Backends digitali basati su FPGA per il Sardinia Radio Telescope

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Workshop su Applicazioni FPGA in ambito Astrofisico –Torino, 20 Maggio 2016

Agenda

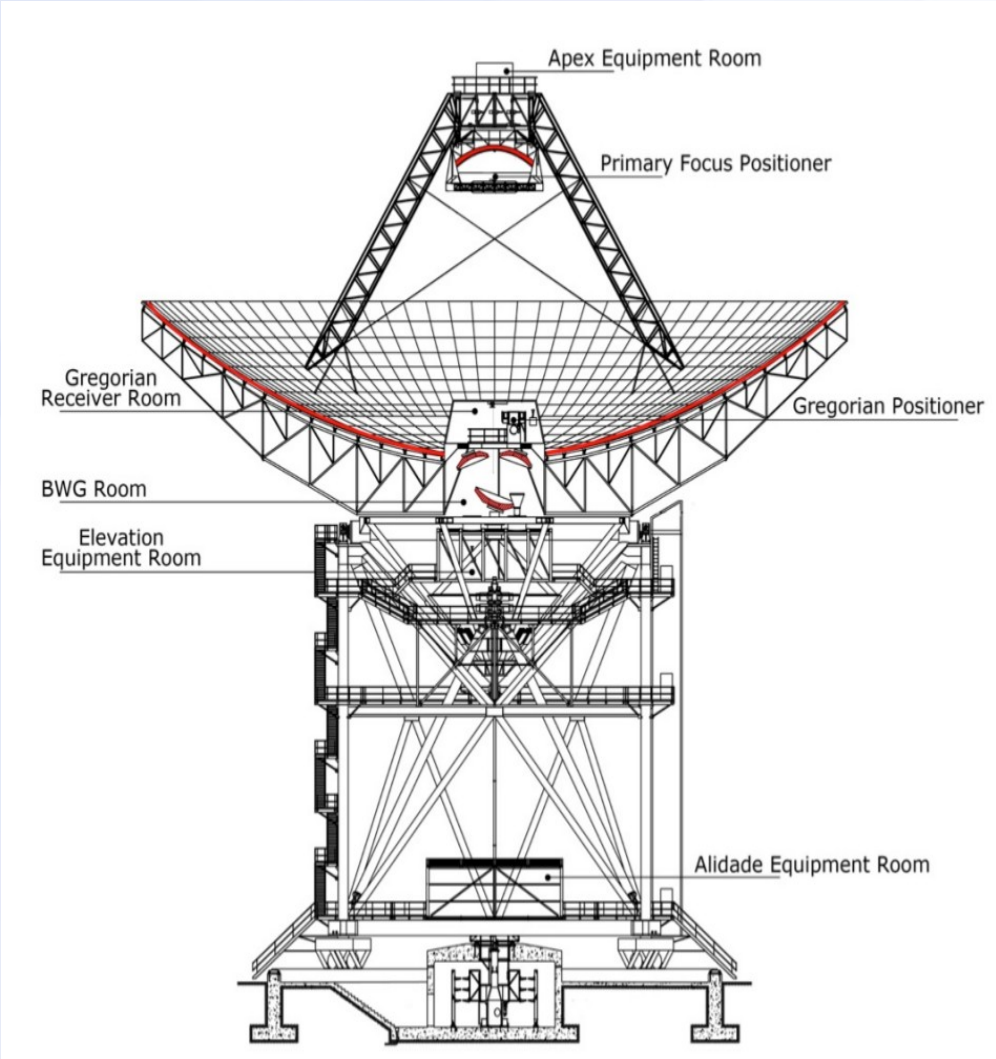
- *Brief presentation of the Sardinia Radio Telescope (SRT)*
- *Digital backends at the SRT*
- *SARDARA*
- *Future works*

Sardinia Radio Telescope

- The Sardinia Radio Telescope is a general purpose fully steerable 64-m diameter radio telescope

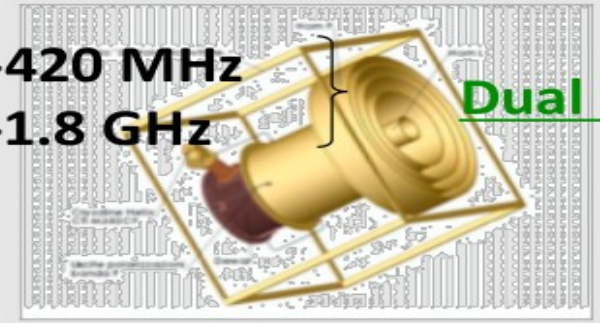
- It is able to function very efficiently into the 300 MHz – 115 GHz range.

- It has three different focal positions: Primary (F1), Gregorian (F2) and Beam-Wave Guide (F3)



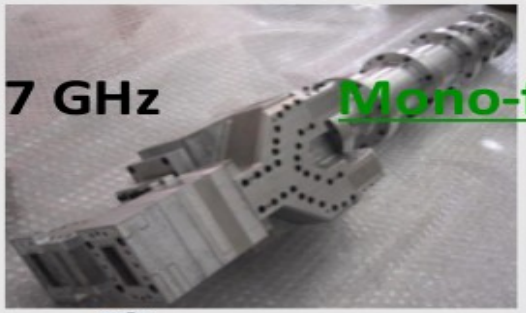
Receivers currently available

310-420 MHz
1.3-1.8 GHz



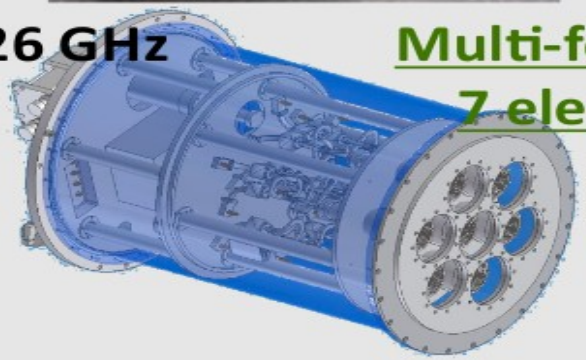
Dual Band

5.7-7.7 GHz



Mono-feed

18-26 GHz



Multi-feed
7 elements

Receivers under developing

- Mono-feed C-low receiver (4.2 – 5.6 GHz)
- 7-feed S-band receiver (3 – 4.5 GHz)
- 19-feed Q-band receiver (33 – 50 GHz)

Digital Backends at SRT

What is a backend?

- A back-end represents the last stage of a telescope receiving chain

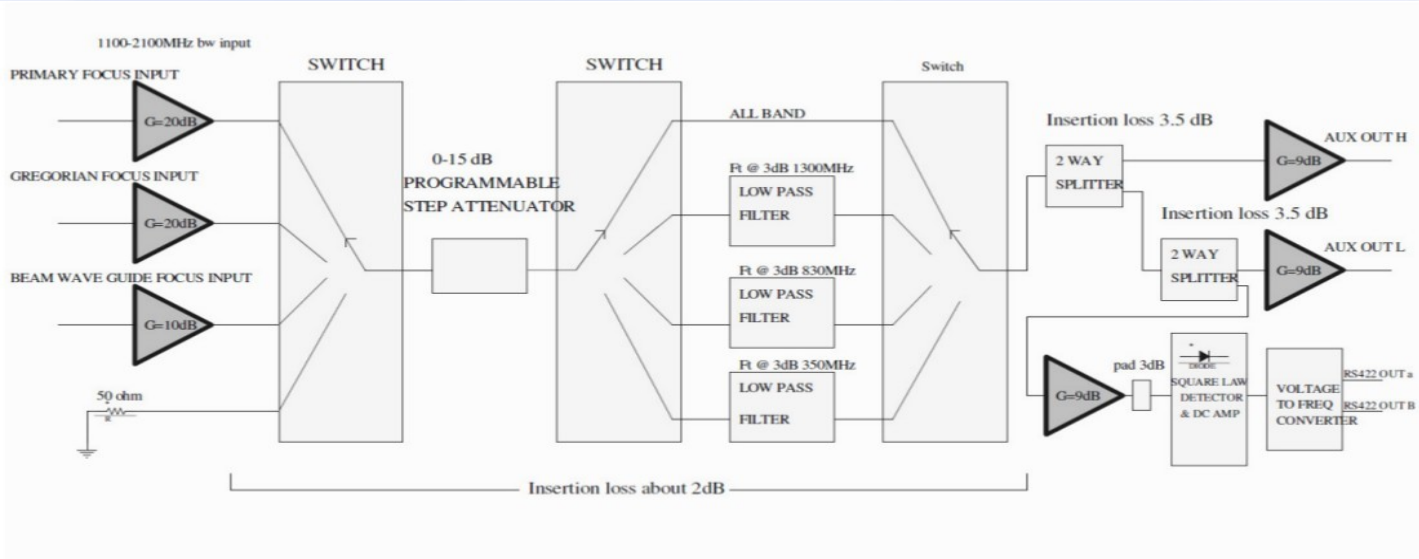
- The celestial signals collected by the antenna must, after a proper RF conditioning, be converted into digital format and then processed

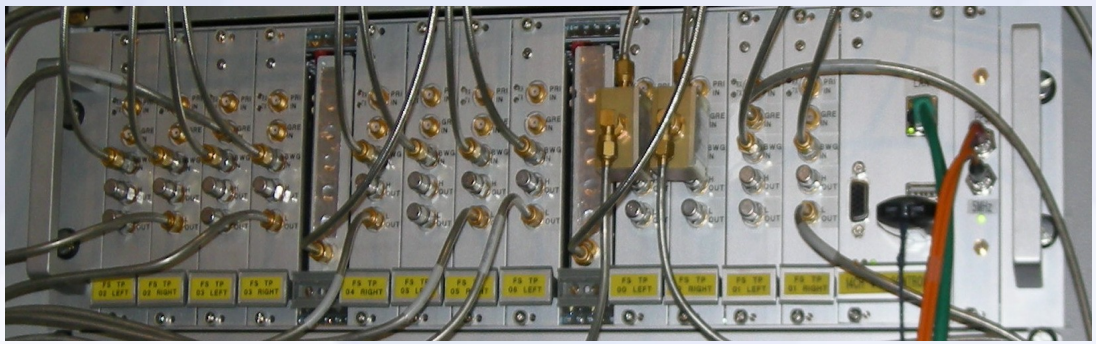
- Due to the wide bandwidth provided by modern radio astronomical receivers, FPGA-based boards are essential.

- GPU-based nodes can be used for the post-processing

Total Power (1)

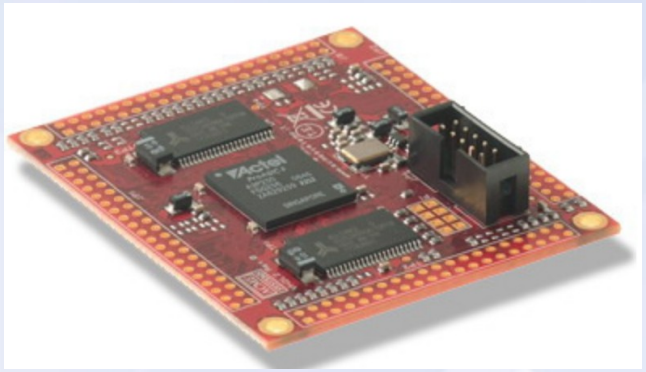
- Developed by IRA Medicina
- Focus selector

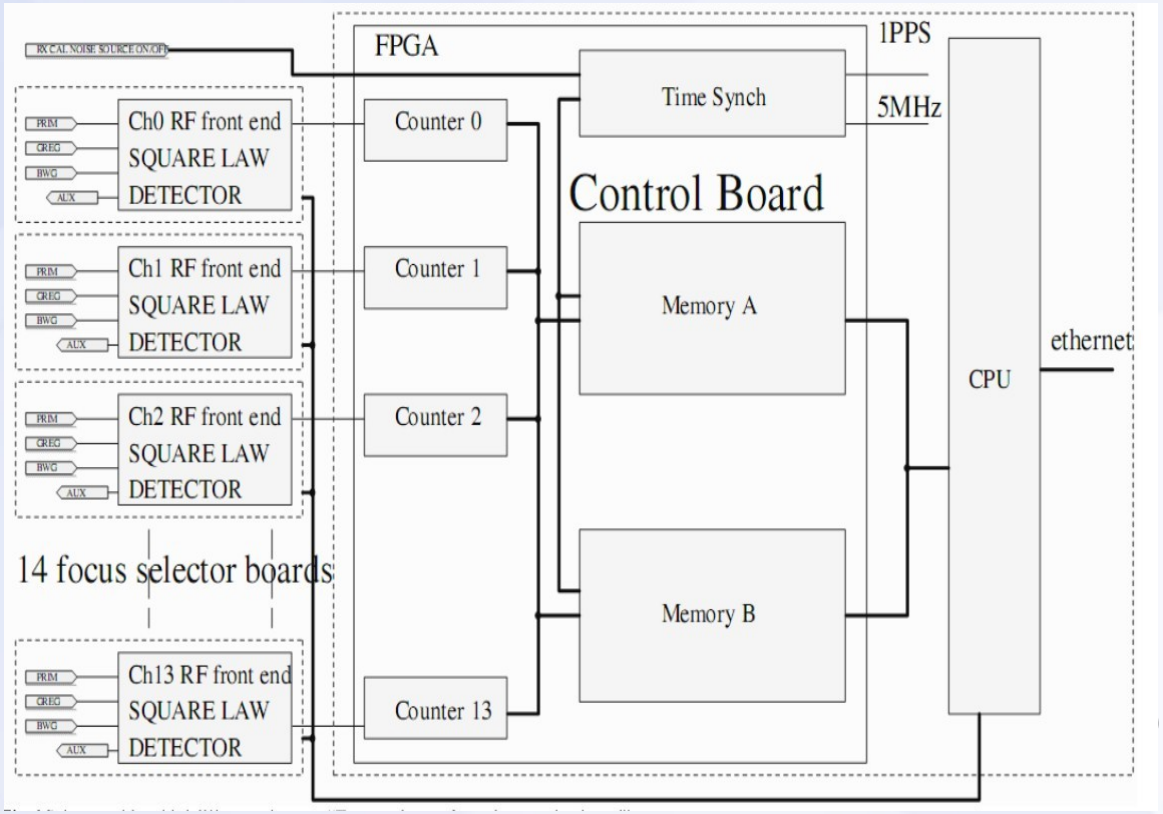




Total Power (2)

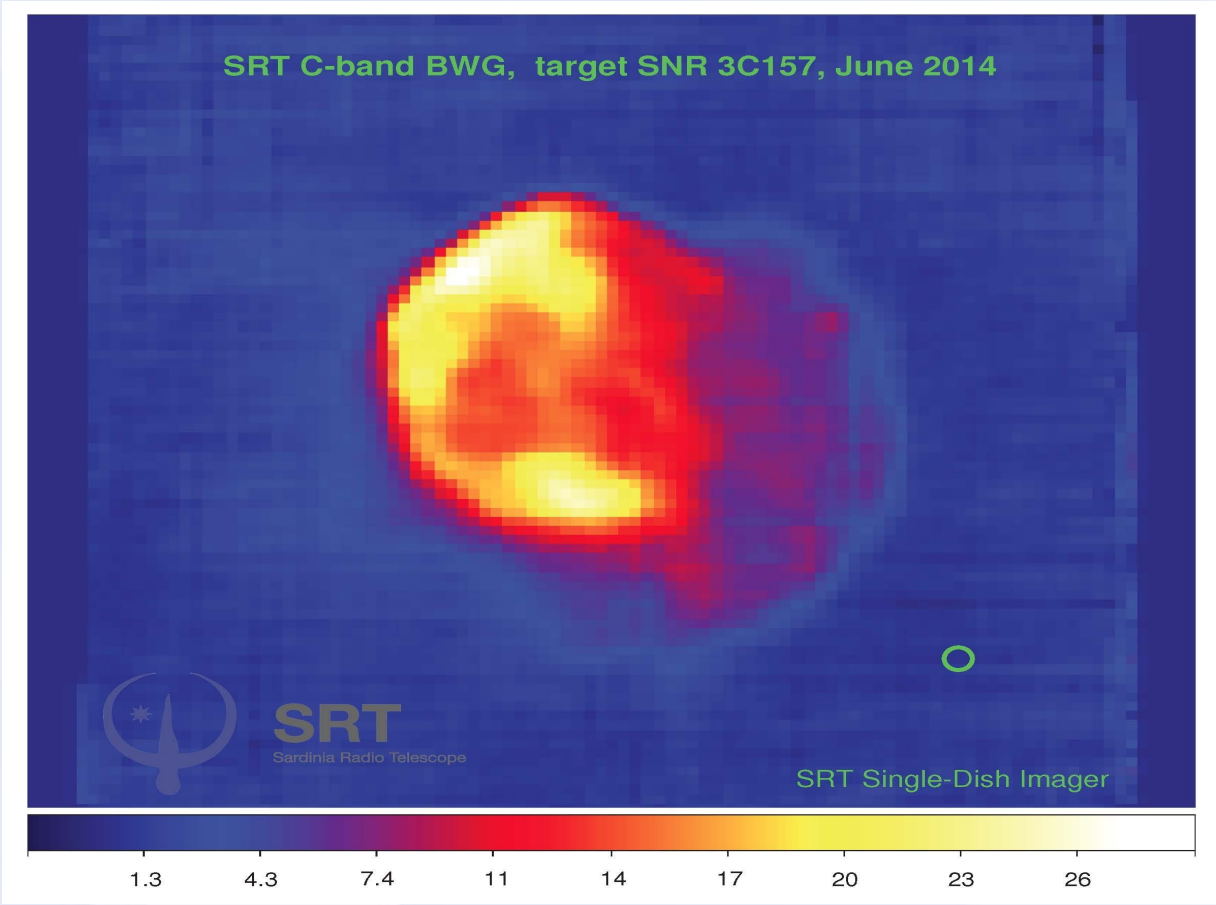
- Backend for continuum studies
- 14 IFs, bandwidth up to 2.1 GHz, dump time up to 1 ms
- The boards contains an FPGA Actel A3P250, programmed in VHDL





Total Power (3)

- ***Supernovae remnants 3C157***



XARCOS (1)

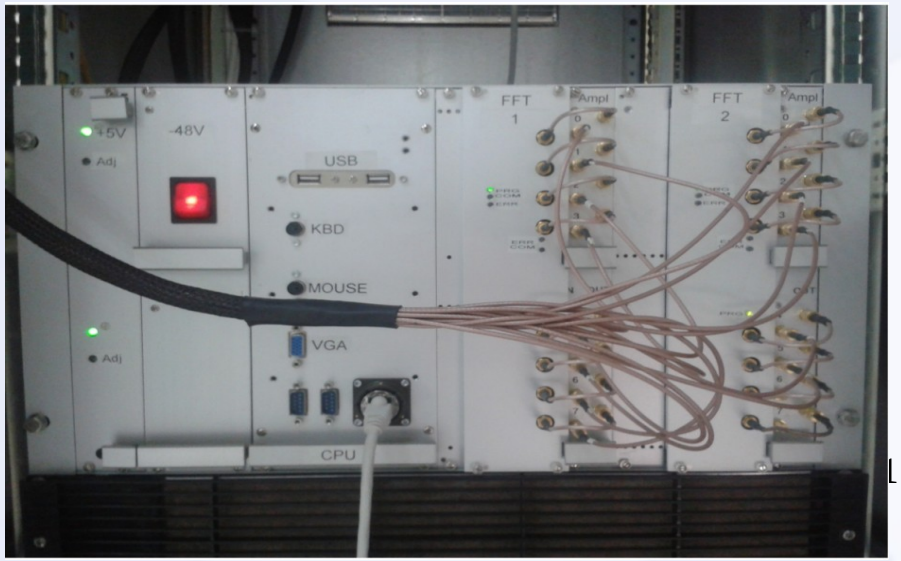
- Developed by Gianni Comoretto (OA Arcetri)

- 14 IFs, 125 MHz, full Stokes spectrometer 2048 channels, dump time 10 s

- It contains 40 FPGAs: 8 Xilinx, 32 Altera

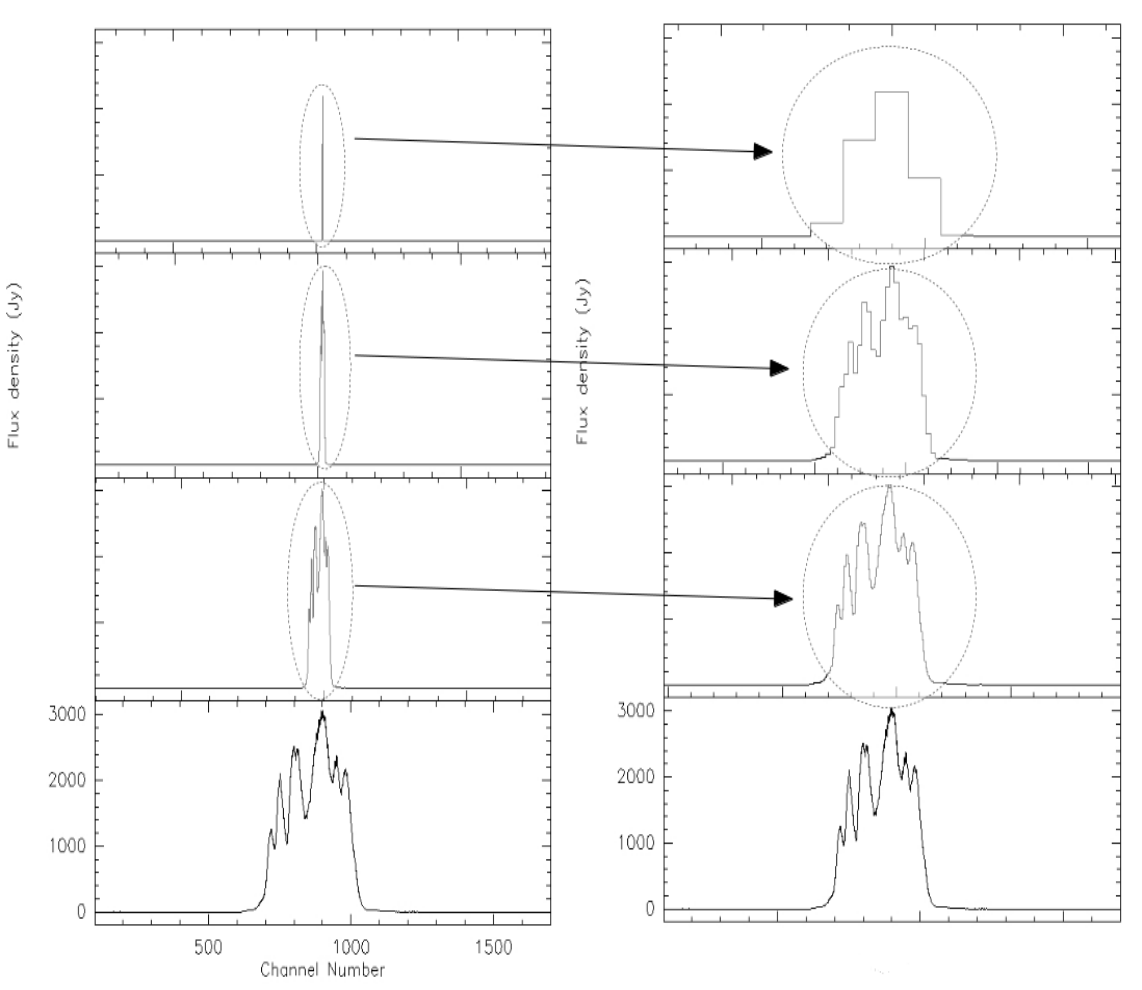
- Two HDL adopted: Verilog & VHDL

- Fully integrated into the control software of the SRT & Medicina: it took approximately 5 years!



XARCOS (2)

- Spectrum of the 6.7 GHz methanol maser emission in W3(OH) observed at SRT



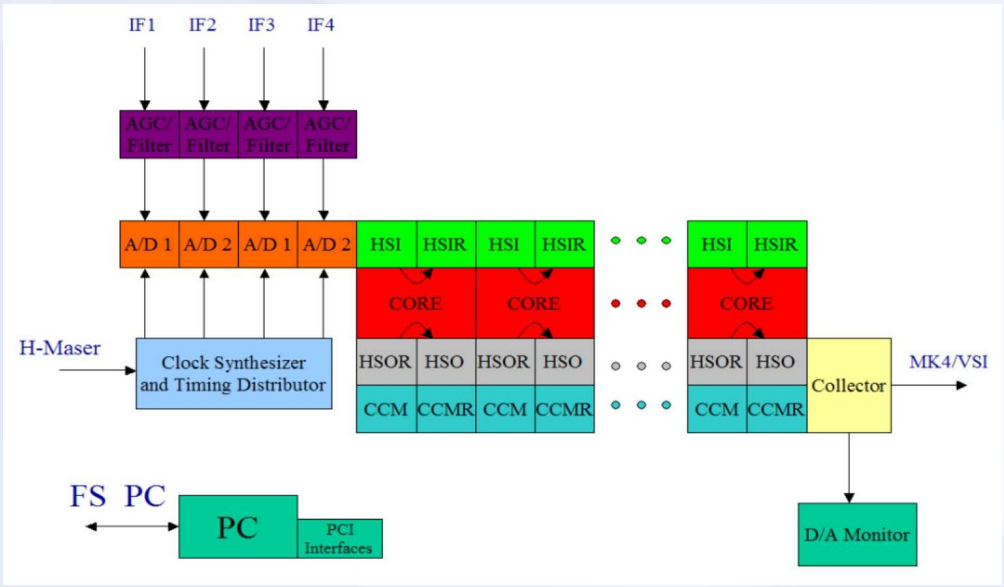
Digital Base Band Converter (1)

- Developed by IRA Noto

- Standard platform of the European VLBI Network

- 4 IF 512 MHz each

- Up to 16 Base Band Converter

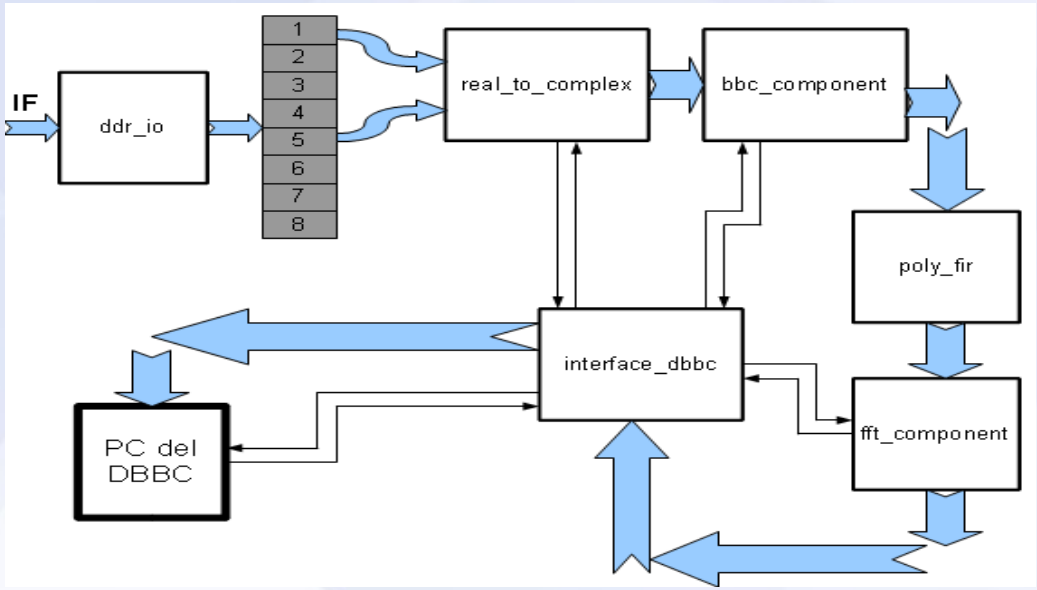


Digital Base Band Converter (2)

- Porting of XARCOS in order to demonstrates the general purpose nature of the platform

- We have decided to entirely rewrite the libraries specific (Xilinx and Altera) to each FPGA in an abstract way, that are then mapped to the particular hardware by the synthesis tools.

- In this way we were able to render the code 100% portable to any FPGA, creating components that are completely independent of the system on which they are being implemented. We have written the code entirely in VHDL.



Digital Base Band Converter (3)

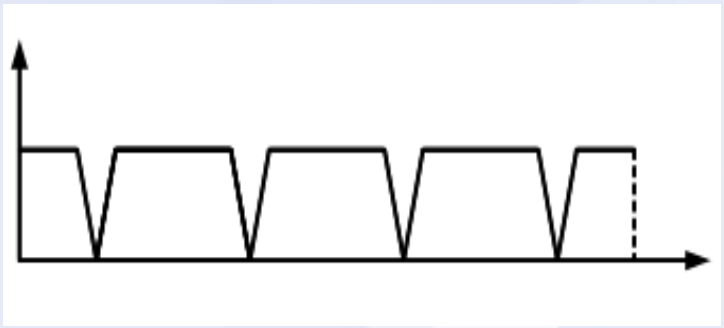
- Two-stage polyphase filterbank spectrometer

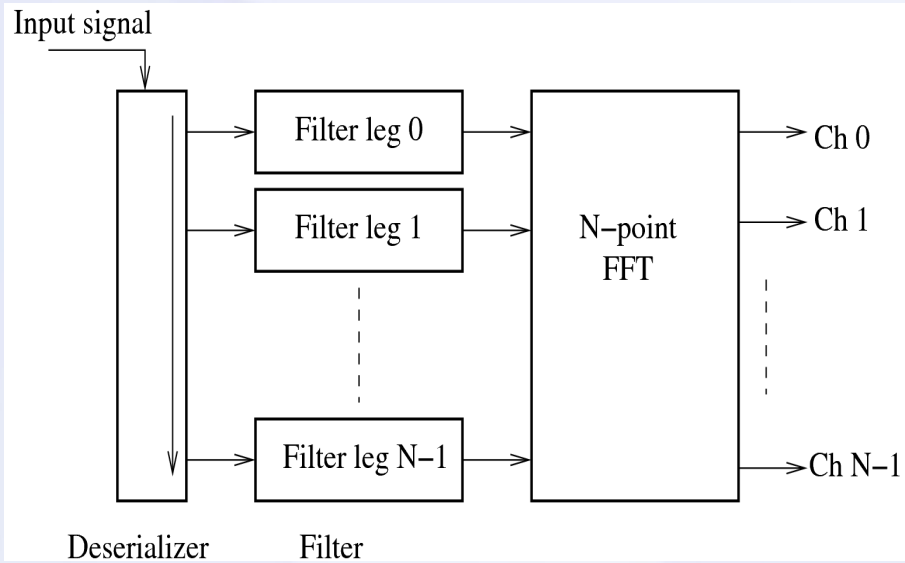
- No spectral “holes”

- Very optimized from a usage resource viewpoint (both Block Ram and DSP)

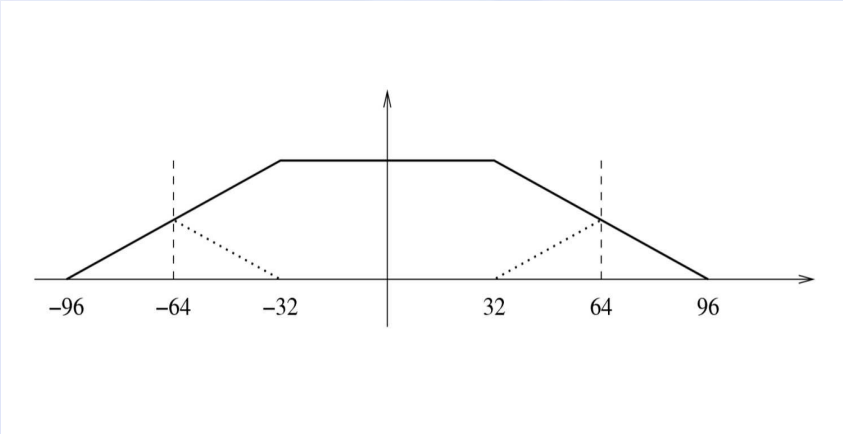
- Very strong from an RFI (Radio Frequency Interference) point of view

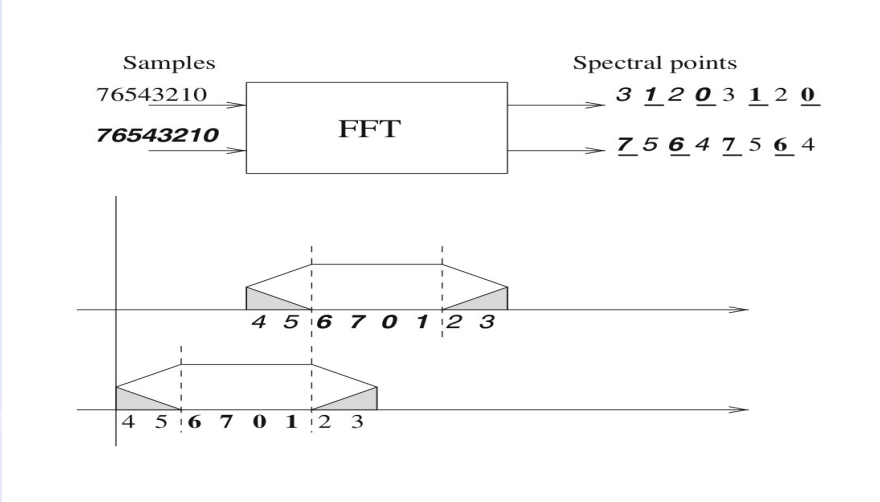
- Entirely written in a platform-independent VHDL code

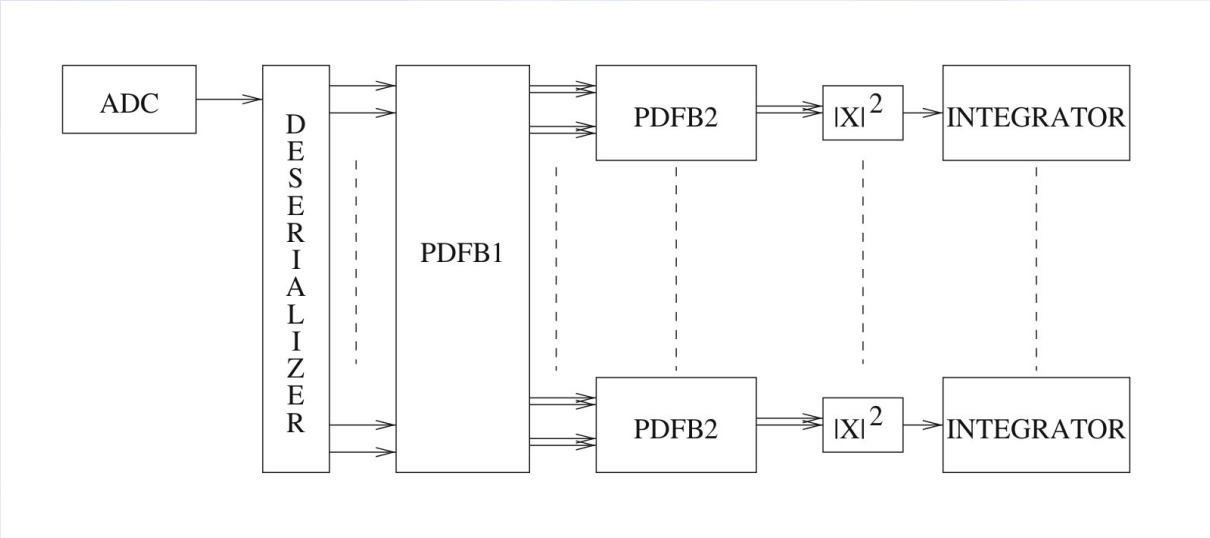




Digital Base Band Converter (4)

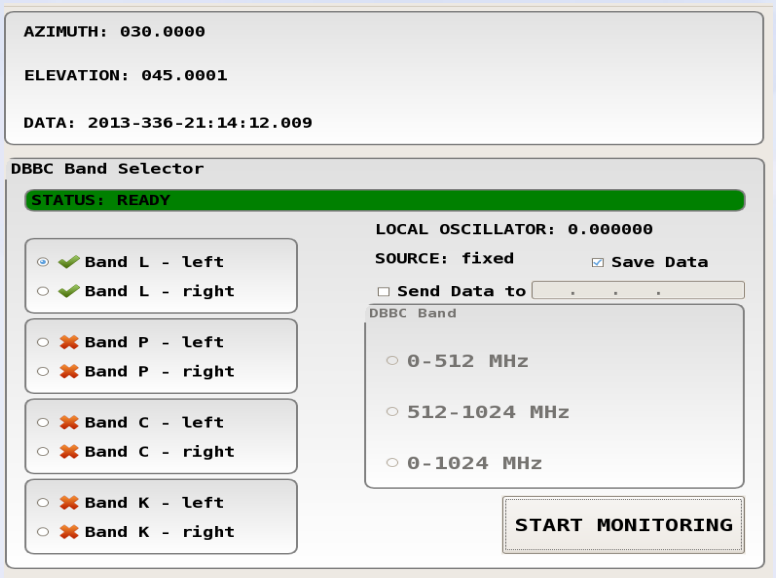


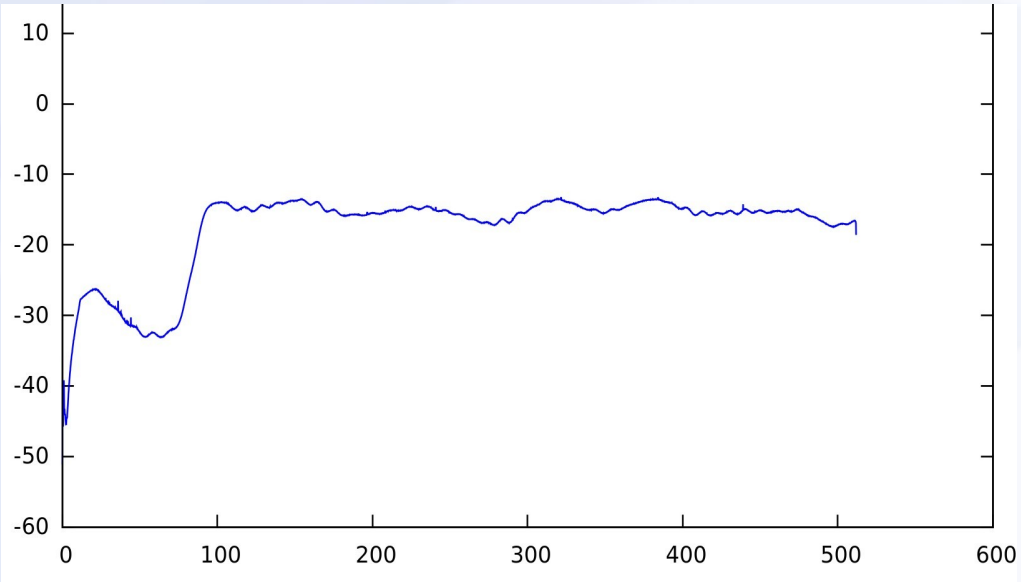


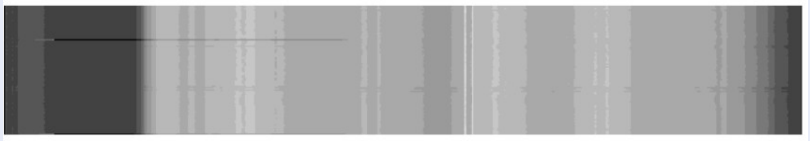


Digital Base Band Converter (5)

- RFI monitoring system







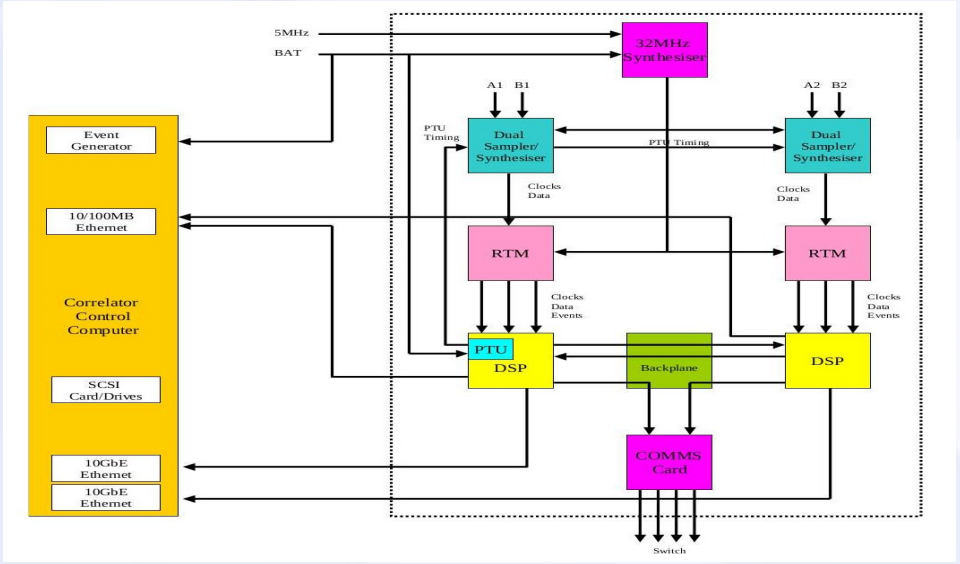
Pulsar Digital Filter Bank (1)

- Developed by Australian Telescope National Facility

- Pulsar timing & search, 4 IF up 1024 MHz each, just two working at SRT

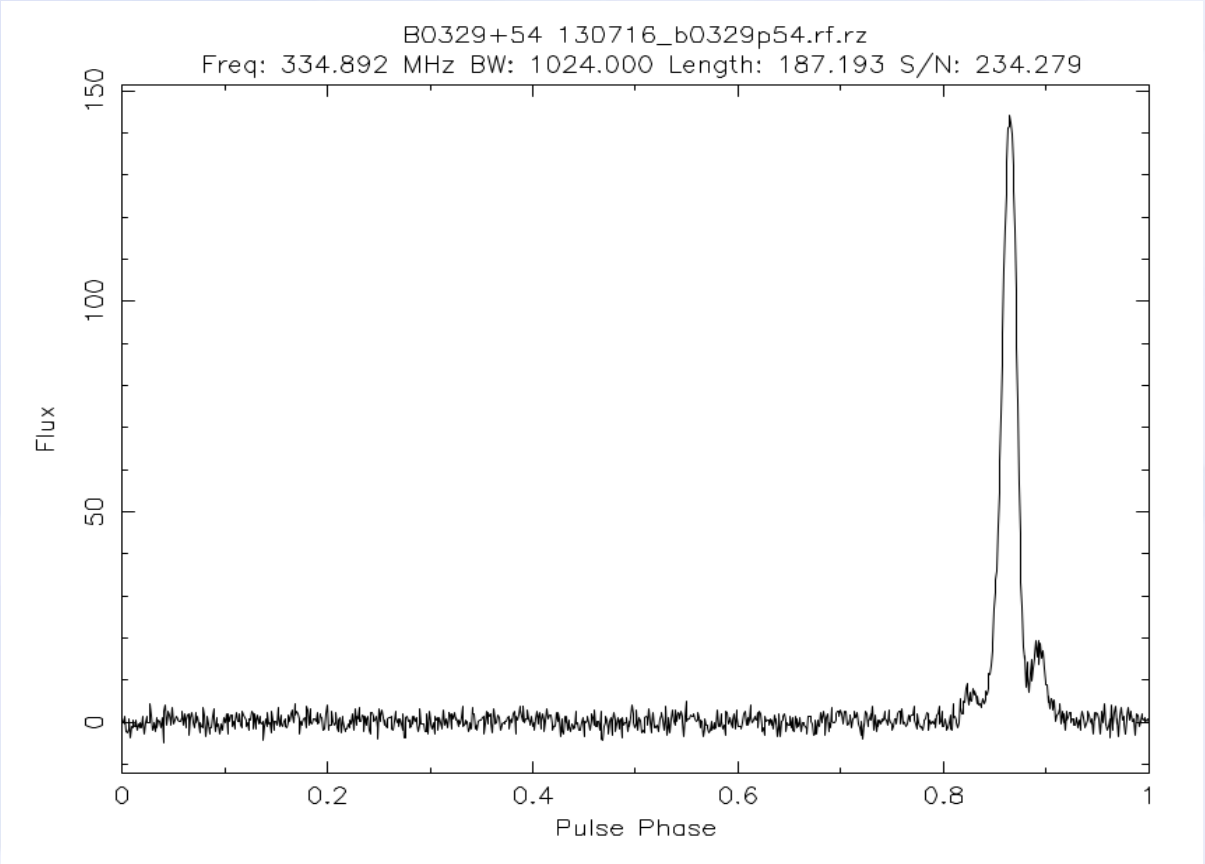
- “Black box” machine: only ATNF can provide new personalities

- It is employed only in “external client” mode



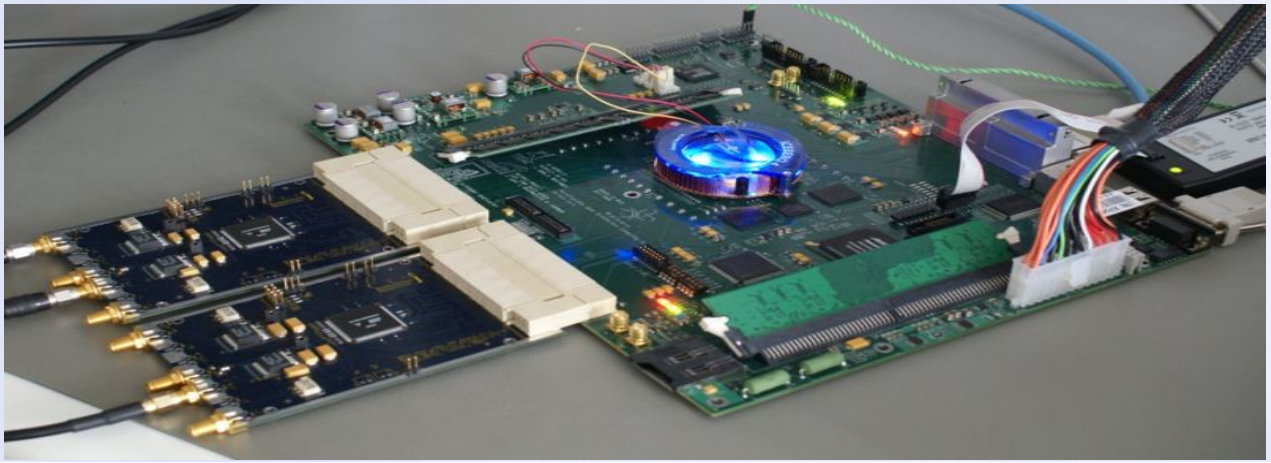
Pulsar Digital Filter Bank (2)

-Pulsar B0329+54 observed in P-band (305 – 410 MHz)



ROACH
(Reconfigurable Open Architecture and Computing Hardware)

- Used for the LEAP (Large European Array for Pulsars) project at SRT.
  pulsar timing, 2 IFs, 512 MHz, 32 sub-bands, base-band recording
  .



Large European Array for Pulsar (1)

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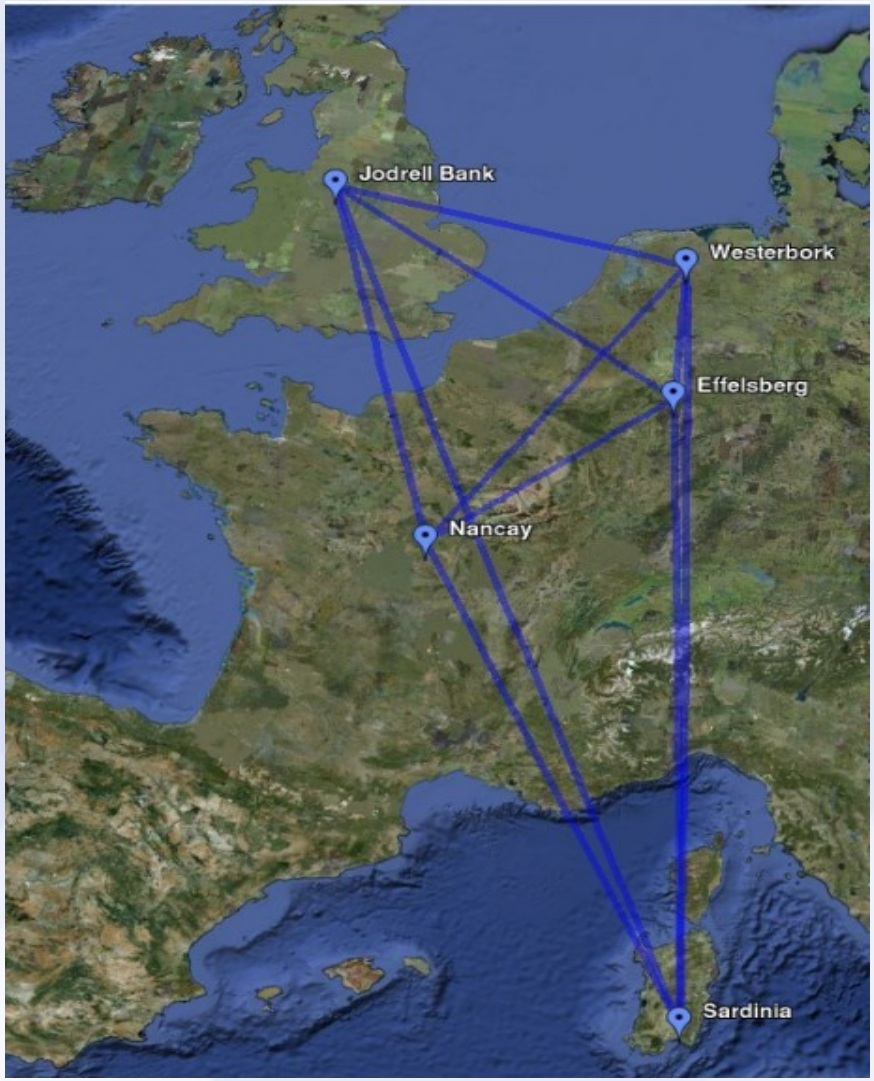
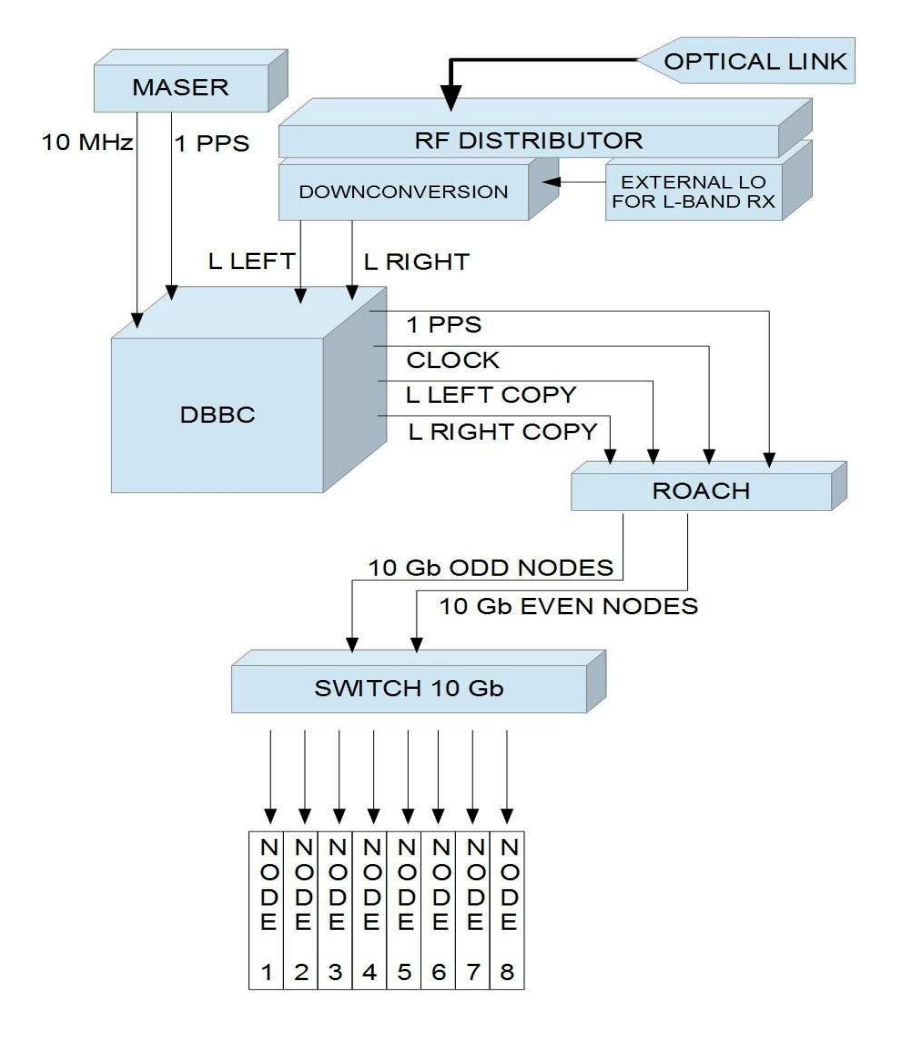
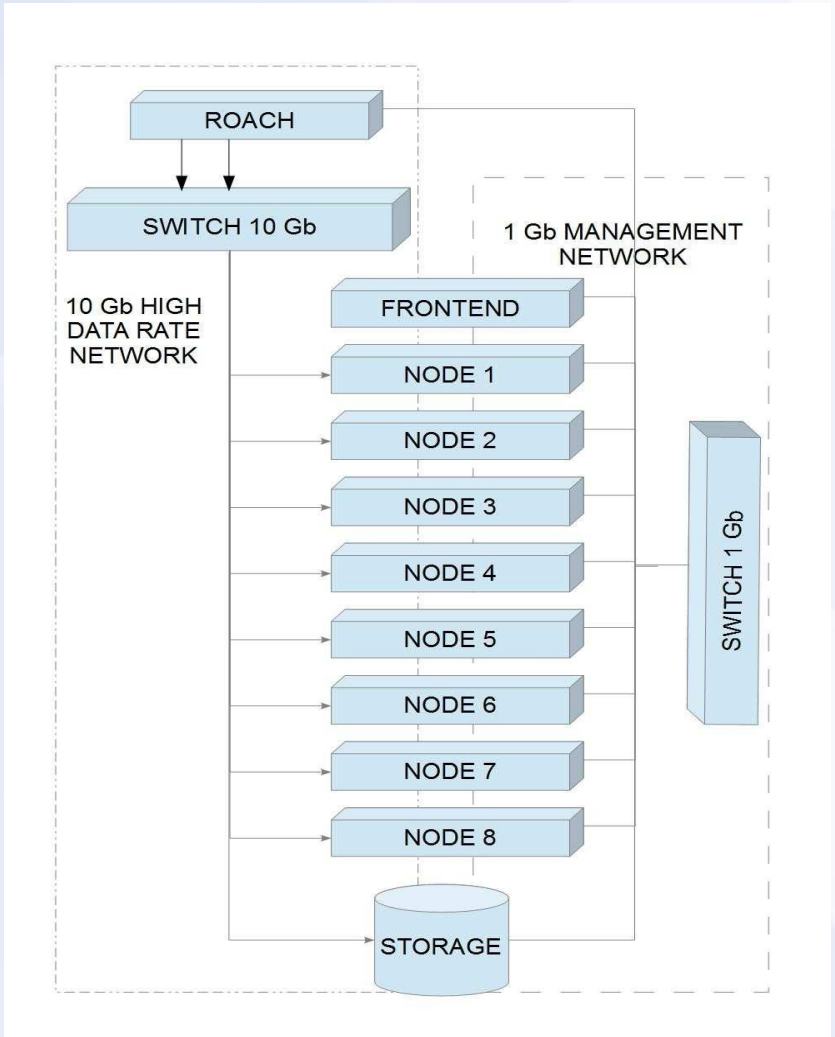


Large European Array for Pulsar (2)





Pulsar observed with the LEAP platform

- B1937+21

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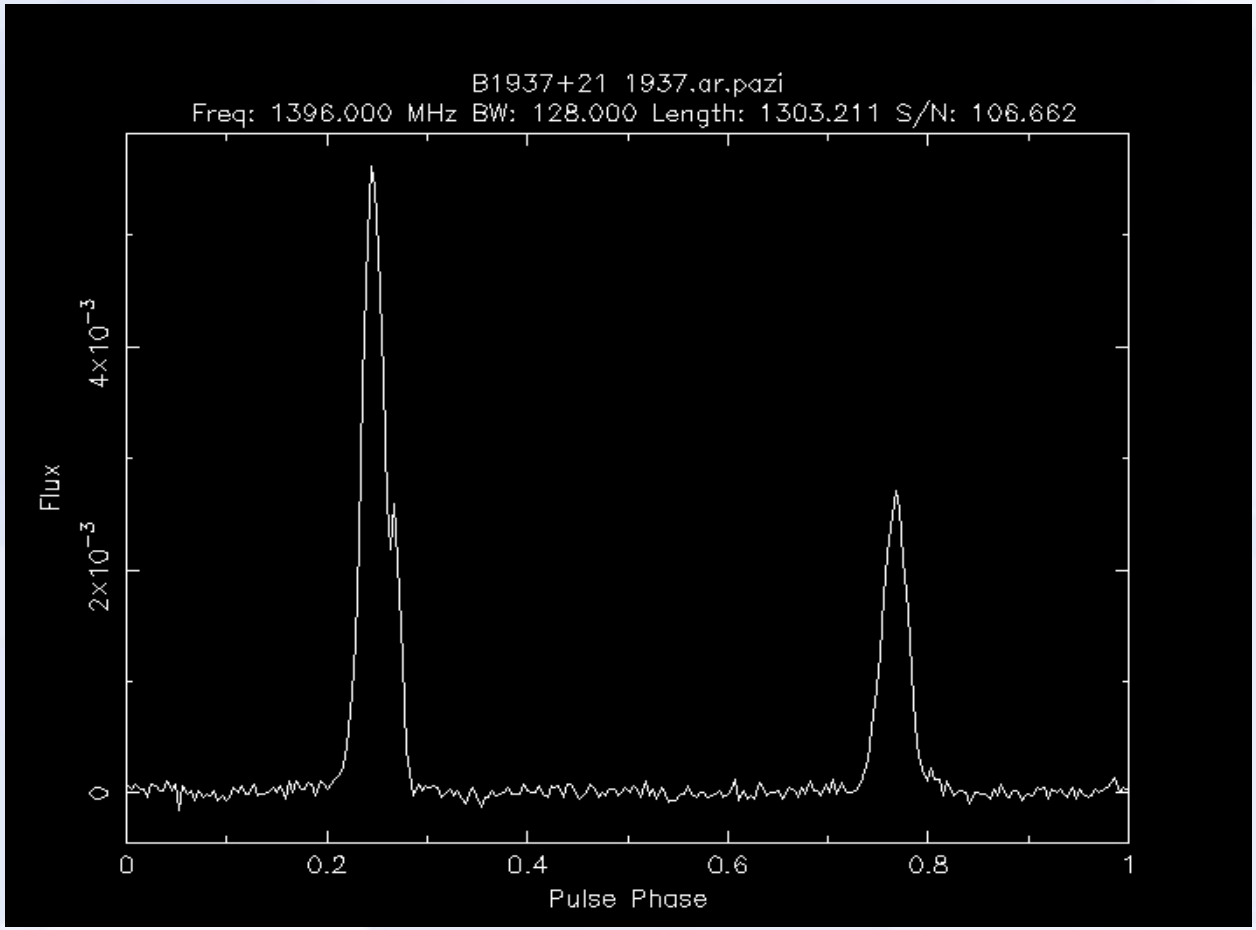


Ideal digital back-end

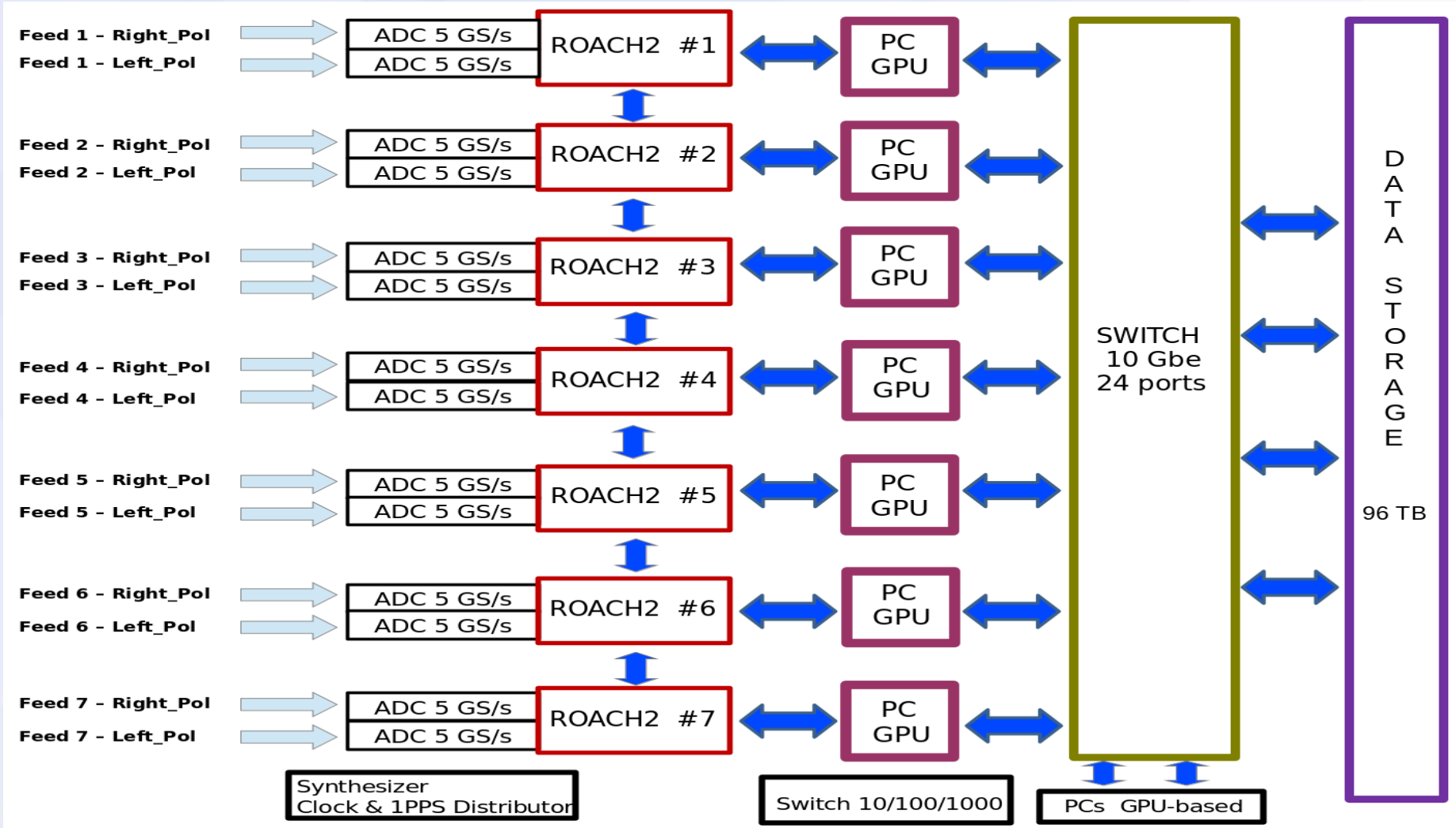
- Italian radio telescopes are equipped with a variety of digital platforms that are applicable to a significant amount of scientific studies.

- However, they present both pros and cons and, more generally, they are not able to satisfy all requests.

- The ideal system for SRT should be able to meet the following:

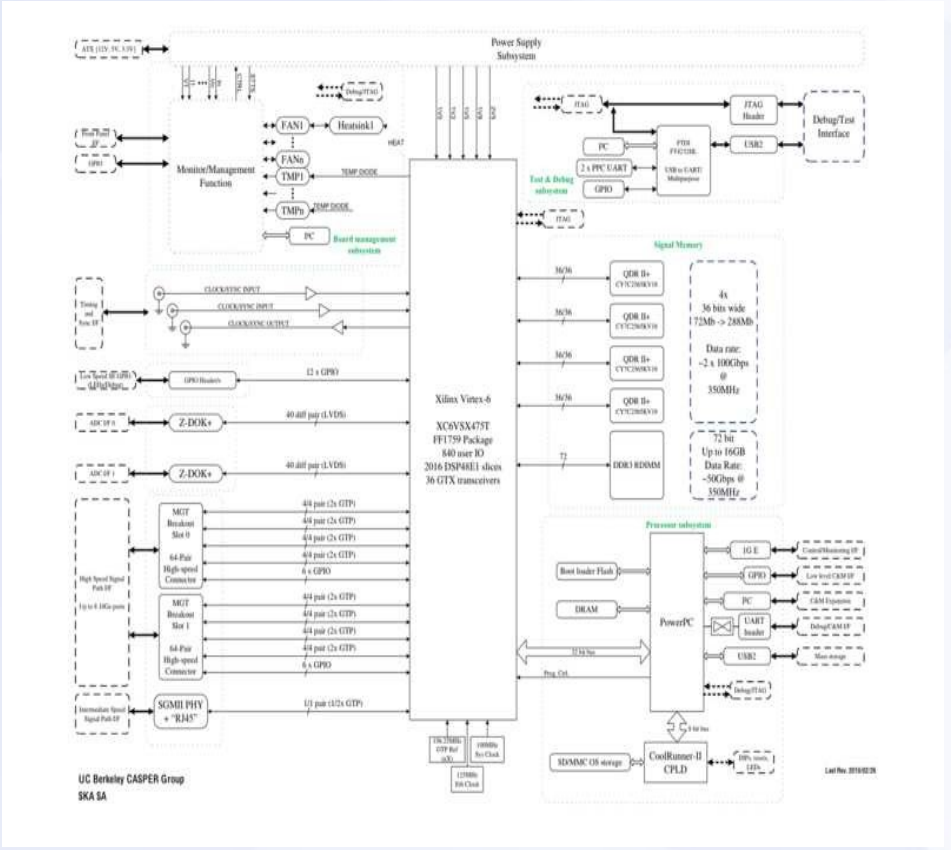
- Up to 14 IFs simultaneously
- Up to 2.1 GHz of bandwidth for each IF
- Full reconfigurability and adaptability for all scientific requirements

SARDARA
SArdinia Roach2-based Digital Architecture for Radio Astronomy

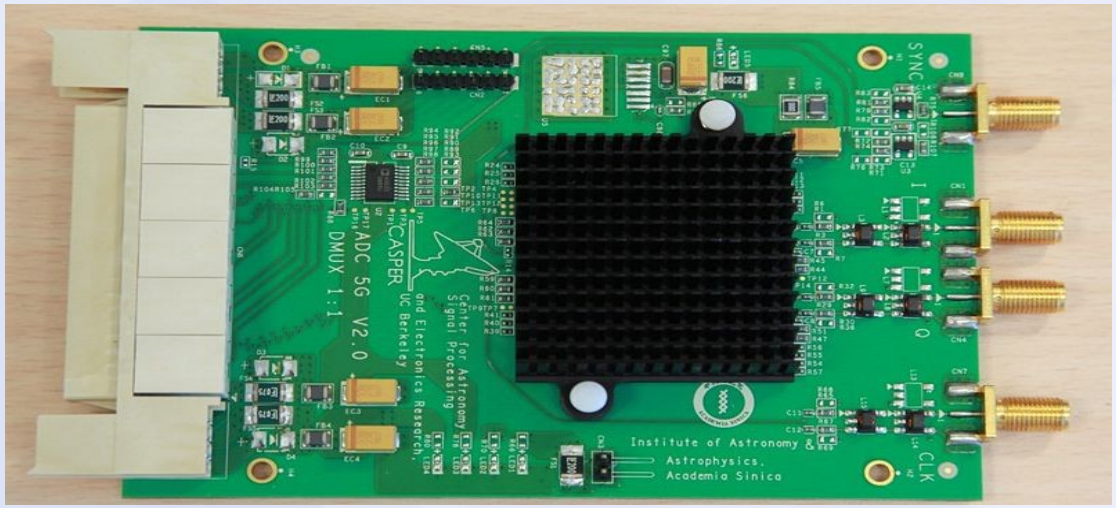


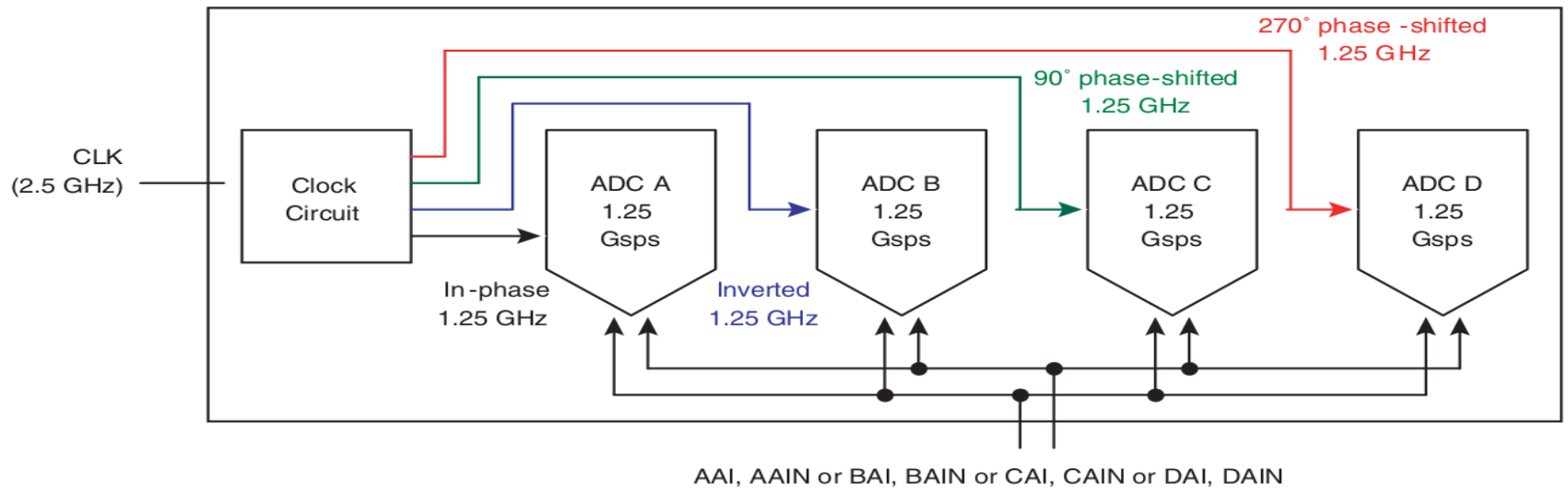
ROACH2

- The ROACH2 is a stand-alone FPGA-based board that represents the successor to the original ROACH board



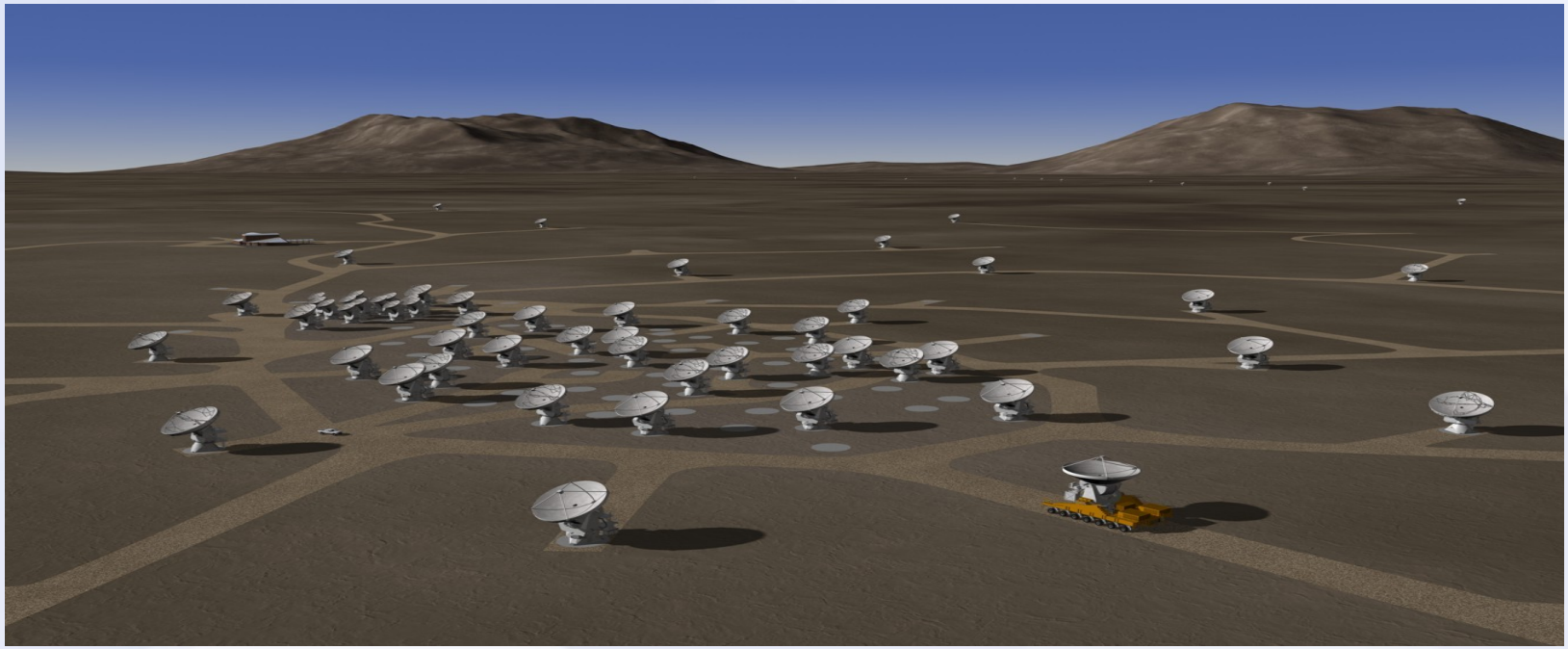
Analog-to-Digital Converters





Control software at Italian radio telescopes (1)

- The control software at Italian radio telescopes is (SRT, Medicina) or will be soon (Noto) based on the framework ALMA Common Software (ACS), namely the one employed at Atacama Large Millimeter Array telescope.



Control software at Italian radio telescopes (2)

- *Even if a single-dish telescope is completely different from an array of antennas like ALMA (especially for data processing), the versatility of ACS lead us to use it in any case.*

- *Digital backend integration represents one of the most complicated tasks in the context of a radio telescope control software.*

- *As the final stage in the receiving chain, data produced by every backend must include overall information concerning the antenna and the ongoing observation.*

- *Albeit the software controlling the telescope is distributed (it is based on CORBA), a central computer deal with the FITS file finalizer, therefore data produced by the interested backend must be sent to it.*

SARDARA approach

- *Experience has now taught us that the way a digital backend fully integrated in the control software ACS-based takes a very long time, of the order of a few years!*

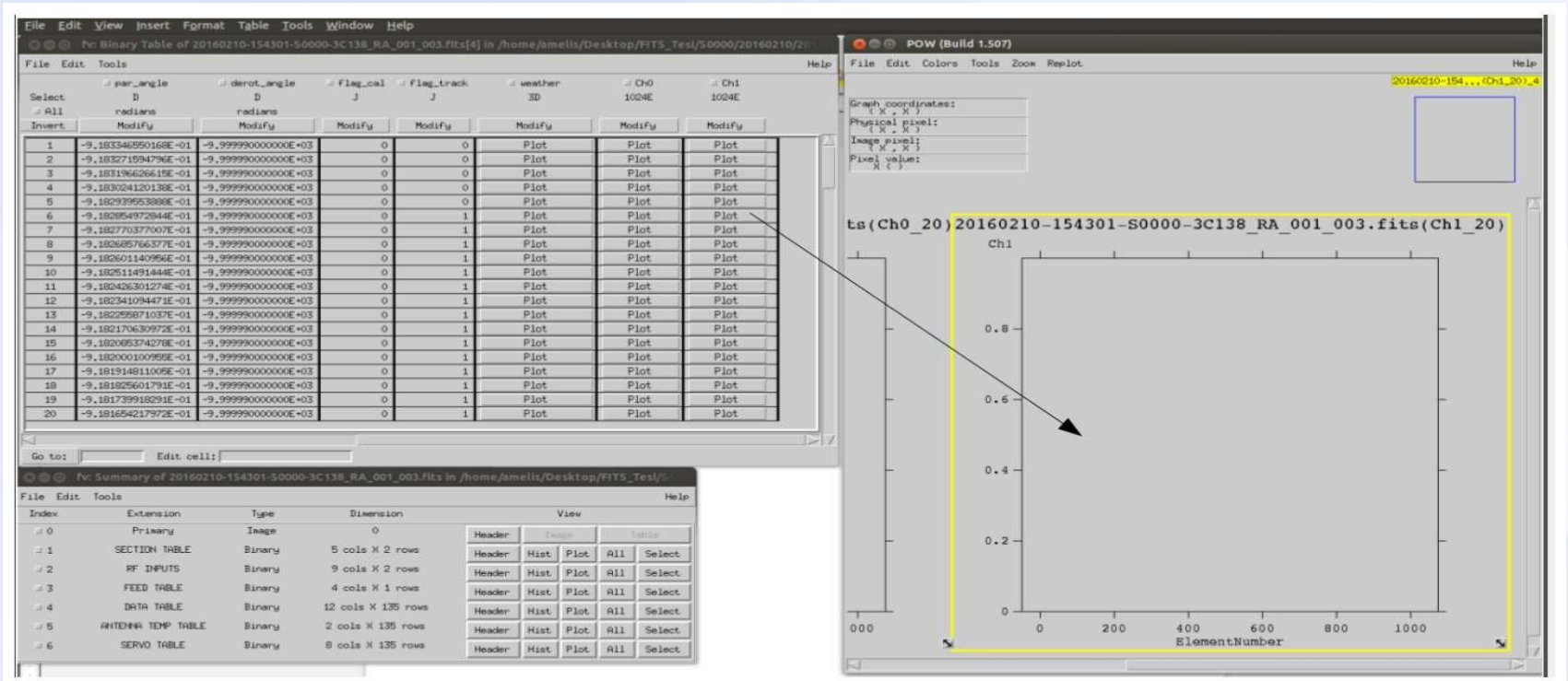
- *The approach conceived for SARDARA follows an opposite trend. In particular, it distinguishes neatly the antenna's parameters and the software controlling the backend, as if they were two entity acting on their own.*

- *The only thing necessary to allow such a independent approach is the overall synchronization of the two systems in terms of time.*

Antenna side

- *In the case of ordinary ACS backend integration, the control software is fully responsible for everything, which includes the retrieving of data produced by the backend.*

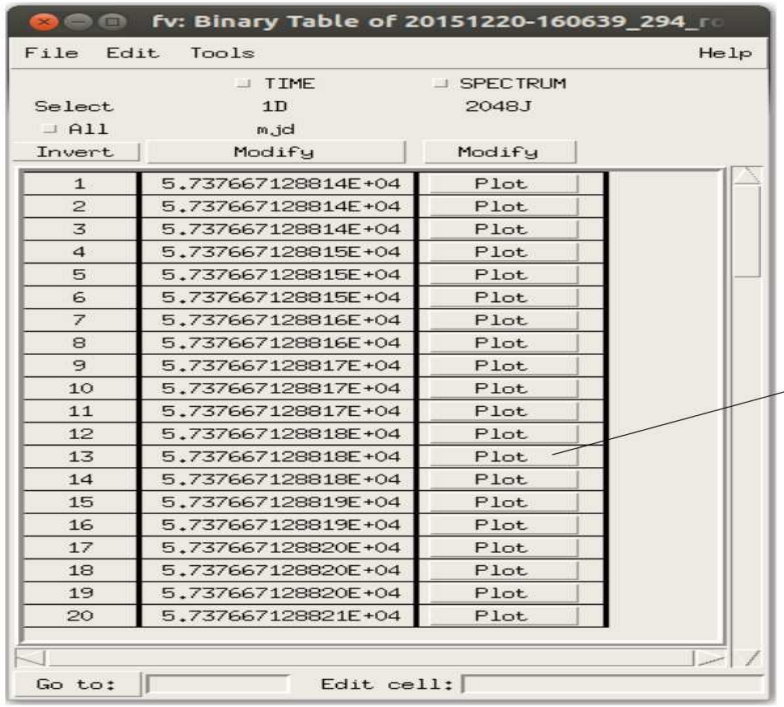
- *On the contrary, in this new approach, the control software works independently, i. e. does not care about what the backend does, except start and stop commands, configuration and little else.*

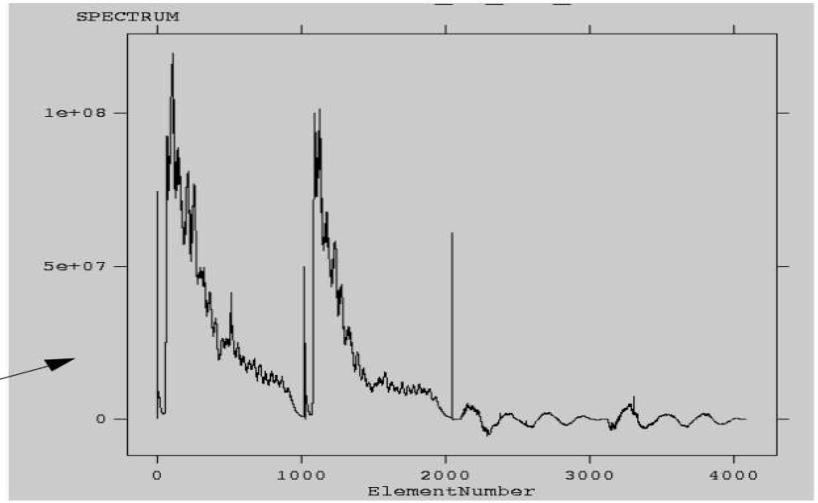


Backend side

- *The handling and the storing of the data are entirely "on board": all of the complicated and dangerous data exchange between nodes involving the software controlling the telescope are avoided*

- *A "fictitious" FITS file format contains only the data - i. e. spectral points provided by the spectrometer running in the ROACH2 – and corresponding time-stamp.*





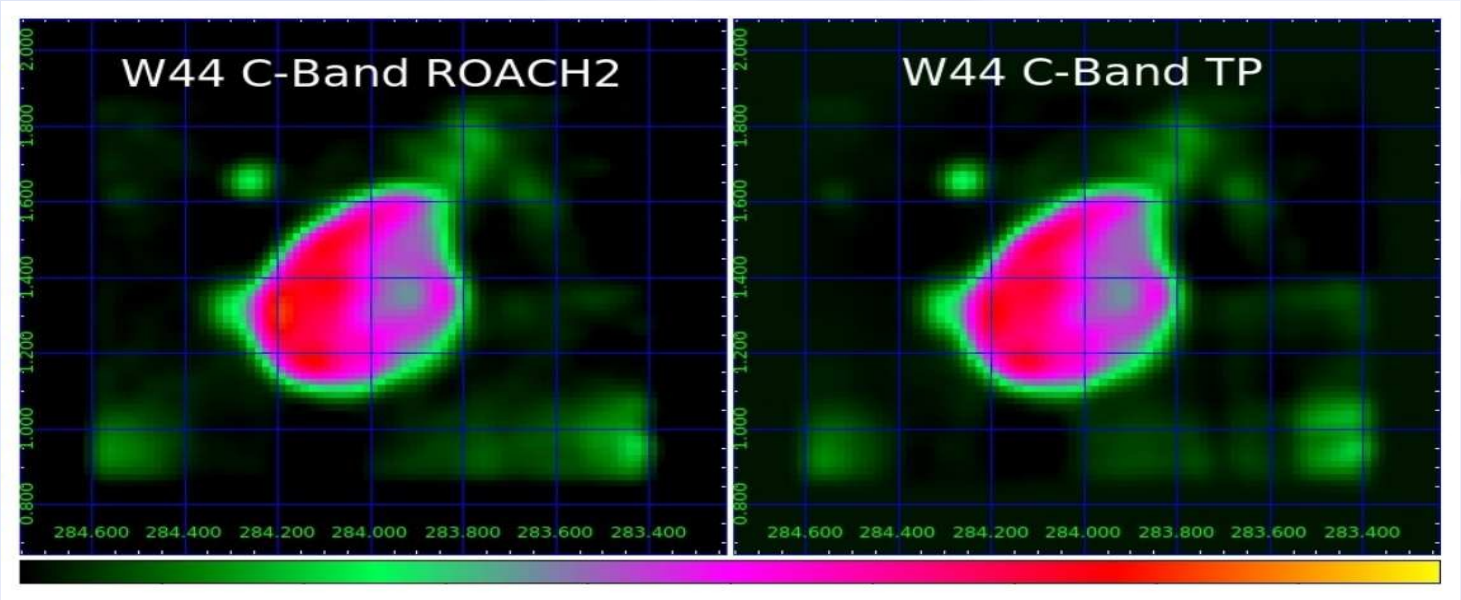
Final merging

- *Incomplete FITS files produced by antenna and backend are, finally, merged in order to get the final FITS files.*

- *A pipeline software check the time correspondence between FITS files.*

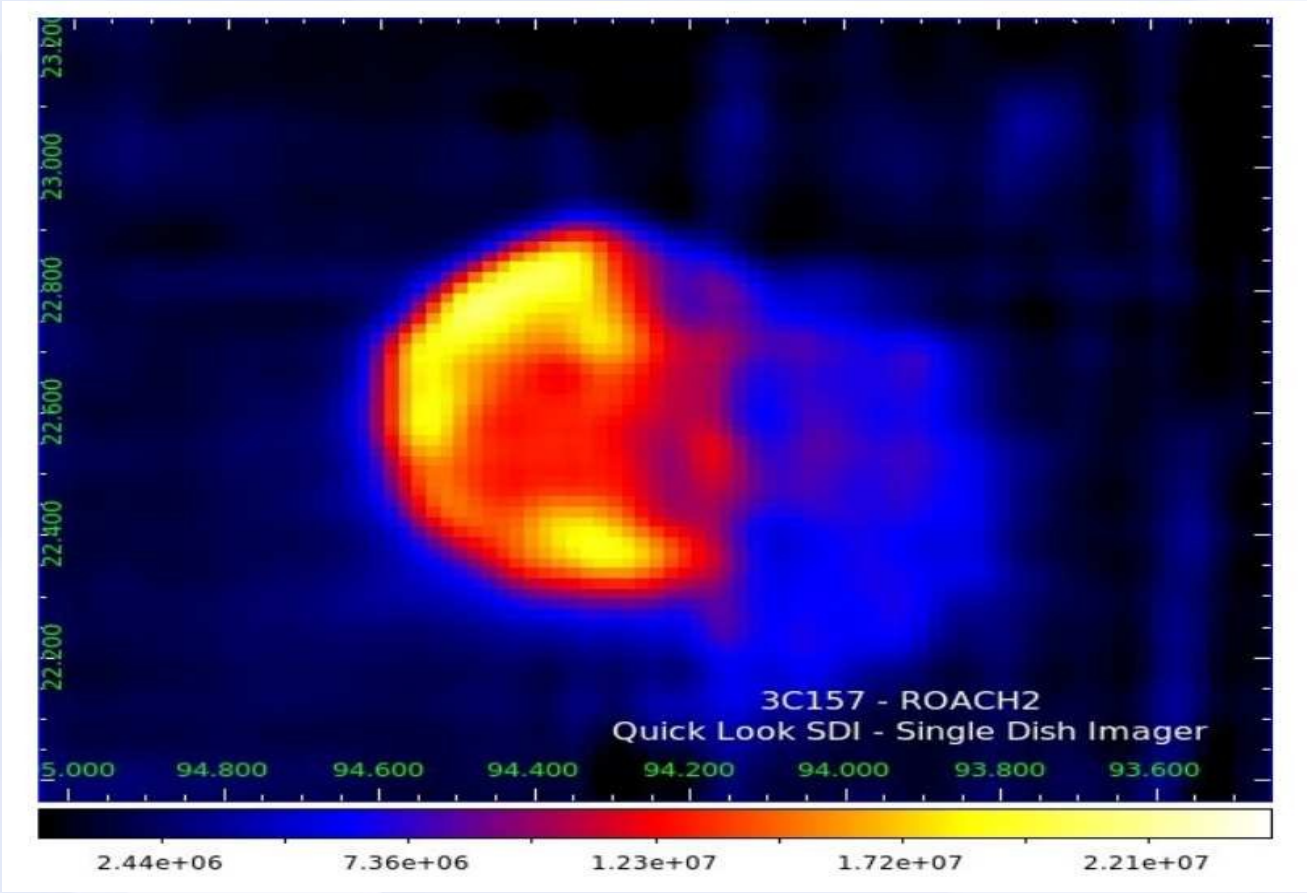
- *The on-the-fly sky mapping represents the worst case and has been immediately tested*

- *The first successful experiment and the general working is confirmed also visually.*



First light of SARDARA (1)

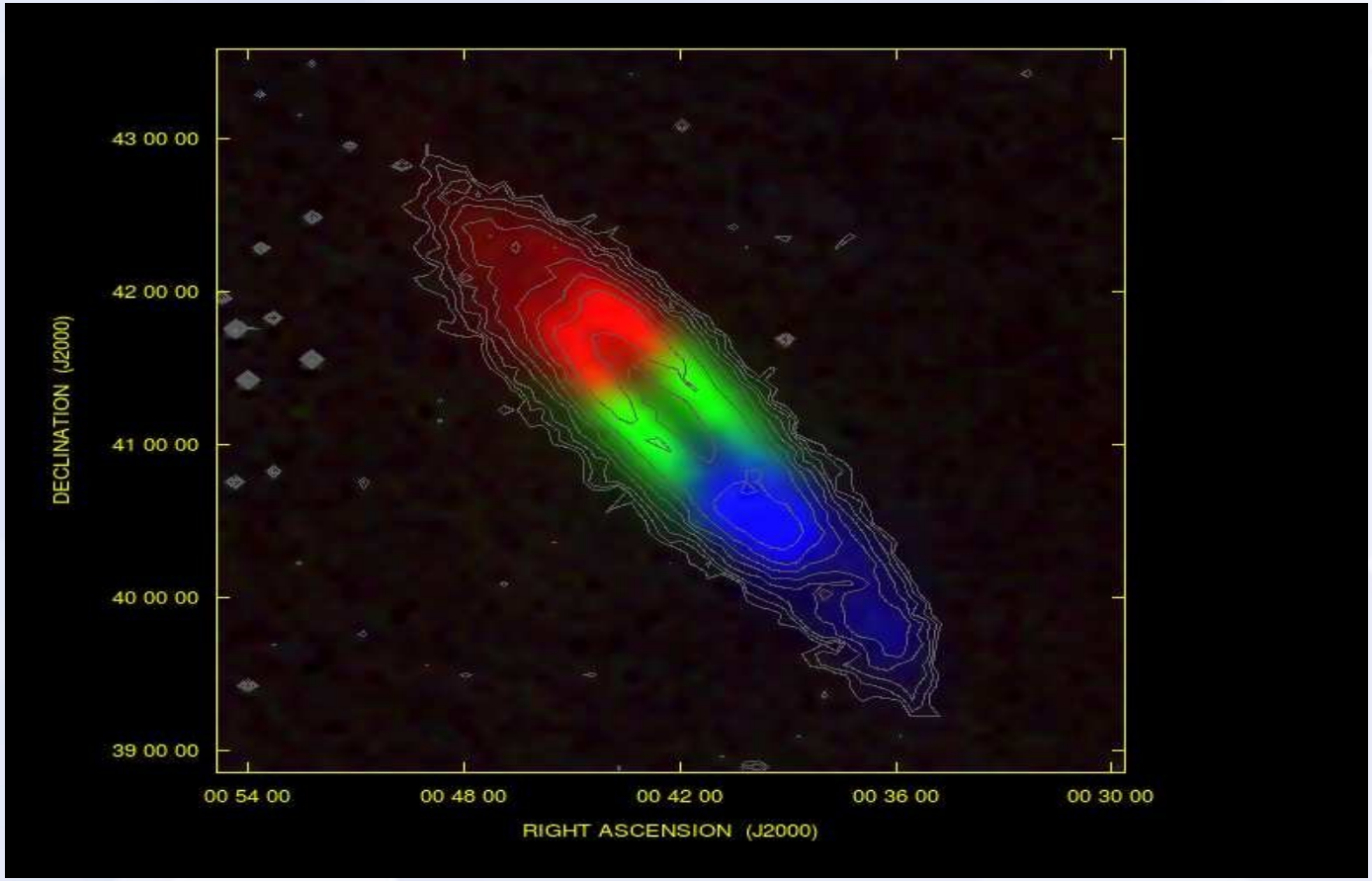
- Supernovae remnants 3C157



Credits: Pellizzoni, Egron, Iacolina, Trois et al.

First light of SARDARA (2)

- Andromeda galaxy (M31)

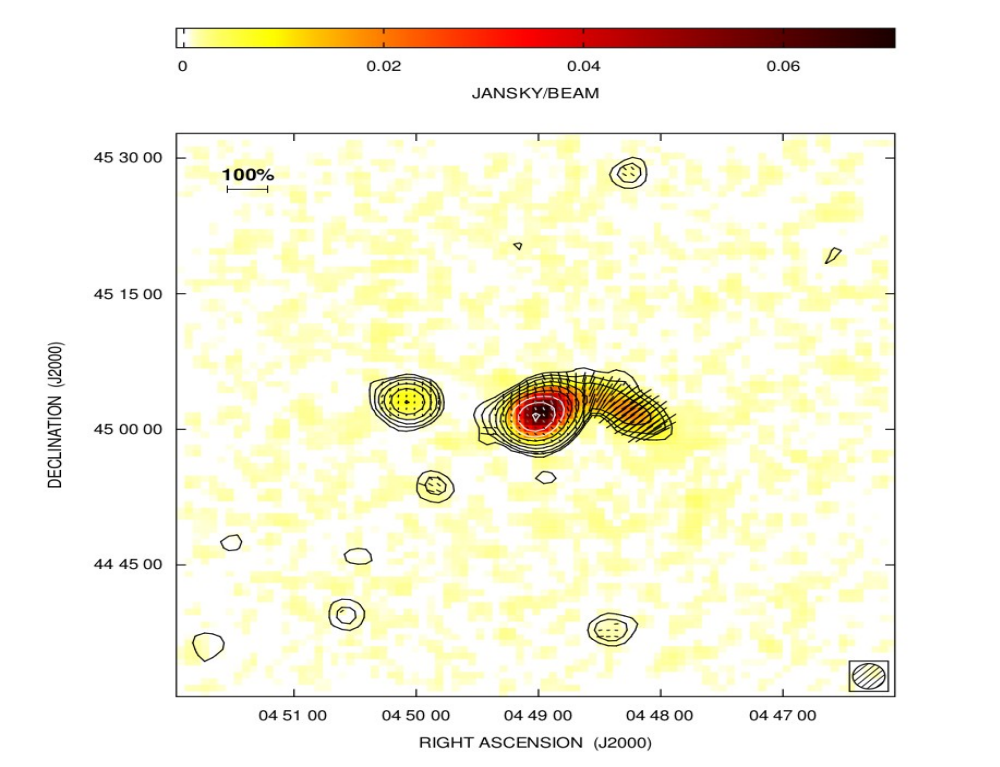


Credits: Murgia, Castangia, Tarchi, Govoni et al.

First light of SARDARA (3)

- Linearly polarized intensity image of the 3C129 galaxy cluster

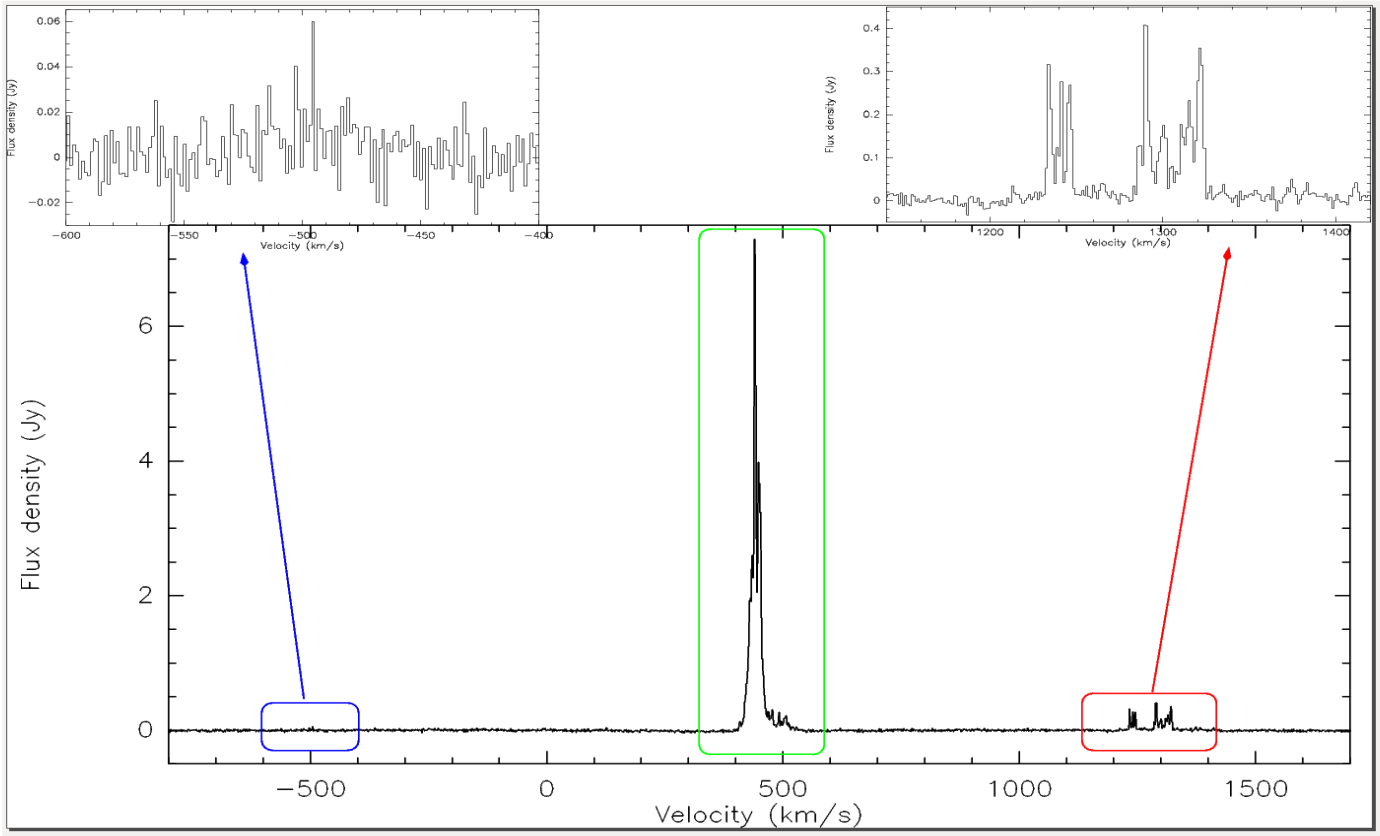
- This is the first image in polarization ever made at SRT.



Credits: Murgia, Govoni, Carretti et al.

First light of SARDARA (4)

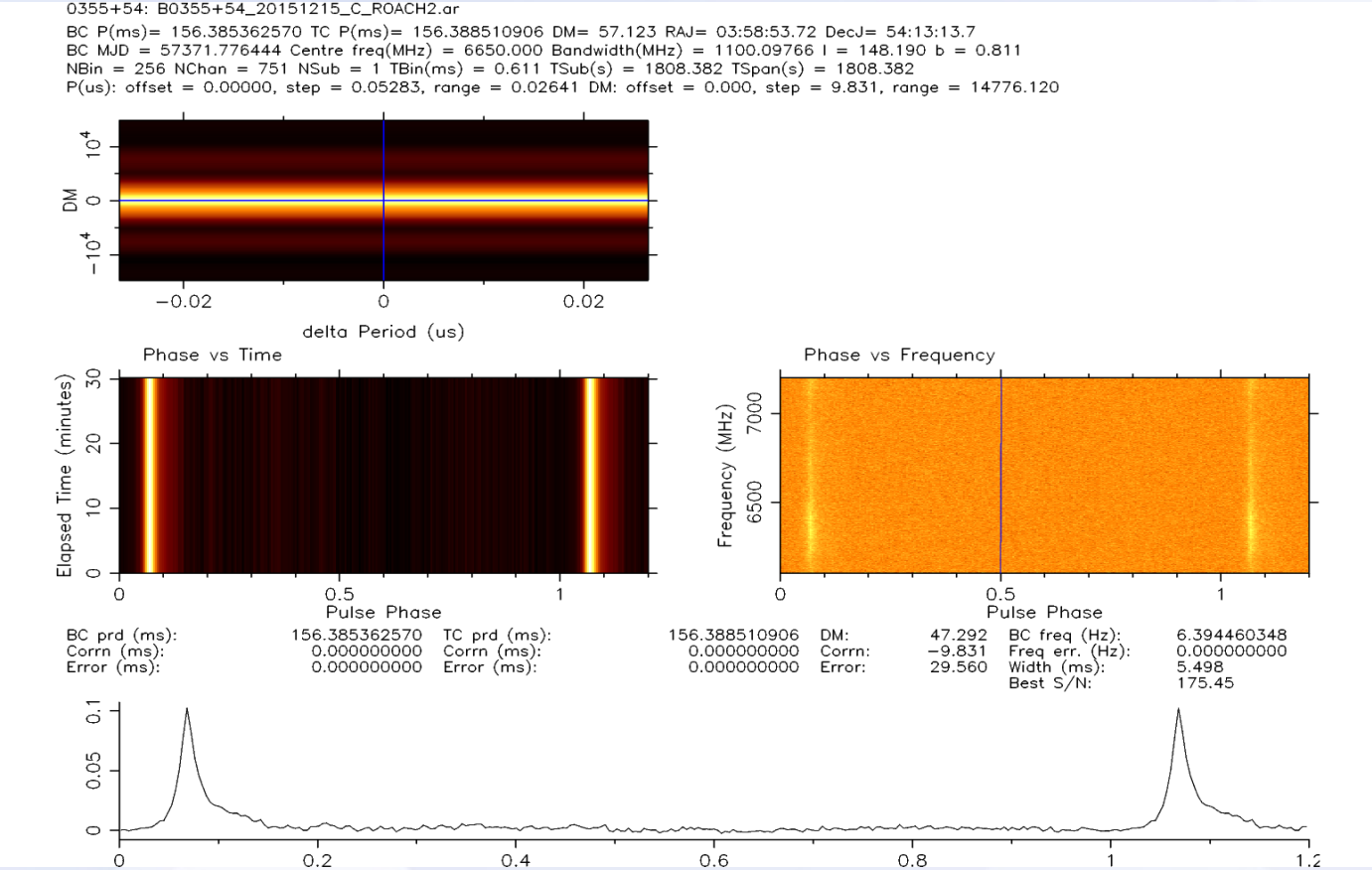
- 22-GHz water maser source observed in NGC4258 taken with the SRT in conjunction with SARDARA.



Credits: Tarchi, Castangia et al.

First light of SARDARA (5)

- *Pulsar B0355+54*

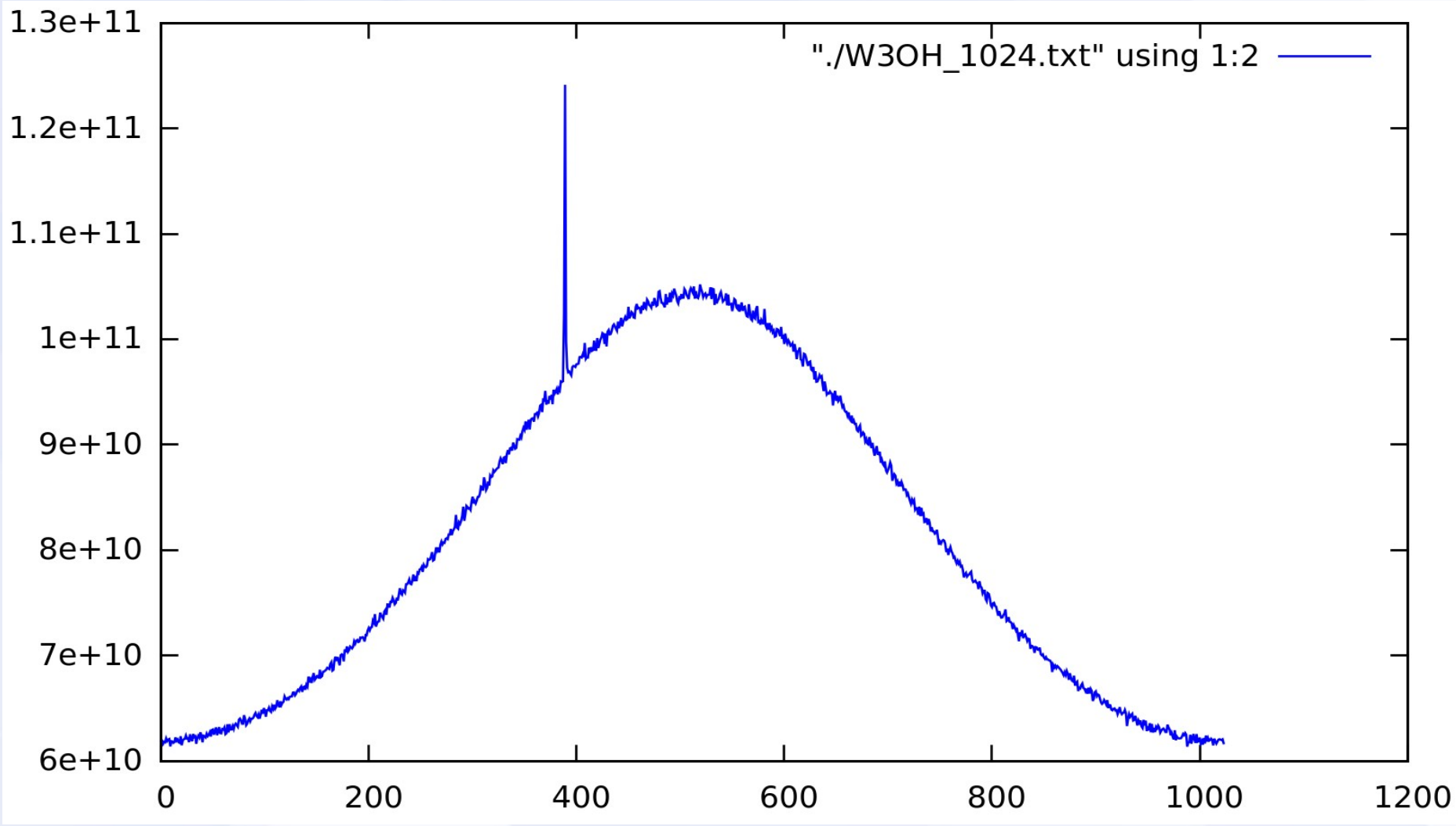


Credits: Pilia, Trois et al.

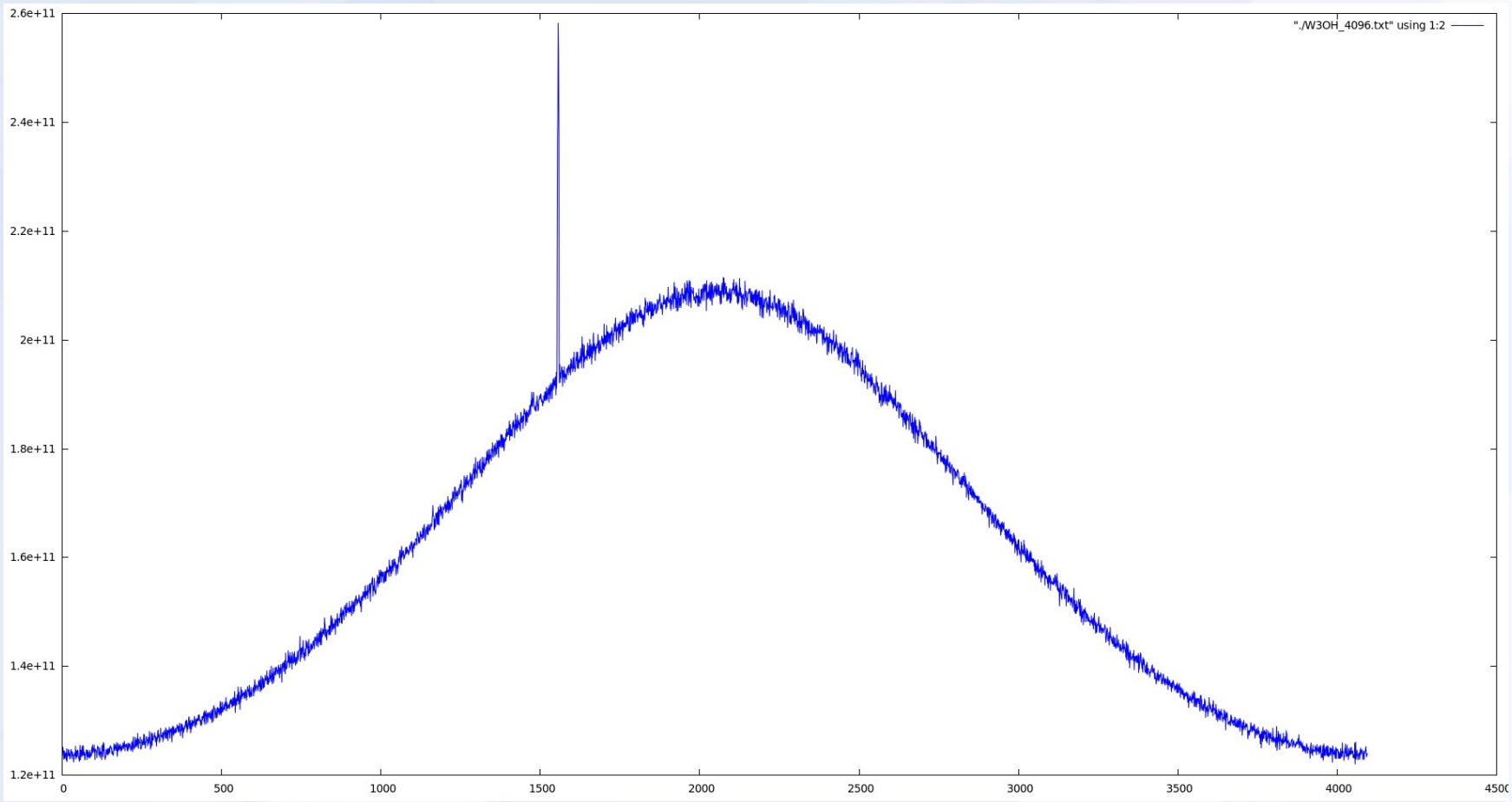
Narrow band spectroscopy

- *Processing distributed between FPGA and GPU*
- *A portion of bandwidth is selected by a digital FIR filter and then sent to a GPU node*
- *Base-band data processed via GPU; each node of SARDARA has 2 GPU NVidia GTX 980 TI (2816 CUDA core, RAM 6 GB)*
- *The number of channels can be chosen between 1024 and 2 millions*

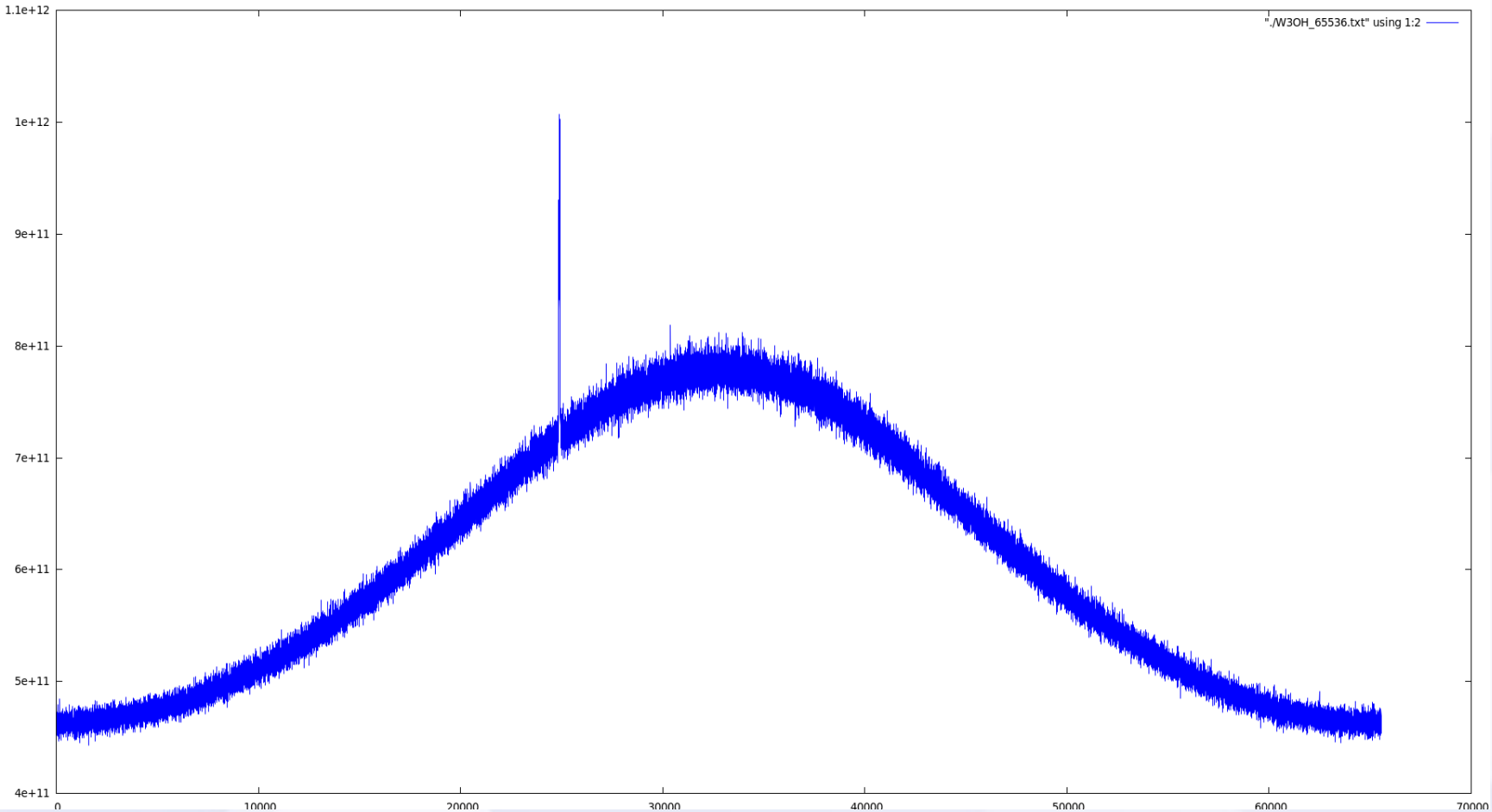
W3OH C-band: 50 MHz, 1024 canali



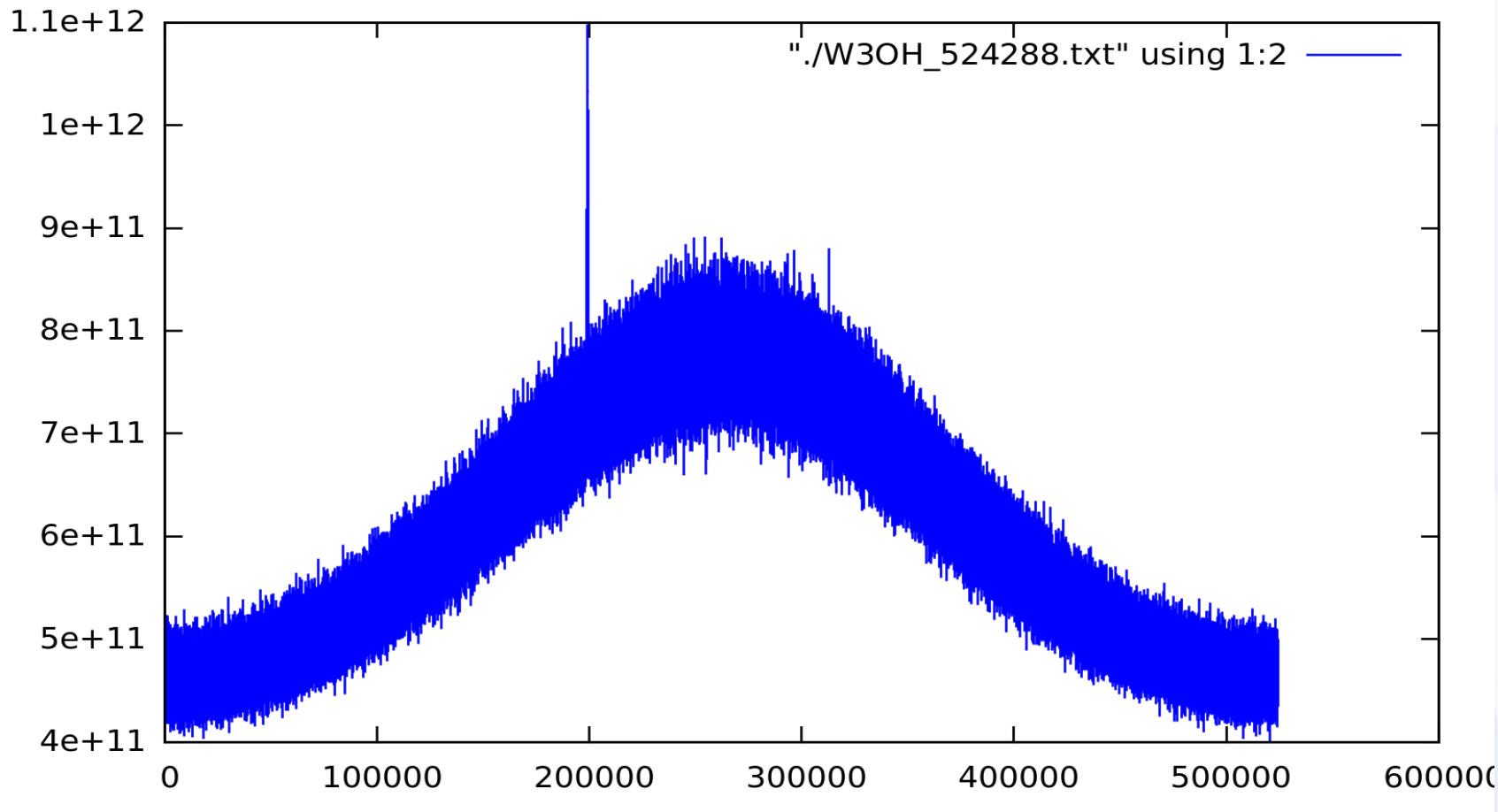
W3OH C-band: 50 MHz, 4096 canali



W3OH C-band: 50 MHz, 65536 canali



W3OH C-band: 50 MHz, 524288 canali

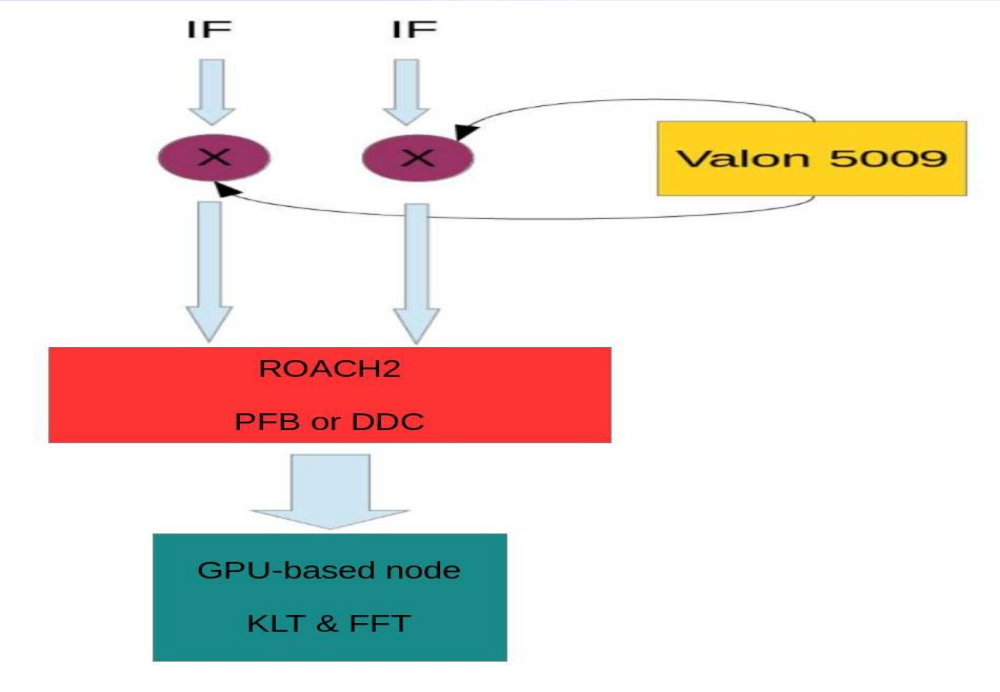


Search for Extra Terrestrial Intelligence

- *Since SETI research is often conducted in piggyback mode only, a dedicated conditioning module is employed at the level of the intermediate frequencies.*

- *In particular, it acts as frequency compensation mechanism that is necessary for keeping the chosen bandwidth stable even when a Doppler tracking system is activated.*

- *In case of long pointing, the Valon 5009 can be exploited to sweep the entire bandwidth as well.*



FFT approach: SERENDIP VI

- *Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations*

- *Project conducted by UC Berkeley*

- *It scans a broad range of frequencies*

- *Implemented at Arecibo radio telescope (Puerto Rico) and at Green Bank Telescope (West Virginia)*

- *Based on the Fourier Transform*

- *This is the best way to find messages intentionally transmitted by alien civilizations*

SERENDIP VI at Sardinia Radio Telescope

- *Collaboration with Dan Werthimer, Andrew Siemion, David MacMahon, Jeff Cobb.*

- *2.4 GHz split up into 4096 pieces by using a polyphase filter bank.*

- *The GPUs break these 4096 course channels up into fine channels (about 1 Hz each), do baseline smoothing, and search for signals above a threshold.*

- *The system can be used, in parallel, to search "Fast Radio Burst".*

- *At SRT, at least a ROACH2 board of SARDARA will be employed to do SETI.*

KLT approach

- Kahrunen-Loeve Transform

- The traditional FFT approach uses sinusoidal functions to represents a certain signal

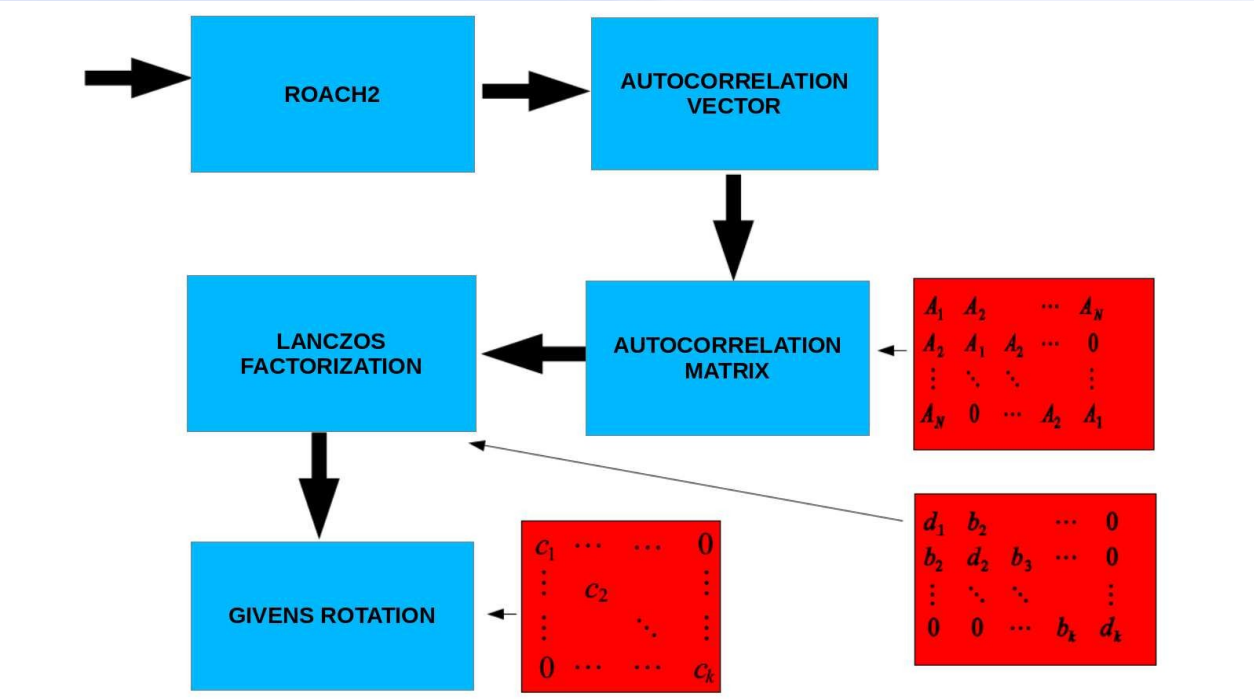
- The KLT, instead, calculates the best orthonormal functions that represents the acquired signal

- The KLT is the best way to find signal unintentionally transmitted by possible alien civilizations (wide-band approach)

Block diagram for the calculations of eigenvalues

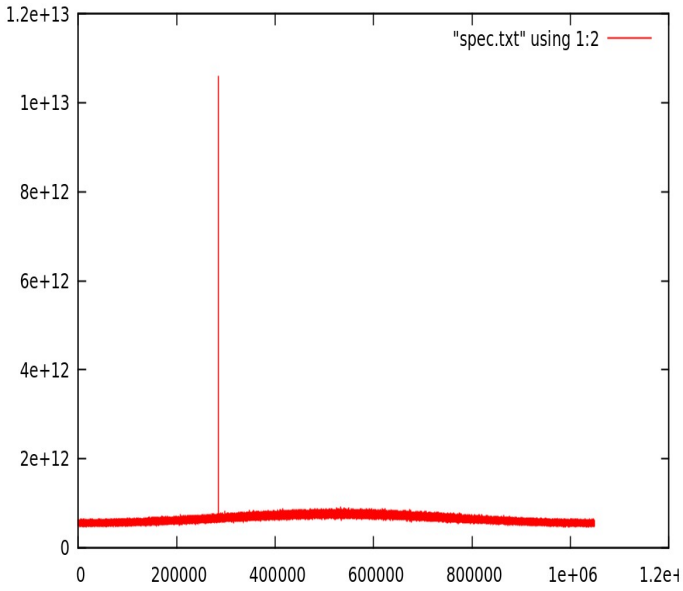
- *Essentially, the goal is to get the privileged axes that describe the acquired signals in the best possible way; this correspond to perform the calculation of eigenvectors/eigenvalues of the autocorrelation matrix of these signals.*

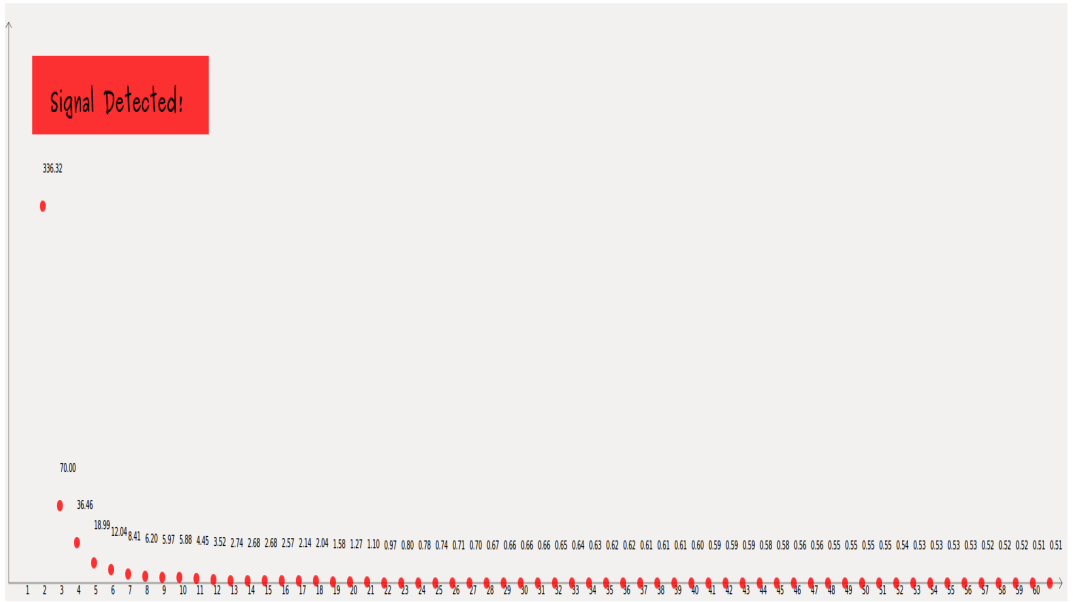
- *Once we get the eigenvalues and the eigenvectors, a specific energy evaluation can be done by SETI experts.*



Test on field at SRT

- *The KLT is really heavy from a computational viewpoint; currently, base-band data are recorded and processed off-line.*
- *A real-time GPU implementation of the KLT is under investigation*
- *Implementation at SRT in collaboration with Pierpaolo Pari and Claudio Maccone.*





Wavelet approach (1)

- *The Fourier transform is a useful tool to analyze the frequency components of the signal. However, if we take the Fourier transform over the whole time axis, we cannot tell at what instant a particular frequency rises.*

- *Short-time Fourier transform (STFT) uses a sliding window to find spectrogram, which gives the information of both time and frequency. But still another problem exists: the length of window limits the resolution in frequency.*

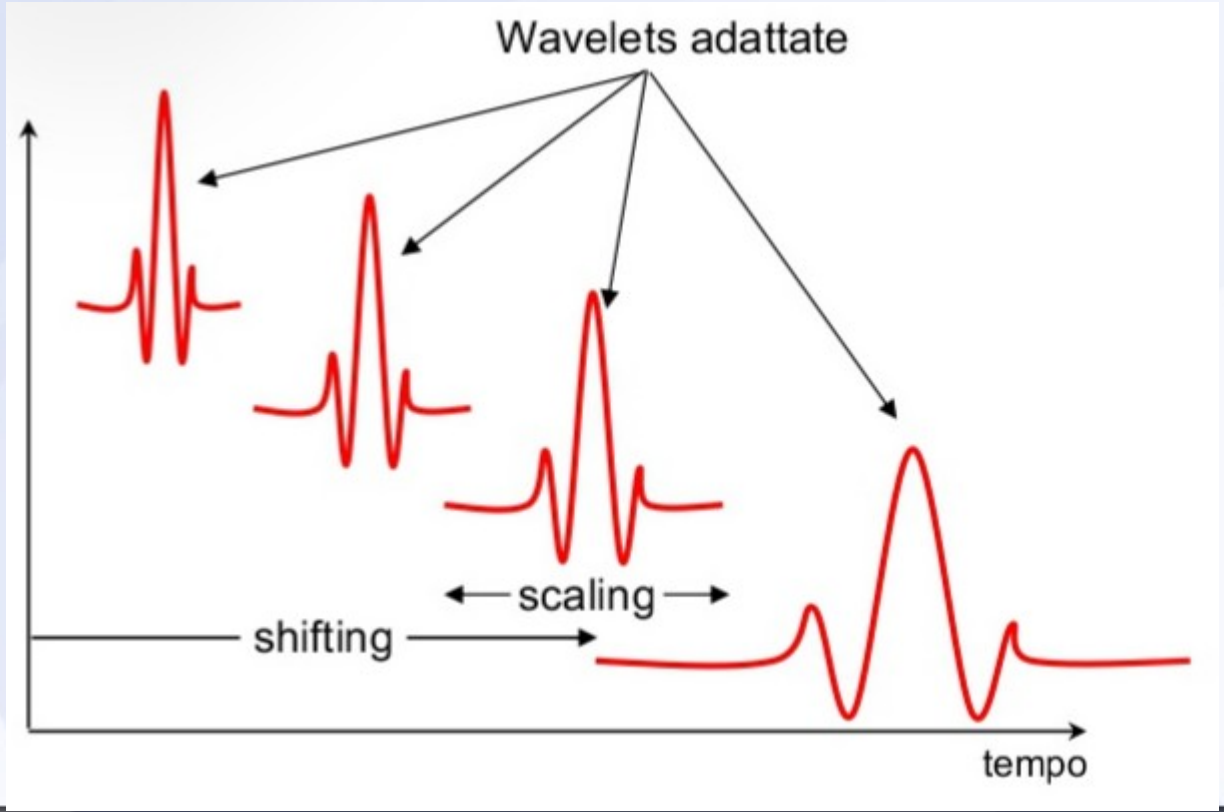
- *Wavelet transform seems to be a solution to the problem above: all the wavelet transforms can be considered as "time-frequency" representation.*

Wavelet approach (2)

$$C(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} s(t) \cdot \psi\left(\frac{t-b}{a}\right) dt$$

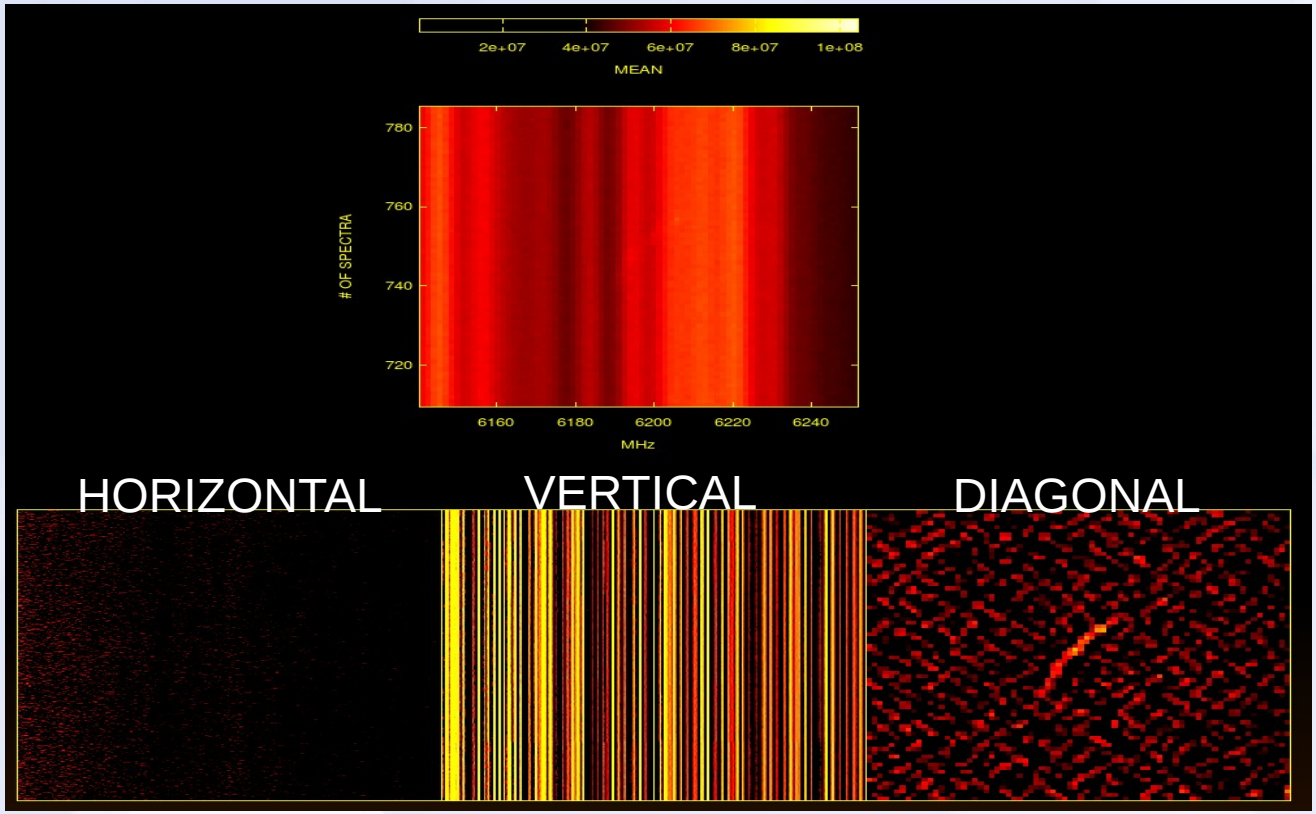
- *a >>1 the wavelet is dilated → contains low frequencies and provides a global approximation of the signal*

- *a << 1 the wavelet is compressed → contains high frequencies and provides a detailed image on a small portion of the original signal*



SRT C-band SARDARA observation during the early science (SMOG program)

- *Wavelet decomposition (bottom panel) of a cold region of the sky (top panel). Showing horizontal, vertical and diagonal detail coefficients, an "inclined" signal is clearly detected in diagonal coefficients*



Credits: M. Murgia et al.

Future works

- *Full implementation of SARDARA at SRT for all of the scientific requests (imaging, spectral polarimetry, spectroscopy, pulsar, FRB)*

- *Porting of SARDARA at Medicina (MEDARA) and Noto (NODARA)*

- *SKARAB (ROACH3) investigation for the ongoing development multi-feed receivers (Q-band in particular)*

- *SETI platform (FFT, Hough, KLT, Wavelet)*

- *Space Debris*

- *ITPM for single dish applications and for a possible PAF (Phased Array Feed) at SRT*