First generation Cryo-PAF for Effelsberg

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Outline

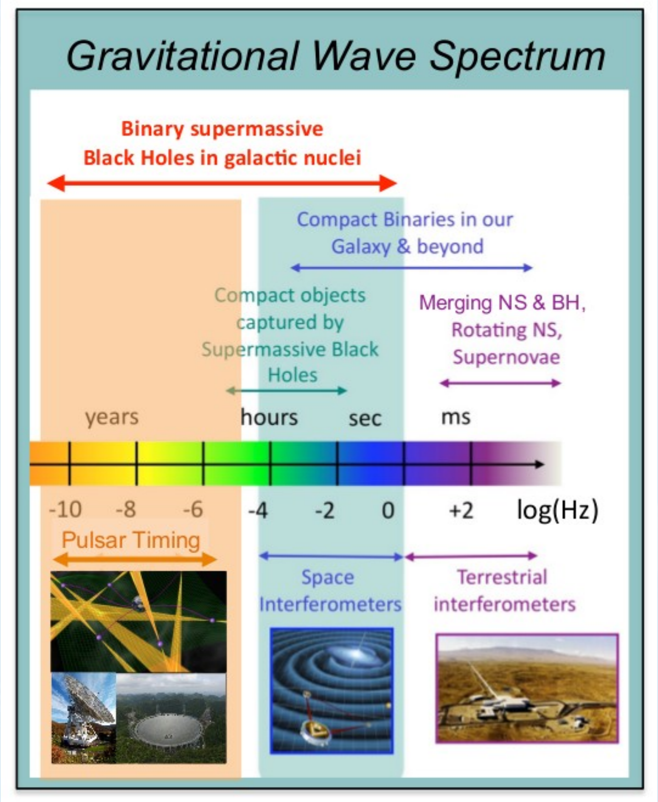
- Introduction / Background
- Overall layout
- The antenna: a modified DRA
- Fully digital cryostat output
- No RF-signal passing the vacuum barrier
- First digital signal processing outside prime focus cabin
- Calibration system
- Beam-former and Backend system

Introduction / Background

- Cryo PAF project at MPIfR is embedded into

"Low Frequency Gravitational Wave Astronomy and Gravitational Physics in Space"

  - in collaboration of CAS and MPG
- MPIfR ramped up the activities in PAF developments back in early 2018
  - ✓ new working group for large development projects
  - ✓ new working group for software developments
    - backend developments for MeerKAT and SKA face similar challenges
  - ✓ identified areas for research and development
  - ✓ issued a 3 year phase of design studies
- first generation cryogenic PAF for Effelsberg
  - ✓ based on the design study results
  - ✓ started late 2021

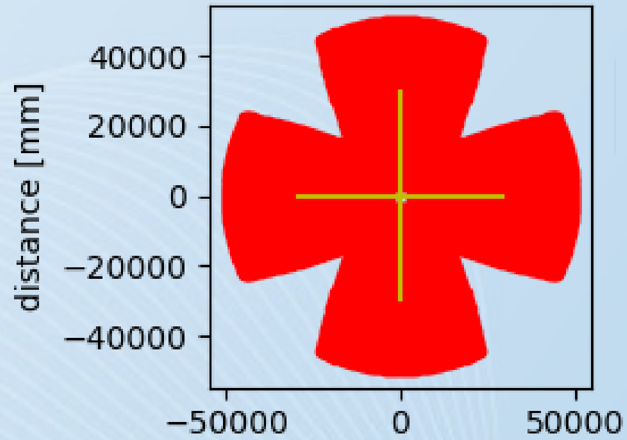


Gravitational waves are a prediction from Einstein's theory of general relativity:

- They are emitted when masses are asymmetrically accelerated, and propagate through the Universe, carrying information about the objects that they created them.
- Their existence has been confirmed first by observations of binary pulsars.

Sub-project B2 targets to develop PAF systems for Effelsberg and FAST

The frequency range



Band definition with astronomers on project start:

above L-band, below C-band

Final down selection due to mainly technical reasons :

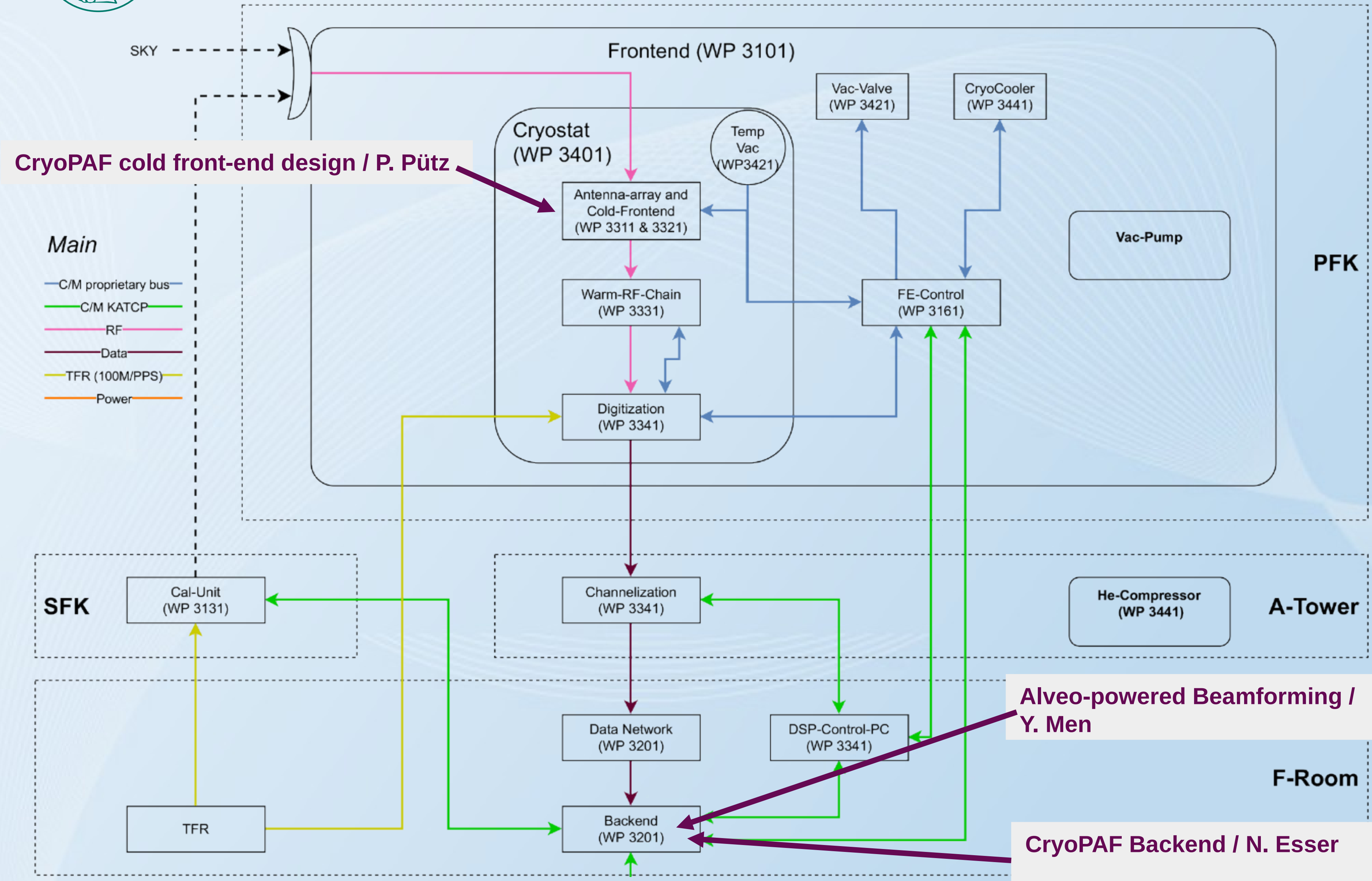
1. <u>Possible physical size of the receiver</u>
   – limits the accessible focal plane area to 60 cm diameter
   ➔ approx. 250 receiving elements (two polarizations, ~125 elements) at 3 GHz
   ➔ but only ~37 pixels at 1.5GHz
   for proper beam-forming with the large blockage of the telescope 37 beams are tight

2. <u>RFI situation</u>
   – below 2.4 GHz the RFI situation is difficult
   ➔ a wider band PAF receiver could suffer from saturation
   ➔ requires many elements to do efficient RFI suppression (degrees of freedom)

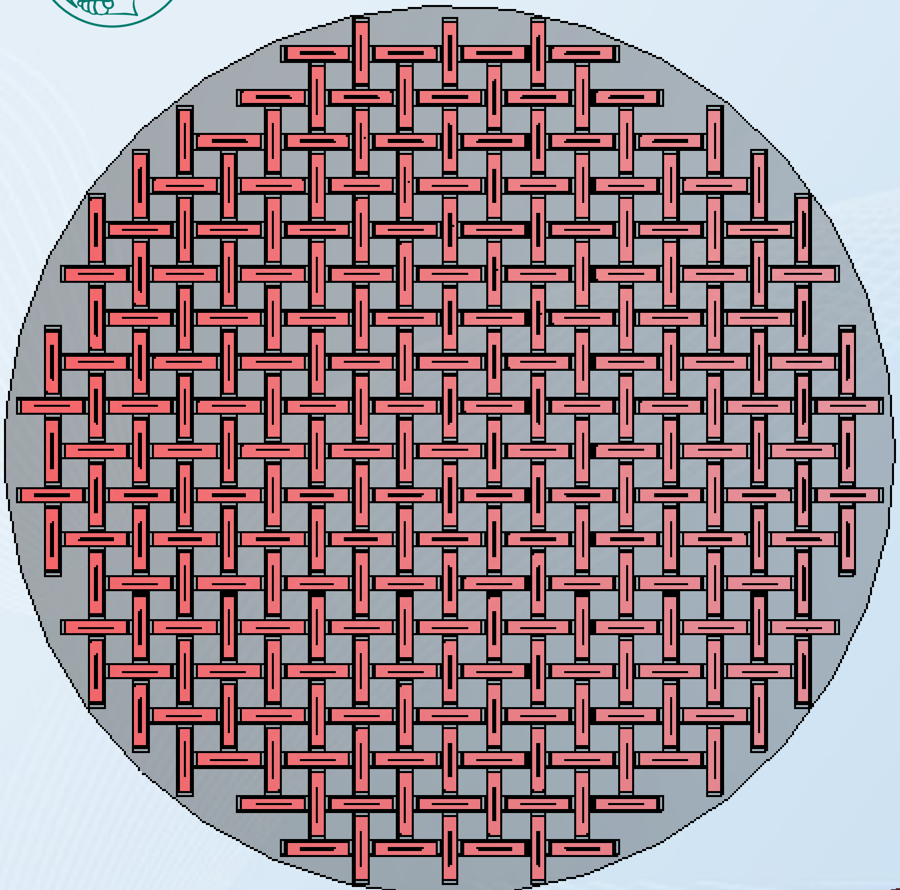
3. <u>Cost, risk, and required effort limit the upper band edge to in maximum 4 GHz</u>
   – realistically even only to ~3.9 GHz

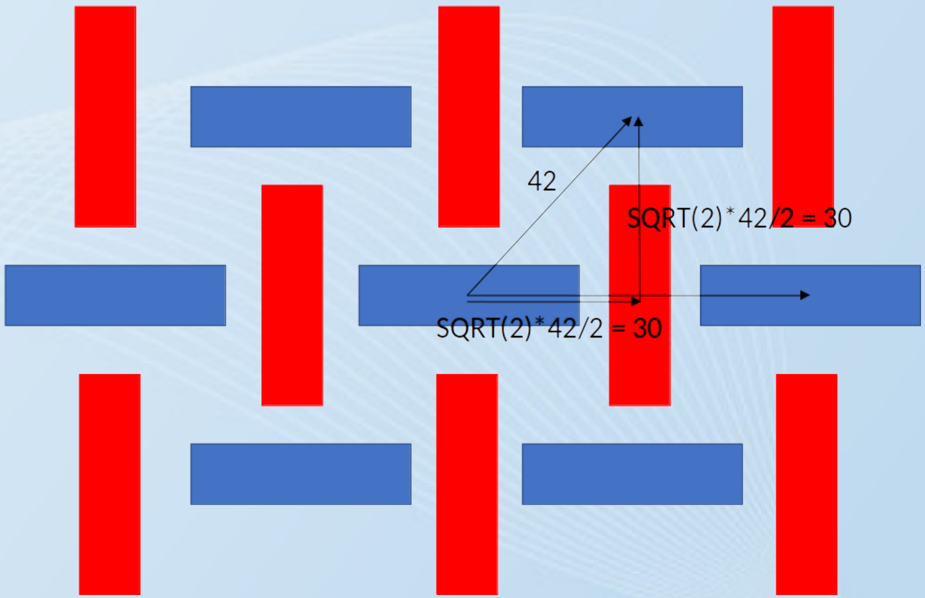
➔ **the given boundary conditions advice for roughly 2.6 to 3.9 GHz**

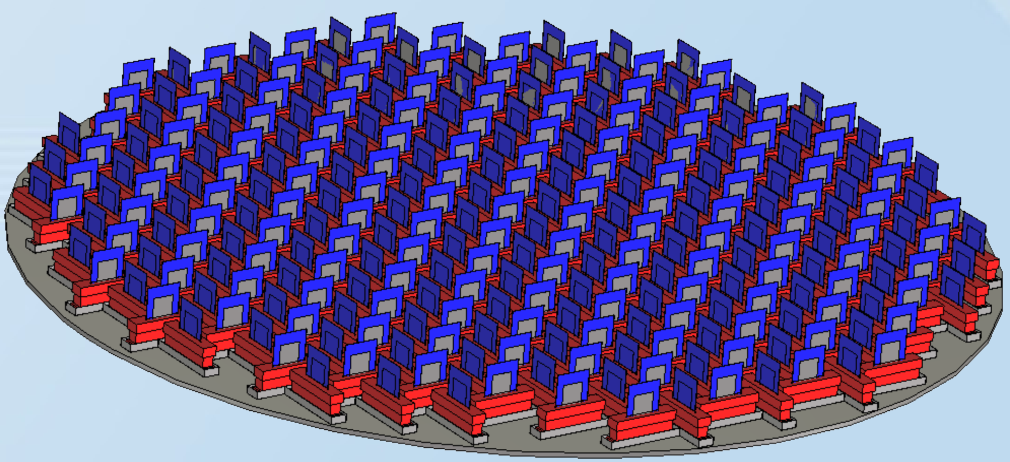
The actual layout



Focal-plane layout







Nominal spacing: **42 mm**

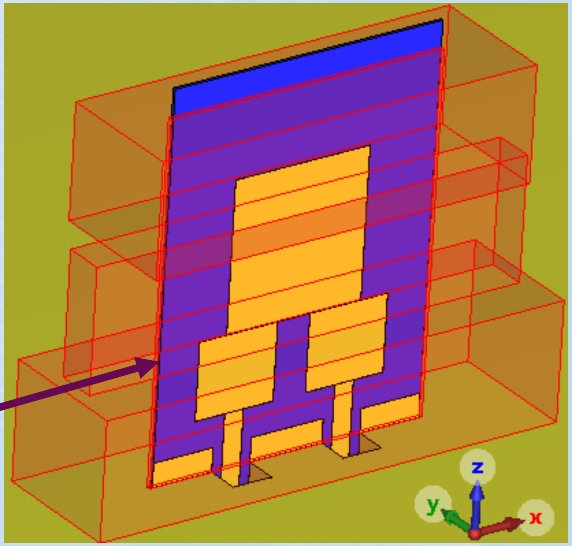
Number of elements: **253**

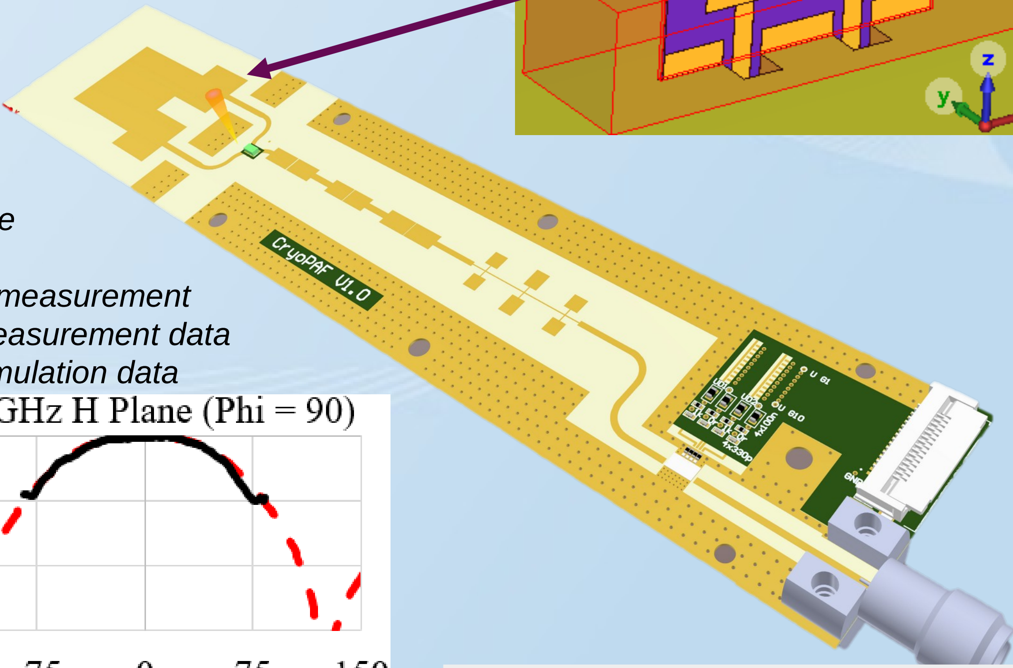
- Horizontal polarization : 124
- Vertical polarization : 129

The antenna

Effelsberg 100 m has a F/D of 0.3 ⟶ huge opening angle required

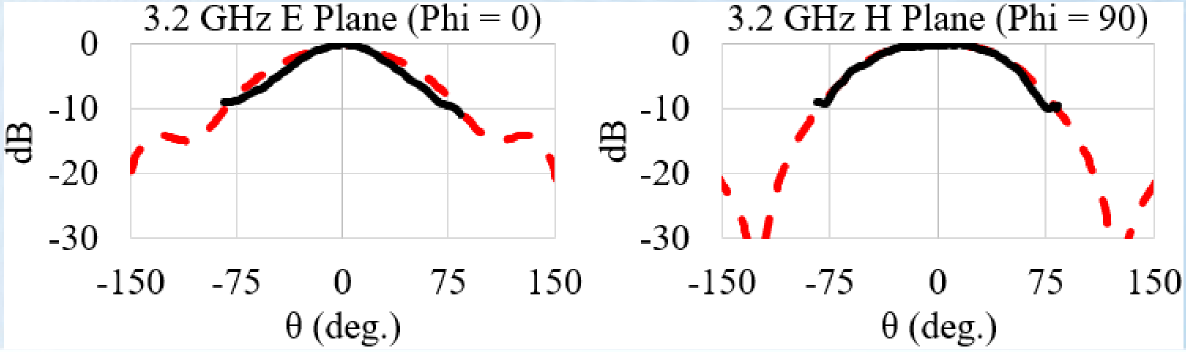
- **Actual choice is a modified DRA:**
  - can illuminate the Effelsberg main dish out of the prime-focus
  - low loss
  - easy to manufacture (e.g. 3D printing)
  - can be fully integrated into the cryogenic frontend structure
  - already tested in house: survives cooling and shows the predicted characteristics



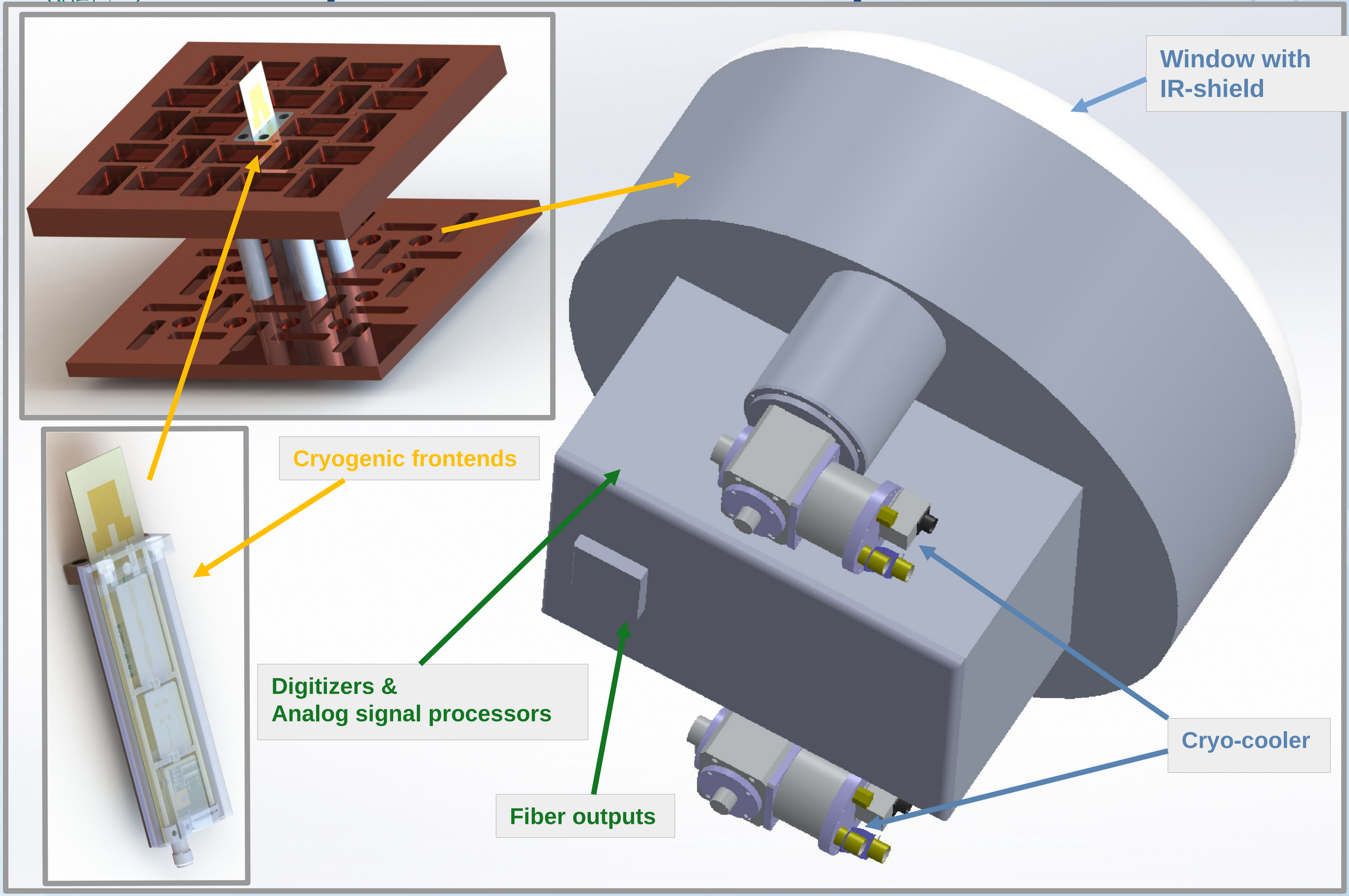


Left, early 3d-printed prototype

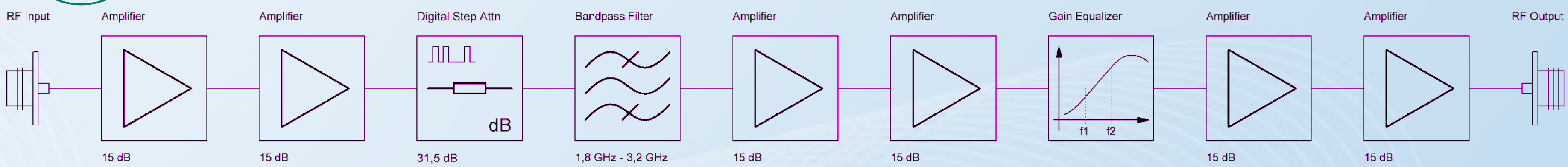
Below: far-field measurement
black: measurement data
red: simulation data



Cryostat, artist impression

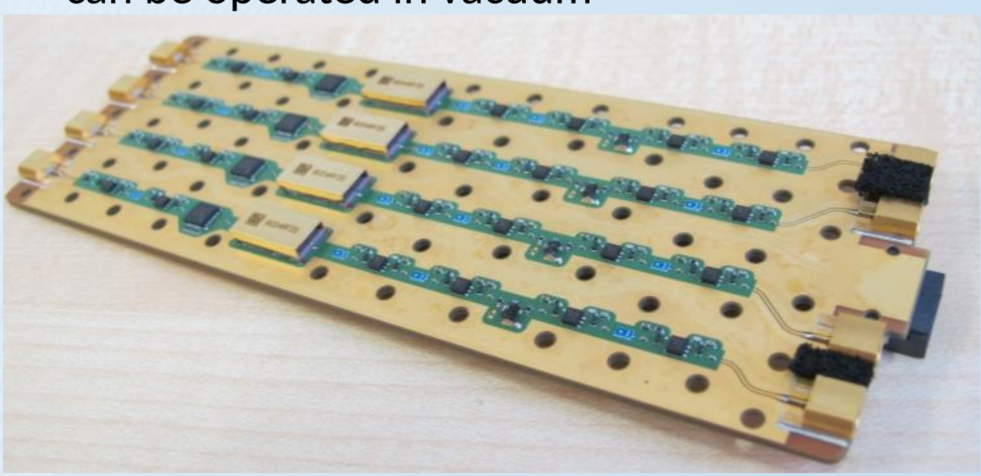


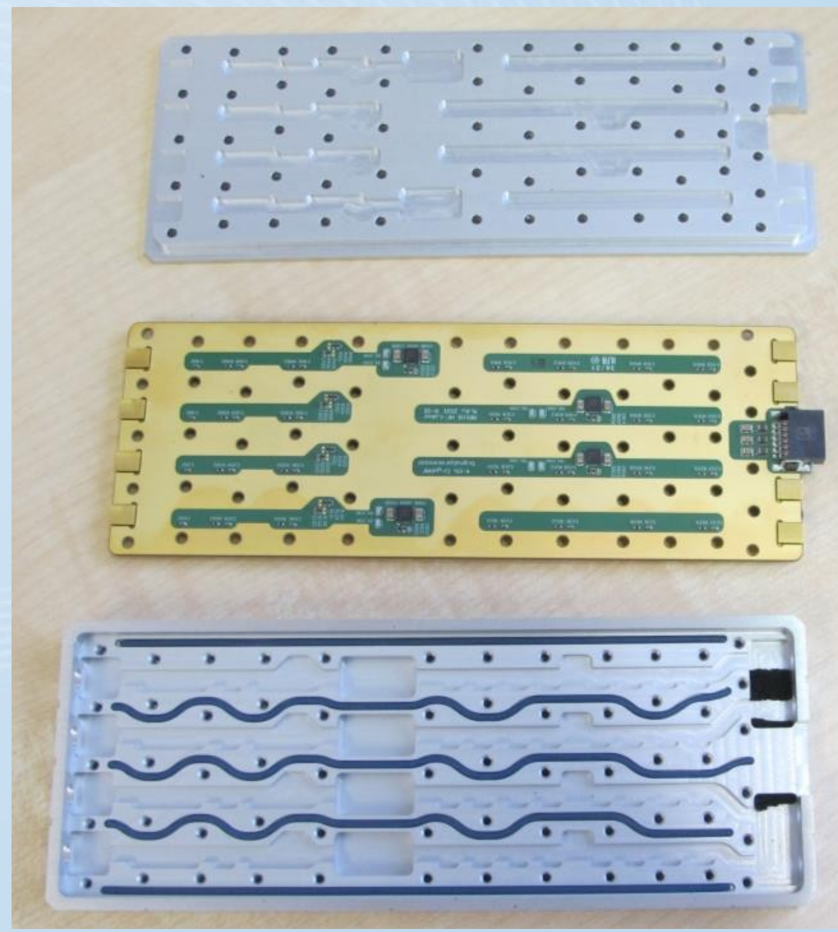
The analog signal processor



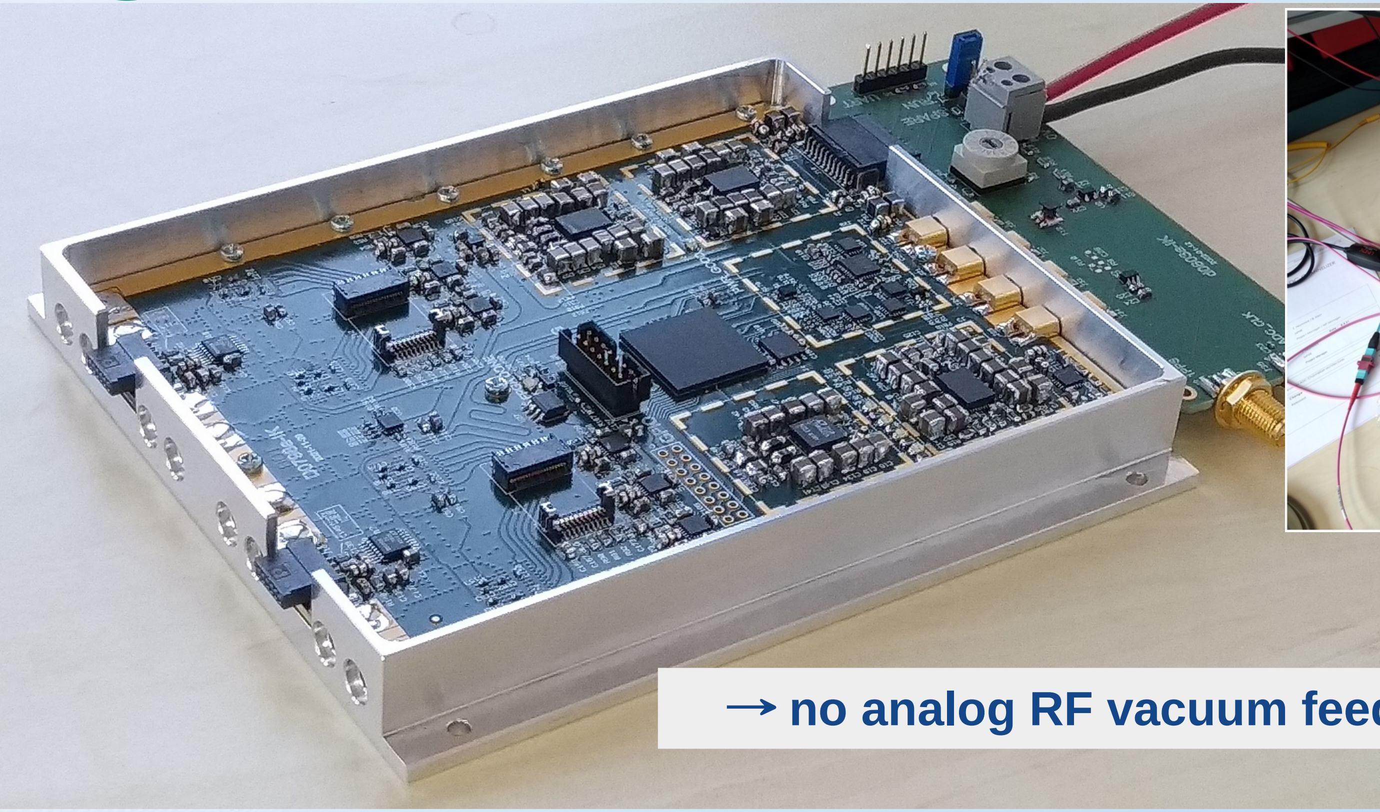
A highly integrated four channel signal processor

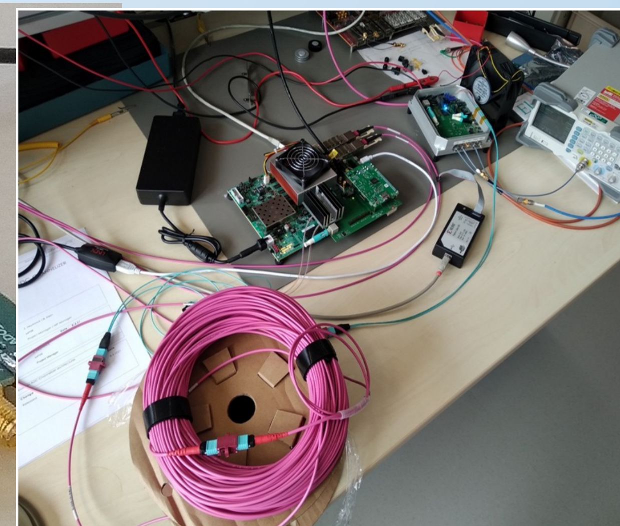
- main difficulty for the development was cross talk between channels
  - gain is > 60 dB
    → cross talk should be < -60 dB !!
- can be 1:1 connected to the digitizer
- is fully remote controlled by the digitizer
- can be operated in vacuum





The digitizer system





Above: Fire-Fly connection testing up to 200 m

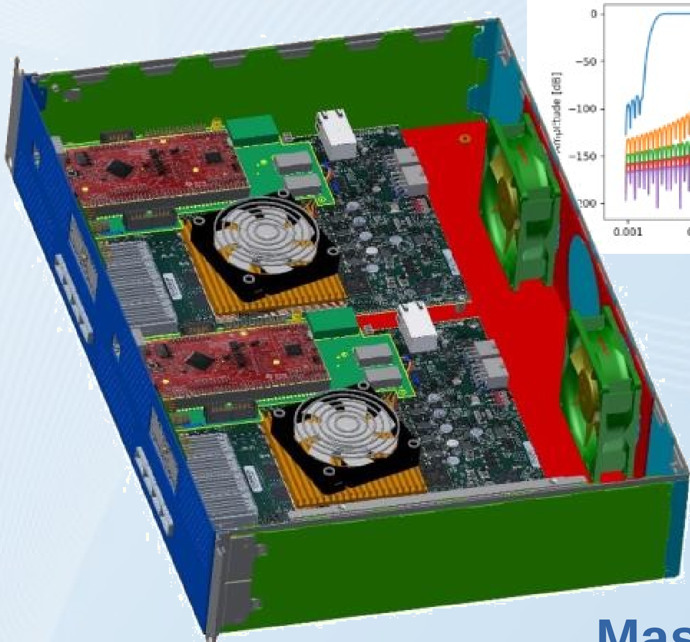
→ no analog RF vacuum feed-through required!!

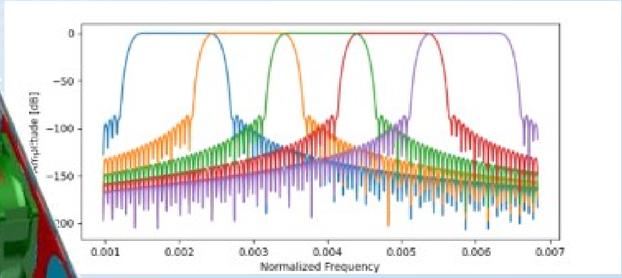
- foot-print and connectors are compatible to analog signal chain
  - can be directly 1:1 connected if required
  - ADC board can handle IO and power of the warm analog signal processor
- four ADCs with 2 inputs each (TI ADC12DJ2700, ADC12DJ4000, or ADC12DJ5200)
  - up to 1.35, 2.0, or 2.6 GHz of bandwidth is possible
  - analog input bandwidth up to 5.2 GHz

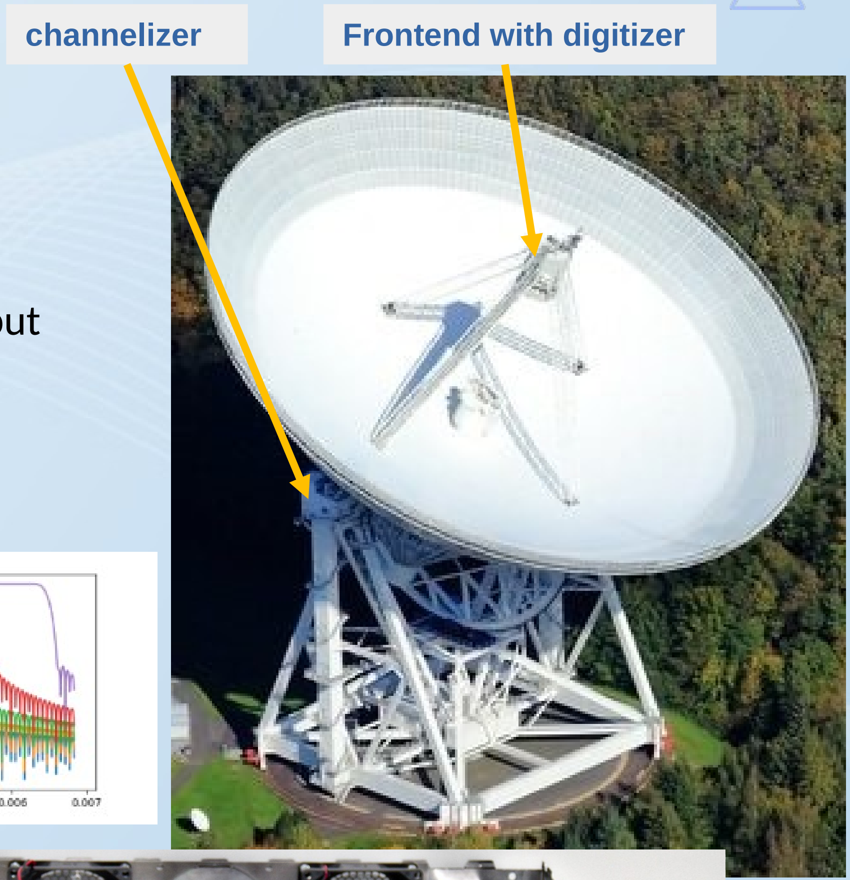
- FireFly (JESD 204C protocol) connection
- can be operated in vacuum
- first prototype is ready

The channelizer

- Dedicated Faraday cage in the A-Tower
- Channelizer
  - two FPGA boards, power supply
  - 16 ADC input channel in total
  - over-sampled poly-phase filter-bank for each input
    - up to 2000 channels per input
  - eight 100 GBit Ethernet connections
- System is under test at the moment



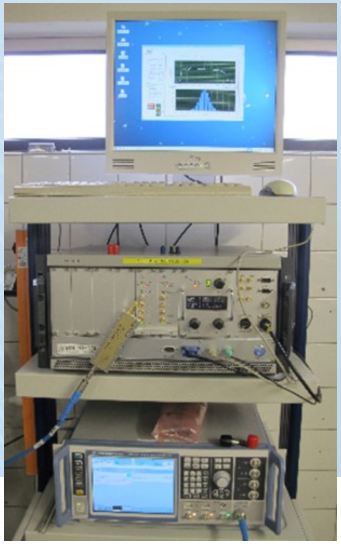


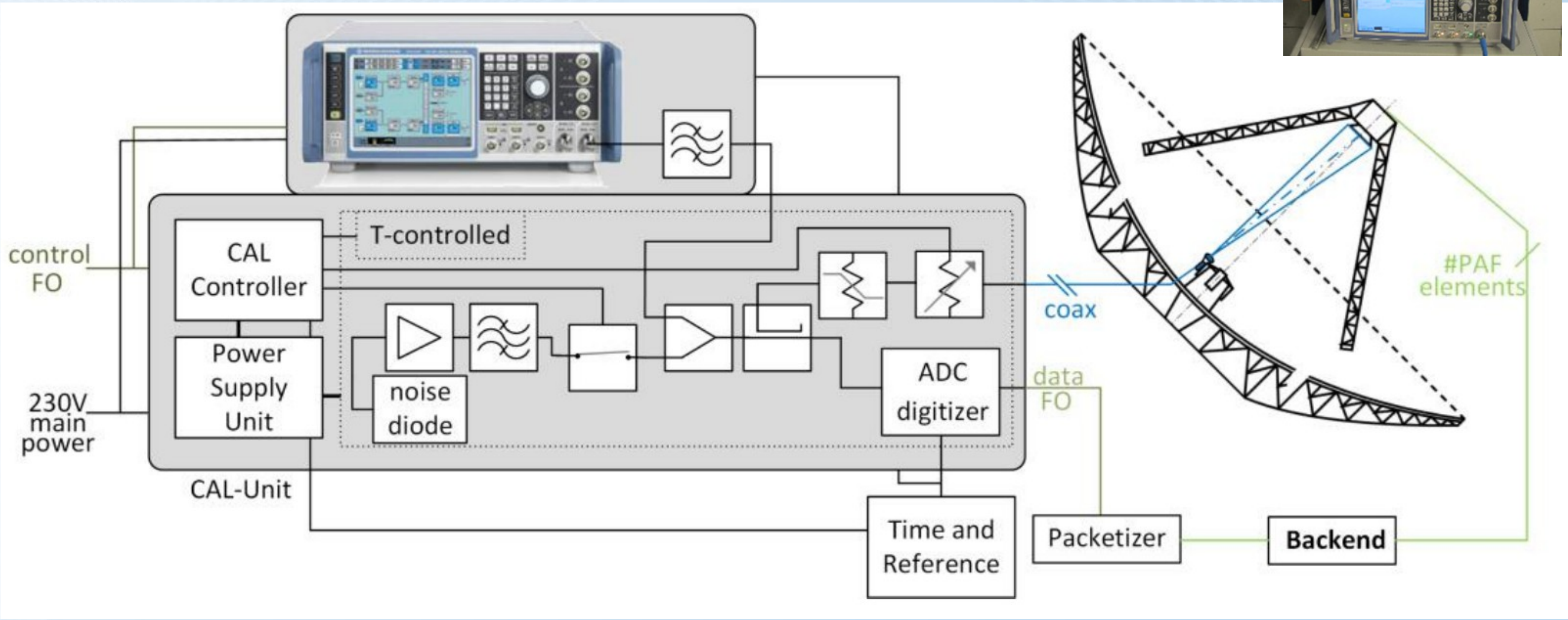


Mass production has started!

The calibration system

- to ensure relative phase & amplitude stability between the elements
- main layout of the system is ready
  - horn antenna is in production
  - tests of backend-connection is ongoing
  - system stability is fine
  - fully digital calibration signal (classical noise diode optional)

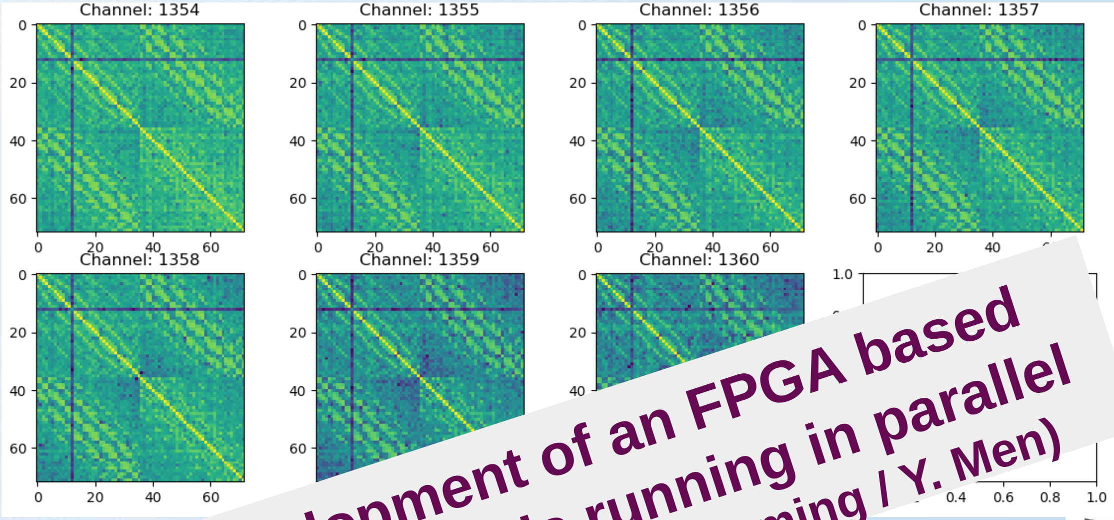


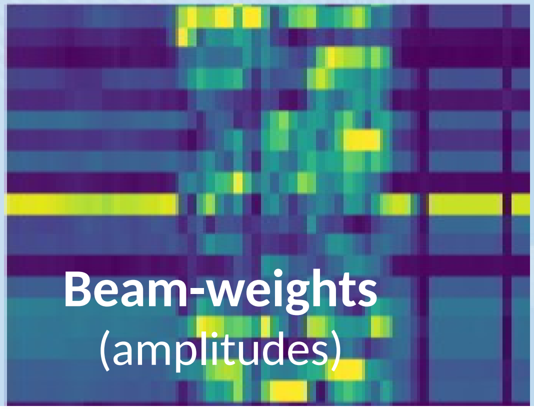


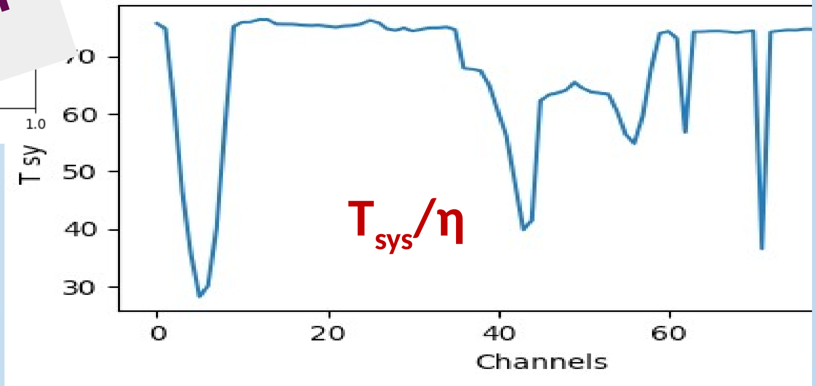
The beam-former

- existing Effelsberg PAF and its GPU cluster was used for a first test
- 36 voltage data streams of the Effelsberg PAF are accessible
  - via modified beam-weights
- first snap-shot data was recorded in December 2020
  - ACMs can be calculated, beam-weight determination algorithms are implemented / tested
- first on sky test-run in July 2021

Top: CSIRO chequerboard PAF for the Effelsberg 100 m telescope during it's fist installation (March 2017)



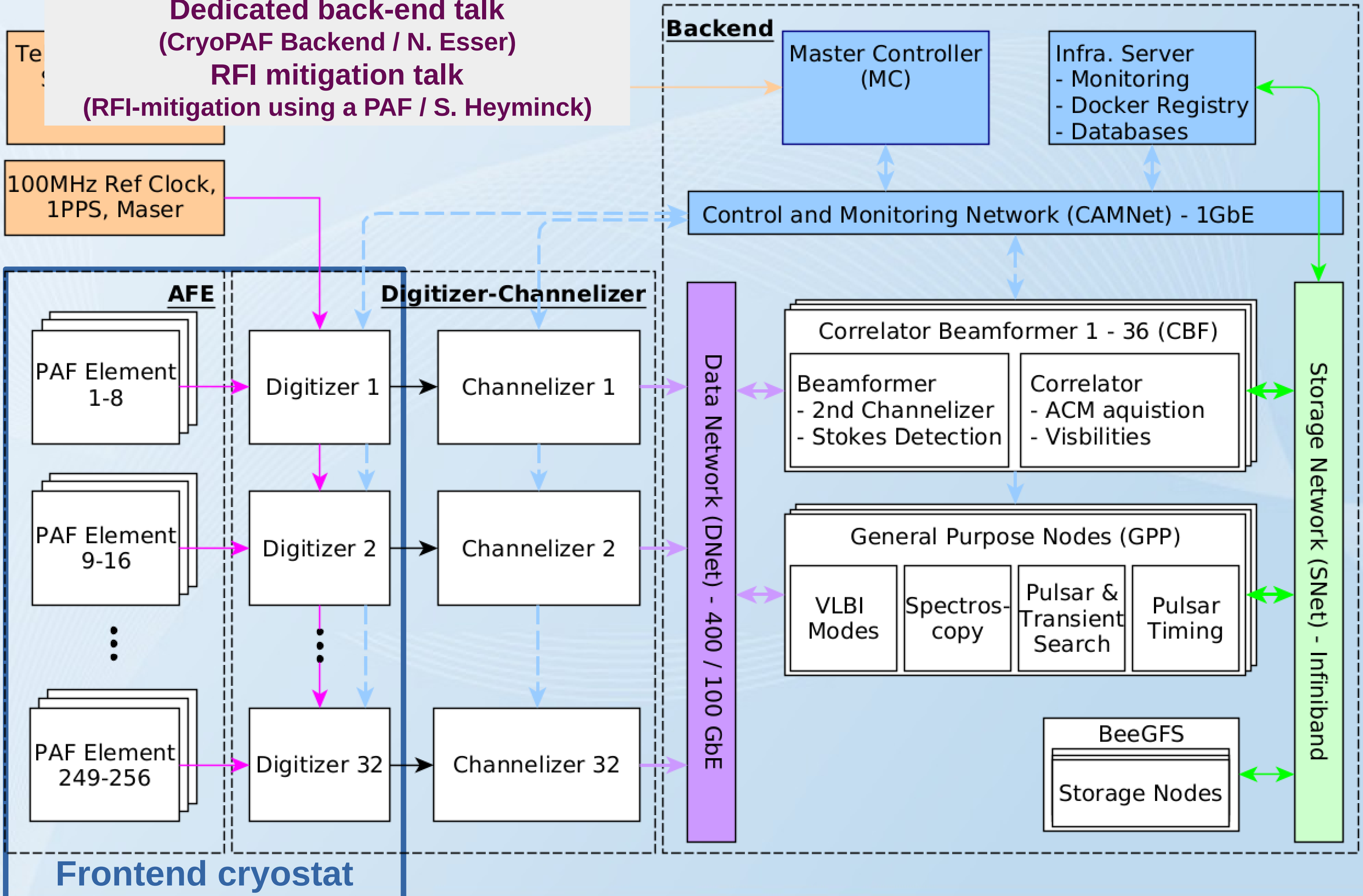




Development of an FPGA based beam-former is running in parallel (Alveo-powered Beamforming / Y. Men)

The data flow

Dedicated back-end talk
(CryoPAF Backend / N. Esser)
RFI mitigation talk
(RFI-mitigation using a PAF / S. Heyminck)



Conclusion

- The first generation cryo-PAF for the Effelsberg 100 m is on its way
  - using a fully integrated cryogenic frontend (antenna to LNA all on one PCB)
  - separating digitization and first FPGA processor by 100 m
  - cryostat has only fiber outputs, no analog RF-lines
- Backend and digitization is in build-up process
- Cryostat is moving into final design
  - antenna is nearly finalized
  - cryogenic frontend is in prototype state