PHAROS2: A C-Band Cryogenic Phased Array Feed

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Overview

- Introduction to Phased Array Feed (PAF)
- SKA Advanced Instrumentation Programme on PAFs
- Science motivations
- The original PHAROS programme
- The PHAROS2 upgrade plan
- Future testing

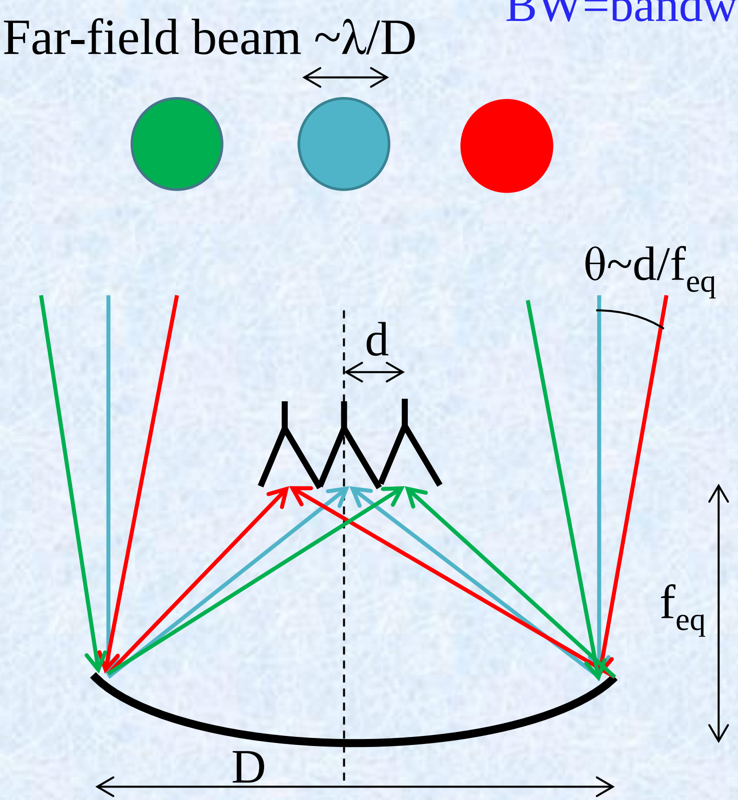
Introduction to Phased Array Feeds

Imaging with a single antenna equipped with an array:

- Off-axis rays are focused to off-axis points in the focal plane.
- Placing an array of feeds in the focal plane increases the survey speed of a radiotelescope by a factor of **N** (with respect to SPF), with **N** number of simultaneous primary beams.

$$\textbf{Survey Speed} \sim N\,\lambda^2\,BW\,(D/T_{SYS})^2$$

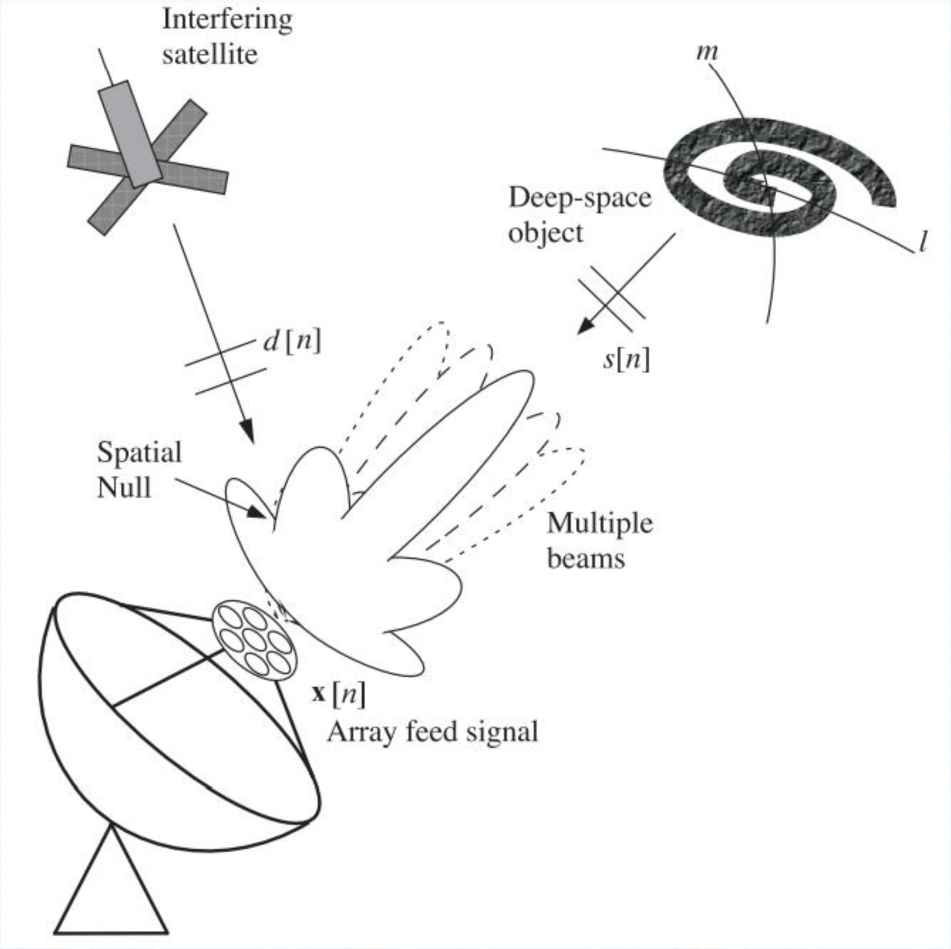
BW=bandwidth T_{SYS}=system noise temperture

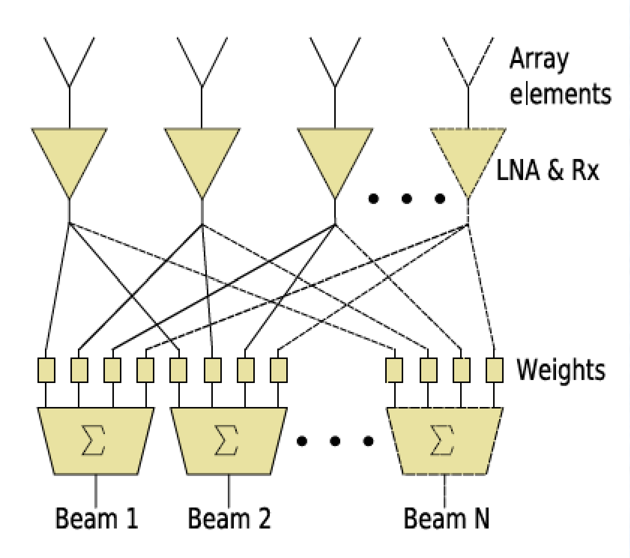


- A Phased Array Feed is made of closely packed antenna elements (d~λ/2) that, by spatially sampling the focal plane, can synthesize multiple independent beams and be set to Nyquist-sample the sky (unlike array of feed-horns that require few interleaved pointings).

- Beam shapes and directions are controlled electronically by weighting the amplitudes and phases of the signals applied to the individual antennas by a beamformer.

Introduction to Phased Array Feeds





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;
- Reduction of bandpass ripples;
- Correct for off-axis aberrations;
- Compensate for large-scale distorsion of dish surface errors;
- Direct one or more beams towards calibrator 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;

SKA Advanced Instrumentation Program (AIP): PAF Consortium

SKA
SQUARE KILOMETRE ARRAY
PHASED ARRAY FEED

- INAF is part of the SKA AIP on PAF;
- The AIP kick-off was held in Cagliari in 2016, following the PAF2016 Workshop organized by INAF;
- PAF Consortium Agreement expires in March 2019. Being extended to June 2020.

8 Full Members:

MANCHESTER 1824 The University of Manchester
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
ASTRON
ONSALA RYMDOBSERVATORIUM CHALMERS TEKNISKA HÖGSKOLA
JLRAT
CSIRO
Max Planck Institute for Radio Astronomy
University of Malta

2 prospective members:

INSTITUTO de ASTROFISICA de ANDALUCIA CSIC I·A·A
IEEC INSTITUT D'ESTUDIS ESPACIALS DE CATALUNYA

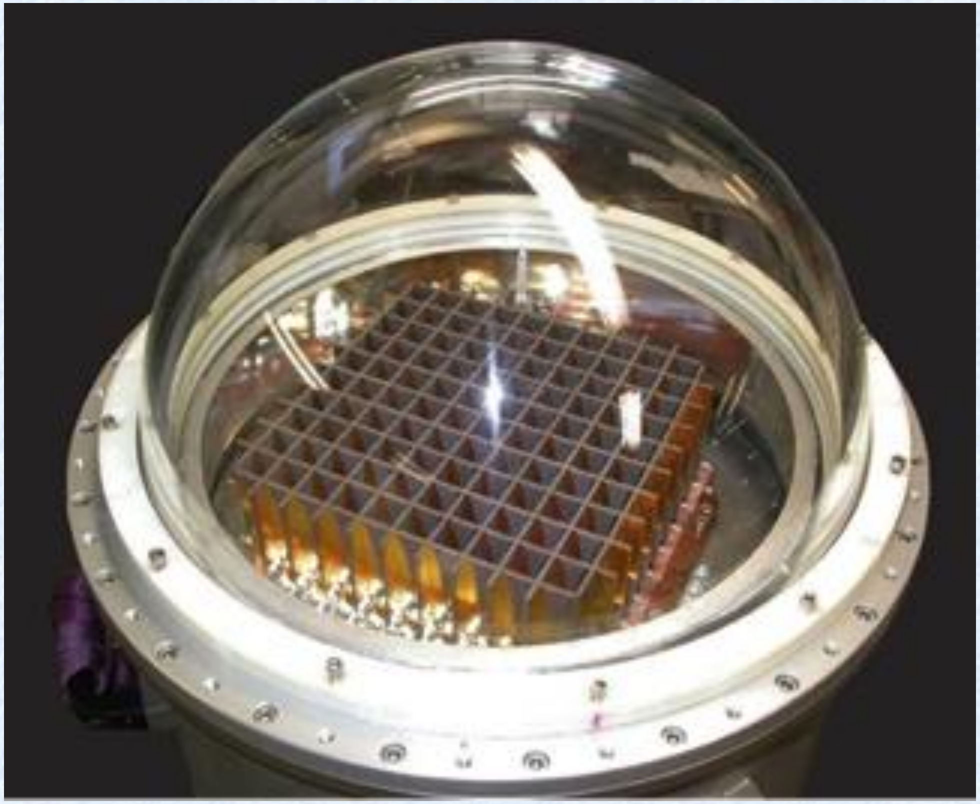
It is currently funded by in-kind contributions of the member institutes that are focussed on their own PAF R&D programs – with no real focus on SKA PAFs yet.

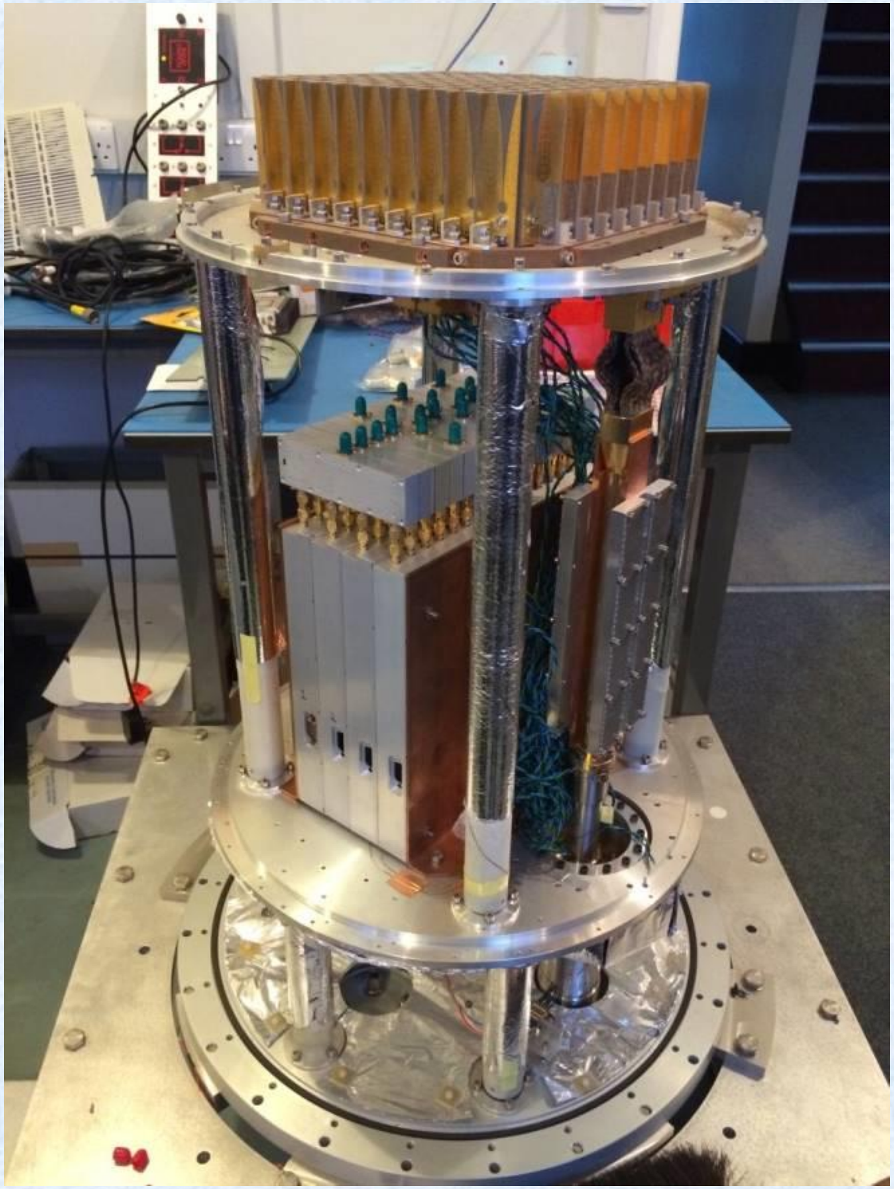
Science motivations for C-band PAF

- SKA Band 5 had 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

The original PHAROS programme

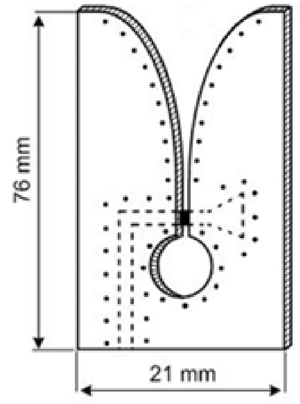
- Cryogenically cooled PAF
- 4-8 GHz
- Analogue beam forming



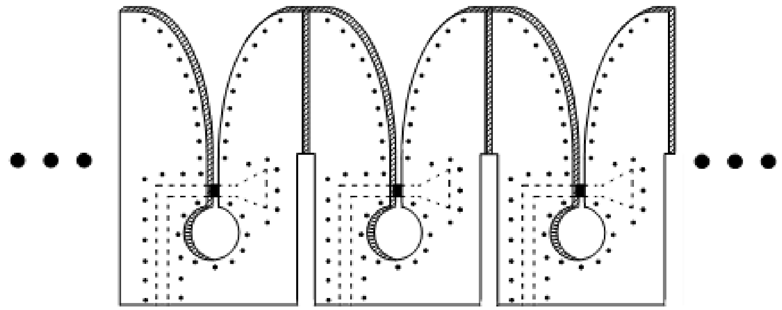


Vivaldi antenna array

- 10x11 dual pol. array
- Only central elements active
- Rest matched terminated



(a)



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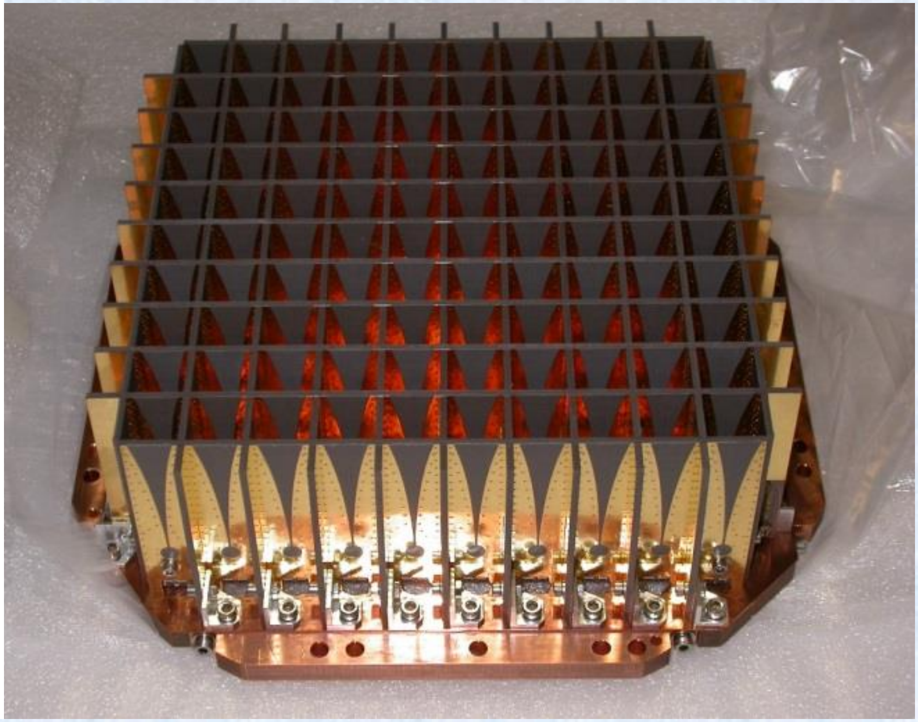
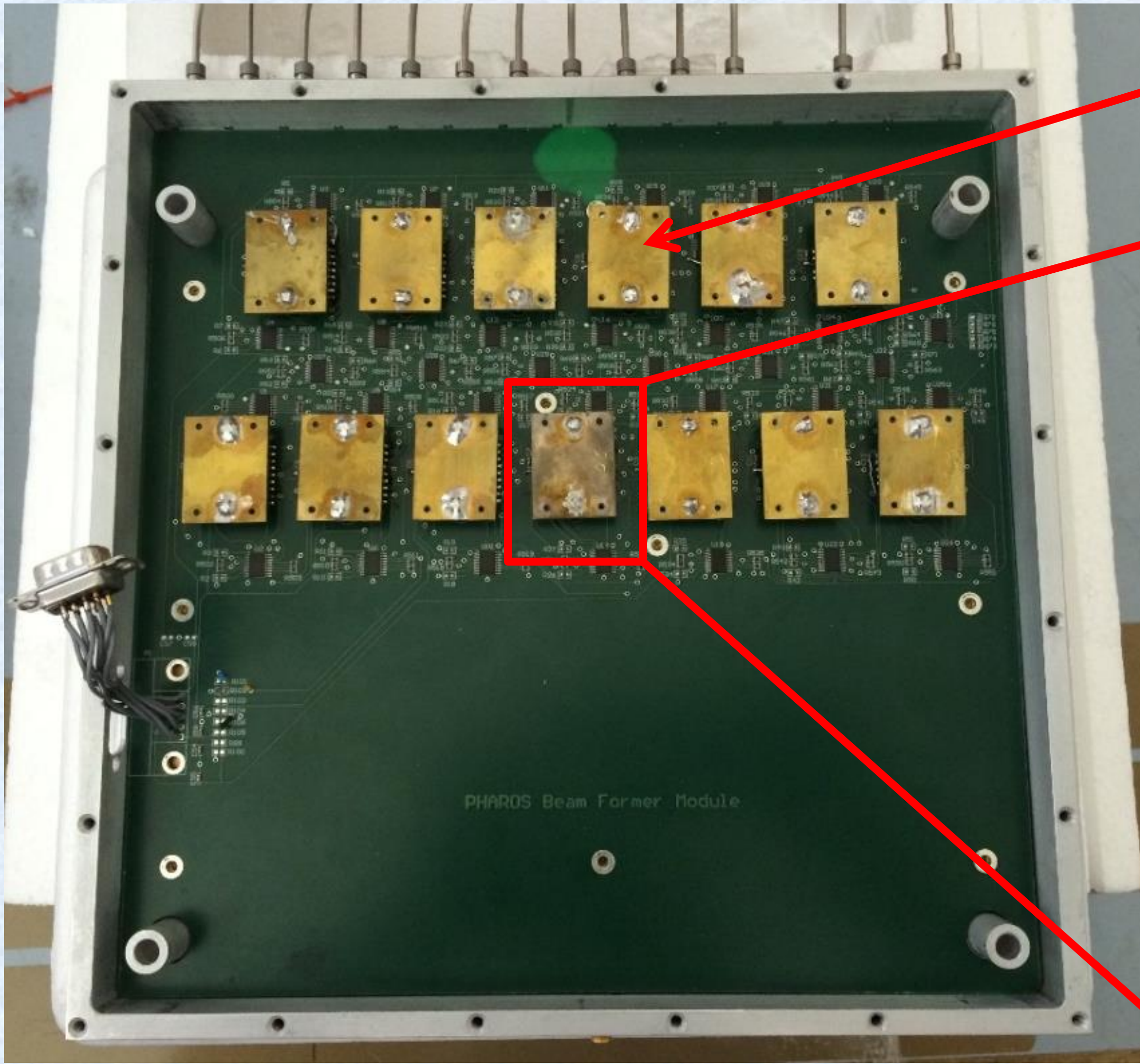


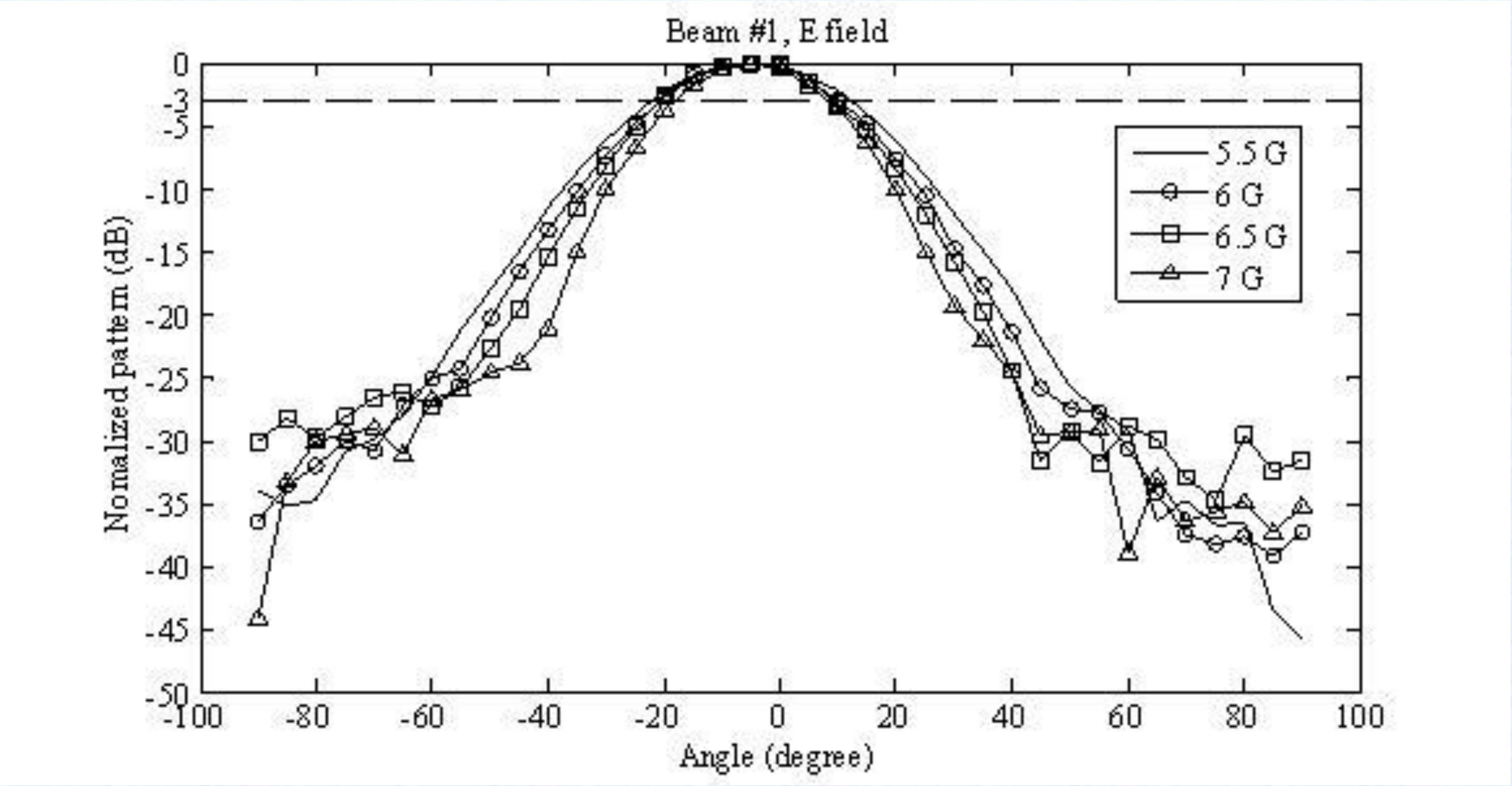
PHAROS Analog beamformer

- 13 input Wilkinson combiner
- Phase and Amplitude Controller (PAC module)
- 4 analogue beams formers



One of the 13 PACs

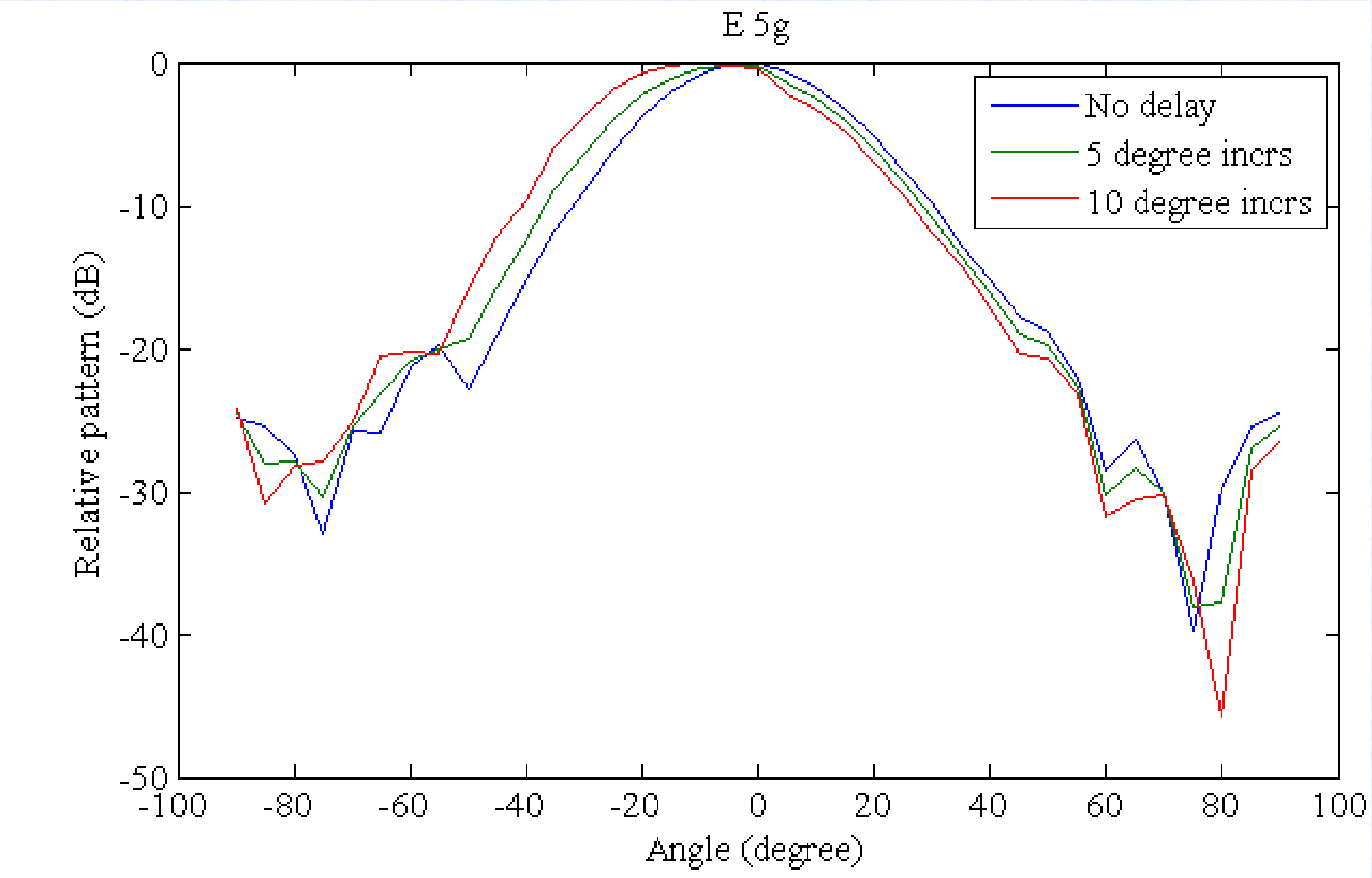
Anechoic chamber tests



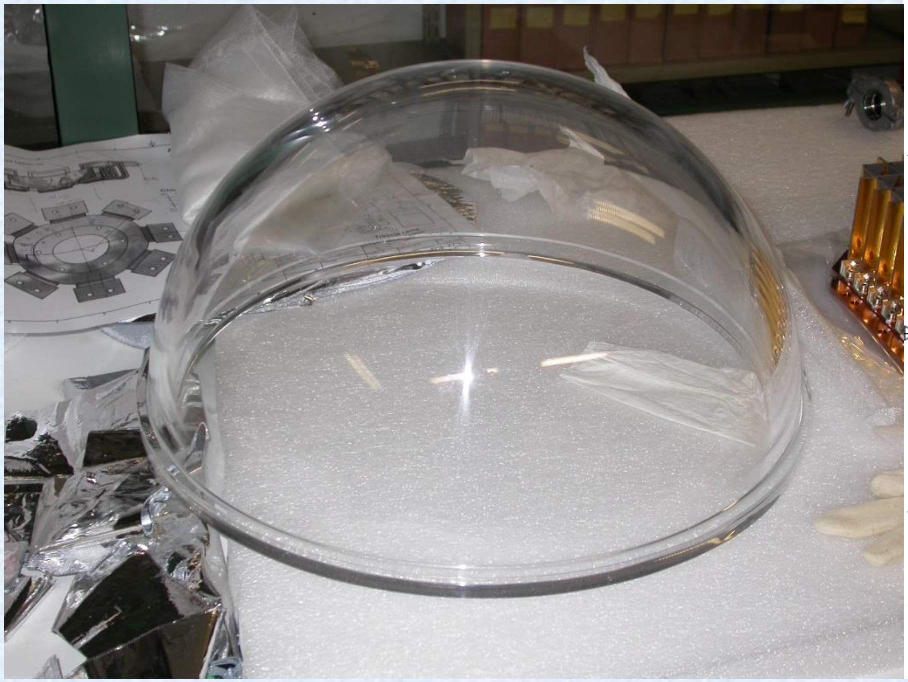
13 element beam-formed patterns

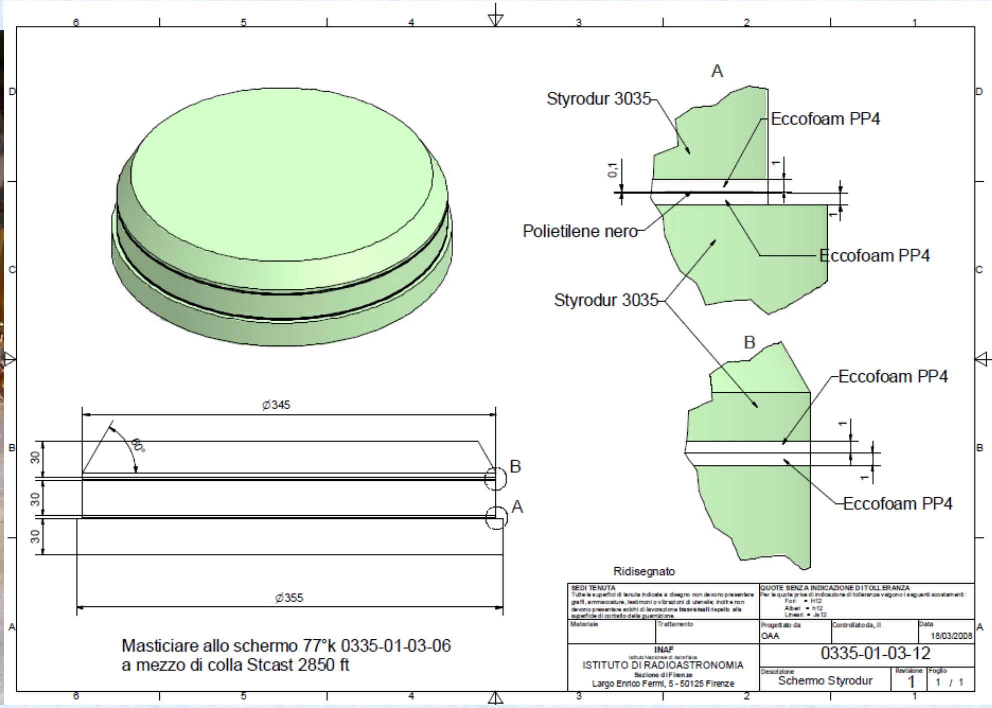
Steering the beam

Using the array in “aperture array” mode



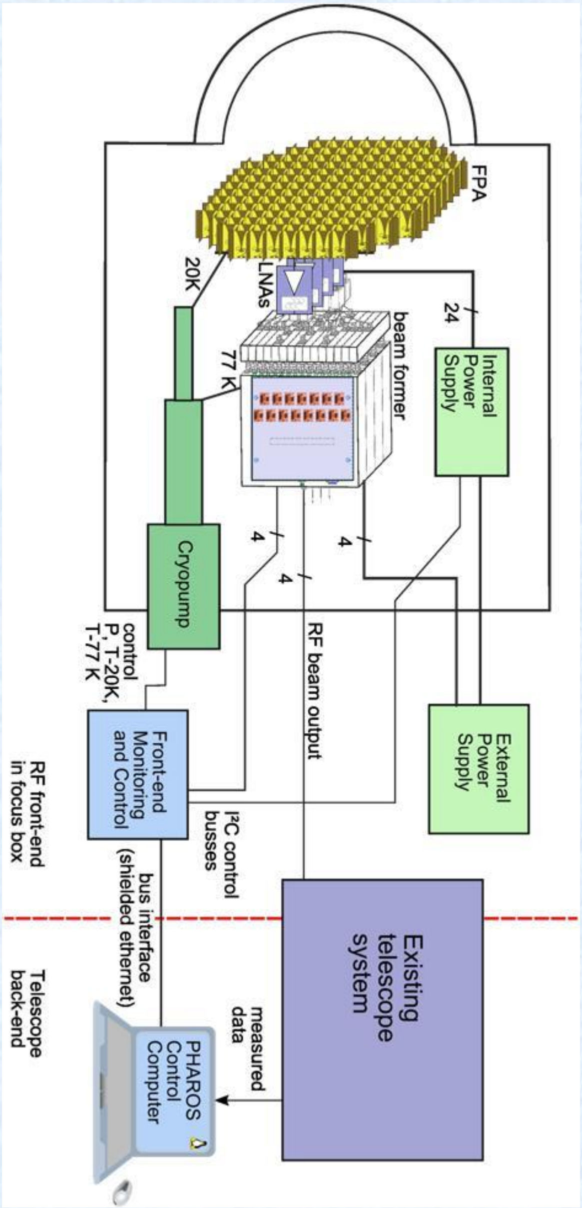
Window and IR filter

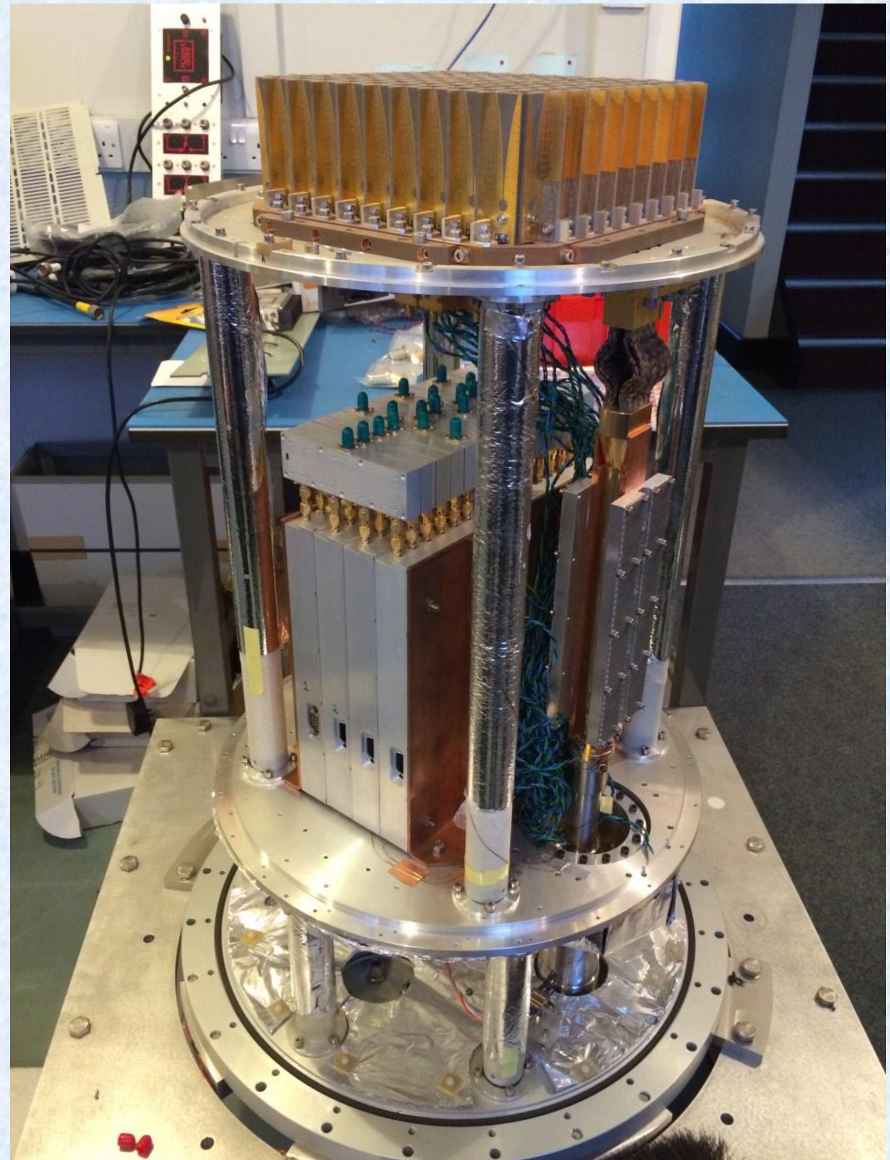




- 15.6 mm thick Plexiglas vacuum window
- IR filter: stacked combination of Styrodur and Eccofoam

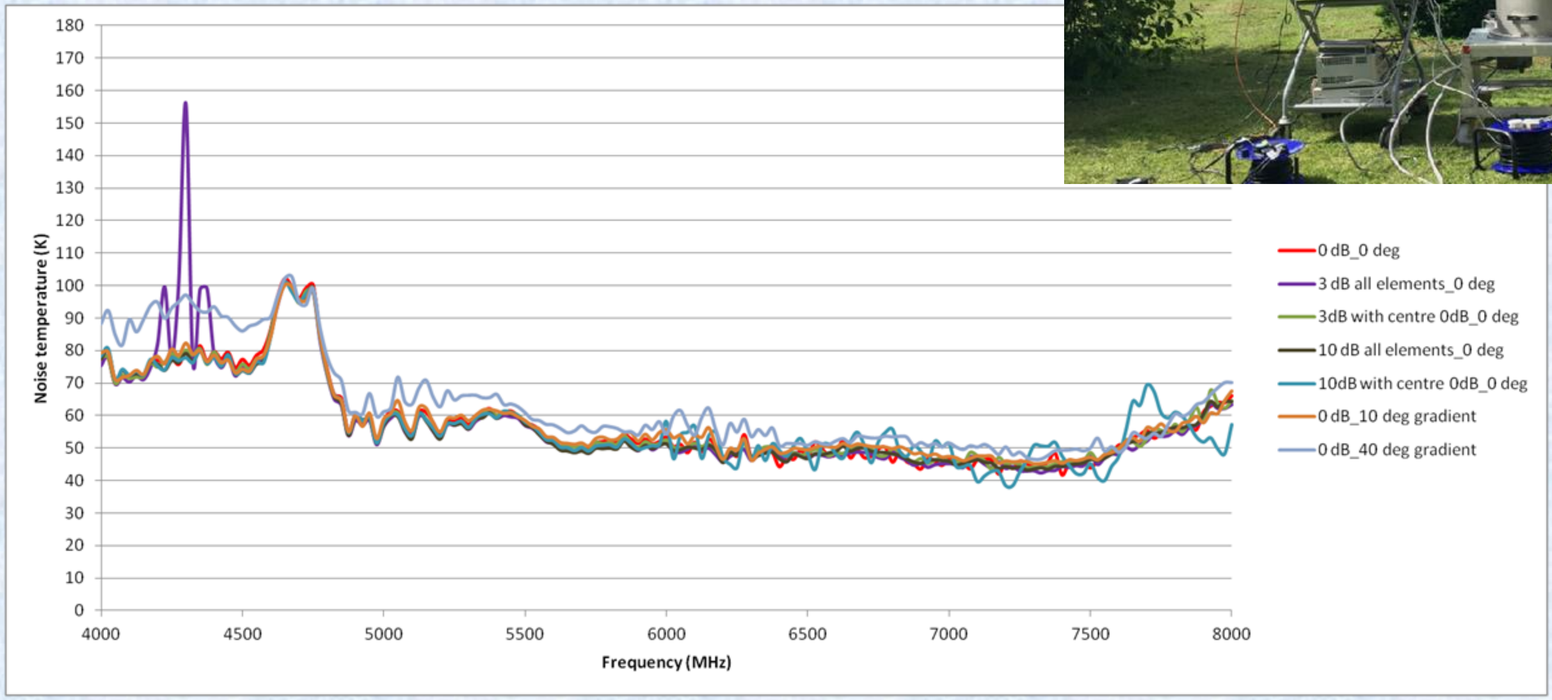
PHAROS RF assembled





Cryo and vacuum systems

System temperature performance

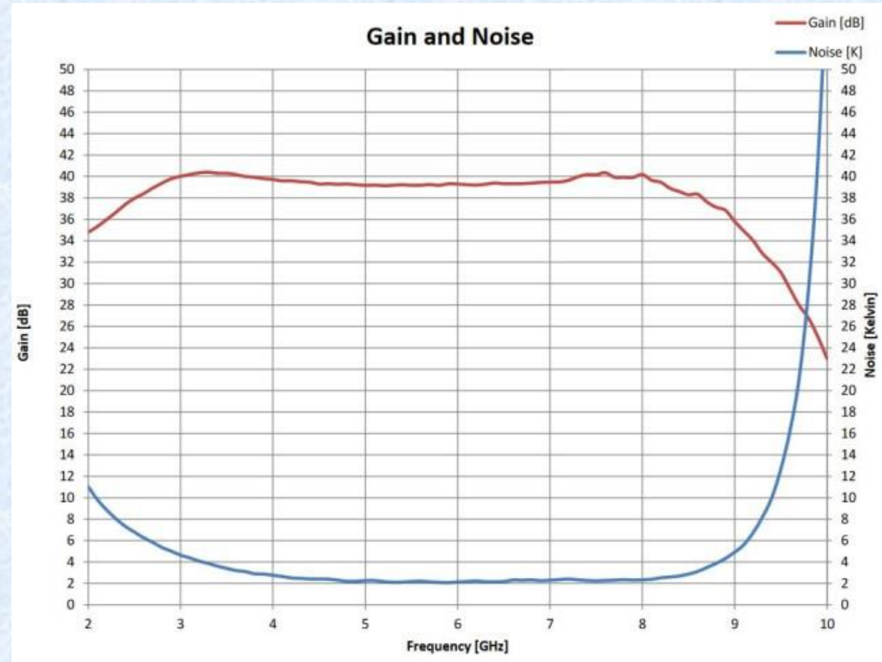


PHAROS2 upgrades

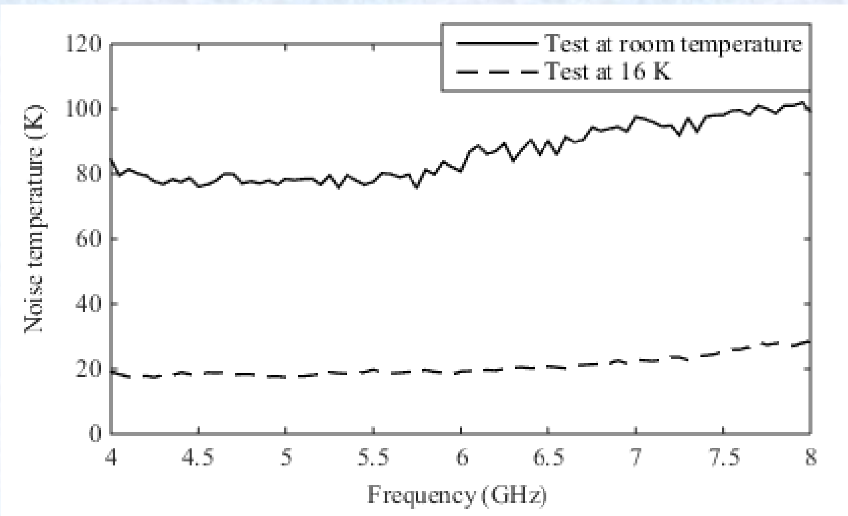
- Prepare for full instrument
  - Improve sensitivity
  - Address scaling issues
- Low noise amplifiers
- Vacuum window
- Digital back-end
- Warm Section downconverter

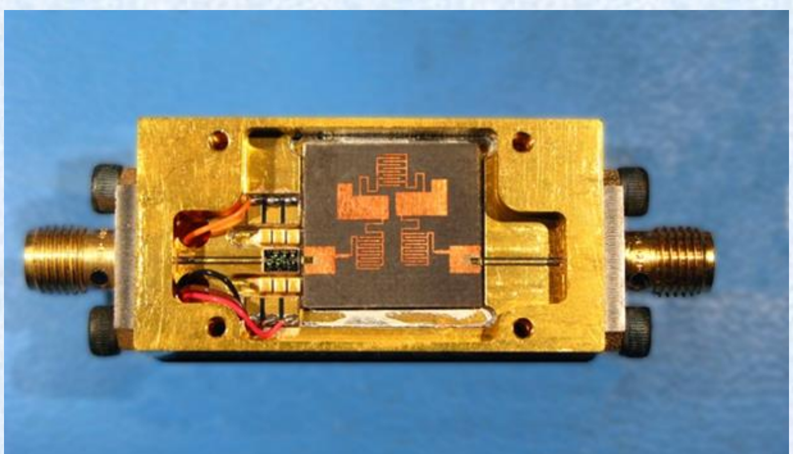
New cryogenic amplifiers: Low Noise Factory LNAs

PHAROS2 LNA



PHAROS LNA



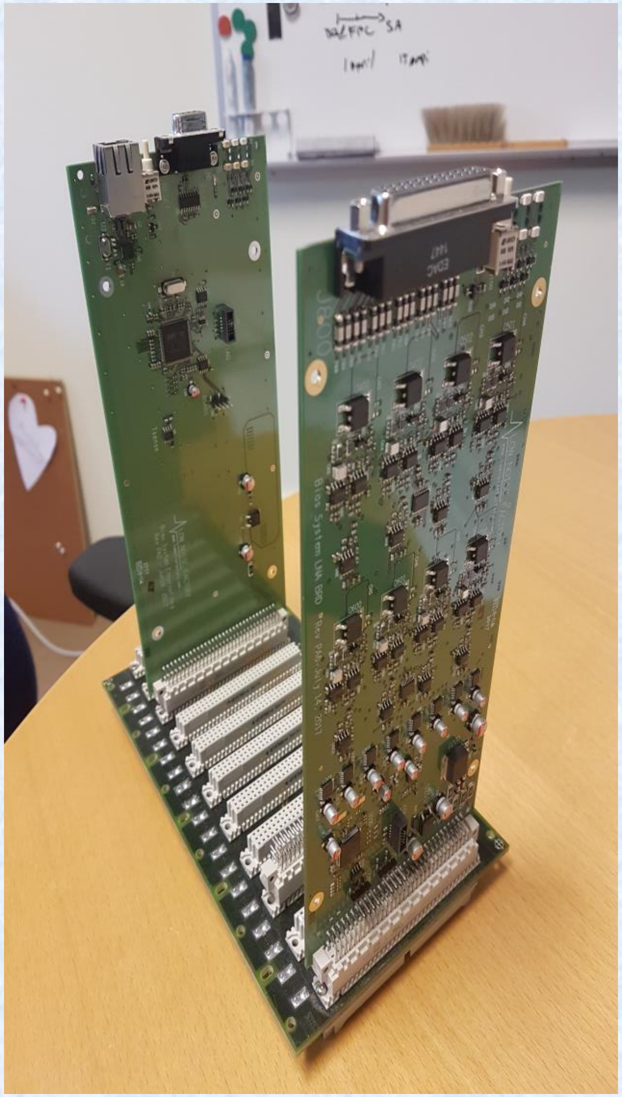


Excellent performance

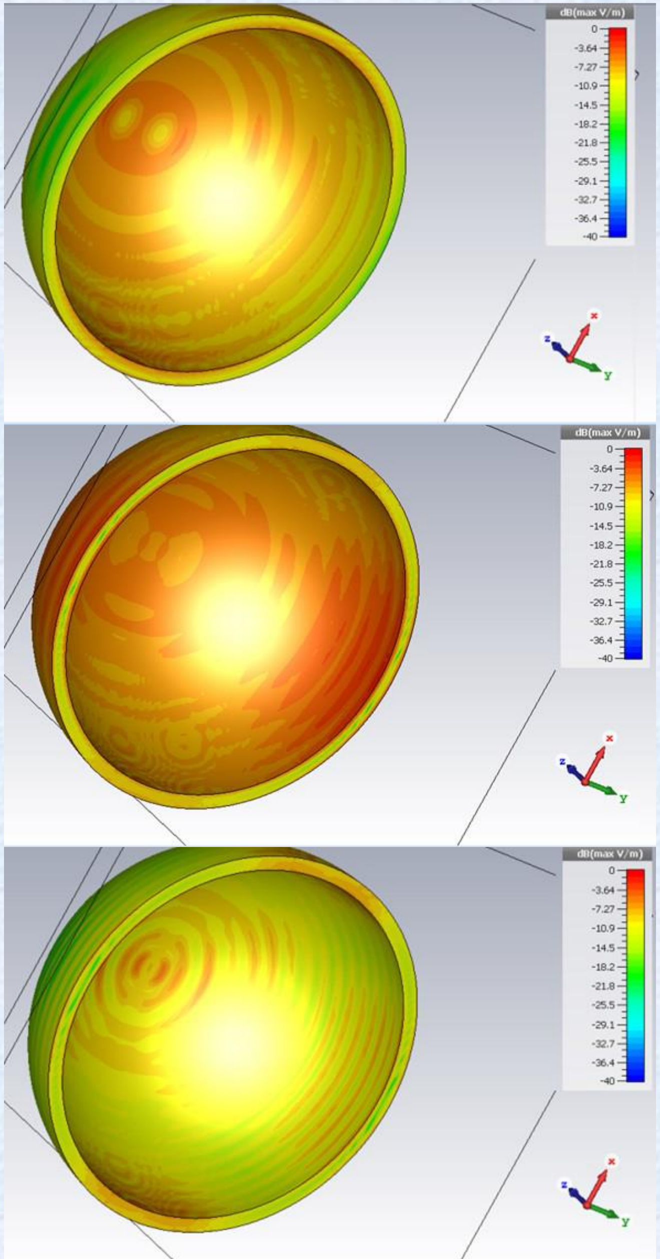
How do we afford populating full array?

Multi-channel LNA bias

- Design of analogue and digital boards
- Each analogue board can handle 8 bias channels
- Each digital board can control and monitor 8 analogue boards
- The interface is ASCII command via TCP/IP or RS 232.



Vacuum window



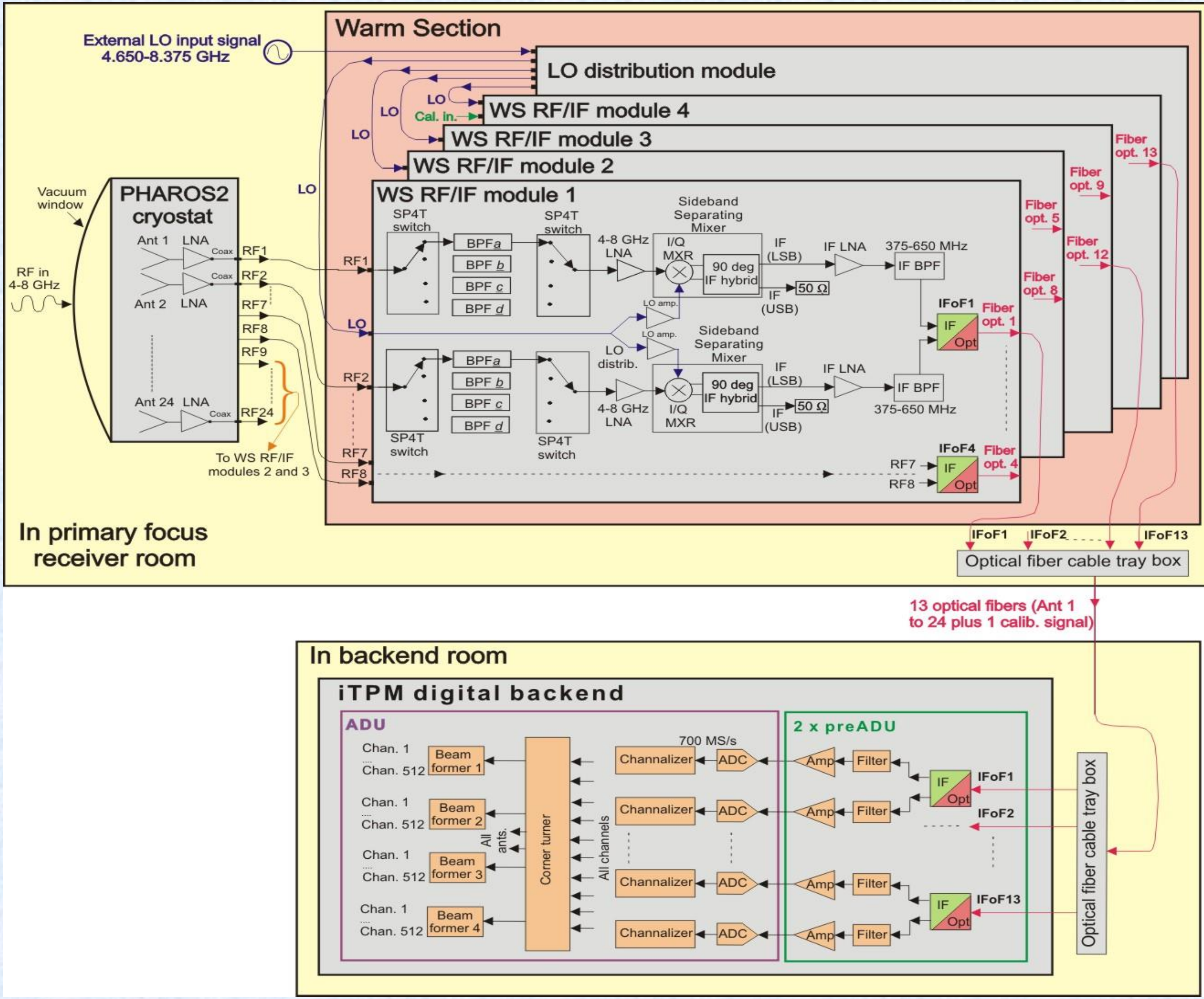
Credit: NRC

- Simulations show significant degradation due to 15.6 mm Plexiglas
- NRC design using TenCate EX-1515 laminate
  - ~1 mm thickness
  - Simulations very promising

Warm Section and Digital backend

- Replace analogue beamformer
- Room temperature multichannel receiver (Warm Section):
  - Downconvert to 375 – 650 MHz IF
  - IQ mixer to extract LSB; additional filters possible
  - Ethernet monitor and control
- IF transmitted over optical fibre:
  - 2 WDM signals per core
  - Developed for SKA LFAA
- iTPM board:
  - 16 dual ADCs and 2 XILINX Ultrascale XCU40 FPGAs
  - Sample at 700MS/s
  - Ethernet out

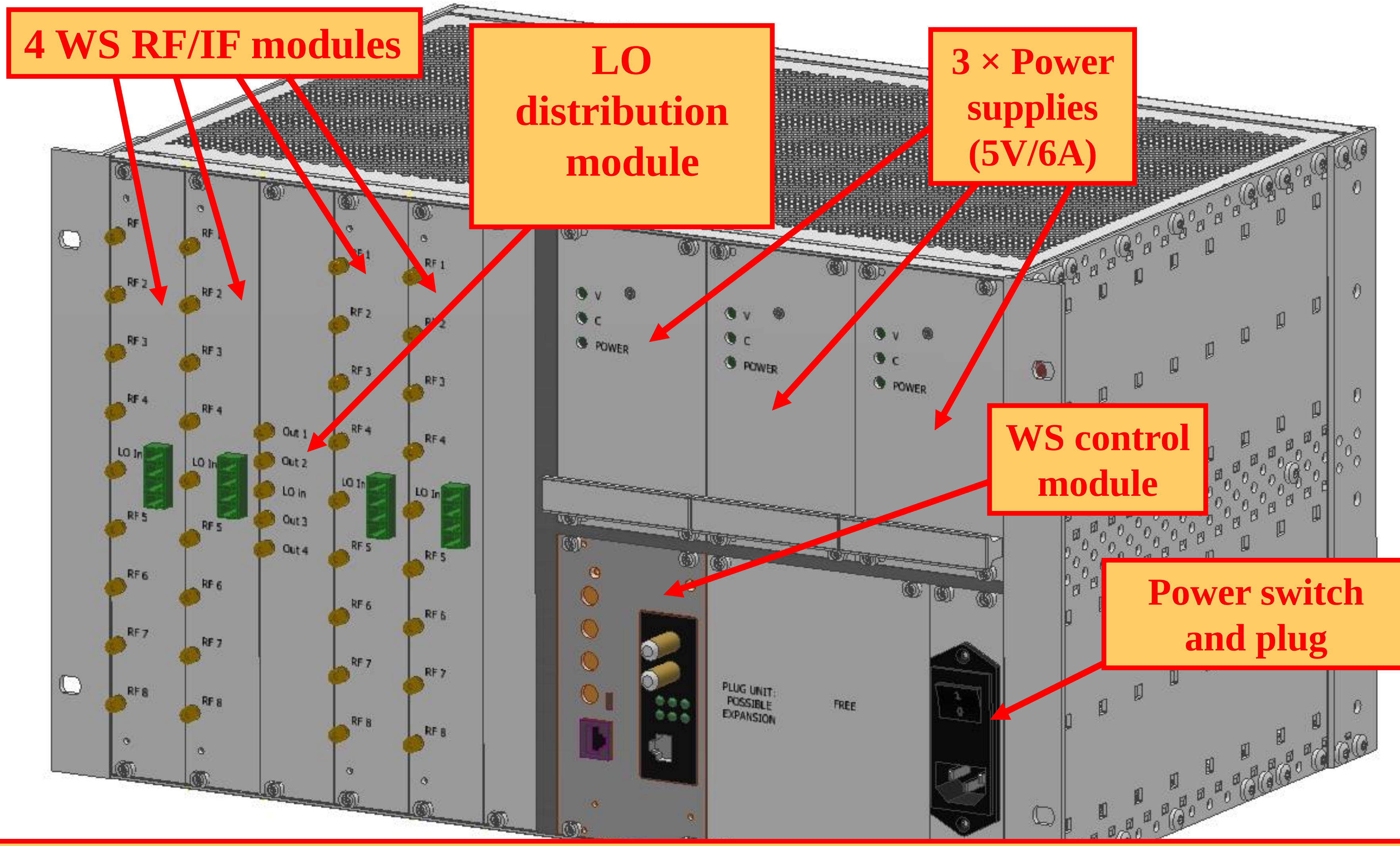
Block diagram of PHAROS2



PHAROS2 specifications	
RF range:	4.0-8.0 GHz
Frequency downconversion type:	Single, with sideband separation mixer (2SB), LSB
LO frequency range:	4.650-8.375 GHz (LSB tuning)
IF frequency range:	375-650 MHz (275 MHz instantaneous bandwidth)
N. of active antenna elements:	24 (out of 220 Vivaldi antenna elements)
N. of compound beams:	4 (using 24 antenna elements)
N. of polarizations:	1 (single-polarization)
Selectable RF filters, frequency ranges and LO tuning frequencies:	Selection of one BPF out of four possible ones: *a)* 4.0-8.0 GHz; LO tunable anywhere across 4.65-8375 GHz *b)* 4.775-5.050 GHz (Formaldhyde at 4.8 GHz and H recombination lines); LO fixed at 5425 MHz; *c)* 5.78-6.055 GHz (Excited rotational states of OH near 6.003 GHz); LO fixed at 6.43 GHz; *d)* 6.445-6.720 GHz (Methanol maser line at 6.668 GHz); LO fixed at 7.095 GHz; When options *b), c) or d)* are chosen the mixer image sideband rejection is increased by the filter rejection (total expected> 60 dB);
IF signal transportation:	Two IF signals transported over a single optical fiber (IFoF) using Wavelength Division Multiplexing (1270 nm and 1330 nm)
Backend and beamforming:	Digital backend with one iTPM (Italian Tile Processing Module) capable of digitizing 32 inputs, 512 frequency channels

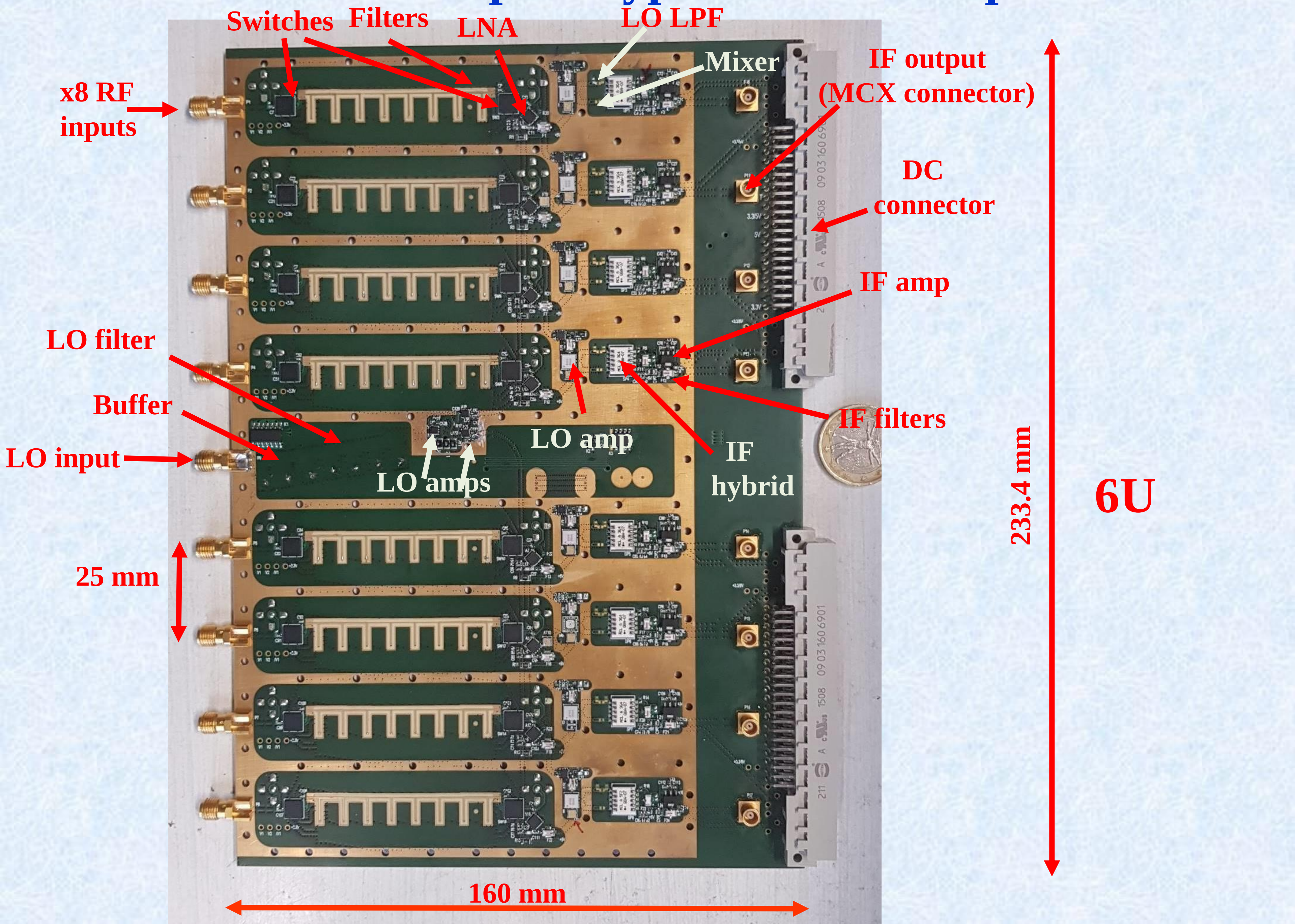
Design of PHAROS2 Warm Section (WS)

32-channel C-band receiver

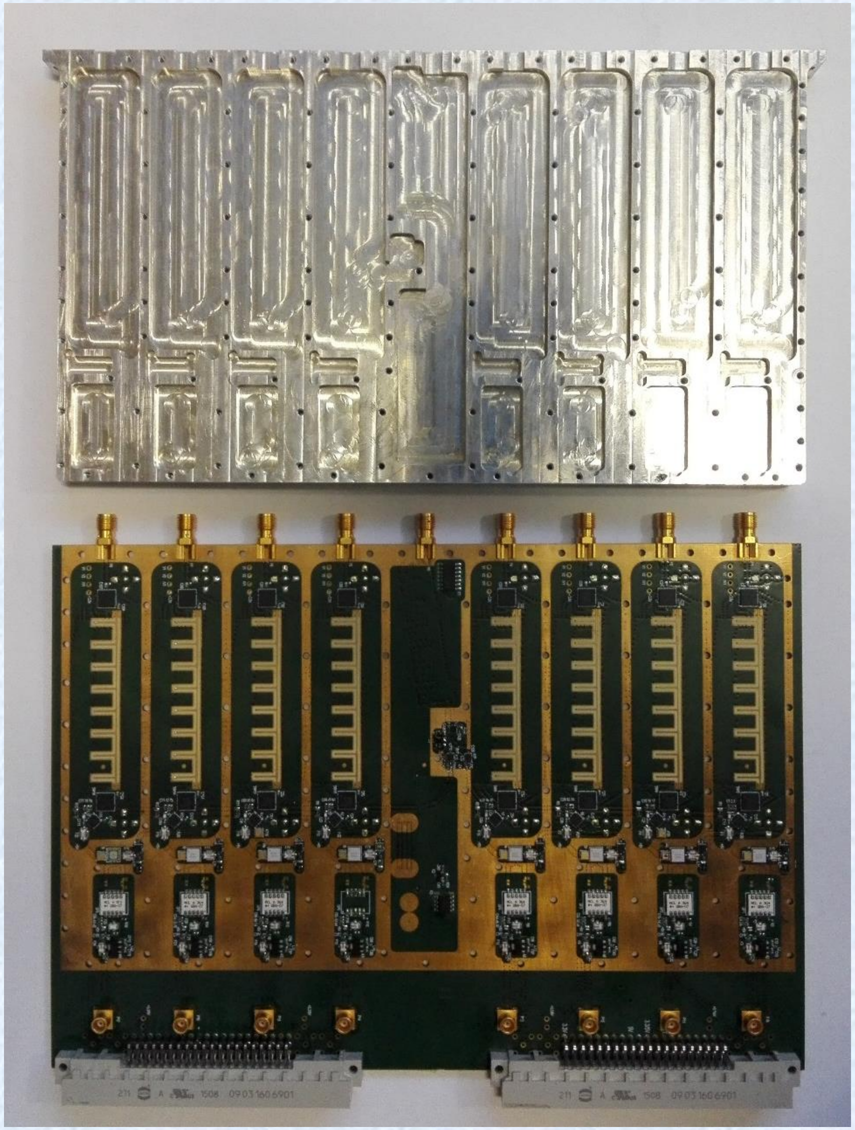


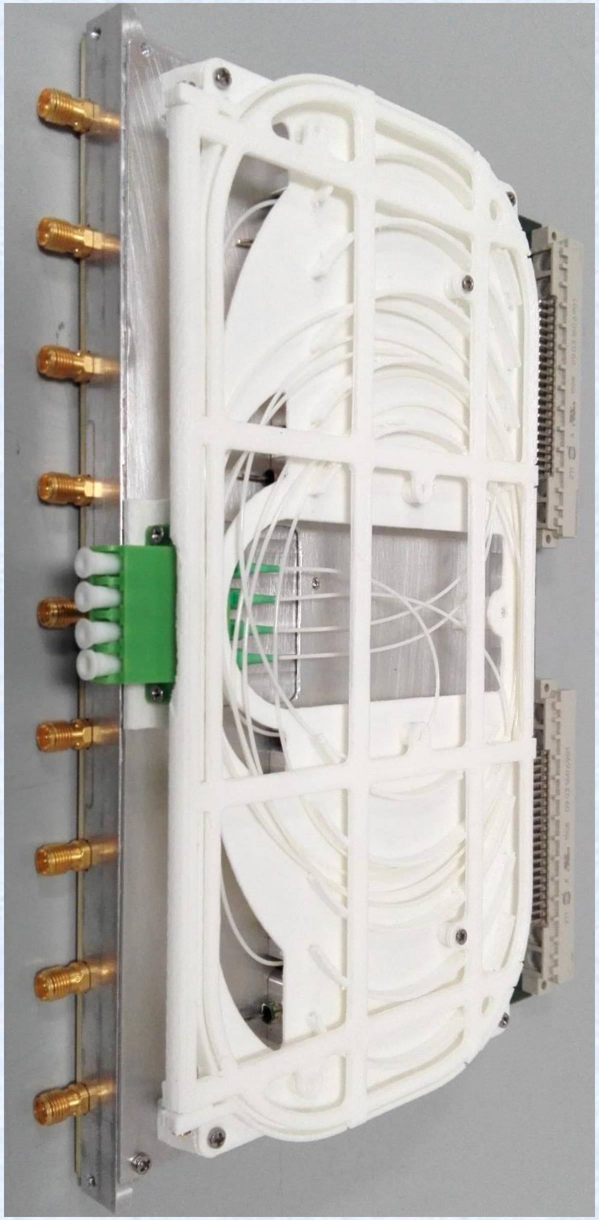
Standard 6U rack (19") with: 4 WS RF/IF modules, 1 LO distribution module and 3 power supplies handling 32 x RF input signals, 24 from cryostat + 1 calibration from noise source (7 unused);

Fabricated prototype: PCB & components



Prototype of PCB, mech. housing and optical transmitters

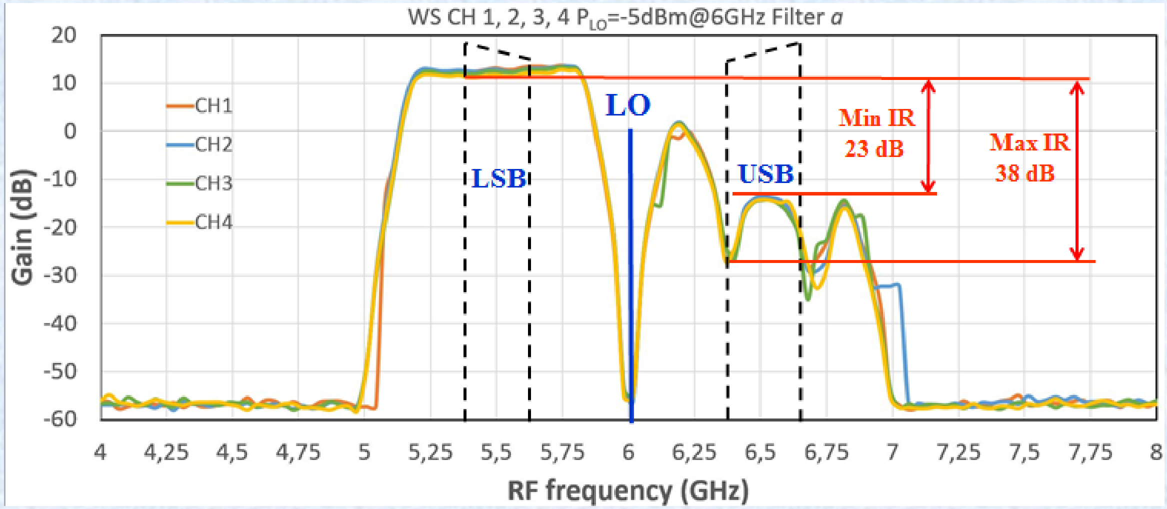




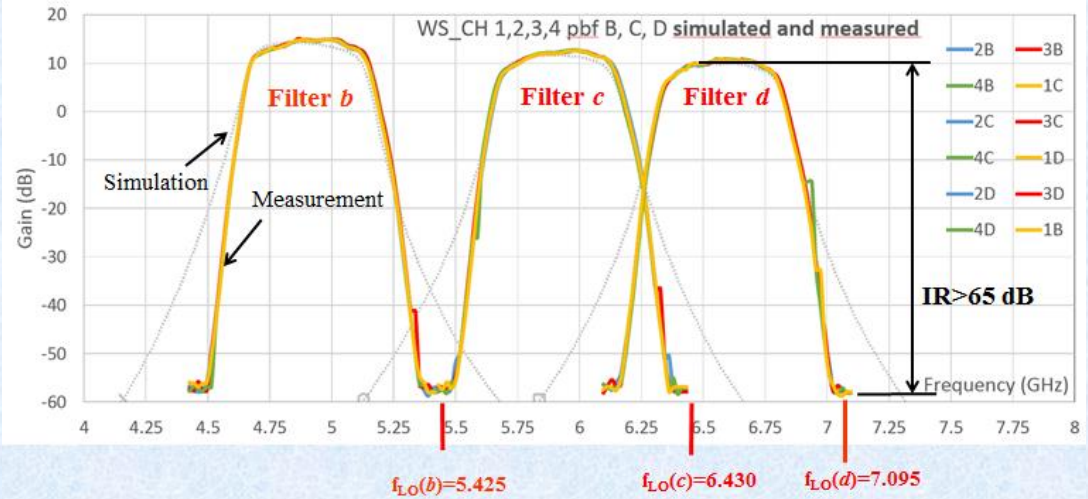
Test of WS RF/IF prototype module

The module works well, according to specifiction

"Filter *a*"



"Filter *b*": 4.775-5.050 GHz, $f_{LO}(b)$=5.425 GHz
"Filter *c*": 5.780-6.085 GHz, $f_{LO}(c)$=6.430 GHz
"Filter *d*": 6.445-6.720 GHz, $f_{LO}(d)$=7.095 GHz



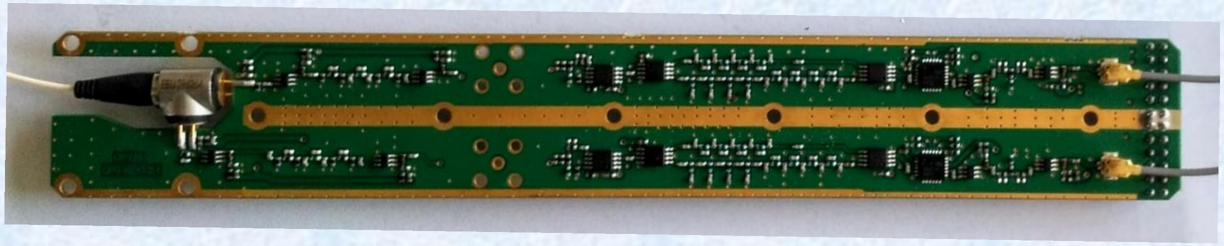
The production modules were slightly modified in design for performance improvement. Recent tests demonstrated that also the production modules are compliant.

PHAROS2 IFoF WDM optical links

Developed for SKA LFAA by INAF-led collaboration:

Some of the optical transmitters (part of WS modules):

One of the optical receivers (part of the preADU)



2 preADUs, each with eight optical receivers:

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

One iTPM utilizes one ADU (Analog Digital Unit) and two preADUs:

ADU

preADU#2

preADU#1

Optical pigtail (from back to front panel)

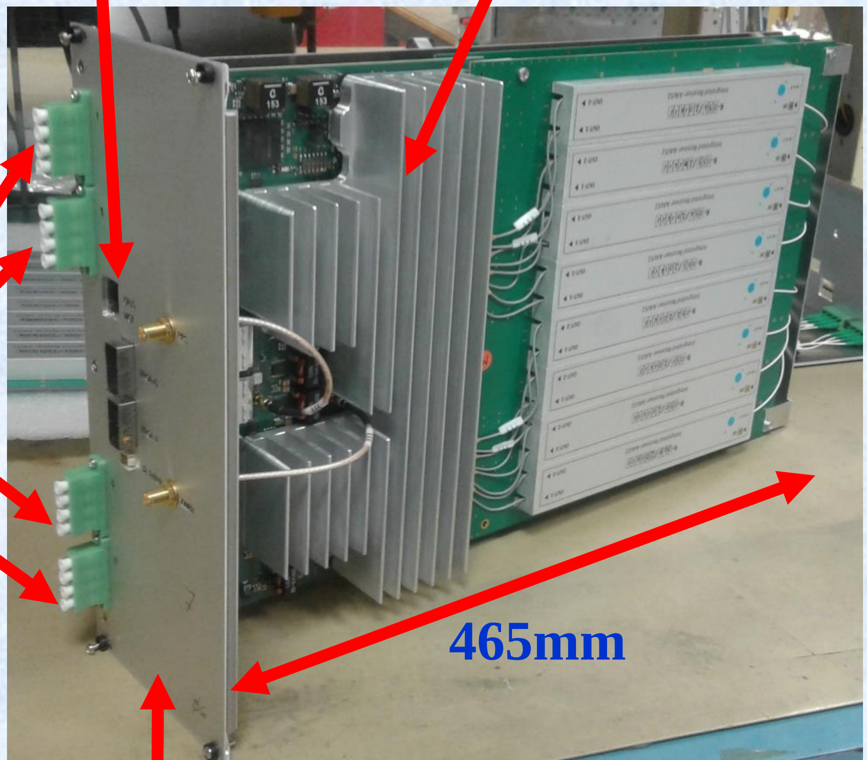
ORXs

PHAROS2 digital backend based on iTPM

1Gb Ethernet

ADU heatsink

16 x LC/APC optical inputs



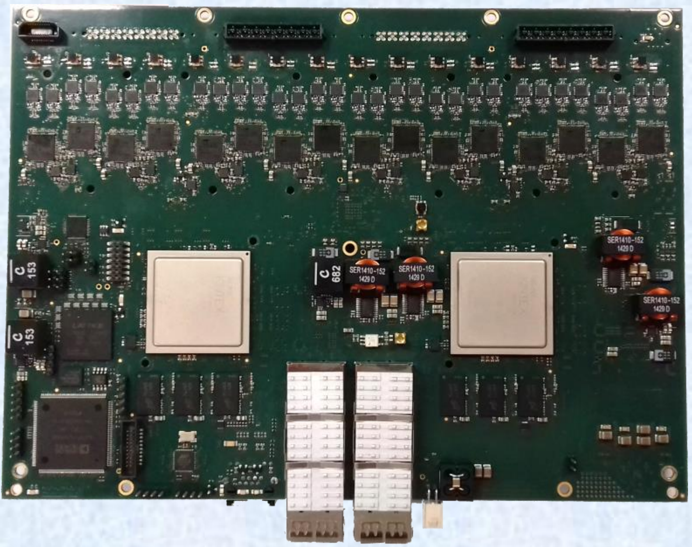
Front Panel Size: 6U, 21HP

PPS input

QSFP+ for 40GbE network

10MHz Input

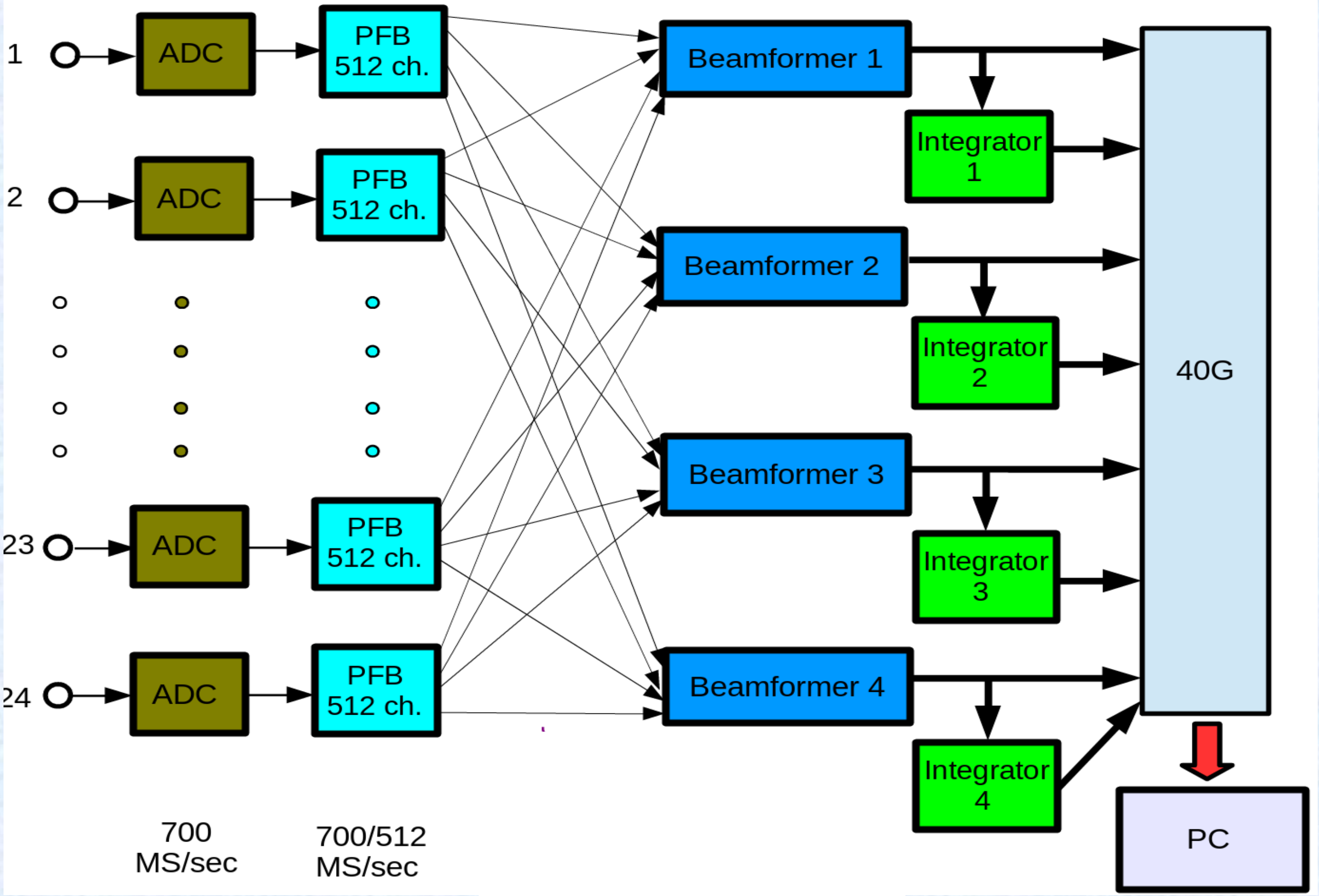
ADU (Analog Digital Unit)

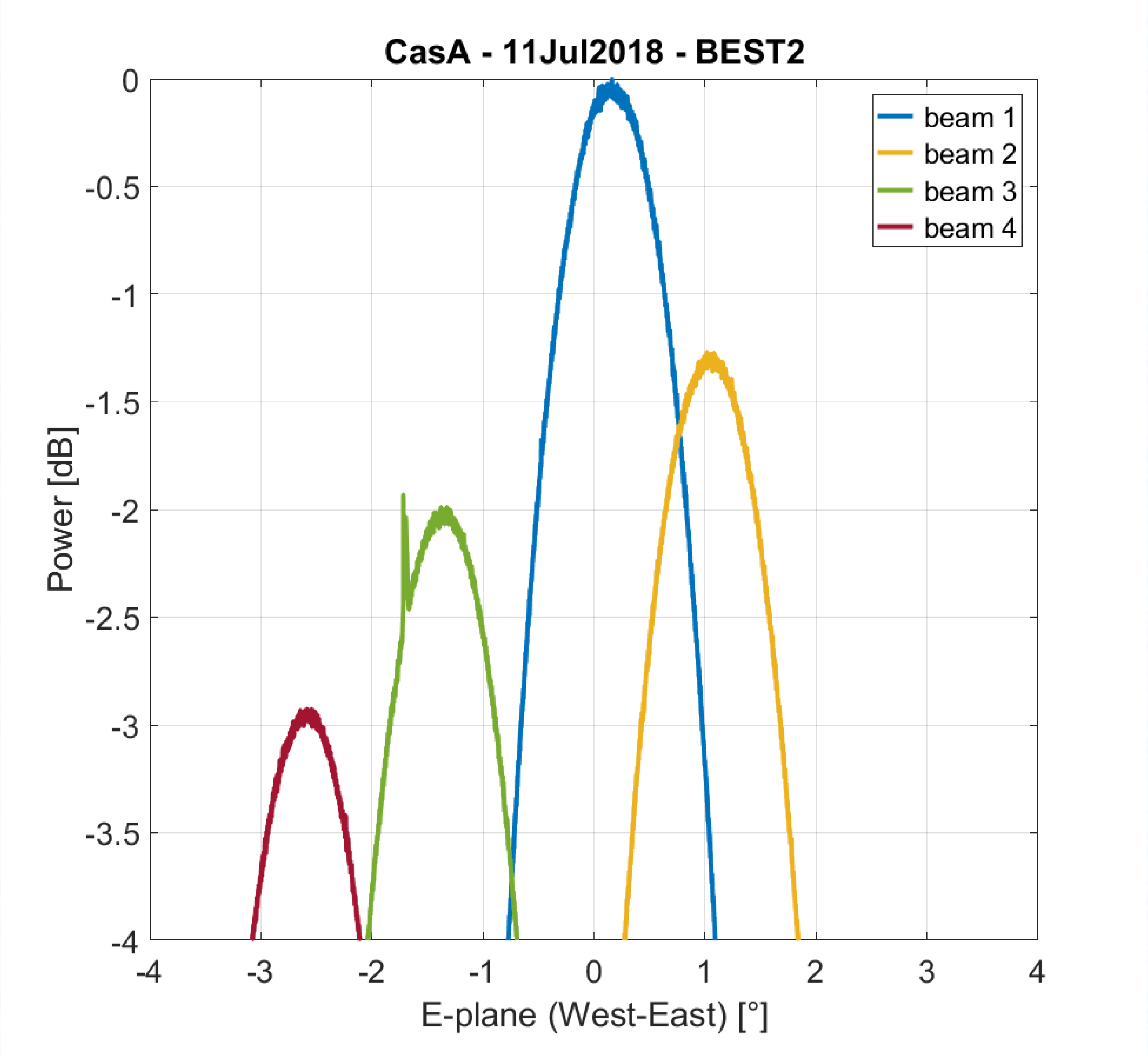


- **Accepts 32 analog inputs, ≈500 MHz BW;**
- **16 dual-ADCs AD9680, JESD204B, 1 GS/s ENOB=10.8;**
- **2 x FPGAs XILINX Ultrascale XCU40 20 nm;**
- **2 x DDR3 96 bit memory banks, 6+6 Gbit total size;**
- **Digitisation at 700MS/s → the 375-650 MHz IF band is sampled in second Nyquist zone; in PHAROS2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

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





Test of iTPM beamforming on the BEST2N section (eight cylindrical-parabolic elements) of the Medicina Northern Cross cylindrical-parabolic transit radio telescope.

Future testing

Warm Section and Digital backend due at JB in early 2019 for integration. Bench tests and trolley-mounted sky test.

Mount on Lovell; improve η; interferometry with eMERLIN

Summary

- Original PHAROS system demonstrated

  T_{sys} ~ 50 K

- Aim of PHAROS2 project to improve performance and implement digital backend

  - Low noise amplifiers
  - Vacuum window
  - Warm module, IFoF, iTPM

- Deploy on telescope next year

Then in a good position to bid for full instrument