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A Review of Front-End Receivers for the INAF Radio Telescopes

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Abstract

This paper describes a rigorous process started within the Italian National Institute for Astrophysics (INAF) to review existing and future radio astronomical front-end receivers for the INAF radio telescopes. The main goal of the review was to increase the level of coordination in receiver development, improving at the same time the scientific impact from the national facilities. The working group in charge of the review collected information on the front-ends in operation and under development at the INAF radio telescopes and new ideas for future receivers from the Italian astronomical community. The outcome of the working group consists of recommendations on receivers under development and on strategies for future receivers at the suite of Italian radio telescopes.

1. Introduction

In the northern summer of 2016, the newly established Section II (Radio Astronomy) of the INAF Scientific Directorate started a process aimed at harmonizing and coordinating efforts and resources in radio astronomy. The first step of this process was to review the radio astronomical front-end receivers for the INAF radio telescope facilities. Three main goals were identified: *i)* develop a list of work to undertake on existing receiver systems that require major maintenance/repair; *ii)* undertake a review of receiver developments currently underway; *iii)* develop a roadmap for future receiver developments.

The process was designed to be science-driven, but also relatively challenging and ambitious regarding engineering developments. Moreover, it was requested to consider boundary conditions, like the telescope operations and dependencies, as well as the International radio astronomical contexts where INAF was involved in technological/astronomical research and development.

A working group composed by ten people from INAF with different professional backgrounds as well as a wide geographic representation from different groups and facilities was charged to conduct this review. The group provides the authorship for this paper.

The working group interacted with many Italian and foreign astronomers and technologists. The two most significant examples of this approach have been: *i)* the survey of the characteristics of some of the major International radio telescopes to benchmark the performance of Italian telescopes against recognized top-class worldwide radio astronomy facilities; *ii)* the call for ideas addressed to the whole Italian astronomical community to survey scientific interest in the development of new receivers. During the review process, a national workshop was held to present to the INAF community the preliminary recommendations of the working group and at the same time to stimulate discussion and collect feedback. Finally, in May 2017 the working group concluded its mandate by delivering the final report, available in [1], to the INAF management.

This paper describes and summarizes the most significant aspects of the review and is organized as follows: Section 2 presents the radio telescopes covered in the review; Section 3 illustrates the receivers currently in operation and under development at the INAF radio telescopes. The scientific perspectives for future receivers that emerged from the Italian community are reported in Section 4. Finally, Sections 5 and 6 contain the final recommendations and the conclusions, respectively.

2. INAF Radio Telescopes

The INAF radio telescopes considered in the review process were the Sardinia Radio Telescope (SRT, [2]), the Medicina Radio Telescope (MED, [3]) and the Noto Radio Telescope (NOTO, [4]). The main technical characteristics of each antenna are reported in Table 1. Even if the original mandate of the review included the Medicina Northern Cross, then it was realized that a significant infrastructure refurbishment in view of its use for radio astronomical studies is required, and this was outside the scope of the review. Also the space science applications of the SRT have been excluded from the review.

In order to provide accurate recommendations, the working group acquired technical information from other areas fundamental for the operational of the radio telescopes. These are briefly summarized in the remaining part of this Section.

The three antennas run the same telescope control software: the worldwide used Field System for Very Long Baseline Interferometry (VLBI) and a modern control system for single dish operations, developed within the DISCOS project and integrating receiver and back-end controls. The data acquisition equipment available at the Italian radio telescopes consists of a total-power detector, two different digital spectrometers, a digital correlator and a digital base band converter adopted by the European VLBI Network (EVN). A software-based correlator can also be used to perform VLBI observations.

Opacity measurements at the SRT site show that in the winter period there is 50% probability to have an opacity below 0.2 Np at 100 GHz; while the other Italian sites, despite their very low altitudes, show opacity values at 90 GHz below 0.25 Np in winter months.

As far as Radio Frequency Interference (RFI) is concerned, below 6 GHz RFI is seriously affecting the operations of the receivers at MED where no geographic shields protect the radio telescope, especially in the not purely passive frequency bands. The situation improves at SRT and NOTO, where above 3 GHz the RFI level is acceptable. At higher frequency (from 13 GHz at MED and from 6 GHz at SRT and NOTO) the RFI environment is considered clean.

Table 1. Main technical characteristics of the INAF radio telescopes

Parameter	MED	NOTO	SRT
Inauguration date	1983	1988	2013
Optical configuration	Cassegrain antenna	Cassegrain antenna	Shaped Gregorian antenna
Primary mirror diameter [m]	32	32	64
Active surface	No	Available	Available
Frequency range [GHz]	1.35 – 26.5	1.4 – 86	0.3 – 116
Frequency agility	Available	Partially available	Available
Surface accuracy [μm]	350÷400	700÷900	300
Pointing accuracy [deg]	0.002	0.002	0.002

3. Front-end receivers in operation and under development

The design and development of front-end receivers for the INAF radio telescopes is in charge to the receiver groups distributed across the three INAF structures: Istituto di Radioastronomia, Osservatorio Astronomico di Cagliari and Osservatorio Astrofisico di Arcetri. Overall, the group is composed by 10 FTE covering almost all the necessary technical areas from active and passive microwave components to mechanics and cooling, integration and testing. However, in specific areas the activity is commissioned to external industries or to Universities and Research institutes. In the last 15 years, the receiver groups have designed and fabricated 13 receivers for the three Italian radio telescopes.

An important step of the review process was to collect technical, scientific and management data for the 14 receivers in operation at the various radio telescopes (five at MED, five at NOTO and four at SRT). The more relevant technical information of these receivers (frequency range, feed system typology, maximum antenna gain and system noise temperature at zenith) are listed in Table 2, where ranges are given whenever the performance is not constant over the whole frequency band.

An analysis of the scientific impact of the receivers in operation has been carried out for MED and NOTO, while it was not possible for the SRT due to its recent start of operations. The percentage of observing time (including VLBI, radio astronomical and geodetic, and single-dish) allocated to each receiver shows that since 2010 at MED the S/X-, Clow- and K-band receivers have been the most used with approximately 25-30% each. The situation at NOTO is slightly different: the total allocated time for S/X-, Clow- and Q-band receivers is 20-25% each, while for the K-band it decreases to 15% due to its lower performance than the one in MED. In terms of publication rate, for MED and NOTO the S/X- and Clow-band receivers are the more productive due to their participation in VLBI observations. Scientific publications in single-dish observing mode typically use the higher-frequency receivers like the Clow-, X-, K- and Q-bands.

Table 2. Frequency coverage and measured performance for the receivers in operation at the INAF radio telescopes

Receiver	Freq. range [GHz]	Feed system*	Gain [K/Jy]	T_sys [K]
MED L	1.35-1.45	S	0.12	55
	1.595-1.715		0.11	65
MED S/X	2.2-2.36	DF	0.12	55
	8.18-8.98		0.14	38
MED Clow	4.3-5.8	S	0.16	28
MED Chigh	5.9-7.1	S	0.15	60-90
MED K	18-26.5	D	0.11	50-80
NOTO S/X	2.2-2.36	DF	0.15	120
	8.18-8.58		0.15	110
NOTO Clow	4.62-5.02	S	0.16	30
NOTO Chigh	5.10-7.25	S	0.13	120
NOTO K	21.5-23.0	S	0.08	110
NOTO Q	39-43.5	S	0.08	120
SRT P/L	0.305-0.410	DF	0.52	50-80
	1.3-1.8		0.55	25-35
SRT Chigh	5.7-7.7	S	0.6	24-28
SRT X/Ka	8.2-8.6	DF	0.64	180
	31.85-32.25		0.57	190
SRT K	18-26.5	M	0.46-0.66	40-70

* Legend for the feed system typology: mono-feed (S), dual-frequency (DF), dual-feed (D) and multi-feed (M).

Seven new receivers are currently under development in the INAF laboratories: four for SRT, one for MED and two for NOTO. Their technical characteristics are summarized in Table 3. The mono-feed in W-band was acquired from IRAM and is under modification to adapt it to the SRT.

The working group carried out an investigation of the main scientific cases for each receiver under development to evaluate their scientific impact (see Section 9 in [1]).

Table 3. Frequency coverage and expected performance for the receivers under development at the INAF labs.

Receiver	Freq. range [GHz]	Feed system*	Gain [K/Jy]	T_sys [K]
MED Ku	13.5-18	D	0.12-0.16	30-36
NOTO L	1.3-1.8	S	0.11	80
NOTO S/X	2.2-2.36	DF	0.12	80
	8.18-8.98		0.14	80
SRT S	3-4.5	M	0.75	30
SRT Clow	4.2-5.6	S	0.70	22-35
SRT Q	33-50	M	0.56	45-120
SRT W	84-116**	S	0.34	115

* See the legend of Table 2.
** 500 MHz instantaneous bandwidth.

Besides the receivers specifically under development for the INAF radio telescopes, INAF is also actively involved in the following International front-end projects, which could possibly be of interest also for the Italian antennas:

- ALMA Band 2+3 receiver being developed by a group of European Institutes under the coordination of ESO to cover the entire frequency range from 67 to 116 GHz, encompassing ALMA bands 2 (67-90 GHz) and 3 (90-116 GHz) in a single receiver cartridge.
- PHAROS2, which is the upgrade of a C-band cryogenically cooled low-noise Phased Array Feed (PAF) system developed as part of an European technology demonstrator project. This activity is carried on as a contribution of INAF to the SKA Advanced Instrumentation Program for PAFs.
- BRAND, which is under development in the framework of the Radionet4 project, will cover a very wide band, from 1.5 to 15.5 GHz. It will be a receiver devoted to astronomical observations in the EVN consortium.

4. Ideas for future front-end receivers

During the review process, a call for ideas aimed at the production of a roadmap for future receiver developments at INAF was opened. This represented an opportunity for the Italian astronomical community to play an active role in the definition of the priorities for future instrumental and scientific developments. The proposers were asked to provide basic technical information, a short science case and possible collaboration/interest within International networks. The call for ideas was successfully concluded with fifteen proposals. The main information of the proposals, like the radio telescope of interest, the frequency coverage etc., are reported in Table 4 after merging similar proposals.

Table 4. Ideas of new receivers as suggested by the Italian radio astronomical community

ID	Radio telescope	Central freq. [GHz]	Band [GHz]	Feed system*	Main observing mode
1	SRT	1.4	0.75	S	VLBI
2	SRT	4.9	1.4	S	VLBI
3	SRT NOTO MED	6	4	PAF	SD
4**	SRT	2.2-2.36 8.18-8.98		DF	VLBI
5	SRT	10	4	S	VLBI
6**	SRT NOTO MED	1.5-15		UWB	VLBI
7	SRT	8.4 32	$2*10^{-3}$	DF	SD
8**	NOTO	38-43		D	VLBI
9**	SRT NOTO MED	18-26 33-50 80-110		TF	VLBI
10	SRT	90	20	BOL	SD
11	SRT	100	>8	MF	SD

* In addition to the legend of Table 2: tri-frequency (TF), bolometer camera (BOL), Phased Array Feed (PAF) and ultra-wide band feed (UWB).
** For these receivers the frequency range is given in place of central frequency and bandwidth.

5. Recommendations

As a general consideration, the working group pointed out that after significant financial and human efforts devoted by the INAF staff, the Italian radio telescope network is almost finalized. The SRT is close to reach full operations. NOTO is expected to complete the restructuring of the observatory operations and managements, while MED has already demonstrated to be a reliable facility and now calls for further exploitation of its instrumental capabilities.

The final recommendations of the working group represent a trade-off between available resources, projects already in progress and the interest shown by the astronomical community. They provide suggestions on receivers under development and on strategies for future receiver development at the INAF radio telescopes, identifying two periods for the receiver development: short term (2017 – 2018), and long term (2019 and beyond). The following sub-sections summarize the recommendations for each radio telescope and include some general suggestions on strategies for improving receiver development activities.

5.1 Sardinia Radio Telescope

In the short-term, the working group recommends to complete the following receivers currently under construction:

- The Clow-band receiver, which is of particular interest for VLBI applications, as demonstrated by the high publication rate of NOTO and MED inside the EVN,

not only within international networks but also within the Italian VLBI array.
- The multi-feed S-band receiver, which would be, at the present time, a front-end receiver unique in the International scenario. Despite its usage for VLBI applications is not foreseen, a number of high-level science topics can be addressed with single-dish observations.
- The multi-feed Q-band receiver, which will have a high impact from a scientific point of view both for single-dish and VLBI observations. No other multi-feeds covering this band are available at foreign radio telescopes. Moreover, it represents also a good opportunity to start testing SRT metrology at relatively high frequency.

Additionally, the ALMA Band 2+3 receiver was identified to be a good opportunity to have a W-band receiver with state-of-the-art performance and requiring a limited amount of additional resources thanks to the synergy with the ALMA project. However, some modifications are needed to adapt the receiver to the SRT.

Starting from 2019, two main projects are seen as of greatest interest for SRT:
- Phased Array Feed receiver at C band. Such an instrument would be of relevant interest both as a new receiver to perform cutting edge science and as a technological demonstrator for future developments at higher frequencies.
- Multi–feed receiver at high frequency. Two proposals have been submitted for such a front-end during the call for ideas. The efforts of the receiver group should concentrate on developing a receiver in W band with a relatively dense array to address the many scientific goals identified by the scientific community.

5.2 Medicina Radio Telescope

In the period 2017 – 2018, it is suggested to proceed with the completion of the Ku-band receiver which, together with the existing K-band receiver, will result in continuous coverage of the band from 12 to 26 GHz at MED. This front-end is of great interest both in VLBI and in single dish modes for continuum studies and for spectral line analysis.

In the period 2019 and beyond, a simultaneous frequency receiver for K/Q/W-band observations would give the opportunity to promote the interest in MED and represents a niche in which also the smaller INAF radio telescopes can give a substantial contribution to some of the current hot topics for modern radio astronomy. However, this development would require a major upgrade of the mirrors.

5.3 Noto Radio Telescope

NOTO requires significant effort to regain its observing efficiency and solve operations issues, like for instance the completion of the frequency agility system and the refurbishment of the actuators mechanical and electronic parts. These criticalities in terms of observing efficiency and management make it difficult to foresee a realistic plan for future receiver developments in the long term.

In the short-term, the L- and S/X-band receivers are recommended to be finalized due to their high scientific interest, especially for VLBI observations.

5.4 Other considerations

Two additional proposals (BRAND and W-band bolometer) are considered of high scientific interest for the INAF radio telescopes and worthy of further interactions and discussions with the proposing teams.

The working group produced also some general guidelines that could be adopted for future receiver development activities. The most relevant are listed below:
- periodically conducting a survey of the interest of the astronomical community in new instrumentation by means of open Call for Projects;
- coordinating the development of radio astronomical instrumentation under the supervision of the INAF Scientific Directorate;
- for an optimal exploitation of the available human and hardware/software resources and to guarantee a timely completion of the projects, each project should be in charge of a specific group and locally managed;
- adopting a more structured approach by applying system engineering methodologies to the various phases of a project.

6. Conclusions

The review process of the INAF front-end receivers took one year to be completed and represented a significant process to assess and coordinate future developments at INAF. It shows the depth of potential that exists within the Italian radio telescopes and the Italian radio astronomy community. This review process forms a very strong basis, which should be repeated in other areas, like for instance in back-ends and infrastructures, to chart a course to the future of radio astronomy within Italy, with benefits for the Italian facilities and astronomers, but also with more International connections for Italian radio astronomy.

7. Acknowledgements

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8. References

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