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Sardinia Array Demonstrator:
Instrument Overview and Status

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Abstract – **In the framework of the Square Kilometer Array (SKA) project, the Italian Institute for Astrophysics (INAF) has addressed several efforts in the design and prototyping of aperture arrays for low-frequency radio astronomical research. The Sardinia Array Demonstrator (SAD) is a national project aimed to develop know-how in this area and to test different architectural technologies and calibration algorithms. SAD consists of 128 prototypical dual-polarized Vivaldi antennas designed to operate at radio frequencies below 650 MHz. The antennas will be deployed at the Sardinia Radio Telescope's site with a versatile approach able to provide two different array configurations: *(i)* all antennas grouped in one large station or *(ii)* spread among a core plus few satellite stations. This paper provides an overview of the SAD project from an instrumental point of view, and illustrates its status after 2 years from its start.**

1 INTRODUCTION

The world's largest radio telescope SKA (www.skatelescope.org) is now moving forward to its final pre-construction phase. The design of the 650 Meuro first phase of the SKA (SKA1) has been defined in March 2015 [1]. The project will consist of two complementary world-class instruments called SKA1-LOW and SKA1-MID to be built respectively in Australia and South Africa. Each instrument includes several elements, whose design has been assigned to different consortia.

The Aperture Array Design Consortium is responsible for the design of the Low Frequency Aperture Array (LFAA) element. This element represents the first part of the receiving chain (from the antennas to the digital beam-former) of the SKA1-LOW instrument. INAF plays a significant role in this consortium being involved in a wide range of interdisciplinary topics like array calibration, antenna characterization, analogue chain analysis, receiver design, photonic development and design, acquisition system design, mechanical rack design and firmware development.

In order to gain experience in LFAA technology, INAF has promoted two national technological research projects aimed at realizing Italian LFAA demonstrators constituted by Vivaldi antennas. The first instrument was the Medicina Array Demonstrator (MAD), a regular array composed of 9 dual-polarized Vivaldi antennas [2]. The activities on MAD were carried out in the period 2013-2014 and included the use of a hexacopter system for calibrating the array and characterizing the embedded antenna patterns [3].

Current efforts are focused on the second instrument called Sardinia Array Demonstrator [4]. SAD will offer more opportunities with respect to those given by the technological test-bench MAD. SAD will have indeed enough sensitivity and angular resolution to allow for some basic astronomical tests and demonstrative observations by using several different methodologies like beam-forming, interferometry and Earth rotation synthesis. Another important aspect of SAD is its timeline, which is well synchronized to the SKA project. The concept of SAD was proposed and funded in 2013, and its design took place in 2014. The demonstrator is now under construction and it is expected to be commissioned in early 2016.

This paper is organized as follows: Section 2 gives a technical overview of the SAD project. The hardware of the receiving chain is described in Section 3, whereas some experimental results, like the Radio Frequency Interference (RFI) monitoring and the calibration activities are discussed in Section 4. Finally, Section 5 presents the current status of the project and draws the conclusions.

2 TECHNICAL OVERVIEW

SAD is a 500 keuro project funded by the Regione Autonoma Sardegna and by INAF. It will be installed in the South of Sardinia in the premises of the Sardinia Radio Telescope (SRT) site, therefore exploiting the existing radio astronomical infrastructure (see Fig. 1).

The array will consists of 128 dual-polarized Vivaldi antennas [2,5] randomly spaced in a flexible configuration, with a maximum baseline around 250

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m. The front-end and the back-end of SAD will adopt similar configurations to those foreseen for SKA-LFAA. Even if the antenna and all the electronic components are designed to work up to 650 MHz, the SAD observing frequency band is selected between 270 and 420 MHz due to the radio spectrum environment at the SRT site.

The mechanical design of the antenna has privileged the capability of the antenna to be moved. As a consequence of this, SAD will have a large flexibility in the array configuration. Currently, two main deployment options are planned: 128 antennas distributed over a core of 64-m in diameter (called 1BIG) or 8 stations of 15-m in diameter with 16 antennas each (called 8SMALL). In this latter configuration, 4 stations will be located inside the core whereas the other 4 will be arranged in satellite stations. The first configuration is best suited for either all-sky imaging through cross-correlation of the array baselines, or for spectral lines and pulsar timing through array beam-forming. The 8SMALL solution, on the other hand, will allow deep imaging of bright discrete radio sources through Earth rotation synthesis. For this latter configuration, the synthetized antenna beam at 327 MHz is 15 arcmin with a sensitivity (with 16 MHz bandwidth, which represents a reference sub-band relatively free of artificial radio signals) of 80 mJy/beam (confusion limit in 1 hour).

Differently from SKA-LFAA, in SAD no metallic ground plane will be placed under the antennas. The best antenna polarization alignment is currently under investigation, the choice being between all antennas identically or randomly aligned. The latter solution is expected to improve the polarimetric performance [6].

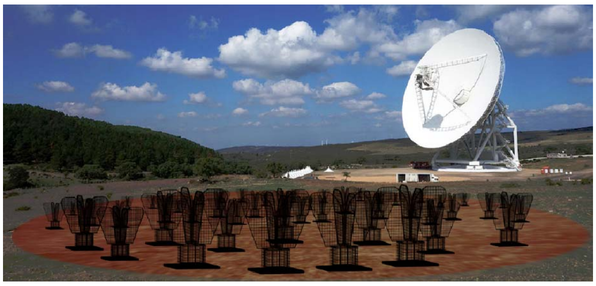

Figure 1: Artistic view of SAD with SRT in the background.

3 HARDWARE

The main elements of the SAD receiving chain, from the antennas to the digital signal processing, are described below.

3.1 Antenna

The antenna selected for SAD, called Vivaldi version 3.1 and sketched in Fig. 2, originates from the Vivaldi antenna proposed by the Italian team for SKA-LFAA. This last version, composed by a cubic cavity under the four wings, is optimized to improve the electromagnetic performance (enhanced directivity and reduced back lobe in order to improve the overall sensitivity) in the operating frequency range of SAD. The most significant modification in the version 3.1 concerns the mechanical layout. Such an antenna is based on a steel mesh (total weight of 16 Kg and dimension of 962x962x1370 mm), while the previous versions were solid antennas. The mesh solution has been chosen to reduce the wind resistance, which has been simulated (by Autodesk Simulation CFD) equal to 484 N with a wind speed of 130 Km/h (wind survival specification). Under the antenna, a concrete plate (composed by 4 tiles, 500x500x40 mm and 21 Kg each) will guarantee enough robustness and stability. Additionally, to keep the cost as low as possible the construction process of the antenna is entirely based on light carpentry.

The antenna is dual-polarized with 50 Ω unbalanced excitations by using two coaxial cables directly connected to the radiators. For each polarization, the inner part of the coaxial connector is attached to one wing. The external one is embedded in the opposite wing in order to prevent any coupled current on the cable. In this way, the balun is not necessary.

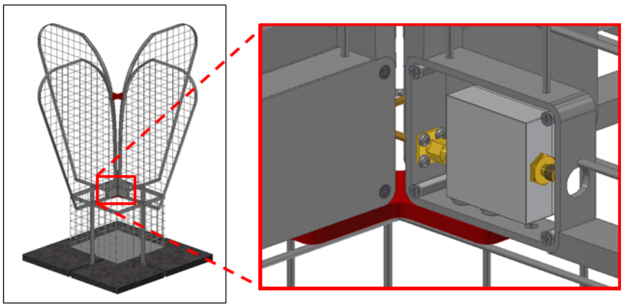

Figure 2: Mechanical design of the Vivaldi 3.1 antenna with detail of the LNA enclosure.

3.2 Low Noise Amplifier

The Low Noise Amplifier (LNA) has been designed by INAF-IRA for single-ended antennas operating in the SKA1-LOW band [7]. In the Vivaldi antenna, the LNA will be installed inside a metallic enclosure located in the bottom part of the antenna wings close to the probes (see Fig. 2). Even if each antenna includes two LNAs, one for each polarization, in order to maintain the antenna symmetry, the metallic enclosures have been placed in all four wings. The one-stage 50 Ω single-ended LNA is based on a MMIC amplifier SPF-5122Z with a total consumption below 200 mW (60 mA @ 3.3 V). The LNA is housed in a waterproof aluminum box with SMA connectors at both input and output. The LNA presents at the same time a noise figure below 30 K in the SAD operative band together with a high dynamic range in terms of both compression point (P1dB≥+18dBm) and IP3 (OIP3≥+30dBm). Since it will be powered through the coaxial cable attached to the output connectors, it is provided by a secondary overvoltages protection.

3.3 Receiver

SAD will make use of the same receiver under development by INAF for SKA-LFAA based on Radio Frequency over Fiber (RFoF) technology for the signal transportation. Therefore, two electrical-optical converters are accommodated under the metallic cavity at the bottom of the antenna. Due to the different operative scenario with respect to SKA-LFAA (RFI environment and antenna/LNA), SAD requires an extra RF board in front of the optical transmitters. Such a board will provide: *(i)* the right RF band shaping for attenuating the strong RFI and *(ii)* an extra gain block for increasing the overall RF gain in front of the optical transmitter.

The 128 links from the antennas to the cabinets will be provided by hybrid cables. Each of them will house a single mode optical fibre (G652.D) for the transport of both polarizations of the received RF signal exploiting the Wavelength Division Multiplexing (WDM) technique. In addition, through the same hybrid cable, the DC power supply for the antenna electronics will be provided. This will be done housing inside the hybrid cable a copper twisted cable or, in few cases, an additional multimode optical fiber and using the Power over Fibre technique [8]. This latter technology will allow to compare the array behavior with and without copper cabling in terms of reliability and antenna/array performance (array pattern and antenna mutual coupling).

Finally, the optical signals are routed to the SRT’s infrastructure where they are converted back to RF and further conditioned by the Rx boards. Each Rx board receives 16 signals (8 antennas x 2 polarizations) and is conceived to be directly packed, together with a second Rx, with a digital board called Analogue to Digital (ADU) board, where digitization and first digital processing will happen (see Fig. 3).

Preliminary measurements have been carried out on the first prototypes for both WDM optical links and Rx boards showing good results. In spite of the high level of electronics integration, a high RF isolation among the RF channels (>40 dB in the WDM modules and >60 dB on the Rx board) has been obtained.

3.4 Back-end

The back-end digital module ADU consists of a board based on the latest 20 nm FPGA technology, the Xilinx Kintex Ultrascale (x2). The module has 32 input signals with 50 – 350 MHz bandwidth (expandable to 350 – 650 MHz) sampled by 16 dual input Analog Device AD9680 analog to digital converters and transmitted via the high speed JESD204B serial interface to the FPGAs. The onboard firmware performs the channelization, the phase and amplitude calibration and the tile beam-forming of each polarization. Two 40 Gb/sec QSFP+ links connect the back-end with the data post-processing infrastructure.

The ADU has been entirely designed, built, tested and optimized in Italy and it has been proposed for a possible usage in SKA-LFAA.

The ADC sampling rate for SAD will be 1000 MHz with a sampling precision of 8 bit and a frequency resolution around 977 KHz (which can improve in later processing).

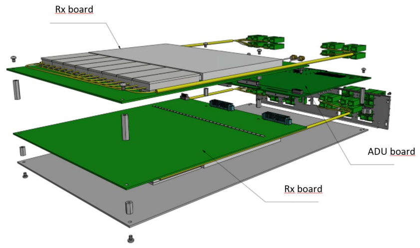

Figure 3: Rx and ADU boards mechanical assembly. A maximum of 32 complete receiver chains are housed in only 6U and 10HP.

4 EXPERIMENTAL ACTIVITIES

4.1 RFI monitoring measurements

An intensive RFI monitoring campaign was conducted in 2014 at the SRT site. This was mainly aimed to: *(i)* verify the statistical spectral occupancy below 500 MHz to identify the portion of the radio spectrum least polluted by other services, and *(ii)* characterize the power levels of the strongest signals (broadcast FM radio, services radio links) to accurately design the receiver chain especially in terms of microwave filters.

The campaign was performed with an automatic acquisition system based on a Vivaldi antenna version 2.0 connected to a spectrum analyzer. In Fig. 4 we report the narrow-band (10 KHz resolution bandwidth) max-hold (10 minutes long) spectra measured separately for the two antenna polarizations which were roughly oriented to the North-South and West-East directions.

The RFI scenario is such that no radio frequency filters are required in front of the LNA. Additionally, the 270 – 420 MHz spectral window turned out to be the best suited for astronomical observations. The SAD band includes the one covered by the P-band receiver installed in SRT (305 – 410 MHz) permitting further interesting applications as interferometry observations between the two systems.

4.2 Array calibration

The array calibration and characterization will be a fundamental step in setting up the instrument. The strategy to be adopted to calibrate the array is currently under investigation. However, it will be based on a combination of both artificial and natural radio-sources for calibrating the instrumental and the atmospherics errors respectively.

In this context, we will intensively use a custom hexacopter based on a GPS-board Mikrokopter and equipped with a CW transmitting antenna [9] successfully tested in MAD [3]. It allows measurements in real operative conditions: far-field antenna patterns, arrays (instrumental) calibration, as well as other applications such as checking the element integrity and measuring the antenna orientation and position. Meanwhile, several improvements of this system have been planned, such as allowing large bandwidth calibration and phase pattern characterization.

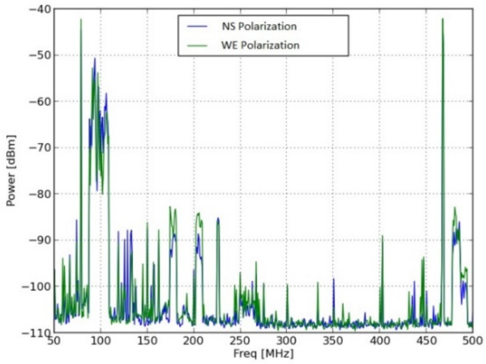

Figure 4: Spectra acquired for the North-South and West-East antenna polarizations at the SRT site.

5 STATUS OF THE PROJECT AND CONCLUSIONS

The tender for the production of 150 antennas (including spare antennas) has been concluded in March 2015. The Sardinian company Termomeccanica Energia was selected for the construction of the antennas at a best cost of 300 euro/antenna. The company will produce a first sample, which will go through preliminary acceptance tests based on mechanical and electromagnetic analysis. If the sample behaves as expected, the company will proceed with the mass production. The antennas are expected to be deployed at the site in October 2015. Currently, the excavation at the site is in progress to flat the station ground and to dig the cable ducts.

Once completed, the Sardinia Array Demonstrator will be the first Italian technological and scientific LFAA test-bed to prove crucial concepts, algorithms and techniques for digital beam-forming, data transportation/acquisition, calibration, imaging, and Radio Frequency Interference mitigation.

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Further financial resources for SAD come from INAF through two TECNO INAF projects entitled “Digital Platform development for back end design of new generation SKA Aperture Arrays” (PI F. Schillirò) and “Advanced calibration techniques for next generation low-frequency radio astronomical arrays” (PI P. Bolli) funded in 2012 and 2014 respectively.

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