The PHAROS2 Phased Array Feeds (PAF) and future perspectives of PAF developments at INAF

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On behalf of the INAF PAF Team and of the International PHAROS2 collaboration

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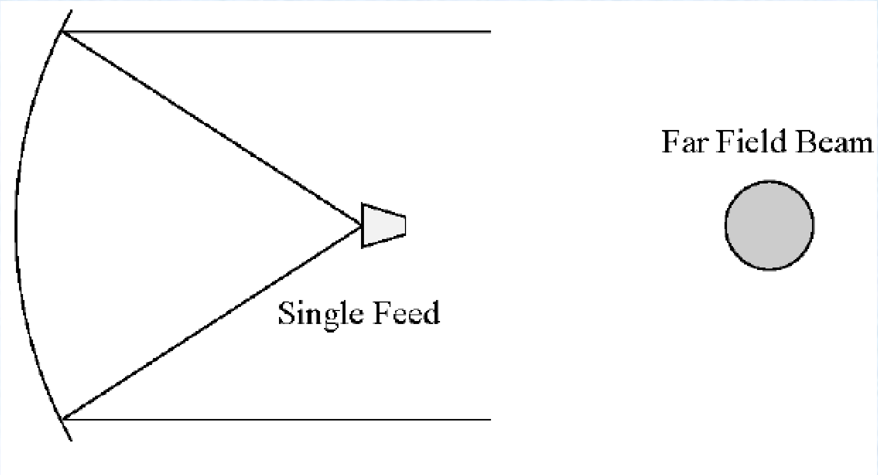
Overview

1. Introduction to Phased Array Feeds;
2. The PHAROS programme;
3. SKA Advanced Instrumentation Programme on PAFs;
4. Science motivations of C-band PAF for INAF community;
5. The PHAROS2 upgrade and antenna tests;
6. Future perspectives;
7. Conclusions.

Introduction to Phased Array Feeds

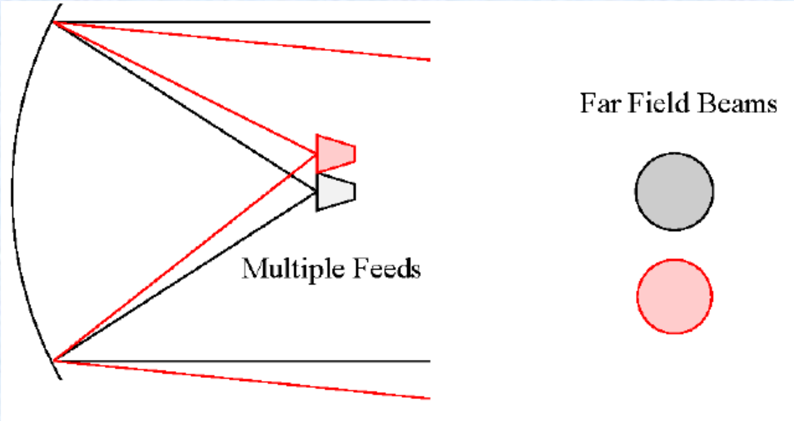
- Single Pixel Feed, Multibeam and PAF
- Difference between PAF and Aperture Array

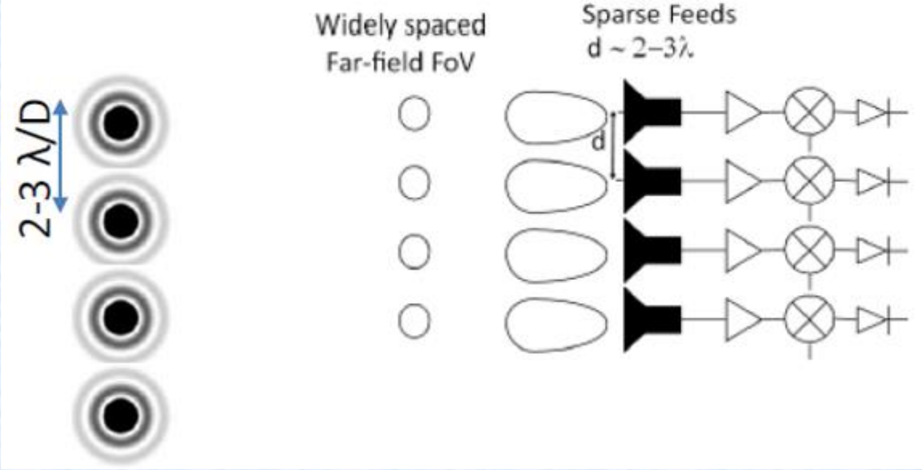
Single Pixel Feeds, Multibeam and PAF



- Single Pixel Feeds (SPFs) are the gold standard for cryogenic microwave receivers
- <0.1 GHz to THz
- Large instantaneous bandwidth
- Feed aperture diameter >λ (depends of F/D), required to achieve high-antenna efficiency

Single Pixel Feeds, **Multibeam** and PAF



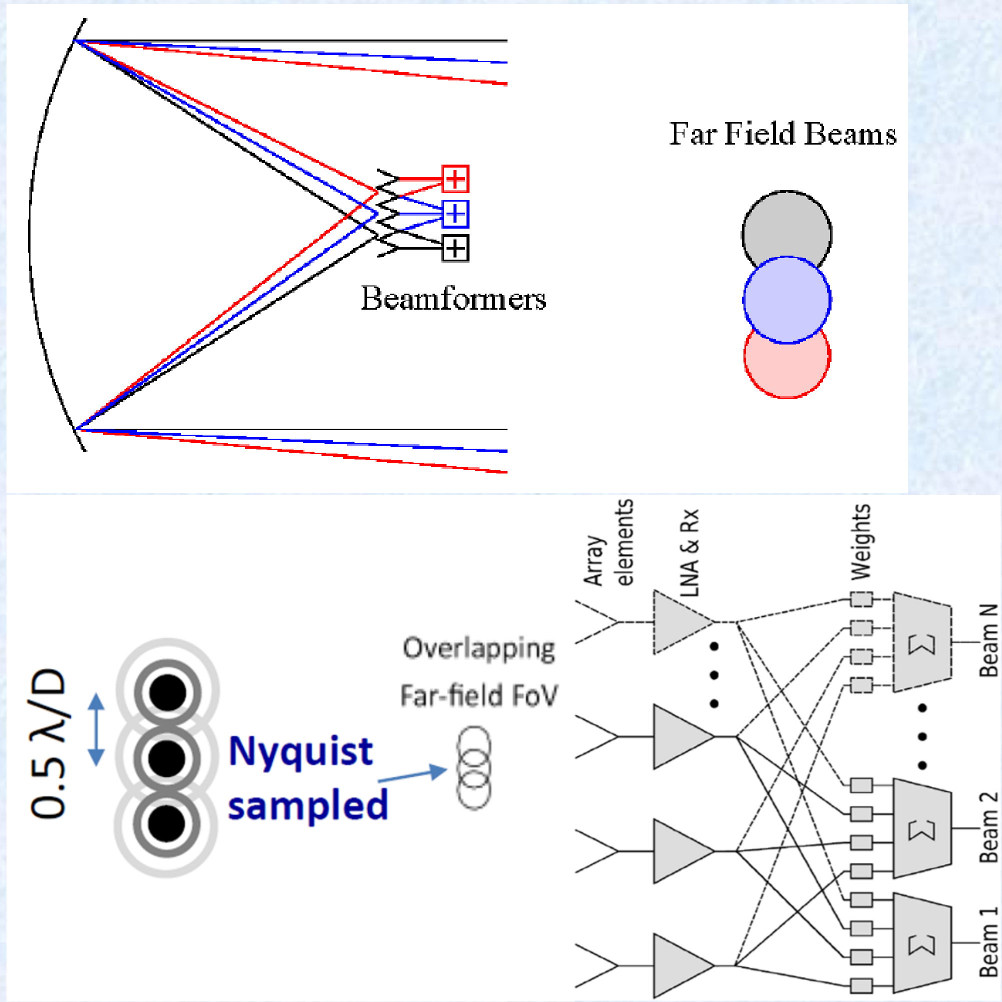


- One feed per beam
- Each feed matched to reflector
- Sparse array
- Frequency-independent separation between far-field beams (but HPBW is frequency dependent)

- Multibeam feeds are a collection of single pixel feeds, placed as close as possible...
- Field of View (FoV) increase is proportional to number of feeds
- But, focal region not evenly sampled
- Offset beams have distorted profile, greater sidelobes, greater cross-pol, lower A_{eff}

Single Pixel Feeds, Multibeam and PAF

Phased Array Feeds

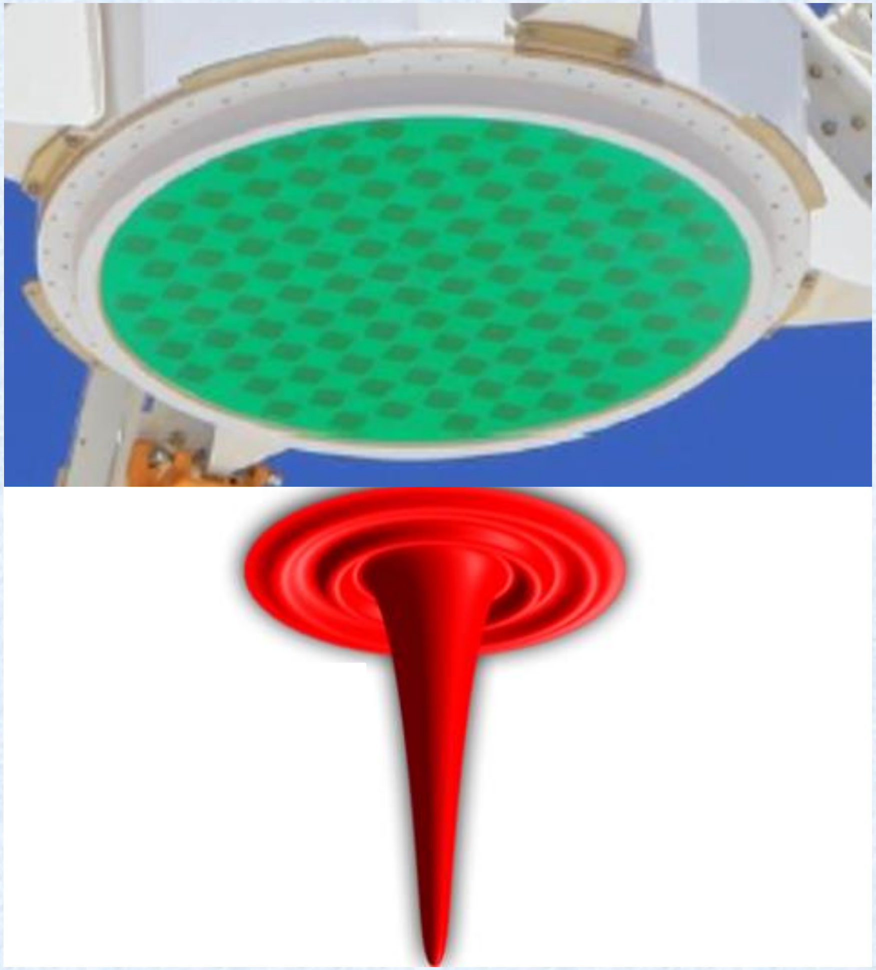


- Phased Array Feeds have even more densely packed feeds than multibeam feeds: d≈0.5 λ
- Interconnected PAF antennas are coherently combined in beamformers with appropriate complex "weights" to synthesize several discrete beams
- Digital beamformer enables optimization on a "per-frequency-channel" basis (≈1 MHz BW)

PAF elements sample the focal plane

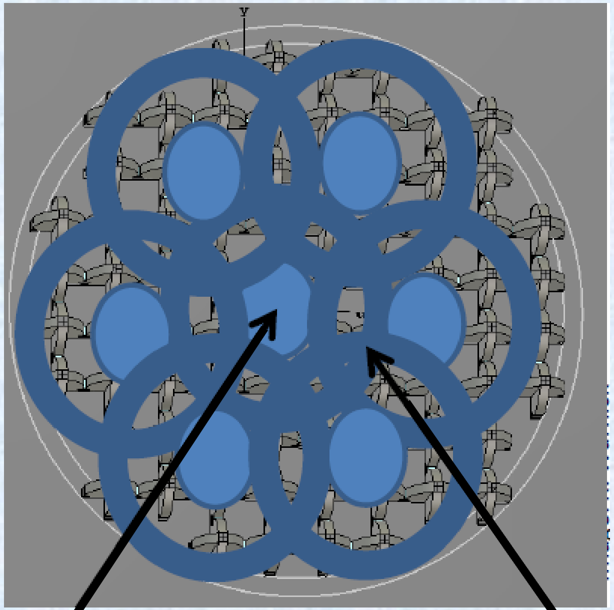
PAF array at the primary focus of a radio telescope

One of the Airy patterns is sampled by various PAF antenna elements



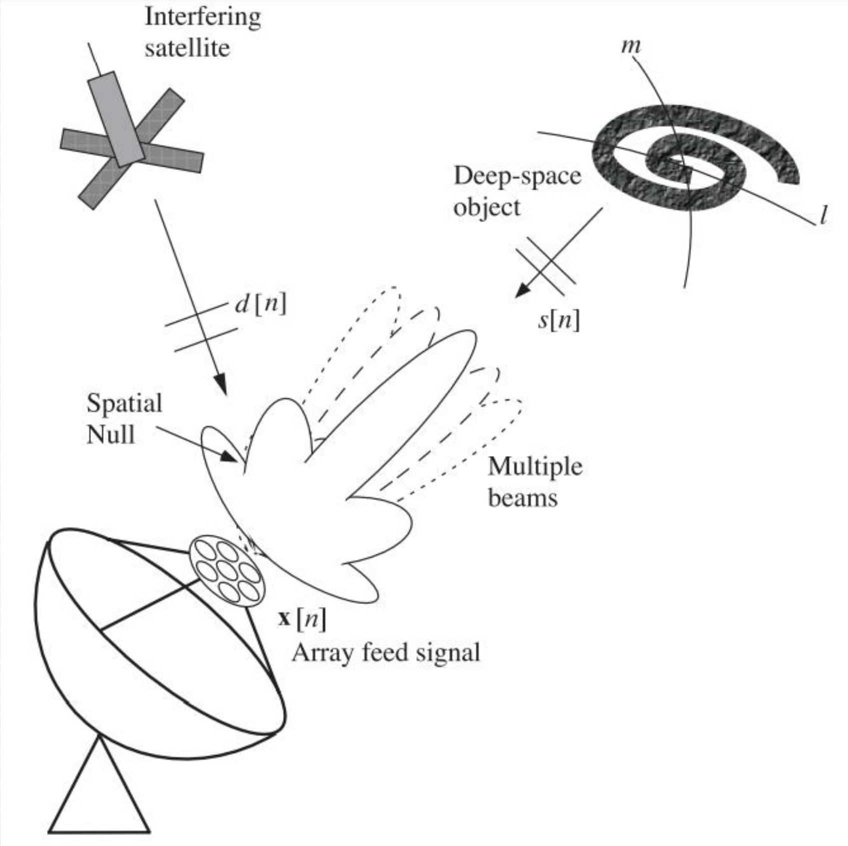
Focal plane sampling, beams, beamforming algorithms and survey speed

Example of 7 Airy patterns superimposed on a PAF array



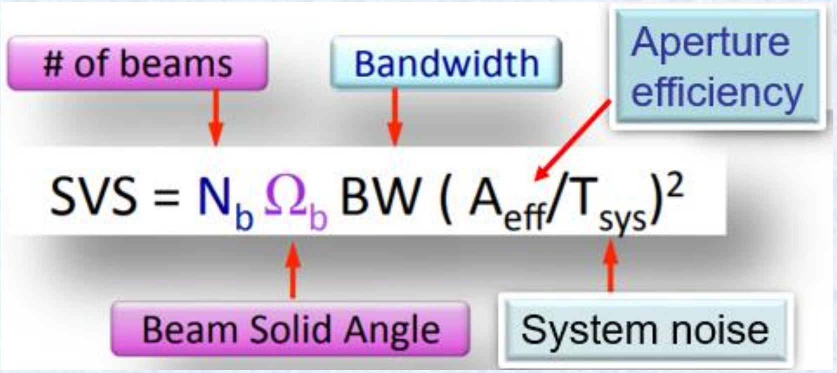
Central Airy disc (focal spot)

Second Airy ring



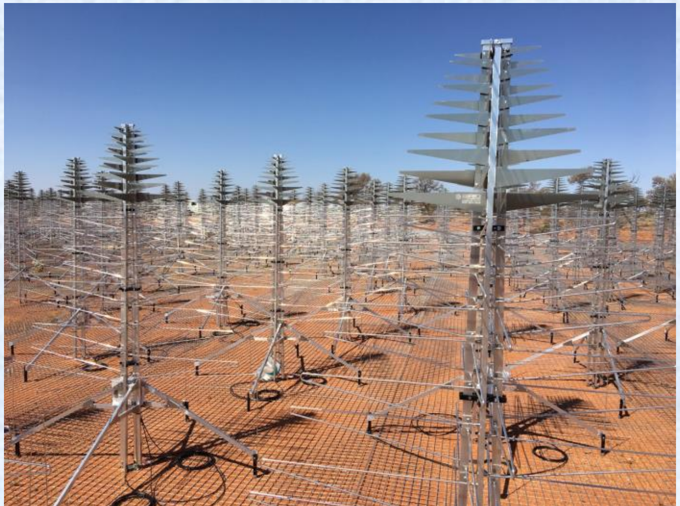
Various different beamforming algorithms can be implemented in a PAF, for example:

- Conjugate Field Match;
- Max SNR;
- LCMV (Linearly Constrained Minimum Variance).



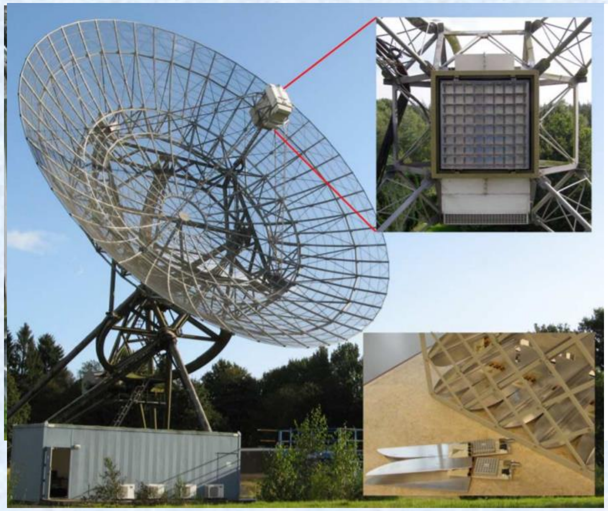
PAFs and Aperture Arrays in radio astronomy

- In modern jargon, a phased array that receives radiation directly from the sky is known as an aperture array (because the elements themselves form the aperture of the telescope).
- LOFAR in the Netherlands, SKA-low and the MWA in Western Australia are all aperture array telescopes.



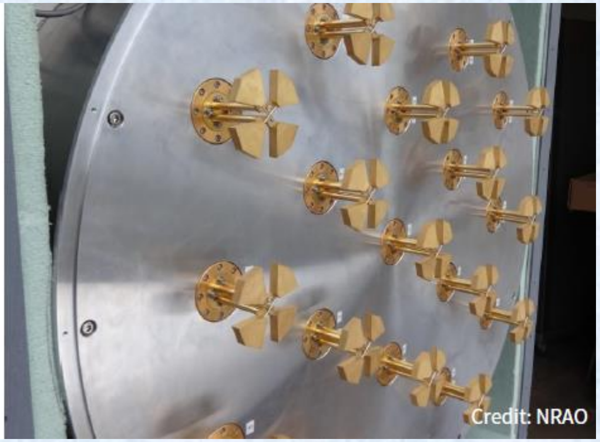
Examples of existing L-band PAFs

APERITIF
(room temperature PAF)



ASKAP
(room temperature PAF)

FLAG
(cryogenic PAF)



0.7-1.8 GHz ASKAP PAF: Each phased array feed (of the 36×12-m antennas) is made up of 188 individual receivers, positioned in a chequerboard-like arrangement. The PAFs create 36 separate (simultaneous) beams to give a field-of-view of 30 square degrees on the sky.

Some of the PAFs under development

- Parkes cryo PAF 700-1900 MHz;
- FAST cryo PAF 1050-1450 MHz;
- Effelsberg cryo PAF 2500-3500 MHz,
- ALPACA – Upgrade of FLAG;
- NCRA GMRT PAF;
- UMan S-band PAF;

Some of the advantages of Phased Array Feeds

- Possibility to achieve complete coverage of the available radio telescope Field of View (FoV) with multiple simultaneous beams, thus increasing the survey speed if compared to a single-pixel feed;
- Improve antenna efficiency over very wide freq. band;
- Correct for off-axis aberration;
- Reduction of bandpass ripples;
- Compensate for large-scale distorsion of dish surface errors;
- Direct one or more beams towards calibrators while observing the astronomy source of interest (reduces total observation time);
- Radio Frequency Interference (RFI) mitigation;
- Improvement of the beams polarization purity;
- Possibility to perform electronic de-rotation of the astronomical field during source tracking.
- Reconfigure the properties of the beams in real time;
- Elaborate observations in post-processing using a post-correlation beam former;

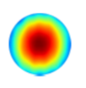
Main challenges of PAF technology for Radio Astronomy application

- System complexity;
- Sensitivity over broad bandwidth (PAF noise temperature versus SPF noise temperature);
- Costs.

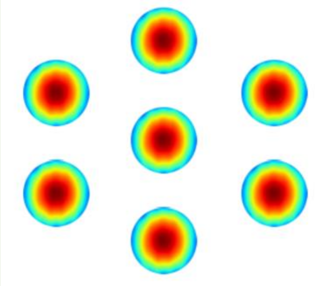
PAFs in summary

A PAF is a radio receiver based on a dense array of interconnected antennas capable of synthesizing multiple independent beams whose shape and direction can be controlled electronically without moving (pointing) the array. The features of each of the beams depend on the amplitude and phase of the signals applied to the individual antennas by a beamformer that can be of analog or digital types. PAFs can simultaneously offer improvements in the efficiency of existing telescopes and open up the widest possible field-of-view.

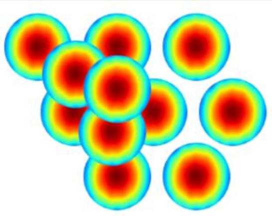
Radiation beam from single pixel feed



Radiation beams from 7-beam multibeam receiver



One possible configuration of the radiation beams from a PAF (with 13 beams)



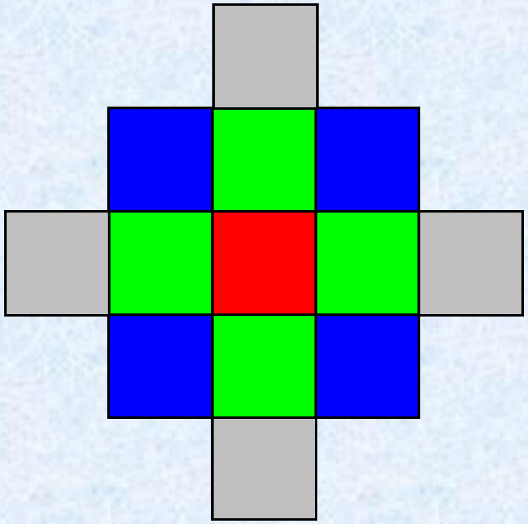
PHAROS

PHased Arrays for Reflector Observing Systems

PHAROS

PHAROS is an Analog Phased Array designed to produce four synthesized beams. Each beam is synthesized with 13 focal plane antenna elements:

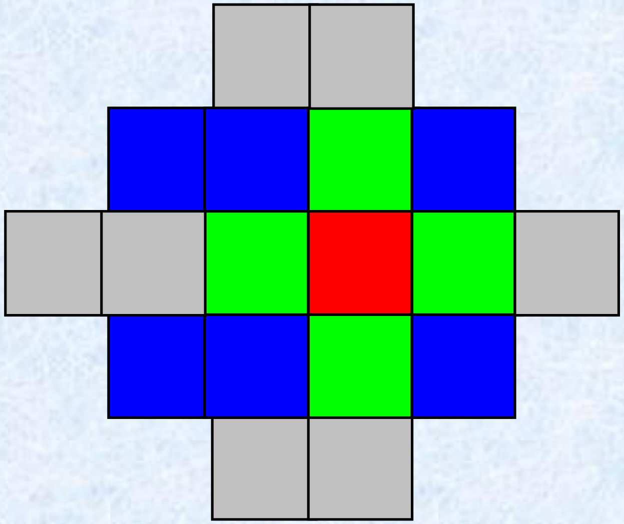
Beam 1



PHAROS

PHAROS is an Analog Phased Array designed to produce four synthesized beams. Each beam is synthesized with 13 focal plane antenna elements:

Beam 2



PHAROS

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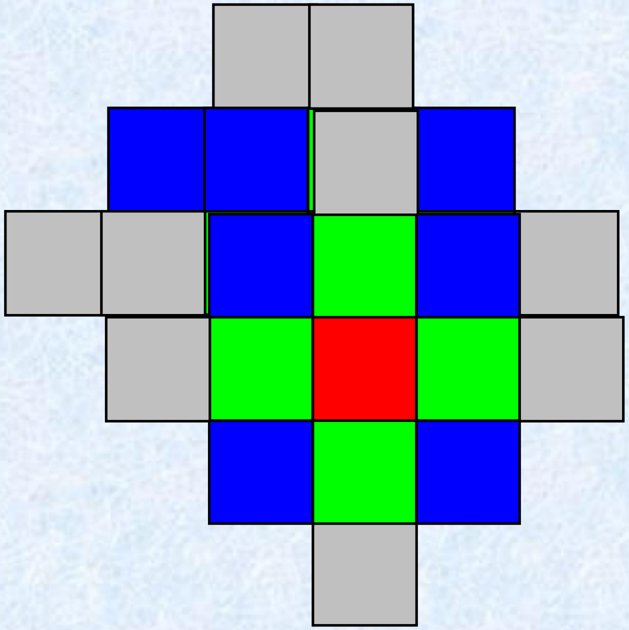
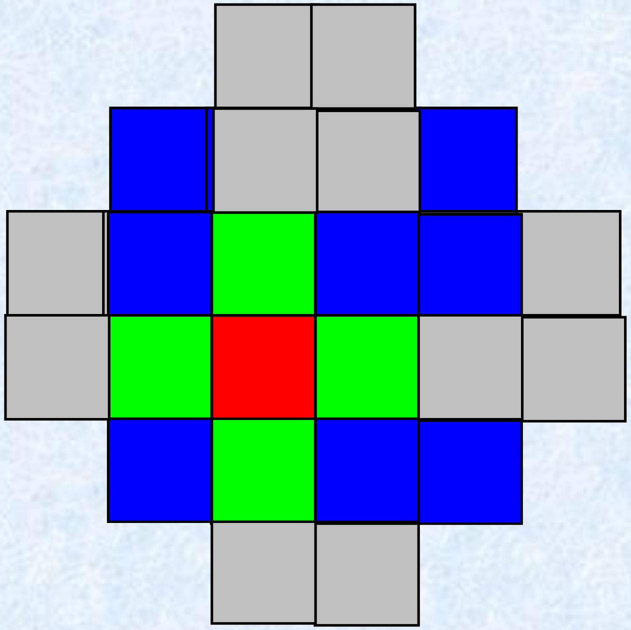


Beam 3

PHAROS

PHAROS is an Analog Phased Array designed to produce four synthesized beams. Each beam is synthesized with 13 focal plane antenna elements:

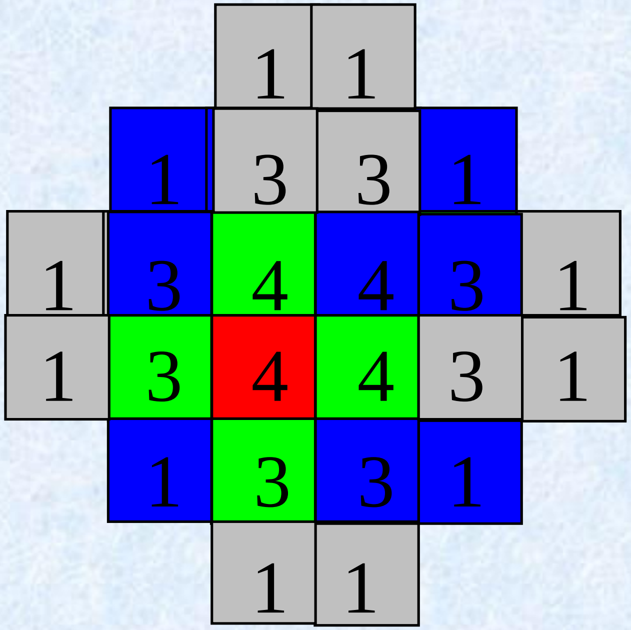


Beam 4

PHAROS

PHAROS is an Analog Phased Array designed to produce four synthesized beams. Each beam is synthesized with 13 focal plane antenna elements:

Some of the elements contribute to form more than one beam;



PHAROS

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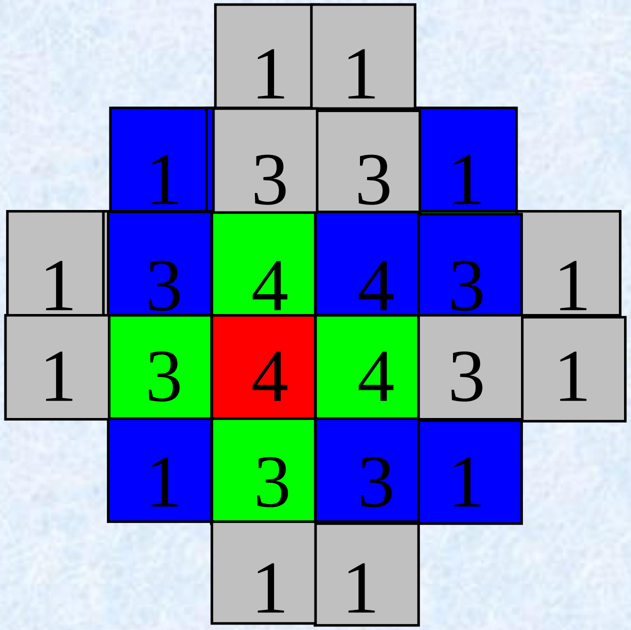


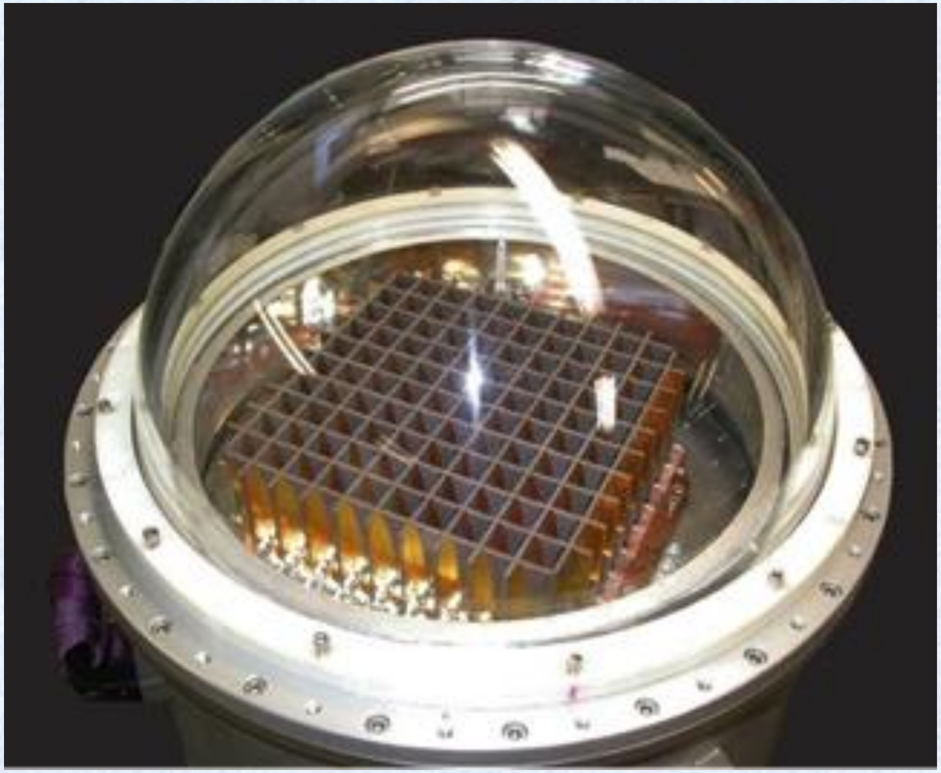
Some of the elements contribute to form more than one beam;

24 active antenna elements in one polarization;

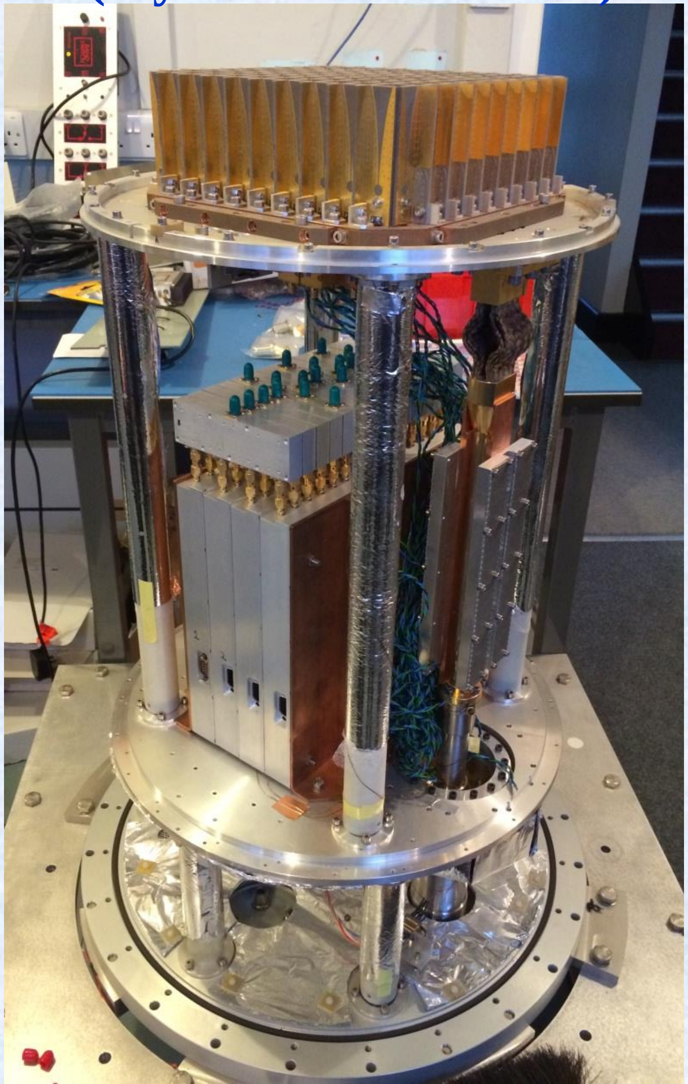
PHAROS

- Collaboration started >12 years ago. Originally, 7 international partners involved;
- Goal: develop a demonstrator of a cryogenically cooled PAF;
- Array of 10x11 dual-pol. Vivaldi antennas;
- 24 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):



PHAROS cryo and vacuum systems

SKA PAF Advanced Instrumentation Programme (AIP)

- PAF technology is not part of SKA1. The SKA Observatory includes a SKA Observatory Development Programme (SODP) of telescope development towards SKA2 for enhancements/extensions of SKA1;
- SKA1-Mid antennas have been designed to incorporate PAF receivers in the future. PAF technology might find application in SKA-Mid;
- The SKA PAF AIP was established in 2016 in Cagliari. Nine international institutions are part of the PAF Consortium, including INAF;
- The SKA AIP on PAF is funded by in-kind contributions of the member institutes that are focussed on their own PAF R&D programs with no real focus on SKA PAFs yet;

Science motivations for C-band PAF

- SKA Band 5 has second highest priority
- C-band continuum surveys and polarization measurement, particularly in the Galactic Plane
- CMB foregrounds
- Gamma Ray Burst and Gravitational Wave event follow-ups
- FRB search
- Flat spectra transients/pulsars, like magnetars
- Excited rotational states of OH near 6.03 GHz
- Zeeman effect, star formation
- CH3OH line (6.7 GHz) survey of methanol masers
- Gas kinematics, UC HII region
- Formaldehyde line emission at 4.8 GHz
- Polarization mapping of Galaxy Clusters and SNRs
- Hydrogen recombination lines around 5 GHz
- Galactic Centre high DM pulsar search

PHAROS2

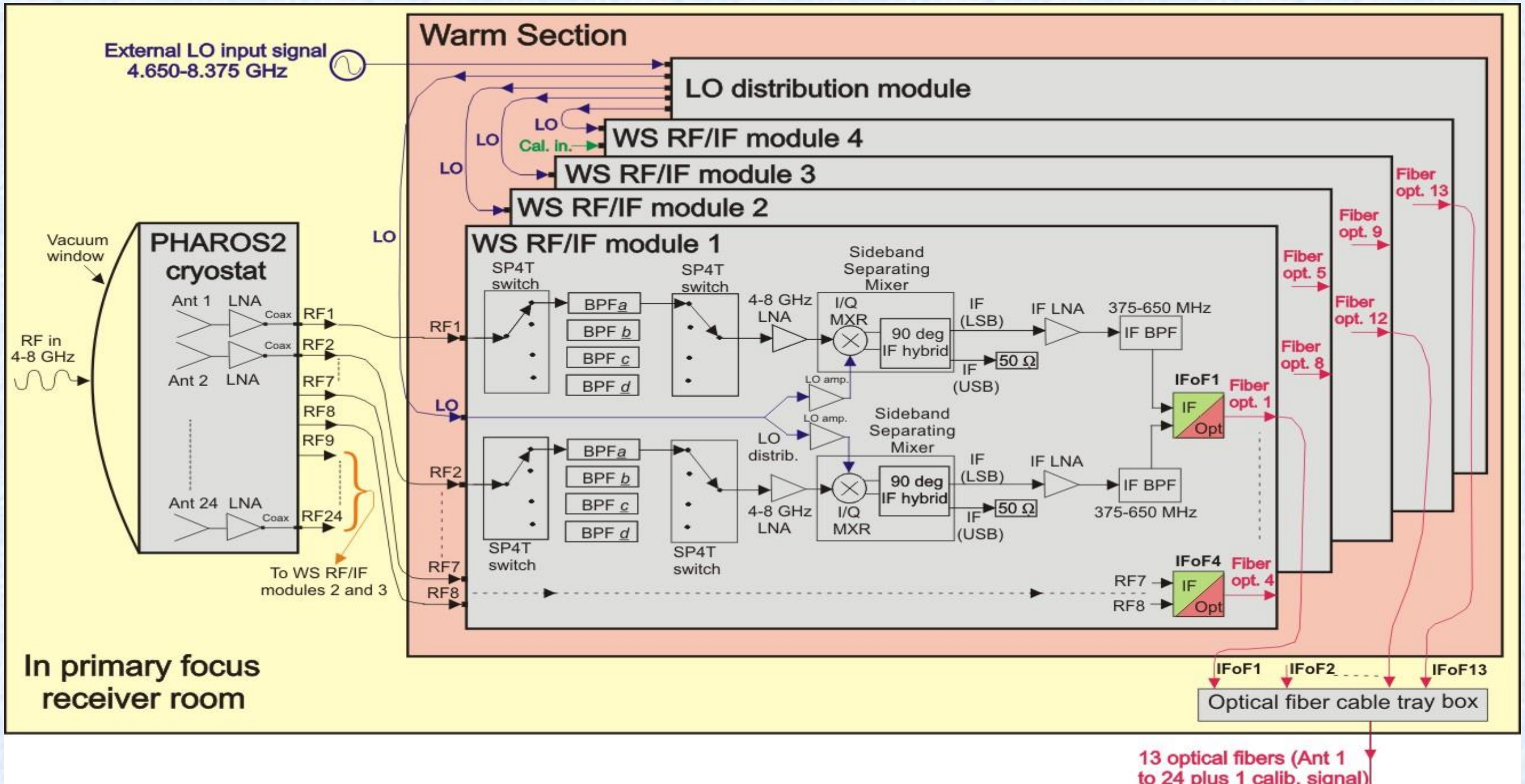
PHAROS2: upgrade of PHAROS PAF

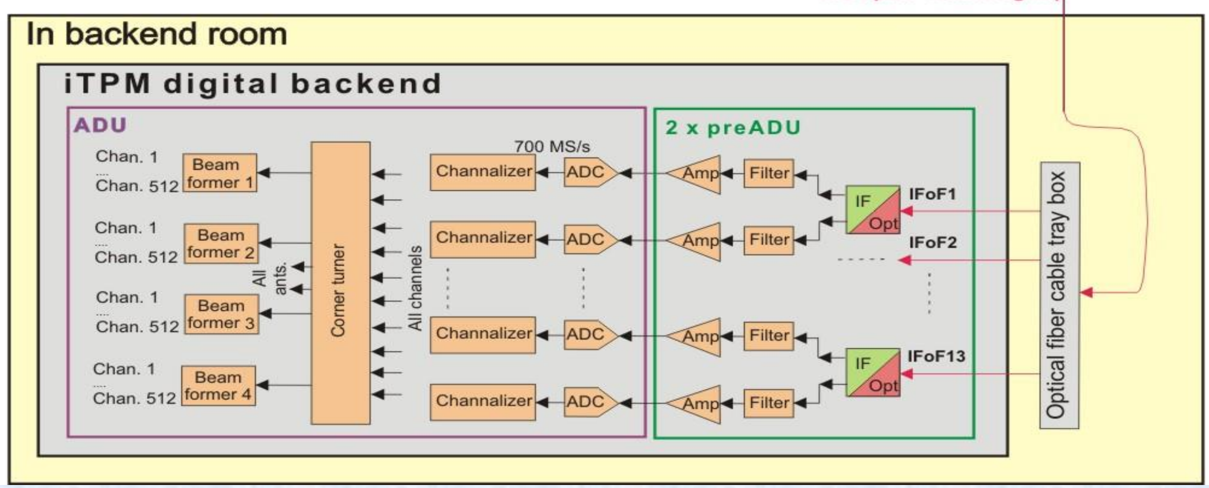
- Demonstrator of possible technologies for the SKA;
- One of the Work Packages of the PAF SKA AIP;
- A collaboration of five institutes:

INAF leadership

- New cryogenic Low Noise Amplifiers (commercial);
- INAF Digital Back-End based on iTPM hardware;
- INAF C-band multi-channel heterodyne receiver (Warm Section) to deliver ≈275 MHz bandwidth to the iTPM Digital Back-End;

Architecture of PHAROS2



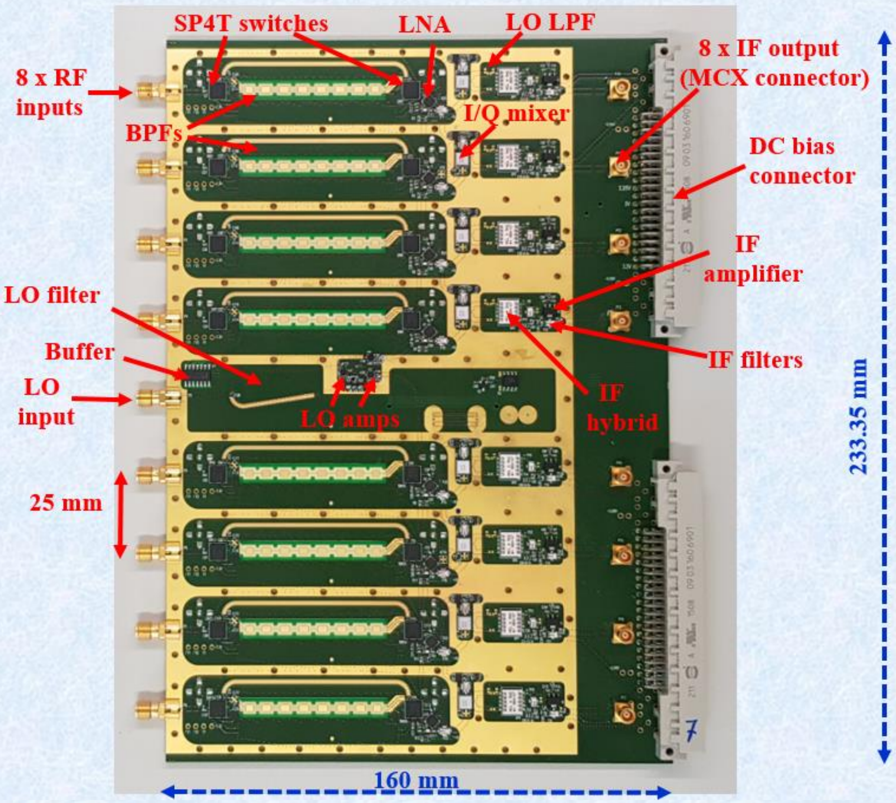


BPF-A: 2.300-8.200 GHz; LO tuning f_{LO}=2.950-8.575 GHz
BPF-B: 4.775-5.050 GHz; f_{LO}=5.425 GHz
BPF-C: 5.780-6.055 GHz; f_{LO}=6.430 GHz
BPF-D: 6.445-6.720 GHz; f_{LO}=7.095 GHz

Eight-channel C-band Warm Section Heterodyne Rx Module

RF: 2.3-8.2 GHz; IF: 375-650 MHz

One eight-channel C-band board:

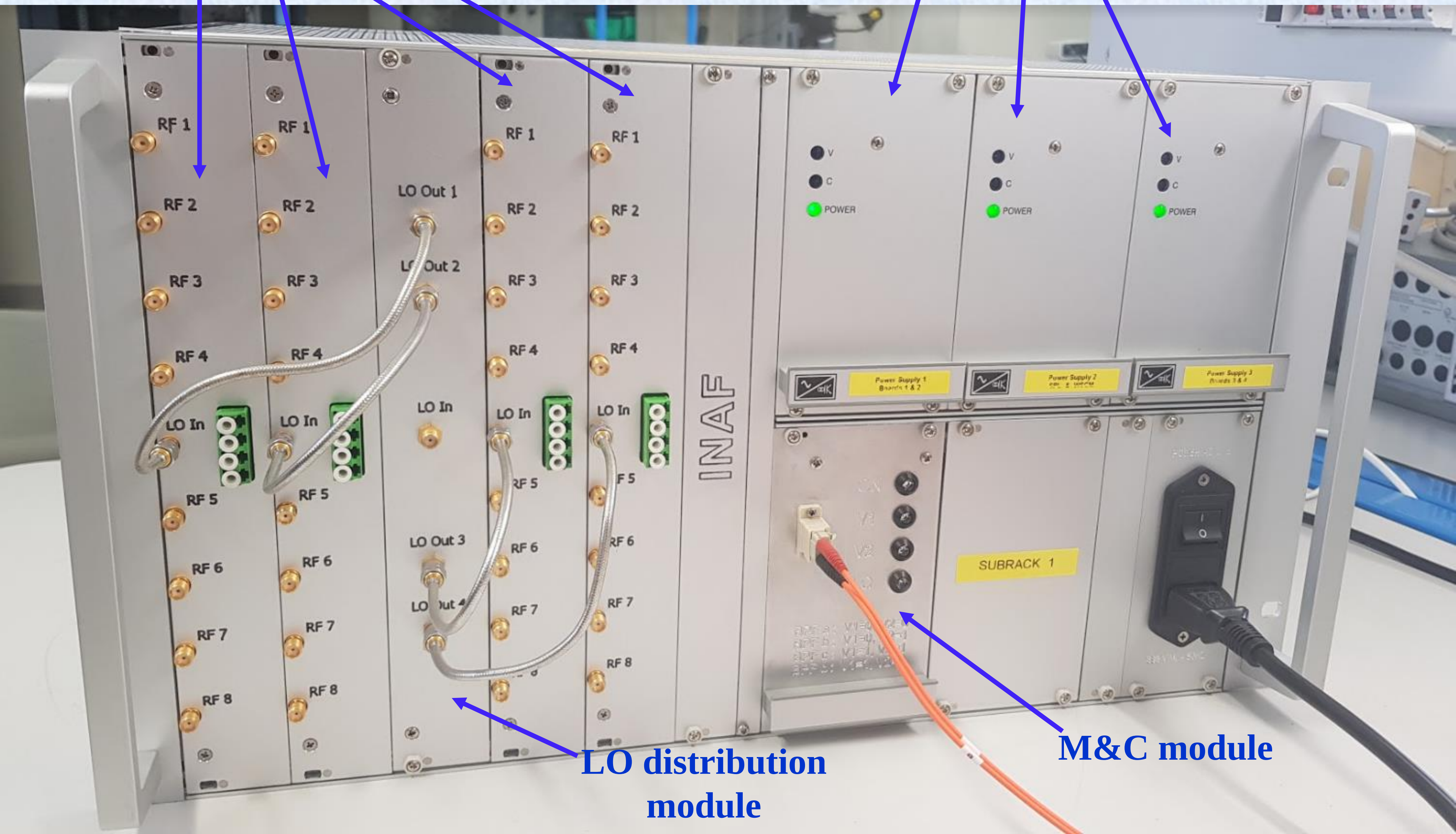


Two eight-channel modules assembled with IF over fiber (IFoF) optical transmitters:

32-channel C-band Warm Section Heterodyne Receiver for PHAROS2 developed at INAF

4×eight-channel modules

Power supplies

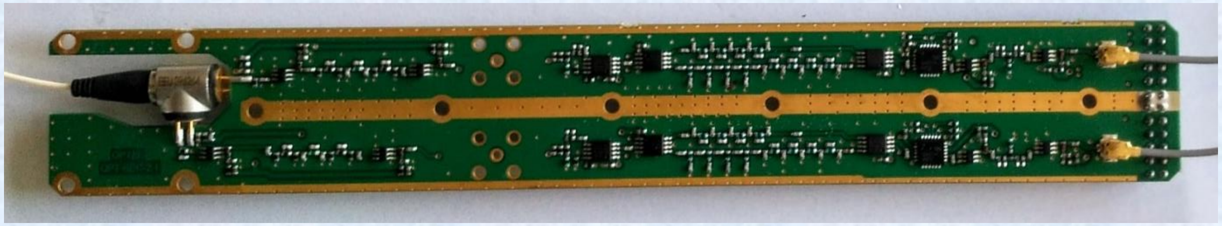


PHAROS2 IFoF WDM links developed for SKA LFAA

- Two different IF signals transmitted over same optical fiber using optical carriers at λ=1270 nm and λ=1330 nm;
- Dual laser sources and dual photodiode detectors in single packages;
- Input IF band in the OTX: 375-650 MHz; Isolation between channels >45 dB;

Some of the OTXs (optical transmitters) before integration into the WS RF/IF modules:

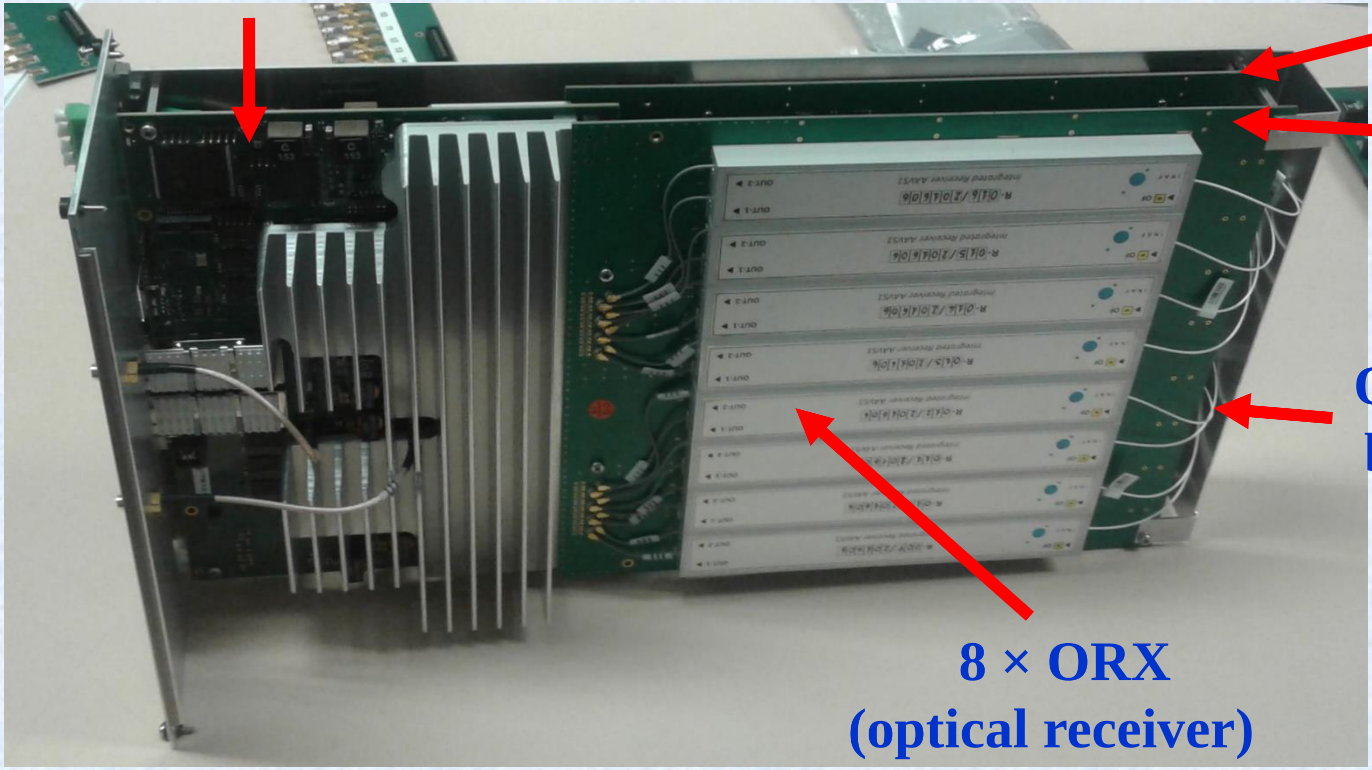
One of the ORXs (optical receivers) with Digital Step Attenuators (DSA), part of the pre-ADU):



Two pre-ADUs, each with 8 ORXs:

PHAROS2 digital backend based on iTPM
(Italian Tile Processing Module, developed for SKA LFAA)

One iTPM utilizes one ADU (Analog Digital Unit) and two pre-ADUs:



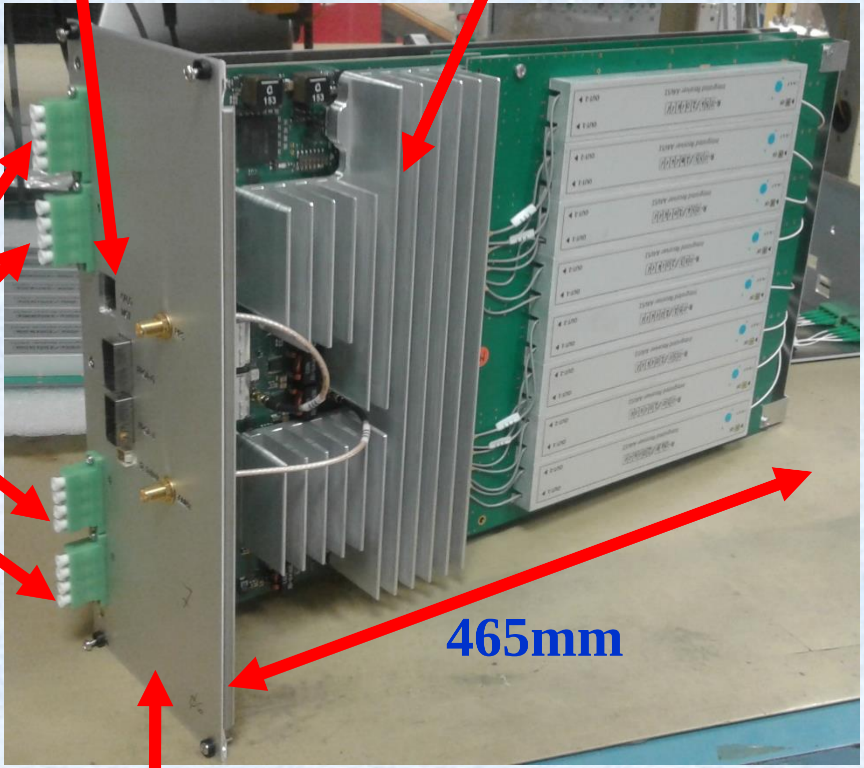
PHARO S2 digital backend based on iTPM

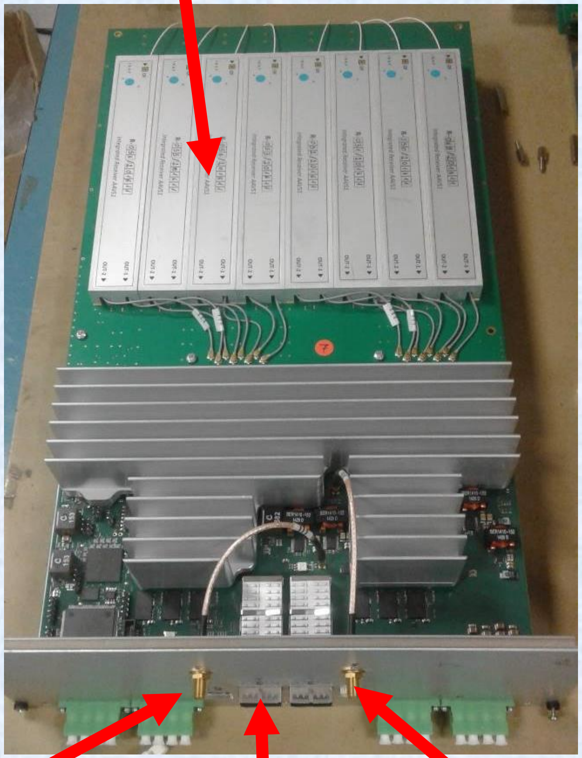
1Gb Ethernet

ADU heatsink

8 × ORX

16 x LC/APC optical inputs





465mm

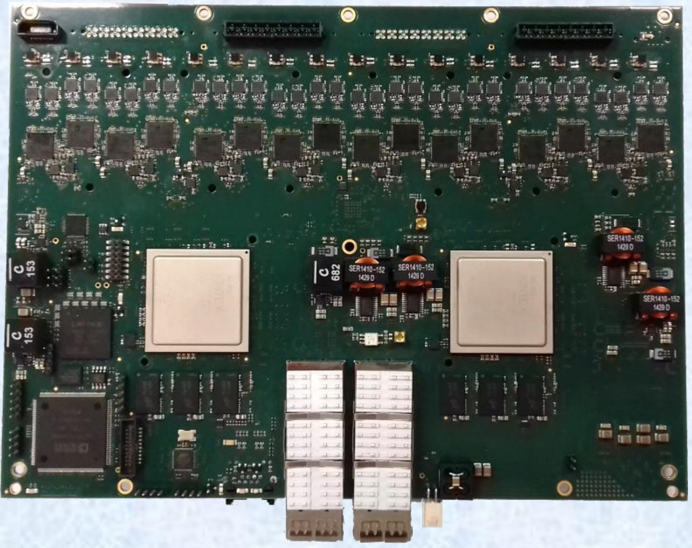
Front Panel Size: 6U, 21HP

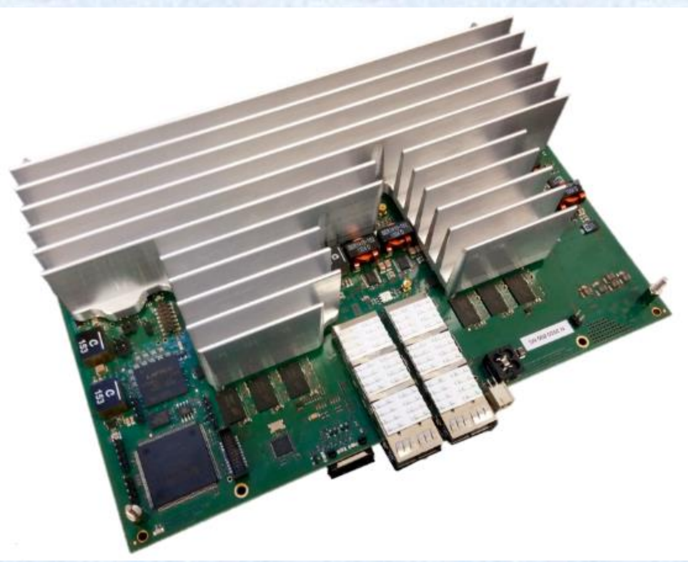
PPS input

QSFP+ for 40GbE network

10MHz Input

ADU (Analog Digital Unit)

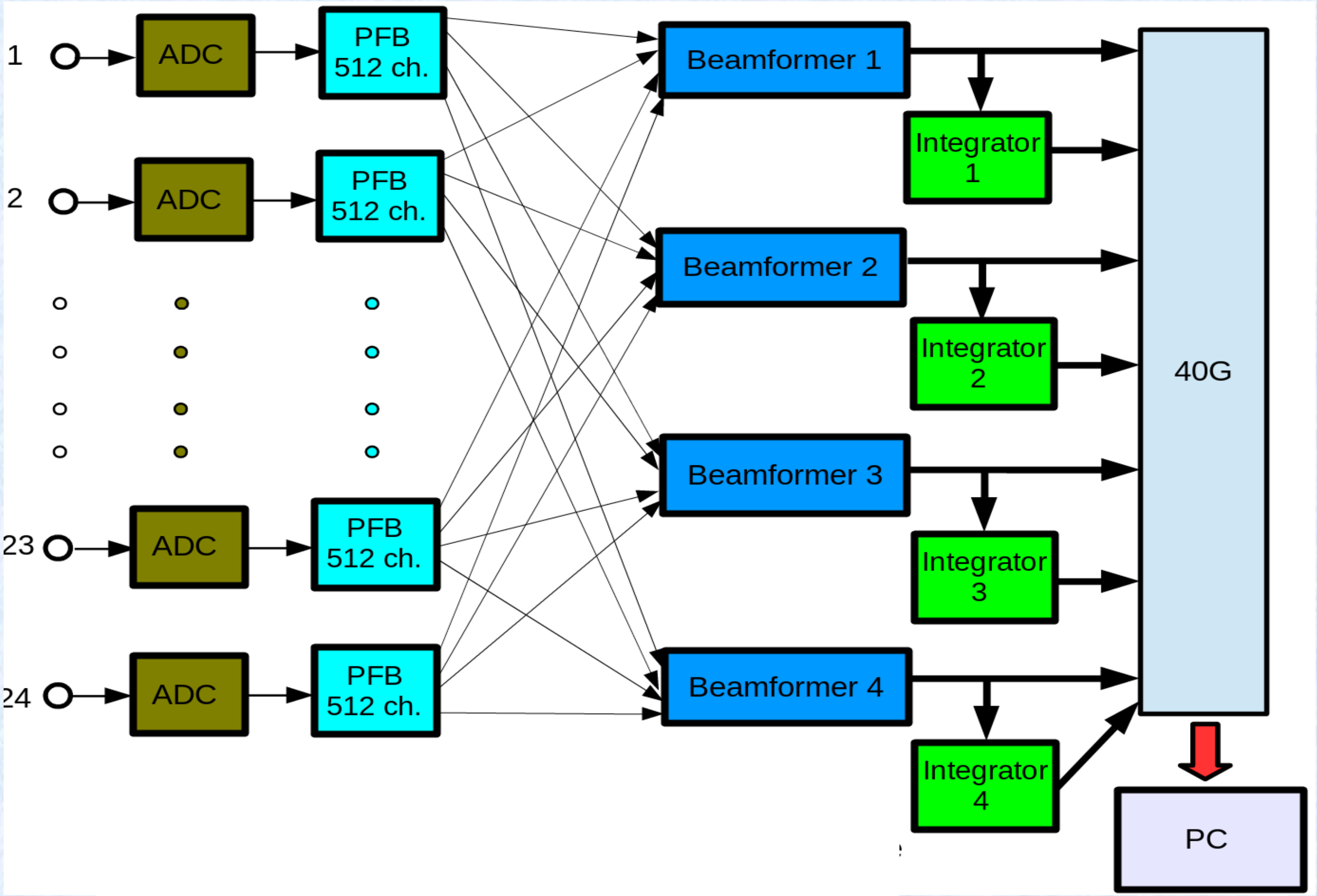




- Accepts 32 analog inputs, ≈500 MHz BW;
- 16 dual-ADCs AD9680, JESD204B, 1 GS/s ENOB=10.8;
- 2 x FPGAs XILINX Ultrascale XCU40 20 nm;
- 2 x DDR3 96 bit memory banks, 6+6 Gbit total size;
- Digitisation at 700MS/s → the 375-650 MHz IF band is sampled in second Nyquist zone; in PHAROS2 the signals are reversed twice (LSB tuning and second Nyquist results in non-reversed passbands);
- 2 x 40Gbps Ethernet interfaces (QSFP), one for each FPGA;
- High speed internal bus to connect the 2 FPGAs, 25 Gbps + 25 Gbps bidirectional;
- Power consumption ≈150 W (iTPM v1.2);

PHAROS2 digital signal processing with iTPM

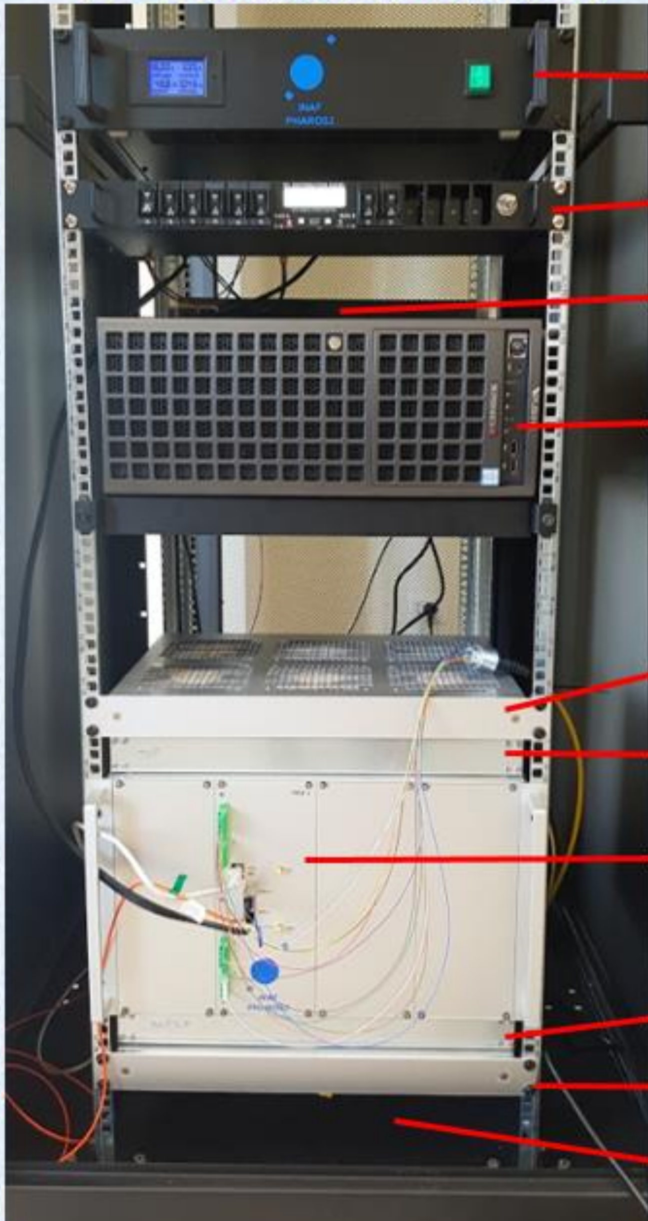
Four beams, ≈275 MHz BW each. Beamforming in the iTPM-FPGAs for 24 single-pol. antenna elements. Each beam provided with time-integrated spectra (pulsar search, on-the-fly mapping) and with non integrated spectra (pulsar timing).



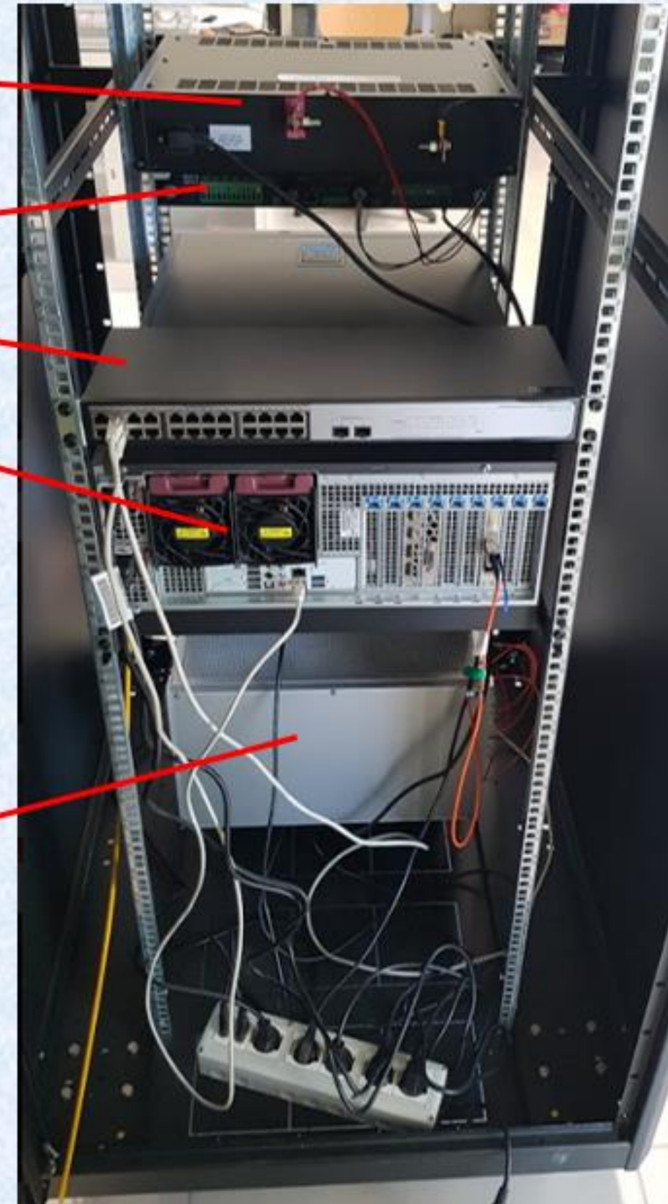
University of Malta

PHAROS2 Digital Back-End

BE cabinet front view



BE cabinet rear view



Power supply (2U)

Power distributor (1U)

Switch 1G (1U)

Server (4U)

Air blower (1U)

Air deflector (1U)

Subrack with one iTPM (6U)

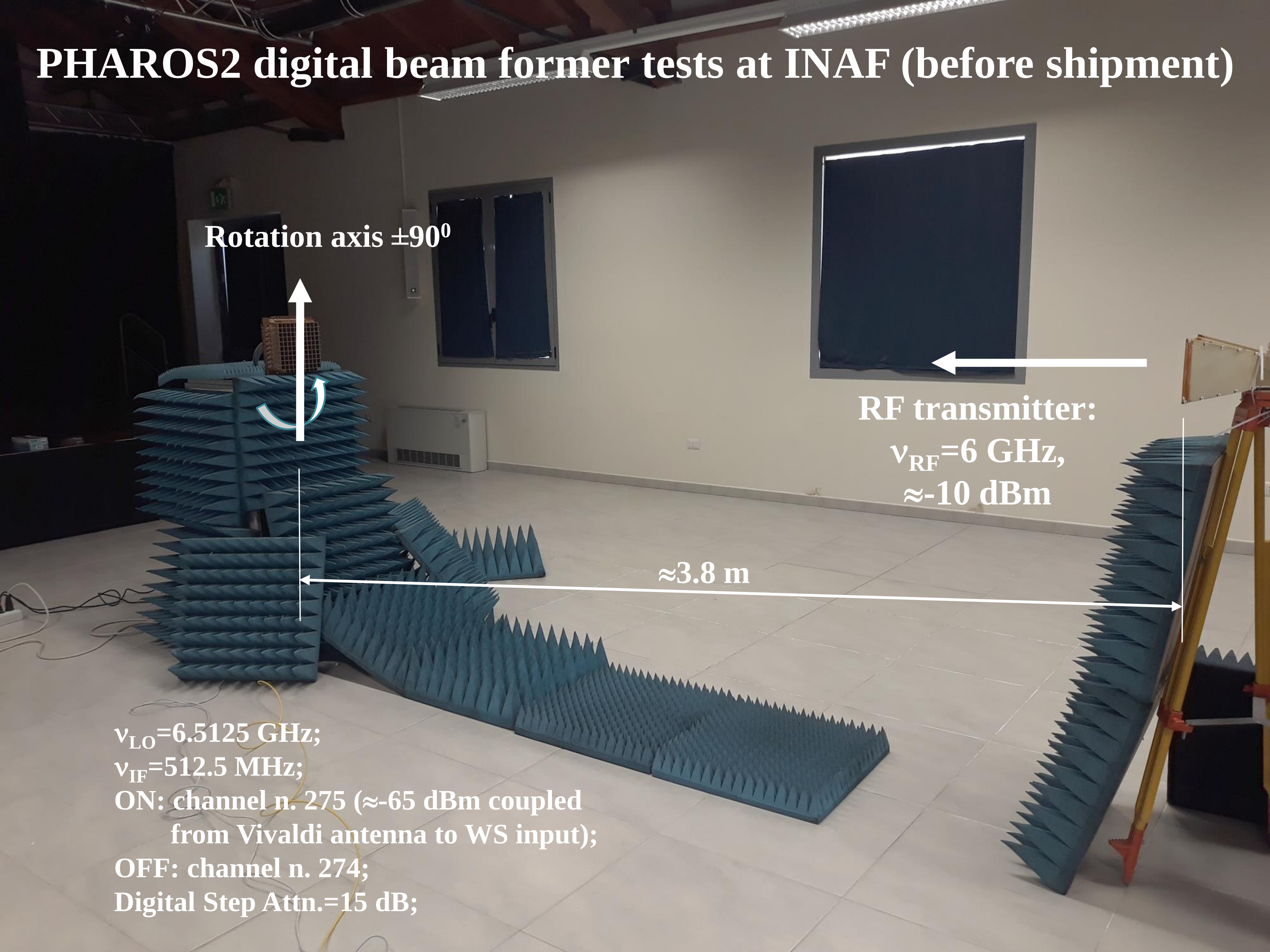
Air deflector (1U)

Air blower (1U)

Empty slot for air circulation (2U)

Connecting the Vivaldi array with Warm Section and digital backend for end-to-end system verification and preliminary lab tests at INAF

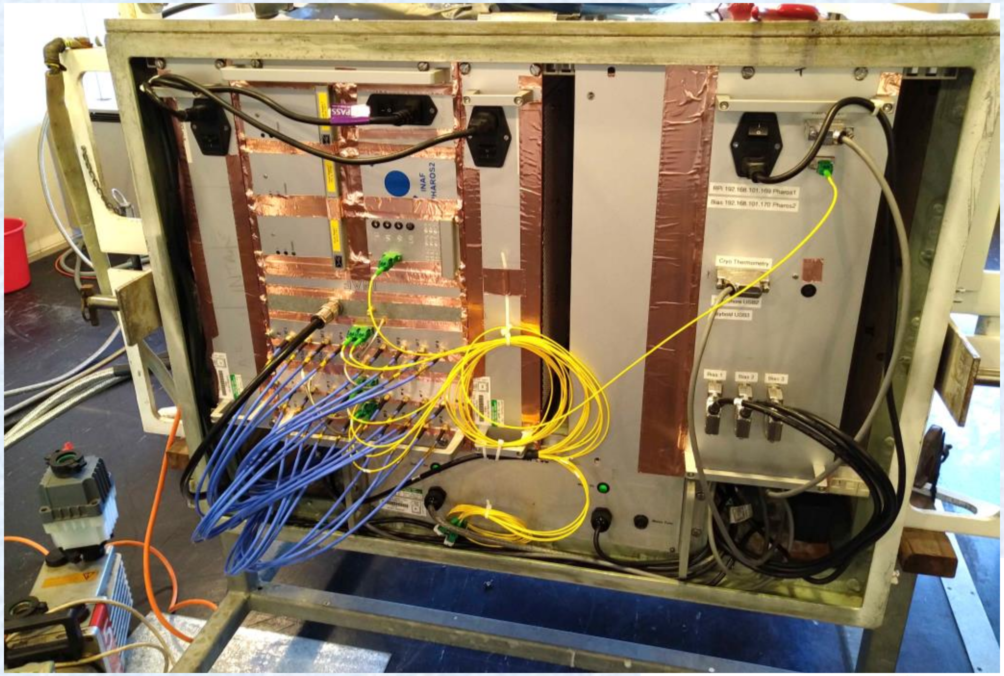
Hardware delivered to the Jodrell Bank Observatory, UK, in July 2019



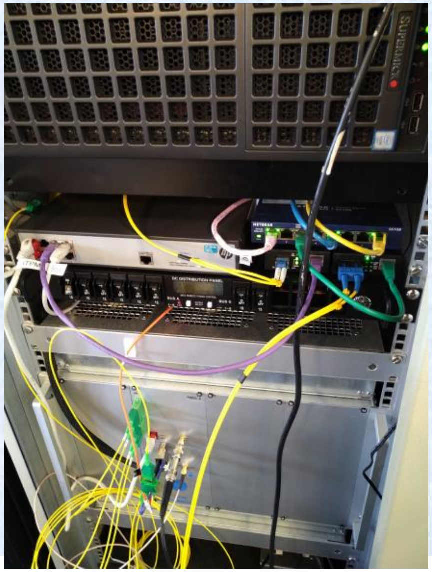
PHAROS2 digital beam former tests at INAF (before shipment)
Rotation axis ±90^0
RF transmitter:
ν_{RF}=6 GHz,
≈-10 dBm
≈3.8 m
ν_{LO}=6.5125 GHz;
ν_{IF}=512.5 MHz;
ON: channel n. 275 (≈-65 dBm coupled from Vivaldi antenna to WS input);
OFF: channel n. 274;
Digital Step Attn.=15 dB;

Integration of PHAROS2 Warm Section and digital backend with cryostat at JBO and preliminary ground tests

Warm Section integrated into focus box:



Digital backend re-assembled:

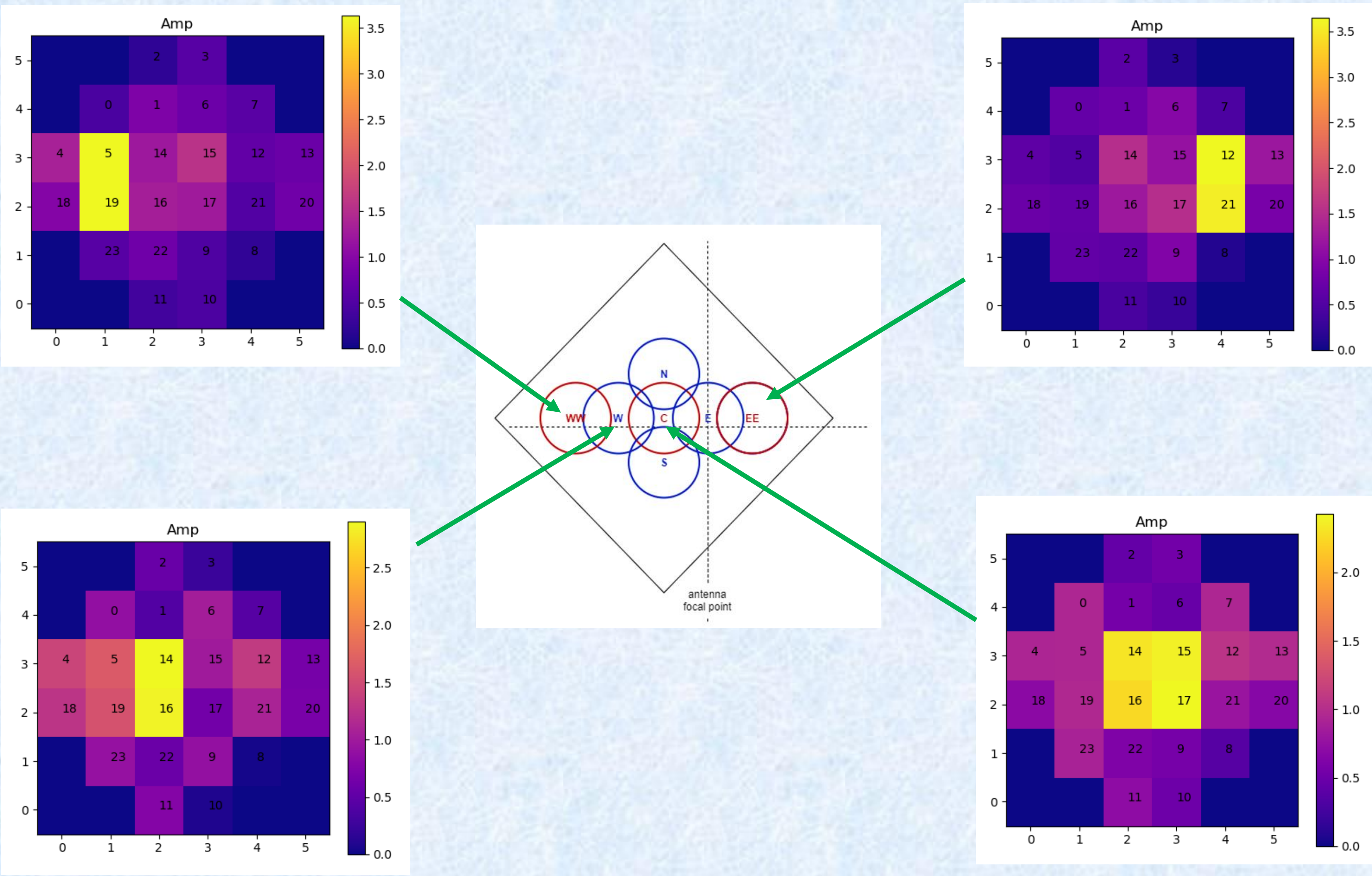


Ground tests at JBO:

PHAROS2 mounted on 25-m Pickmere antenna (UK)

Test results of PHAROS2 on Pickmere antenna

Amplitude weights of four test beams formed on Cyg A, around 6.5GHz:

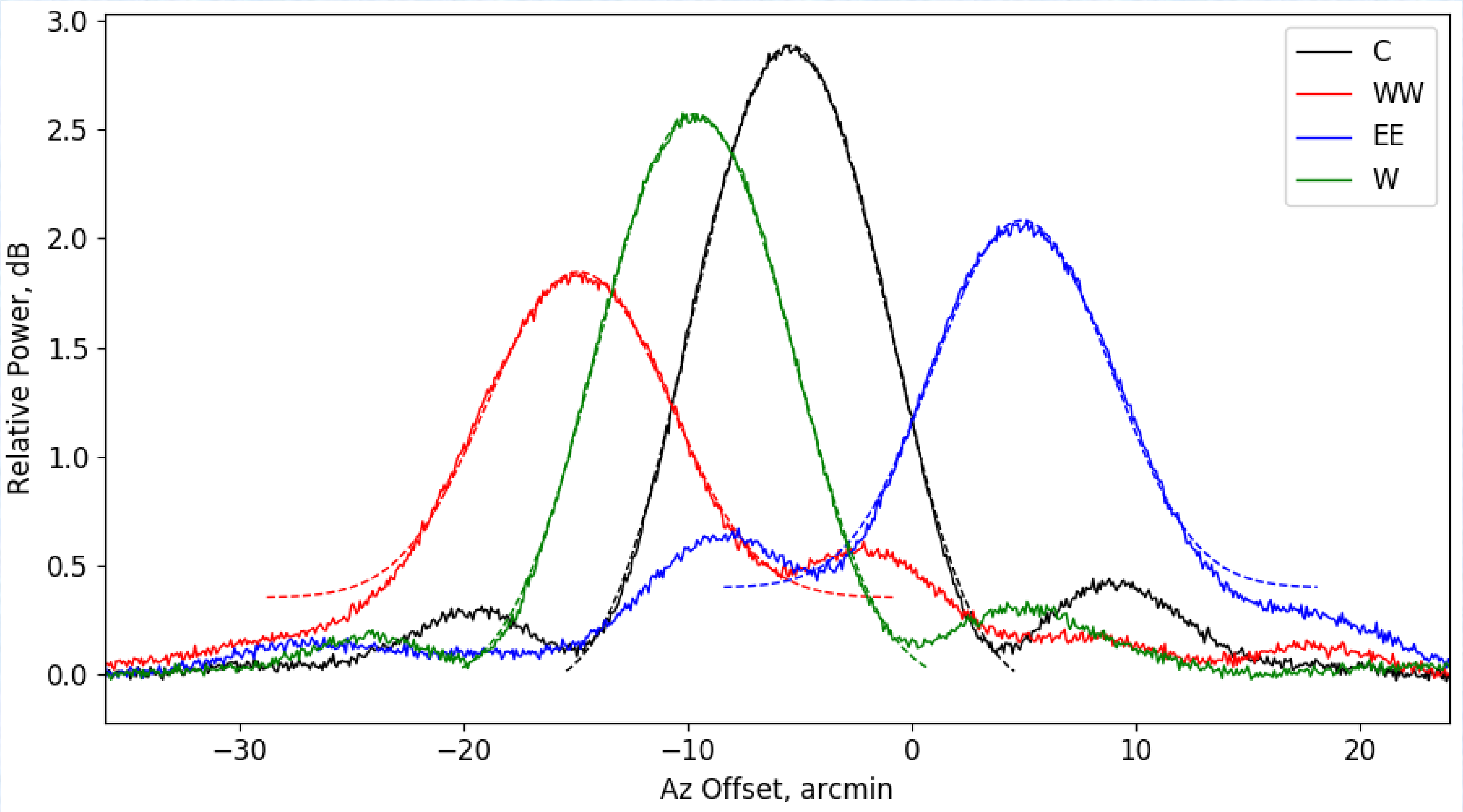


Test results of PHAROS2 on Pickmere antenna

…resulted in four well-formed beams!

Beams tested on Cas A yield approx. SEFDs:
C: 480Jy, W: 550Jy, WW: 1100Jy, EE: 1000Jy,

All with approx. 9 arcmin HPBW and centred at the intended offset



Future perspective of PAF development at INAF

Future perspective of PAF development at INAF

- Develop a demonstrator of a cryogenic PAF with antennas and LNAs integrated in a compact module for extended C-band based on RFSoC (Radio Frequency System-on-Chip) technology.
  The instrument will be entirely developed by INAF;

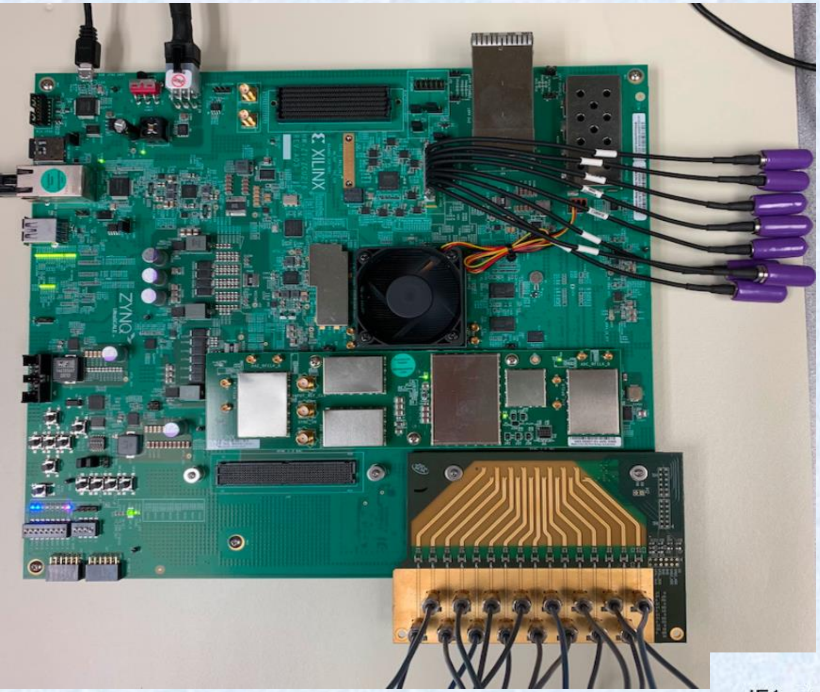
- Test the demonstrator on a TBD radio astronomy antenna;

- Verify INAF PAF demonstrator with reduced hardware (32 PAF elements and few beams), but up-scalable architecture;

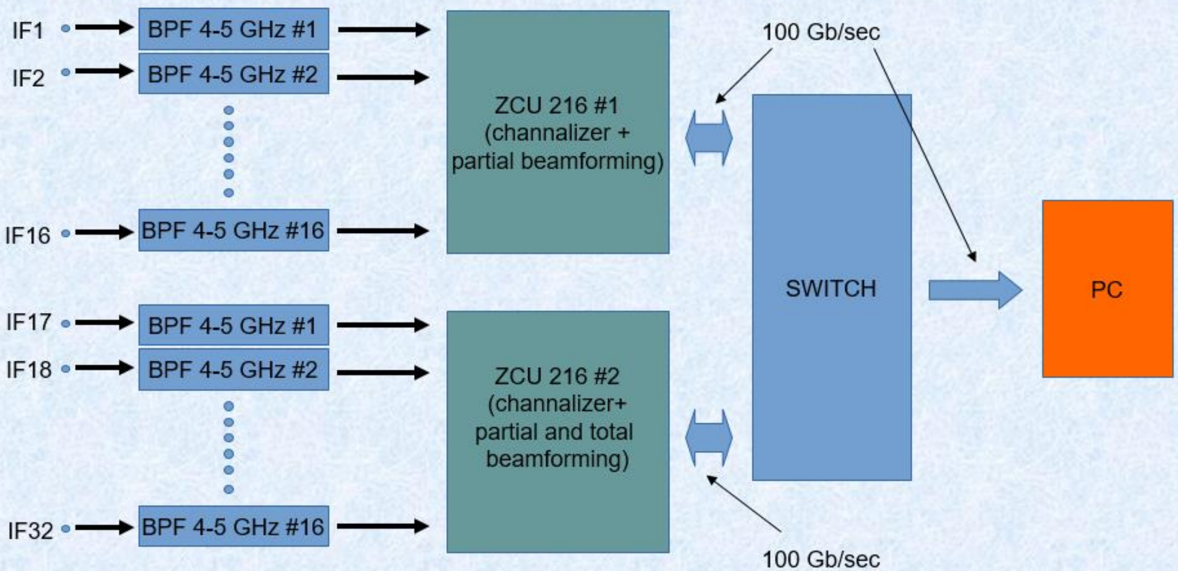
- Develop the key technologies, capability and design knowledge for PAF systems enabling to commence a specific SKA PAF design in 2024;

- Possibility to adopt the INAF developed PAF technologies for a PAF facility-instrument (>30 beams, dual-pol, >1 GHz BW, extended C-band) for the INAF antennas (SRT, Medicina and Noto).

A possible beamforming of 32-element PAF-demonstrator with 1.25 GHz BW using two RFSoC boards



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



An alternative up-scalable solution adopts RFSoC + Alveo boards

Conclusions

- PAFs have great advantages over multibeam receivers, speeding up mapping of extended sources;
- Radio astronomy PAFs are being developed for various bands, covering the frequency range from 70 MHz to ≈8 GHz;
- The number of facilities considering PAF's is increasing. Most large single dish facilities have or have plans towards PAF's (Effelsberg, FAST, GBT, JBO, Parkes, SRT);
- Interferometers, such as APERTIF and ASKAP, adopt PAFs;
- PAF technology is not part of SKA1;
- INAF is part of the PAF SKA Advanced Instrumentation Program;
- INAF has contributed to develop the PHAROS and the PHAROS2 C-band PAF demonstrators and is developing a new demonstrator whose technologies could find application on SKA and on the Italian radio astronomy antennas;
- A steady improvement in PAF sensitivity is demonstrated, both for room temperature as well as cryo cooled systems;
- For competitiveness, capital and operational costs of PAF's (including power consumption) needs to be reduced, in particular for PAF's proposed to be built in significant quantities;
- Constant improvement of digital backend capabilities might enable PAF developments at relatively low-cost in the future.

Thank you