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R&D AT NANÇAY FOR RADIO ASTRONOMY DETECTORS AND SYSTEMS

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Abstract. Nançay radio astronomy station teams are involved in several aspects of the Research and Development (R&D) for radio astronomy detectors and systems:
i) Microelectronics: Low Noise Amplifiers (LNA), receiver on chip and system in package. The long-term goal is to provide sub-systems for the future Square Kilometer Array and its Pathfinders. A beamformer chip has been integrated in the FP6 SKADS dense aperture array technology demonstrator EMBRACE. Wide band SiGe LNAs are developed, beamformers with in-chip control are studied and more complex integrated receivers are designed for the european Aperture Array Verification Programme demonstrator.
ii) Digital signal processing: EMBRACE beamforming has been implemented in the digital backend and RFI-mitigation oriented signal processing has been designed for realtime systems, including work for FP6 SKADS and FP7 PrepSKA.
iii) A study of Phased Array Feeds has started in 2008, in order to study the radio electric properties of PAFs at the focus of large F/D telescopes, such as the Nançay Radio Telescope, as well as to test PAF systems in collaboration with the SPP/IRFU and LAL/IN2P3 laboratories.

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1 Introduction

The Nançay radio astronomy station is a scientific department (the Unité Scientifique de Nançay) of Paris Observatory, and it is also associated to the CNRS (the French National Scientific Research Council) as the “Unite de Service et de Recherche B704”. It also belongs to the “Observatoire des Sciences de L’Univers en Région Centre”. The Nançay station hosts 3 main radio astronomical facilities (the large decimetric radio telescope, the radioheliograph and the decameter array), and several smaller instruments. The technical teams are mainly involved in projects dedicated to radio astronomy and in particular, the Nançay station will host a Square Kilometre Array dense aperture array technology demonstrator (SKADS EMBRACE, see SKADS 2009) and a LOFAR station (LOFAR 2009). The station is also involved in several other research and development (R&D) projects (Nançay 2009). In the following sections, we present some results on microelectronic circuit development for the new generation of giant radio telescopes, and in the domain of signal processing.

2 Microelectronics R&D

2.1 Integrated Low Noise Amplifiers

A number of integrated low noise amplifiers have been designed using SiGe technologies, for the frequency band 300–2000 MHz. All these designs are to be used at ambient temperature (no cooling system – all noise factors given for ambiant temperature):

In 0.35 μm SiGe (AMS): Input and ouput single ended, 50 Ohms matching: Measured Noise Factor of 1.3 dB at 2GHz.

In 0.25 μm SiGe (NXP): Input and output differential, 100 Ohms matching: Measured Noise Factor of 1.1 dB at 2GHz.

In 0.25 μm SiGeC (NXP): Input and output single ended, 50 Ohms matching: Measured Noise Factor of 0.82 dB (or 60 K) at 1.0 GHz.

In 0.25 μm SiGeC (NXP): Cascode topology, input and output single ended, 50 Ohms matching: Measured Noise Factor of 1 dB at 1.5 GHz.

A recent design is presented in figure 1.

2.2 Beam Former for European SKA Dense Aperture Array Demonstrators

Using arrays of antenna elements, an RF beam can be synthetized in one celestial direction by appropriately phase shifting signals from all antenna elements in the array and summing them. We designed an RF beamformer chip in the 500–1500 MHz frequency band, phase shifting and summing signals from 4 antenna elements, for 2 independent RF beams outputs. Using 0.25 μm SiGe technology, this chip has a silicon area of 5.2 mm^2 and dissipates 1.1 W. 8 phase shifts steps (45° steps up to 360°) are available for each RF beam, together with 8 gain steps

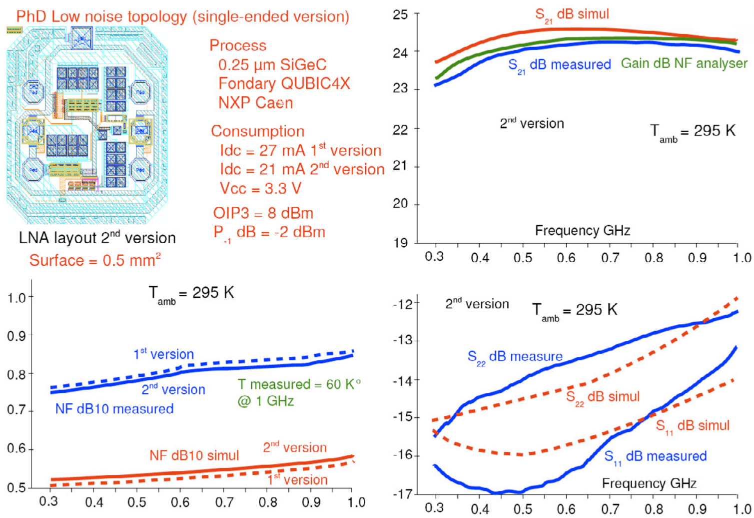

Fig. 1. Nançay design of a low noise amplifier for the lower frequency band 300–1000 MHz, which is expected for the planned european *Aperture Array Verification Programme* scientific demonstrator of dense aperture arrays for the SKA.

(for a max. total gain correction of 5 dB). This chip is used in the EMBRACE dense aperture array technology demonstrator project of the EC-funded SKA Design Studies, SKADS, and future, more complex versions will be implemented in the next european demonstrator, the Aperture Array Verification Programme (Bosse *et al.* 2008; AAVP 2009). Figure 2 shows the beam former chip integrated on the back of one of the EMBRACE tiles.

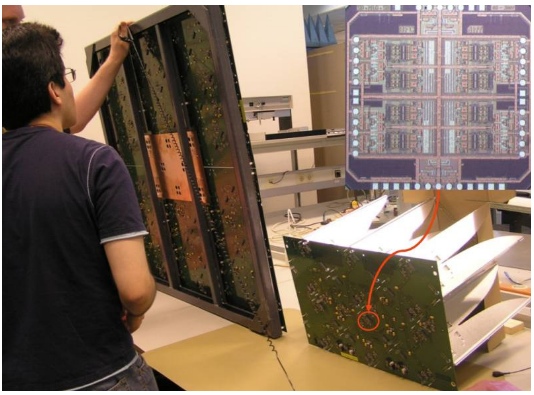

Fig. 2. The beam former chip developed by the Nançay microelectronics group integrated on the back of one of the EMBRACE tiles, with the densely packed Vivaldi antennas on the reverse side. The tile is about one square metre in size.

2.3 PICS Technologies

In the framework of SKADS, whose objectives include the realisation of very compact electronic systems, a technology proposed by NXP Semiconductors has been evaluated (see Grima 2007) – PICS stands for Passive Integration Connecting Substrate. It is a passive technology, which can be used as interconnection substrate to assembly the active dies by bumps and forms this way a SiP (System in Package). But it is also a technology, which can be used to design passive filters.

We used PICS to realize a band-pass filter and to interconnect active dies in order to obtain an heterodyne integrated receiver composed of a LNA, the filter and a mixer. Figure 3 shows the cross-section picture of the desired SiP and the photograph of the SiP that was realized.

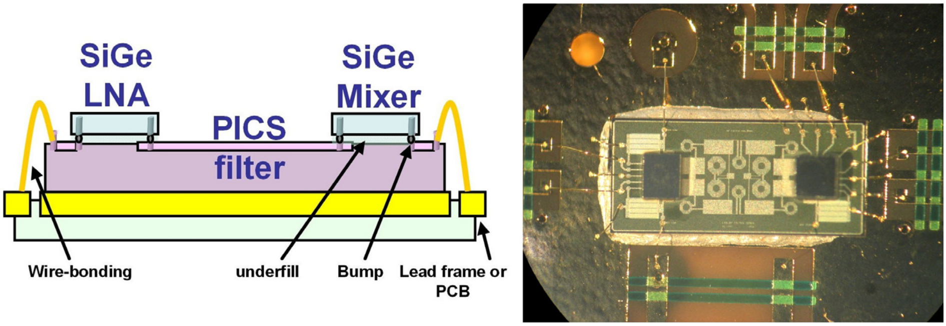

Fig. 3. *Left*: cross-section of the SiP developed using PICS technology: the underfill is a non-conductive adhesive, which connects the whole surface of the active die to the substrate. It protects the inter-connection area from moisture, consolidates mechanical connections and improves thermal dissipation. *Right*: photograph of the SiP. Substrate dimensions: 5.2 mm × 2.3 mm.

As can be seen in Figure 3, in a SiP the active dies are upside down onto a substrate to directly connect pads by means of conductive bumps. This technique of assembly is called flip-chip. As the inter-chip connections are no longer formed by wire bonds or lines of a board, the effects induced by those are reduced and the performances improved. In the first SiP that was realized only the LNA is flipped onto the PICS susbtrate, and it was measured by means of a probe station and a 4-port VNA. Figure 4 shows that the measurement results are in close agreement with the simulations.

Measurements of the complete SiP (LNA-filter-mixer) have shown equally good results, close to the simulation expectations. The validation of both PICS technology and the flip-chip technique have therefore demonstrated that this process is reliable and viable, and that it can be used to design a System in Package for projects where a huge number of elements are needed (such as the SKA).

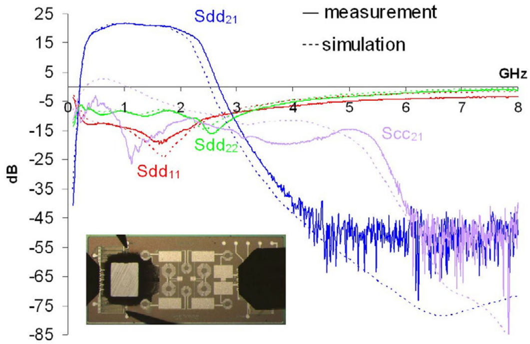

Fig. 4. SiP (LNA-filter) under test and its measurement results. Sdd21: differential mode gain; Scc21: common mode gain; Sdd11, Sdd22: input & output matching.

3 Signal Processing

3.1 EMBRACE Backend

The EMBRACE demonstrator is a dense aperture array radio telescopes operating in the 500–1500 MHz frequency band. Vivaldi antenna elements are used as front ends in a dense array configuration, with 72 elements for each 1.06×1.06 m tile. The EMBRACE demonstrator that will be implanted at Nançay will consist of 80 such tiles. Each tile delivers two independent RF beams made by two independent phased sums of signals coming from all elements in the tile.

An heterodyne RF receiver delivers IF (100–200 MHz) signals. The EMBRACE backend digitizes up to 288 IF (12 bits, 200 Ms/s) and applies digital beamforming algorithms to deliver up to 200 digital beams for each of the two RF beams (see Fig. 5). The hardware platform for signal processing makes intensive use of dense FPGAs. Main signal processing functions are polyphase filters and digital phase shifters.

3.2 Radio Frequency Interference Real-Time Cancellation

Radio astronomical observations have always had to deal with Radio Frequency Interference (RFI). Sensitive radio astronomical observations of faint cosmic sources are susceptible to distortions due to close –and therefore relatively strong– radio emissions from other users of the radio spectrum, such as telecommunication services. Furthermore, many physical phenomena that astronomers want to study (such as Doppler-shifted line emissions from distant galaxies) occur in frequency bands which are not allocated to radio astronomy. As a consequence, our observations often need to be made in highly corrupted environments.

Classical radio observations are made possible when avoidance schemes can be used. If not, digital signal processing aimed at RFI-mitigation can be used. Many research groups work throughout the world on this subject, providing more or less

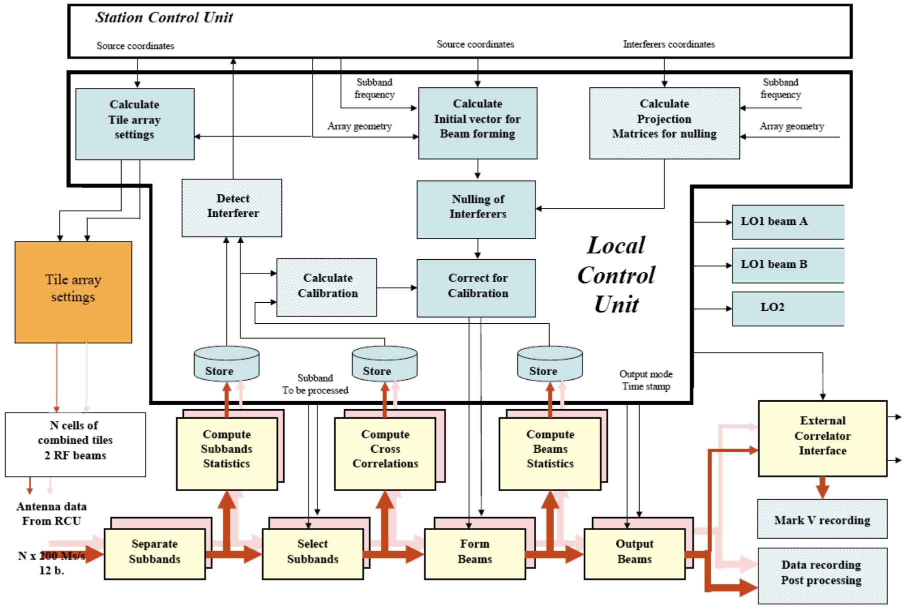

Fig. 5. An EMBRACE backend. Based on a LOFAR backend, the system has been reconfigured and the command and control system have been adapted for the EMBRACE design by the Nançay team.

advanced algorithms to suppress RFIs (see *e.g.*, Fridman 2001; Ellington 2002; Dong *et al.* 2004; Boonstra 2005).

At Nançay, practical implementations for daily observations have been developed, such as real-time power detector based blanking systems (Dumez-Viou 2007) that perform a statistical analysis of the observed noise and then used the measured parameters for thresholding (Weber *et al.* 2005) in order to provide clean spectra (see Fig. 6).

Cyclostationary detector are currently tested on hardware platforms, including developments for SKADS. Cyclostationary signals belong to a class of non-stationary signals whose statistics evolves periodically as function of time. Such signals are very common in digital modulations of telecommunication signals where the cyclic period is closely related to the symbol rate. They can be detected even if they are buried within the noise (Weber *et al.* 2007, see Fig. 7). Implementation in FPGAs is in progress. Tests will be done with the Nançay decametric and decimetric radio telescopes.

All the projects which include radio frequency mitigation capabilities are developed in collaboration with the Orléans University PRISME laboratory. Among these projects, an R&D study has been done for the FASR (Frequency Agile Solar Radio telescope) project. A 2 elements interferometer has been build. It has a 50 MHz bandwidth, 14 bits dynamics, and a 12.5 KHz frequency resolution

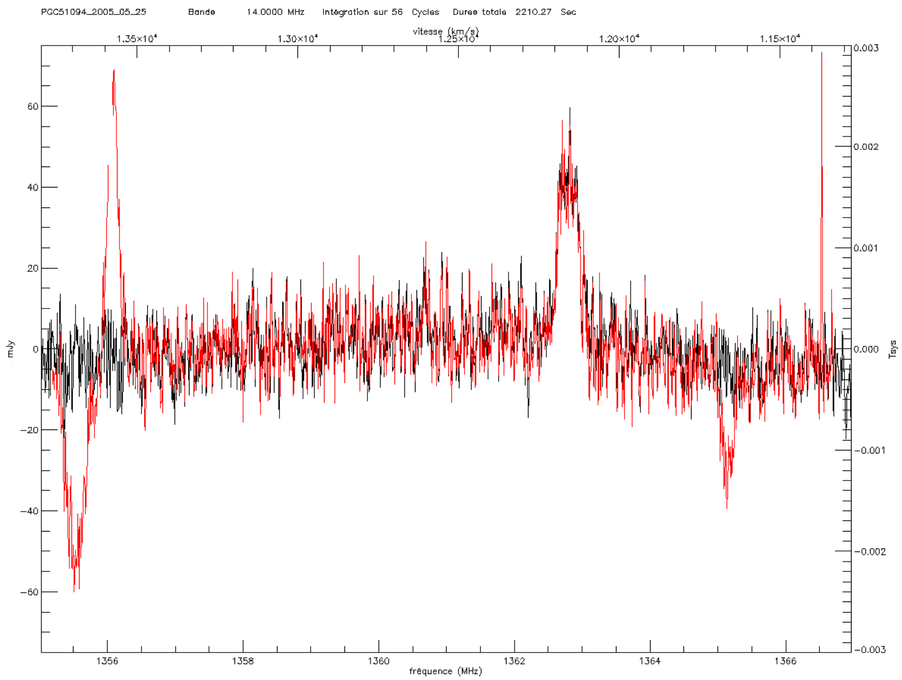

Fig. 6. Example of a real-time RFI mitigation system implemented at the Nançay Radio Telescope: redshifted 21-cm HI line of the galaxy PGC 51094 with (black) and without (red) radar blanking.

obtained with a 2 stages polyphase filter. A software correlator computes clean visibilities on a 1.5 MHz bandwidth, and allows the study of various RFI detection algorithms, in order to test their compatibility with solar radio bursts.

4 Phased Array Feed Study

The NRT is one of the three 100-m class single-dish radio telescopes in the world; only the 305-m Arecibo radio telescope (USA) is significantly larger. In practice, it has proven to be an instrument perfectly suited for very large and/or long-term monitoring or survey programmes. New observational techniques, and new scientific needs for large blind surveys have emerged in the recent years, which need large feld-of-view capabilities. The NRT has a unique spherical mirror and off-axis focus, with an also uniquely large F/D ratio. This means that this instrument could be operated with a multibeam Phased Array Feed focal receiver system, and is perfectly suited for R&D studies of these systems. The FAN (Focal Array at Nançay) project is a R&D study of a full 1 beam receiver, based on the dense aperture array detectors designed for the EMBRACE prototype, and on receivers developed in the context of a Paris Observatory (Nançay, Meudon)–IN2P3

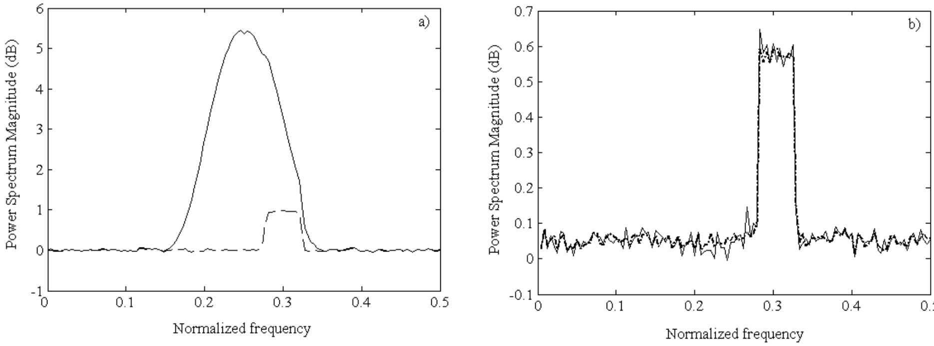

Fig. 7. Simulation with a continuous spread spectrum emission. a) Spectrum estimated without cyclic cancellation. The position of the simulated cosmic source is drawn as a dashed line – it cannot be detected through classical spectral analysis. b) Spectrum estimated with cyclic cancellation. The dashed profile is the expected one (Bretteil 2005).

(Orsay)–CEA (Saclay) collaboration. This project will use the LNAs designed by the Nançay microelectronics team.

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