design of a Room Temperature C-band Phased Array Feed Prototype with Digital Back-end Based on RFSoC

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ISTITUTO NAZIONALE DI ASTROFISICA INAF

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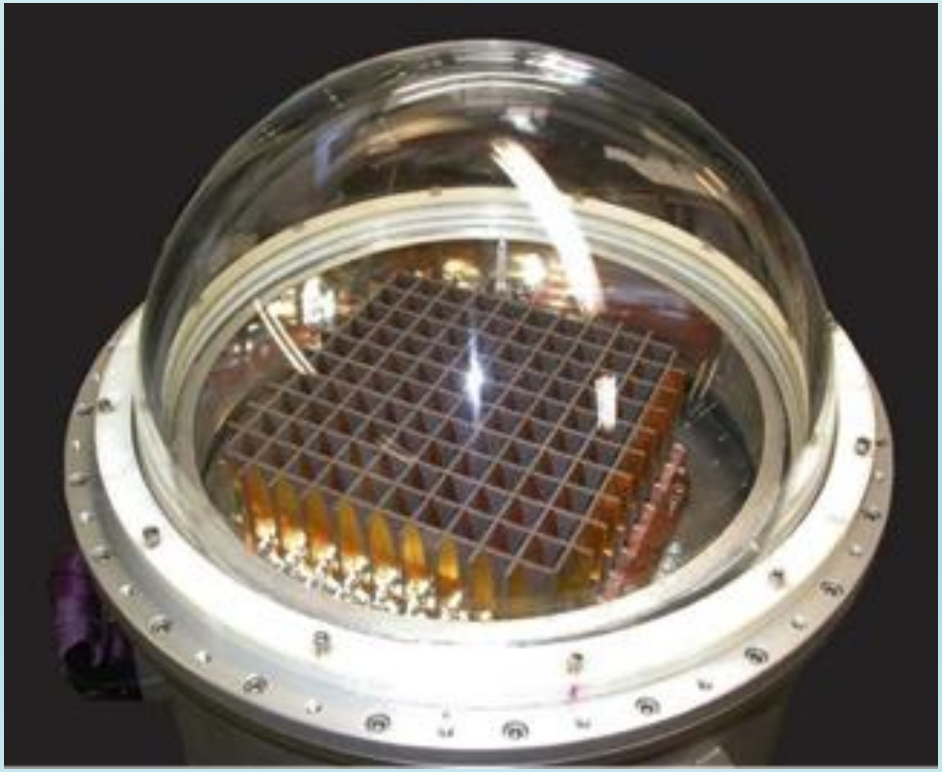
Overview

1. PHAROS/PHAROS2 experience;
2. Architecture of the new INAF C-band PAF with RFSoC;
3. Future perspectives and conclusions;

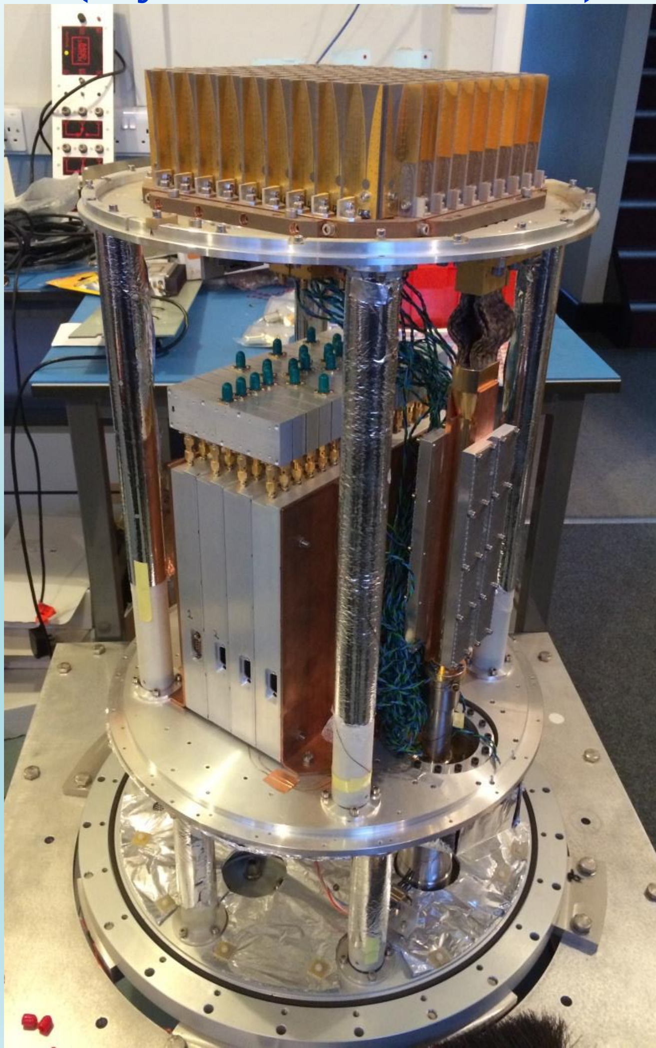
PHAROS: PHased Arrays for Reflector Observing Systems

- Collaboration started ≈15 years ago. Originally, 7 international partners involved;
- Goal: develop a demonstrator of a cryogenically cooled PAF;
- Array of 10x11 dual-pol Vivaldi antennas;
- 24 LNAs/active antennas in one polarization at ≈20 K;
- Four 13-element analog beamformers at ≈70K;
- C-Band, 4-8 GHz;

Vivaldi array and vacuum window:



PHAROS PAF (cryostat internal view):



PHAROS2: upgrade of PHAROS with digital beamformer

Period ≈2016-2020

One of the Work Packages of the PAF SKA AIP

A collaboration of five institutes

INAF ISTITUTO NAZIONALE DI ASTROFISICA

MANCHESTER 1824 The University of Manchester

University of Malta

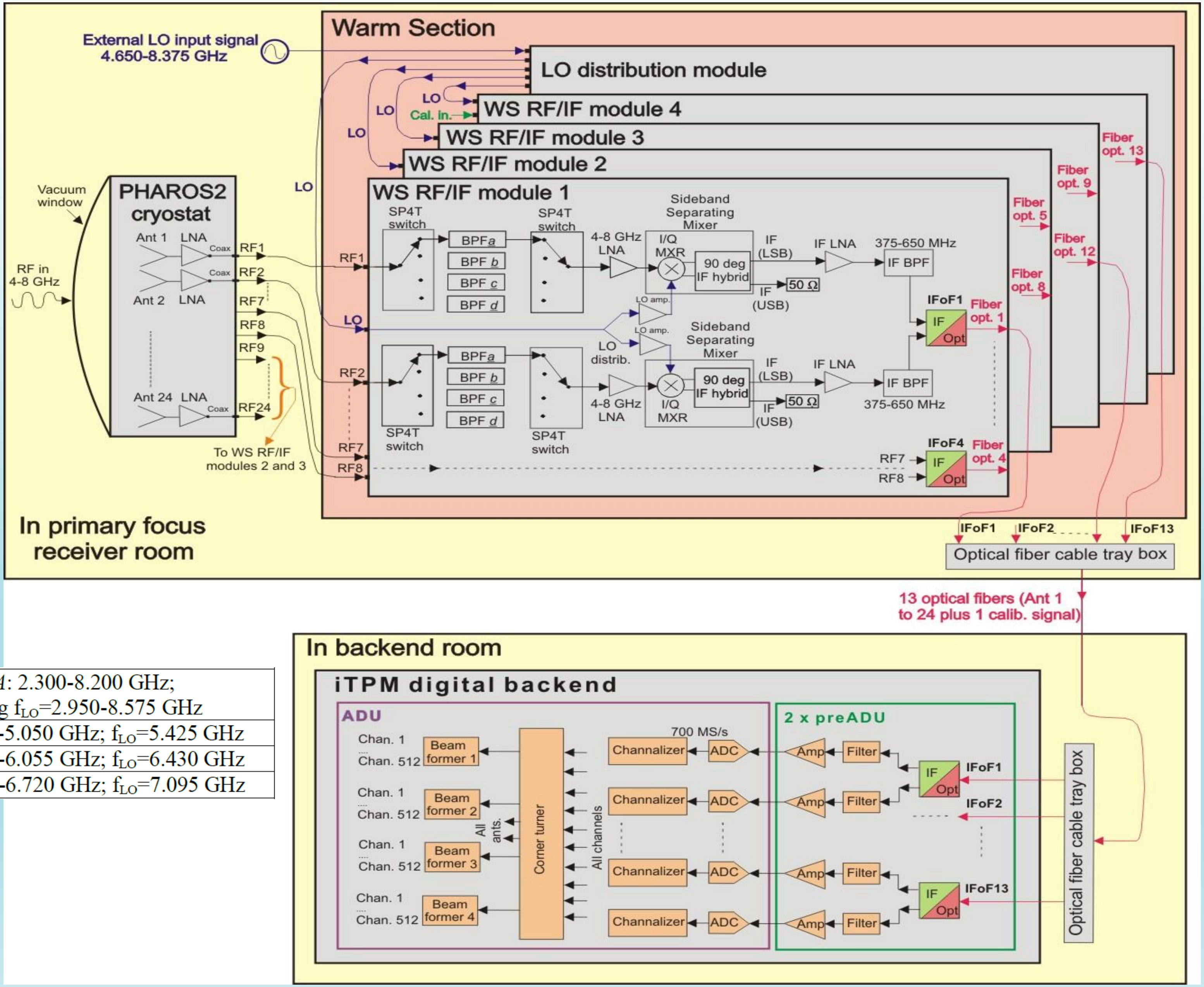
ONSALA RYMDOBSERVATORIUM CHALMERS TEKNISKA HÖGSKOLA

ASTRON

PHAROS2 hardware, software, firmware:

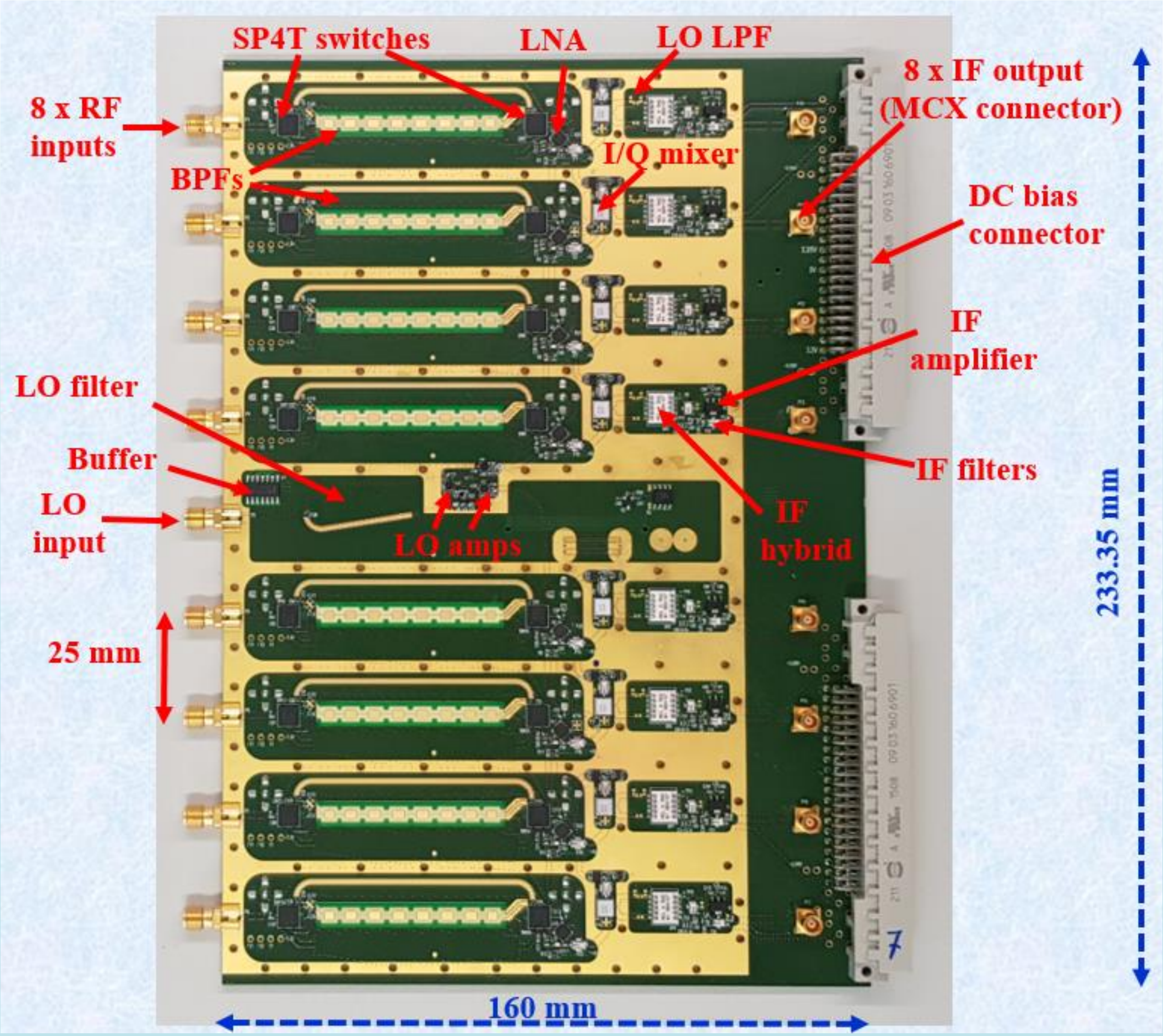
- New cryogenic C-band LNAs with <3K noise temperature;
- INAF digital beamformer based on iTPM hardware for the 375-650 MHz IF;
- INAF C-band multi-channel heterodyne receiver (Warm Section) to deliver ≈275 MHz bandwidth to the digital back-end;

Architecture of PHAROS2

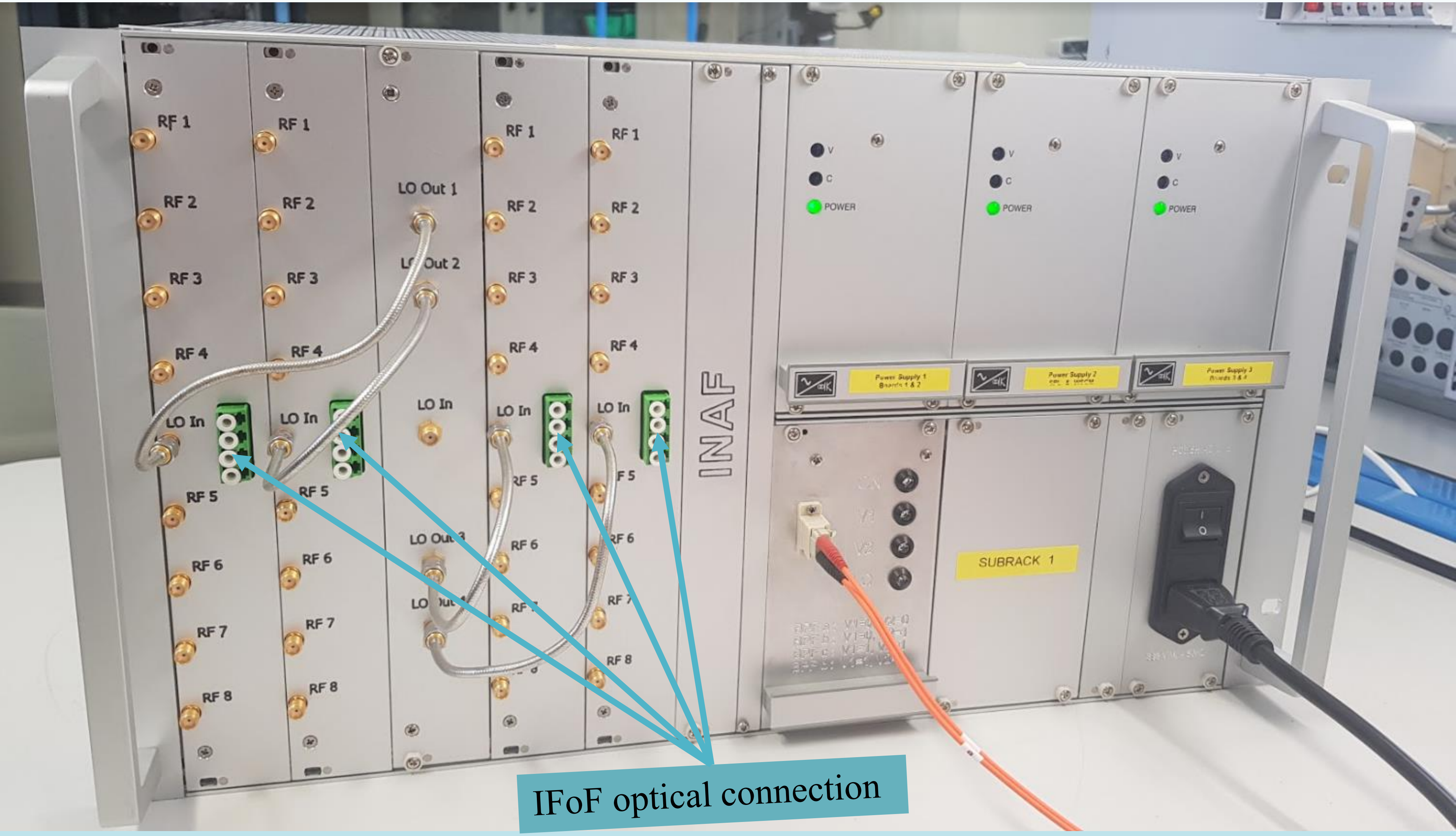


BPF-A: 2.300-8.200 GHz; LO tuning f_{LO}=2.950-8.575 GHz	
BPF-B: 4.775-5.050 GHz; f_{LO}=5.425 GHz	
BPF-C: 5.780-6.055 GHz; f_{LO}=6.430 GHz	
BPF-D: 6.445-6.720 GHz; f_{LO}=7.095 GHz	

PHAROS2 Warm Section RF/IF board

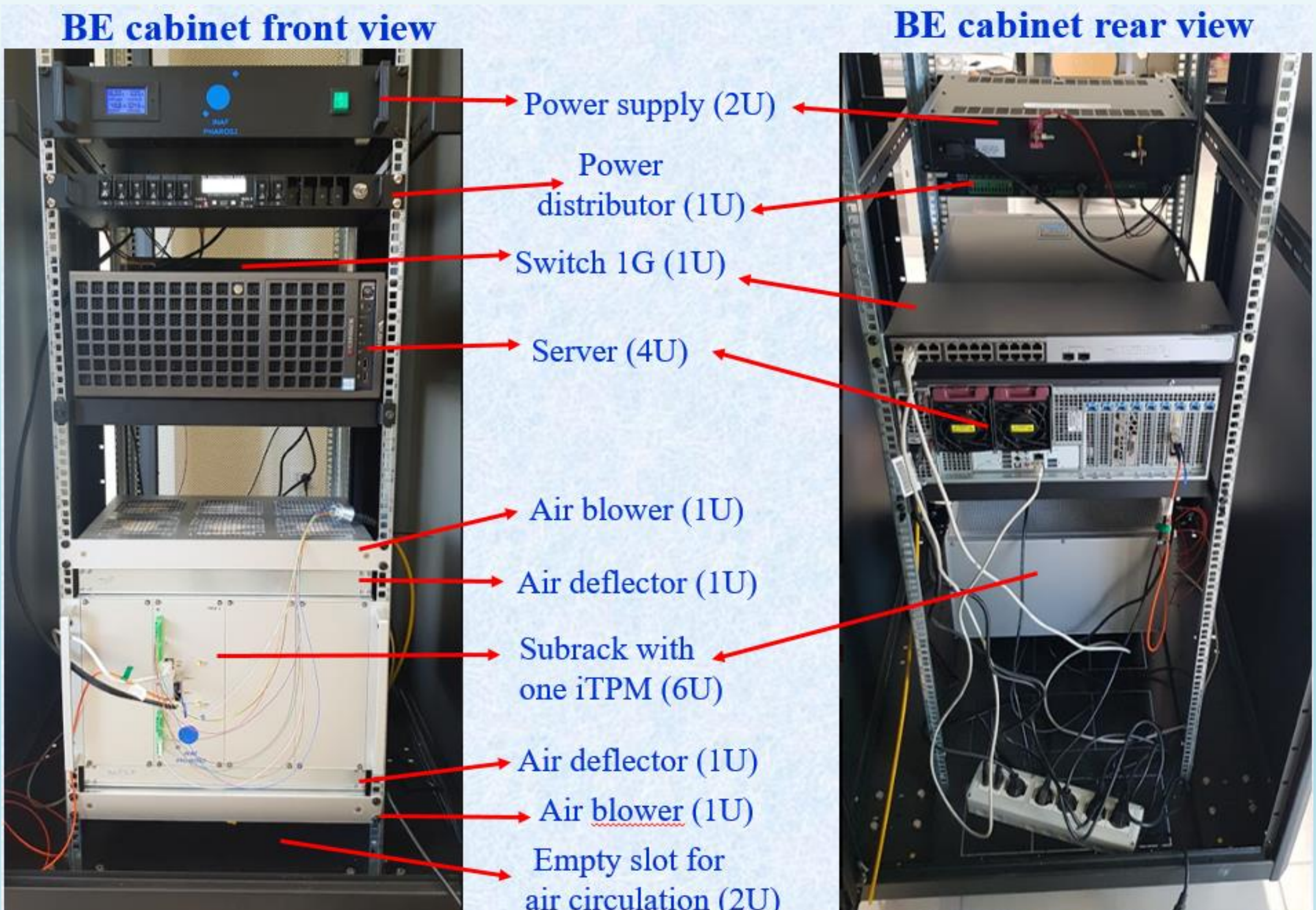


PHAROS2 32-channel Warm Section Heterodyne Receiver

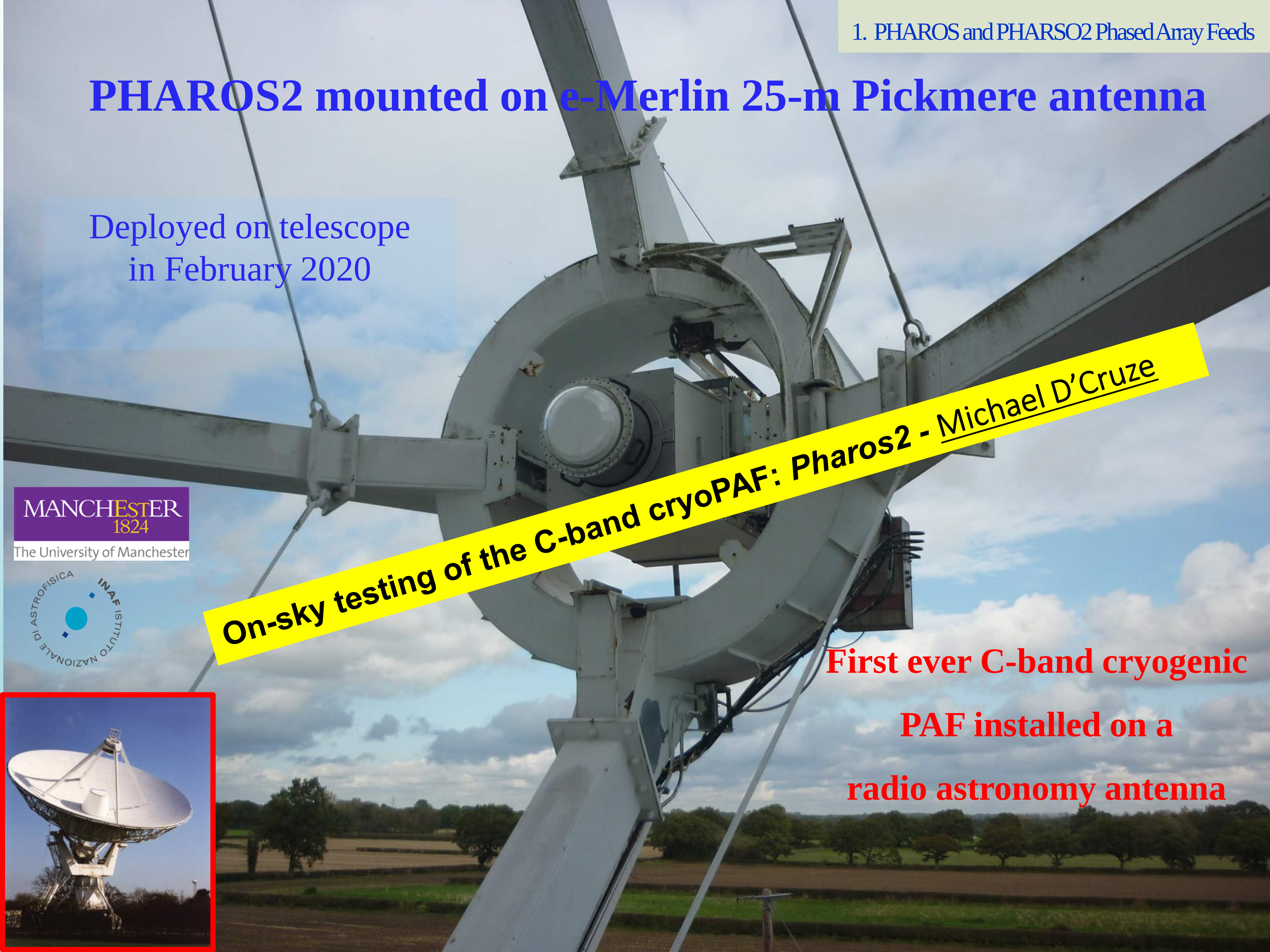


PHAROS2 Digital Back-End

Four beams, ≈275 MHz BW, beamforming in the iTPM-FPGAs for 24 single-pol. antenna elements. Each beam provided with time-integrated spectra (pulsar search, on-the-fly mapping) and with non integrated spectra (pulsar timing).



PHAROS2 mounted on e-Merlin 25-m Pickmere antenna



Deployed on telescope in February 2020

On-sky testing of the C-band cryoPAF: *Pharos2* - Michael D'Cruze

First ever C-band cryogenic PAF installed on a radio astronomy antenna

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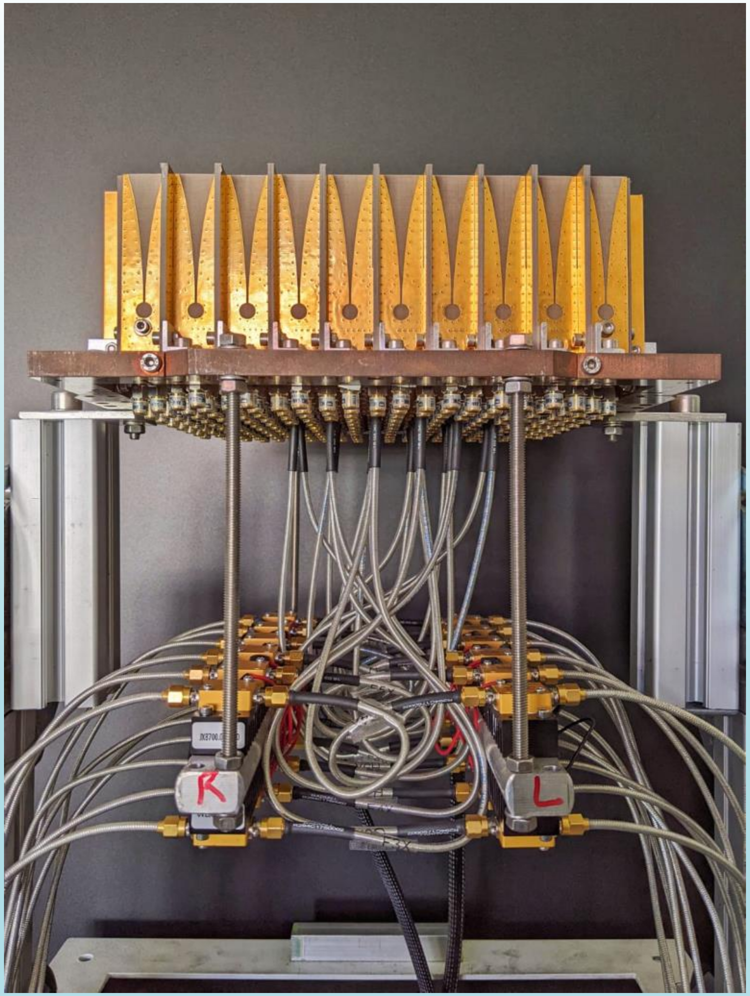
Vivaldi array, 32-channel receiver module to test digital backend @ INAF laboratories



Gain: 55dB Typical
•Noise Figure: 0.85dB Typical
•P1dB Output Power: +18dBm Typical
•Supply Voltage: +15V
•50 Ohm Matched

PHAROS will be an hardware platform to test the new RFSoC at the moment with 32 LNA

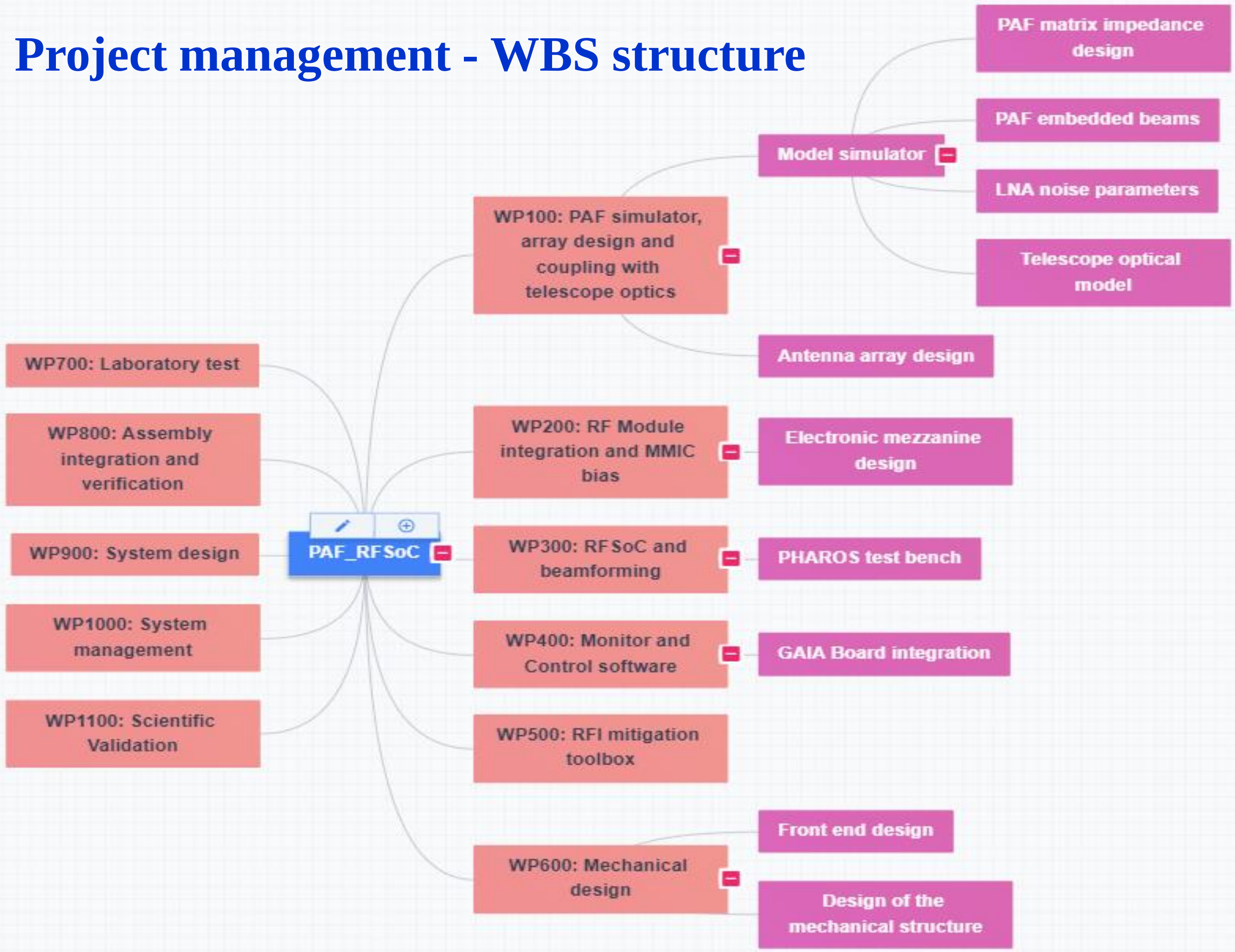
2. Architecture of INAF C-band PAF with RFSoC

Our goals

- Design and build a small Room Temperature PAF demonstrator in C-band based on RFSoC with up-scalable architecture;
- Direct sampling of the RF signals up to 6 GHz eliminates the need of downconversion (no Warm Section required);
- Four synthesized beams, ≈1 GHz BW;
- Fully-integrated design based on an 8×8 array of dual-pol antennas, with 32 active elements;
- Two RFSoC boards, each digitizing 16 inputs, 1.25 GHz BW;
- Optimized for best sensitivity;
- Test the demonstrator on the SRT;

2. Architecture of INAF C-band PAF with RFSoC

Project management - WBS structure



PAF Simulator model

- In collaboration with Anish Roshi

Given

- **the source direction (θ_s , ϕ_s)**
- **the reflector geometry (on-axis or off-axis)**
- **the PAF impedance matrix (Z)**
- **the PAF embedded beam patterns (ε^e)**
- **the amplifier noise parameters (R_n, g_n, ρ) and its input impedance (Z_{in})**

The model can:

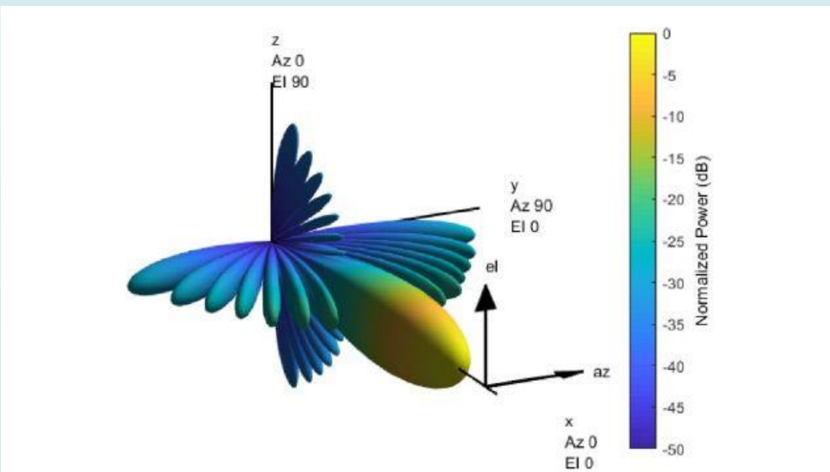
1. **Constructs the system-characteristics-matrix M for the *PAF + Telescope + Receiver***
2. **Calculates the weight vector w as the maximum eigenvalue e_{max} of M for the best SNR**
3. **Estimates the T_{sys}/η_{ap} from the knowledge of telescope and source flux density**

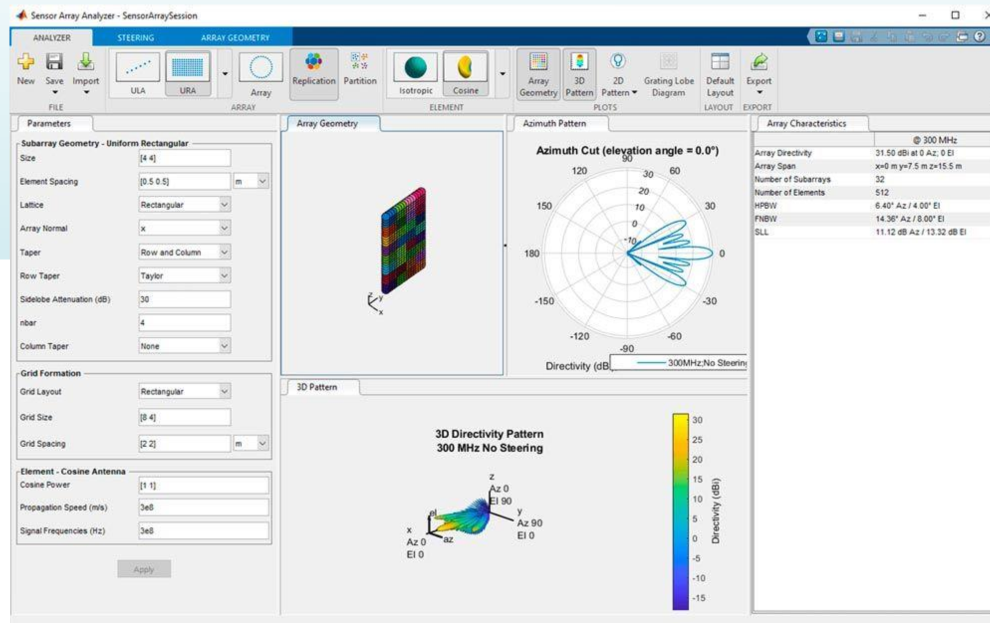
PAF Simulator

- Collaboration with Mathworks – Antenna Array Designer / Sensor array analyzer toolboxes

Honglei Chen

Babak Memarzadeh



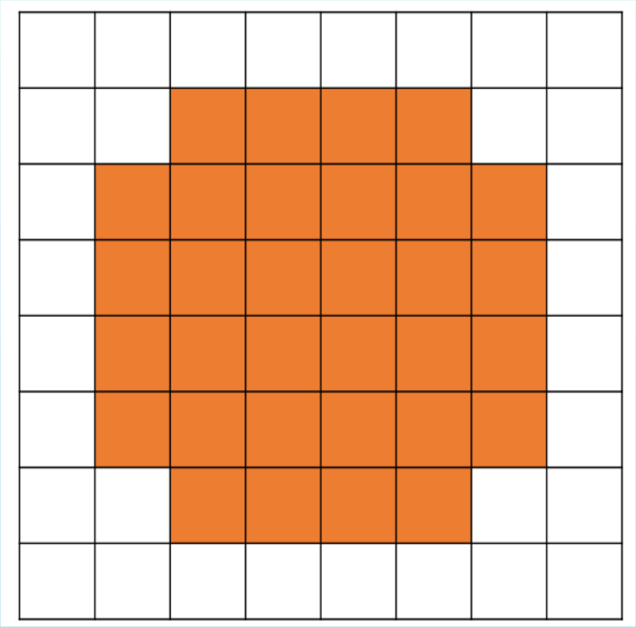


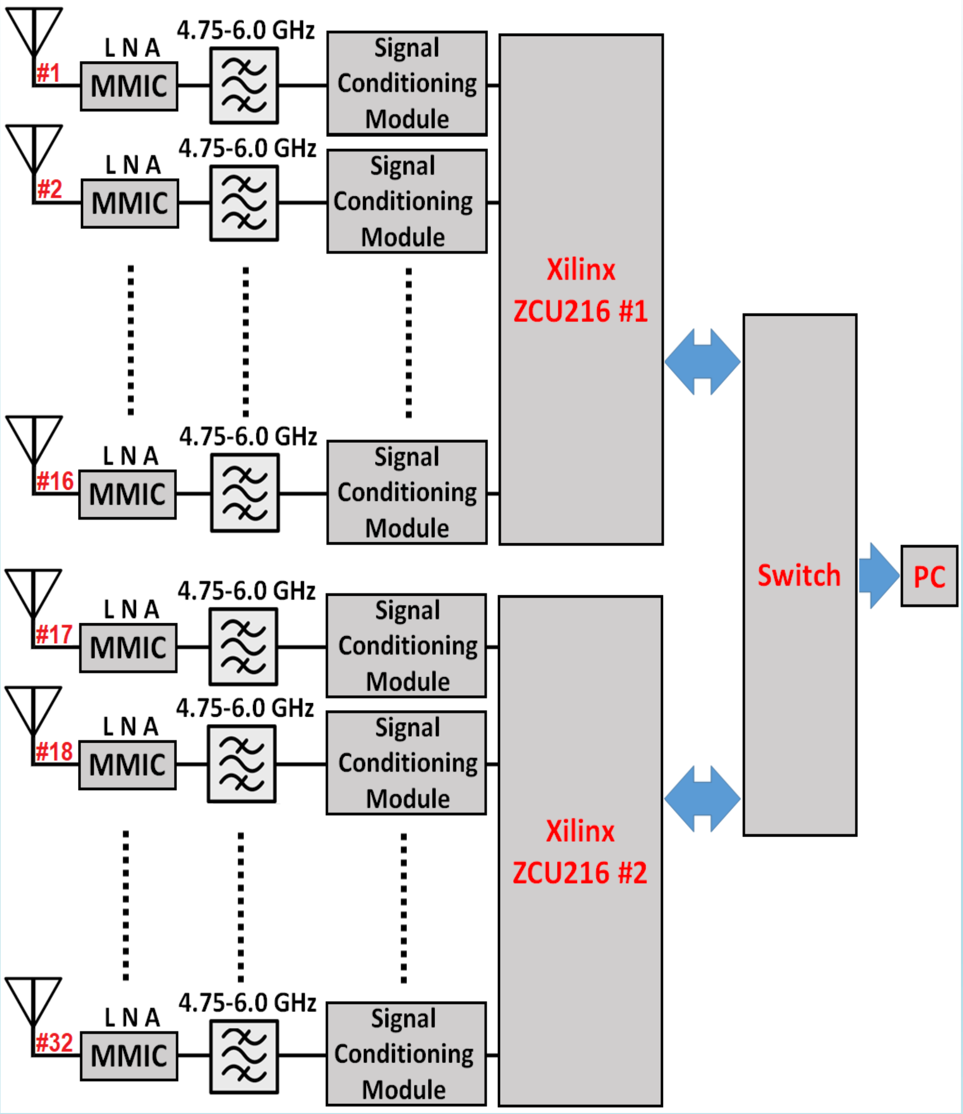
- Upgrade with an intervening reflector for radioastronomical applications

32-element PAF with two digital RFSoC boards

(connected to a 100 Gbps network switch and a PC)

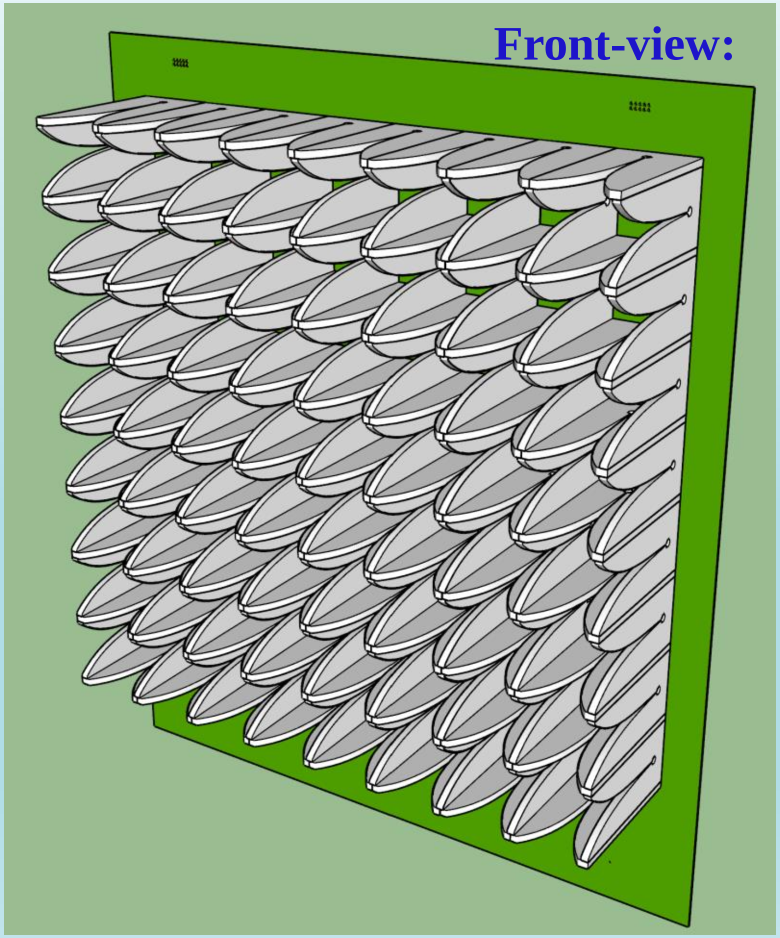
Schematic of dual-pol 8×8 array with inner 32 active antennas in one pol

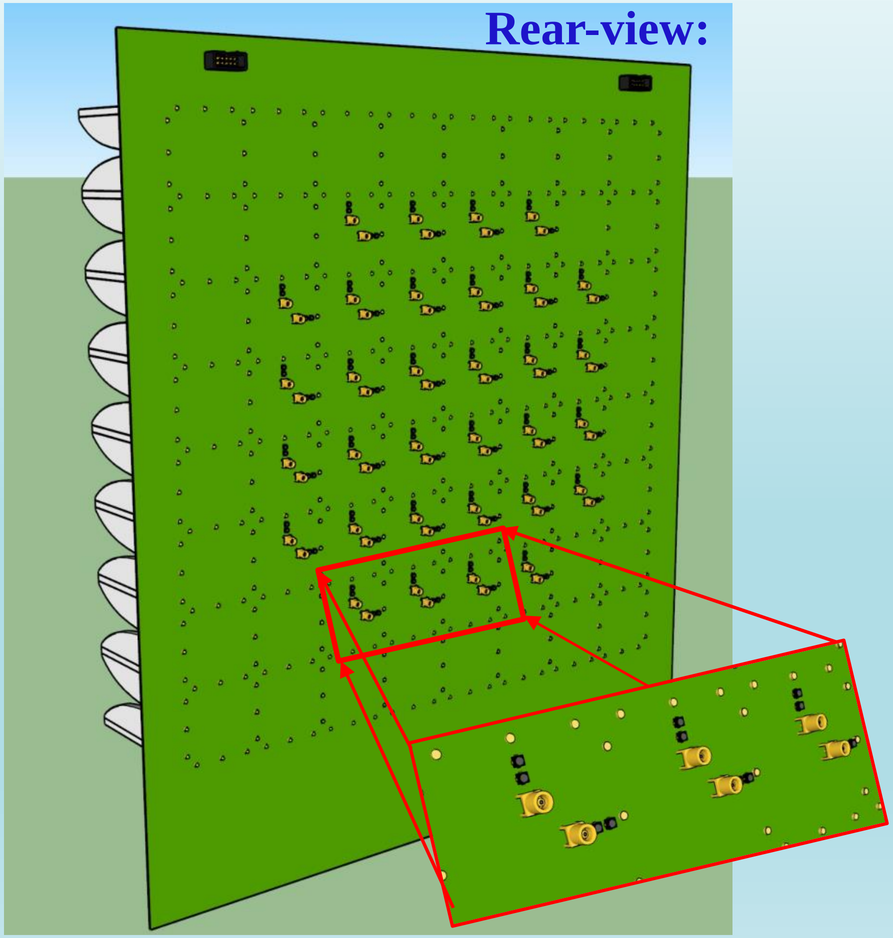




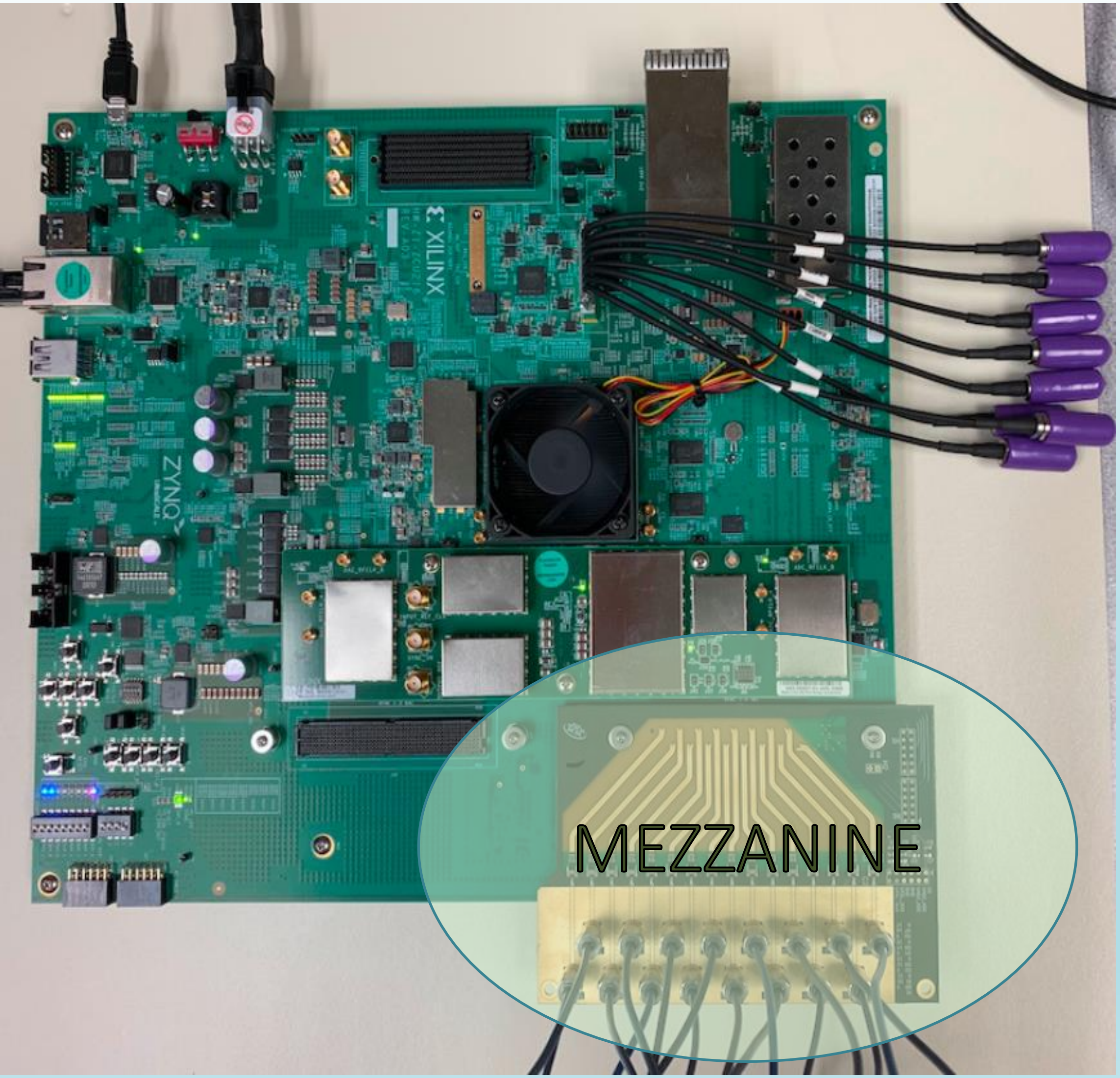
Preliminary 3D sketch showing a 8×8 array with Vivaldi antennas, 32 of which are active

- Aluminium antennas bolted on supporting low-loss dielectric board;
- RF signals extracted from the antenna probe to the board backside through via-holes;
- RF signals amplified by LNAs are cascaded with coaxial connectors;



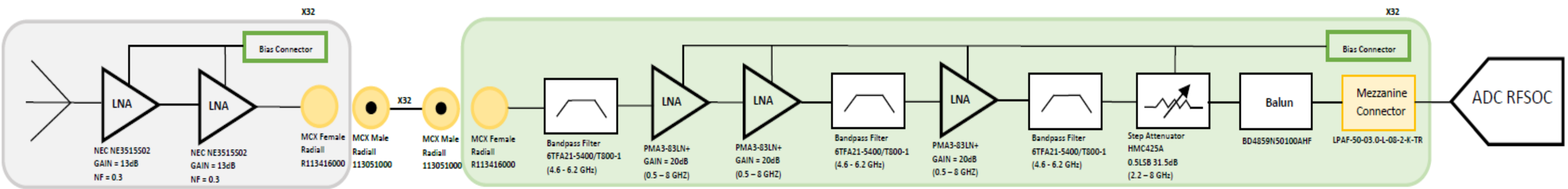


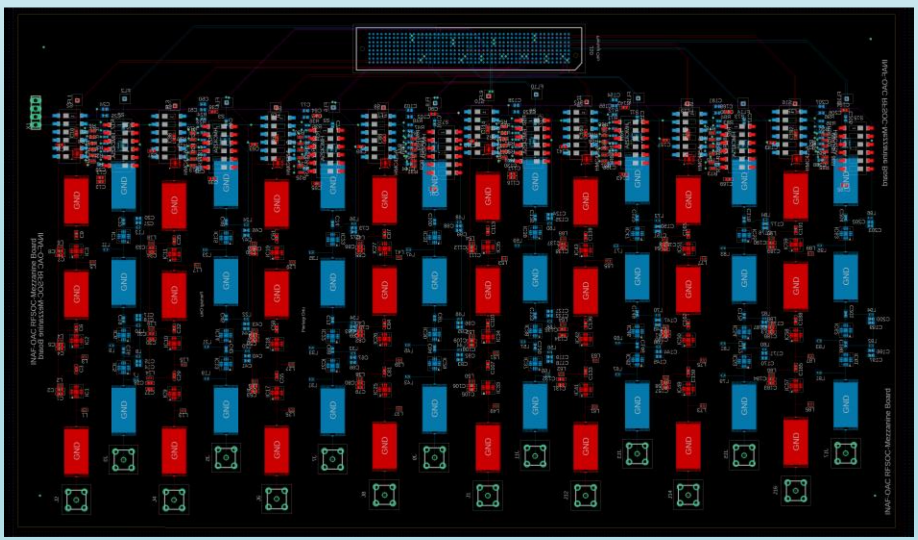
Xilinx Zynq UltraScale+ RFSoC board

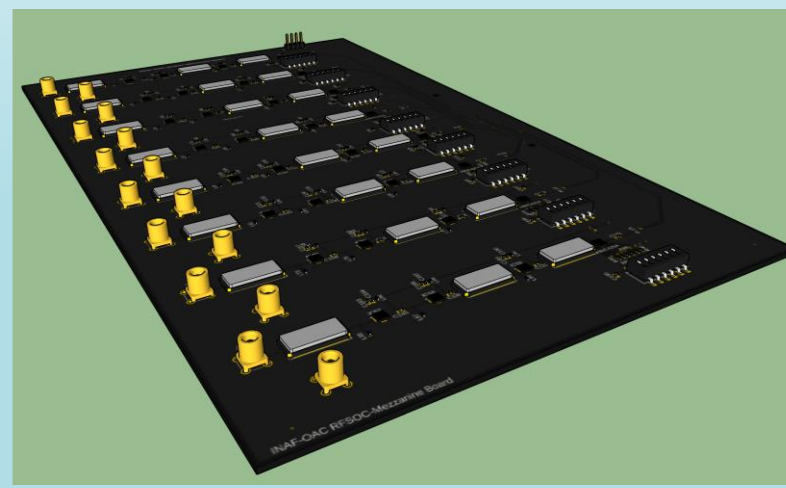


Xilinx Evaluation kit ZCU216:
- 16 inputs, 1.25 GHz BW;
- Each sample coded with 14 bit;
- Max input frequency: 6 GHz;
- I/O capacity: 4x25 Gbps.

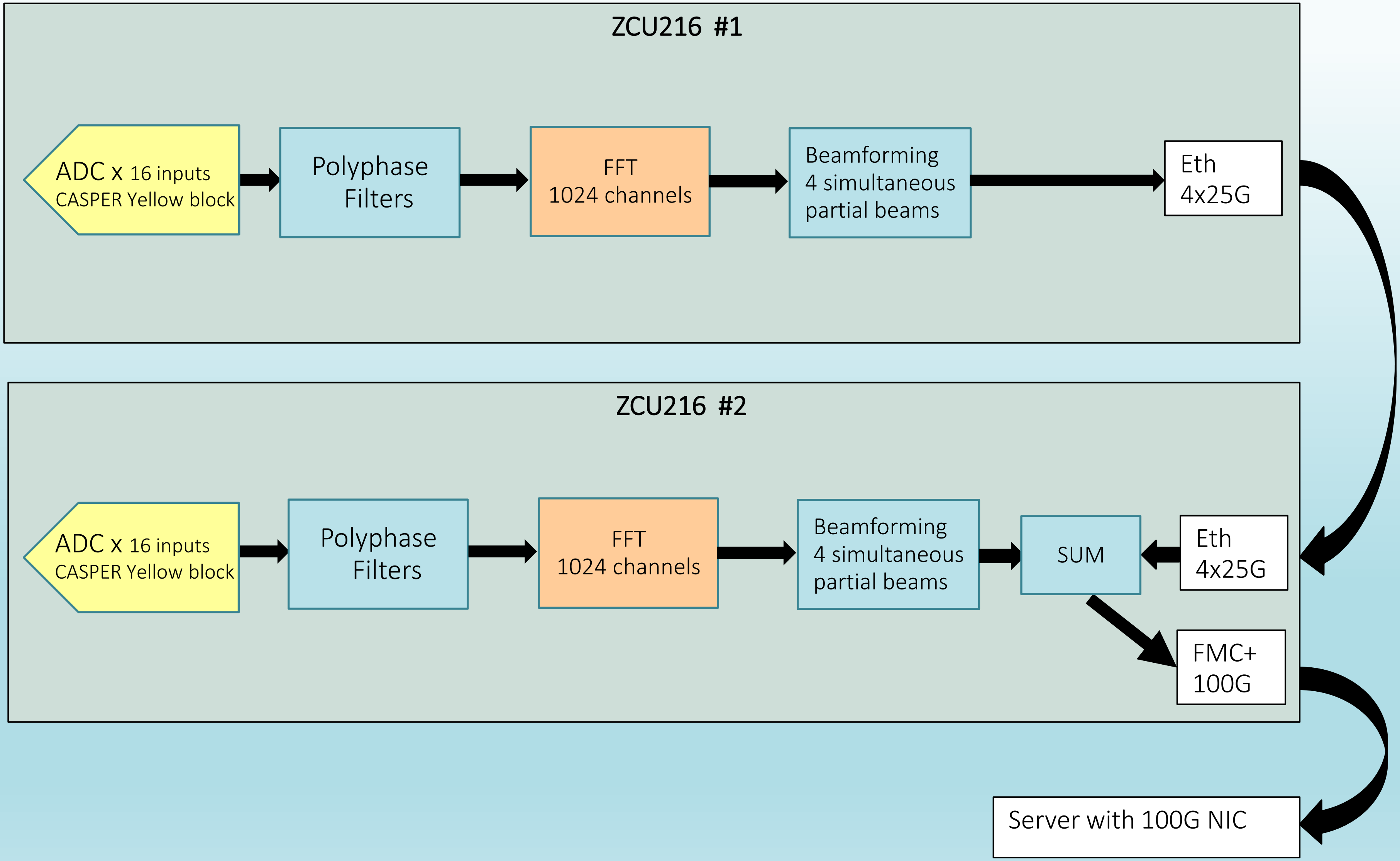
PAF mezzanine circuit schematic and board







Digital beamformer schematic



SRT main technical specifications

Primary Mirror D=64 m; Secondary Mirror D=7.9 m

Gregorian Configuration with shaped surfaces

Active Surface: Primary mirror adjustable with 1116 actuators

0.3-115 GHz frequency coverage

Six focal positions: Primary, Gregorian, & four Beam Wave Guide

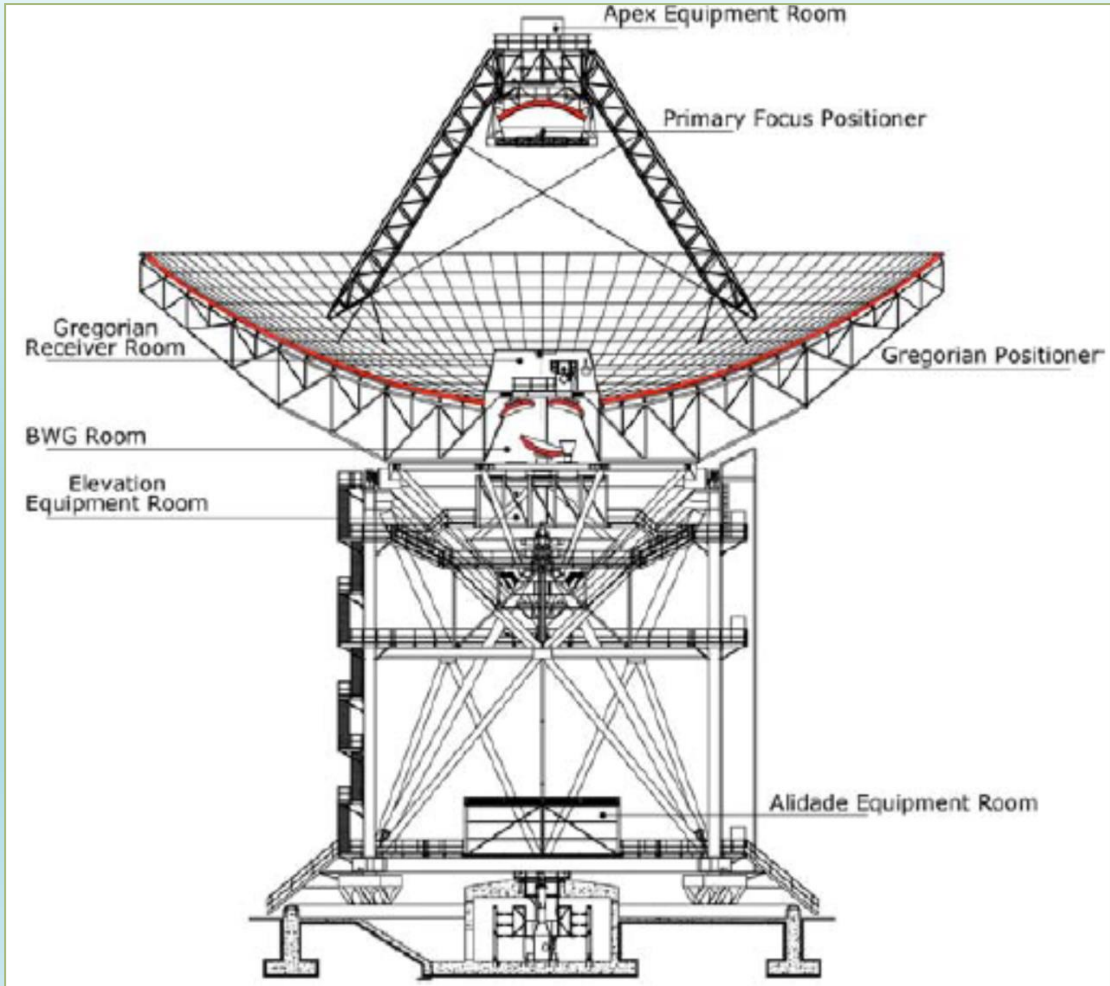
Can host up to 20 dual polarization receivers: mono feed, dual frequency, multibeam, phased array feeds;

Primary surf. accuracy:≈180 μm RMS

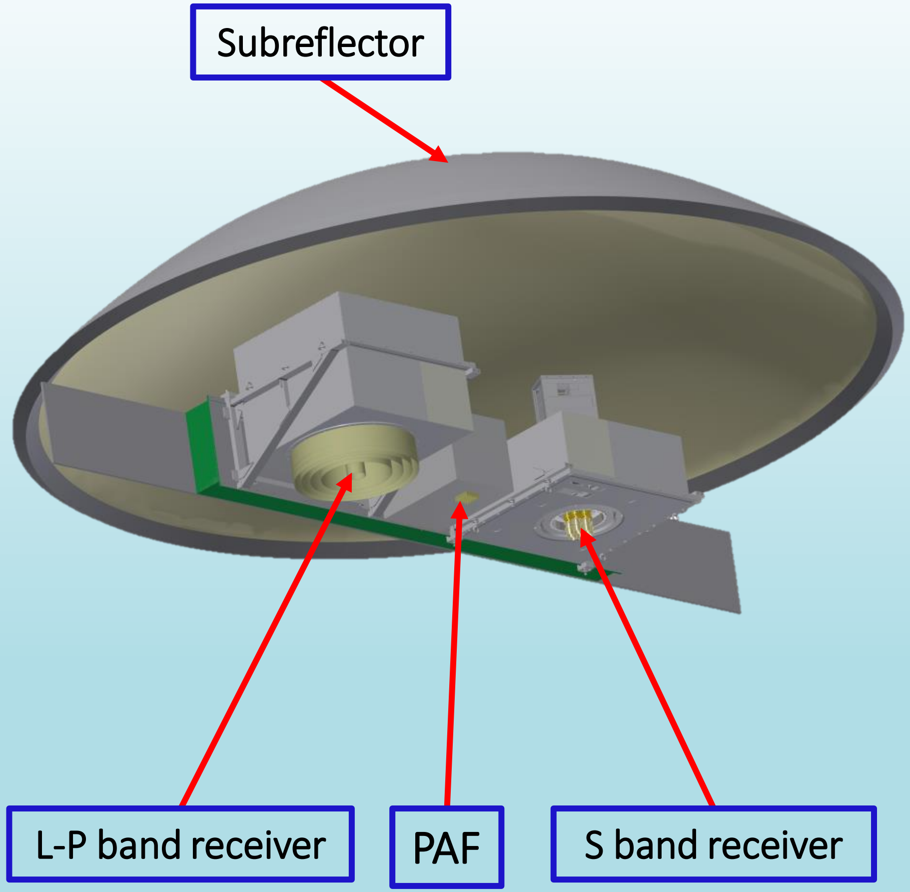
Max antenna efficiency: ≈ 60 %

Frequency agility

Pointing accuracy (RMS): 2 ÷ 5 arcsec



Preliminary 3D sketch showing an 8×8 array with Vivaldi antennas, at the primary focal position of the SRT



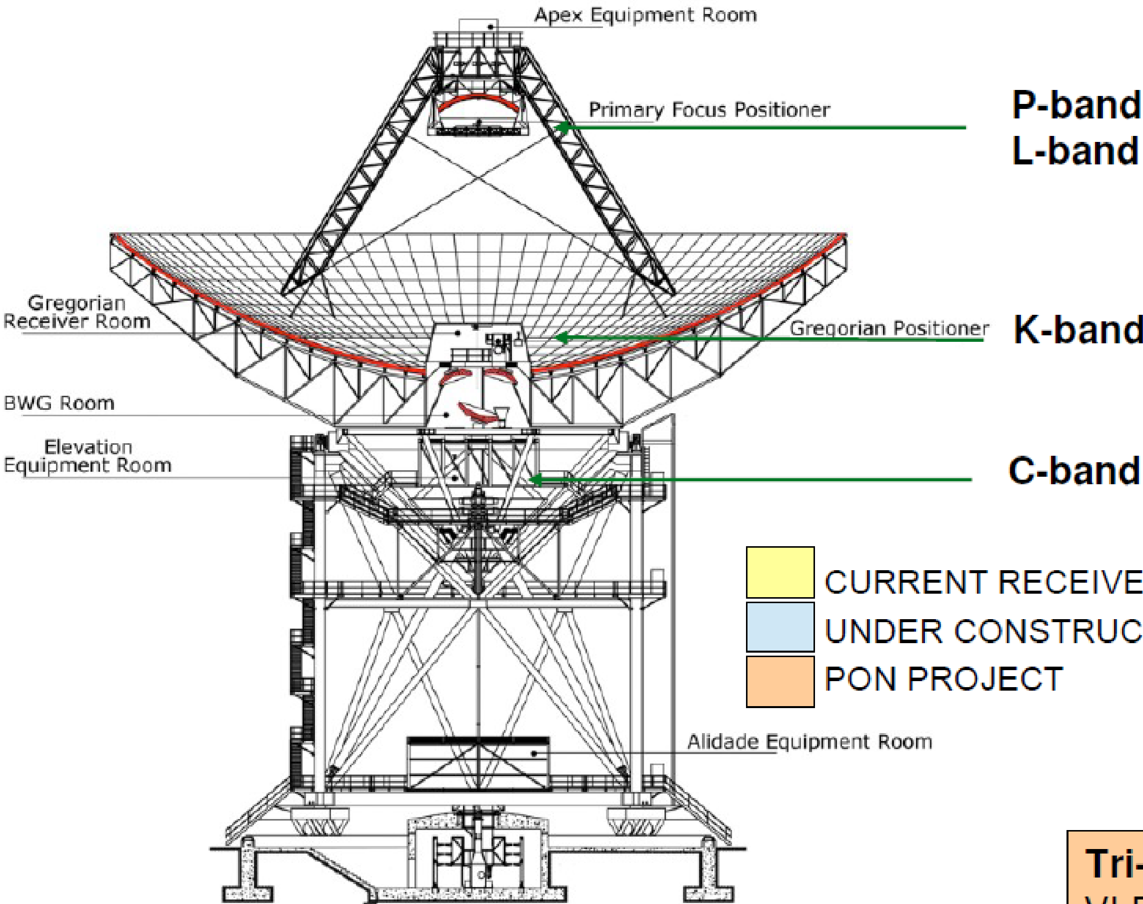
Sardinia Radio Telescope

UNIONE EUROPEA
Fondo Sociale Europeo
Fondo Europeo di Sviluppo Regionale

Ministero dell'Istruzione, dell'Università e della Ricerca

PON RICERCA E INNOVAZIONE

2. Architecture of INAF C-band PAF with RFSoC



CURRENT RECEIVERS
UNDER CONSTRUCTION
PON PROJECT

GREGORIAN RECEIVERS ROOM

Tri-band K/Q/W
VLBI (SRT, Medicina, Noto)
18-26, 35-50, 86-116 GHz

Millimeter Camera
80-116 GHz

P-band
305-425 MHz

L-band
1.3-1.8 GHz

C-band
5.7-7.7 GHz

K-band multibeam
18-26.5 GHz

Frequency

S-band
3.0-4.5 GHz

Clow-band
4.2-5.6 GHz

Q-band
multibeam
33-50 GHz

W-band
multibeam
75-116 GHz

Future perspectives

- Design and build a cryogenic PAF covering 3.0-7.7 GHz with at least 12×12+ array of dual-pol antennas, with 30+ synthesized beams, 1GHz+ BW for the 64-m Sardinia Radio Telescope (SRT);

- A steady improvement in PAF sensitivity is demonstrated by the international community, both for room temperature as well as for cryo cooled systems. For each PAF beam, the goal is to match the performance of best Single Pixel Feed receivers across broad bands;

- For competitiveness, capital and operational costs of PAFs needs to be reduced, in particular for PAFs proposed to be built in significant quantities;

- Constant improvement of digital backend capabilities, including the RFSoC technology currently being explored by INAF, might enable PAF developments at relatively low-cost in the future.

Conclusions

- Our INAF team has contributed to develop the PHAROS and the PHAROS2 C-band PAF demonstrators and is currently developing a new up-scalable demonstrator C-band PAF based on RFSoC that directly samples the RF;

- These technologies could find application for the Italian radio astronomy antennas and for the SKA

- We plan to integrate in the PAF the high C-band and the S band SRT receivers

THANK YOU!