Digital Beamforming with the Cryogenic C-Band PHAROS2 PAF

A. Navarrini, A. Scalambra[2], A. Melis[1], S. Rusticelli[2], R. Concu[1], P. Ortu[1], G. Naldi[2], G. Pupillo[2], A. Maccaferri[2], A. Cattani[2], A. Ladu[1], L. Schirru[1], F. Perini[2], M. Morsiani[2], J. Monari[2], J. Roda[2], P. Marongiu[1], A. Saba[1], M. Poloni[2], M. Schiaffino[2], A. Mattana[2], G. Bianchi[2], G. Comoretto[3], R. Nesti[3], E. Urru[1], T. Pisanu[1], F. Schillirò[4], K. Zarb Adami[5,6], A. Magro[5], R. Chiello[6], K. Grainge[7], M. Keith[7], S. Melhuish[7], M. D'Cruze[7], M. McCulloch[7], W. van Cappellen[8]

[1] INAF-Osservatorio Astronomico di Cagliari, Selargius, Italy
[2] INAF-Istituto di Radioastronomia, Bologna, Italy
[3] INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy
[4] INAF-Osservatorio Astrofisico di Catania, Catania, Italy
[5] University of Malta, Malta
[6] University of Oxford, Department of Physics, UK
[7] University of Manchester, Jodrell Bank Observatory, Manchester, UK
[8] ASTRON, The Netherlands

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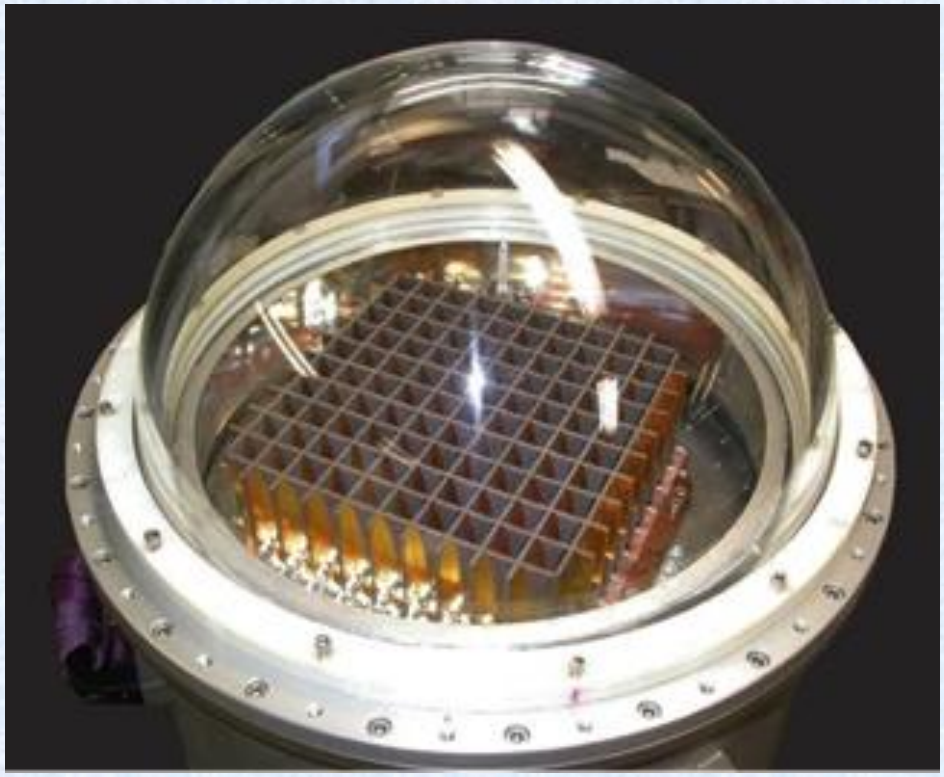
Overview

- PHAROS and PHAROS2 PAFs;
- PHAROS2 multichannel warm receiver section (WS);
- PHAROS2 digital backend;
- Beam pattern characterization results of PAF with digital beamformer;
- PHAROS2 ground tests;
- PHAROS2 tests on 25-m Pickmere antenna (on-going);

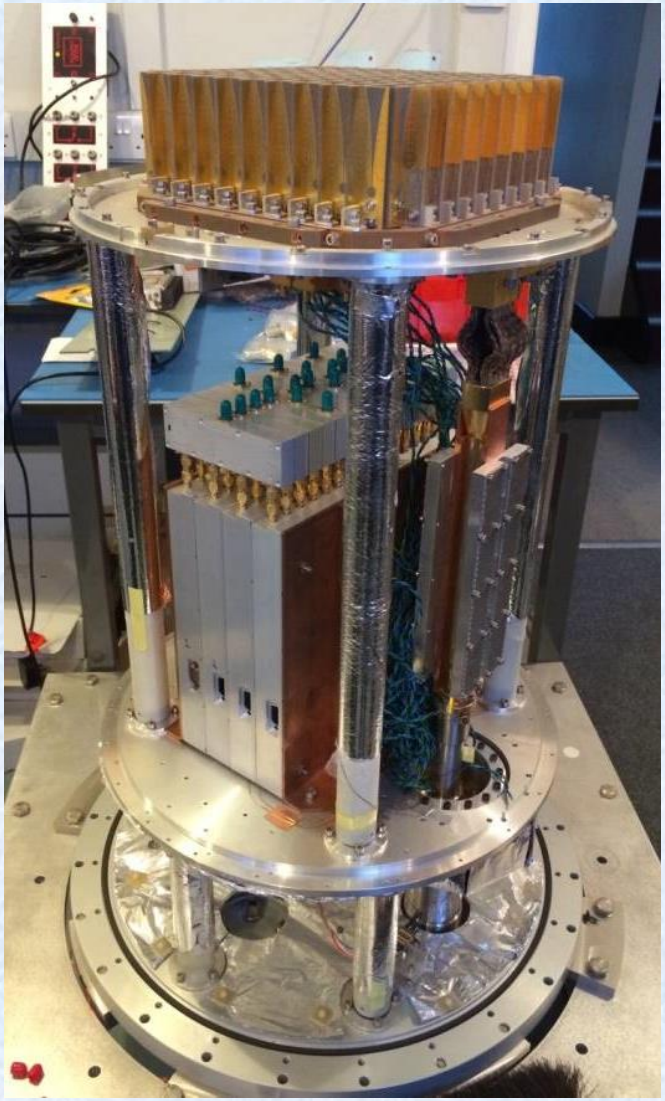
PHAROS

- International collaboration;
- 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, with focus on 5-7 GHz;

Vivaldi array and vacuum window:

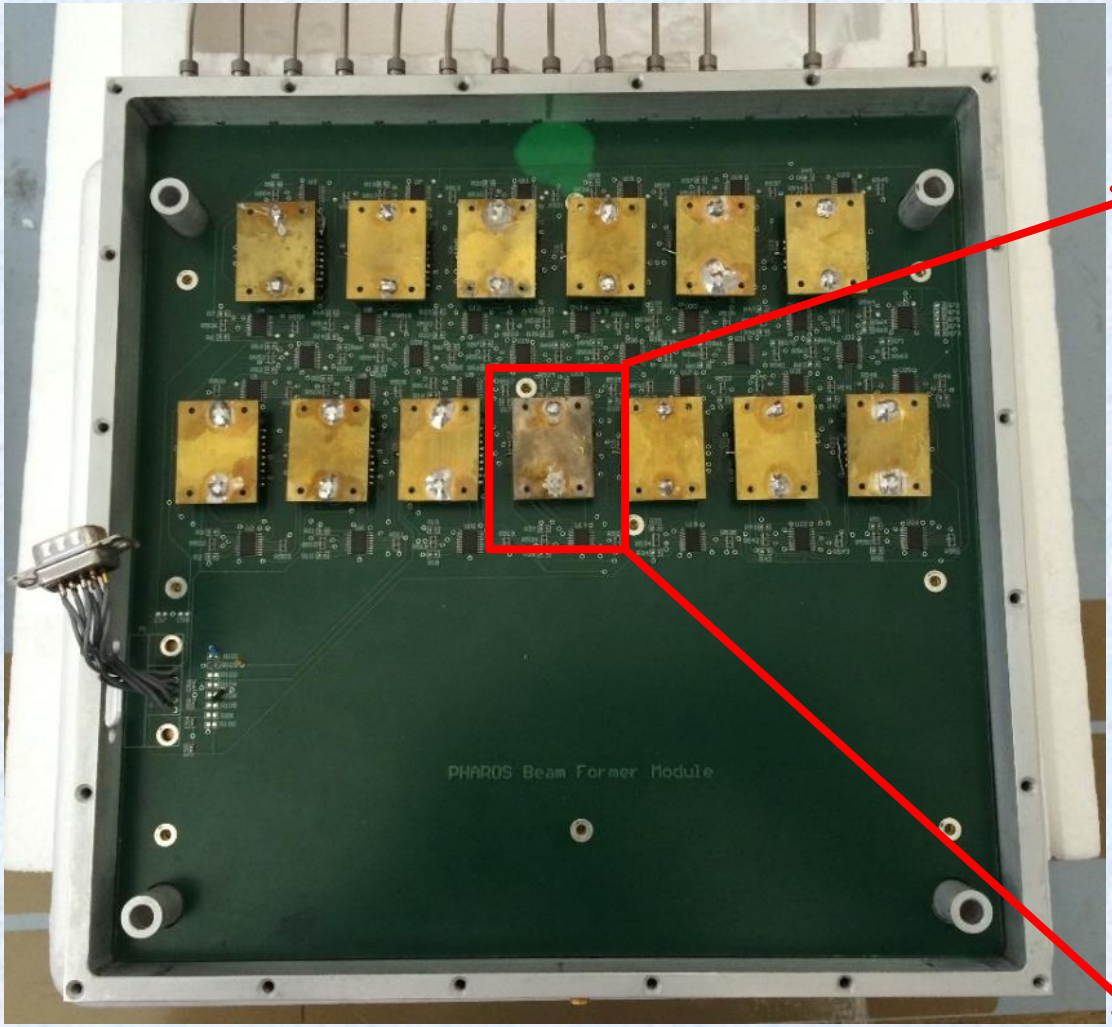


Cryostat internal assembly:



PHAROS analog beamformer board cooled at ≈70 K

- 13 input Wilkinson combiner;
- 13 Phase and Amplitude Correction (PAC) modules;
- 4 analogue beamformers;

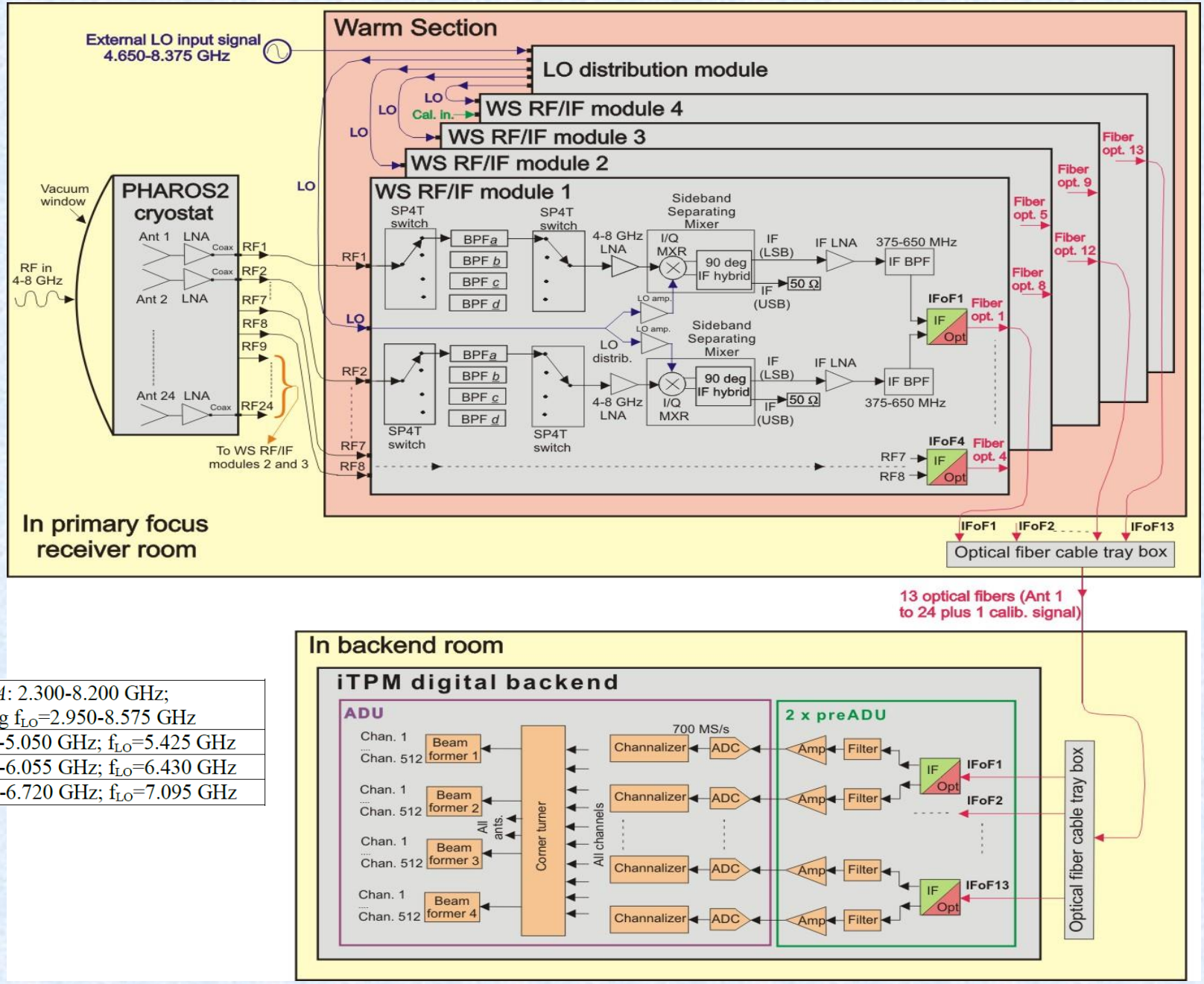


PHAROS2: upgrade of PHAROS

- New low noise amplifiers
- Digital backend
- Warm Section downconverter
  (room temperature multi-channel receiver)

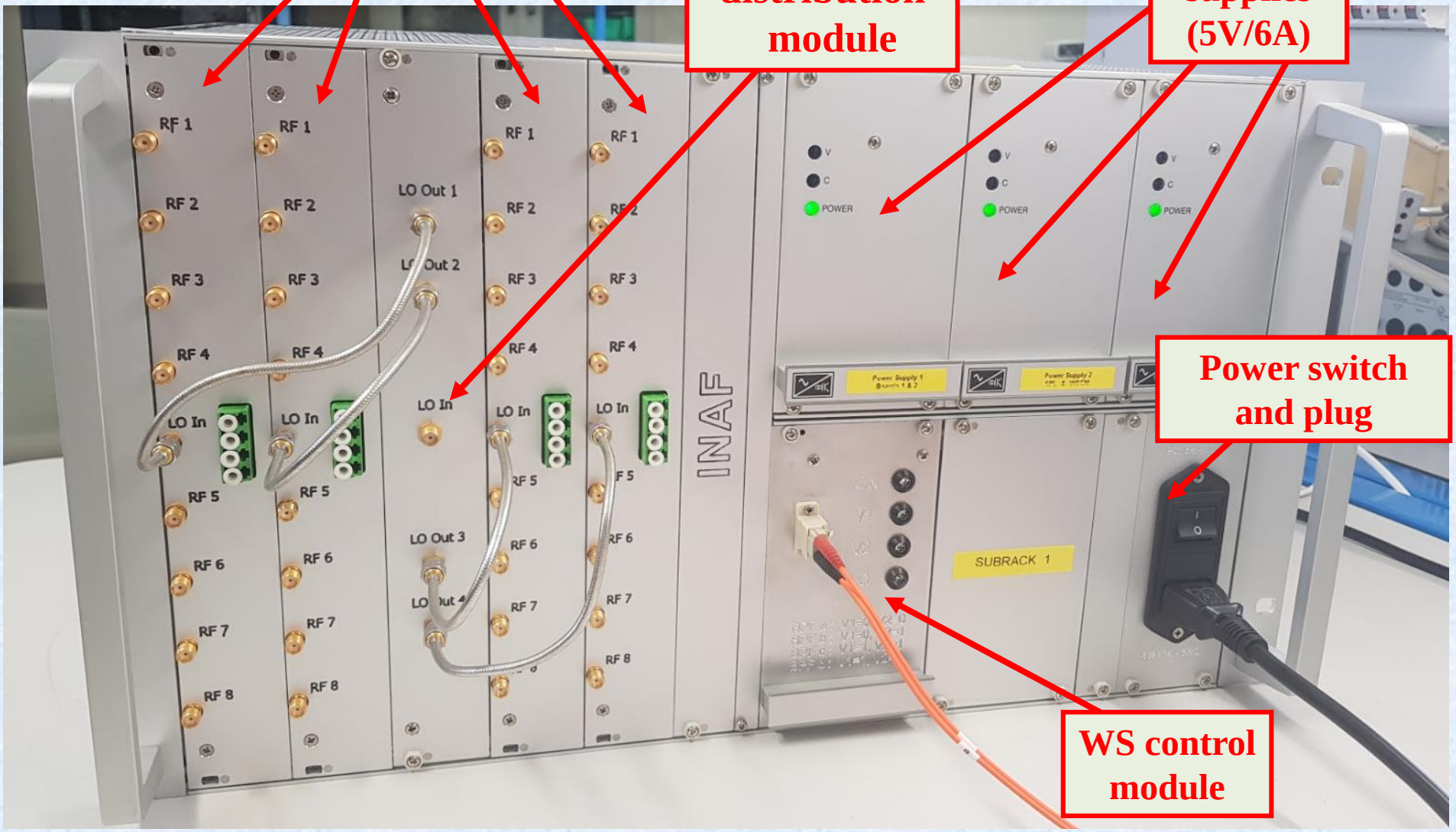
In the framework of the PAF SKA
Advanced Instrumentation Program

Block diagram 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

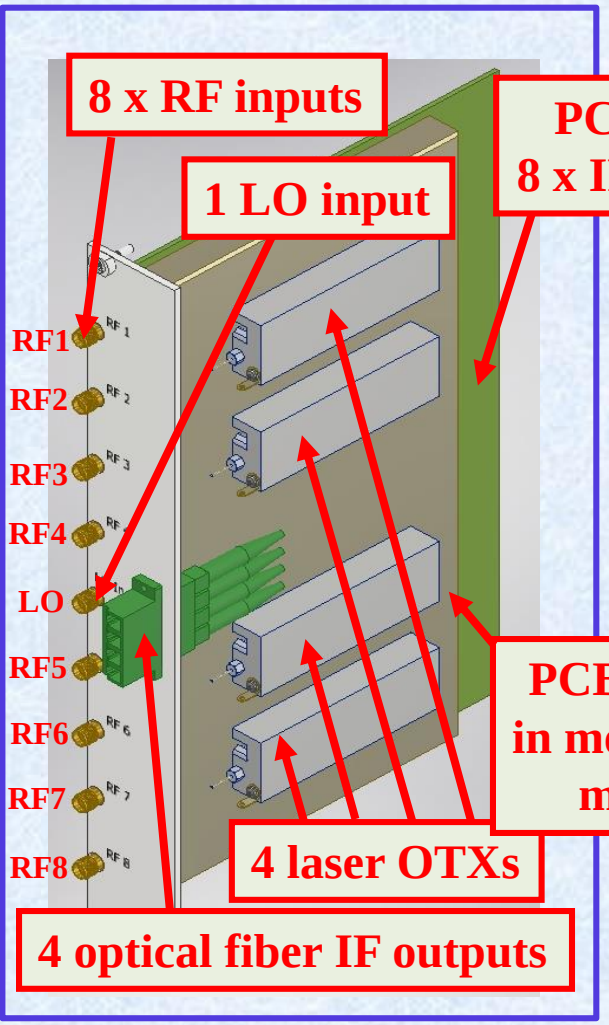
32-channel WS receiver



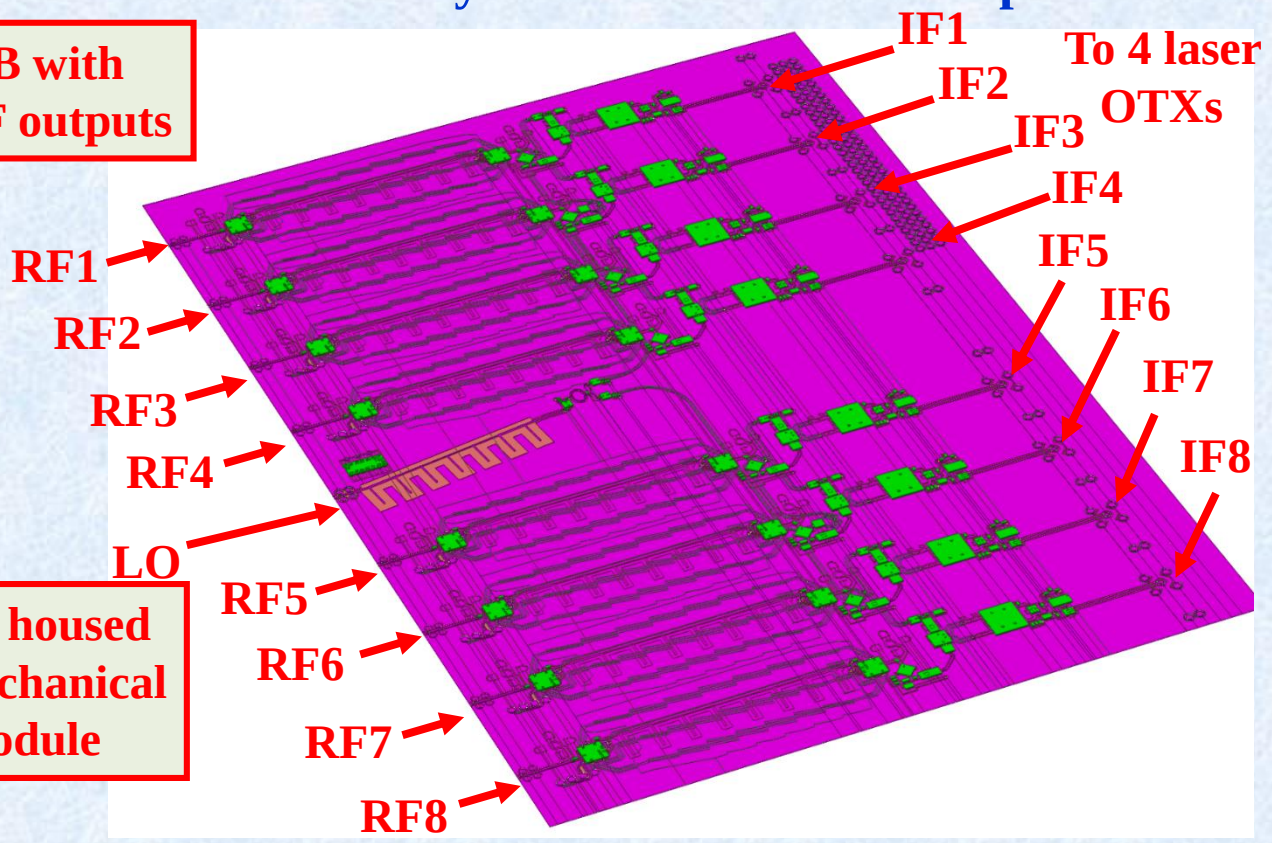
Standard 6U rack (19”): 32 x RF input signals, 24 from cryostat (8 spare inputs)

Design of WS RF/IF module:

- One WS module has 8 x RF inputs, 1 LO input and 4 WDM IFoF outputs (4 laser TX);
- Single four-layer PCB with surface mount components (no bonding, easy assembly, low-cost) inside mechanical housing. Biased with a single 5 V voltage;
- 1 LO input internally distributed with 8-way splitter (+filtering section and LO ampl.);

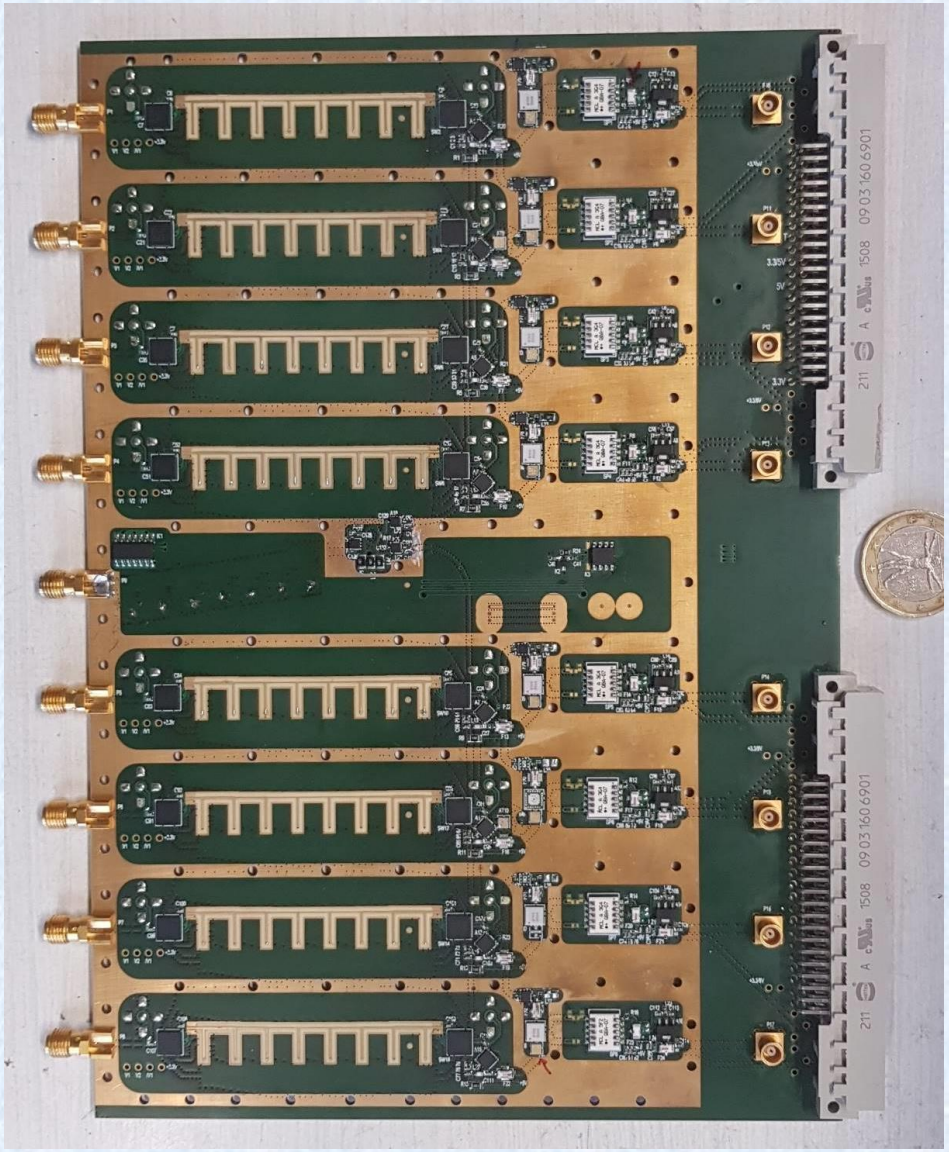


View of PCB layers and RF/LO/IF components:

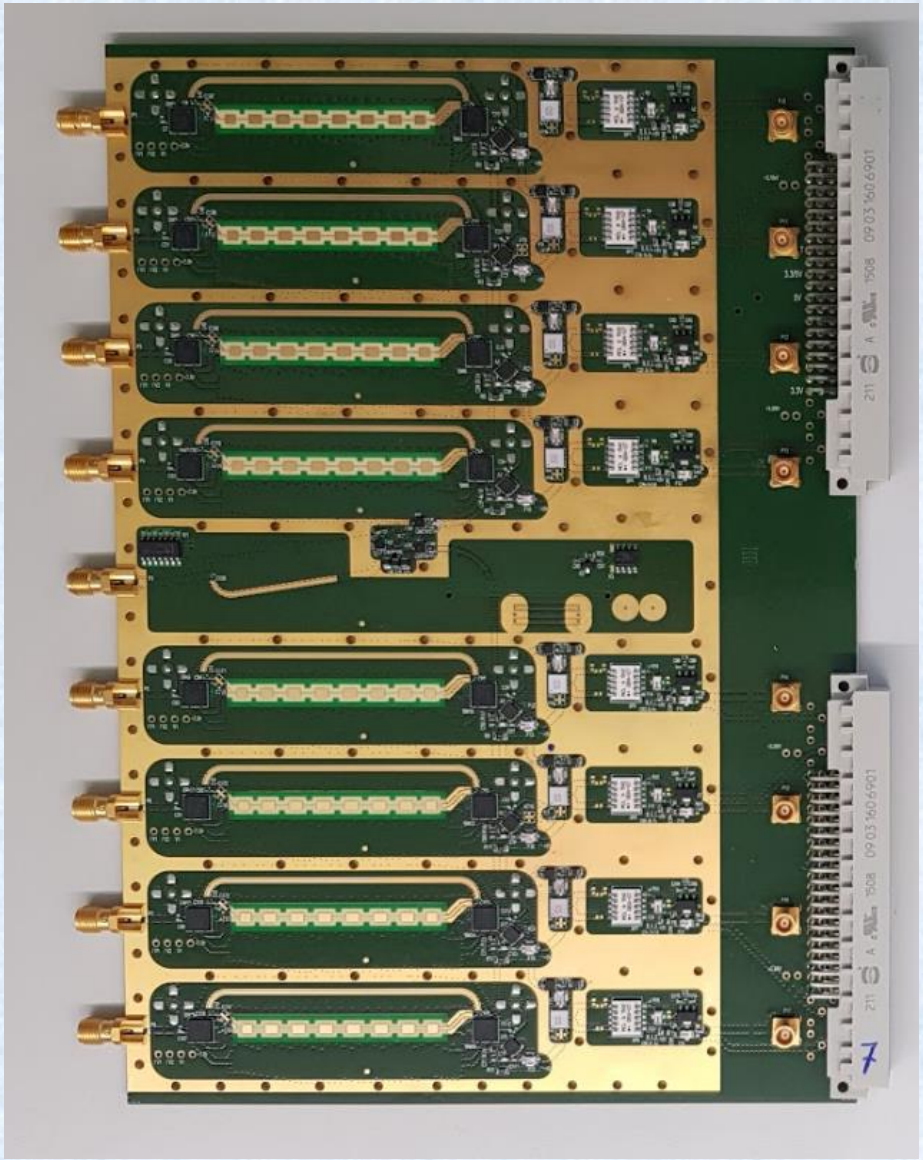


Two versions of eight-channel PCB for WS RF/IF module

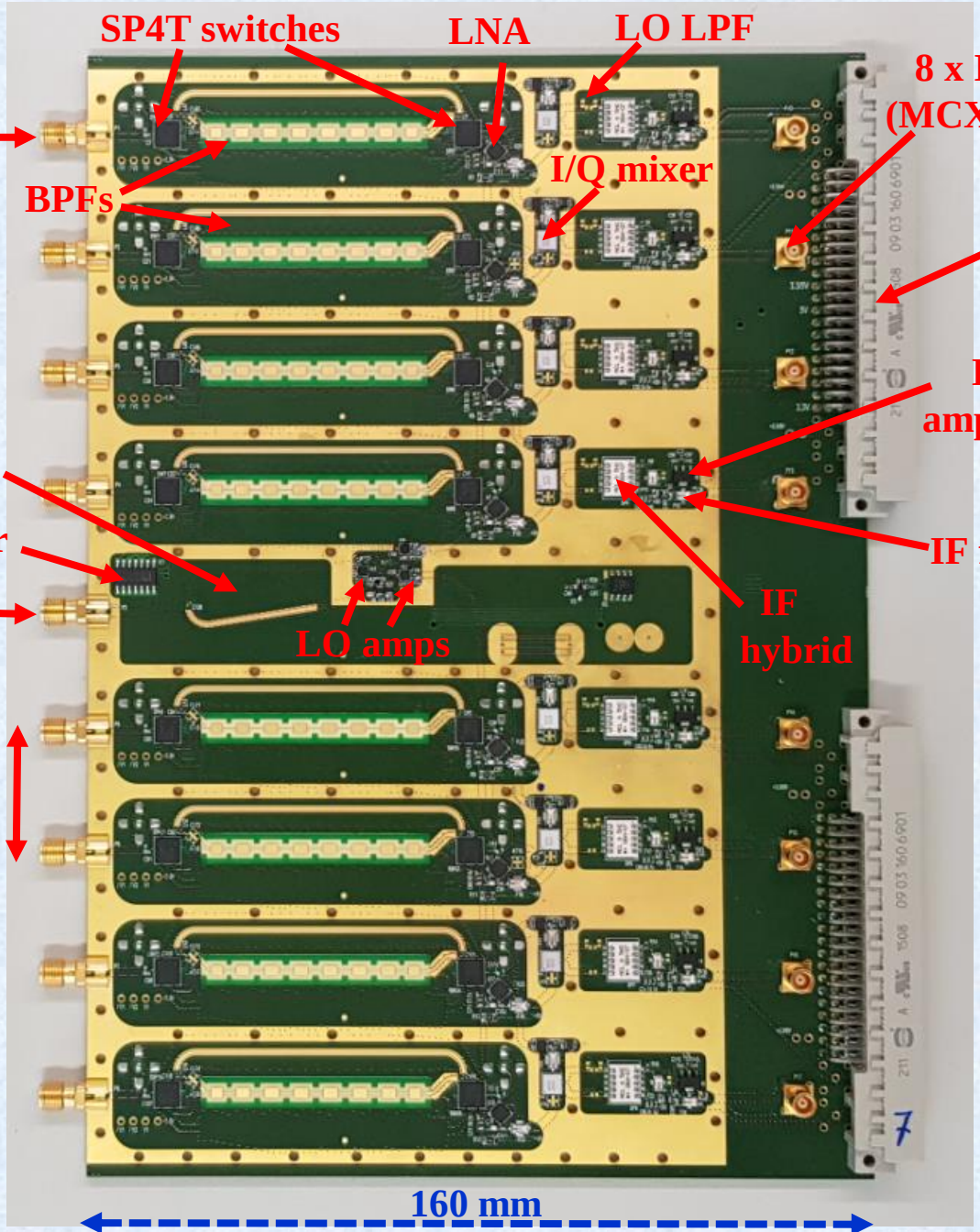
First prototype PCB version: BPF-A: 4-8 GHz



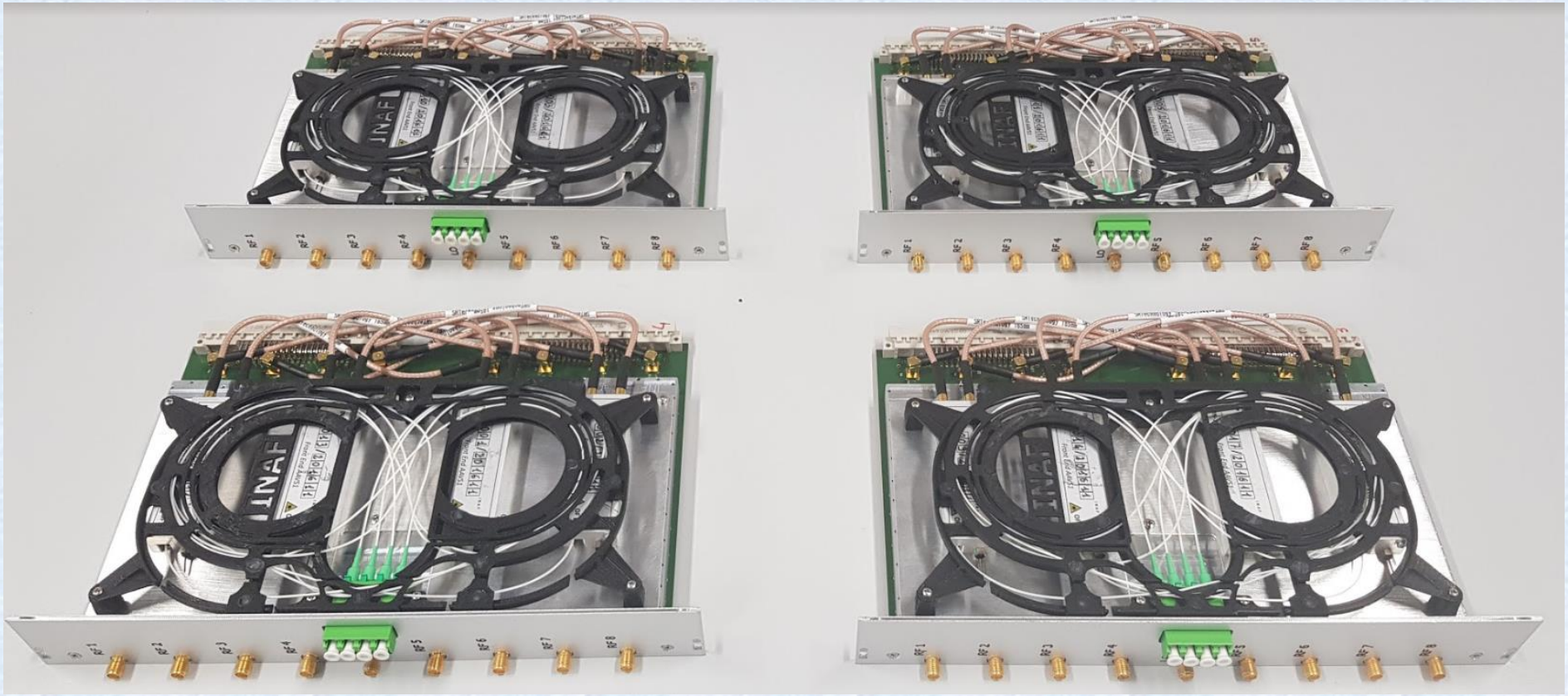
“Production” PCB version: BPF-A: 2.3-8.2 GHz



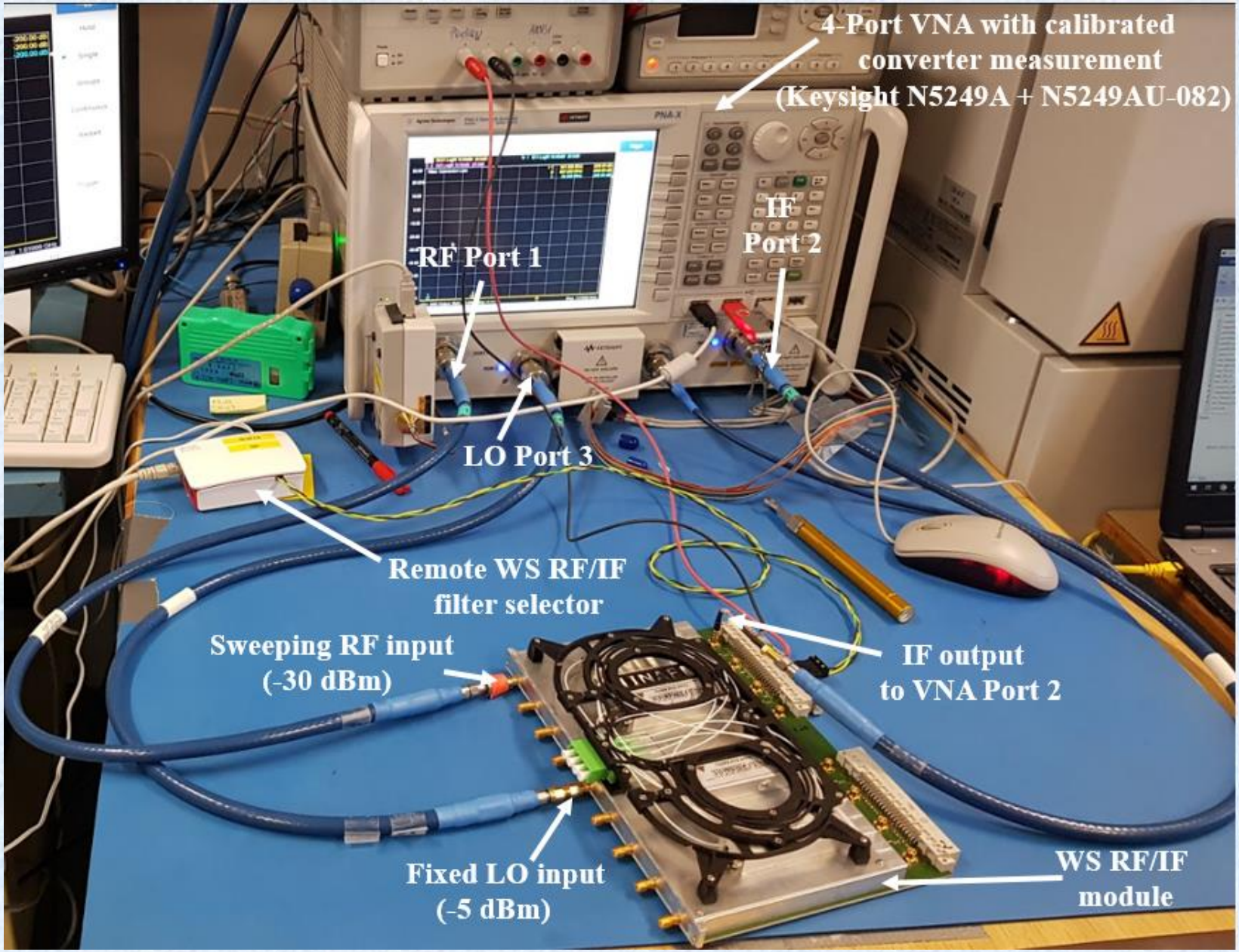
“Production” PCB version for 2.3-8.2 GHz :



Four fully assembled WS RF/IF modules for one WS rack



VNA testing of new WS RF/IF board (without FO link)



Measurement results for one of the modules (Board #6)

Gain BPF-A (ν_{LO}=5 GHz):

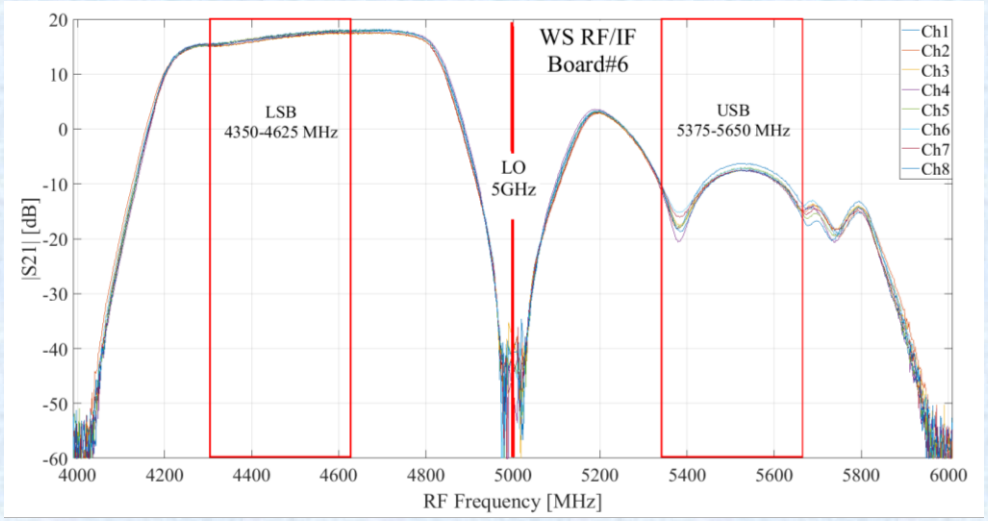
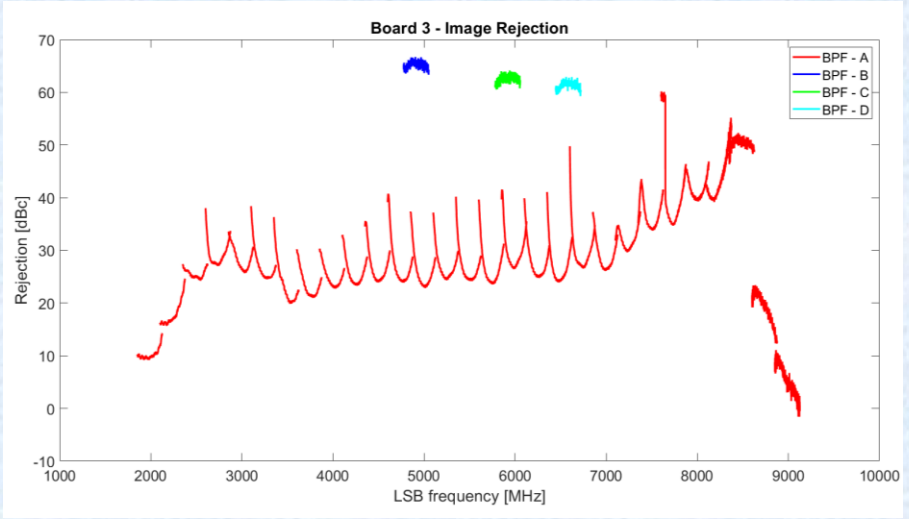
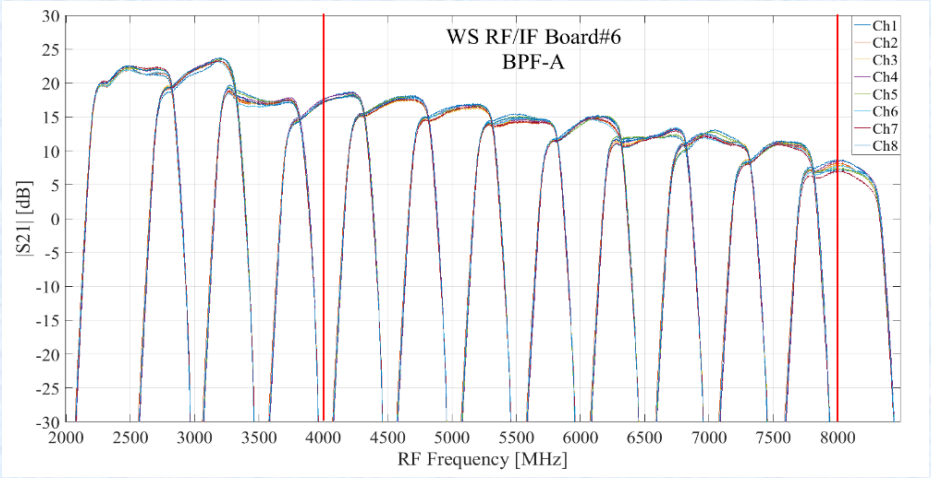


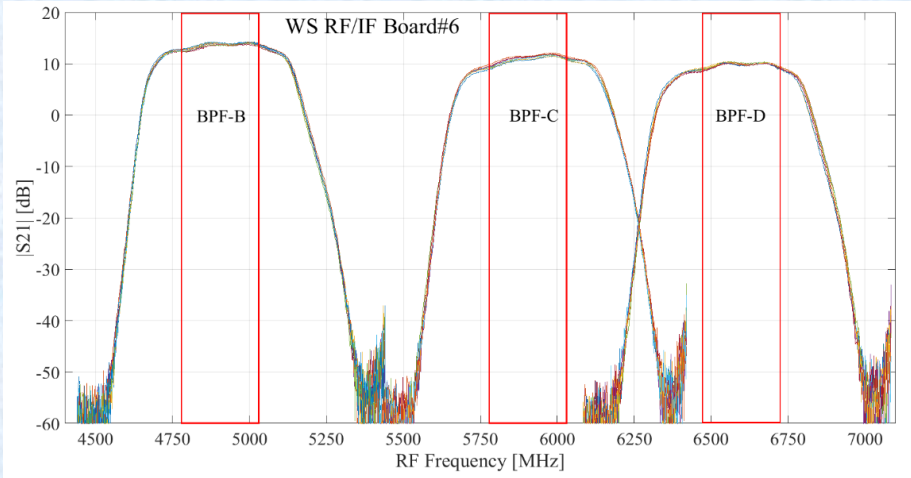
Image sideband rejection:



Gain BPF-A (for 12 different LO freqs ν_{LO}):



Gain BPF-B, C and D:

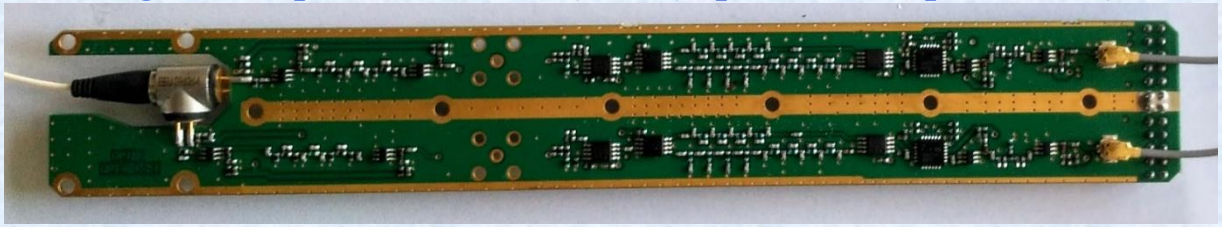


PHAROS2 IFoF WDM links developed for SKA LFAA

- 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:

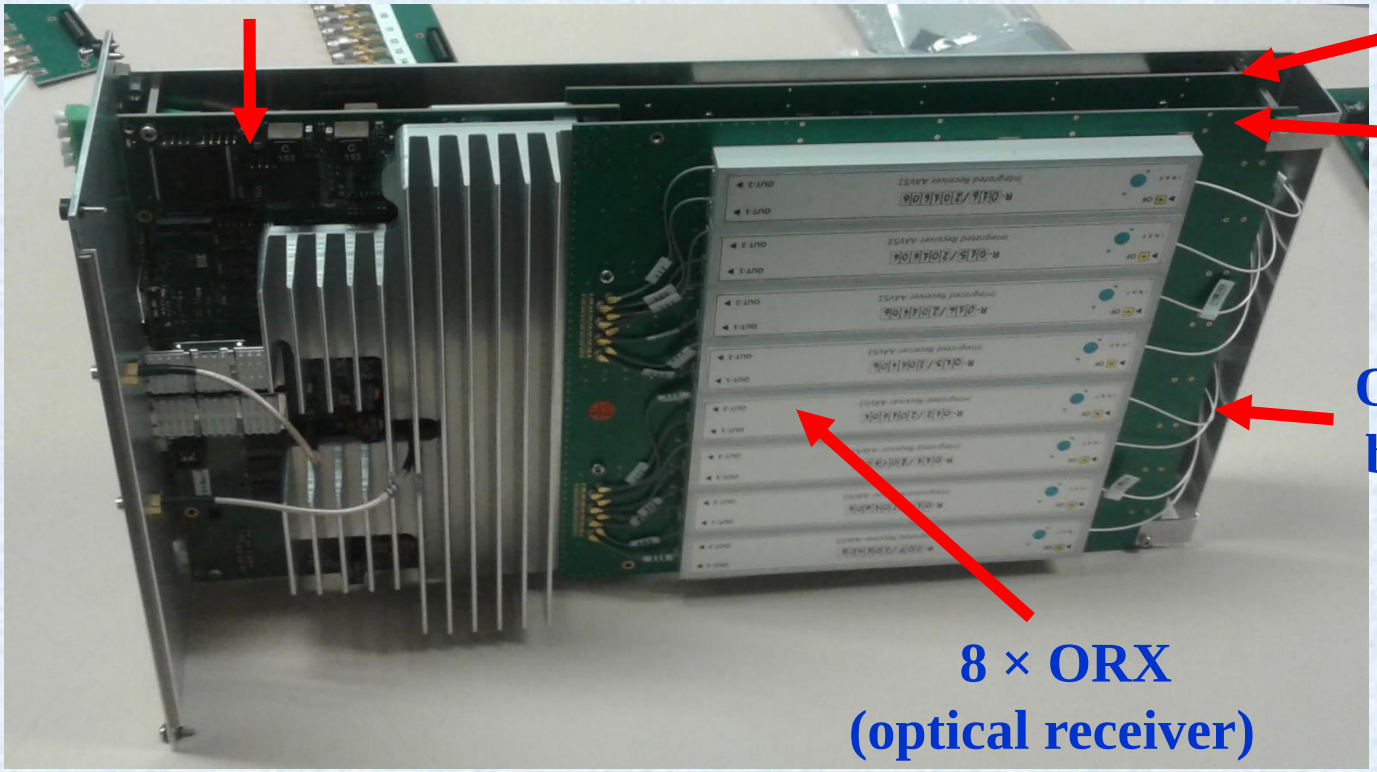
One of the ORXs (optical receivers) with Digital Step Attenuators (DSA), part of the pre-ADU):



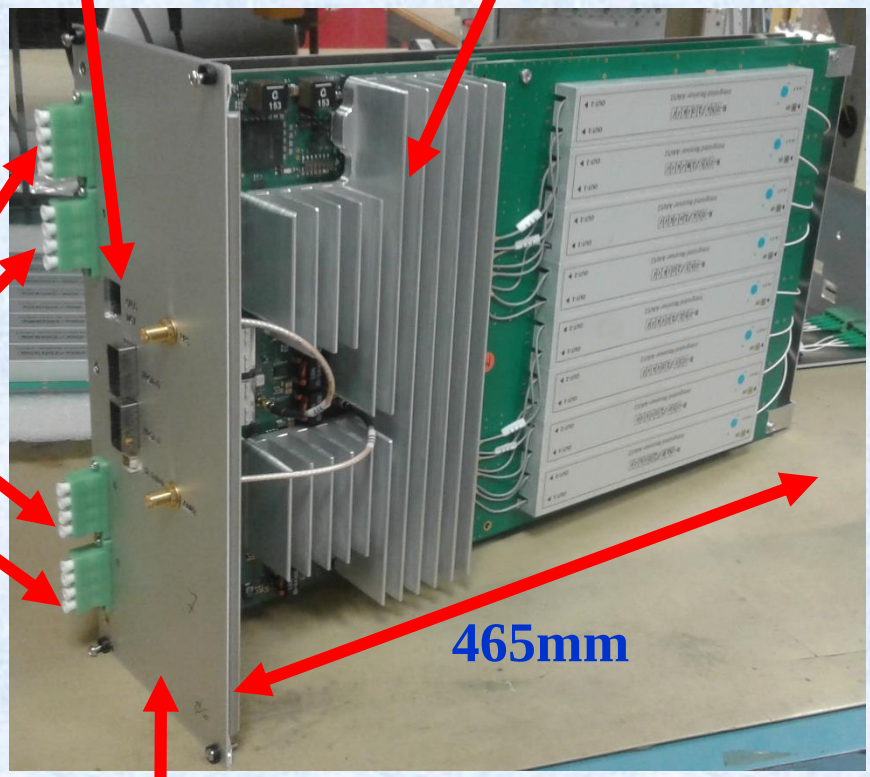
Two pre-ADUs, each with 8 ORXs:

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

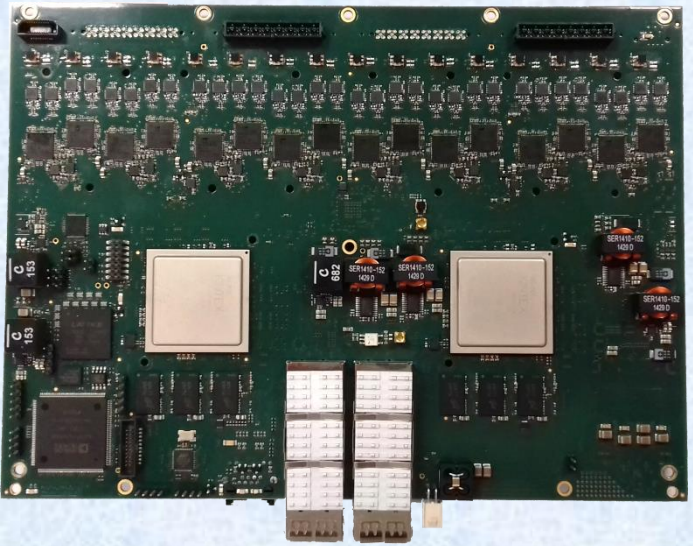
One iTPM utilizes one ADU (Analog Digital Unit) and two pre-ADUs:

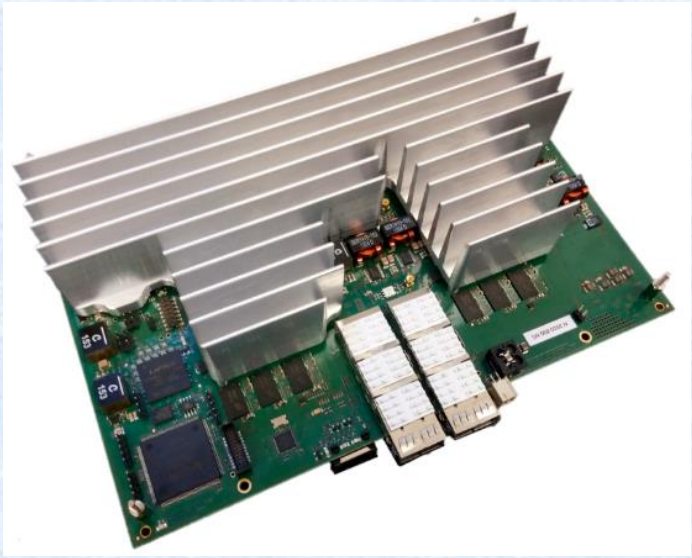


PHAROS2 digital backend based on iTPM



ADU (Analog Digital Unit)



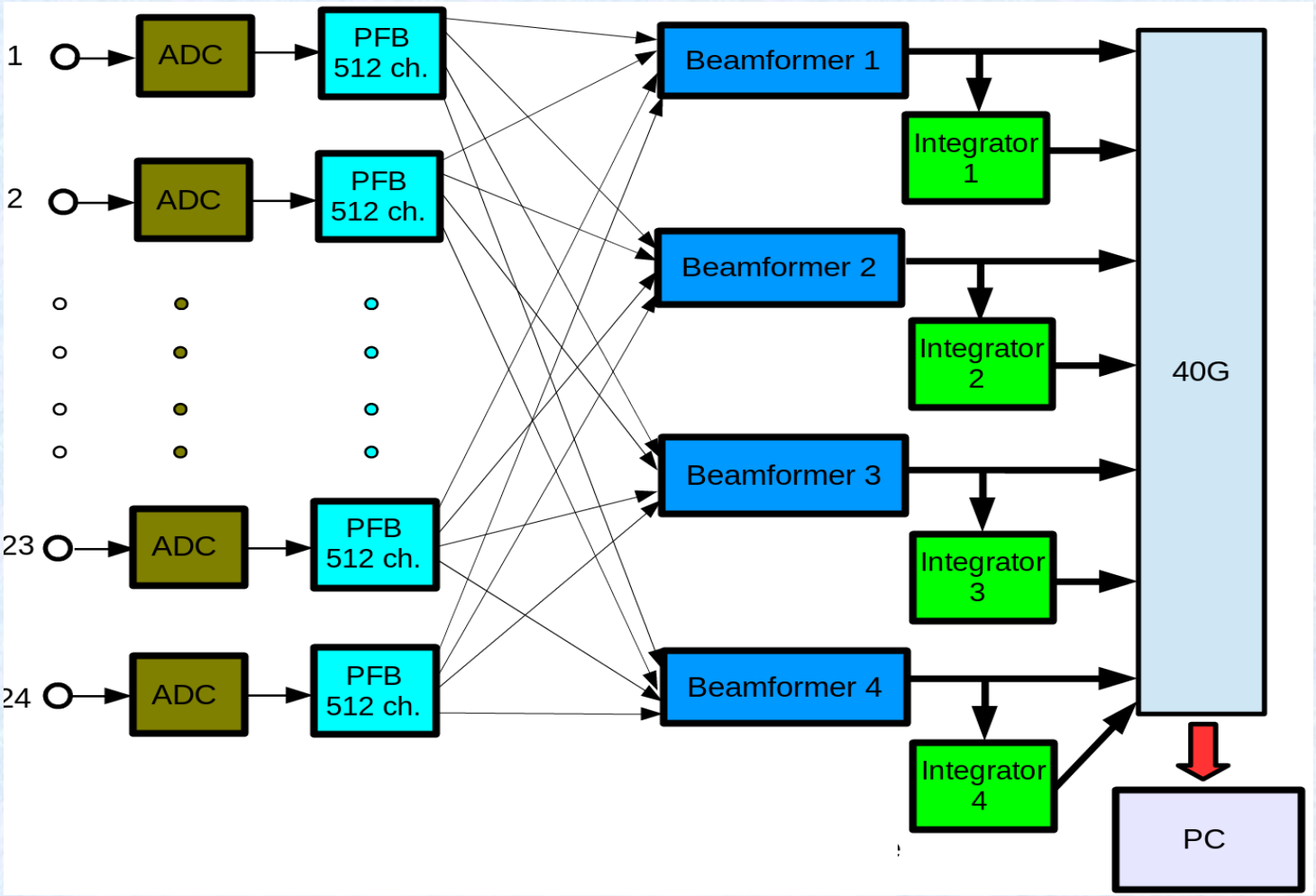


- Accepts 32 analog inputs, ≈500 MHz BW;
- 16 dual-ADCs AD9680, JESD204B, 1 GS/s ENOB=10.8;
- 2 x FPGAs XILINX Ultrascale XCU40 20 nm;
- 2 x DDR3 96 bit memory banks, 6+6 Gbit total size;
- Digitisation at 700MS/s → the 375-650 MHz IF band is sampled in second Nyquist zone; in PHAROS2 the signals are 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

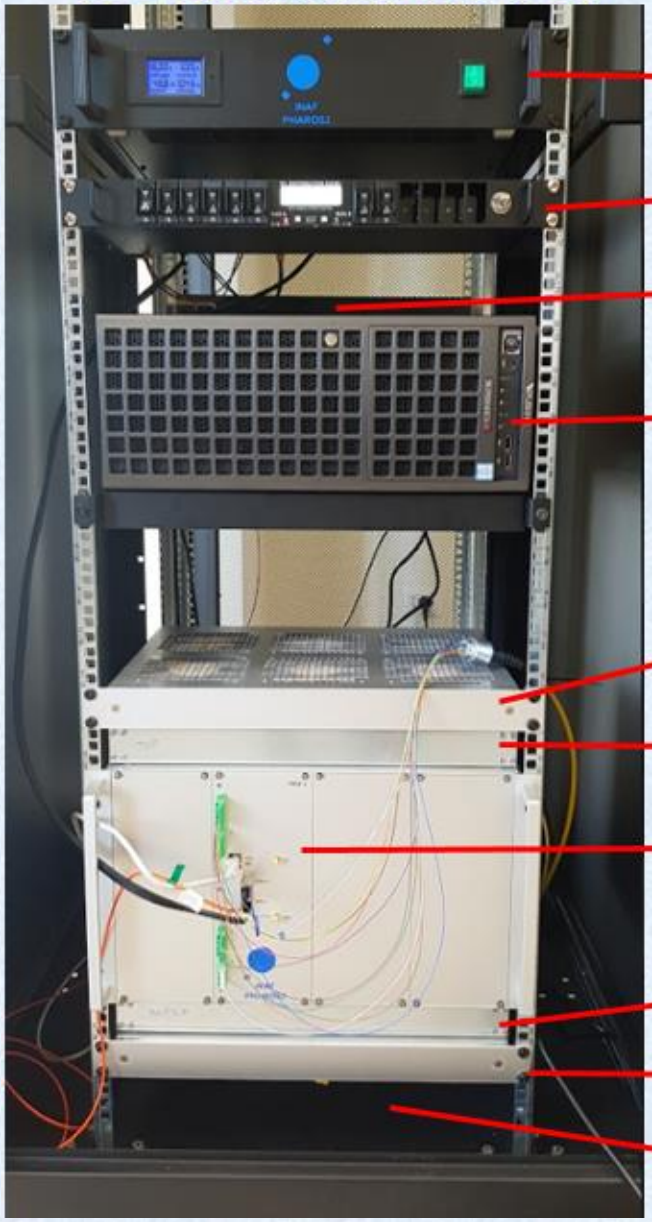
Beamforming implemented in the iTPM-FPGAs for 24 elements, single-pol., four beams, with ≈275 MHz BW.

Each beam provided with time-integrated spectra (pulsar search, on-the-fly mapping) and with non integrated spectra (pulsar timing).



PHAROS2 digital backend cabinet

BE cabinet front view



Power supply (2U)

Power distributor (1U)

Switch 1G (1U)

Server (4U)

Air blower (1U)

Air deflector (1U)

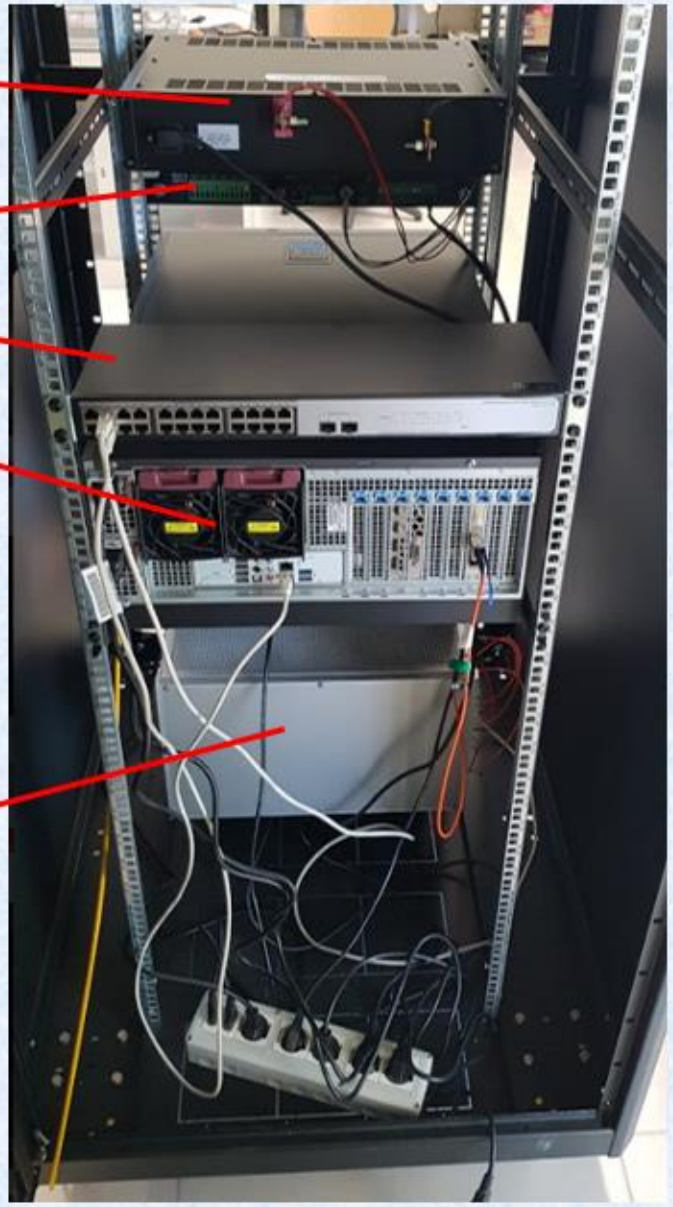
Subrack with one iTPM (6U)

Air deflector (1U)

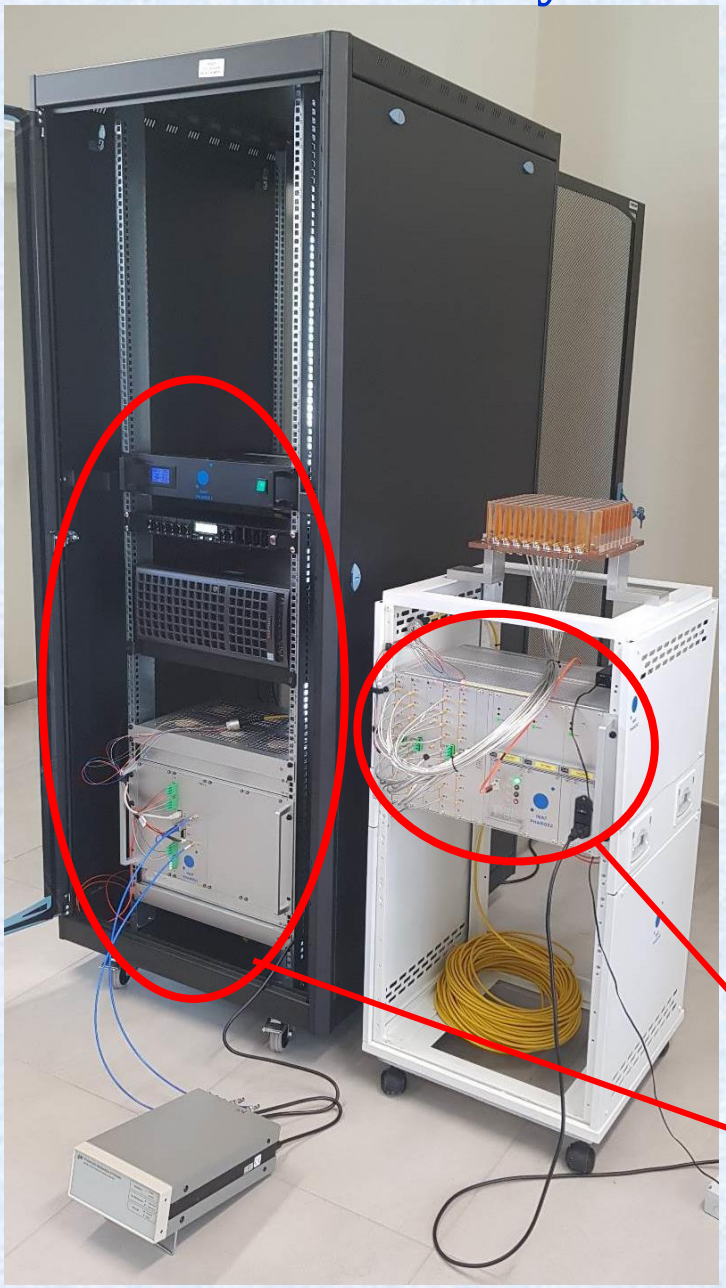
Air blower (1U)

Empty slot for air circulation (2U)

BE cabinet rear view

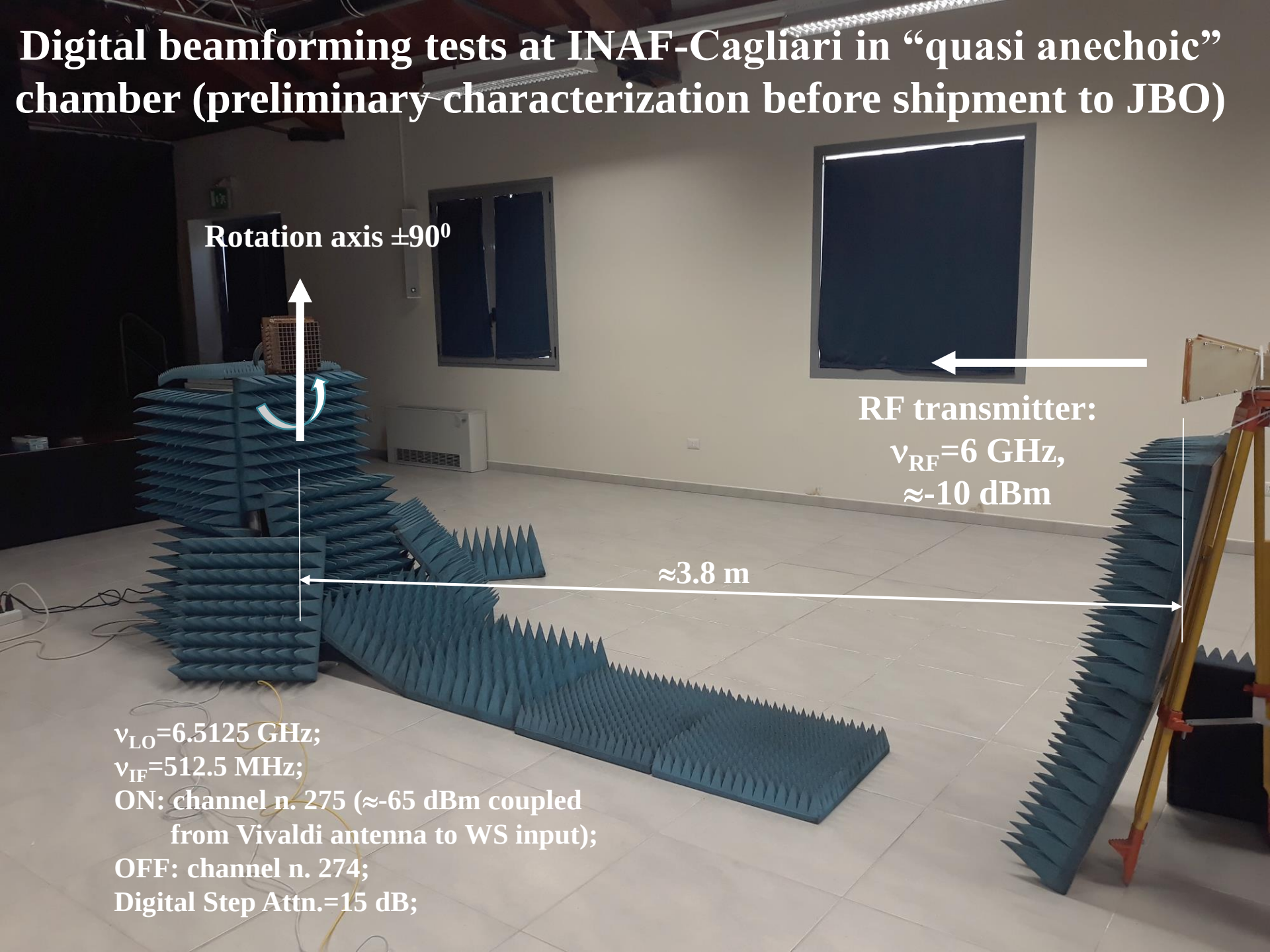


Connecting the Vivaldi array with Warm Section and digital backend for end-to-end system verification and preliminary lab tests



Hardware delivered to Jodrell Bank Obs. (UK) in July 2019

Digital beamforming tests at INAF-Cagliari in “quasi anechoic” chamber (preliminary characterization before shipment to JBO)



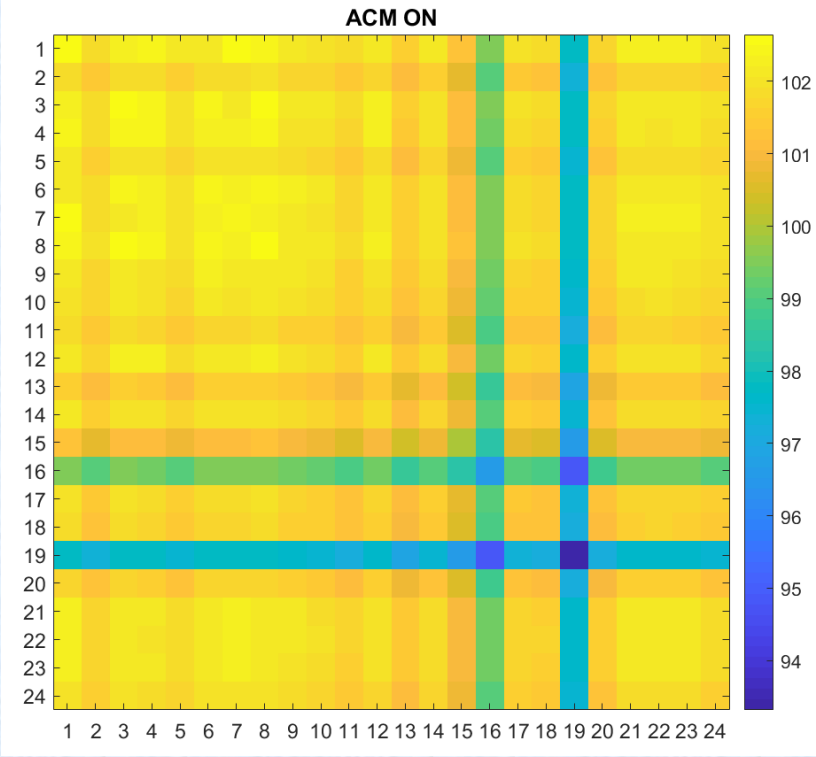
ν_{LO}=6.5125 GHz;
ν_{IF}=512.5 MHz;
ON: channel n. 275 (≈-65 dBm coupled from Vivaldi antenna to WS input);
OFF: channel n. 274;
Digital Step Attn.=15 dB;

Characterization of PHAROS2 beam pattern

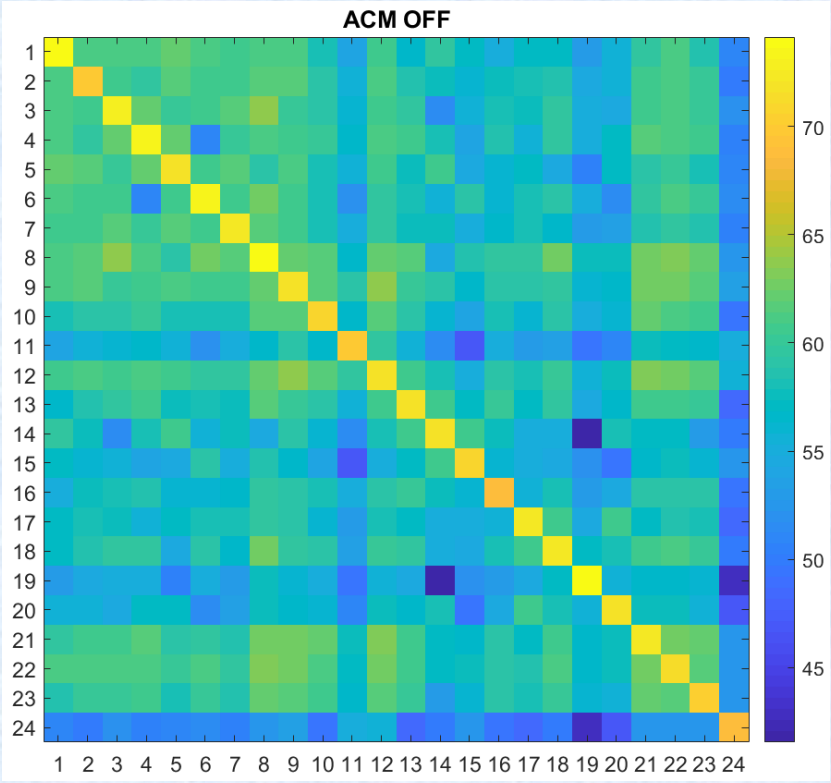
- PHAROS2 pointed towards the transmitter (boresight) for acquisition of calibration coefficients;
- Offline calculation of ACM and beamformer weights for the 24 antennas using max SNR algorithm;
- Beamformer weights of the antennas uploaded on the iTPM-FPGAs;
- $\pm 90^0$ beam scan in azimuth, with 2.5^0 steps;
- Offline calculation of four formed beams;
- Comparison of measured beam patterns with electromagnetic simulations;

Array Covariance Matrix

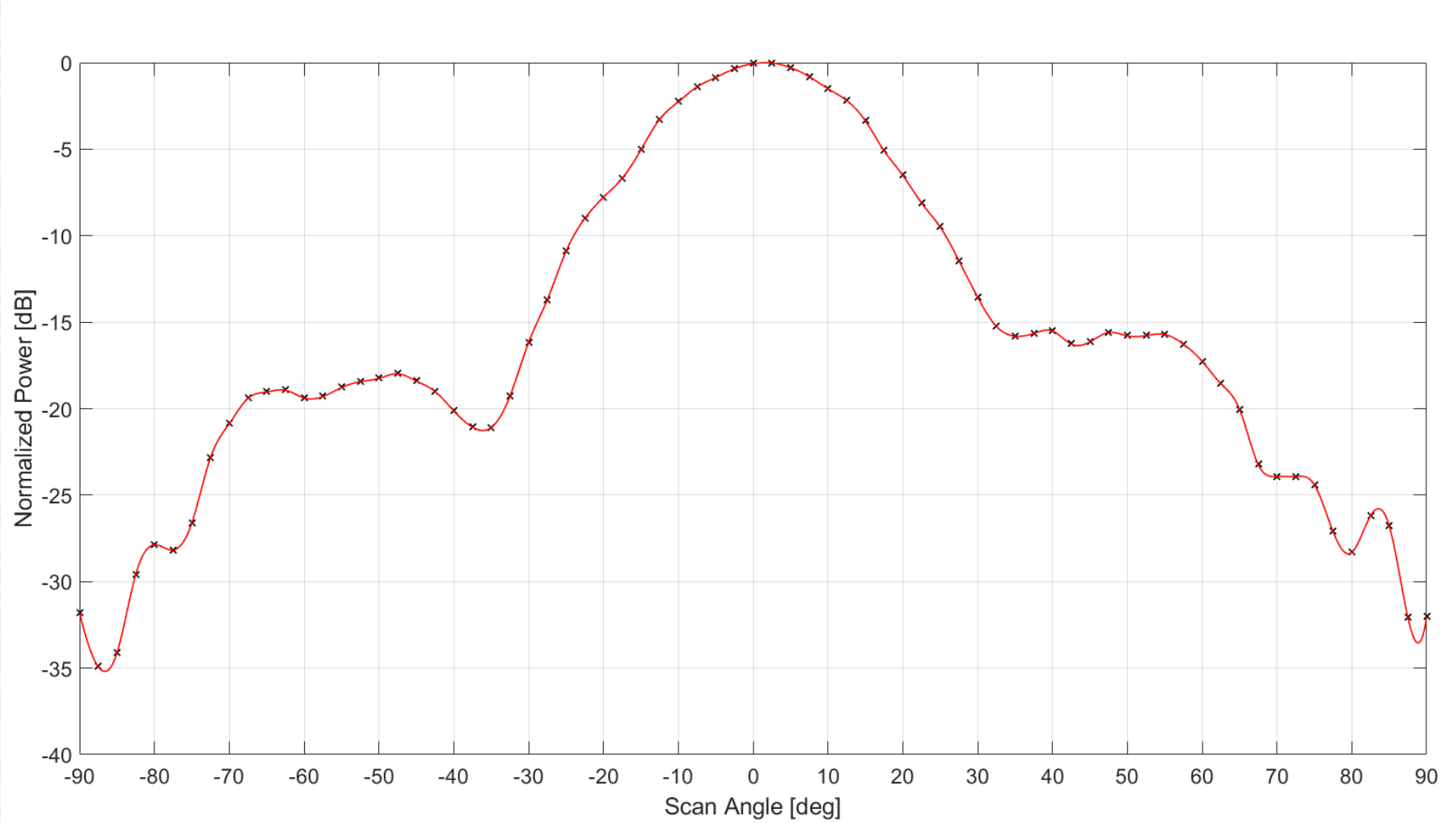
ACM ON: ch. n. 275



ACM OFF: ch. n. 274

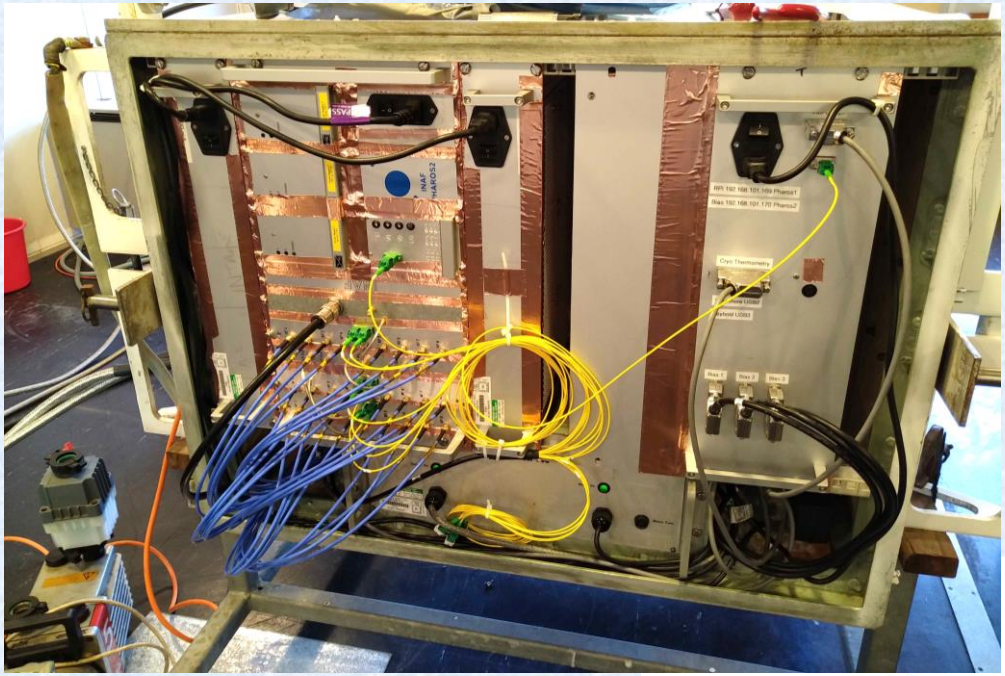


Preliminary beam pattern characterization results of PHAROS2 array with iTPM digital beamformer (maxSNR)

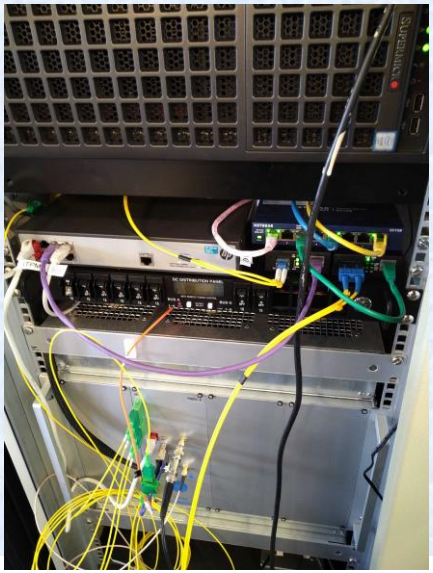


Integration of PHAROS2 warm section and digital backend with cryostat at JBO and preliminary sky test from the ground

Warm Section integrated into focus box:



Digital backend re-assembled:

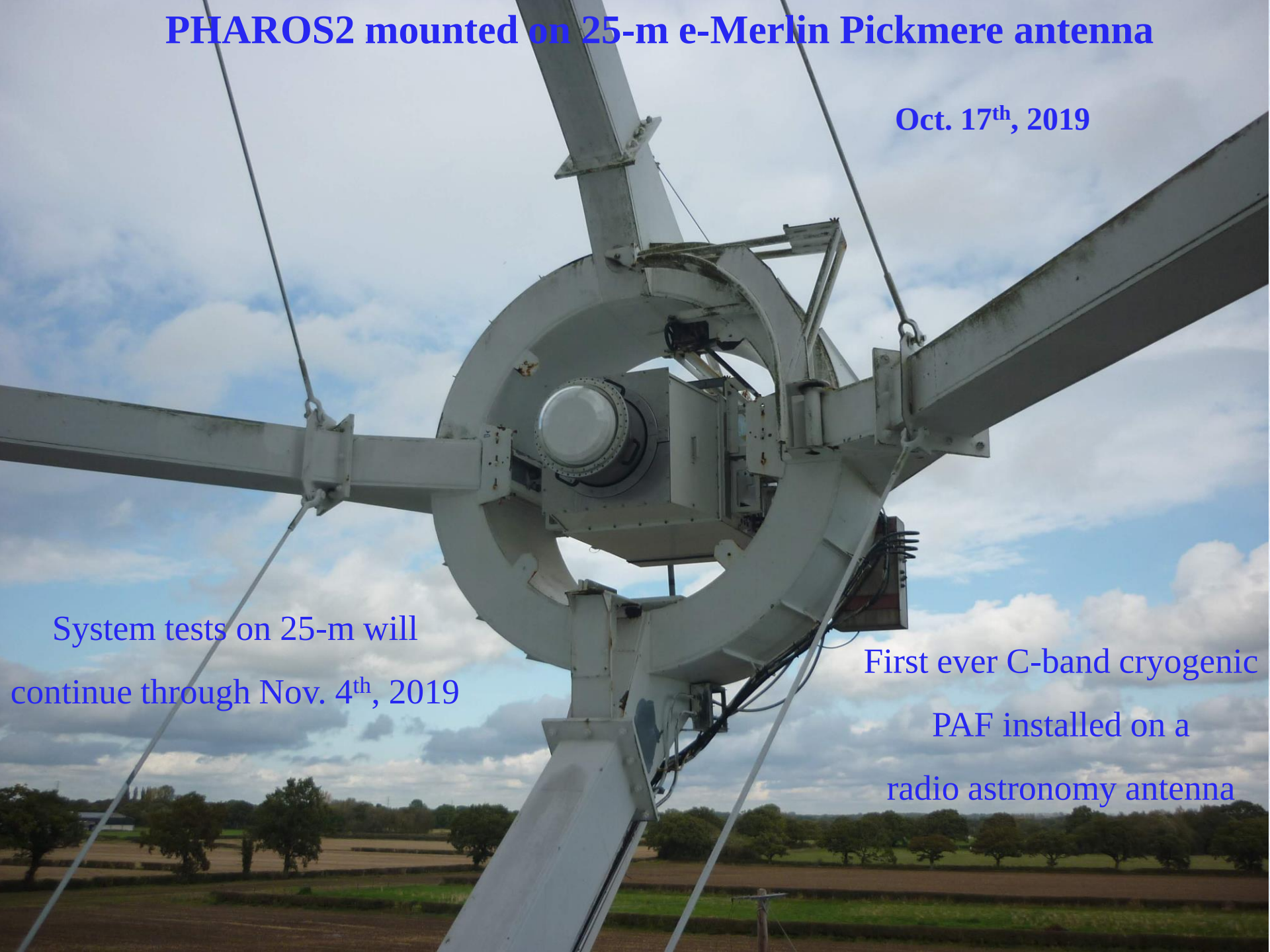


Ground tests at JBO:

Oct. 16th, 2019

Mounting PHAROS2 on 25-m e-Merlin Pickmere antenna

Oct. 17th, 2019


PHAROS2 mounted on 25-m e-Merlin Pickmere antenna
Oct. 17th, 2019
System tests on 25-m will continue through Nov. 4th, 2019
First ever C-band cryogenic PAF installed on a radio astronomy antenna

Observing modes for PHAROS2 technical/scientific test on 25-m diameter Pickmere antenna

1) Imaging and pulsar search modes:

Four integrated beams (spectral channel width 0.81 MHz) covering 275 MHz instantaneous bandwidth with integration time t_{INT} from 50 μsec to 1 sec.
Max data rate ≈1 Gbps;

2) Spectroscopic mode:

Single beam with ≈25 frequency channels covering ≈20 MHz instantaneous bandwidth. Fine channelization achieved through FFT by polyphase filter bank on GPU (Nvidia GTX 1080TI) mounted on the iTPM server.
Frequency resolution down to 100 Hz.
Max data rate ≈380 Mbps.

Science motivations for C-band PAF

- 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