Mem. S.A.It. Vol. 88, 195

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FPGA-based digital back-ends for the Sardinia Radio Telescope

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Abstract. The Sardinia Radio Telescope (SRT), located in San Basilio, about 35 km north of Cagliari, is the largest (64-m diameter) radio telescope in Italy. It is a general-purpose, fully-steerable radio telescope designed to operate in the 300 MHz - 116 GHz frequency range, which allows it to perform a wide variety of scientific studies. The advanced electronic digital platforms that are installed at SRT play a key role, in particular those based on FPGAs (Field Programmable Gate Array), both because of their processing capability and their reconfigurability. In this paper, we present an overview of the digital back-ends available at SRT, as well as the ones under development; it is important to underline that, for all of them, FPGAs are the beating heart.

Key words. FPGA, Back-ends, Sardinia Radio Telescope

1. Introduction

The Sardinia Radio Telescope (SRT) is a new general purpose, fully-steerable 64-m diameter parabolic radio telescope capable of operating in the 0.3-116 GHz frequency range. The project is the result of a scientific (Prandoni et al. 2016) and technical (Bolli et al. 2015) collaboration among different structures of the Italian National Institute for Astrophysics. SRT is located in Pranu Sanguni, 35 km north of Cagliari. The telescope was inaugurated in 2013; the Astronomical Validation (AV) is now over and early science started at the beginning of 2016.

Once collected by the antenna and properly conditioned, the acquired signal must be converted into digital format and then processed in order to provide the data in a convenient format for later studies. Depending on the nature of the received radiation, different back-ends allow the measurements of the received power as a function of time, frequency and the eventual polarization state. In this paper, we describe both the back-ends that are currently available and the ones that are under development at SRT.

2. Available digital back-ends at SRT

2.1. Total Power

The Total Power (TP)(Scalambra et al. 2013) back-end is a platform developed by the Institute of Radio Astronomy (IRA). It has two main functions: it works in "focus selector" mode (fig. 1) and as a continuum back-end (fig. 2).

The TP is available at all three Italian radio telescopes; at SRT, in particular, the over-

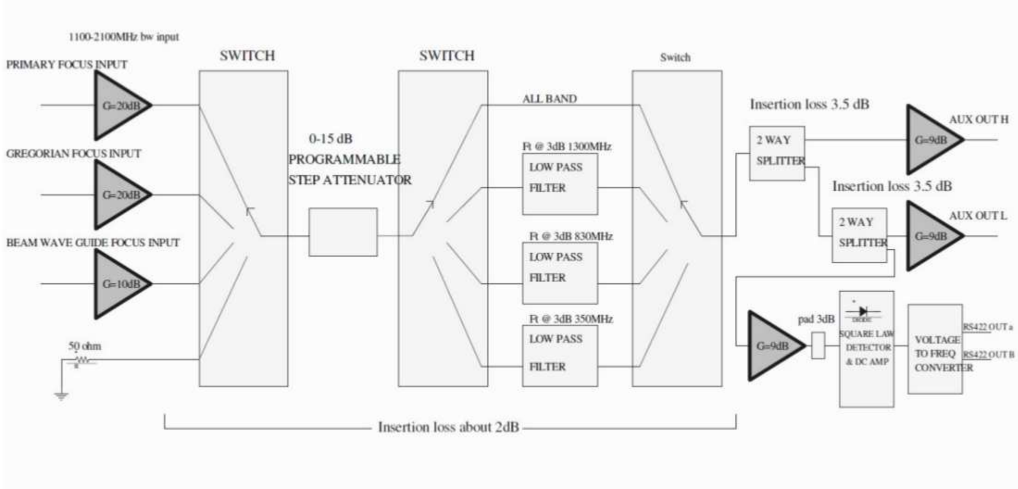

Fig. 1. Focus Selector.

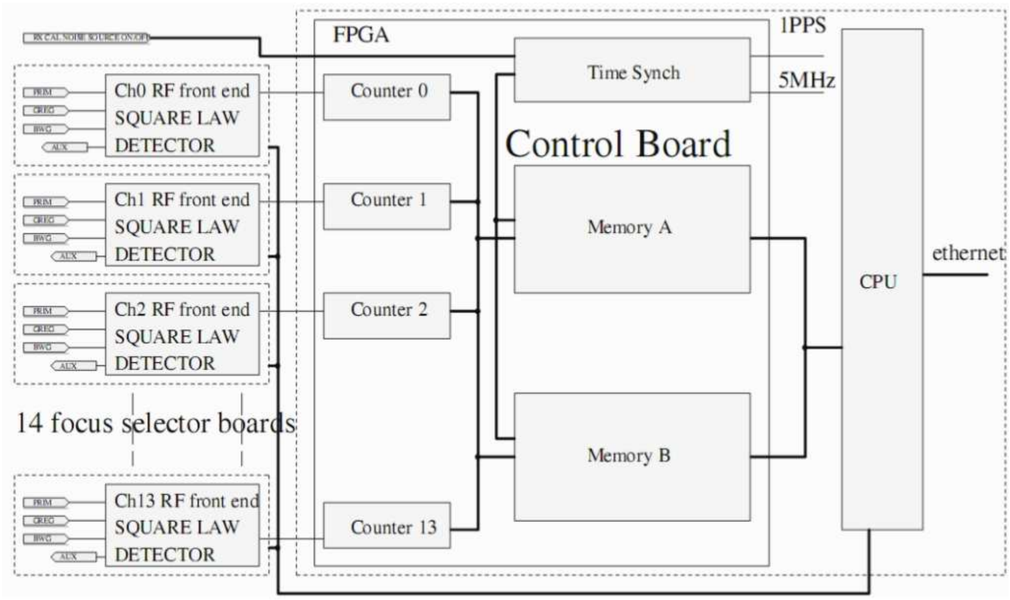

Fig. 2. Total Power.

all system is made up of 14 identical boards. Each board can manage three IFs from all three foci of the telescope. The selected signal can be attenuated (the allowed range is 0-15 dB) and thus filtered; afterwards, we can select one of the following low pass filters: 100-350 MHz, 100-830 MHz, 100-1300 MHz and, finally, 100-2100 MHz. The system provides three copies of the signal so as to employ them with the back-ends described in the next sections; another copy is sent to the Total Power back-end itself. Signals are sent to square law detectors, then are converted into digital format by voltage-to-frequency converters. An

FPGA-based controller contains the needed digital counters that count the pulses generated by the various voltage-to-frequency converters. Memory A and B are interchangeable: while one accumulates counts, the internal computer reads the previous acquisition data set from the other memory; they then switch roles. The integration time can be set from 1 ms to 0.5 sec. The back-end is entirely integrated in the ACS (ALMA Common Software)-based control software of Italian radio telescopes. It is important to underline that the Total Power back-end is currently the only back-end capable of performing on-the-fly (OTF) mapping for the multi-feed K-band receiver.

2.2. XARCOS

XARCOS (Comoretto et al. 2006) is a spectral-polarimeter developed by the Astrophysical Observatory of Arcetri. The system contains a total of 40 FPGAs and is capable of processing up to sixteen signals, each with 125 MHz of bandwidth, and of providing total power and spectral-polarimetric information. Figure 3 shows the back-end cabled(Melis et al. 2013) in the Elevation Equipment Room (EER) at SRT, while figure 4 shows a simplified block diagram (with just four inputs instead of 16).

The first stage is the amplification of the signal coming from the front-end system and, after a pass-band filtering (125 - 250 MHz range), signals are converted from analog to digital format by two ADC boards. Each ADC board has eight analog-to-digital converters operating in their second Nyquist window, therefore signals are base-band converted in the range 0-125 MHz. Once the data are in digital format, real signals are converted into complex-valued samples at a frequency of 125 MSample/s. The signals are then sent to the FFT boards, in which several variable decimating digital filters are implemented. Different values for the input bandwidth can be selected for each IF; available bandwidths are: 125 MHz, 62.5 MHz, 31.25 MHz, 15.625 MHz, 7.8125 MHz, 3.90625 MHz, 1.953125 MHz, 0.9765625 MHz and, finally, 0.48828125 MHz. Thus, an FFT spectral-polarimeter provides both spectral auto- and cross-correlation of the left and right polarizations; the number of available FFT channels is always 2048. Finally, four output signals (two auto-correlations and two cross-correlations) are integrated for a programmable time, which is a multiple of 10 seconds. The back-end is able to zoom in up to four sub-bands simultaneously. XARCOS is available both at Medicina and SRT, and is fully integrated (Melis et al. 2015) in the control software of the telescopes.

It is very important to emphasize that the FFT boards were designed for entirely different purposes, specifically for a system based on the ALMA tunable filterboard (Quartier et al. 2003). The boards were reconfigured for a totally different digital signal processing to develop XARCOS, an application for single dish telescopes. This demonstrates the versatility of the FPGA-based technology from all viewpoints.

2.3. Digital Base Band Converter

The Digital Base Band Converter (DBBC)(Tuccari et al. 2012) is a project which was developed by IRA Noto and consists of a reconfigurable modular data acquisition platform for radio astronomical applications; fig. 5 shows a block diagram of the DBBC.

It is mainly used as a VLBI (Very Long Baseline Interferometry) machine: almost all the stations of the EVN (European VLBI Network) employ a DBBC for VLBI observations. The DBBC has a flexible architecture with more FPGA-based boards that can be stacked together. One of the strengths of the DBBC is that is a complete platform: indeed, it contains a control personal computer, a synthesizer, a digital-to-analog board and, more generally, all that is necessary to make it an independent machine.

The adopted philosophy is the following: two boards are placed at the beginning and at the end of the stack; they are called FILA (FIrst-LAst) and provide signals to control and communicate with the stack. The LAst board is also used to send out the data via a VSI (VLBI Standard Interface) directly towards the

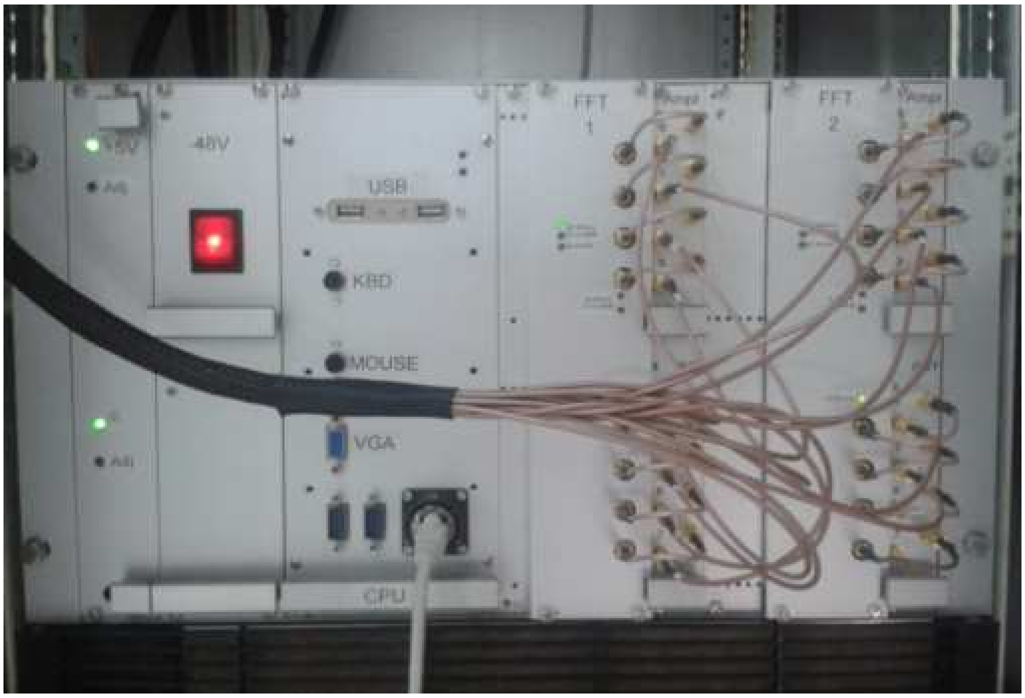

Fig. 3. XARCOS).

VLBI recorder (Mark5C in case of SRT) or to the "FILA10G" that converts the data into an optical format. Between the FIrst and LAst boards, a variable number (up to sixteen) of pairs of ADC-CORE2 boards can be stacked; in the case of SRT, 4 pairs of boards are employed. Each ADC module receives inputs from a COMO (COnditioning MOdule) analog board, which contains a set of the following filters: 10-512 MHz and 512-1024 MHz, corresponding to the first and second Nyquist zones; a 1.024 MHz clock is conventionally generated. Moreover, an isolation amplifier and a programmable attenuator are available. A High Speed Output (HSO) single differential 64 bit wide bus is generated by the CORE2 boards. The Control, Command and Monitor (CCM) bus is a bus used for control purposes. Finally, a JTAG interface is employed to program the FPGAs.

A 32 bit parallel interface is used to control both COMOs and the FPGA of the corresponding CORE2 board with a generic framework control (Melis et al. 2010). Essentially, the specific design in the FPGA is controlled by a string of 16 bit write registers, and its status is read using a set of 32 bit read registers.

Just like XARCOS, we wish to highlight how the re-usability of the FPGAs contained in the CORE2s lets us "transform" a machine designed as a VLBI terminal into a backend for single dish purposes. There are two main projects developed for the DBBC: a porting of an XARCOS channel and an innovative spectrometer based on a two-stage polyphase filterbank configuration. The former (Melis et al. 2009) is a wonderful example, because the original design was distributed among several FPGAs of different models, different vendors (Xilinx and Altera) and with different hardware description languages (VHDL and Verilog). Moreover, part of the code used specific libraries of the corresponding vendors, therefore the major effort was to render this code 100 % portable to any FPGA, creating components that were completely independent of

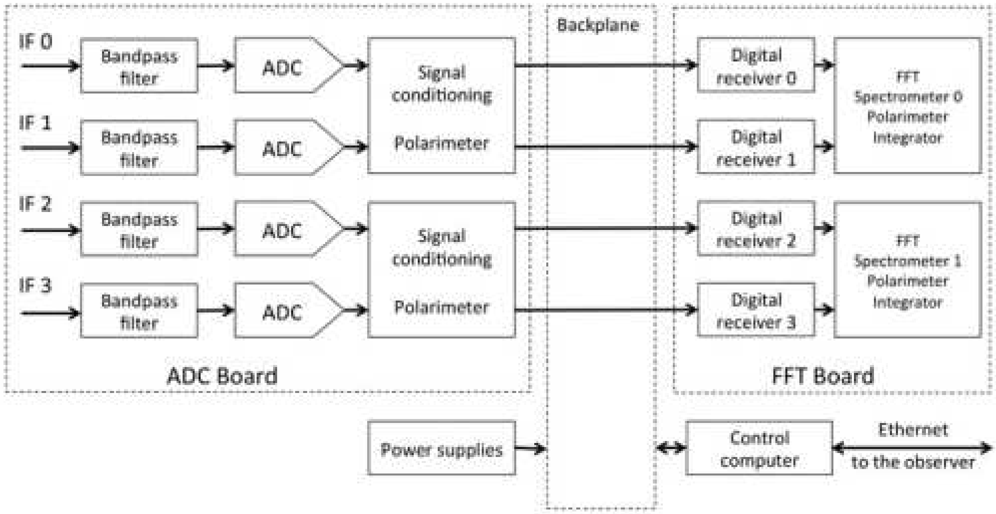

Fig. 4. XARCOS simplified block diagram (with 4 inputs instead of 14).

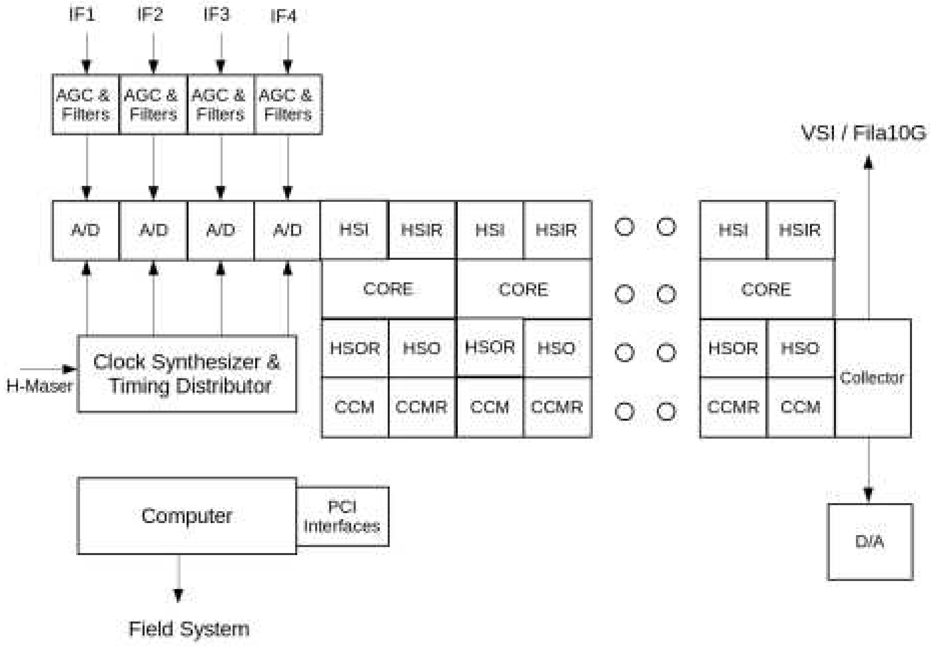

Fig. 5. DBBC architecture.

the system on which they are being implemented. The result is a design entirely written in VHDL code, implemented in a single Xilinx FPGA, for which each individual part can be exploited for any FPGA-based platform. The second project (Comoretto et al. 2011) follows the same logic: we have also employed part of the VHDL components to achieve an extremely strong spectrometer from an RFI point of view and used, at SRT, as an RFI monitoring system(Melis et al. 2014) outside of VLBI sessions. One of the future works is to exploit the full portability of this design to develop new generation wide-band high-resolution spectrometers.

2.4. Pulsar Digital Filter Bank

The Digital Filter Bank (DFB) is a digital back-end developed by CSIRO-ATNF (Australia Telescope National Facility) for either pulsar or spectropolarimetric (continuum and spectroscopy) observations; fig. 6 shows a picture of the platform. A full description can be found in (Hampson et al. 2008); here we report only its major characteristics.

The system is based on four 2048 MS/s 8-bit samplers to detect both polarizations of two frequency bands with a bandwidth of up to 1024 MHz. It provides full Stokes information of two receivers simultaneously.

The spectra are computed by FPGAs with polyphase filters which perform an isolation between neighboring channels that are higher than 60 dB. This prevents even strong in-band RFI from contaminating the other detected channels during an observation. A full set of configurations for pulsar and spectropolarimetric observations is available, although at SRT, it is currently used only for pulsar observations.

In pulsar folding mode, configurations with up to 2048 frequency channels and 2048 time bins are possible. In search mode, configurations with up to 1024 frequency channels and a time resolution down to 100 μs have been successfully used.

The Data Acquisition System SEADAS (Corongiu A. 2014) has been developed to manage pulsar observations with multiple back-ends, including the DFB.

The possibility provided by this back-end to simultaneously acquire data from two (coaxial) receivers is of great importance for a range of observing projects, for example those related to pulsar science. By means of their extremely stable rotation, millisecond pulsars (MSPs) can in fact be used as cosmic clocks for a variety of high-precision experiments. When in a binary system with another compact star, they represent unique laboratories for testing the predictions of General Relativity (and alternative theories) in the strong field regime (Stairs 2003, Living Rev. Relativity Vol 6, 5). Monitored as part of an array of precision cosmic clocks, they can serve as probes to measure the space-time distortions due to a passing gravitational wave (Foster & Backer 1990, ApJ, 361, 300). These kinds of experiments rely strongly on the possibility to accurately measure the times of arrival (and their perturbations) of the radio pulses from pulsars. To do so, one of the key ingredients is to account correctly for the effect of the dispersion delay of the radio signal in the interstellar medium, which is inversely proportional to the square of the observing frequency. Acquiring data simultaneously at two different frequencies allows us to measure this dispersion with a much higher precision than that achievable in one single receiver's band.

2.5. Reconfigurable Open Architecture and Computing Hardware

The Reconfigurable Open Architecture and Computing Hardware (ROACH, `https://casper.berkeley.edu/wiki/ROACH`) is a digital board developed by CASPER (Collaboration for Astronomy Signal Processing and Electronic Research, `https://casper.berkeley.edu/`). The centerpiece of the board is a Xilinx FPGA Virtex 5, while Z-DOK connectors, CX4 connectors and further features allow us to acquire, process and then send data for radio astronomical applications. A minimal PowerPC runs Linux and is used to interact with the FPGA and external devices through Ethernet. These boards have had great success due primarily to CASPER's efforts in simpli-

Fig. 6. *PDFB.*

Fig. 7. *ROACH at SRT.*

fying the design flow of radio astronomical instrumentation; the open source philosophy (both hardware and software) has always been the CASPER motto.

The ROACH board for SRT is equipped with an ADC 1024 Msample/s that allow either the processing of two 512-MHz bandwidth IFs or a single 1-GHz bandwidth IF. As shown in figure 7, the ROACH board at SRT is mainly employed for the Large European Array for Pulsars (LEAP) project. However, the same configuration can be used for other purposes: indeed, a lot of different personalities are being developed for every kind of scientific request. At present, the back-end is not fully integrated in the control software of SRT. For pulsar observations, this backend can be controlled by SEADAS.

2.5.1. Large European Array for Pulsars

The Large European Array for Pulsars (LEAP)(Bassa et al. 2016; Prandoni et al. 2014; Perrodin et al. 2016, 2014) project performs simultaneous observations of millisecond pulsars at five large European radio telescopes: the Lovell telescope at Jodrell Bank Observatory (UK), the Westerbork Synthesis Radio Telescope (Netherlands), the Effelsberg Telescope (Germany), the Nancay Radio Telescope (France) and the Sardinia Radio Telescope (Italy). This project is part of the European Pulsar Timing Array (EPTA)'s effort to directly detect gravitational waves from supermassive black hole binaries using an array of millisecond pulsars. Pulsars are observed simultaneously, therefore baseband data from each telescope can be added coherently in phase, which leads to a greater increase in the signal-to-noise of the observed pulsars. Observations with LEAP are equivalent to observing with a single dish of 196 meters in diameter, which is similar to the illuminated area of the Arecibo dish, but with a larger range of observable declinations. Observations are performed monthly and are 25 hours long.

At SRT, LEAP observations are made in L-band using the ROACH backend in baseband mode. The L-band receiver detects the two linear polarizations of the incoming electromagnetic waves in the 1300-1800 MHz frequency range, which are then mixed with a monochromatic signal generated by a synthesizer, and down-converted to an adequate frequency range. The signal is then sent to the DBBC and to the ROACH backends. The 10 MHz clock and 1 PPS provided by a maser allow the synchronization of the synthesizer contained in the DBBC; it provides the 1024 MHz sampling clock necessary for the analog-to-digital converters (ADCs) of both the DBBC and the ROACH.

The employed ROACH backend is identical to the ones used at Effelsberg and Jodrell Bank for LEAP. The analog-to-digital converters work at a sampling frequency of 1024 MS/s with an 8-bit representation, providing 512 MHz of bandwidth for each polarization. At SRT, the ADCs operate in the second Nyquist zone (512 - 1024 MHz). The ROACH produces 32 complex channels of 16 MHz each.

A CPU cluster enables the data acquisition from the ROACH backend in base-

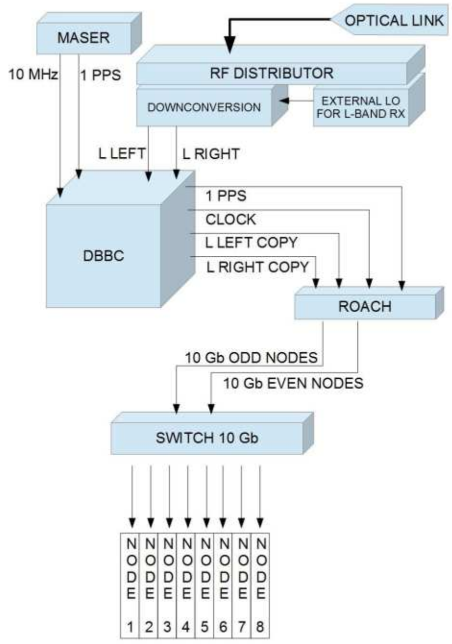

Fig. 8. *General setup (radio astronomical signal from antenna to computer cluster).*

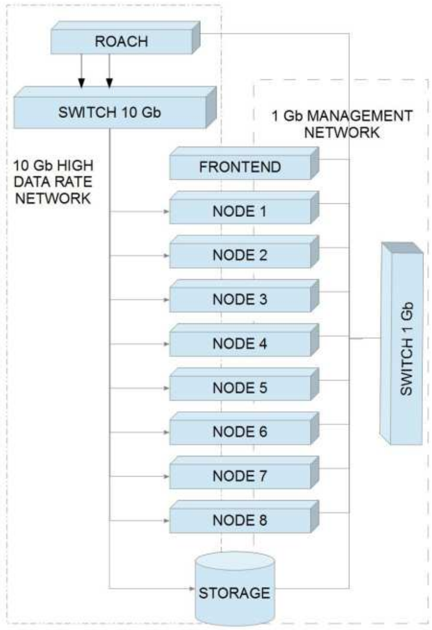

Fig. 9. *ROACH/cluster/storage system, composed by a Roach board and 8 CPU based computing nodes*

band mode using the PSRDADA software (psrdada.sourceforge.net) , covering the LEAP bandwidth (1332-1460 MHz) in 8 16-MHz sub-bands (one sub-band per node). The cluster is composed of 8 nodes and 1 management server (frontend or head node), with a dual-socket motherboard (G34). Each node is equipped with:

- 2 × AMD Opteron 8-core 6212 2.6 GHz CPUs (16 cores in total for each node)
- 64 GB of RAM (DDR3-1600)
- RAID: Adaptec 6805 SAS/SATA
- HDD: 4 × 2 TB
- LAN: 4 × 1 Gbe ports and 1 port dedicated to IPMI

In order to send data from the ROACH to the cluster, a 10 Gbe switch equipped with four CX4 connectors was installed.

Because of the high volume of data (64 MB/sec for each 16 MHz sub-band), each 25-hour run needs about 40 TB of space at each telescope. A storage cluster with a capacity of 96 TB was installed on-site to copy the data and later ship the disks to Jodrell Bank Observatory for correlating.

The general setup of the observing system (astronomical signal from antenna to ROACH and cluster) is illustrated in Figure 8, while the ROACH/cluster/storage system is illustrated in more detail in Figure 9. Figure 10 shows the plots of power vs. phase for the millisecond pulsar J1600-3053.

3. SARDARA

SARDARA (Melis et al. in prep. 2017) is the acronym for “SArdinia Roach2-based Digital Architecture for Radio Astronomy”. As mentioned in chapter 2, SRT is equipped with a variety of digital back-ends that are applicable to a significant breadth of radio astronomical studies. However, they each present strengths

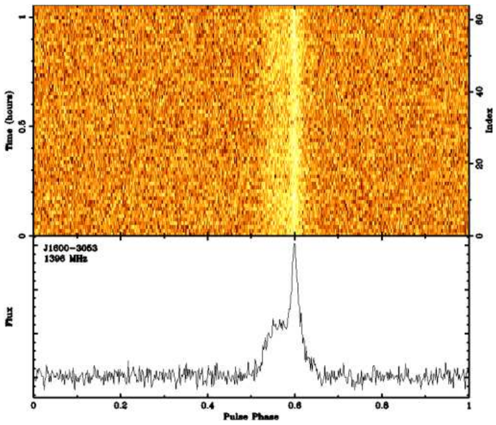

Fig. 10. *Pulsar J1600-3053 observed by the 5 telescopes of LEAP.*

and weaknesses: the Total Power backend is the only backend capable of providing the entire bandwidth (2.1 GHz) and all 14 IFs, but can be used solely for continuum observations; XARCOS can act as a full-Stokes spectrometer, but 125 MHz - reduced to half because of its far from optimal antialiasing filters - is the widest available bandwidth; the DFB can be used as a spectro-polarimeter as well and with a larger instantaneous bandwidth (1 GHz) than XARCOS, but the system is equipped with only 4 ADCs. As a consequence, we need an infrastructure that can overcome the aforementioned drawbacks. In particular, a possible optimal solution for SRT should provide up to 14 IFs, a bandwidth of (up to) 2.1 GHz and, more generally, an easier and quicker re-use for any scientific observing mode: this is what SARDARA offers. Figure 11 shows a block diagram of the system.

The ROACH2 boards are reconfigurable and suitable for the wide required bandwidth; additionally, we are part of CASPER, namely a consortium where the motto is "hardware and software are open source".

The system consists of seven ROACH2 boards equipped with two 5 GSample/s ADCs and mezzanine cards 10 Gbe SFP+. The eight outputs of the mezzanine cards are used to connect each ROACH2 board to all of the others and to a GPU-based PC, in which a dual-port SFP+ 10 Gbe is installed. A 24-port SFP+ 10 Gbe is employed to interface computers with a high-performance data storage unit. The idea is to create an architecture that is able to cover all possible scientific requirements that a single-dish radio telescope can satisfy: in particular, spectroscopy, spectral-polarimetry and pulsars. The first paper, published by using acquired data with SARDARA, is described here (Murgia et al. 2016).

4. Conclusions

In this paper, we provided an overview of the digital back-ends employed at SRT, as well as the ones under development. In the past, ad-hoc digital back-ends were usually developed for each particular scientific goal; however, although fully reconfigurable insofar FPGA-based, they very often do not keep up with the times, thus the central question was what could be done to change this trend. In order to overcome the aforementioned drawbacks, the SARDARA platform - described in chapter 3 - was born. It allows us to exploit the same reconfigurable hardware to cover all possible scientific requirements a single-dish radio telescope needs, and in particular: continuum, spectroscopy, polarimetry, pulsars, fast radio bursts, search for extraterrestrial intelligence programs, space debris mapping and so on. On the other hand, a porting of SARDARA will be done in the other two Italian radio telescopes: MEDARA for the 32-m diameter dish located in Medicina and NODARA for the 32-m diameter dish located in Noto a On the other hand, a porting of SARDARA will be done in the other two Italian radio telescopes: the 32-m diameter dish located in Medicina and the 32-m diameter dish located in Noto.

Acknowledgements. The development of the SARDARA back-end has been funded by the Autonomous Region of Sardinia (RAS) using resources from the Regional Law 7/2007 "Promotion of the scientific research and technological innovation in Sardinia" in the context of the research project CRP-49231 (year 2011): "High resolution sampling of the Universe in the radio band: an unprecedented instrument to understand the fundamental laws of nature" (P.I. of the project:

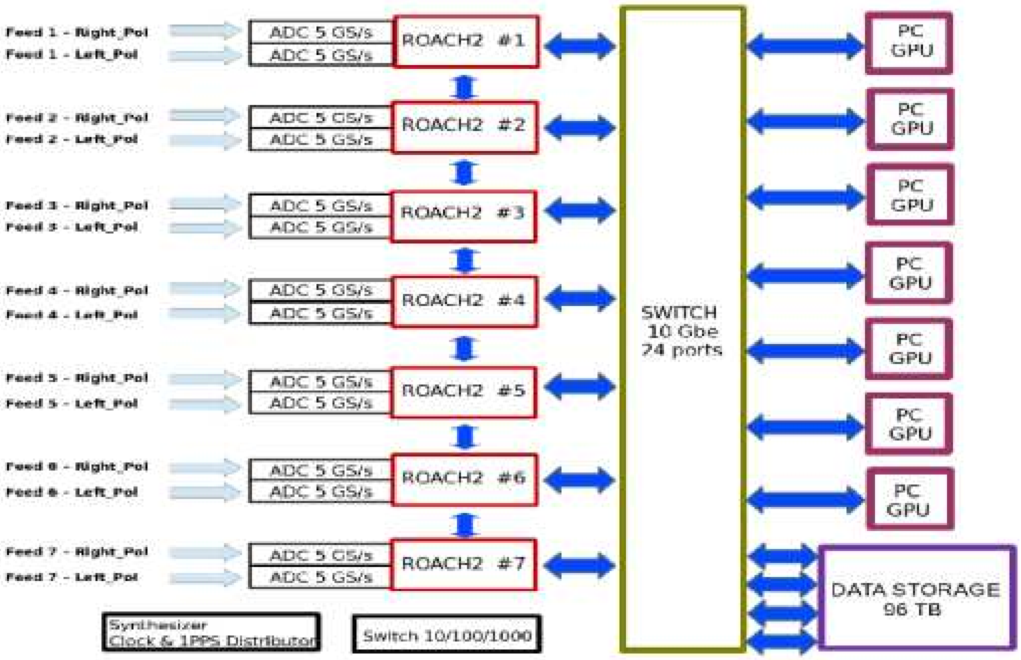

Fig. 11. SARDARA's block diagram.

Dr. Andrea Possenti). The implementation of the ROACH backend for LEAP was made possible thanks to an ERC-Advanced Grant, Grant agreement number 227947 (PI: Michael Kramer). The authors thank the enormous contributions of the Technical Commissioning and Scientific Validation teams in making this project possible.

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