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Front-Ends and Phased Array Feeds for the Sardinia Radio Telescope

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Abstract

We describe the design and performance of the Front-Ends for the 64-m diameter Sardinia Radio Telescope (SRT). An early science program was completed with SRT in August 2016, following a successful technical and scientific commissioning of the telescope and of its instrumentation. We give an overview of the three cryogenic Front-Ends, covering four bands, that were deployed on SRT during the early science program: P-band (305-410 MHz), L-band (1.3-1.8 GHz), high C-band (5.7-7.7 GHz) and K-band (18-26.5 GHz).

In addition, we describe the cryogenic Front-Ends that are currently under development, among which a seven-beam for S-band (3.0-4.5 GHz) a mono-feed for Low-C-band (4.2-5.6 GHz), a 19-element for Q-band (33-50 GHz) and a mono-feed for 3 mm band.

Finally, we describe the development status of a demonstrator of a cryogenic C-band Phased Array Feed (PAF) for potential use at the SRT primary focus.

1. Introduction

The Sardinia Radio Telescope (SRT, www.srt.inaf.it), a challenging scientific project of the Italian National Institute for Astrophysics (INAF), is a new general purpose fully steerable 64 m diameter radio telescope designed to operate with high efficiency across the 0.3-116 GHz frequency range [1]. The telescope (Fig 1) is located 35 km North of Cagliari, Sardinia, Italy, at about 600 m above the sea level. The technical and scientific commissioning of the telescope [2] was finalized and a six-month early science program was successfully completed in August 2016.

The SRT optical design is based on a classic Gregorian configuration (Fig. 2) with shaped primary (M1) and secondary (M2) reflectors to minimize spillover and standing waves. The primary active surface consists of 1008 aluminum panels (with panel manufacturing RMS<65 µm) and of 1116 electromechanical actuators under computer control that compensate the gravitational deformation of the backup structure and convert the shaped primary reflector into a paraboloid for operations at the prime focus. The primary reflector was aligned to an RMS of ~300 µm (using photogrammetry). Work is ongoing to improve the total optics surface accuracy down to an RMS of ~120 µm (using holography) to allow high efficiency observations up to the highest frequencies (~115 GHz).

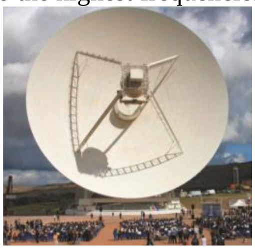

Figure 1. Sardinia Radio Telescope at the opening ceremony on Sep. 30th, 2013.

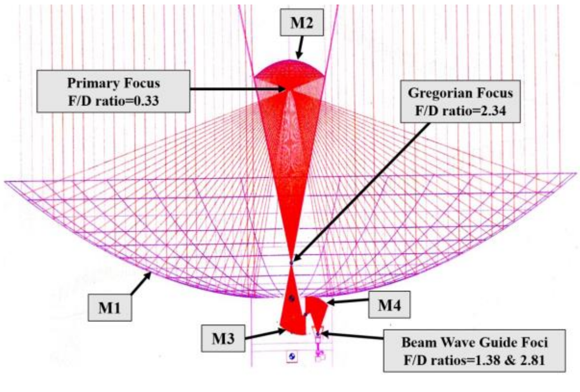

Figure 2. Optical configuration and ray tracing of the SRT showing the 64-m diameter primary (M1), the 7.9-m secondary (M2), and two additional Beam Waveguide (BWG) mirrors (M3 and M4). Three out of six possible focal positions (primary, Gregorian and BWG) are shown together with corresponding focal ratios.

2. Front-Ends deployed on SRT during the early science program

SRT has been designed to be equipped with up to twenty receivers to be installed in six focal positions (Fig. 2): Primary focus (F1), Gregorian focus (F2) and Beam-Wave Guide foci (F3&F5 and F4&F6), respectively with focal length to diameter ratio (F/D) and frequency ranges equal to 0.33 (0.3-20 GHz), 2.35 (7.5-115 GHz), and 1.37 & 2.84 (1.4- 35 GHz).

The SRT early science program was completed using the three following cryogenic receivers developed by INAF [3]: *a)* a primary focus (F1) dual linear and circular polarization coaxial receiver, which simultaneously covers the P-band (305-410 MHz) and the L-band (1.3-1.8 GHz), and is mostly used for Pulsars observations (Fig. 1b); *b)* a secondary focus (F2) dual circular polarization seven-beam receiver operating in K-band (18-26.5 GHz); *c)* a Beam-Wave Guide (F3) dual circular polarization mono-feed receiver for High-C-band (5.7-7.7 GHz). The K-band and C-band use a heterodyne down-conversion to the 0.1-2.1 GHz IF bands that are delivered to various backends.

A primary focus X-Ka room temperature coaxial receiver, which simultaneously cover the 8.2-8.6 GHz (X band) and the 31.85-32.25 GHz (Ka band) was temporarily installed at the SRT primary focus and used for testing spacecraft downlink capabilities (Fig. 3).

Figure 3. Photo of the Front-Ends at the SRT primary focus. The L-P band receiver is located between the X-Ka band and the holographic receivers. All Front-Ends are mounted on the primary focus positioner (PFP), a robotic arm that brings the Front-Ends at its focal position during primary focus observation. The 7.9-m diameter quasi-ellipsoidal secondary mirror is visible in the back.

2.1 L-P Band cryogenic coaxial receiver for primary focus

Fig. 4 shows a cross-section of the L-P band cryogenic coaxial Front-End. Details of the receiver design and performance are described in [4]. The room temperature illuminators are arranged in coaxial configuration with an inner circular waveguide for L-band (diameter of 19 cm) and an outer coaxial waveguide for P-band (diameter of 65 cm). Choke flanges are used outside the coaxial section to improve the cross-polarization performance and the back-scattering of the P-band feed. A vacuum vessel encloses two P-band hybrids and two L-band hybrids that are cooled respectively at 15 K and 77 K by a commercial closed-cycle cryocooler. The RF signals are amplified by coaxial low noise amplifiers (LNAs) thermalized at 15 K inside the cryostat. Two High Temperature Superconductor (HTS) band-pass filters, one per polarization channel, are located in front of the LNAs to mitigate the Radio Frequency Interference (RFI) in P-band. Room temperature noise calibration sources can be injected, under remote control, through coaxial cables and coupled into the RF signal paths, also located in front of the LNAs. The noise temperatures at the input flanges of the receiver measured in the laboratory are in the range 17-22 K in P-Band and in the range 10-13 K in L-Band for both linear polarization channels.

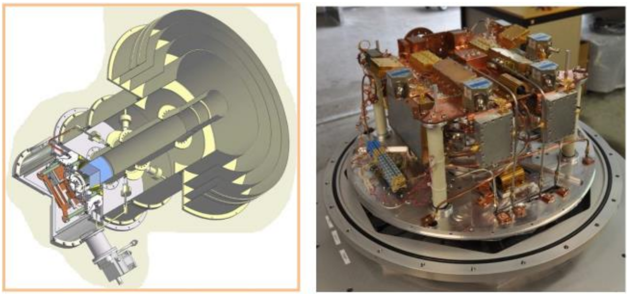

Figure 4. L-P band coaxial receiver: cross-section view of the full Front-End (left); view of the cryogenic assembly (right).

2.2 High C-band cryogenic mono-feed receiver for BWG focus

SRT detected its first radio source in the summer 2012 using the high C-band (5.7-7.7 GHz) receiver. The passive waveguide chain cascaded to the corrugated feed-horn consists of a calibration noise injector, a DPS (Differential Phase Shifter) and an OMT (Orthomode Transducer). The DPS and OMT are thermalized at 15 K inside a cryostat. A photo of the high C-band Front-End installed at the BWG, given on the left panel of Fig. 5, shows the room temperature feed horn, the remotely controlled vacuum pump as well as the downconversion and electronics control modules arranged in racks. The Front-End is hold in place inside the antenna receiver cabin, which moves in elevation (and azimuth) as the antenna tracks the astronomical sources, through a mechanical frame. Laboratory measurements of the Front-End, followed by tests in open-air, allowed accurate determination of the noise temperature of the receiver before its installation in SRT [5]. The receiver noise was derived by the Y-factor method, which utilized room temperature and cold loads respectively given by microwave absorber and cold sky (the method also allowed to characterize the noise calibration source). The measured

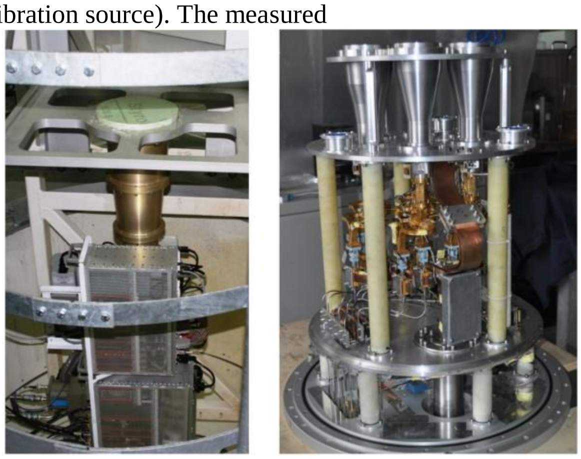

Figure 5. Monofeed High-C-band receiver installed at the BWG focus (left); view of the cryogenic assembly of the K-band multibeam receiver (right).

receiver noise temperature at the feed-horn input was below 9 K for both circular polarization channels (RHCP and LHCP).

2.3 K-Band multifeed cryogenic receiver for Gregorian Focus

A detailed description of the K-band (18-26.5 GHz) seven-beam multibeam receiver is given in [6]. The seven beam system allows to increase by a factor of seven the mapping speed of extended radio astronomy sources when compared to a monofeed. The feed-horns are arranged in hexagonal configuration plus a central one. The cryogenic part of each of the seven receiving chains includes a corrugated feed-horn, a circular waveguide directional coupler for noise calibration injection, a differential phase shifter, an orthomode transducer and an InP MMIC (Monolithic Microwave Integrated Circuit) low noise amplifier, all cooled at a physical temperature of ≈20 K. A photo of the instrument showing the inner part of the cryostat is given on the right panel of Fig. 5.

The room temperature parts of the receiver include down-conversion and local oscillator (LO) distribution chains. Two down-conversions are used. The receiver delivers a total IF bandwidth of 28 GHz (7 feeds x 2 pols x 2 GHz).

A mechanical rotator is used in the receiver to compensate for the Earth's rotation and maintain the parallactic angle, thus avoiding the astronomical field derotation caused by the SRT altitude-azimuth movement when tracking sources in the sky.

The noise temperature at the vacuum window of the receiver measured in the laboratory for the 14 channels (seven dual polarization beams) is in the range 20-40 K across most of the 18-24 GHz band. The noise increases at frequencies above 24 GHz to values in the range 40-80 K.

2.4 X-Ka band coaxial receiver for Primary Focus

A coaxial dual-frequency X-Ka band (X: 8.2-8.6 GHz, Ka: 31.85-32.25 GHz) room temperature receiver [7] was installed on the primary focus of the SRT to perform an experimental verification of the antenna potential capabilities in Space Science. The single circular polarization receiver was originally developed for the INAF 32-m diameter Noto radiotelescope (Italy) in order to track the Cassini spacecraft. The receiver delivers two 400 MHz wide IF bandwidths (one per band) using two internal local oscillators. The measured noise temperatures are 150 K for the X-band receiver and 130 K for the Ka-band receiver. The huge collecting area of SRT compensates the relatively high system temperatures of these two uncooled receiver with respect to other Deep Space antennas. A view of the X-Ka band receiver installed at the SRT primary focus is visible in Fig. 3.

The SRT telescope is soon going to be equipped with a new Front-End for DSN downlink to be installed at a BWG focus (activity coordinated by the Italian Space Agency).

3. Front-Ends under construction for SRT

Four additional cryogenic Front-Ends for radio astronomy application are currently being constructed for SRT: an S-band (3.0-4.5 GHz) seven-beam dual-linear polarization receiver for primary focus [8]; a Q-band (33-50 GHz) 19-element dual-circular polarization receiver for Gregorian focus [9]; a low C-band (4.2-5.6 GHz) monofeed receiver for the BWG focus at F/D=2.81; a W-band (84-116 GHz) monofeed receiver for the Gregorian focus [10].

A 3D view showing the design of the S-band seven-beam cryogenic receiver is given on the left panel of Fig. 6. Each receiving chain includes a coaxial feed with a single external corrugation and a ridged-waveguide orthomode transducer with antenna probe for calibration noise injection, all located at 15 K. The receiver delivers 1.5 GHz instantaneous bandwidth for each polarization channel (total of 1.5 GHz × 7 feeds × 2 pols = 21 GHz of IF band delivered to the backends).

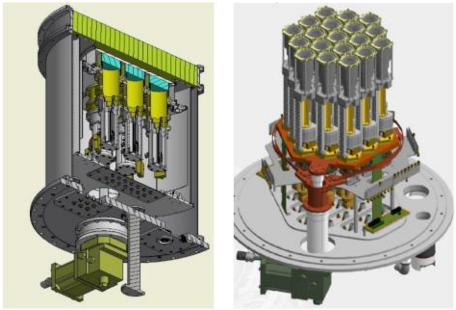

Figure 6. Design of the S-band seven-beam Front-End for primary focus (left) and of the Q-band 19-beam Front-End for Gregorian focus.

The design of the 19-element Q-band Front-End is shown on the right panel of Fig. 6. The cryogenic section of each element includes a corrugated feed-horn and an OMT realized in platelet technique by stacking together several aluminium layers. A calibration signal is injected through a waveguide transition ahead of a waveguide differential phase shifter, located between the feed and the OMT, to transform the two linear polarizations in circular polarizations. A room-temperature first conversion module is used to down-convert and amplify each polarization in to a 1-18 GHz IF band. The Front-End delivers 1.6 GHz × 8 sub-bands × 2 polarizations for each feed.

The Low-C-band monofeed receiver design is similar to the High-C-band and will be used mainly for VLBI observations.

A W-band monofeed receiver based on superconducting Single Side Band SIS mixer, designed and built by IRAM, was purchased by INAF following its decommissioning from the IRAM PdB Interferometer. The receiver is being adapted for installation at the SRT gregorian focus, where it will be used for testing the telescope performance up to the highest frequencies (≈115 GHz), while allowing the first scientific observations across the 3 mm atmospheric window. Several modifications were made to the IRAM receiver, including: a new cryogenic system, new optics, a new control system and a new local oscillator (ALMA Band 3 LO module), which was purchased from NRAO.

4. Demonstrator of a cryogenic C-band Phased Array Feed

PHAROS, (PHased Arrays for Reflector Observing Systems) is a C-band cryogenically cooled low noise Phased Array Feed (PAF) developed as part of a European technology demonstrator project cooperated by an international collaboration that includes INAF. The PAF consists of 220 elements Vivaldi array (Fig. 7) cooled to 20 K along with 24 low noise amplifiers (LNAs) mounted directly behind the antennas. The LNAs are followed by low-loss low thermal conduction RF connections to the analog beam forming system designed to operate at 77 K.

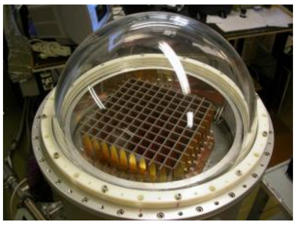

Figure 7. View of PHAROS Vivaldi antenna array and dome-shaped Plexiglas vacuum-window.

In the framework of the PAF Advanced Instrumentation Program for SKA, we are upgrading PHAROS to a new instrument named PHAROS2. PHAROS2 is a technology development program towards SKA Phase2 to demonstrate feasibility and competitiveness of high-frequency PAF technology. The instrument will be mounted on the Lovell telescope (at Jodrell Bank Observatory, UK), then on SRT, in order to perform radio astronomy observation across the 4-8 GHz range. PHAROS2 will be a cryogenically cooled C-band PAF demonstrator with a down-conversion system, Radio Frequency over Fiber (RFoF) analog signal transportation and digital beamformer capable of forming 4 independent beams using 24 active elements. The architecture of the beamforming is chosen to allow rescaling to much larger number of beams and bandwidth.

References

1. G. Grueff, G. Alvito, R. Ambrosini, P. Bolli, A. Maccaferri, G. Maccaferri, M. Morsiani, L. Mureddu, V. Natale, L. Olmi, A. Orfei, C. Pernechele, A. Poma, I. Porceddu, L. Rossi, G. Zacchiroli, "Sardinia Radio Telescope: The new Italian project," *Proc. SPIE Ground Based Telescopes*, Vol. 5489, p. 773, 2004.

2. P. Bolli, A. Orlati, L. Stringhetti, A. Orfei, S. Righini, R. Ambrosini, M. Bartolini, C. Bortolotti, F. Busa, M. Buttu, A. Cattani, N. D'Amico, G. Deiana, A. Fara, F. Fiocchi, F. Gaudiomonte, A. Maccaferri, S. Mariotti, P. Marongiu, A. Melis, C. Migoni, M. Morsiani, M. Nanni, F. Nasyr, A. Pellizzoni, T. Pisanu, M. Poloni, S. Poppi, I. Porceddu, I. Prandoni, J. Roda, M. Roma, A. Scalambra, G. Serra, A. Trois, G. Valente, G. P. Vargiu and G. Zacchiroli, "Sardinia Radio Telescope: General Description, Technical Commissioning and First Light," *Journal of Astronomical Instrumentation*, Vol. 4, No 3&4, 1550008, 2015.

3. G. Valente, A. Orfei, R. Nesti, A. Navarrini, S. Mariotti, P. Bolli, T. Pisanu, J. Roda, L. Cresci, P. Marongiu, A. Scalambra, D. Panella, A. Ladu, A. Cattani, L. Carbonaro, E. Urru, A. Cremonini, F. Fiocchi, A. Maccaferri, M. Morsiani, M. Poloni, "Status of the radio receiver system of the Sardinia Radio Telescope," *Proc. SPIE 9914 Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 991425,* Edinburgh, UK, 26 June-July 1, 2016.

4. G. Valente, T. Pisanu, P. Bolli, S. Mariotti, P. Marongiu, A. Navarrini, R. Nesti, A. Orfei, "The dual-band LP feed system for the Sardinia Radio Telescope prime focus," *Proc. SPIE Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V*, Vol. 7741, 774126, 2010.

5. A. Orfei, A. Cattani, M. Poloni, J. Roda, S. Mariotti, A. Maccaferri, A. Orlati, A. Scalambra, "Caratterizzazione del ricevitore nella banda 5.7-7.7 GHz," *SRT Memo Series* GAI04-FR-5.0 May 5th, 2011.

6. A. Orfei, L. Carbonaro, A. Cattani, A. Cremonini, L. Cresci, F. Fiocchi, A. Maccaferri, G. Maccaferri, S. Mariotti, J. Monari, M. Morsiani, V. Natale, R. Nesti, D. Panella, M. Poloni, J. Roda, A. Scalambra, G. Tofani, "A Multi-Feed Receiver in the 18 to 26.5 GHz Band for Radio Astronomy," *IEEE Antennas Propag. Mag.* 52(4), 62, 2010.

7. A. Scalambra, J. Roda, S. Mariotti, R. Ambrosini, "Doppio Ricevitore Coassiale per le Bande X-Ka dedicato alla missione Cassini," *INAF-Institute of Radio Astronomy, Internal Report* N. 331/03, 2004.

8. G. Valente, P. Marongiu, A. Navarrini, A. Ladu, T. Pisanu, M. Pili, A. Saba, G. Montisci, S. Dessi, A. Uccheddu, M. Buttu, E. Egron, N. Iacolina, A. Melis, D. Perrdin, C. Tiburzi,V. Vacca, "The 7-Beam S-Band Cryogenic Receiver for the Sardinia Radio Telescope Primary Focus: Status of Project," *Proc. SPIE Astronomical Telescope and Instrumentation*, 2016.

9. A. Orfei, A. Cattani, A. Cremonini, L. Cresci, A. Maccaferri, S. Mariotti, R. Nesti, D. Panella, M. Poloni, J. Roda, A. Scalambra, "Elementi per la realizzazione di un multifeed per SRT nella banda 33-50 GHz," *SRT Memo* TM-19.1, 2013.

10. A. Ladu, T. Pisanu, A. Navarrini, P. Marongiu, G. Valente, "A 3 mm band SIS Receiver for the Sardinia Radio Telescope," *Proc. SPIE 9153 Millimeter, Submillimeter and Far-Infrared Detectors and Instrumentation for Astronomy VII*, July 2014.