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The SRT in the Context of European Networks: Astronomical Validation & Future Perspectives

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The Sardinia Radio Telescope (SRT) is the new 64-m dish operated by INAF (Italy). Its active surface, made of 1,008 separate aluminium panels supported by electromechanical actuators, will allow us to observe up to frequencies of $\sim$ 100 GHz. For its first light, three receivers (one per focal position) were installed and tested: a 7-beam K-band receiver, a mono-feed C-band receiver and a coaxial dual-feed L-P band receiver. The SRT officially opened in September 2013 upon completion of the technical commissioning phase. Post-commissioning activities are in a highly advanced status. The integration and optimization of the telescope sub-systems (*fine-tuning*) are completed, and the *Astronomical Validation* is well under way. This paper presents the current status of ongoing activities, aimed at transforming a powerful technological instrument into a real radio-astronomical facility. Particular emphasis will be given to the work done to test and validate the use of the SRT as part of VLBI and pulsar timing networks. We now consider the SRT to be fully validated for European VLBI Network (EVN) observations. In addition, since early 2015, the SRT is participating in EVN observing runs in *shared-risk mode*.

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1. Introduction

The Sardinia Radio Telescope (SRT) is a new general purpose, fully steerable 64-m diameter parabolic radio telescope capable of operating with high efficiency in the 0.3-116 GHz frequency range. The instrument is the result of a scientific and technical collaboration among three research centers of the Italian National Institute for Astrophysics (INAF): the Institute of Radio Astronomy (IRA), the Cagliari Astronomy Observatory (OA Cagliari), and the Arcetri Astrophysical Observatory (OA Arcetri). Funding agencies are the Italian Ministry of Education and Scientific Research (MIUR), the Sardinia Regional Government, and the Italian Space Agency (ASI).

The SRT is located in the plain of Pranu Sanguni, 35 km north of Cagliari. The manufacturing of its mechanical parts and their on-site assembly was commissioned in 2003 and completed in mid 2012. The SRT has a shaped Gregorian optical configuration with a 7.9 m diameter secondary mirror and supplementary Beam-WaveGuide (BWG) mirrors. With six possible focal positions (primary, Gregorian, and four BWGs), the SRT will be able to allocate up to 20 remotely controllable receivers. One of the most advanced technical features of the SRT is its active surface: the primary mirror is composed of $1,008$ panels supported by electromechanical actuators that are digitally controlled to compensate for gravitational deformations.

In its first light configuration, the SRT is equipped with three receivers: a 7-beam K-band receiver (Gregorian focus, Orfei et al. 2010), a mono-feed 5cm (5.7-7.7 GHz) receiver (BWG focus) and a coaxial dual-feed L-P band receiver (primary focus, Valente et al. 2010). A mono-feed 90 GHz receiver is also available and will be mounted at the telescope as soon as the active surface will be fully implemented (close loop). C-band, S-band (Valente et al. 2014) and Q-band receivers are currently under development. The suite of backends currently available on site includes:

1. the commissioning backend, a *Total Power* (TP) with a maximum instantaneous bandwidth of 2 GHz and 7×2 input channels to match the 7-beam 2 polarization K-band receiver outputs;

2. a narrow band spectro-polarimeter with 8x2 input channels (XARCOS);

3. the *Digital Base Band Converter* (DBBC), a digital wide-band (four 1 GHz Boards) spectro-polarimeter mainly designed for VLBI observations;

4. the *Digital Filter Bank Mark 3* (DFB3), an FX correlator developed by the Australia Telescope National Facility, suitable for precise pulsar timing and search, spectral line and continuum observations with high time resolution;

5. a ROACH FPGA[1] board providing 32 complex channels of 16 MHz each (total bandwidth 512 MHz), mainly designed for pulsar observations in the context of LEAP (Large European Array for Pulsars) and EPTA (European Pulsar Timing Array).

The antenna was officially opened on September 30th 2013, upon completion of the technical commissioning phase (Bolli et al. 2015). The SRT will be used for astronomy, geodesy and space

[1] Reconfigurable Open Architecture Computing Hardware (ROACH) FPGA board developed by the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) group; http://casper.berkeley.edu

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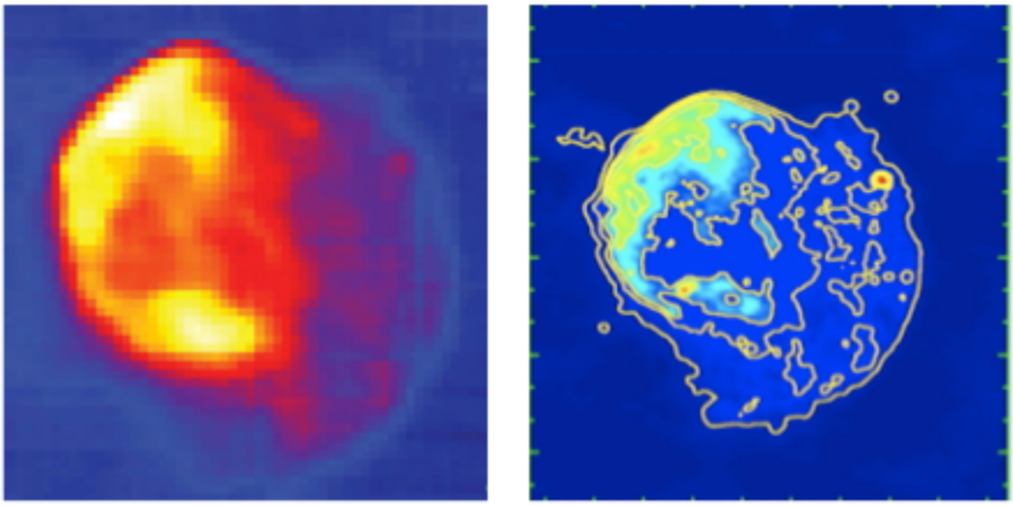

Figure 1: *Left:* Total Power C-Band (7 GHz) continuum image of SNR 3C 157, produced with the ad-hoc SDI software developed for Single-Dish OTF scan observations. Spatial Resolution: 2.8 arcmin. *Right:* Same source observed with the VLA interferometer at 330 MHz at a factor ~ 2 better resolution (64" $\times$ 74"). From Hewitt et al. 2006.

science, both as a single dish and as part of European networks. This paper briefly discusses the first results of the *Astronomical Validation* (AV) activity, aimed at validating the telescope for standard observing modes and at transforming the SRT from a technological project into a real general-purpose astronomical observatory (for more details we refer to Prandoni et al. 2015, in preparation). This paper focuses on the validation of the SRT in the framework of VLBI (Very Long Baseline Interferometry) and pulsar timing array observations.

2. The SRT as an astronomical observatory

The telescope is managed by means of a dedicated control software, called *Nuraghe*, developed in the ALMA Common Software (ACS) framework (Orlati et al. 2012). Nuraghe controls the mount and minor servo motions (Buttu et al. 2012), the frontend setup and the data acquisition performed with the TP and XARCOS backends, producing standard FITS output files (MBFITS is foreseen to be available in the near future). The other backends can be managed in semi-integrated or external modes. The user interface allows the real-time monitoring of all of the telescope devices. Automatic procedures let the user easily carry out essential operations like *skydip* scanning, focusing, and pointing calibration. Nuraghe supports observing modes such as sidereal tracking, ON-OFF, On-The-Fly (OTF) cross-scans and mapping (in Equatorial, Galactic and Horizontal coordinate frames).

The AV included a preparatory phase that was carried out during the commissioning of the telescope, in which several external software tools were developed in order to support the observers in the preparation and execution of the observations, as well as in the data inspection and reduction. In the following, we provide an initial list of the tools currently available to SRT observers. For details and updates we refer to the SRT web site (`http://www.srt.inaf.it`):

- ETC: Exposure Time Calculator (Zanichelli et al., in prep.)
- CASTIA: Source Visibility Tool (Vacca et al. 2013)
- ScheduleCreator: tool that produces properly formatted schedules for Nuraghe, for all available observing modes (Bartolini et al. 2013)
- Meteo forecasting: a tool that allows dynamic scheduling 12/24 hours in advance (Buffa et al., in prep.)
- FITS Quick Look: quasi real-time display of both mono-feed and multi-feed FITS TP data (Righini et al. in prep.)
- RFI Monitoring: piggy-back RFI monitoring system using the DBBC, during observations with other backends (Melis et al. 2014)
- RFI Detection pipeline: tool that produces waterfall plots from the DBBC spectra acquired during RFI monitoring (Ricci et al. in prep.)
- OSCAR: data reduction software able to integrate and calibrate continuum cross-scans acquired on point-like sources (based on software originally developed for the Simultaneous Medicina-Planck Experiment, Procopio P., et al. 2011)
- SDI: SRT Single-Dish Imager, a data reduction software package that allows us to produce images from SRT OTF scans obtained with either mono- and multi-feed SRT receivers (Pellizzoni et al., in prep.). A 7 GHz image of the extended SNR source 3C157 obtained at SRT in June 2014 is shown as an example in Figure 1.
- Output file converters: a number of tools that allow us to convert the SRT FITS output files to formats that can be read by standard data reduction packages (GILDAS, etc.)

In addition to developing software tools, a list of sources is being monitored at the SRT as part of the AV activities. These observations are aimed at validating such sources as pointing and/or flux calibrators at the SRT.

3. Astronomical Validation of the SRT

The AV is organized in steps, from basic tests aimed at verifying the general performance and/or the limits of the telescope and the acquisition systems, to more complex acquisitions aimed at assessing the actual SRT capabilities for typical scientific observations. Examples of the former are: the verification of the backend linearity range, the verification of the On-The-Fly (OTF) scan pointing accuracy and maximum exploitable speed, the verification of the gain curves for the various receivers/backends, the measurement of the confusion noise (see e.g. Fig. 2, left) and an accurate characterization of the beam sidelobes (see e.g. Fig. 2, right). Examples of the latter are continuum and/or spectroscopic acquisitions, including mapping of extended sources (see e.g. Fig. 1), pulsar timing, etc. The validation of the SRT in *single-dish* operation mode is well under way and the first results are reported in detail in Prandoni et al. (in prep.). In parallel, we do

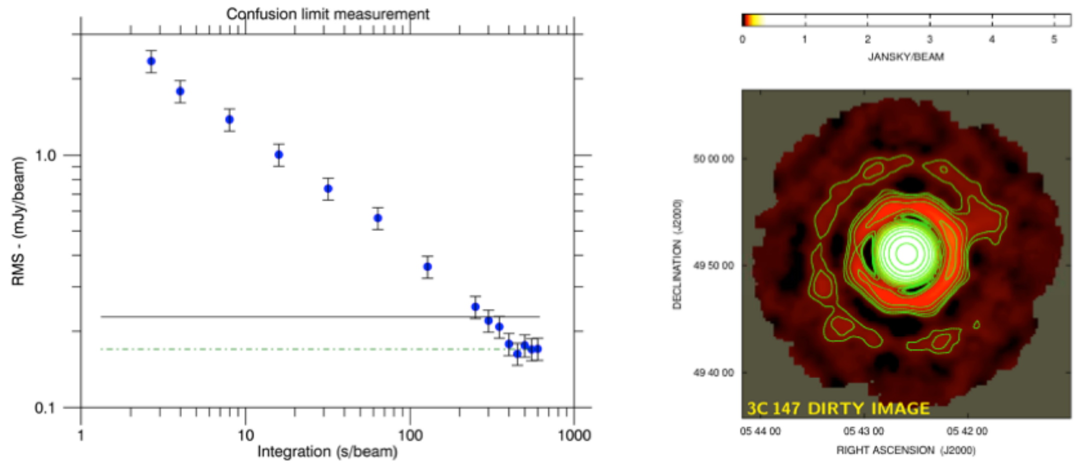

Figure 2: *Left:* Confusion limit test at C-band: rms noise (mJy/beam) vs integration time, as measured with the Total Power at 7.3 GHz (i.e. at a spatial resolution of 2.8 arcmin). The rms noise distribution flattens due to confusion after ~ 400 seconds of integration, where it reaches a value of 0.17 ± 0.02 mJy/beam (green dot-dashed line). This measured value is slightly lower than the reference value of ~ 0.23 mJy/beam (see black solid line), extrapolated from existing 1.4 GHz source counts assuming a spectral index $\alpha = -0.5$ ($S \sim \nu^{\alpha}$). *Right:* Image of the point source 3C 147, resulting from the combination of about 300 On-The-Fly scans, obtained in the April-September 2014 period. The noise rms is 1.2 mJy/beam, contours start from 3σ and increase by a factor of 2. The second and third beam sidelobes are clearly visible.

conduct validation activities for the purpose of making the SRT fully operational for coordinated observations in the framework of international networks (VLBI, Pulsar Timing Arrays, etc.). In the following, we will focus on these latter activities and we will summarize the current status of the validation of VLBI and LEAP (Large European Array for Pulsars) observations.

4. The SRT as part of the EVN

Since 2013 the VLBI experts of the SRT AV team have been working on tuning up the SRT DBBC-2/Mark5C system, with the help of the VLBI teams in Bologna, Medicina and Noto, in order to make it ready for coordinated VLBI experiments. The first successful data correlation was obtained with Medicina on January 27th, 2014. In 2014, the SRT regularly participated in EVN (European VLBI Network) test observations, and in a limited number of EVN and/or RadioAstron observing programs. As a result, the system was commissioned and fine-tuned, and can now be considered to be fully validated in the three EVN bands currently available at the SRT: L-, K- and 5cm bands. Observing tests are still on-going in P-band and for stand-alone Italian VLBI network observations. Ongoing activities for the validation of the Italian VLBI Network (Medicina, Noto, SRT) are reported in Stagni & Nanni (2015). From 2015, the SRT is offered as an additional EVN station (identified as Sr) in *shared-risk mode* (examples of fringes obtained during the first 2015 EVN observing run are shown in Figure 3).

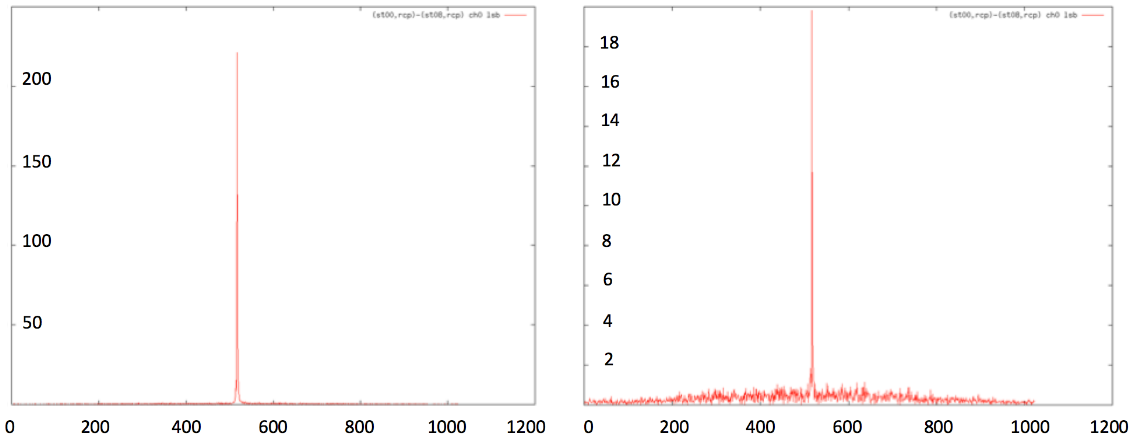

Figure 3: Successful Effelsberg-SRT 5cm ftp fringe tests obtained during the February/March 2015 EVN observing run. Integration time: 2 seconds. *Left:* Source 3C84. *Right:* Source 0528+134.

5. The SRT as part of LEAP

The AV team has made great progress on the implementation of the LEAP project at SRT, which involves the simultaneous observing of millisecond pulsars at five large European telescopes. The recorded baseband data from each telescope are added coherently, leading to high signal-to-noise in the pulsar signals that could enable the direct detection of gravitational waves from supermassive black holes binaries. LEAP runs consist of monthly 25-hour observations at L-band with a bandwidth of 128 MHz (Kramer & Champion 2013).

The backend used at SRT for LEAP is the ROACH (see § 1), which was installed on-site in July 2013 and equipped with the PSRDADA[2] software that enables the recording of baseband data to disk. The first LEAP session at SRT was conducted in July 2013 for a single 16 MHz channel, and was repeated monthly. In February 2014, a computer cluster with eight nodes was installed at SRT to enable the simultaneous recording of baseband data in eight 16 MHz channels. The team then obtained its first observations of millisecond pulsars with the ROACH backend in all eight bands (see Figure 4, bottom left). Since March 2014, SRT has been participating in monthly LEAP runs with the full 128 MHz bandwidth. In addition, a storage unit of 96 TB of capacity was installed at the site in April 2014 to allow the copying of data onto disk and regular shipping of the baseband data to Jodrell Bank Observatory in Manchester, where the data from all five telescopes are stored and correlated.

Each monthly observation provides SRT timing data for 22 millisecond pulsars. In addition, the baseband data is correlated in Manchester with the other four telescopes. The first fringes between SRT and the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands were obtained in May 2014, using the LEAP correlation software developed by the LEAP team specifically for this project (see Figure 4, right). Later in the year, fringes were found between SRT and all other four telescopes during analysis of the monthly LEAP data (Bassa et al., in prep.). The quality of the

[2]http://psrdada.sourceforge.net

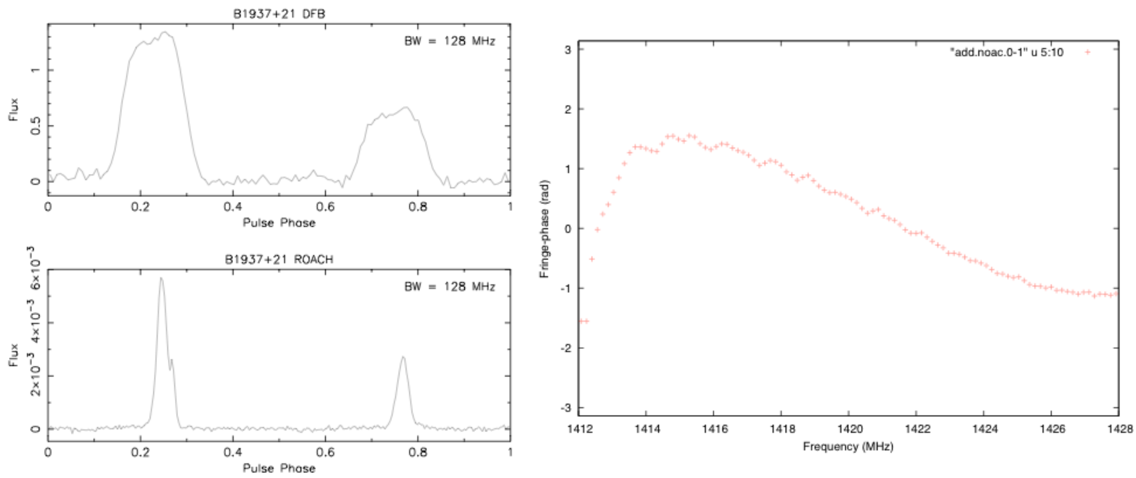

Figure 4: *Left:* Pulse profile of PSR B1937+21 obtained at SRT in the full LEAP band (1332-1460 MHz). Comparison between the ROACH backend (bottom) used in the context of LEAP and the DFB backend (top), also available at the SRT. The flux scale is arbitrary. The coherent de-dispersion allowed by the ROACH yields much better defined profiles than DFB incoherent de-dispersion (1 MHz channels). *Right:* First fringes between SRT and WSRT using the LEAP correlation software: 5 seconds of quasar 3C454 at 1420 MHz (May 2014). Fringe phase (rad) vs. frequency (MHz).

SRT data is limited however by the heavy presence of RFI in the LEAP band. Efforts to mitigate the RFI situation are currently under way by the SRT team.

6. Summary

With the completion of the technical commissioning phase and the official opening of the SRT in September 2013, post-commissioning activities have started. This includes the telescope *Astronomical Validation*, aimed at validating the SRT for standard observing modes and at transforming the SRT from a technological project into a real general-purpose astronomical observatory. The AV is organized in steps, from basic tests aimed at verifying the general performance and /or the limits of the telescope and the acquisition systems, to more complex acquisitions aimed at assessing the actual SRT capabilities for typical scientific observations. In addition, several external software tools are being developed in order to support observers in the preparation and execution of the observations, as well as in the data inspection and reduction.

The validation of the SRT in *single-dish* operation mode is well under way (for first results see Prandoni et al., in prep.). In parallel, work has been done to test and validate the use of the SRT as part of VLBI and pulsar timing networks. After the first successful VLBI data correlation, obtained between the SRT and Medicina stations in January 2014, the SRT regularly participated in EVN test observations, and since 2015 the SRT is offered as an additional EVN station in *shared-risk mode*. In addition, we have successfully implemented the LEAP project at SRT, having installed all of the hardware and software necessary for the project. The SRT participates in monthly LEAP runs, for which data acquisition is now fully automated. The implementation of the LEAP project has also accelerated the commissioning of the ROACH backend for general pulsar observations in timing and search modes. The main aspect that remains to be investigated is the mitigation of RFI that currently limits the SRT data quality.

It is finally worth mentioning that, as advertised on the SRT website, we support a limited amount of Target of Opportunity (ToO) observations as part of the AV activities. The first of such observations was performed in May 2013 in response to the discovery of the Magnetar PSR J1745-2900 in the Galactic Center region (Buttu et al. 2013).

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