Publication Year	2017
Acceptance in OA@INAF	2021-01-26T15:49:08Z
Title	RECEIVERS FOR RADIO ASTRONOMY: CURRENT STATUS AND FUTURE DEVELOPMENTS AT THE ITALIAN RADIO TELESCOPES
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Handle	http://hdl.handle.net/20.500.12386/30018

RECEIVERS FOR RADIO ASTRONOMY:

CURRENT STATUS AND FUTURE DEVELOPMENTS AT THE ITALIAN RADIO TELESCOPES

P. Bolli, M. Beltrán, M. Burgay, C. Contavalle, P. Marongiu, A. Orfei,
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INAF
PRESS

RECEIVERS FOR RADIO ASTRONOMY: CURRENT STATUS AND FUTURE DEVELOPMENTS AT THE ITALIAN RADIO TELESCOPES

Review version 8.1 – December, 22th, 2017

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This Report has been sponsored by Prof. S. J. Tingay, Head of Section II – Radio Astronomy of the INAF Scientific Directorate.

Printed with the financial support of the INAF Scientific Directorate.

INAF PRESS

INAF Istituto Nazionale di Astrofisica – INAF Press, Viale del Parco Mellini 84, I-00136 , Roma, Italy

Cover picture:
The INAF radio telescopes and some highlights of the front-end receivers

Graphic Design:
S. Righini – INAF IRA

ISBN 978-88-9898-504-3

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List of acronyms

ADC	ANALOG TO DIGITAL CONVERTER
AGB	ASYMPTOTIC GIANT BRANCH
AGN	ACTIVE GALACTIC NUCLEI
AIP	ADVANCED INSTRUMENTAION PROGRAM
AIV	ASSEMBLY INTEGRATION AND VERIFICATION
ALMA	ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY
ASI	AGENZIA SPAZIALE ITALIANA
AS	ACTIVE SURFACE
ASKAP	AUSTRALIA SKA PATHFINDER
ASM	ATMOSPHERE MONITORING SYSTEM
ASTRON	NETHERLANDS INSTITUTE FOR RADIO ASTRONOMY
ATM	ATMOSPHERIC TRANSMISSION AT MICROWAVES
ATNF	AUSTRALIA TELESCOPE NATIONAL FACILITY
BBC	BASEBAND CONVERTER
BCG	BRIGHTEST CLUSTER GALAXY
BEST	BASIC ELEMENT FOR SKA TRAINING
BRAND	BROADBAND EVN
BWG	BEAM WAVE GUIDE
CABB	COMPACT ARRAY BROADBAND BACK-END
CMB	COSMIC MICROWAVE BACKGROUND
CASPER	COLLABORATION FOR ASTRONOMY SIGNAL PROCESSING AND ELECTRONIC RESEARCH
Chigh	UPPER FREQUENCY RANGE OF THE C BAND
Clow	LOWER FREQUENCY RANGE OF THE C BAND
COM	COMPLEX ORGANIC MOLECULES
CSIRO	COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION
CSO	COMPACT SIMMETRIC OBJECT
CSS	COMPACT STEEP SPECTRUM

CTA	CHERENKOV TELESCOPE ARRAY
DBBC	DIGITAL BASEBAND CONVERTER
DFB	DIGITAL FILTER BANK
DiFX	DISTRIBUTED FOURIER TRANSFORM OF CROSS MULTIPLIED SPECTRA
DISCOS	DEVELOPMENT OF THE ITALIAN SINGLE-DISH CONTROL SYSTEM
EC	EUROPEAN COMMUNITY
ECC	ELECTRONIC COMMUNICATIONS COMMITTEE
EER	ELEVATION EQUIPMENT ROOM
EOP	EARTH ORIENTATION PARAMETERS
EPTA	EUROPEAN PULSAR TIMING ARRAY
ESA	EUROPEAN SPACE AGENCY
ESCS	ENHANCED SINGLE-DISH CONTROL SYSTEM
ESO	EUROPEAN SOUTHERN OBSERVATORY
EVN	EUROPEAN VLBI NETWORK
FEAC	FRONT-END ACTIVE COMPONENTS
FEPC	FRONT-END PASSIVE COMPONENTS
FFT	FAST FOURIER TRANSFORM
FoV	FIELD OF VIEW
FPGA	FIELD-PROGRAMMABLE GATE ARRAY
FRB	FAST RADIO BURST
FTE	FULL TIME EQUIVALENT
GARR	GRUPPO PER L’ARMONIZZAZIONE DELLE RETI DELLA RICERCA
GBT	GREEN BANK TELESCOPE
GMVA	GLOBAL MILLIMETER VLBI ARRAY
GNSS	GLOBAL NAVIGATION SATELLITE SYSTEMS
GPS	GLOBAL POSITIONING SYSTEM
GPU	GRAPHICS PROCESSING UNIT
GW	GRAVITATIONAL WAVES
HTS	HIGH TEMPERATURE SUPERCONDUCTOR
IASF	INSTITUTE OF SPACE ASTROPHYSICS

IC	INVERSE COMPTON
ICRF	INTERNATIONAL CELESTIAL REFERENCE FRAME
IEIIT	INSTITUTE OF ELECTRONICS, INFORMATION AND TELECOMMUNICATION ENGINEERING
ITRF	INTERNATIONAL TERRESTRIAL REFERENCE FRAME
I&T	INTEGRATION AND TEST
IF	INTERMEDIATE FREQUENCY
ILW	INTEGRATED LIQUID WATER
IMT	INTERNATIONAL MOBILE TELECOMMUNICATIONS
INAF	ISTITUTO NAZIONALE DI ASTROFISICA
IRA	ISTITUTO DI RADIOASTRONOMIA
IRAM	INSTITUT DE RADIOASTRONOMIE MILLIMÉTRIQUE
ISM	INTERSTELLAR MEDIUM
IVS	INTERNATIONAL VLBI SERVICE FOR GEODESY AND ASTROMETRY
I&T	INTEGRATION & TEST
ITU	INTERNATIONAL TELECOMMUNICATIONS UNION
IWV	INTEGRATED WATER VAPOUR
JLRAT	JOINT LABORATORY FOR RADIO ASTRONOMY TECHNOLOGY
JPL	JET PROPULSION LABORATORY
KaVA	KVN AND VERA ARRAY
KVN	KOREAN VLBI NETWORK
LCP	LEFT-hand CIRCULAR POLARIZATION
LEAP	LARGE EUROPEAN ARRAY FOR PULSARS
LEO	LOW EARTH OBJECTS
LFAA	LOW FREQUENCY APERTURE ARRAY
Lhigh	UPPER FREQUENCY RANGE OF THE L BAND
Llow	LOWER FREQUENCY RANGE OF THE L BAND
LNA	LOW NOISE AMPLIFIER
M&C	MECHANICS AND COOLING
MED	MEDICINA 32-m RADIO TELESCOPE

MIRFA	MILITARY RADIO FREQUENCY AGENCY
MISE	MINISTRY OF ECONOMIC DEVELOPMENT
MIUR	MINISTERO PER L'UNIVERSITA' E LA RICERCA SCIENTIFICA
MMIC	MONOLITHIC MICROWAVE INTEGRATED CIRCUIT
MPI	MESSAGE PASSING INTERFACE
MPIfR	MAX PLANCK INSTITUT für RADIOASTRONOMIE
MOJAVE	MONITORING OF JETS IN ACTIVE GALACTIC NUCLEI WITH VLBA EXPERIMENTS
NC	NORTHERN CROSS
NOTO	NOTO 32-m RADIO TELESCOPE
Np	NEPER
OAA	OSSERVATORIO ASTROFISICO DI ARCETRI
OAC	OSSERVATORIO ASTRONOMICO DI CAGLIARI
OTF	ON THE FLY
PAF	PHASED ARRAY FEED
PFB	POLYPHASE FILTER BANDPASS
PFP	PRIMARY FOCUS POSITIONER
PHAROS	PHASED ARRAYS FOR REFLECTOR OBSERVING SYSTEMS
PMR	PRIVATE MOBILE RADIO
PMSE	PROGRAM MAKING AND SPECIAL EVENTS
PPDR	PUBLIC PROTECTION AND DISASTER RELIEF
PWN	PULSAR WIND NEBULA
PWV	PRECIPITABLE WATER VAPOUR
RAI	RADIOTELEVISIONE ITALIANA
RAID	REDUNDANT ARRAY OF INDEPENDENT DISKS
RAS	RADIO ASTRONOMY SERVICE
RCP	RIGHT-hand CIRCULAR POLARIZATION
R&D	RESEARCH & DEVELOPMENT
RF	RADIOFREQUENCY
RFI	RADIO FREQUENCY INTERFERENCE
RM	ROTATION MEASURE

RMS	ROOT MEAN SQUARE
ROACH	RECONFIGURABLE OPEN ARCHITECTURE COMPUTING HARDWARE
RSS	ROOT SUM SQUARE
RT	RADIO TELESCOPE
SD	SINGLE-DISH
SEADAS	SRT EXPANDABLE DATA ACQUISITION SYSTEM
SEFD	SYSTEM EQUIVALENT FLUX DENSITY
SETI	SEARCH FOR EXTRA TERRESTRIAL INTELLIGENCE
SIS	SUPERCONDUCTOR–INSULATOR–SUPERCONDUCTOR TUNNEL JUNCTION
SKA	SQUARE KILOMETER ARRAY
SN	SUPERNOVA
SNR	SUPERNOVA REMNANT
SRT	SARDINIA RADIO TELESCOPE
SST	SPACE SURVEILLANCE AND TRACKING
TETRA	TERRESTRIAL TRUNKED RADIO
TTL	TRANSISTOR-TRANSISTOR LOGIC
UWB	ULTRA WIDE BAND
VDIF	VLBI DATA INTERCHANGE FORMAT
VERA	VLBI EXPLORATION OF RADIO ASTROMETRY
VGOS	VLBI GLOBAL OBSERVING SYSTEM
VLBA	VERY LONG BASELINE ARRAY
VLBI	VERY LONG BASELINE INTERFEROMETRY
VNA	VECTOR NETWORK ANALYZER
WG	WORKING GROUP
WP	WORKPACKAGE
WRC	WORLD RADIO CONFERENCE
XARCOS	ARCETRI CROSS CORRELATOR SPECTROMETER

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Terms of Reference

Background

Section II (Radio Astronomy) of the Scientific Directorate is starting a process aimed at harmonizing and coordinating efforts and resources in radio astronomy. The goal of this process is to realize efficiencies that allow a higher level of productivity (better instruments, better facilities, and more high impact science output) within the discipline of radio astronomy at INAF.

This process includes a review of the existing and future radio astronomical front-end receivers for the INAF radio telescope facilities: 64-m SRT; 32-m Noto; 32-m Medicina; and Northern Cross.

A specific Working Group (WG) to pursue this topic has been nominated by the Head of Section II of the Scientific Directorate.

Working Group composition

The WG composition aims to represent different professional backgrounds as well as wide geographic representation from the different groups and facilities involved in radio astronomy at INAF.

The following people have been identified as members of the WG (together with their affiliations and profiles):

	OAA	OAC	IRA-BO	IRA-MED	IRA-NOTO	DS Section II
Technologist	P. Bolli	T. Pisanu	A. Orfei			
Astronomer	M. Beltrán	M. Burgay	A. Zanichelli C. Stanghellini[1]			
Technician		P. Marongiu		G. Zacchiroli	C. Contavalle	
Manager						S. Tingay

Objectives

The activities of the review include the production of:

1) a comprehensive list of all receiver developments currently underway within INAF, including their status, the people working on the developments, the science goals that they are addressing, and the estimated cost to complete;

2) a priority list of work to undertake on existing receiver systems that require maintenance/repair, identifying the people to do the work, and initial estimates of cost and time. This list should be driven by science priorities and practical considerations such as the RFI environment at the different telescopes or other factors at play at the different sites;

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[1] Responsible of IRA-NOTO.

3) a roadmap for future receiver developments at INAF. This should be a science-driven set of developments, but should also be relatively challenging and ambitious on the engineering front, coupled (where possible) with developments in other directions, such as the SKA.

The planning process will take into account, as boundary conditions, other aspects of the telescope operations and dependencies (for example upgrades to antenna control systems, frequency agility upgrades, or digital back-end developments) as well as international radio astronomical projects where INAF is involved in technological/astronomical research and development (for example SKA, ALMA, VLBI etc.).

The review will eventually also need to connect with other reviews, such as a planning process to bring the SRT into a full state of operations and reviews of required infrastructure work at Medicina and Noto.

As the financial resources allocated to receiver development for the next few years are not yet defined, the review is not expected to take into account any financial constraints. It should be noted that this review process will help to inform and define future funding decisions and should help guide future external funding requests.

Modus Operandi

The WG will meet monthly either by teleconference or physically. However, it is expected that specific activities will be carried out by selected members identified as expert in the specific topic of interest.

The WG might also involve in this review process other colleagues, either from INAF or from other radio astronomical Institutes, in case their opinions are considered valuable for the review.

Deliverables

The WG will report its considerations and recommendations in a written form. Besides the priority lists of existing, under-development, and future receivers, the report will identify possible teams to pursue the developments and some initial cost and schedule estimates.

The report will be presented to the Italian radio astronomical community during a dedicated Workshop expected to be held in spring 2017. Relevant feedback from this community consultation will then be incorporated into the final form of the report.

The report will ultimately be transmitted to the Scientific Director of INAF for consideration.

Closing remarks

In order to position radio astronomy within INAF for a future that includes a high level of high impact science output from its national facilities and increased participation in large-scale international projects, an increased level of coordination is likely to be required within INAF. The goal of Section II of the Science Directorate is to help achieve this end. An efficient and coordinated targeting of effort on focused goals will represent a major step in this direction. This receiver review process will be an early test of this strategy, in an area of fundamental importance that spans technology and astrophysics.

Working Group members

- Pietro Bolli: microwave engineer specialized in analysis, design, fabrication and characterization of technological components for radio astronomy
- Maite Beltrán: researcher on the field of galactic star formation and astrochemistry at millimeter and sub-millimeter wavelengths, with experience in interferometric and single-dish observations
- Marta Burgay: staff researcher in the field of relativistic astrophysics working mainly on studies and observations of pulsars and Galactic neutron stars
- Corrado Contavalle: cryogenic and RF technician at the Noto telescope
- Pasqualino Marongiu: mechanical designer involved in the development of receivers, metrology and mechanical design for the Sardinia Radio Telescope
- Alessandro Orfei: senior technologist in charge of 32-m Medicina antenna and Head of the receiver team
- Tonino Pisanu: technologist involved in the receivers design and development and in the research of metrology systems for the use of the SRT at high frequency
- Carlo Stanghellini: researcher with main research activity in the field on AGN and Extragalactic Radio Sources
- Giampaolo Zacchiroli: technician belonging to the 32-m Medicina antenna staff, his interest include antenna structural and mechanical design, and cryogenic for receivers
- Alessandra Zanichelli: researcher in the field of extragalactic astronomy with experience in single-dish radio observations

Executive summary

In Spring 2016 Prof. Steven Tingay, Head of Section II (Radio Astronomy) of the INAF Scientific Directorate, established a Working Group to review the existing and future radio astronomical receivers for the INAF radio telescope facilities: 64-m SRT, 32-m Noto, 32-m Medicina and Northern Cross. This initiative is the first step of a more general process aimed at harmonizing and coordinating efforts and resources in radio astronomy. The receiver review included the front-end developments underway within INAF, the existing instrumentation requiring major maintenance/repair, and a roadmap for future receiver developments at INAF. As stated in the Terms of Reference, the result of the review process had to be a science-driven set of developments, which should also be relatively challenging and ambitious on the engineering front.

The composition of the WG was characterized by a large variety in professional background and position as well as in the geographical affiliation among the main structures of INAF involved in developing radio astronomical receivers (Astronomical Observatory of Cagliari, Institute of Radio Astronomy and Arcetri Astrophysical Observatory). A Working Group characterized by so many different points of view was found to be a fundamental key-point, assuring the production of a set of conclusions that are both objective and in principle more easily approvable by people belonging to different areas. This second aspect is particularly relevant in view of the implementation phase.

Additionally, the WG contacted many INAF colleagues to contribute with additional information necessary to have a clear and comprehensive picture of both the technical aspects at the telescope sites and the national and international scientific scenario in which future development must take place. Contributing people are acknowledged in a dedicated Section of this report. In order to broaden the participation to the writing of the final report, a dedicated Workshop organized in Rome on March 21, 2017 gave the opportunity to illustrate the conclusion of the WG to the scientific and technological community, and to collect their feedbacks. It is important to point out that the report discussed at the Workshop was still in a preliminary version and its finalization came only after the Workshop itself.

The WG activities started with a kick-off meeting held on June 6, 2016 and the first WG initiative was to survey the status of receivers in Italy. Several technical, scientific and management information were collected for the operational and under development receivers. All these data have been used to fill a table (Appendix A), which summarizes the receivers status at national level. After that, the WG has considered appropriate to survey the status and future plans of receivers at several International radio astronomical observatories. The idea was to benchmark the internal review against recognized top-class international radio astronomy facilities and to identify the directions of the future receiver developments at INAF. Therefore, several foreign radio astronomers have been contacted asking to provide data of their operational and under development receivers (Appendix B). In parallel to these national and international surveys, we examined also three projects of future receivers where INAF was involved but which were not developed for the Italian radio telescopes. These projects were PHAROS, BRAND and ALMA Band 2+3, which represent very different projects but each of them with a possible interest in being installed in the Italian antennas. Finally, an evaluation of the productivity in terms of scientific publications in the last five years was made for the existing receivers at Medicina and Noto, while for SRT the output in terms of receiver-related technological publications and Early Science Program was considered (Appendix C).

A fundamental milestone of the process has been the issue of a Call for Ideas for future receivers, which has been open for one month around November 2016. In this call, the Italian astronomical and technological communities (not only within INAF) had the opportunity to propose ideas for possible future receivers to be installed on one or more of the Italian radio telescopes. The form required to be filled with general information on basic technical characteristics of the proposed receiver (frequency band, typology of feed-system) and on short scientific cases. The Call was successfully concluded, with a total of fifteen ideas ranging on a wide variety of different interests from the astronomers and technologists involved.

The WG met nine times on a monthly basis before the Workshop, and on a further occasion later on to recap the inputs received from the community and finalize the report. The Workshop was attended by about fifty people coming from different INAF institutes, ASI and other University Departments. A streaming connection allowed the Workshop to be followed remotely by interested people. The final discussion has been very fruitful and served to complement the recommendations of the WG.

All the information acquired by the WG have been used to draw the final recommendations, which represent the conclusion of this review process. The recommendations include suggestions on receivers under development and on strategies for future receiver development at the Italian radio telescopes, and represent a trade-off between available resources (financial and human), projects already in progress and the interest shown by the astronomical community. Another goal of the recommendations has been the identification of the best strategies in receiver development so to capitalize, both in terms of scientific production and technological knowledge, the financial investment made by INAF in the Italian radio telescopes.

The effort of the WG was to identify the directions to follow in the next years to allow the SRT to compete with the top-class international facilities, whereas Medicina and Noto to find niches where they can continue to contribute to high-level astronomical research. Basically, the WG recommends to dedicate the years 2017 and 2018 to complete several projects now in progress and to pursue the adaptation of the ALMA Band 2+3 receiver for its installation on the SRT. Then, starting from 2019 three new generation receivers should be realized: a W-band multi-feed and a C-band Phased Array Feed receiver for SRT, and a K/Q/W-band simultaneous frequency receiver for Medicina. This latter receiver implies the refurbishment of the MED mirrors by adopting one of the possible solutions described in Appendix D of the report. The project for a simultaneous frequency receiver could be also of interest for the other telescopes and in particular for Noto, as soon as the organization and technical matters at the Observatory have been solved.

Furthermore, the successful participation of the Italian radio telescopes in existing and new international observing networks motivates the WG in recommending the prosecution and strengthening of such activities also through the finalization of a national VLBI network. Within this context, the BRAND international project has been identified as an interesting opportunity for the Italian antennas and collaboration with the developers team is encouraged.

An additional proposal regarding the construction of a W-band bolometer receiver was found to be potentially of high interest for the SRT. The management of this project is in charge of the

University of Rome "La Sapienza" and further interaction between INAF and that group is recommended.

The WG also identified some possible guidelines that could be adopted to guarantee an efficient organization in the development of future receivers. Currently the most part of receiver development within INAF is carried out at IRA and OAC. The interaction with other INAF teams involved in front-end development at IASF-Bologna and IRA-Medicina (SKA group) is encouraged as well as the prosecution of the involvement of OAA staff in new-generation projects.

For what concerns the Northern Cross, this WG concluded that a further refurbishment in view of its use for radio astronomical studies - despite being possibly of interest under some aspects in the international context - is outside the scope of this report. Moreover, the role of ASI in SRT operations for space science applications was addressed in view of the need to guarantee a safe coexistence of instrumentation and a fruitful collaboration to better exploit the antenna for both radio astronomical and space science applications.

The final report consists of four parts: the first one presents the status of the radio telescopes where the receivers, purpose of this review, should be installed. This part also includes an analysis of the boundary conditions like back-ends, radio frequency interference and opacity conditions at the sites as well as some information on the various groups working on receiver development within INAF. The second part illustrates the national and international survey on radio astronomical receivers, as well as other international projects having possible links with the future receivers at the Italian radio telescopes. The third part of the report discusses the science cases of the receivers under development and the output of the Call for Ideas for future instrumentation. Finally, the recommendations of the WG and a description of the Workshop are presented in the fourth part.

Though the report contains a large amount of data and information, the Chapters are organized in such a way that they can be read individually. People interested in particular aspects can thus go directly to the Section(s) of interest.

As a final remark, the WG warmly thanks the Workshop participants and all the colleagues who gave valuable input for the writing of this report and whose names are listed in the Acknowledgements Section.

Part I - Infrastructure

1. Main characteristics and status of the Italian radio telescopes

This Chapter is intended to be a source of information, definitions, and parameters useful to the reader in order to gain knowledge about the Italian antennas and their present condition. The first three Sections deal with main parameters and facilities at the telescopes, whereas the last three give information about already executed maintenance, thus giving a figure of reliability for the years to come.

1.1 Medicina Radio Telescope

The 32-m antenna was inaugurated on October 18, 1983.

Optical configuration
Primary mirror dish (D): 32 m (paraboloid)
Secondary mirror dish (d): 3.2 m (hyperboloid)

Primary mirror focal length (F_1) = 10.259 m
Focal Ratio (F_1/D) = 0.33

Cassegrain focal length (F_2) = 97.36 m
Focal Ratio (F_2/D) = 3.04

Total Surface Accuracy (RSS): 700÷900 μm (versus elevation angle)
Medicina is the only Italian telescope without a facility for extending its operating frequencies up to 3 mm; deformations due to gravity prevents good aperture efficiency at frequencies higher than the K band.

Aperture Efficiency (theoretical maximum, i.e. not including surface effects = 58%)

- 57% @ 5 GHz (measured);
- 38% @ 22 GHz (measured);
- 12% @ 43 GHz (expected peak).

Pointing Accuracy
On both axes, azimuth and elevation, 0.002 degrees RMS. Thanks to an accurate pointing model, the pointing doesn't need to be calibrated during standard antenna operations.

Frequency Agility
It is possible to change the observation configuration of the antenna by fast switching among receivers, as reported in the following:

- between receivers installed in Primary focus within 45 second max;
- between receivers installed in Cassegrain focus within 14 second max;
- between Primary focus receivers to Cassegrain focus receivers (or vice versa) within 4 minutes.

Focal Position F_1 (Primary focus)

Facilities

- Servo axes in two directions: Z axis (focus axis) and Y axis (normal to elevation antenna axis);
- helium line for cryogenic receivers;
- maximum loads on servo axes = 350 Kg;

- in case different receivers are to be moved to the focal position, a total volume of about 0.64 m^3 (0.75x0.9x0.95 m (Y,X,Z)) is available;
- as an alternative, a volume of about 0.85 m^3 (1.0x0.9x0.95 m (Y,X,Z)) is available for the installation in fixed position of a single multi-feed or PAF receiver.

Current status

In the Primary Focus position a box of 0.44 m3 is installed, hosting a coaxial cryogenic S/X-band receiver and an uncooled L-band receiver.

Focal Position F_2 (Cassegrain focus)

Facilities

At the center of the primary mirror dish there is a room (vertex room) of about 27 m^3 where receivers and other services and devices are installed:

- helium line for cryogenic receivers;
- up to nine coexisting receivers can be installed, from C band to higher frequencies:
    - one receiver can be installed on the optical axis with or without a mechanical rotator. Therefore this position is suitable for multi-feed front-ends like for instance a 7-beam K-band receiver;
    - concentric to the antenna optical axis, up to eight receivers can be installed on a radius of 0.735 m 45 degrees apart. Each receiver must be inclined at an angle of 4.2 degrees, pointing toward the primary focus; the subreflector is consequently tilted in order to point to the selected receiver. In these eight positions, receivers operating in C band are allowed only if mono-feed, while from X band to higher frequencies also dual-feed receivers can be installed. Furthermore, the installation of a mechanical rotator is not possible.

Current status

In the Cassegrain focus position three receivers are installed:

- Clow-band receiver, mono-feed, cryogenic;
- Chigh-band receiver, mono-feed, not cooled;
- K-band receiver, dual-feed, cryogenic.

1.2 Noto Radio Telescope

The 32-m antenna was inaugurated on October 28, 1988.

Optical configuration

Primary mirror dish (D): 32 m (paraboloid) with an active surface system consisting of 244 actuators

Secondary mirror dish (d): 3.2 m (hyperboloid)

Primary mirror focal length (F_1) = 10.259 m

Focal Ratio (F_1/D) = 0.33

Cassegrain Focal length (F_2) = 97.36 m

Focal Ratio (F_2/D) = 3.04

Total Surface Accuracy (RSS): 350÷400 μm (antenna efficiency is quite constant vs. elevation, due to the primary mirror active surface system which compensates for the gravitational deformations).

Aperture Efficiency (theoretical maximum, i.e. not including surface effects ≈ 58%)

- 57% @ 5 GHz (measured);
- 50% @ 22 GHz (measured);
- 40% @ 43 GHz (measured).

Pointing Accuracy

On both the azimuth and elevation axes, 0.002 degrees RMS. Thanks to an accurate pointing model, the pointing doesn't need to be calibrated during standard antenna operations.

Frequency Agility

It is possible to change the observation configuration of the antenna by switching among receivers, as reported in the following:

- the frequency agility between receivers in the Cassegrain focus is not yet available; the interchange among them must be scheduled to be done during working hours and it takes about 4 hours;
- between Primary focus receivers to Cassegrain focus receivers (or vice versa) is possible within 4 minutes.

Focal Position F_1 (Primary focus)

Facilities

- Servo axes in two directions: Z axis (focus axis) and Y axis (normal to elevation antenna axis);
- helium line for cryogenic receivers is available but it needs a refurbishment;
- maximum loads on servo axes = 350 Kg;
- in case different receivers are to be moved to the focal position, a volume of about 0.64 m^3 (0.75x0.9x0.95 m (Y,X,Z)) is available;
- as an alternative, a volume of about 0.85 m^3 (1.0x0.9x0.95 m (Y,X,Z)) is available for the installation in fixed position of a single multi-feed or PAF receiver.

Current status

In the Primary focus position a box is installed, hosting a coaxial, uncooled, S/X-band receiver.

Focal Position F_2 (Cassegrain focus)

Facilities

At the center of the primary mirror dish, there is a room (vertex room) of about 27 m^3 where receivers and others services and devices are installed:

- Helium line for cryogenic receivers
- up to nine coexisting receivers can be installed, from C-band to higher frequencies:
  - one receiver can be installed on the optical axis with or without a mechanical rotator. Therefore this position is suitable for multi-feed front-ends like for instance a 7-beam K-band receiver;
  - concentric to the antenna optical axis, up to eight receivers can be installed on a radius of 0.735 m 45 degrees apart. Each receiver must be inclined at an angle of

4.2 degrees, pointing toward the primary focus; the subreflector is consequently tilted in order to point to the selected receiver. In these eight positions, receivers operating in C band are allowed only if mono-feed, while from X band to higher frequencies also dual-feed receivers can be installed. Furthermore, the installation of a mechanical rotator is not possible.

Current status

In the Cassegrain Focus position, four receivers are available:

- Clow-band receiver, mono-feed, cryogenic;
- Chigh-band receiver, mono-feed, not cooled;
- K-band receiver, mono-feed, cryogenic;
- Q-band receiver, mono-feed, cryogenic.

1.3 Sardinia Radio Telescope

The 64m antenna was inaugurated on 30th September 2013 just before the completion of the technical commissioning, which lasted from June 2012 to October 2013. The years 2014 and 2015 were dedicated to astronomical validation activities. Finally, the Early Science Programme took place in the period Jan 2016 - August 2016.

Optical configuration

Primary mirror dish (D): 64 m shaped profile with an active surface system consisting of 1116 actuators

Secondary mirror dish (d): 7.9 m (concave – shaped profile)

Tertiary mirror dishes (portions of ellipsoid): M3 (size: 3.9 – 3.7 m), M4 (3.1 – 2.9 m) and M5 (3.0 – 2.8 m)

Primary mirror focal length (F_1) = 21.0234 m
Focal Ratio (F_1/D) = 0.33

Gregorian focal length (F_2) = 149.87 m
Focal Ratio (F_2/D) = 2.34

Beam waveguide foci (F_3 and F_4)
M3 + M4 focal length (F_3) = 83.91m
Focal ratio (F_3/D) = 1.37
M3 + M5 focal length (F_4) = 179.87m
Focal ratio (F_4/D) = 2.81

In combination with an appropriate rotation of M3, two additional mirrors (M6 and M7), planned to be added at a later stage, can produce two more foci for Space Science applications.

Total surface accuracy (**RSS**): 305 μm (antenna efficiency is quite constant vs. elevation, due to the primary mirror active surface system compensating for gravitational deformations).

Aperture Efficiency (theoretical maximum, i. e. not including surface effects ≈ 60%)

- 52% @ 6.7 GHz (measured);
- 56% @ 22 GHz (measured);

- 43% @ 43 GHz (expected with 305 μm).

Pointing Accuracy

On both axes, azimuth and elevation, 0.002 degrees RMS. Thanks to an accurate pointing model, the pointing doesn't need to be calibrated during standard antenna operations.

Frequency Agility

It is possible to change the observation configuration of the antenna by fast switching among the receivers, as reported in the following:

- between receivers installed on Prime Focus within 2 minute max;
- between receivers installed on Gregorian Focus or Beam-waveguide (BWG) within 2 minute max;
- between Prime Focus Receivers to Gregorian Focus Receivers or vice versa is possible within 4 minutes.

Focal Position F_1 (Primary focus)

Facilities

- Servo axes PFP in three directions: Z axis (focus axis), X axis (parallel to the elevation axis) for receivers translation and swing axis (perpendicular to the elevation axis) with a rotation 0 – 76 degrees to place PFP on focus from parking condition and vice versa. The swing axis is also used to compensate quadripod gravity deformations;
- on the PFP two Helium lines for cryogenic receivers are installed. Each line has its own compressor located in the basement room;
- Maximum loads on servo axes = 1700 Kg;
- An overall volume of about 6.7 m^3 (2.97x1.5x1.5 m (X,Y,Z)) is available for placing boxes where mono-feed, dual-frequency, multi-feed, or PAF receivers can be installed;
- In this focus, frequencies from 0.3 to 22 GHz are allowed due to the active surface system that allows the primary mirror profile to be modified from shaped to parabolic.

Current status

In the Primary focus position three receivers are installed

- P/L band receiver, coaxial, cryogenic;
- X/Ka band, coaxial, not cooled;
- a holographic receiver.

Focal Position F_2 (Gregorian focus)

Facilities

At the center of the primary mirror dish there is a room (vertex room) of about 200 m^3 where receivers and other services and devices are installed:

- Three Helium lines are available. Each line has its own compressor in the basement room;
- a Gregorian rotation turret system is available where up to seven coexisting receivers with maximum dimension 1.1 m^3 (0.6x0.6x2.9 m (X,Y,H)) can be installed, starting from C band to 116 GHz . In these seven positions, mono- dual- and multi-feed receivers are allowed, with or without a mechanical rotator. By rotating the turret system, each receiver can be placed on the optical axis.

Current status

In the Gregorian focus position one receiver K-band, multi-feed 7-beams, cryogenic is installed.

Focal Positions F_3 and F_4 (BWG foci)

Facilities

- It is possible to place the Gregorian rotation turret system in by-pass position. This position allows the beam to reach the BWG room where a rotating mirror (M3), placed 7 m from F_2, reflects the beam to different positions. Currently, reflection from M3 can be intercepted by two mirrors (either M4 or M5);
- two Helium lines are available. At the moment one compressor is available in the basement room;
- for each focal position only one mono-feed receiver can be installed, from L band up to 32 GHz;
- receivers in the BWG foci are parallel to the optical axis.

Current status

In the BWG Focus F3 one receiver Chigh-band, mono-feed, cryogenic is installed.

1.4 Status and perspective of the Medicina Radio Telescope

In the following a chronology starting from 2012 is reported, including a brief description of the maintenance and upgrades that resulted in major stops of the antenna for on-site installations.

Year 2012

Replacement of the Helium lines for the cryogenics receivers on both primary and Cassegrain focus. Antenna stop: 15 days on weeks 12 and 13, for on-site installation.

Year 2014

Telescope out of service for about 10 months, due to unexpected breakages of mechanical parts and already planned maintenance:

a) Complete revision of one driving wheel bogie was needed due to an unexpected breaking on the wheel shaft. Antenna stop: 90 days from week 14 to week 26, for on-site installation

b) Replacement of the antenna elevator. Antenna stop: 50 days from week 24 to week 30, for on-site installation

c) Complete upgrade of the subreflector and Primary Focus Positioner Servo Systems, including their software. Antenna stop: 85 days from week 28 to week 39, for on-site installation and test

d) Replacement of the gears segments and pinion of the elevation drive system. Antenna stop: 70 days from week 42 to week 51, for on-site installation and alignment

Year 2015

Painting of the antenna steel structure and of the backsides of the primary mirror panels. Antenna stop: 50 days from week 13 to week 19, for on-site work.

Planned maintenance - Year 2017

a) Replacement of the azimuth track and of the other driving wheel bogie. An antenna stop of about 40 days is foreseen for on-site installation and alignment, scheduled in May and June

b) Painting of the primary mirror panels reflecting surface. An antenna stop of about 30 days is foreseen for on-site work, scheduled during September and October

Conclusion

In order to guarantee the reliability and efficiency of the telescope for scientific observations, during the years from 1996 to 2003 a number of upgrades of structural parts and replacement of obsolete parts (like the Servo System) were designed and implemented on the Medicina antenna.

A long period of intensive use of the radio telescope followed, lasting for about 11 years until 2014 and during which the antenna stops were due to ordinary maintenance only.

Tab. 1.I summarizes all the maintenances and upgrades (both already executed and to be done) from 1996 onward.

ITEMS	***MAINTENANCE*** Made in Year *Planned in Year*	***REPLACEMENT*** Made in Year *Planned in Year*	***REPAINTING*** Made in Year *Planned in Year*
AZIMUTH AXIS			
Azimuth Track		1996; 2000; **2017**	
4 Azimuth Wheel Bogies (2 Driving/2 Idle)		1996	
First Azimuth Driving Wheel Bogie		2014	
Second Azimuth Driving Wheel Bogie		**2017**	
Azimuth Gears		*NEVER DONE*	
Concrete Foundation Proofing	1996; 2015		
SUBREFLECTOR and PRIMARY RECEIVER POSITIONER			
Subreflector Hw + Servo Driving System	2014	1996	
Primary Rx Hw + Servo Driving System	2014	1996	
MIRROR SURFACE			
Primary Mirror Surface			2002; **2017**
Subreflector Mirror			2002; 2014
ELEVATION AXIS			
Elevation Axis Gear And Pinion		2014	
Elevation Gears		*NEVER DONE*	
SERVOSYSTEM			
Azimuth/Elevation Servosystem		2003	
Cabling		2003	
MISCELLANEOUS			
Antenna Steel Structure, Painting			2015
Elevator		2014	
He Pipeline		2012	

Table 1.I – 32-m Medicina antenna, maintenance and upgrade summary

Enhancement of the Medicina telescope efficiency could be made to allow observations at 43 and 86 GHz, and consequently make it possible the participation in 3 mm VLBI network experiments. This could be achieved in two possible ways. The first option would consist in providing the Medicina antenna with an active surface system like the other two Italian facilities. An alternative option would foresee the substitution of the primary mirror panels and of the subreflector surface. Further details are given in Appendix D. Besides that, it must be stressed that both panels and subreflector surface are more than 35 years old, and their substitution/upgrade would be motivated merely by maintenance-related considerations.

1.5 Status and perspective of the Noto Radio Telescope

In the following a chronology starting from 2010 is reported, including a brief description of the maintenance and upgrades which resulted in major stops of the antenna for on-site installations.

Year 2010 - 2012

A long period of stop for the Noto antenna started in March 2010 due to an unexpected breakage on the driving wheel bogie. The telescope stayed out of service for about 30 months until August 2012, to perform:

a) replacement of the azimuth track with the new-design already built at Medicina, which foresees a continuous annular steel plate between the track and the concrete grout
b) Replacement of the four wheel bogeys
c) Proofing and painting of the concrete foundation

ITEMS	*MAINTENANCE* Made in Year	*REPLACEMENT* Made in Year	*REPAINTING* Made in Year
AZIMUTH AXIS			
Azimuth Track		2011	
4 Azimuth Wheel Bogies (2 Driving/2 Idle)		2011	
Azimuth Gears		*NEVER DONE*	
Concrete Foundation Proofing	2011		
SUBREFLECTOR and PRIMARY RECEIVER Positioner			
Subreflector Hw + Servo Driving System	2014	1998	
Primary Rx Hw + Servo Driving System	2014	1998	
MIRROR SURFACE			
Primary Mirror Surface + Active Surface System		2002	2014
Subreflector Mirror		2002;2015	2014
ELEVATION AXIS			
Elevation Axis Gear And Pinion		*NEVER DONE*	
Elevation Gears		*NEVER DONE*	
SERVOSYSTEM			
Azimuth/Elevation Servosystem		2002	
Cabling		1996; 2015	
MISCELLANEOUS			
Antenna Steel Structure, Painting		NEVER DONE	
Elevator	2015		
He Pipeline			

Table 1.II – 32-m Noto antenna, maintenance and upgrade summary

Year 2014 - 2015

a) As a step toward the implementation of the frequency agility facility, the support allowing up to nine receivers to be mounted was installed on top of the vertex room

b) Painting of the primary mirror panels reflecting surface. Antenna stop: about 4 months from September 2014 to January 2015, for on-site installation and painting work

c) Upgrade of the Subreflector and Prime Focus Positioners Servo System (mechanical parts only). Antenna stop: about 2 months in November and December 2015, for on-site installation and test

Upgrade and maintenance planned in coming years

a) As the last step towards frequency agility, a mechanical refurbishment of all the existing receivers must be done in order to allow their installation

b) Upgrade of the Servo System drives (electric and electronics part, plus control software) for the subreflector and Prime Focus positioners

c) Refurbishment and upgrade of the active surface system

d) Replacement of the subreflector with a new one having better surface accuracy

e) Painting of the antenna steel structure and of the backsides of the primary mirror panels

Tab. 1.II summarizes all the maintenances and upgrades (both already executed and to be done) starting from 1998 onward.

1.6 Status and perspective of the Sardinia Radio Telescope

The telescope is in its early stages of scientific use. The commissioning terminated in 2015 and a 6-month Early Science Program has been run from February to August 2016. The telescope has now entered a shutdown phase that will last till the end of 2018 for two major works: migration of control room and equipment room to the new buildings and repair of the active surface actuators, as presented in a Workshop held in Cagliari in December 2016 and open to all INAF staff.

The operations of the Early Science Program were run from temporary control and equipment rooms and the final new buildings for regular operations were recently completed; they comprise offices, control room, and equipment/shielded room. The work to procure and set up all equipment to gear them up is in progress and the migration will take place during 2017. The second work consists in the repair of the active surface actuators that went through an unexpected and rapid corrosion phenomenon. The repair work is expected to end by September 2017.

A commissioning period will follow, in order to test and calibrate the new surface as well as to test all the observation operations from the new control and equipment rooms. This commissioning activity is expected to last until the end of 2018. Full SRT operations are expected to resume in 2019.

2. Back-end, opacity and Radio Frequency Interferences

This Chapter gives information about the present data acquisition equipment at the Italian radio telescopes, together with an overview of the atmospheric noise and radio frequency interference situation.

2.1 Software integration at the Italian radio telescopes

All the three Italian reflector antennas run the same telescope control software, developed by the team of the DISCOS project [1]. The control system version installed at MED, called Enhanced Single-Dish Control System, has been available since 2008 for software and hardware commissioning purposes, and since then it has become the control system used for single-dish observations. The version implemented at the SRT, called Nuraghe, has been available since the very first phases of the telescope technical commissioning. More recently, ESCS has been installed also in Noto and its commissioning is ongoing at the time of writing this Report.

This common infrastructure provides a twofold advantage. On one hand, the integration of new receivers and back-ends can be indifferently performed and tested at any of the three Italian sites. On the other hand, a receiver or back-end could be replicated at each telescope with a limited effort (see below the example of SARDARA at SRT and Medicina). This is specially true for the receivers, where all the integration phases are already designed and implemented between 2006 and 2012. These phases concern all aspects of the receiver control: electronics/firmware, high level libraries and antenna control software (DISCOS).

The architecture is illustrated in Fig. 2.1, and is intended to be used for any further receiver development. It is a reliable and well tested receiver control system, deployed on all available SRT receivers (P/L-, K-, and Chigh-band), and on the K-, X-, Chigh- and Clow-band Medicina receivers.The upcoming SRT S-band receiver will also be controlled by this system.

In order for a receiver to be controlled by this system, two teams have to be contacted during the receiver design phase: the Medicina staff coordinates the board integration and the DISCOS team takes care of the software integration.

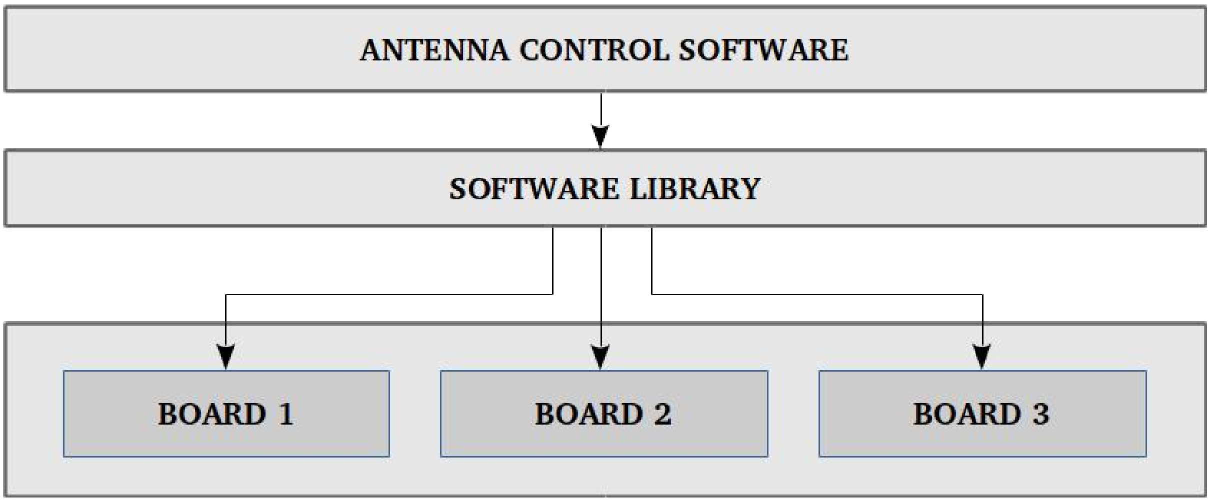


Figure 2.1 – Receiver control system at the Italian radio telescopes

Firmware

Each receiver must be controlled by at least two boards, hosted inside the receiver itself. One board monitors the LNAs values (voltages and currents), and the other one controls the dewar. Sometimes a third board is required, in order to control additional components. At the SRT, the K- and C-band receivers host two boards while the P/L-band receiver hosts three boards. Each board has a micro-controller that executes a firmware accepting commands from outside the receiver (via TCP socket) and making actions depending on the issued command. Commands are encoded using a binary custom protocol, designed at IRA [2]. The board, the firmware and the protocol have been designed at Medicina. The protocol has been implemented by the DISCOS team, as reported below.

Library

In 2012 the DISCOS team implemented a C++ library to communicate with the boards. The library has two independent layers: a lower level one implementing the binary protocol, and a second layer implementing a high level API.

Antenna control software (DISCOS)

To be fully operative, a receiver must be integrated in the antenna control software. In this way it could be configured and operated during observations with DISCOS. This integration step is in charge of the DISCOS team and usually requires about one month of work.

Derotator

The DISCOS team also implemented a software component that allows the dewar rotation, in case of multi-feed receivers. This prevents the field rotation during long acquisitions (while performing OTF/raster mapping or simple sidereal tracking). In order to use the derotator component the receiver feeds must be symmetric, that is, the angle between two feeds has to be the same for all the feeds. Several configuration are available, like the so called Best Space Coverage, Fixed or Custom [3].

2.2 Back-ends at the Italian radio telescopes

This Section illustrates the back-ends available at SRT, Medicina, and Noto. Each back-end is described in a dedicated subsection, containing essential information according the following scheme:

- Technical specification: a sketched description of the instrument is provided along with some technical data
- Remarks: some relevant facts regarding the instrument and its possible future developments
- Status and integration at the telescopes

As the back-ends and the telescope control software are closely related, an optimal exploitation of the back-end capabilities is available in terms of observing modes, data handling, and scheduling.

2.2.1 Total Power

Technical Specifications

The total power detector is based on a voltage to frequency converter and a counter implemented in an FPGA chip [4].

Features	Continuum Selectable attenuator Four selectable IF filters Three selectable focal positions Fast switching of calibration diode
Number of inputs	Up to seven dual polarization or 14 single polarization
IF bandwidth	300 MHz, 730 MHz, 1250 MHz, 2000 MHz
Integration time	1-1000 ms
Spectral channels	Not applicable
Spectral resolution	Not applicable
Remote interface	Ethernet / TCP

Table 2.I – Technical data of the total power back-end

Remarks

At the SRT this back-end has proved to be very useful for general calibration purposes (pointing and amplitude calibration) and has been used for first light measurements. The total power back-end has been available at MED since 2008 and is being extensively used for single-dish scientific projects dedicated to blind surveys of the sky and source monitoring (see list of publications in Appendix C). This back-end has mild to severe issues in the presence of RFI.

Sardinia Radio Telescope

The back-end is presently installed in the EER. The SRT version is equipped with 14 boards in order to serve all IF chains of the K-band receiver. The C-band receiver and P/L coaxial receiver are also served exploiting the three different focal connectors in each board. At the SRT, this back-end acts as a focus selector for all other back-ends and is also the forwarder of the TTL square wave (through optical fiber) generated by other back-ends in order to drive the calibration diode. The total power back-end currently serves the DFB3 and, in the near future, also the DBBC. It is fully integrated in ESCS/Nuraghe; all the supported observing modes are available.

Medicina

Presently this back-end is installed in the control room and is equipped with four boards. Currently it can be used together with the C-band, X-band, and K-band (both feeds) receivers. It is scheduled to serve the DBBC for the fast switching of the calibration diode (80Hz, continuous calibration, during VLBI). It is fully integrated in ESCS; all the supported observing modes are available.

Noto

The back-end is installed in the control room and is equipped with two boards. In 2016 preliminary successful observations have been carried out using the C-band receiver, with the commissioning planned to be finished in 2017.

2.2.2 XARCOS

Technical Specifications

The system is composed of two ADC boards, each hosting four AD 250 MS/s converters. The signal is bandpass-filtered before digitization (125 MS/s complex). A 92-bit bus connects the ADC boards to the FFT board. This board hosts a FPGA chip that performs a radix 2 FFT [5, 6, 7].

Features	Full Stokes spectrometer Multiple, simultaneously-observed sub bands at different resolutions Tuneable bands Zoom-Mode, allowing observations at different resolutions and bandwidths.
Number of inputs	Up to eight pairs of IF signals, each pair representing the output of a full polarization receiver
IF bandwidth	125-250 MHz
Integration time	10 s
Spectral channels	2048
Spectral resolution	Up to 250 Hz
Remote interface	Ethernet / TCP

Table 2.II – Technical data of the XARCOS back-end

Remarks

XARCOS is presently the only spectrometer able to simultaneously exploit all the 7 feeds of the SRT K-band. The minimum integration time (10 s) is not compatible with On-The-Fly observing techniques. Beam switching or raster scanning are thus the only supported modes. No system temperature measurement is presently available, required to exploit some alternative calibration procedures. No control or monitoring of the input signal level is implemented and this sometimes causes problems of FFT overflow.

Sardinia Radio Telescope

XARCOS is installed in EER. Its inputs are directly derived from the focus selector. Two receivers are currently supported: the C-band and the K-band receivers. The supported observing modes are summarized in Tab. 2.III. This back-end is fully integrated in the telescope control software.

	XK77	**XK00**	**XK03**	**XK06**	**XC00**
Feeds	7	1	2	2	1
Receiver	K	K	K	K	C
Simultaneous bands (per feed)	1	4	2	2	4
Default bandwidth (MHz)	62.5	62.5 7.8125 1.953125 0.48828125	62.5 3.90625	62.5 3.90625	62.5 7.8125 1.953125 0.48828125
Full Stokes	Y	Y	Y	Y	Y
Bins	2048	2048	2048	2048	2048
ADC resolution (bits)	6	8	8	8	8

Table 2.III – Observation modes of XARCOS at SRT

Medicina

XARCOS is installed in the control room. The inputs are directly derived from the total power back-end. Two receivers are now supported: the C-band; and the K-band. The version deployed in Medicina is equipped with only one ADC board. The observation modes are summarized in Tab. 2.IV. This back-end is fully integrated in the control software.

	XK00	XK01	XC00
Feeds	1	2	1
Receiver	K	K	C
Simultaneous bands (per feed)	4	2	4
Default bandwidth (MHz)	62.5 7.8125 1.953125 0.48828125	62.5 3.90625	62.5 7.8125 1.953125 0.48828125
Full Stokes	Y	Y	Y
Bins	2048	2048	2048
ADC resolution (bits)	8	8	8

Table 2.IV – Observation modes of XARCOS at Medicina

2.2.3 SARDARA

Technical Specifications

The system is based on ROACH2 boards provided by the CASPER Consortium [8]. The boards are equipped with Virtex6 FPGA chips that guarantee high performance in terms of data processing and I/O streaming both through memory and network (up to 80Gbit/sec). The boards are supplemented by two ADC boards that work with 8 bits at up to 5GS/s.

Features	Full Stokes spectrometer Large bandwidth High frequency and time resolution
Number of inputs	1 pair of IF signals, representing the output of a full polarization receiver
IF bandwidth	500-2300 MHz
Integration time	Up to 0.5 ms
Spectral channels	1024 or 16384
Spectral resolution	About 90 KHz
Remote interface	Ethernet / TCP

Table 2.V – Technical data of the SARDARA back-end

Remarks

The large bandwidth, the high time resolution, and the good spectral resolution make this back-end a general-purpose device to be employed in many science cases: continuum; polarimetry; spectro-polarimetry; and wide- as well as narrow-band and multi windows spectroscopy.

Presently one ROACH chain is implemented, allowing exploitation of only one full polarization feed (2 IFs). Back-end development to support at least 14 simultaneous IFs, each with a bandwidth of 2.1 GHz, is foreseen in the near future. This further implementation will allow the full exploitation of the multi-feed K-band receiver installed at the SRT.

The Early Science Program was completed using a back-end software version that is partially integrated in the SRT control software. A fully integrated version, allowing a more flexible preparation and execution of the observation, is almost complete at the time of writing this report and will soon be available.

Currently SARDARA does not support fast calibration diode switching.

Sardinia Radio Telescope

SARDARA was offered and used during the execution of the Early Science projects. Presently it is installed in the box apparatus and it allows observations with all the available receivers. It relies on the focus selector attenuators and filters in order to feed the ADC board with a proper level signal and antialiasing filtering. For this reason the real sampled band is 1250 MHz (300 MHz if the P-band receiver is used).

Medicina

The needed infrastructure (hardware/computing/cabling) to deploy the SARDARA single-ROACH back-end has been prepared in the MED control room. The software and firmware installation was completed in December 2016 and the technical commissioning is ongoing.

2.2.4 Digital Filter Bank Mark 3

Technical Specifications

The DFB3 is a digital correlator developed by ATNF for pulsar and spectroscopic observations [9]. The hardware is based on two CABB boards. The CABB boards perform analog-to-digital conversion of two dual-polarization signals, each with a maximum total bandwidth of 1 GHz. These signals are sub-divided in frequency using a polyphase filter bank programmed into the CABB FPGA logic blocks, and streamed to the cluster switches via four 10 GbE connections. Two PCs control the correlator.

The possible observing modes are pulsar folding, pulsar search, spectroscopy and baseband.

Features	Full Stokes correlator Large bandwidth (1GHz) Dual beam Pulsar folding Pulsar search
Number of inputs	Two pairs of IF signals, with each pair representing the output of a full polarization receiver
Bandwidth	1024 MHz, 512 MHz, 256 MHz (narrower BWs are possible)
minimum sampling rate for pulsar search	It depends on the configuration and the computing power required. A typical value is 100 µs
Spectral channels	Max 8192, for pulsar folding is limited to 2048
Minimum pulsar period	From 8 µs to 8 ms depending on the configuration
Remote interface	Ethernet / TCP

Table 2.VI – Technical data of the DFB3 back-end

Remarks

The DFB3 back-end is currently available at the SRT site. For any update or problem solving the support of the ATNF team is indispensable.

Sardinia Radio Telescope

This back-end is installed at the SRT only. Pulsar folding and pulsar search are the only observing modes offered to the observers. A list of all the available configurations for the DFB3 can be found in [10, 11, 12, 13]. The DFB3 has a dedicated control software, called SEADAS, which is interfaced with the SRT telescope control system.

2.2.5 Digital Base Band Converter

Technical Specifications

The DBBC is a European VLBI network project developed under INAF's leadership [14]. The system is essentially composed of an Analog Conditioning Module, an Analog-Digital converter (ADboard2), a Data Processing Unit (Core2board), a Time and Clock board, and a Control Computer. An optional board (FILa10G) implements a multidirectional "triangle" I/O connection:

- 2x10Gb/s optical fiber;
- 2VSIx64ch@128MHz (from VSI connectors);
- 1 High Speed , 10 bit, channel (connected to ADBoard2);
- Internal or external version.

The Conditioning Module and the AD conversion can be shortlisted as follow:

- Analog Input: 0-3.5 GHz;
- 4 RF/IF input selection;
- Sampling clock: 2.2 GHz;
- Piggy back connection to FILa10G.

The basic processing unit (Core2):

- FPGA based, programmable architecture;
- Max I/O data rate: 32.768 Gbps.

Thanks to the flexibility of the FPGA of the Core2Board, this architecture allows the design of a general-purpose back-end both for VLBI and single-dish activities.

VLBI observations are performed by exploiting the base-band-converter firmware. In this case a single Core2 board provides 4 BBCs computed in one of the four IF inputs ranging from 0-512, 512-1024, 1024-1536, 1536-2048, 1-1024 or 1024-2048 MHz. The BBC can be tuned at 1 Hz resolution and provides from 512 KHz to 32 MHz, upper and lower, sideband. No firmware for single-dish observations with the DBBC is currently available at the Italian antennas.

Remarks

Recent developments provided the network with a PFB firmware. A successful fringe test with 32x32 MHz bands corresponding to a full 512 MHz dual polarization band (4Gb/s @ 2 bits/sample) was conducted the first half of 2016. The third generation of this digital back-end (DBBC3) is also available. The DBB3 essentially provides a larger exploitable bandwidth in view of the EVN wide-band VLBI and the VGOS ultra-wide-band VLBI system.

Sardinia Radio Telescope

At the SRT a DBBC2 unit with 4 Core2boards (16 BBCs) is installed. An internal FILa10G is also available. A PFB firmware was also available at the SRT, a configuration designed for RFI monitoring purposes. This application is deployed in piggy-back mode when the telescope is not running a VLBI experiment.

Medicina

At Medicina a DBBC2 unit with 4 Core2Boards (16 BBCs) is installed. An external FILa10G is also available.

Noto

At Noto a DBBC2 unit with 4 Core2Boards (16 BBCs) is installed.

2.2.6 ROACH-1

Technical specifications

The ROACH-1 back-end is an FPGA-based board that was developed by the CASPER Consortium [15]. It consists of a Xilink Virtex 5 FPGA, together with two ADC boards. It provides 32 complex channels of 16 MHz each, for a total bandwidth of 512 MHz.

Features	Recording of raw (baseband) voltage data onto disk (to be reduced at a later time) Real-time folding and coherent de-dispersion for pulsar timing Spectrometer
Number of inputs	2 single polarization inputs
Bandwidth	up to 512 MHz for each polarization, in multiples of 16 MHz
Minimum sampling rate for pulsar search	1024 MS/s, 8-bit
Spectral channels	
Minimum pulsar period	
Remote interface	communicates with Nuraghe via externalClient

Table 2.VII – Technical data of the ROACH-1 back-end

Remarks

The ROACH-1 back-end has been commissioned in the context of the LEAP project starting in July 2013. It has mostly been used in pulsar mode, both for pulsar timing and pulsar searching. It allows for both baseband recording (for LEAP observations), and real-time folding and de-dispersion (for EPTA observations). The ROACH-1 will continue to be used for LEAP and EPTA observations. Aside from the pulsar mode, the ROACH-1 can also be configured to do spectroscopy.

Sardinia Radio Telescope

The back-end is presently installed in box-AP. The back-end is not integrated in Nuraghe. It currently communicates with Nuraghe via the ExternalClient.

2.2.7 DiFX Bologna Correlator

The Italian antennas are part of an Italian network that allows the execution of VLBI observations at 1.6, 5, 6, 13 and 23 GHz with a resolution up to 0.002 arcsec. The geodetic antenna in Matera (property of ASI) has also participated in some experimental geodetic VLBI observations together with MED and NOTO, and the data have been correlated with DiFX.

The DiFX software correlator consists of three servers and was successfully installed and placed in operation at IRA headquarters in 2012. Each server provides up to 50 TB of storage space to host the raw astronomical data coming from the antennas. The servers are connected with a 10 Gbit optical fiber line to the GARR and GÉANT networks. In addition, a 40 Gbit Infiniband connection is in place to allow fast MPI correlation processes for data residing on disks set up in RAID arrays allowing a up to 1 GB/sec throughput.

Thanks to this configuration, the servers can act as recorders for a direct network stream of data from the antennas that are connected through optical fiber, and are used both as storage space for postponed correlation and as raw data retrieval place for international VLBI observations (e.g. EVN or RadioAstron). As an example, the correlation processing rate with the DiFX software is of the order of 720 GB/h per antenna when correlating data recorded at 1 Gbit/s from three antennas.In such a case the correlation time would add further 2/3 of the experiment duration. At present, correlation is carried out including the new astronomical data standard VDIF.

Recent experiments also involved radio telescopes at Onsala (Sweden), Yebes (Spain), Torun (Poland) and Ventspils (Latvia), transferring their data through the network to IRA headquarters.

2.2.8 Additional notes on fast calibration diode switching

The fast-switch of the front-end calibration diode is a technique that permits gain variations in the receiving chain to be tracked. This allows the achievement of better data quality by improving the calibration. Both VLBI and single-dish observations benefit from this technique. In order to support this feature, a back-end must be able to generate the pulse train to turn on and off the diode and to adequately treat the samples. Presently the Total Power, DFB3 and DBBC back-ends provide this feature.

2.3 Opacity at radio telescope sites

This Section provides a brief description of the atmospheric conditions at the Italian radio astronomical facilities together with a comparison with other sites abroad.

2.3.1 Sardinia Radio Telescope

The SRT is equipped with an atmosphere monitoring system (ASM) [16, 17] that provides all the fundamental atmospheric parameters required for observation and the calibration, such as Tsys, opacity, PWV, ILW, and brightness temperature. The ASM is based essentially on a historical data archive (radio soundings time series, 1950-2016), on real time measurements (microwave radiometer, GPS, weather gauges), and on forecast data (time span = 48 h). The goals of the ASM are: (*i)* to characterize the atmospheric site parameters; (*ii)* to give a support to observations in real-time; and (*iii)* to forecast the weather conditions, to match the best experiment to the predicted atmospheric status (dynamic scheduling).

In the past, historical time series of radiosonde profiles conducted at the airport of Cagliari have been acquired. The radiosonde measurements and an appropriate radiative transfer model allowed a statistical analysis of the SRT site atmosphere that accounts for atmospheric opacity at different frequencies, PWV, ILW, and cloud cover distributions during the year [18]. This helped to investigate in which period of the year astronomical observations at different frequencies should be preferably performed. The quantities of interest have been calculated by using radiosonde profiles; the dataset embraces nearly 50 years of measurements.

The results show that K-band observations are possible all year round. Precipitable water vapor during winter months ranges, on average, between 8 and 17 mm, respectively, for 25% and 75% of the percentile (see Fig. 2.2). Fig. 2.3 indicates the amount of cloud during the year (ILW=0 means clear sky). The median opacity at 22.23 GHz is 0.10 Np in winter and 0.16 Np in summer (see Fig. 2.4). The atmospheric opacity study indicates that observations at higher frequencies may be performed usefully; the median opacity at 100 GHz is usually below or equal to 0.2 Np in the period that ranges from January to April (Fig. 2.5). Finally, Fig. 2.6 compares the effects between clear and cloudy sky at 100 GHz.

Tab. 2.VIII and 2.IX show for various frequencies the probability to get PWV, ILW and opacity values below specific thresholds throughout the year.

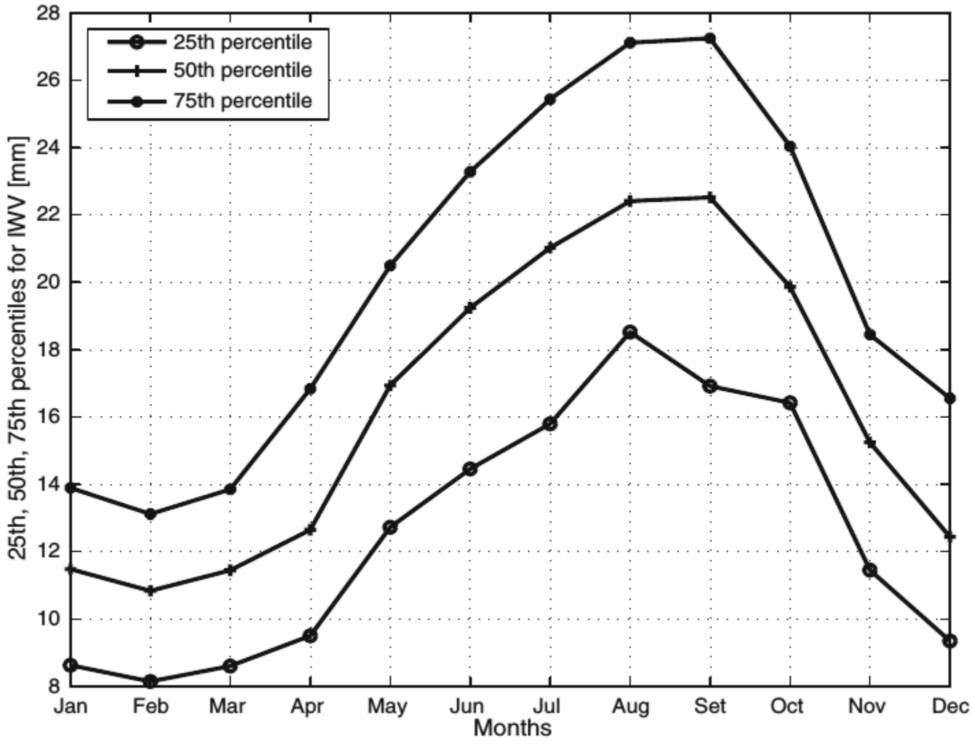


Figure 2.2 – Monthly quartile plots for precipitable water vapour at the SRT site

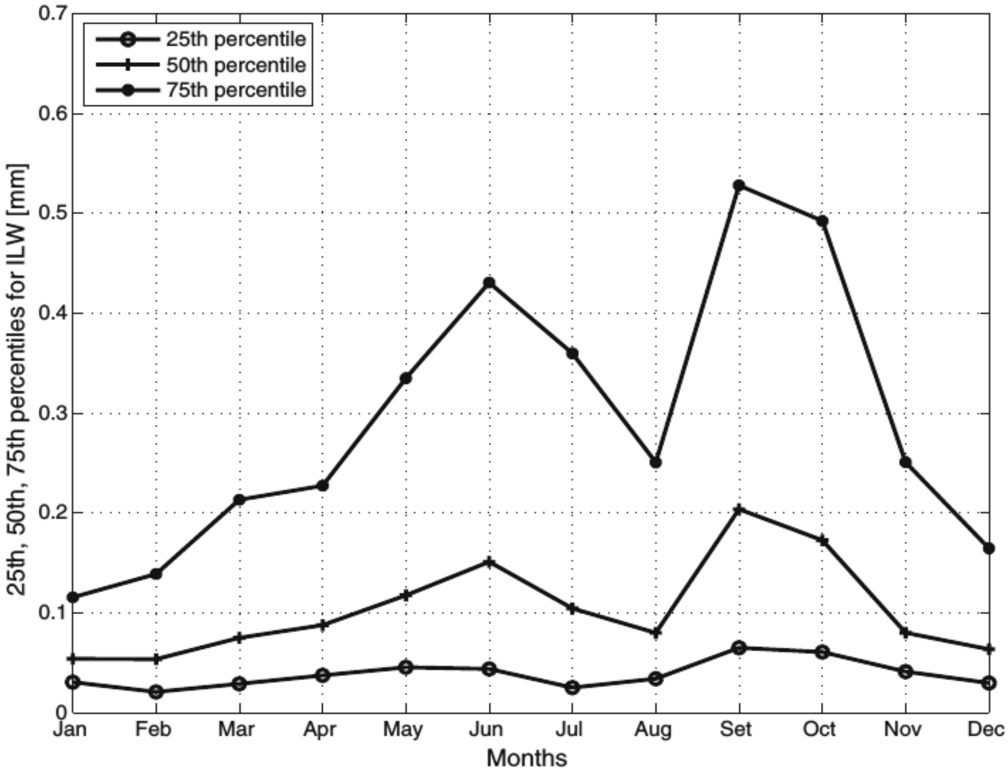


Figure 2.3 – Monthly quartile plots for integrated liquid water at the SRT site

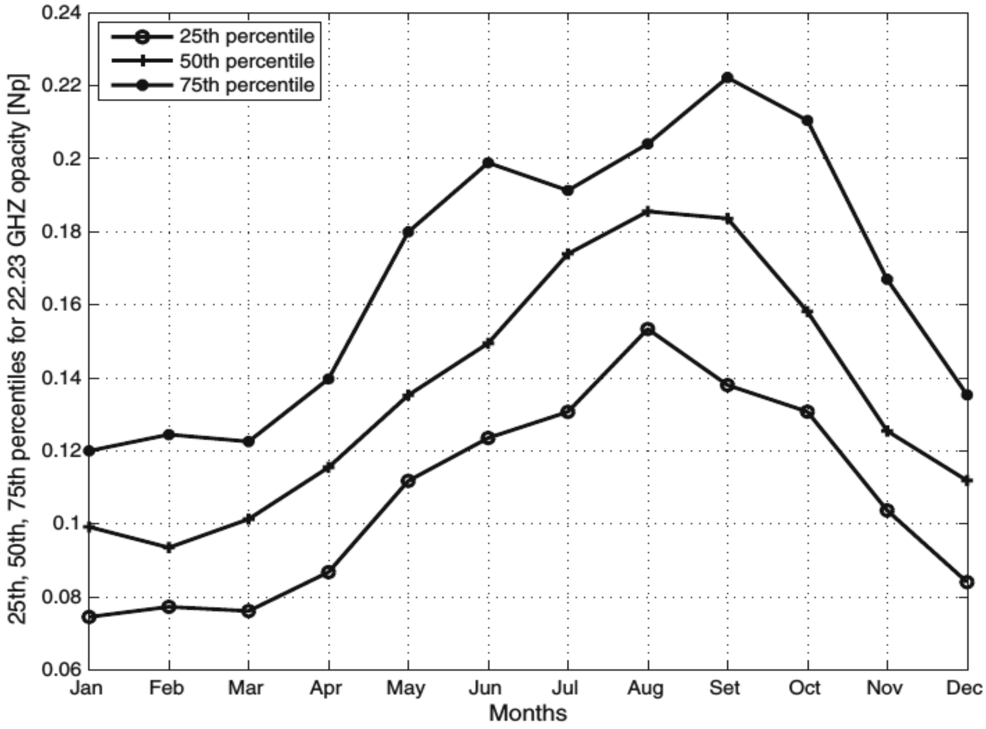


Figure 2.4 – Monthly quartile plots for 22.23 GHz opacity at the SRT site

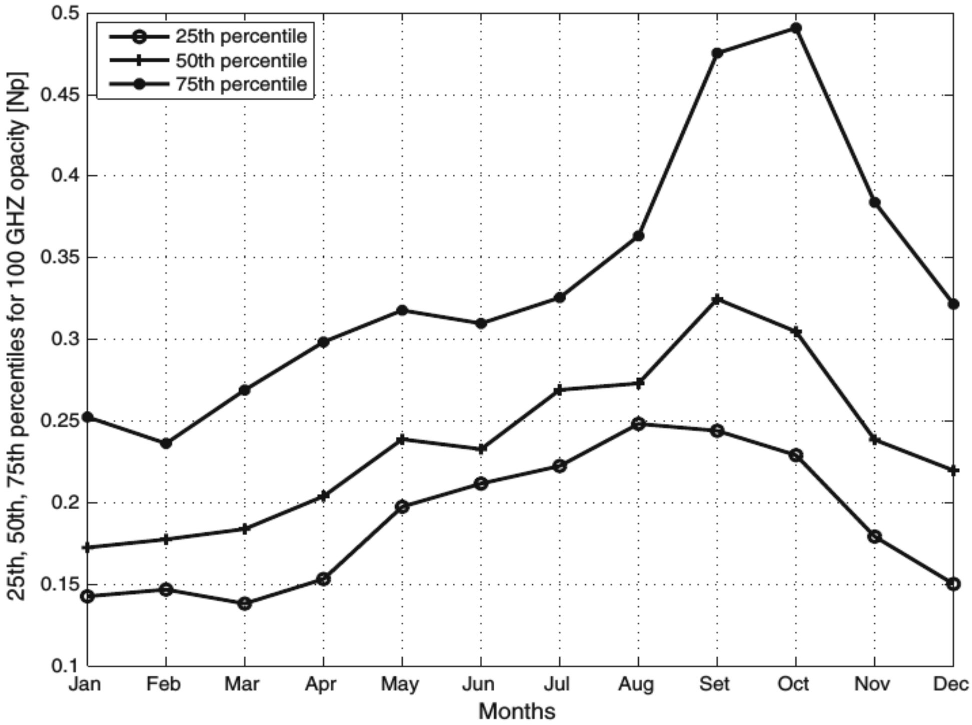


Figure 2.5 – Monthly quartile plots for 100 GHz opacity at the SRT site

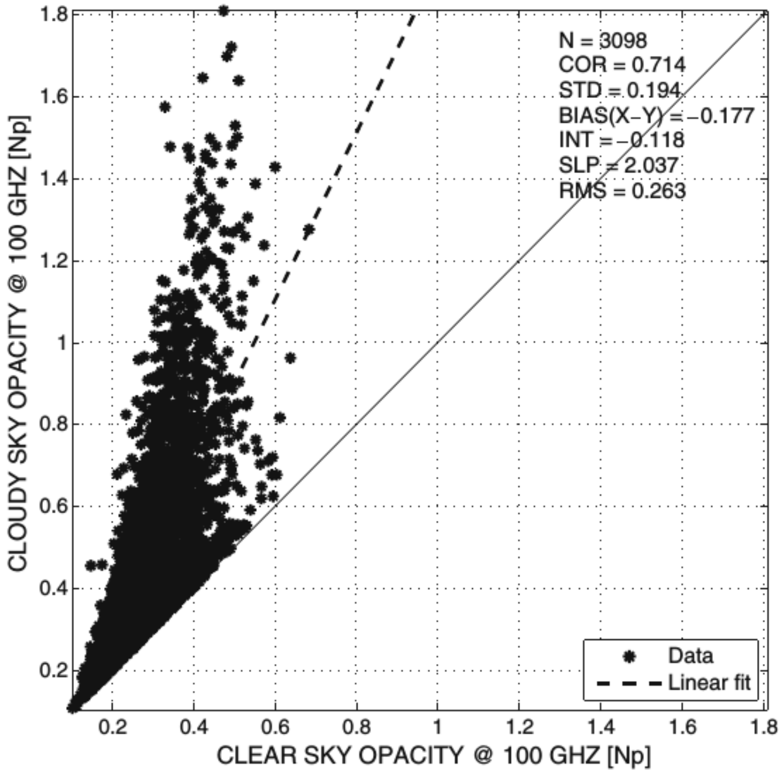
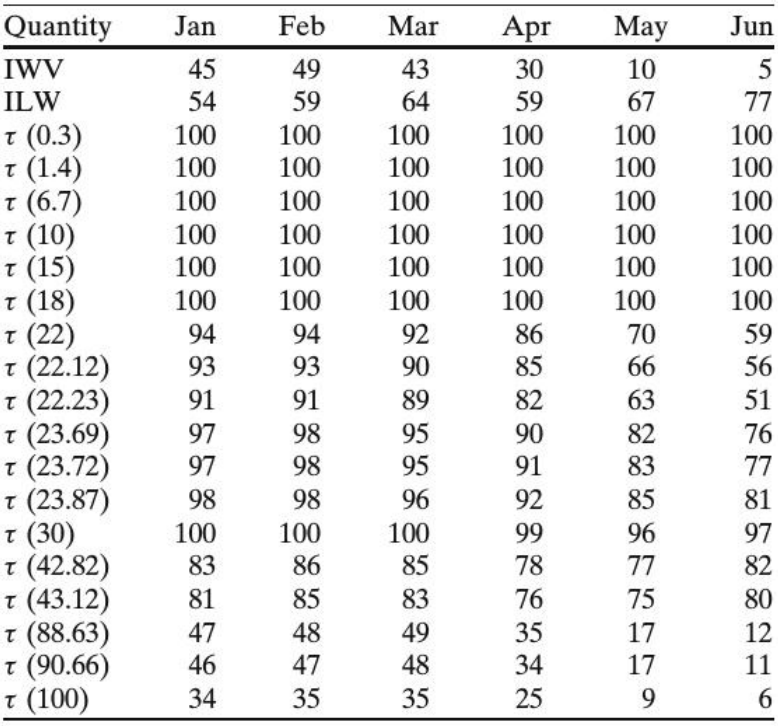
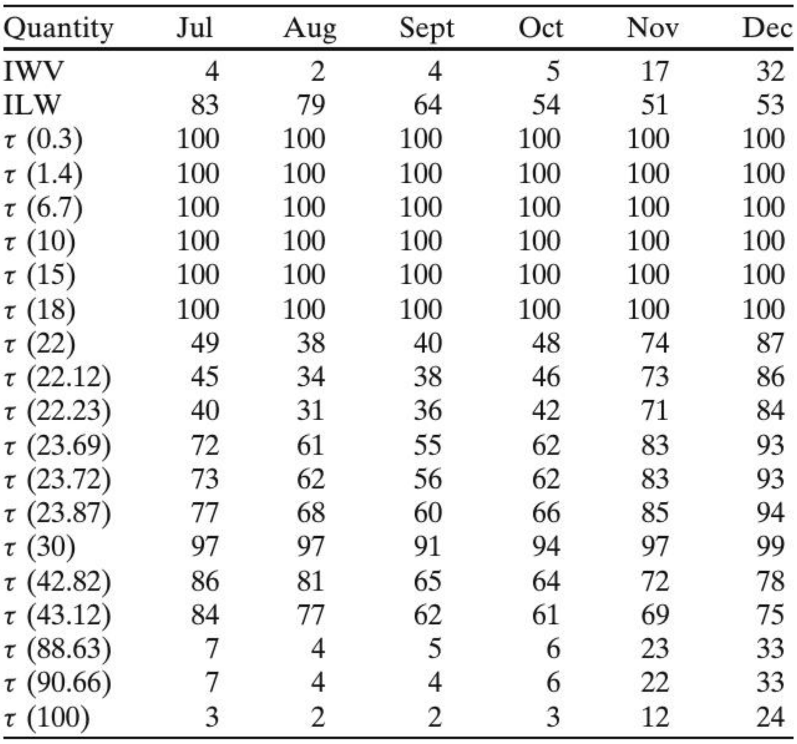


Figure 2.6 – Comparison between 100 GHz clear sky opacity and 100 GHz cloudy sky opacity, data simulated by using radiosonde measurements, ARTS radiative transfer model, and cloud liquid empirical model



Quantity	Jan	Feb	Mar	Apr	May	Jun
IWV	45	49	43	30	10	5
ILW	54	59	64	59	67	77
τ (0.3)	100	100	100	100	100	100
τ (1.4)	100	100	100	100	100	100
τ (6.7)	100	100	100	100	100	100
τ (10)	100	100	100	100	100	100
τ (15)	100	100	100	100	100	100
τ (18)	100	100	100	100	100	100
τ (22)	94	94	92	86	70	59
τ (22.12)	93	93	90	85	66	56
τ (22.23)	91	91	89	82	63	51
τ (23.69)	97	98	95	90	82	76
τ (23.72)	97	98	95	91	83	77
τ (23.87)	98	98	96	92	85	81
τ (30)	100	100	100	99	96	97
τ (42.82)	83	86	85	78	77	82
τ (43.12)	81	85	83	76	75	80
τ (88.63)	47	48	49	35	17	12
τ (90.66)	46	47	48	34	17	11
τ (100)	34	35	35	25	9	6

Table 2.VIII – Monthly percentage probability for PWV, ILW and atmospheric opacity to have in the January-June period values below specific thresholds: PWV (= IWV) < 10 mm, ILW = 0 mm (clear sky condition), atmospheric opacity τ < 0.15 Np at different frequencies expressed in GHz



Quantity	Jul	Aug	Sept	Oct	Nov	Dec
IWV	4	2	4	5	17	32
ILW	83	79	64	54	51	53
τ (0.3)	100	100	100	100	100	100
τ (1.4)	100	100	100	100	100	100
τ (6.7)	100	100	100	100	100	100
τ (10)	100	100	100	100	100	100
τ (15)	100	100	100	100	100	100
τ (18)	100	100	100	100	100	100
τ (22)	49	38	40	48	74	87
τ (22.12)	45	34	38	46	73	86
τ (22.23)	40	31	36	42	71	84
τ (23.69)	72	61	55	62	83	93
τ (23.72)	73	62	56	62	83	93
τ (23.87)	77	68	60	66	85	94
τ (30)	97	97	91	94	97	99
τ (42.82)	86	81	65	64	72	78
τ (43.12)	84	77	62	61	69	75
τ (88.63)	7	4	5	6	23	33
τ (90.66)	7	4	4	6	22	33
τ (100)	3	2	2	3	12	24

Table 2.IX – Monthly percentage probability for PWV, ILW and atmospheric opacity to have in the July-December period values below specific thresholds: PWV (= IWV) < 10 mm, ILW = 0 mm (clear sky condition), atmospheric opacity $\tau < 0.15$ Np at different frequencies expressed in GHz

2.3.2 Medicina and Noto Radio Telescopes

In the following plots statistics and measurements of opacity are shown for the Medicina observatory. The data and conclusions presented for MED are to be considered valid also for NOTO because historical measurement series of the Zenith Wet Delay (proportional to the PWV) taken during almost two decades with VLBI, radiosondes, and GPS techniques show a very similar trend [19] at the two sites.

Fig. 2.7 summarizes the results of daily atmosphere soundings made by balloons launched from the S. Pietro Capofiume station, a few kilometres away from the Medicina observatory. Only days with PWV ≤ 10 mm are taken into account because that threshold is an upper limit under which high frequency observations are worthwhile. Data collected are focused on a winter period, being the most favourable season for high frequency observations. On a total of 121 days per year (from 1 December to 31 March and considering that approximately 30 days per year are lost due balloon failure), the number of days with PWV ≤10 mm is around 50% of the winter period except two years.

One further topic to deal with is the amount of PWV fluctuation within every day. Since Capofiume sounds the atmosphere three times each day it is possible to get a rough statistics about this parameter. The main result is that days with PWV≤10 mm show absolute daily fluctuations mostly lower than 3 mm and about 25-30% with respect to daily mean value. This means that the whole 24 hours are available for observation in good days. Moreover, there are periods where the condition PWV≤10 mm persists for days, thus allowing the possibility of long observing campaigns at high frequencies.

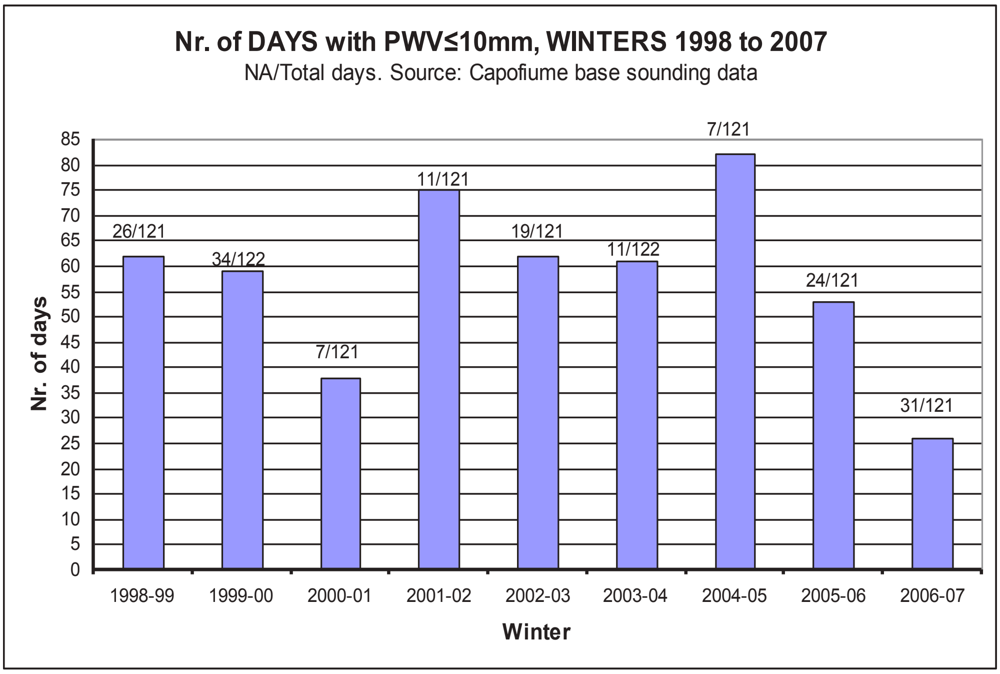


Figure 2.7 – Number of days suitable for observing at 90 GHz during winter at Medicina. For each year, the two numbers above the bar indicate the number of days without data and the total days respectively

Unfortunately, the Capofiume station stopped monitoring activity in 2008. Therefore, it is useful to compare sounding data with PWV values calculated by using meteorological data that are available for the site. Getting water vapour content by means of temperature, pressure, and relative humidity gives a rough evaluation of PWV. The PWV range considered was not limited to values lower than 10 mm. Fig. 2.8 shows that the RMS of the differences between measured and calculated PWV is about 4 mm and therefore the PWV computed from local meteorological data is an acceptable estimate.

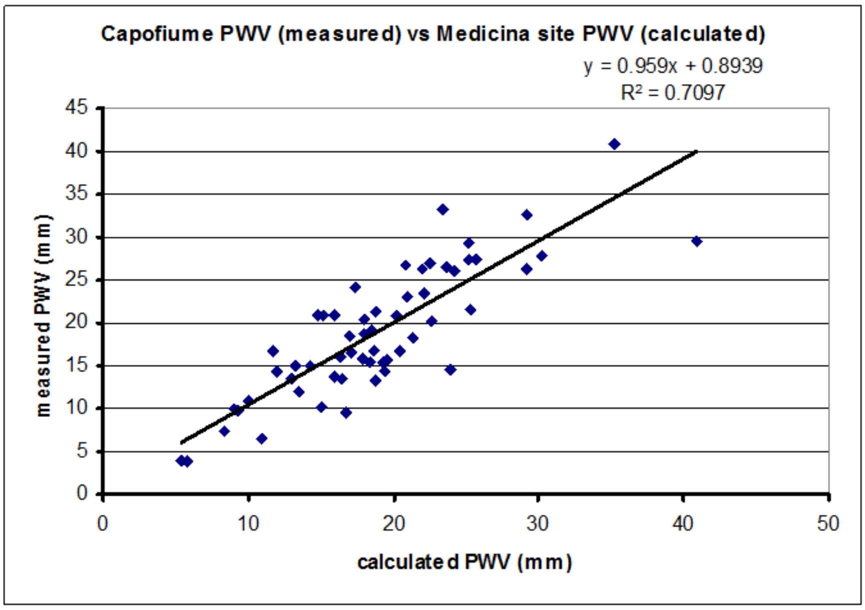


Figure 2.8 – Measured vs calculated PWV data

Finally, measurements of opacity at the zenith ($\tau 0$) at 22 GHz were performed by means of antenna sky-dips in the period May 2006 - March 2007, and were correlated with PWV data coming both from local meteorological data (Fig. 2.9) and from Capofiume sounding data (Fig. 2.10). Both plots show that the equations of the two straight lines interpolating τ0 data are very close each other.

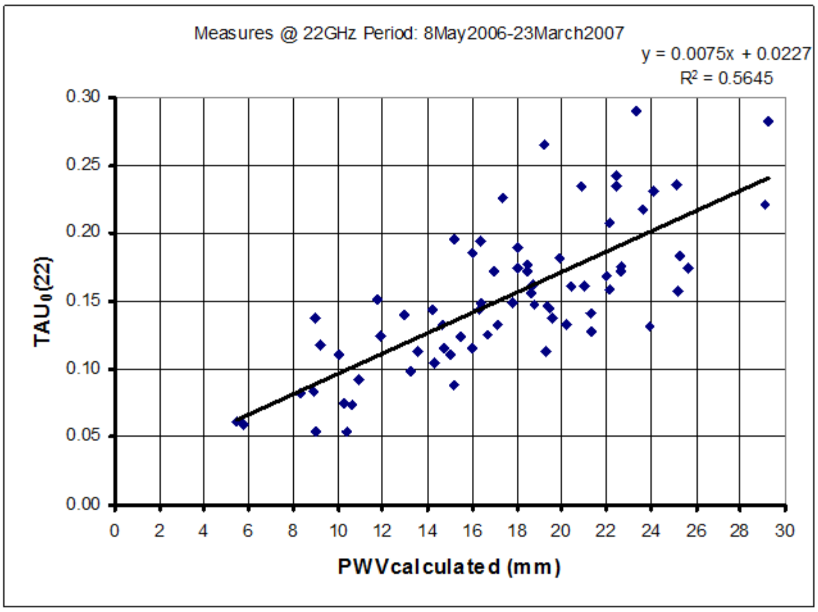


Figure 2.9 – Measured τ0 at Medicina observatory vs PWV from weather data at the site

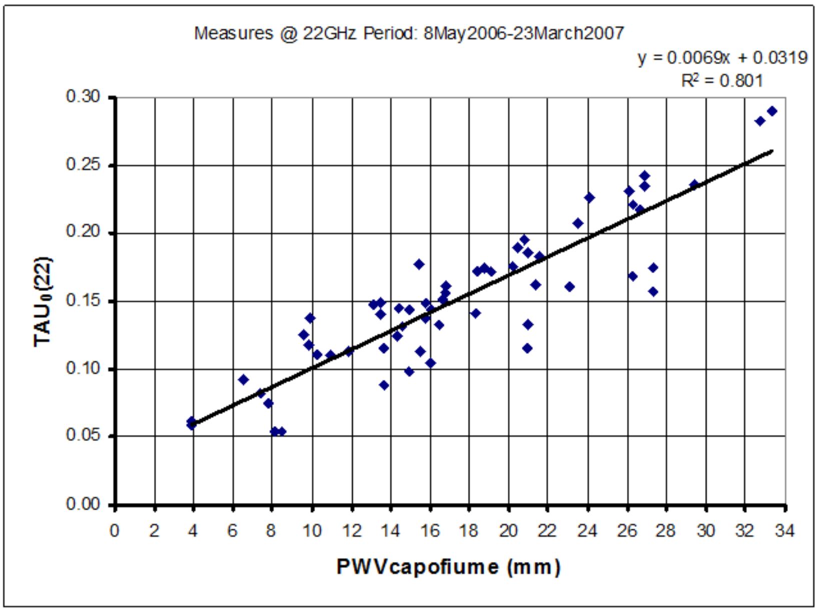


Figure 2.10 – Measured τ0 at Medicina observatory vs PWV from Capofiume base

The last step is to derive an estimation of τ0 at 90 GHz at the site from the knowledge of τ0 at 22 GHz. This has been done by using the ATM simulator (used at mm/sub-mm antennas like IRAM). Fig. 2.11 shows the opacity ratio at the two frequencies and suggests that for PWV≤10 mm τ0(90 GHz) is about 2-2.5 times τ0(22 GHz). Fig. 2.9 and 2.10 indicate that for water vapour content lower than 10 mm, the corresponding 22 GHz opacity at the zenith is ≤ 0.1. Therefore, it could be stated that for the days included in Fig. 2.7 the opacity at 90 GHz could be estimated to be ≤ 0.25.

In [20] calculations show the performance at 3 mm of the Italian 32-m antennas.

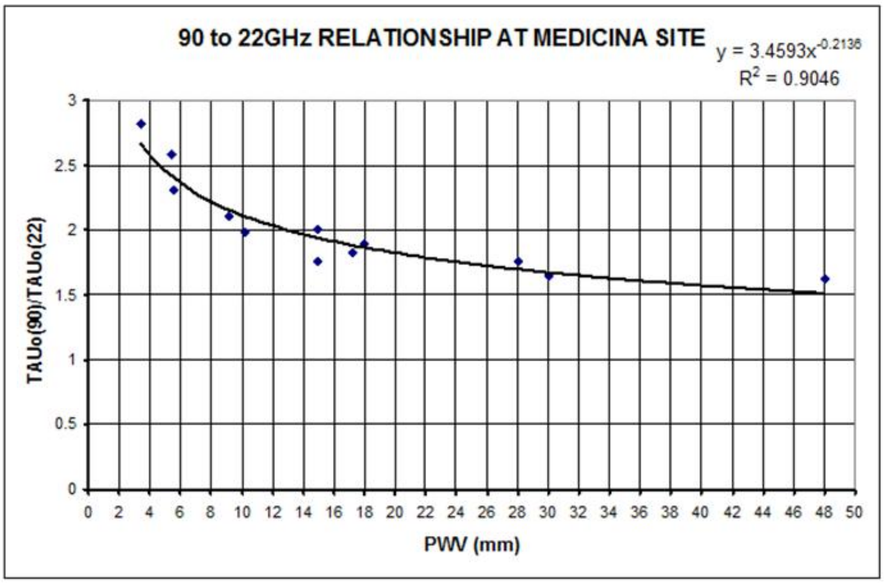


Figure 2.11 – 90 to 22 GHz opacity ratio vs PWV

2.3.3 Opacity at International Radio Telescopes

The performance at high frequencies, like the 3 mm band, is heavily influenced by the amount of water vapour column at the site and, in turn, this is strictly correlated with the altitude of the telescope location. This is the reason why telescopes designed to work at frequencies higher than 90 GHz, like Pico Veleta, must be placed at very high altitude. The Nobeyama radio telescope, which works between 20 and 116 GHz, exploits its high altitude, while the KVN copes with its sea level altitude despite working between 20 and 140 GHz. Tab. 2.X ranks the altitude of each radio telescope considered in this report. Besides different altitudes of the radio telescopes another caveat that should be considered is that for some observatories data are present at about 86 GHz, while for others at 100 GHz and the opacity values at these two frequencies are quite different.

TELESCOPE	*Altitude (m)*	*Data*
Pico Veleta	2850	Yes
Nobeyama	1349	No
Yebes	931	Yes
Mopra	860	No
GBT	807	Yes
SRT	600	Yes
Parkes	415	Yes
Effelsberg	319	No
KVN	120; 260; 320	Yes
NOTO	78	Yes
VERA	60	No
MED	25	Yes
Onsala25 + Onsala20	20	Yes
Tianma	7	No

Table 2.X – Altitude of the radio telescopes and opacity data available for analysis

The best single-dish radio telescope working at millimeter wavelengths, in particular at 3 mm, included in our analysis is the Pico Veleta antenna. There are however other telescopes, such as the GBT, Onsala, Nobeyama, the three KVN antennas, and Yebes that, besides observing at centimeter wavelengths, are also equipped with receivers working at 90 GHz.

Based on the opacity data retrieved for some radio telescopes (third column in Tab. 2.X), some general comments on the Italian antennas compared to other sites can be drawn.

Typical winter opacities for Pico Veleta are about 0.06 (corresponding to IWV < 2 mm), while in poor winter conditions the opacities are about 0.08 (IWV ≤ 4 mm).

The GBT reports a zenith opacity at 86 GHz equal to 0.12 or less for 45% to 55% of the time, in the period October 1 - May 1. This corresponds to a PWV column of 10 mm [21].

Onsala reports a typical zenith opacity of 0.2, 0.3 and 0.8 at, respectively, 86, 100, and 115 GHz ([22] pag. 13).

Yebes is a very good site showing good values of PWV. The extreme values during a summer day for the water vapour content are 2 mm and 14 mm. However, the water vapour column in winter has an approximately constant value of 8 mm throughout the day which favors the observation in this season [23] and a corresponding winter opacity of 0.08 to 0.09 at 88 GHz [24].

Finally, KVN measurements [25] show good opacity values at 100 GHz for all three antenna sites, even if their altitudes are not very high. Reported values are 0.09 in January at Yonsei, 0.13 at Ulsan in April, and 0.12 at Tamna in December.

The median (50% of time) opacity at 100 GHz in the winter period at SRT is 0.2 (Fig. 2.5) and the corresponding IWV is 12mm (Fig. 2.2). In the first three months of the year, the SRT has a 50% probability of an opacity below 0.15 at 88 GHz (Tab. 2.VIII).

A rigorous comparison of the opacity at SRT and at other telescopes is out of the scope of this report. However, it is not presumptuous to say that at 86 GHz the SRT is well aligned to other telescopes placed at similar altitudes.

The MED and NOTO sites, despite their very low altitudes, show opacity values at 90 GHz below 0.25 in winter months, well aligned with the Onsala site.

2.4 Radio Frequency Interference at radio telescope sites

RFI is one of the most critical threat to radio astronomy. This is especially true when radio telescopes are not located in remote areas, as it generally happens in Italy and in Europe. Due to the growth of demand for new and more powerful telecommunications systems, spectrum management plays a fundamental role to keep the frequency bands used for radio astronomical observations free from interference.

The IMT related to the mobile phone and Internet access service represents an example of one of the most relevant threats to radioastronomy. In fact, during the 2015 ITU World Radio Conference an agenda item was dedicated to consider additional spectrum allocations for the mobile service on a primary basis, and to the identification of additional frequency bands for IMT up to 5 GHz. With respect to radio astronomy, the most relevant outcome from the WRC15 has been the identification of the bands 1427-1452 and 1492-1518 MHz for IMT worldwide. Additionally, even if the band 1452-1492 MHz was not identified for European countries, the primary mobile allocation and the ECC Decision (13)03 form the basis for IMT use of this band in Europe.

One of the agenda items for the next WRC19 is to identify frequency bands for the future development of IMT at higher frequencies (24.25-27.5 GHz, 31.8-33.4 GHz, 37-40.5 GHz, 40.5-42.5 GHz, 42.5-43.5 GHz, 45.5-47 GHz, 47.2-50.2 GHz, 47- 47.2 GHz, 50.4-52.6 GHz, 66-76 GHz, and 81-86 GHz). This agenda item will require a lot of attention from radio astronomers since a number of radio astronomy bands may be affected by these future IMT allocations.

During a meeting held in Medicina on October 2014 among radio astronomy specialists and a delegate of the Frequency Spectrum Management Division of the Ministry of Economic Development, the following (non-exhaustive) scenario for the frequency bands between 470 and 3800 MHz was foreseen by MISE:

- 400 MHz → Mobile and wireless applications such as the LTE technology for PPDR and PMR, as well as wireless microphones for PMSE
- 470-862 MHz → White Space Device based on cognitive technology
- 694-790 MHz → Radio mobile WB
- 790-862 MHz → Radio mobile
- 1452-1492 MHz → Radio mobile 5G
- 1620 MHz → Iridium Next
- 1900-2025 MHz → Radio mobile 5G (also from satellite?)
- 2300-2400 MHz → Radio mobile 5G
- 2500-2690 MHz → Increase of the use of this band for Radio mobile 4G, including airplanes
- 3400-3800 MHz → Radio mobile 5G

At higher frequencies, it is expected an extension of the band used for the R-LAN Outdoor service from the current 5470-5725 MHz to 5350-5925 MHz (actually, this new band is already illegally used by this service). It is also expected an increase in the use of the 76-81 GHz band by Short Range Radar mainly for automotive application. Finally, discussions are underway to allocate the frequencies above 275 GHz to active services.

In combination with spectrum management, each radio telescope is active in trying to locally reduce the RFI environment. Monitoring is performed by the local RFI team equipped with proper hardware and software. In this framework, the main relevant activities currently in progress at each site are listed below.

Medicina

- Negotiation, coordinated by MISE, with RAI to solve an interference problem at 6660 MHz produced by a RF link in-line with the Medicina radio telescope
- Activity with the Territorial Department of MISE to limit the proliferation of R-LAN systems in the band 4950-5000 MHz
- In order to limit auto-RFI, two shielded racks have been bought for the control room of the 32-m antenna to install inside them those digital devices that are potential RFI sources
- A new policy to avoid auto-RFI has been established in order to switch off the local oscillators of the unused receivers when observing with the C- and S-band receivers

- The new “Piano Regolatore” of the municipality of Medicina confirms a Radio Quiet Zone around the Medicina radio observatory. The opinion of IRA is requested in advance of the construction of new buildings/farms/plants

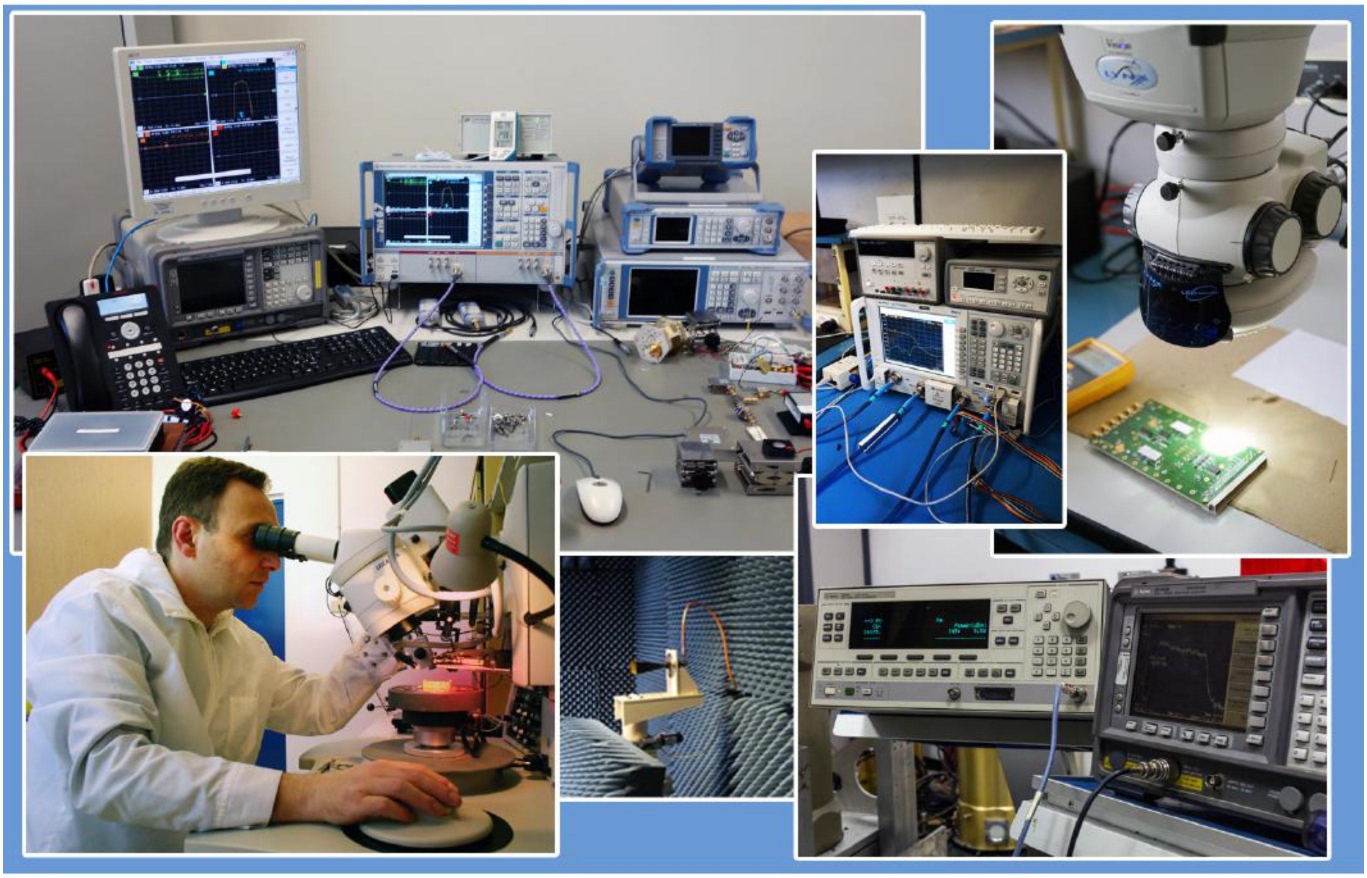
SRT

- Contacts with the MIRFA to solve an RFI in the RAS exclusive band at 21 cm, originated by a military radar
- A new automatic metallic shielding is under design in order to close the aperture of the vertex dome during primary focus observations
- The new SRT site building will be ready in 2017. At that time, it will be possible to receive the IF signals from SRT for continuous and real-time RFI monitoring
- During 2017-2018 all the back-ends and electronic equipment will be moved to the Faraday Room available in the new building
- A new weather radar close to SRT is expected to start regular operations around 5650 MHz (currently under test)
- A new base-station for the TETRA system is planned to be installed in Monte Ixi (few km in line of sight from SRT). The telecommunication standard is designed for use by government agencies and emergency services and it is expected to severely affect astronomical observation in P and L bands due to its harmonics
- Contrary to what happens in Medicina, the 4950-5000 MHz band is currently not interfered by R-LAN systems

Noto

- Contacts with the MISE Territorial Department have been established to solve RFI issues in the frequency band 4950 – 5000 MHz
- The L-band is affected by some RFI at 1400 MHz produced by military radars. However, scientific observations have not been performed in this band since 2014 due to the lack of a suitable receiver
- An increase of auto-RFI is reported, which is due to the electronic equipment and to the lack of common procedures for the local activities.

3. INAF receivers groups



In this Chapter, we report on the laboratory facilities and human resources involved in Research and Development of front-ends to be installed on the Italian radio telescopes. An INAF national group in charge of such R&D for the Italian radio telescopes has never been officially appointed. Despite this, such a group actually exists as a natural continuation of the team established for developing the commissioning receivers for SRT. The activities of this group started in 2003 with a team composed by technicians and technologists from IRA and OAA. Later on, in 2007, a group from OAC joined the team.

In the following the IRA headquarters and the Medicina Observatory are considered together, whereas the Noto Observatory is discussed separately.

3.1 Laboratory facilities

The overall equipment spread among the various laboratories shows both peculiarity and redundancy. Being the main center for passive microwave components development, OAA has an anechoic chamber that should be worthless having also at other sites. The other three sites show some redundancy, given that they regularly operate radio telescope facilities and perform maintenance, as well as undertake development of instrumentation. Such redundancy makes the intervention in case of failure agile.

In the past, there has been some discussion on the opportunity to avoid equipment at the three observing sites but, as a matter of fact, the bulk of the equipment is regularly used for characterization, maintenance, and development, thus making their availability at the sites essential.

Institute of Radioastronomy

A clean room (class 10000) is available in Bologna, which allows operations on MMIC components. Other major instruments include: a semi-automatic bonding machine (wedge bonding, deep-access); a manual pick & place machine for positioning and gluing the electronic components; and a probe station for RF measure on planar components. Additionally, the laboratory is equipped with a chemical extractor fan with an ultrasonic bath. A stainless steel cryostat (size 40 x 40 x 24 cm) can cool devices with maximum volume of about 2.3 dm^3 (220 mm diameter and 60 mm height). Six ports are available on the cryostat for input/output connections.

Scalar and vector analyzers are available for measuring gain/loss, reflection coefficients (10 MHz to 110 GHz), and scattering parameters (up to 40 GHz). Additionally, measurements of the following physical quantities are possible up to 110 GHz: noise; power; spectral frequency; and 1 dB compression point. Finally, it is also possible to measure the 1/f noise and Allan variance.

Institute of Radioastronomy - Noto

The most relevant system available for front-end R&D is the wedge-bonder Hybond Model 572 (25.4 x 30.3 cm) X-Y work platform.

Astronomical Observatory of Cagliari

The 2-port VNA, model Rohde & Schwarz ZVA 67, allows the measurement of microwave passive and active components. It consists of two modules to single sweep the frequency up to 67 GHz plus an additional module to cover the 75 - 110 GHz band by connecting waveguide ports. Auxiliary commercial components allow the characterization of all the devices that compose the receivers. The system is also equipped with proprietary software to remotely and automatically perform the measurements. The VNA can be connected to a cryostat (size 40 x 40 x 24 cm) allowing the measurement of devices at cryogenic temperature.

The laboratory is provided with a working bench for maintenance and fabrication of the front-end devices. It is equipped with auxiliary instruments to operate on electronic boards like soldering iron, pick & place, hot plate, riveter for via hole (0.4 ÷1 mm), bonding machine, RF flexible and rigid cable machining, ultrasonic cleaning machine, and circuit board plotter. Finally, instruments for measuring electric and magnetic fields, and testing of optical fibers are also available.

Astrophysical Observatory of Arcetri

The anechoic chamber, size of 4.5 x 3 x 3 (height) m, is coated with absorbing panels whose material and shape are adequate to reach the minimum frequency of 2 GHz. It is also equipped with systems for alignment, pointing, shifting, and measuring of the antenna patterns.

The millimeter VNA to measure the scattering parameters of microwave components is composed of a base module plus an additional module to cover the frequency range between 10 MHz and 120 GHz. Such a system enables accurate characterization of the front-end passive and active microwave components (LNA included). The VNA can be connected to a cryostat to measure devices at cryogenic temperatures. Such a cryostat has a cubic size of 50 cm, and it is equipped with vacuum pumps, cryo-generator, pressure, and temperature sensors.

3.2 Human resources and external collaborations

The receiver group is a quite large team involving almost 10 FTE distributed among the four INAF Structures. The expertise of this group includes different areas that can be classified in six roles:

- Group management (Man).
- Front-End Passive Components (FEPC). Design, fabrication and characterization of passive components: feed-horn, polarizer, marker injector, filter, etc.
- Front-End Active Components (FEAC). Design, fabrication and characterization of active components: LNA, mixers, etc.
- Mechanics and cooling (M&C). Design and fabrication of the mechanics of the whole receiver as well as of each single component. Receiver cooling aspects are included in this category.
- Intermediate Frequency (IF). Design and fabrication of the electronics for conditioning the signals in terms of filtering, amplification, and frequency conversion.
- Integration and Test (I&T). Integration of all the devices to have a receiver ready for the final tests in the laboratory and later, after the installation on the radio telescope, for the commissioning.

Tab. 3.I lists the human resources involved in the receiver group. For each structure, names, level, permanent or temporary position, role, and FTE are listed. The listed FTE includes only R&D activity devoted to the development of new receivers and does not include maintenance to operational receivers. Additionally, Tab. 3.I shows the external collaborators who have worked with the INAF team in the last 10 years. These collaborations are not permanent, but are activated in case of convergence between INAF needs and the interests and availability of the external partners. Additionally, they may foresee some payment or may be not-profitable scientific collaborations.

INAF PERSONNEL				
Name	**Structure**	**Level (Permanent or Temporary Position)**	**Role**	**FTE**
Orfei A.	IRA	First technologist (PP)	Man	0,7
Cattani A.	IRA	Technician (PP)	I&T	0,3
Maccaferri A.	IRA	Technician (PP)	I&T	0,2
Mariotti S.	IRA	Technician (PP)	FEAC, I&T	0,4
Morsiani M.	IRA	Technician (PP)	IF, I&T	0,2
Poloni M.	IRA	Technologist (PP)	IF, I&T	0,5
Roda J.	IRA	Technician (PP)	M&C	0,5
Scalambra A.	IRA	Technician (PP)	IF, I&T	0,6
Zacchiroli G.	IRA	Technician (PP)	M&C	0,3
Gaudiomonte F.	OAC	Technician (PP)	IF, I&T	0,2
Ladu A.	OAC	Technician (TP)	FEPC	1
Marongiu P.	OAC	Technician (PP)	M&C	0,8
Navarrini A.	OAC	First technologist (PP)	Man, FEPC, I&T	0,5
Pisanu T.	OAC	Technologist (PP)	Man, FEPC, I&T	0,4
Valente G.	ASI/OAC	Technologist (PP)	FEPC, FEAC, M&C, I&T	0,8
Bolli P.	OAA	Technologist (PP)	FEPC	0,3
Cresci L.	OAA	Technician (PP)	M&C	0,4
Nesti R.	OAA	Technologist (PP)	FEPC	0,5
Panella D.	OAA	Technician (PP)	M&C, I&T	0,5
Contavalle C.	IRANoto	Technician (PP)	M&C, I&T	0,2
Nocita C.	IRANoto	Technician (PP)	M&C	0,2
Nicotra G.	IRANoto	Technician (PP)	M&C, I&T	0,2
			TOTAL	9,7
EXTERNAL COLLABORATIONS				
Name	**Institution**	**Level**	**Role**	
Pisano G.	UniCardiff	Lecturer	FEPC	
Peverini O.	CNR-IEIIT	Senior Researcher	FEPC	
Bersanelli M.	UniMilano	Full Professor	FEPC	
Mazzarella, G.	UniCagliari	Full Professor	FEPC	
Zannoni M.	UniMi-Bicocca	Researcher	FEAC	

Table 3.I – INAF personnel at IRA, OAC and OAA involved in front-end R&D

Finally, Fig. 3.1 reports in graphical form the FTE for each role and for each structure. In the case of people involved in more than one role, the FTEs have been assumed to be uniformly distributed among the different roles.

Fig. 3.1a shows that M&C is the role with the highest presence of FTE. This comes with no surprise, since a considerable part of the staff in these Institutes possess the skills needed to work on that topic, as demonstrated by their past and present production.

FEAC and IF are the roles with less resources (the former being mainly concentrated at IRA and OAC and the latter at IRA). For what concerns FEAC, after many years of investment in developing LNAs (e.g. the production of LNA, both cooled and warm, for the SRT K-band multi-feed) IRA gave up producing LNAs: today more than one firm can supply modern amplifiers at a very competitive cost with respect to an in-house production and with a short delivery term (especially in case of

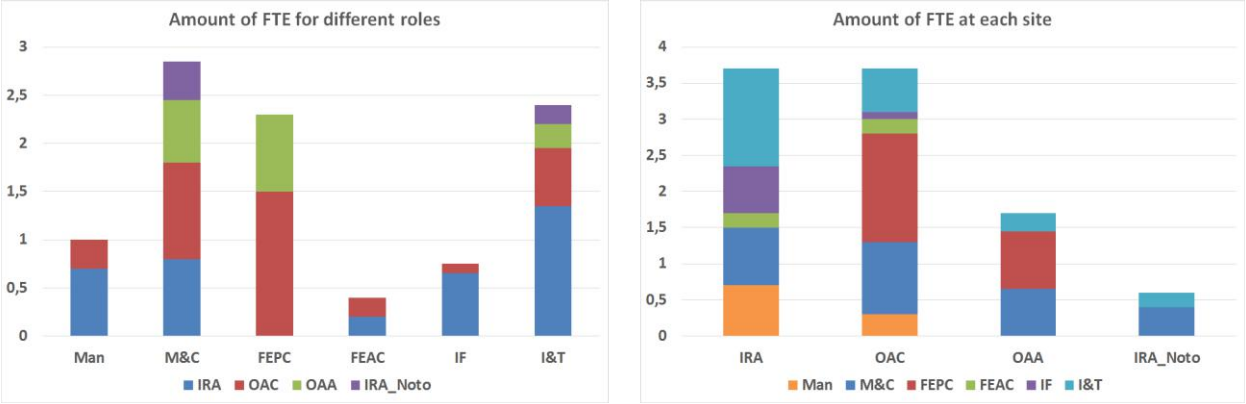
European suppliers). Despite the limited human resources, the development of new intermediate frequency section analog modules has gained significant momentum. The focus here is on the development of complete frequency conversions on a single board, easy to replicate, showing added capabilities, like choice of filters with different bandwidth, choice of appropriate attenuation and equipped with a built-in full Stokes continuum detector. All this makes such boards a true conditioning module, able to exploit the entire frequency range provided by the new generation of wideband receivers.

FEPC has been historically developed by OAA. However, in the last years the group in OAC added a significant increasing contribution to this field.

I&T shows the larger contribution coming from IRA. I&T includes the production of boards for the power supply of the LNA and the (hardware and software) control by means of which the overall receiver can be configured, switched on and off, cooled or warmed, and monitored. These boards are an in-house general purpose design that can be used on any receiver planned or under construction.

Finally, Man takes a non negligible amount of time. The main contribution comes from IRA, which still manages the majority of receivers under development. However, the involvement of the OAC group has been increasing since when OAC started to take care of SRT receivers as well. For clarity, it must be noted that in this scheme Man includes also the administrative tasks and exchange of information required to purchase the components from industries and external partners. This task is obviously more demanding in the areas where the outsourcing to external suppliers is higher, like for LNAs.

Fig. 3.1b uses the same data as Fig. 3.1a with the aim to highlight at first glance the engagement of each institution. IRA and OAC are now the main contributors to the development of new receivers, more than a factor of two higher than the contribution coming from OAA. Finally, only half an FTE is provided by IRA Noto.



(a) (b)

Figure 3.1 – Distribution of FTE for: (a) different roles and (b) different sites

3.3 Other INAF groups involved in receiver development

Two INAF groups have been identified, having competences similar to those of the front-end group and with whom, therefore, possible synergies could be established. These groups are:

- The SKA group at IRA Medicina, contributing to the LFAA Element for the Square Kilometer Array project. The group is in charge of the receiver Work Package, led by Jader Monari. Other INAF staff from IRA, OAA, OACt, and IASF-Bologna are members of the work package team, representing at total of 42.36 FTE in the period 2012 – 2017. Research contracts as part of the work package have been agreed with CNR, University of Bologna, and University of Firenze, for a total of 6.92 FTE during the same period. Contracts with Italian industry have been agreed with OPTEL, Lightech, Finmeccanica, Sanitas EG, and Campera ES, for a total investment with industry of 929 k€ between 2012 and 2017. The Italian team has been involved in the design and prototyping control over two main elements of the SKA-low signal path working from 50 to 650 MHz: *i)* the front-end (after the LNA to optical transmission of RF over fibre with Wave Division Multiplex technique) and *ii)* the signal conditioning before the analog to digital conversion. Both these elements have been the result of Italian design, prototyping, and industry involvement and they represent excellent opportunities for an Italian in-kind contribution to the SKA-low budget. Further, these technologies could be reused for different project or architecture as PAF or generic single pixel receiver as well.
- The cryo-waves group mainly based at IASF-Bologna, whose expertise derives from space-borne and ground-based instrumentation development. It comprises expertise on antenna design and simulations, antenna development, thermal engineering, system engineering and AIV management, testing and verification, qualification of flight hardware, and outreach. This group consists of seven technologists and researchers (three of them with temporary contract) and it owns state-of-the-art cryogenic facilities (plus additional RF instrumentation and software facilities). It collaborates also with INAF personnel involved in the receiver group for the Italian radio telescopes. The more relevant radio astronomical projects in which this group has been involved in the last period are: *i)* ALMA receiver band 2+3 (67-116 GHz), see Section 8.1, and *ii)* STRIP within the Large Scale Polarization Experiment project. STRIP is a Q-band 49-element and a W-band 6-element focal plane array facing a 1.5-m off-axis crossed dragone telescope, to be placed at Teide Observatory (Tenerife, Spain) in 2018.

4. Northern Cross

This Chapter gives basic information about the Northern Cross interferometer situated at the Medicina site. Owned by the University of Bologna and managed by INAF-IRA, the NC is one of the world's biggest transit radio telescopes and its inauguration dates back to 1964.

The NC was designed to operate at 408 MHz with a bandwidth of 2.5 MHz. It is composed of East-West (E-W) and North-South (N-S) arms, fully steerable in elevation only, for a total collecting area of 27.000 m^2. The E-W arm is constituted by a single cylindric-parabolic antenna 564 m long and 30 m wide equipped with 1536 dipoles. The N-S section is a linear array of sixty-four cylindric-parabolic antennas for a total arm length of 640 m. Each N-S antenna is 23.5 m long and 7.5 m wide and is equipped with 64 dipoles.

In the period 2005-2009, a re-instrumentation of part of the NC has been made to set up a receiver demonstrator (BEST) for the Square Kilometre Array within the EU-FP6-funded SKA Design Studies program. BEST was articulated in three main phases aimed at the installation and test of new low frequency receivers as well as analog fiber optic and new digital back-end for some elements of the N-S and E-W arms.

4.1 Current status

At present, only the part of the Northern Cross N-S arm upgraded for the BEST-2 phase is working. The BEST-2 demonstrator is an array composed of eight cylindric-parabolic concentrators operating at 408 MHz central frequency and with 14 MHz bandwidth (Fig. 4.1).

Figure 4.1 – BEST-2 elements in the N-S arm of the Northern Cross

The BEST-2 total collecting area is about 1400 m^2, equivalent to a 42-m parabolic dish. Every cylinder contains four receivers; each one connected to 16 dipoles (Fig. 4.2).

By means of beamforming techniques the 32 receivers in the array provide 24 independent beams (pixels) in the antenna FoV. A MATLAB simulation of the BEST-2 FoV is shown in Fig. 4.3.

The characteristics of the BEST-2 array are summarized in Tab. 4.I.

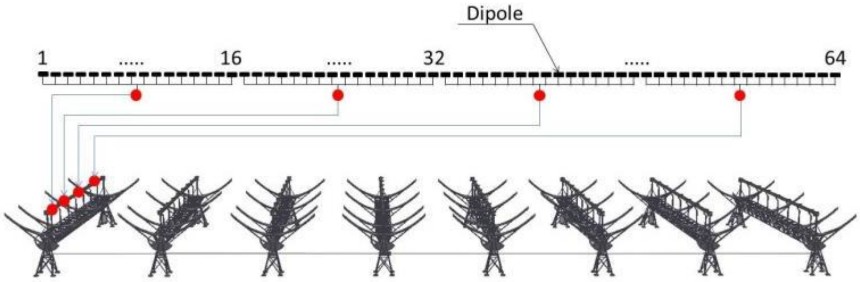


Figure 4.2 – Single BEST-2 antenna architecture (red points correspond to the receivers)

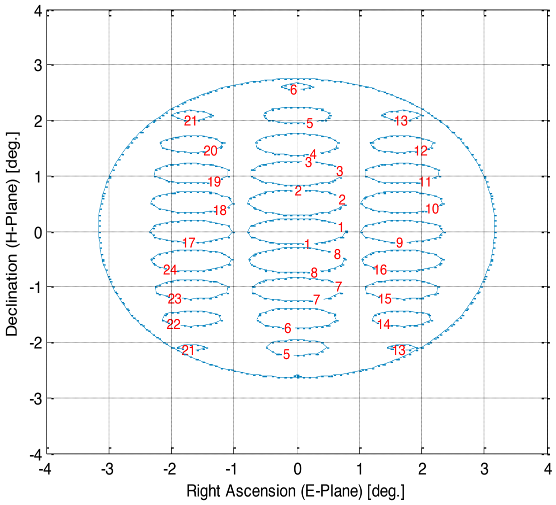


Figure 4.3 – BEST-2 FoV and Synthetized Beam allocation

Frequency (center band)	408 MHz
Instantaneous bandwidth (3 dB)	14 MHz
Mechanical elevation pointing	>45 deg
Electrical azimuth pointing	-3.3 deg ÷ 3.3 deg 176.7 deg ÷ 183.3 deg
Instantaneous FoV	~30 deg^2 (Dec 5.7 deg, RA 6.6 deg)
Synthetized beam (pixel)	0.7 deg^2 (Dec 31.1 arcmin, RA 104 arcmin)
Number of independent beams	24

Table 4.I – BEST-2 system characteristics

4.2 Planned developments

The NC telescope is a sensor selected for participation in the European SST programme, in particular to support the detection and monitoring of LEO in survey mode. Also the SRT is involved in the SST program for tracking mode monitoring. The SST Consortium is composed of five member States: Italy; France; United Kingdom; Spain; and Germany.

Very good results have been obtained from bistatic radar tests with BEST-2 as the receiving part and a transmitter located in the East of Sardinia, with transmission power ≈4kW in the bandwidth

410-415 MHz. Thanks to these results, within the H2020 Programme the European Commission financed the upgrade of a further part of the Northern Cross N-S arm, including in particular a duplication of BEST-2.

The upgraded array, named BEST-4, will include 16 cylindric-parabolic antennas for a total collecting area of 2800 m^2, equivalent to a 60-m parabolic dish. With the 64 receivers of BEST-4, it will be possible to generate 48 independent beams inside a FoV of 30 $degrees^2$ and a synthetized beam of 0.35 $degrees^2$.

For what concerns the back-end for BEST-4, new FPGA-based CASPER hardware is available. A digital beamforming system has been designed, generating electronically steered beams inside the antenna FoV. Signals from each beam can be fed simultaneously to two different outputs: a high-resolution spectrometer with 10 Hz resolution; and a total power back-end. An analogue beamformer is also under development for the measurement of space debris range, as well as a high-level and user-friendly interface.

BEST-4 is a nonpareil instrument and an interesting array for the international astronomical community combining both high sensitivity and wide FoV, and it could be used in particular to explore the following science topics:

- Pulsars.
- Radio source surveys.
- Carbon radio recombination lines.
- Monitoring of SNR secular flux decrease.
- Transients.

Currently the European Commission granted ≈550 k€ for the upgrade of the NC and the realization of BEST-4, as well as to support LEO monitoring. Further support to the SST program until 2020 is foreseen with an economical contribution of 106 M€ from EU-SST dedicated funds (Copernicus-Galileo and H2020 Space Economy programmes). New proposals will be submitted to the EC, in agreement with INAF and the SST Consortium, to continue the NC upgrade and to support the monitoring of orbital objects within the European sensor network.

4.3 Strengths, critical issues and possible upgrades

A number of strengths and possible weak points can be identified for the NC. Among the former, we mention:

- Large collecting area.
- Modularity of the array guaranteeing an easy expansion of the upgrade to the whole N-S arm at a very low cost. This is possible thanks to the experience acquired in the past upgrade phase (prototype boards are not needed, project and design are still valid, etc.).

The main critical issues are:

- NC is an old and big antenna and for this reason it currently needs extraordinary maintenance. This is particularly urgent for the E-W arm which, at the moment is the most critical part of the array. The E-W arm however could be an important addition to the NC

upgraded array, thanks to the large collecting area of about 17000 m^2 (see f.i. the recent refurbishment of the Molonglo telescope, [1, 2]).
- NC is a transit radio telescope. Despite the capabilities of BEST-4 electronic beamforming, the antenna beam cannot be pointed toward any possible direction in the sky and it is necessary to wait for the source to transit in the antenna FoV.

The most important upgrade for the NC would be the increase of sensitivity obtainable by enlarging the BEST-4 collecting area. The whole N-S arm could be equipped with 256 receivers to obtain an effective area of the order of 11000 m^2. The estimated cost for this upgrade is about 400 k€. The resultant collecting area would be 60% of UTMOST, the recently refurbished Molonglo telescope. It must be stressed that the NC N-S arm FoV is four times larger than UTMOST and, more importantly, it can be populated with several independent beams. Such a pixelization of the FoV would make the upgraded NC an instrument for the search and study of fast transient phenomena.

5. Space applications at the Sardinia Radio Telescope

ASI is one of the main financial contributors of the SRT, with 20% of the antenna total time allocated to its activities. The main activities for which ASI is interested to use the SRT are deep space tracking, radio science (and related scientific opportunities such as Near-Earth objects), and space debris monitoring. At the moment, the two more advanced activities are:

1. ground station for deep space tracking;
2. space debris observations.

Regarding the first activity, ASI plans to divide it in three phases. During the first phase, which will be carried out in 2017, ASI aims to install an X band (8.2 - 8.6 GHz) downlink receiver on SRT. In the second phase the plan is to install an X/Ka (34 GHz) band receiver for downlink at both frequencies. Finally, the third phase foresees the installation of a full X-band uplink and downlink as well as Ka-band uplink and downlink.

Regarding the space debris monitoring, ASI takes part in the European Consortium for SST established on 2014 and already mentioned in Section 4.2. Within the SST framework the EC has allocated a total of about 20 M€ in the “Copernicus and Galileo” and in the H2020 “Space Economy” funding lines.

5.1 Deep Space Tracking

The ASI receiver that will be installed on SRT in 2017 is on loan from NASA JPL in the framework of an international cooperation involving also ESA. This receiver is cryogenically cooled, single polarization, and operates in the X band, currently the mostly used one for deep space communications even if the Ka band is present in almost all missions under development. The X-band JPL receiver will be installed in the F4 BWG focal position of the SRT because this is the only freely available and ready position on the antenna that can host such a front-end. The ASI program is in fact to have this receiver installed and ready to receive the signal from the splash down of the Cassini spacecraft on Saturn that will occur on 2017, September 15th.

The F4 BWG focal position was planned to host the radioastronomical Clow-band (4.2-5.6 GHz) receiver which is in a very advanced construction phase but, due to the pressing requirement from ASI to have a ready and easy-to-manage focal position, INAF agreed to move the Clow-band receiver to the Gregorian focal position. The X-band JPL receiver has a total height of 2515 mm and a distance from the base to the centre of phase of about 2211 mm. The back end will be provided by ESA and will be installed in the ground buildings, inside the shielded room.

5.2 Space debris monitoring

In 2014 INAF performed some space debris observations at P band (410 MHz) with SRT in a bi-static radar configuration, together with the Northern Cross at Medicina and a military transmitter. During the tests, the echoes from all the pointed debris have been received and the power and Doppler frequency shift of the signal have been measured by using a spectrum analyzer as a back end. These observations demonstrated SRT capabilities in space debris monitoring. In Fig. 5.1 the spectrogram of an observed debris is shown.

The plan for this activity at SRT includes an upgrade of the P-band receiver in the near future by installing a selectable narrow-band filter in the receiving chain and developing a dedicated back-end.

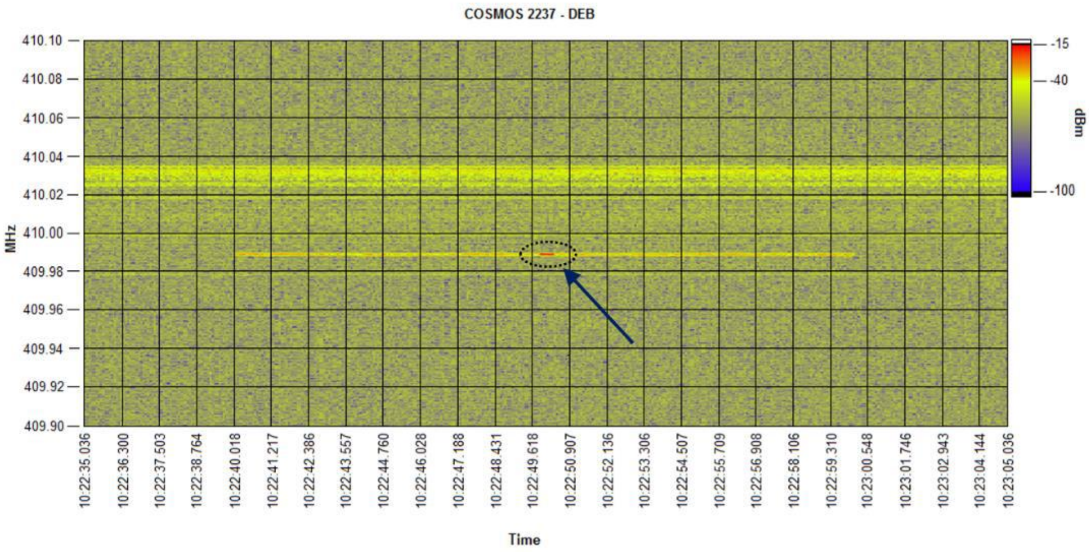


Figure 5.1 – Spectrogram of a space debris observation

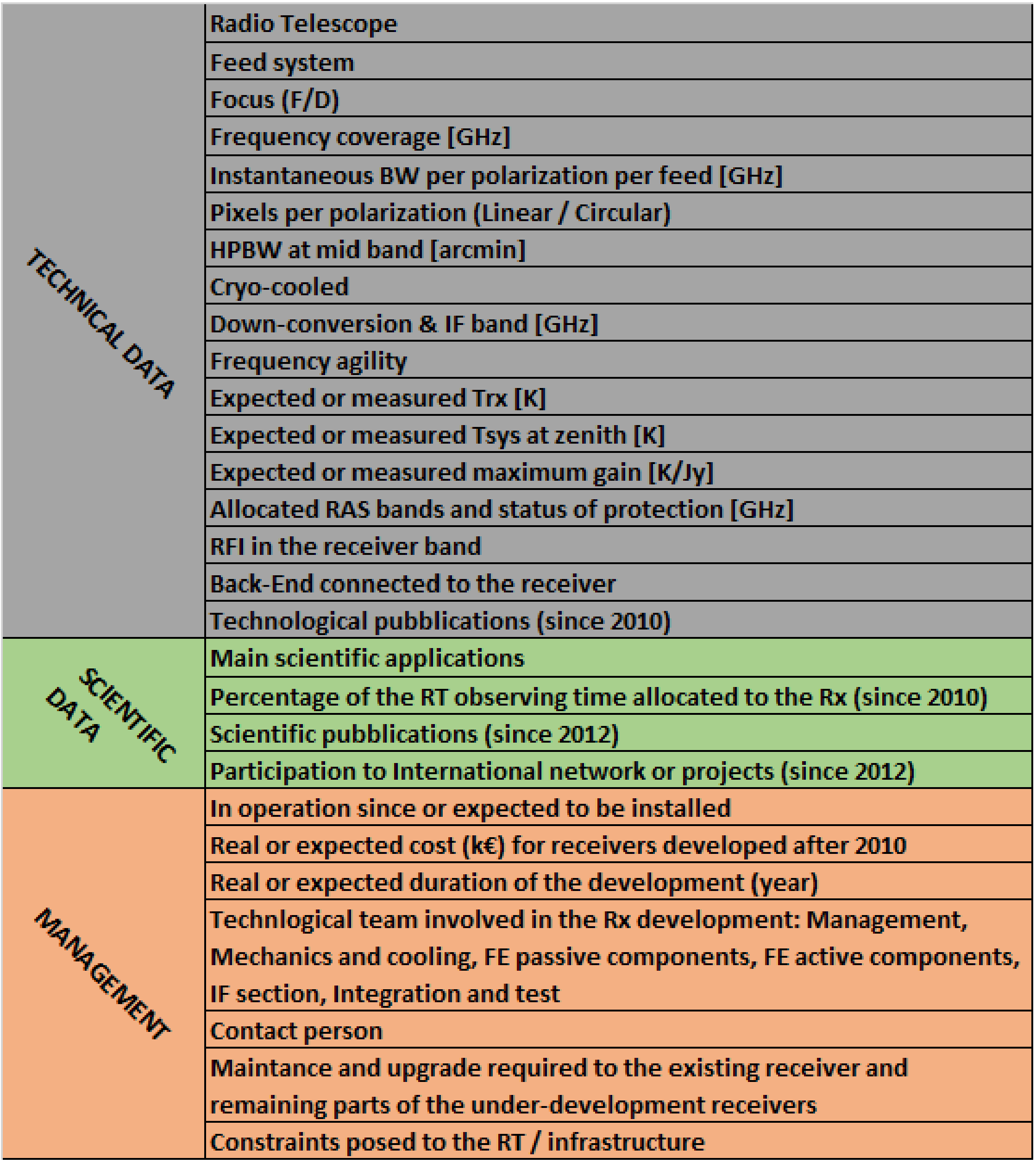
In the longer period, the plan is to develop a Phased Array Feed that can allow the tracking of the debris in order to improve the knowledge of its orbital parameters. This will allow the alert of satellite operators in case of collision risks with their assets as well as the determination of a more precise and reliable impact point in case of re-entry of the debris in the atmosphere.

Part II - Italian receivers and the International context

6. Receivers at the Italian radio telescopes

This Chapter analyzes the data collected during the survey on the receivers in operation, under development and under evaluation at the Italian radio telescopes. By in operation we mean those receivers installed on the radio telescopes, commissioned and used for scientific purposes. The receivers under development are those in the design/fabrication phase having been, at least partially, funded. Finally, by under evaluation we mean those receivers whose development started some time ago, but they are now in a stand-by phase waiting for evaluation on how to proceed.

Several parameters grouped in three main areas (technological, scientific and managerial) have been selected as the most relevant for producing a complete picture of the status of the receivers (see Tab. 6.I). The complete survey is reported in Appendix A.



TECHNICAL DATA	**Radio Telescope**
	Feed system
	Focus (F/D)
	Frequency coverage [GHz]
	Instantaneous BW per polarization per feed [GHz]
	Pixels per polarization (Linear / Circular)
	HPBW at mid band [arcmin]
	Cryo-cooled
	Down-conversion & IF band [GHz]
	Frequency agility
	Expected or measured Trx [K]
	Expected or measured Tsys at zenith [K]
	Expected or measured maximum gain [K/Jy]
	Allocated RAS bands and status of protection [GHz]
	RFI in the receiver band
	Back-End connected to the receiver
	Technological pubblications (since 2010)
SCIENTIFIC DATA	**Main scientific applications**
	Percentage of the RT observing time allocated to the Rx (since 2010)
	Scientific pubblications (since 2012)
	Participation to International network or projects (since 2012)
MANAGEMENT	**In operation since or expected to be installed**
	Real or expected cost (k€) for receivers developed after 2010
	Real or expected duration of the development (year)
	Technlogical team involved in the Rx development: Management, Mechanics and cooling, FE passive components, FE active components, IF section, Integration and test
	Contact person
	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers
	Constraints posed to the RT / infrastructure

Table 6.I – Information collected for each receiver during the national survey. Expected values refer to receivers under development and under evaluation

Even if the survey included the Northern Cross, owing to its peculiarity with respect to the other Italian radio telescopes, the discussion in this Chapter is focused on the receivers for the parabola antennas only: Medicina (MED), Noto (NOTO) and the Sardinia Radio Telescope (SRT).

6.1 Technical data analysis

As shown in blue in Fig. 6.1, the Italian radio telescopes are currently operating 14 front-ends uniformly distributed among the three radio telescopes: five at MED; five at NOTO; and four at the SRT. In respect of the SRT, three first-light receivers have been used for the technical commissioning (2011-2013), for the Astronomical Validation (2014-2015), and finally for the Early Science Program (2016). The fourth receiver (X/Ka-band) was developed in 2000 for tracking the Cassini probe with the NOTO antenna, and then temporary moved to SRT in 2015 to test its space science capabilities. At MED and NOTO almost all the receivers in operation have been developed for astronomical purposes, with the coaxial S/X-band specifically made for geodetic observations but used for radio astronomy as well.

As can be seen in red from Fig. 6.1, the INAF receiver group is now involved in the development of five new receivers (four for SRT and one for MED) and is evaluating the future of four receivers in NOTO. The S-, C-low-, Q-band for the SRT and the Ku-band for MED are entirely designed within the INAF receiver group, whereas the W-band receivers under evaluation at NOTO and under development at SRT have been produced in foreign research Institutes (IRAM and MPIfR), then acquired by INAF mainly for metrology tests and for mm-VLBI observations. However, in order to make these receivers compatible with the Italian radio telescopes, several modifications must be implemented. The other two receivers under evaluation for NOTO (L- and S/X-bands) are strictly related since they share several mechanical parts and for this reason they will be also identified as L/S/X-band receiver. Their construction started a long time ago and a technical investigation of their status and possible upgrade has been carried out at the Medicina Observatory [1]. The S/X under evaluation for NOTO is uncooled and with similar performance with respect to the existing receiver, apart from a bandwidth (800 MHz) at X-band receiver being two times larger than the current bandwidth (400 MHz). Additionally, it would have the advantage of accommodating also the L-band receiver inside the same mechanical structure.

The frequency bands of all these receivers are reported in Tab. 6.II for both receivers in operation (Tab. 6.IIa) and under development/under evaluation (Tab. 6.IIb). In particular, this table allows us to mention some specific points:

- the MED L-band receiver allows observations in two different frequency ranges covering the lines of HI (1420 MHz) and OH (1612, 1665 and 1667 MHz), respectively: these two bands will be identified as Llow and Lhigh;
- the ex-IRAM W-band receiver has a 500 MHz instantaneous band tunable between 84 and 116 GHz, whereas the ex-MPIfR receiver has a 100 MHz (optional 600 MHz) band almost fixed around 86 GHz.

Tab. 6.IIc lists also the dismantled receivers produced at the very beginning of the telescope's lives. We note that the dismantled K-band for MED was originally enclosed in the box of the current primary focus S/X-band.

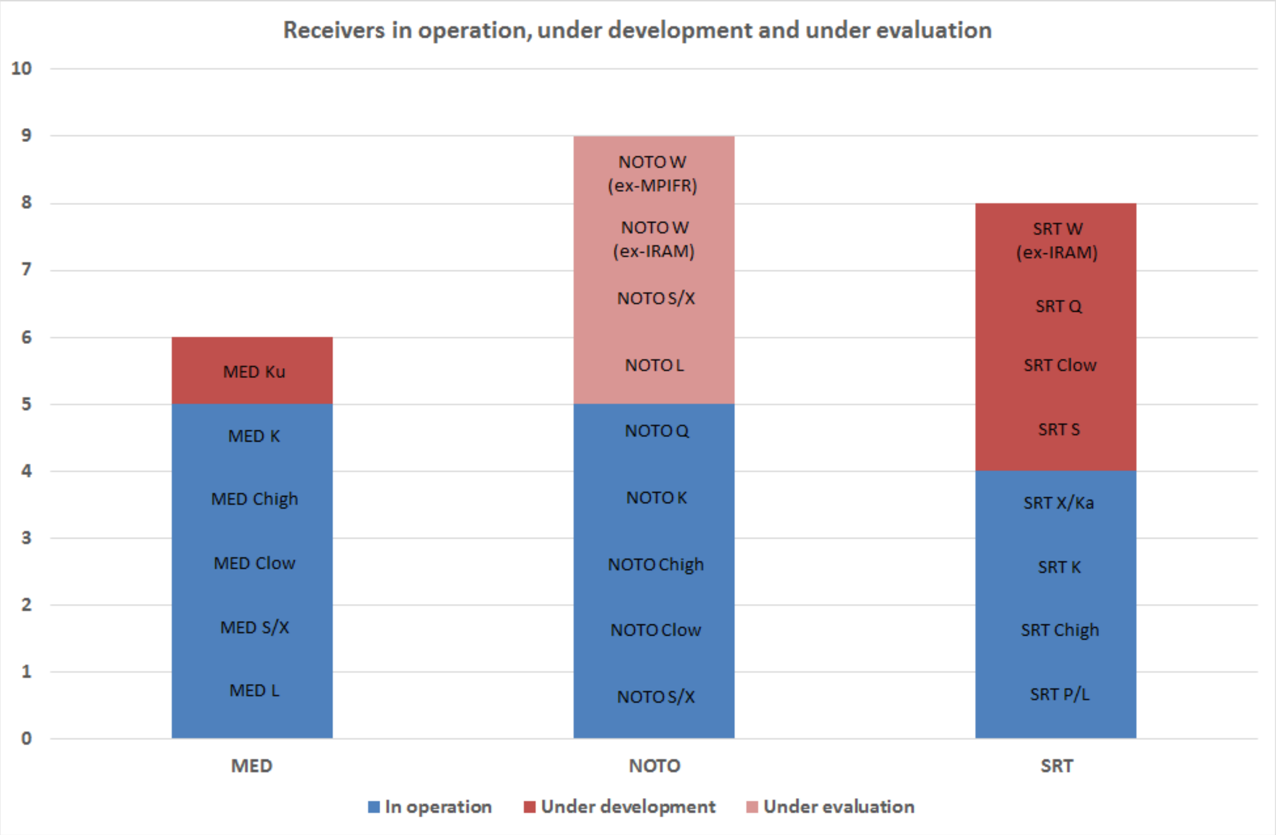


Figure 6.1 – Receivers in operation, under development and under evaluation at the three radio telescopes (blue, red and light red respectively)

Receivers in operation

Receiver ID	Frequency coverage [GHz]	
	Min	Max
MED L	1,35	1,45
	1,595	1,715
MED S/X	2,2	2,36
	8,18	8,98
MED Clow	4,3	5,8
MED Chigh	5,9	7,1
MED K	18	26,5
NOTO S/X	2,2	2,36
	8,18	8,58
NOTO Clow	4,62	5,02
NOTO Chigh	5,1	7,25
NOTO K	21,5	23
NOTO Q	39	43,5
SRT P/L	0,305	0,410
	1,3	1,8
SRT Chigh	5,7	7,7
SRT K	18,0	26,5
SRT X/Ka	8,2	8,6
	31,85	32,25

(a)

Receivers under development / under evaluation

Receiver ID	Frequency coverage [GHz]	
	Min	Max
MED Ku	13,5	18
NOTO L	1,3	1,8
NOTO S/X	2,2	2,36
	8,18	8,98
NOTO W (ex-MPIFR)	85,945	86,545
NOTO W (ex-IRAM)	84	116
SRT S	3	4,5
SRT Clow	4,2	5,6
SRT Q	33	50
SRT W (ex-IRAM)	84	116

(b)

Receivers dismantled

Receiver ID	Frequency coverage [GHz]	
	Min	Max
MED L	1,363	1,443
	1,622	1,702
MED Clow	4,65	5,15
MED Chigh	6	7
MED K	21,86	24,14
NOTO L	1,363	1,443
	1,622	1,702

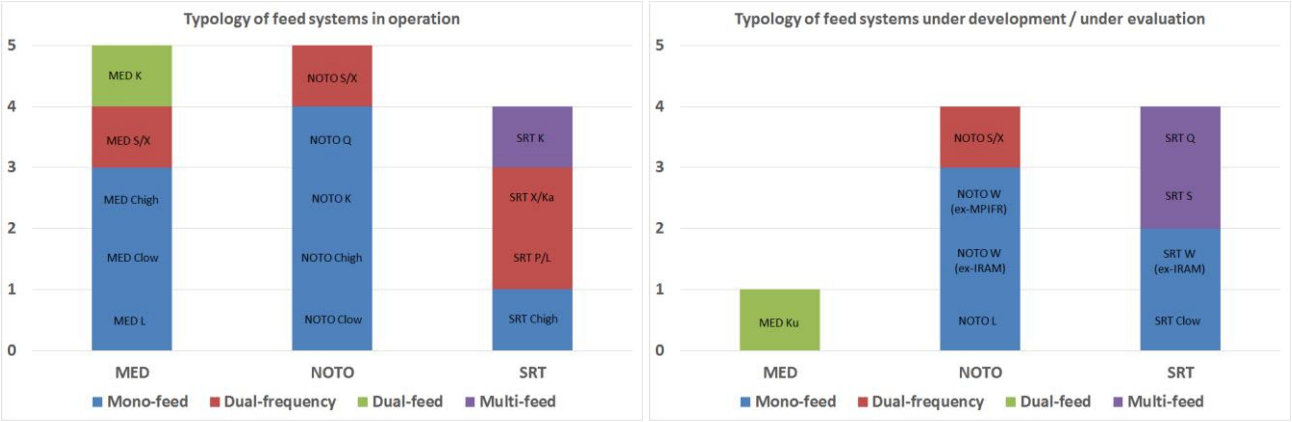
(c)

Table 6.II – Frequency coverage for the Italian receivers: (a) in operation, (b) under development/under evaluation and (c) dismantled receivers

As it is evident from Fig. 6.2a, the receivers in operation at SRT implement different feed-system typologies, ranging from traditional mono-feed (Chigh-band) to more sophisticated multi-frequency (P/L-band) or multi-feed solutions (K-band). Almost all the existing receivers at NOTO are mono-feed with the exception of the dual-frequency coaxial S/X-band. At MED, besides the dual-frequency S/X-band receiver, since 2013 there is also a K-band dual-feed receiver.

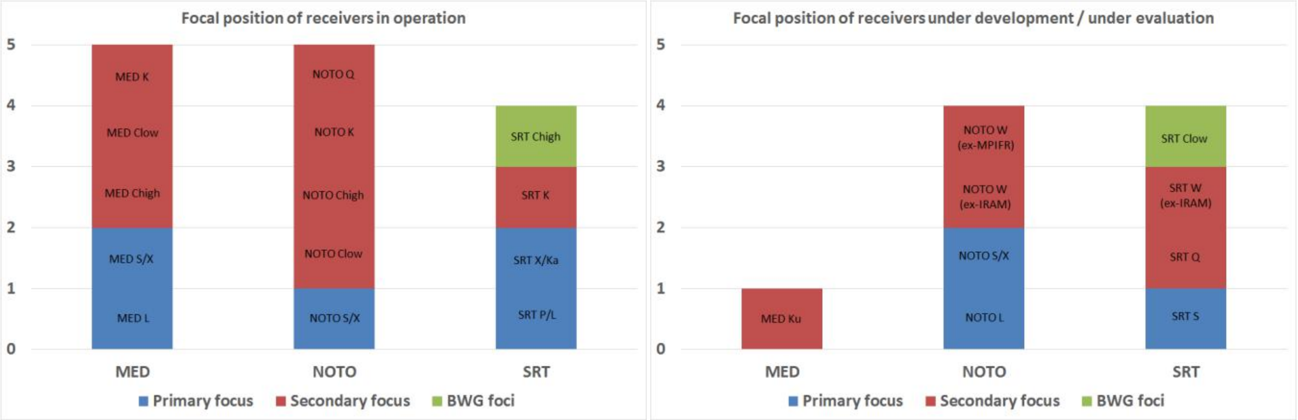
In respect of the receivers under development (see Fig. 6.2b) the SRT and MED are moving toward multi-feed or dual-feed solutions: 7-pixel S-band plus 19-pixel Q-band for the SRT; and 2-pixel Ku-band for MED. At the same time, there are two projects in progress for mono-feed receivers for the SRT: Clow- and W-band. Except for the new dual-frequency S/X-band, the receivers under evaluation for NOTO are all mono-feed.

Dual-reflector radio telescopes like MED and NOTO offer two focal positions, whereas at the SRT, thanks to the BWG, the number of focal positions increases. Fig. 6.3a shows the distribution of receivers among the available focal positions, mainly related to the operating frequencies: high frequency receivers are located in the secondary focus whereas low frequency in the primary focus. From Fig. 6.3b we see that new receivers at the SRT will populate all the existing foci, whereas the new receiver for MED will be located at the Cassegrain position. At NOTO, the receivers under evaluation have been developed for both focal positions.



(a) (b)

Figure 6.2 – Receivers divided by feed-system type and radio telescope: (a) in operation and (b) under development/under evaluation



(a) (b)

Figure 6.3 – Receivers divided by focal position and radio telescope: (a) in operation and (b) under development/under evaluation

The frequency coverage of both the operational and the under development/under evaluation receivers is reported in Fig. 6.4 as a graph.

Below 1 GHz, the RFI environment makes it very difficult to perform astronomical observations at the Italian sites. Therefore, only one receiver, the P/L-band for SRT, is in operation. The commissioning in P band has been extremely difficult due to the strong RFI (especially the one self-generated by the local equipment) present in this band, and this band has been used only for a short period of time (two weeks) during the Early Science Program, when a screening lid was temporarily installed to cover the Gregorian dome. Ongoing efforts to limit the RFI self-generation at the SRT site are expected to have a positive impact on the future use of this band, as already partly demonstrated during the Early Science Program observations.

The frequency band 1-10 GHz is the most populated one, with receivers operating in the L-, S-, Clow-, Chigh- and X-band at almost at all sites. Exceptions are the L-band, which is missing at NOTO, and the Clow-band absent at SRT. However, the latter band will be covered by a receiver under development and for the L-band at NOTO there is a plan to develop a receiver even if not yet defined. Thanks to the receivers under development in Clow- and S-band, SRT will have a continuous frequency coverage from 3 to almost 8 GHz.

A specific note is to be made for the S and X bands, currently accessible with the dual-frequency coaxial receivers at NOTO and MED (respectively uncooled and cooled). The uncooled NOTO is mostly used for VLBI and geodesy, while the cooled MED S/X is also used for single-dish astronomical observations, as shown by the usage statistics (see Section 6.3). Vice versa, choices made for the S/X bands at SRT follow a different philosophy. The absence of a coaxial S/X receiver at SRT prevents the possibility of geodetic observations with this telescope. The X band is currently observable with the uncooled X/Ka receiver (designed for space science), whose high noise temperature makes it of relatively little interest for single-dish observations. A new, cooled multi-feed for the S band in the frequency range 3 - 4.5 GHz, different to the one typically used for geodesy and not including the VLBI band, is under development for single-dish science at SRT. This S-band receiver will be installed in place of the existing X/Ka-band receiver due to the limited available space at the primary focus.

At higher frequencies the number of receivers decreases. For all the telescopes, a gap between the X and K bands exists mainly due to the RFI. This will be partially filled at MED, where a Ku-band receiver is currently under development in the frequency range adjacent to that of the K-band receiver. The minimum frequency of this receiver will be 13.5 GHz.

The high astronomical interest for the 22 GHz band is demonstrated by the existence of a K-band receiver in operation at all sites. However, different technical implementations have been adopted: a 7-beam system for SRT, a 2-beam for MED and a 1-beam for NOTO. The latter underperforms in comparison with the others both in terms of bandwidth and receiver noise temperature, mainly because of its early construction date (1990).

Finally, the highest frequency domain currently observed by Italian radio telescopes is the Q-band at NOTO. However, there is an attempt to go toward higher frequencies both at NOTO (in W-band) and at the SRT (in Q- and W-band). A similar route may be possible in MED, at least up to the Q-band with new primary mirror panels and a more accurate subreflector; then to reach the W-band, an active surface system would be necessary (see Appendix D).

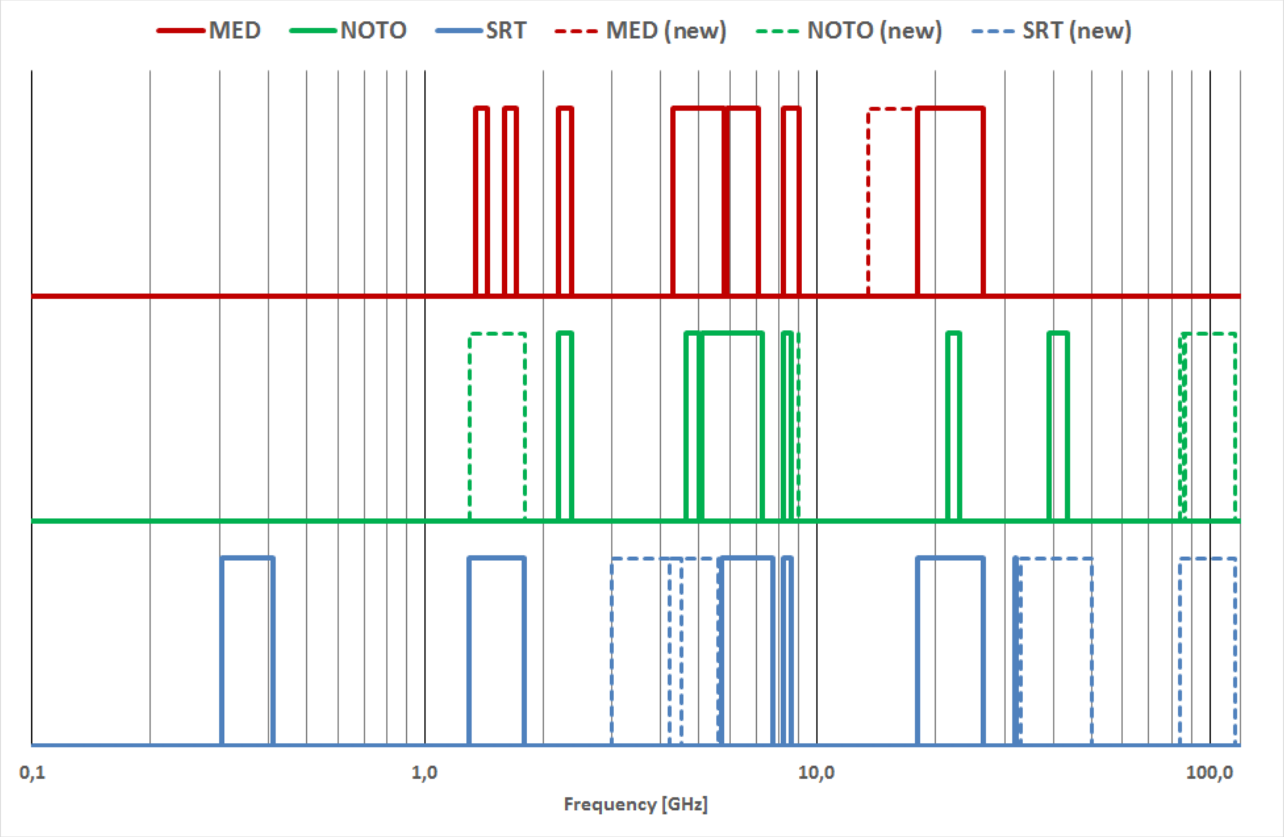


Figure 6.4 – Frequency coverage of receivers at the Italian radio telescopes: in operation (continuous lines) and under development/under evaluation (dashed lines)

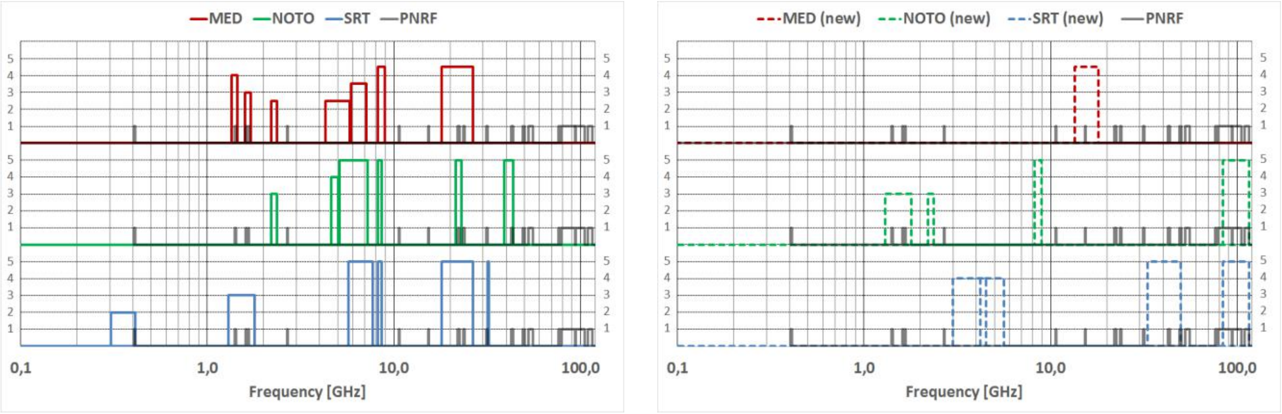
The RFI environment is described for the receivers in operation (Fig. 6.5a) and under development/under evaluation (Fig. 6.5b), where the ordinate of the diagrams reflect the RFI pollution in that band ranging between 5 units (meaning “Fully clean --> RFI in <10% of band or time”) to 1 unit (“Strongly polluted --> RFI in >75% of band or time”). In the same figures, the black rectangles show the frequency bands assigned to the Radio Astronomical Service with primary or exclusive status by the Italian Plan for Frequency Regulation.

Below 6 GHz, RFI is seriously affecting the operations of the receivers at MED where no geographic shields protect the radio telescope. However, the Llow band at MED is clean since it is very narrow and centered in the exclusive protected band, whereas the signals emitted by Iridium satellites partially compromise the Lhigh band. The RFI level in the observed bands at MED is acceptable above 8 GHz.

Below 3 GHz SRT and NOTO are also quite affected by RFI, then it improves significantly as expected in the frequencies of the planned S- and Clow-bands receivers. At higher frequency (from X-band at MED and from Chigh-band at SRT and NOTO) the RFI environment is defined fully clean.

In order to assure the highest performance most of the front-ends of the receivers installed on the Italian radio telescopes are cryo-cooled, with few exceptions:

- MED: L- and Chigh-band
- NOTO: Chigh- and S/X-band
- SRT: X/Ka-band



(a) (b)

Figure 6.5 – Quality of frequency bands in terms of RFI and RAS primary/exclusive bands: (a) receivers in operation and (b) receivers under development/under evaluation. The units in the y-axis correspond to the following categories: 5 units → Fully clean (RFI in <10% of band or of time); 4 units → Almost clean (RFI in >10%,<25% of band or of time); 3 units → Partially clean (RFI in >25%,<50% of band or of time); 2 units → Moderately polluted (RFI in >50%,<75% of band or of time); 1 unit → Strongly polluted (RFI in >75% of band or of time). In black the primary/exclusive RAS bands

We note that the absence of a cooling system has a major impact in the usage of a receiver for single-dish astronomical observations, as already discussed for the case of the S/X receiver at NOTO. The same holds true for the Chigh front-ends at MED and NOTO, whose resulting system temperatures are a factor of 3-4 higher with respect to that obtained with the cooled Chigh receiver of SRT. This makes the MED and NOTO Chigh front-ends less attractive for single-dish observations with respect to the cooled Clow ones installed on the same telescopes, as it is pointed out also in their rate of scientific publications and percentage of observing time (see Section 6.2).

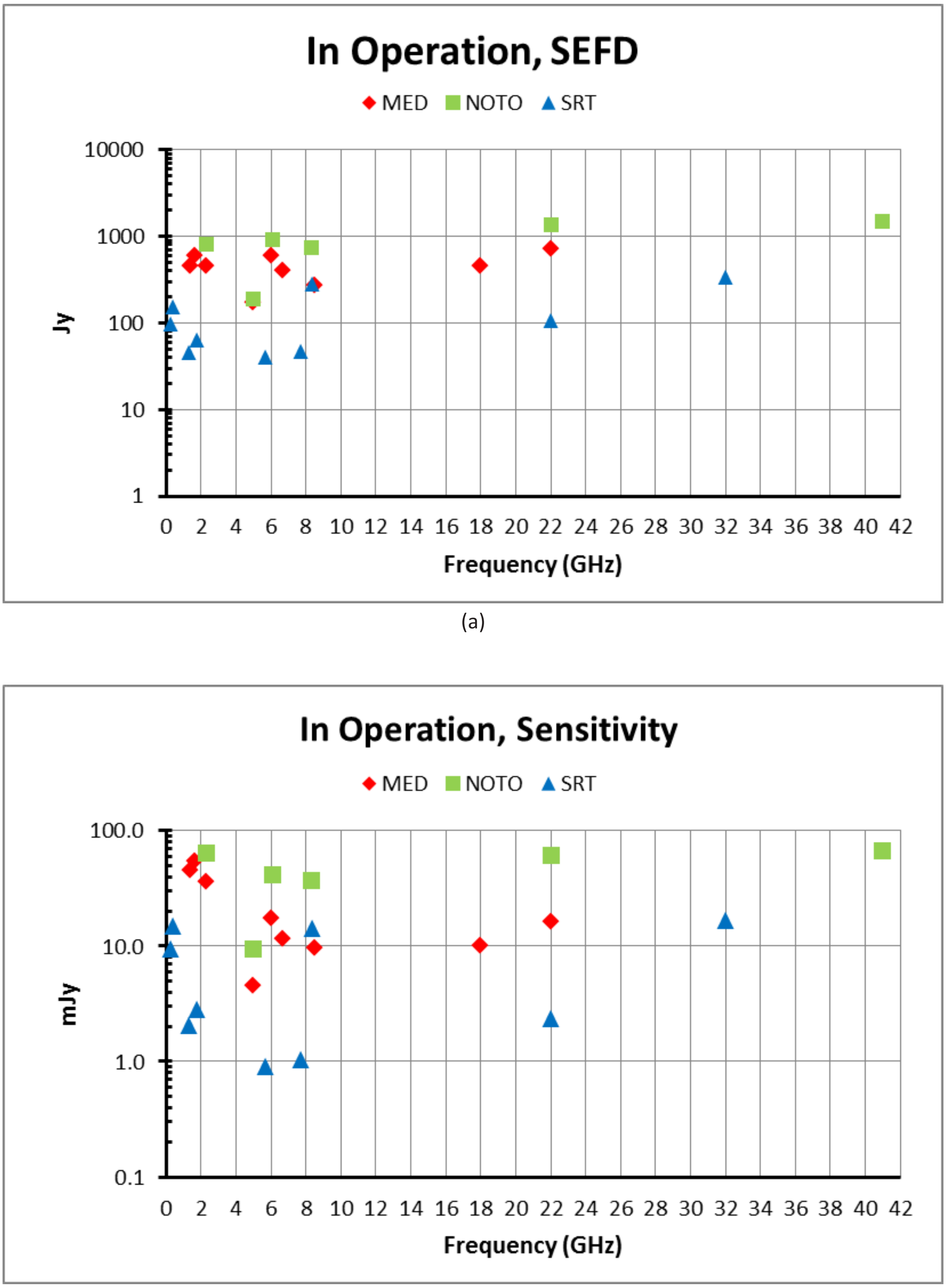
With regard to polarization properties, almost all receivers output dual circular polarization (LCP and RCP). These are mandatory for VLBI observations and recommended for single-dish polarimetric observations. In fact, with respect to linear polarization receivers, circular polarization receivers allow a more accurate determination of the Q and U Stokes parameters describing the polarization properties of an astronomical source. Again, a few exceptions are present:

- SRT: P/L-band offers both circular and linear polarization, the latter dedicated to pulsar studies, X/Ka-band outputs only one circular polarization for each frequency band and S-band under development with native linear polarization, but without the possibility to recombine the signals to obtain the circular polarizations (polarizers would have dimensions preventing their use in the very populated cryogenic chamber).
- NOTO: S/X-band outputs only one circular polarization for each frequency band;
- SRT and NOTO: W-bands under development/under evaluation offer only one single circular polarization.

As a conclusive indication of the performance of the receiving system as a whole, two different parameters are generally used:

- SEFD (Jy), which is the ratio between the system noise temperature (Kelvin) and the antenna gain (Kelvin/Jansky). These two parameters describe the performance of the receiver and the characteristics of the antenna. The SEFD does not include the instantaneous bandwidth available at the receiver output.

- Theoretical sensitivity, which is the 1-sigma RMS noise (Jy) detectable by the instrument back-end with the nominal instantaneous bandwidth in 1 second of integration time. This parameter has to be taken as a lower limit to the actual sensitivity for a number of reasons: *(i)* the presence of RFI effectively reduces the available instantaneous bandwidth, *(ii)* receiver performance are typically worse than theoretical, *(iii)* the confusion limit itself poses a limit to the sensitivity actually reachable in a given frequency band.

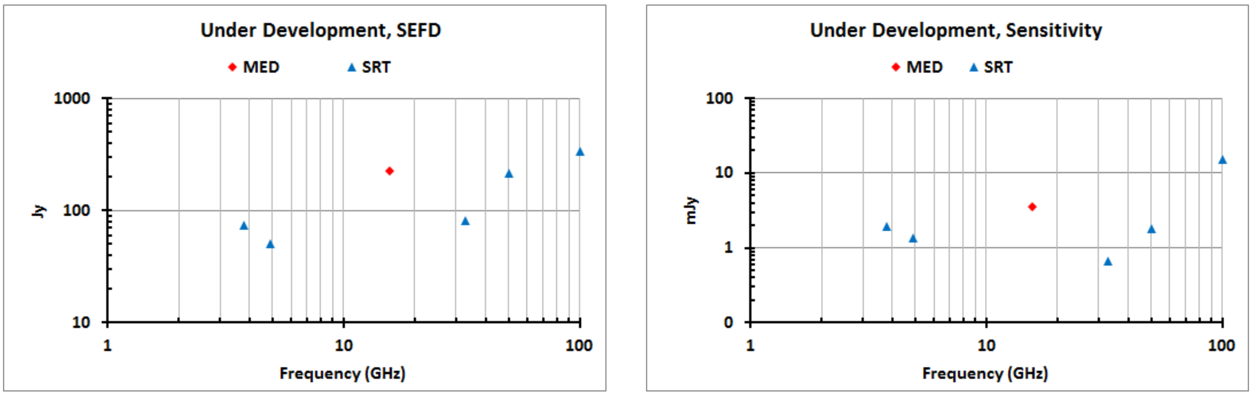


(b)

Figure 6.6 – Receivers in operation: (a) SEFD and (b) sensitivity

Fig. 6.6 shows the SEFD and sensitivity for each antenna and frequency band in operation. When available, more than one value for each band are reported (for instance, MED gives two values at L, Chigh and K bands, while for the SRT at P, L, and Chigh bands). As expected, the SRT shows the best performance because of its larger diameter and its most recent instrumentation. Except for the X/Ka-band receiver, all the others show a SEFD around or better than 100 Jy. At the other extreme, NOTO pays the cost of older and not cooled (2 out of 5 bands offered) receivers. As a result, the SEFD is very close to 1000 Jy for every NOTO receivers except for Clow-band which is competitive with its MED counterpart. MED shows similar SEFDs, around 600 Jy, for most bands, exceptions are Clow- and X-band close to 200 Jy. The sensitivity, shown in Fig. 6.6b, is clearly affected by the bandwidth sent to the back-end from each receiver; for example the MED receivers have quite different bandwidths (2 GHz of the K-band, 800 MHz for the Clow-, Chigh- and X- and 100 MHz for the lower frequency) and this produces a significant variation in the receiver performance.

Fig. 6.7 shows the same parameters (SEFD and sensitivity) as Fig. 6.6 for the receivers under development at MED and SRT (under evaluation front-ends at NOTO have not been included). Estimation of SEFD for Ku-band at MED is about 200 Jy, the same value of the two best receivers in operation, but obtained at a much higher frequency. The foreseen sensitivity should be the best value for MED because of the large band offered to the detector (4 GHz each output). The SRT will show SEFD and sensitivity at Clow-band practically equal to the already available Chigh-band receiver. The Q-band receiver is foreseen to have state-of-the-art performance with a very high sensitivity due to high antenna gain, low noise and wide band available at the back-end (about 15 GHz each output). Finally, in spite of its age the W-band is also estimated to be a very sensitive receiver as soon as the microwave holography and the metrology system at SRT will be able to assure a surface accuracy around 200 μm.



(a) (b)

Figure 6.7 – Receivers under development: (a) SEFD and (b) sensitivity

Finally, we plot in Fig. 6.8 the publications related to technological development of the SRT front-ends. The total amount of refereed papers and proceedings to International conferences is about 20 works dealing with the receivers developed after 2010 (including also those under development). This significant production shows that the INAF receiver group is working on state-of-the-art technological projects, which found space in international journals and conferences. The complete list of such papers is reported in Appendix C.

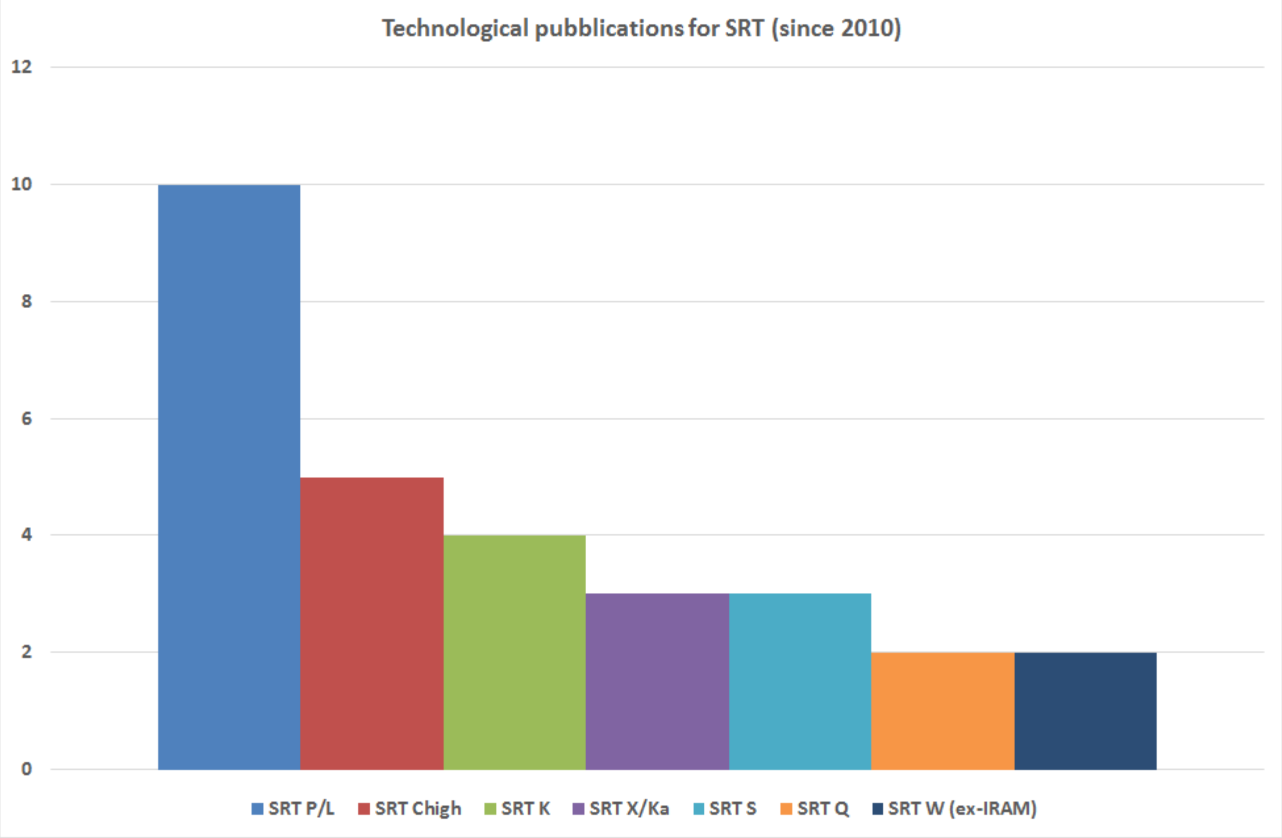


Figure 6.8 – Number of technological papers for each receiver operating at SRT. To be noticed that 3 papers are attributed to more receivers since they give an overview of the first-light receivers of SRT

6.2 Scientific data analysis

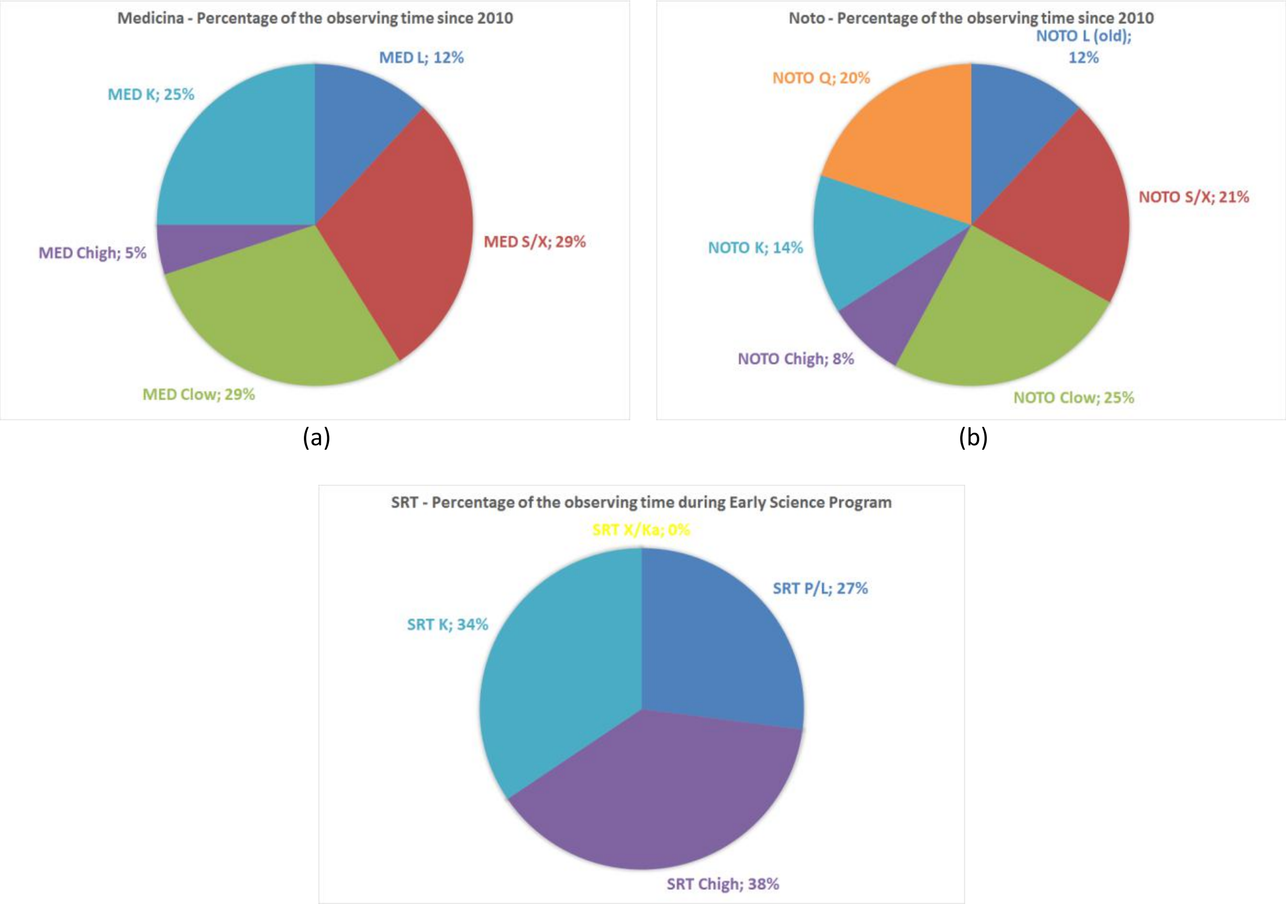
In this Section we summarize and discuss the receiver performance from the perspective of their astronomical usage and scientific output. After a general overview for the three telescopes, a more detailed discussion of the results obtained with the various observing techniques (VLBI, single-dish and geodetic VLBI) is given.

The first result we want to present is the relative usage of each operational receiver given in terms of the allocated observing time (see Fig. 6.9). Due to the recent start of observing activities at SRT, we used a different approach for this antenna with respect to MED and NOTO. For the 32-m telescopes we have considered the percentage of observing time assigned to each receiver since 2010, whereas for SRT we have taken into account the observing time allocated to each receiver during the 7-months of the Early Science Program.

SRT statistics shows an almost uniform usage of the first light receivers with the total 27.2% of the P/L receiver divided in 14.7% of proposals requiring the L band only and 12.5% requiring both frequencies. The statistics in Fig. 6.9c, however, likely does not reflect the actual fraction of time that will be allocated to each receiver in the future, because of two main reasons: *i)* given the aforementioned problem of RFI, projects requesting 350 MHz or simultaneous dual-frequency P/L band observations were scheduled only in the two weeks during which the screening cover was installed on the Gregorian focus, hence were assigned only a limited amount of observing time; *ii)* no dynamic scheduling was offered during Early Science Program, so that high-frequency observations may have been over-scheduled to take into account possible adverse weather conditions.

Overall, at MED the S/X-, Clow- and K-band receivers are the most used. The observing time allocated to L-band is more or less half that of the previously mentioned receivers, while the Chigh-band is scarcely used. The low percentage of observing time allocated to the Chigh receiver may be interpreted in view of various factors affecting the performance and the scientific output of this front end. For instance, the presence of strong RFI surely affects the observations at 6.7 GHz, as well as the fact that this receiver is uncooled. Also, the lack of state-of-the-art spectroscopic back-ends may have limited the exploitation of this receiver. Finally, the multi-feed methanol masers survey performed with the Parkes radio telescope ([2] and references therein) represents nowadays a statistically exhaustive reference catalog for spectroscopic studies at 6.7 GHz, possibly reducing the interest in single-dish methanol observations with antennas like MED.

NOTO receivers show a distribution similar to that for MED, again with the Chigh band being the less used, very likely for the same reasons described for MED. The K-band receiver at NOTO is less used than that at MED probably due to its lower performance, whereas we note the relatively high usage of the Q-band receiver. As discussed in Section 6.1, until 2014 NOTO was also equipped with an L-band receiver, which was used for observations in the VLBI network and produced a significant number of publications. For this reason, we included this receiver in the present statistics.



(a) (b)

(c)

Figure 6.9 – Percentage of observing time for each radio telescope receiver: (a) MED, (b) NOTO and (c) SRT. For MED and NOTO, the observing time is computed including all the observing modes: VLBI (radio astronomical and geodetic) and single-dish. The statistics of SRT is based on the Early Science Program

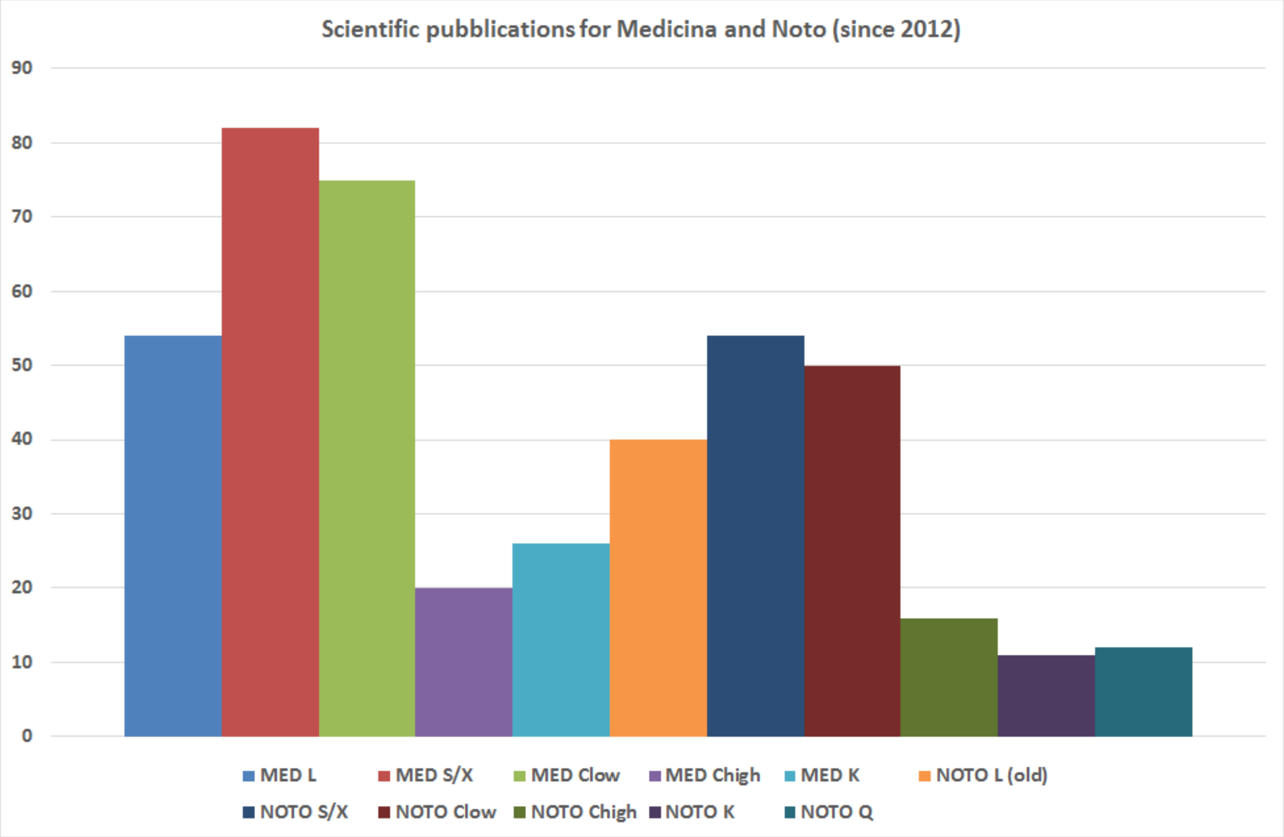


Figure 6.10 – Scientific production for each receiver operating at MED and NOTO

For MED and NOTO we evaluated the scientific output by plotting the number of refereed papers that make use of observations made with those telescopes in the period January 2012 – December 2016 (see Fig. 6.10). To gather a more detailed perspective on the publication rate of each receiver, Fig 6.11 shows the number of refereed papers versus the observing mode. With respect to VLBI, papers quoting the use of a generic "EVN" array, i.e. not specifying which antennas took part in the observation, have been attributed to both MED and NOTO. A detailed report on the scientific publications for the Italian radio telescopes is given in Appendix C.

Overall, the 32-m MED and NOTO telescopes have been used in 208 refereed papers in the considered time period, divided in 176 VLBI publications and 32 single-dish publications. In a non-negligible number of cases the same publication makes use of data acquired with more than one receiver. In such cases, the publications in Fig. 6.10 and 6.11 have been counted for both the involved receivers.

As expected, VLBI (both radio astronomical and geodetic) is the most productive observing technique in terms of papers production in the considered period. However, the situation has significantly improved for single-dish observations at MED thanks to the advent of the new ESCS observing software, particularly suited to optimally exploit telescope characteristics. ESCS has been available at MED since 2008 and, in its extended version (Nuraghe), is the control system for the SRT. The majority of single-dish observations performed at MED in the considered period make use of the ESCS.

It is worth mentioning that the statistics on publications presented in this Section are strongly affected by some extra-ordinary maintenance stops that affected MED and NOTO in the period

2012-2016 as discussed in Chapter 1. Additionally, between May 2011 and February 2013, MED was equipped with an old K-band receiver not suited for observations with ESCS.

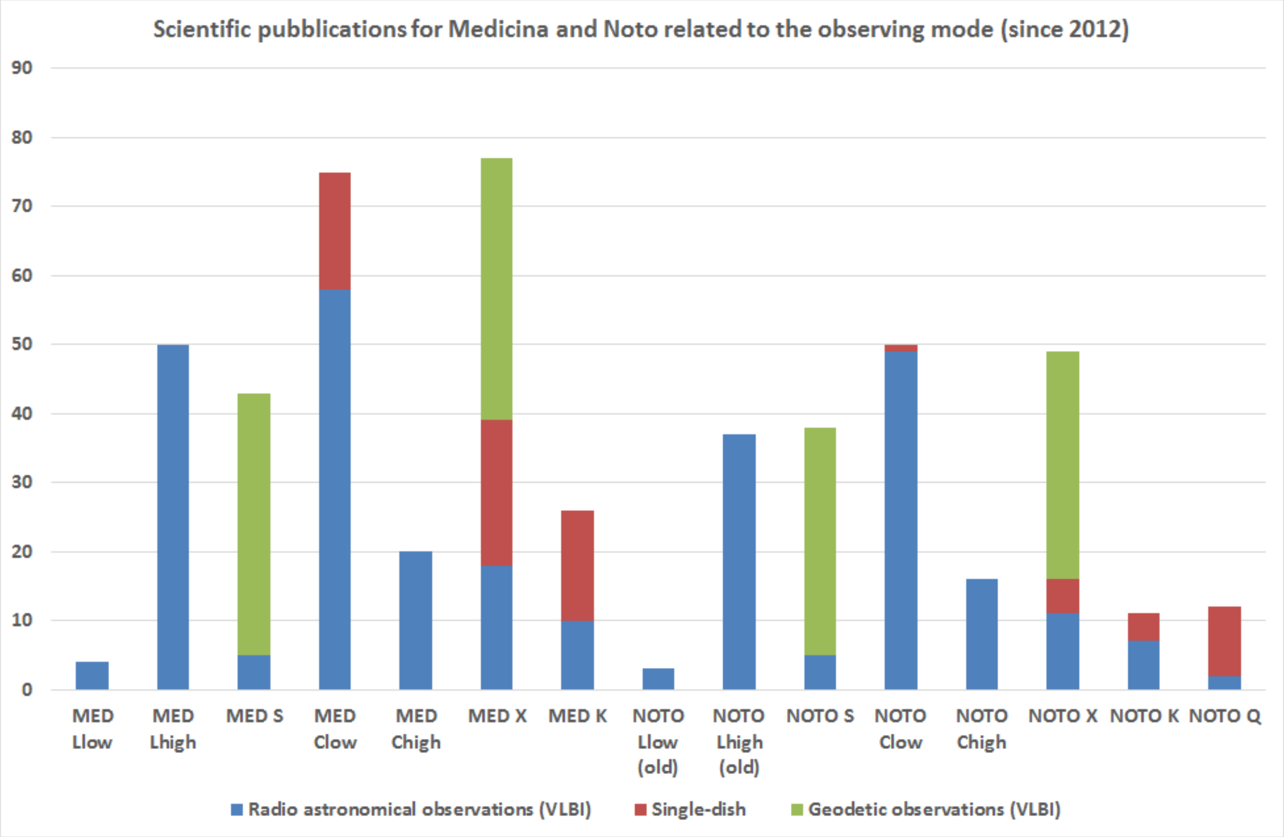


Figure 6.11 – Scientific production per observing and frequency band at MED and NOTO. The publications related to the geodetic observations with the S/X receivers are accounted twice, one for each frequency band

On average, the total amount of papers making use of MED data is 30% higher than that using NOTO irrespective of the receiver. This is likely due to a combination of factors: the later installation of ESCS at NOTO, which has been completed at the time of writing this report so 7 years later than at MED, the higher receiver noise temperature in the NOTO receivers with respect to the MED receivers, and the longer extra-ordinary maintenance stops of the NOTO radio telescope.

For both telescopes, the S/X- and the Clow-band receivers are the more productive due to their participation in VLBI observations. Despite the low percentages of allocated observing time (see Fig. 6.9) the L-band receiver rank in third position in terms of its scientific production for both MED and NOTO. The Chigh-band was not very much used either at MED or at NOTO and is one of the less productive receivers in terms of scientific publications.

Scientific publications in single-dish observing mode typically use the higher-frequency receivers like the Clow-, X-, K- and Q-bands. Lower frequency receivers, like the Llow, at the 32-m antennas are characterized by very large beam sizes and have been used only for VLBI or geodetic observations in the period 2012-2016. In particular, from Fig 6.11 it is evident a strong EVN demand for observations at high (1.7 GHz) rather than low (1.4 GHz) L-band and, similarly, at low rather than high C-band.

At first glance, the K- and Q-band NOTO receivers appear to be less productive than the average even if a significant amount of time is allocated to them. With respect to the Q-band, as can be seen in Fig. 6.11 this receiver has been mostly used for single-dish observations, an observing mode which requires a much larger observing time with respect to VLBI. In the future it is expected that the productivity of the NOTO Q-band receiver can increase significantly thanks to its participation in the KVN/VERA interferometric array observations. Moreover, NOTO is going to be involved in GMVA observations at 43 GHz as well. With respect to the K-band at NOTO, which is regularly used in VLBI observations, it is to be noticed that this receiver has the drawback of being a mono-feed system. This means that, when used in single-dish mode it is particularly affected by atmospheric conditions that may heavily impact on the observing efficiency. The much higher scientific productivity of the K-band at MED is related to the availability of the 7-feed receiver (now on board the SRT), which has been installed on MED for commissioning purposes until May 2011. Moreover, since spring 2013 MED is equipped with a modern dual-feed receiver for the K band.

A similar analysis on the publication rate and scientific impact is of course not possible for SRT, due to its recent start of operations. However, by considering publications (not only refereed) made during the Technical Commissioning and Astronomical Validation phase as well as the scientific proposals accepted for the Early Science Program, the most used receivers are those for the Chigh and K bands. This result is not unexpected given the critical RFI situation in the P/L band already discussed in the Section 6.1 and the fact that this lower frequency receiver has been the last to be installed and commissioned.

Tab. 6.III summarizes the scientific keywords associated to the various receivers. This table has been created by listing all the astronomical keywords quoted in the MED and NOTO publications. It is thus not to be intended as an exhaustive list representative of all the possible scientific applications, but only of those actually performed in the last five years. A similar analysis using existing publications is not possible for the SRT receivers. For these receivers, using the MED/NOTO list as a starting point, we reviewed the science cases that can be addressed on the basis of their expected performance (also considering the Astronomical Validation and Early Science Program results for the SRT) and assigned the keywords accordingly.

Some level of grouping of the astronomical keywords quoted in the publications has been made starting from the list obtained for MED and NOTO, namely:

- *AGN* include = quasars: general, absorption lines, emission lines; galaxies: active, Seyfert; blazars; black hole physics; accretion disks;
- *galaxy formation and evolution* include = galaxies: high-redshift, starburst, evolution, jets, spiral, star formation, interactions, halos, luminosity function, mass function, kinematics and dynamics, structure, nuclei, ISM; supermassive black holes (in BCG); spiral density waves; cosmological parameters; radio continuum: galaxies; X-rays: galaxies; gamma rays: galaxies;
- *Galaxy structure* include = Galaxy: structure, kinematics and dynamics; Galaxy: Galactic parameters;
- *pulsar* include = stars: neutron;
- *supernovae* include = SN remnants;
- *star formation and evolution* include = stars: late-type, AGB and post-AGB, winds, pre-main sequence, emission-line, Be, mass-loss, supergiants, formation, kinematics and dynamics; radio stars; Galaxy: stellar content; binaries: general; radio continuum: stars; gamma rays: stars;

RECEIVER		AGN	Galaxy formation and evolution	Galaxy structure	HI	Pulsar	X-ray binaries	Supernovae	Masers	Star form. & evolution	Radio line emission	Physics of radio sources	Gravitational lensing	Astrometry	Extragalactic surveys	Variability monitoring	Geodesy	Radar astronomy	Magn. fields & pol.	Comets	ISM	Space science	SZ effect in clusters	Magnetars
MED	**Llow**	X	X	X	X																			
	Lhigh	X	X			X	X	X	X	X	X	X	X								X			
	S	X	X				X	X		X		X	X	X	X	X	X				X			
	Clow	X	X			X	X	X		X	X	X			X	X		X	X		X			
	Chigh	X	X	X					X	X	X			X					X		X			
	X	X	X				X	X		X		X	X	X	X	X	X				X			
	K	X	X	X				X	X	X	X	X		X	X	X			X	X	X			
NOTO	**Llow**	X	X	X	X					X														
	Lhigh	X	X			X	X	X	X	X		X	X								X			
	S	X	X					X				X	X	X	X		X				X			
	Clow	X	X			X	X	X		X	X	X							X		X			
	Chigh	X	X	X					X	X				X					X		X			
	X	X	X					X				X	X	X	X		X				X			
	K	X	X	X				X	X	X		X		X	X						X			
	Q	X	X						X			X											X	
SRT	**P**	X	X	X		X	X	X					X		X	X								
	L	X	X	X	X	X	X	X	X		X	X			X	X			X		X			X
	Chigh	X	X	X		X	X	X	X	X	X	X		X	X	X			X		X			X
	X/Ka	X	X				X	X				X				X						X		X
	K	X	X	X			X	X	X	X	X	X		X	X	X			X	X	X			X

Table 6.III – Distribution of the astronomical keywords for the Italian radio telescope receivers. Keywords are taken from refereed papers (published in the 2012-2016 period) in the case of NOTO and MED receivers. For SRT receivers, keywords describe the possible scientific applications.

- *radio line emission* includes = radio lines: ISM, stars;
- *physics of radio sources* include= radiojets; magnetohydrodynamics; relativistic processes; evolution; hydrodynamics; instabilities; radiation mechanisms: non-thermal, thermal; acceleration of particles; astroparticle physics; elementary particles; scattering; plasmas;
- *geodesy* include= Mt. Etna; VLBI; GPS; Mantle; Crust; Earthquakes; Eruptions; Triggering mechanisms; Ground deformation; Flank eruptions; Magma, Interferometry, Evolution, Extension; Southern hemisphere reference frames; IVS; Time-series analysis; Space geodetic

surveys; Intraplate processes; Geodetic VLBI; Earth orientation parameters; Earth rotation variations; Earth's rotation, tidal deformations; Earth rotation variations; Co-locations; Space geodesy; International Celestial and Terrestrial Reference Frames etc.;

- *magnetic fields and polarization* include = magnetic fields; polarization; galaxies: magnetic fields;
- *ISM* include = ISM: structure, jets and outflows, bubbles, clouds, kinematics and dynamics, molecules, dust, extinction.

Since these keywords were derived with different methods, a direct comparison among receivers in the same band at different telescopes cannot be done. Nevertheless as an overall comment on Tab. 6.III it is evident the large variety of scientific case studies that characterizes almost all the radio astronomical instrumentation.

Finally, the Italian reflector telescopes are involved in a number of international projects and networks, namely:

- The European VLBI Network, of which IRA is a full and founding member. MED and NOTO antennas regularly participate in EVN observing sessions, which are performed three times per year and have a typical duration of 3 weeks each. In addition several e-VLBI and out-of-session experiments are made during the year. Recently, the SRT joined some of the EVN experiments and, once fully operational, it is expected to regularly take part in EVN observations.
- The Global mm-VLBI Array, an array of radio telescopes performing coordinated global VLBI observations at 86 GHz and, for a small fraction of time, at 43 GHz with a subset of antennas. There are two GMVA observing sessions per year. NOTO already participated in 43GHz GMVA past observations. Given the size and the location of the SRT and NOTO respectively, once they are equipped with the 86 GHz receivers INAF will be able to fully participate to the GMVA offering an improvement of the array in terms of sensitivity and UV coverage.
- The International VLBI Service for Geodesy and Astrometry is an international collaboration of organizations providing VLBI services for geodesy, astrometry, earth science research and operational activities. MED and NOTO radio telescopes participate in IVS observations, on a monthly basis, with the S/X receivers mounted on the primary focus of both antennas. The SRT is not equipped with receivers suited for geodetic observations.
- The RadioAstron is an international space VLBI project led by Russia and exploiting the spacecraft-based Space Radio Telescope Spektr-R together with a number of ground-based antennas. The 32-m MED and NOTO telescopes participate in RadioAstron experiments for about 20/30 hours per month, performing observations in the Lhigh (currently MED only), Clow and K bands. The SRT participated during its science commissioning.
- VERA, KVN and KaVA: VERA is a Japanese VLBI array, consisting of four antennas operating in the K and Q bands. The KVN is a dedicated VLBI network of three radio telescopes located in South Korea, operating at 22, 43, 86, and 129 GHz. The KaVA is the VLBI array that combines KVN and VERA. IRA is planning to participate with MED and NOTO in joint KaVA observations at 22 GHz, and with the NOTO antenna at 43 GHz. Joint observations at 86 GHz with KVN are also possible once the Italian antennas are equipped with 86 GHz receivers.

6.3 Management data analysis

In this Section, the following aspects are deeply analyzed: development time and human and financial resources.

An important aspect investigated by this survey is the time-path in receiver development and manufacture, as summarized in Fig. 6.12. In this analysis, we have considered receivers: in operation; under development; and dismissed. Apart from a few exceptions, apparently the duration of the development phase of receivers for SRT is higher with respect to those for MED and NOTO. The average development time of the first-light receivers for the SRT has been 6 years, whereas the NOTO and MED receivers have been fabricated on average in less than 3 years. This longer development time is due to the following two main reasons: they have been developed simultaneously with other receivers and they consist of new-generation front-ends. Fig. 6.12 suggests the following considerations:

- Because of the simultaneous development of different receivers, the most representative quantity is not the amount of time required to build each receiver, but the so-called ‘development efficiency’, i.e. the amount of receivers completed in a certain period of time. It can be noticed that in the period 1983-1994 ten receivers have been produced, corresponding to 0.83 receivers per year. On the other hand, in the period 1999-2016 the INAF receiver group has worked on 13 receivers (the X/Ka-band has not been included since it has been fabricated externally), i.e. an average production rate of 0.72 receivers per year, very close to the figure of the previous period.
- While receivers designed in the ‘90s have been tailored to scientific cases specific of VLBI, this landscape has changed for the new generation front-ends. They have to be general-purpose, therefore suitable for different astronomical applications and observing modes, challenging the designer to fulfill the best performance possible.
- As already pointed out, the commissioning receivers for the SRT are new generation receivers in many aspects: larger bandwidth, new architecture and new technologies. For instance, the 7-horn K-band has been the first multi-feed receiver ever produced by the Italian group, indeed it was the first produced throughout the world, and it uses MMIC LNAs that have been designed, developed, constructed, and characterized in house with a small production quantity of 20 pcs. Also, the P/L receiver construction was started by the IRA/OAA receiver group and then carried on by the OAC staff, representing an extremely important test-bed for the growth of a new generation of technicians, now engaged autonomously in the development of new receivers.
- The production of receivers seems to be independent by the team organization. In the period 1983-1994, two teams (IRA and OAA) were working on the construction of new receivers. We should also notice that the members of the IRA group had at the same time the responsibility of maintenance and development of everything related to the 32-m antenna, from mechanics to electronics etc.; thus, up to the year 2000 the IRA antenna group was taking care also of receiver development. This organization changed in the following years, particularly with the kick-off of the SRT construction. Starting from 2003 a receiver group including staff from IRA and OAA and devoted to the production of receivers for the commissioning of SRT was formalized. Later on, in 2007 a group from OAC joined this team, specifically to work at the construction of the P/L receiver.

- In some cases the development of a receiver has been slowed down owing to fault of the firms involved in the construction. This has been the case for the MED K-band receiver, for which there has been a one year delay in the delivery of the passive front-end components by the workshop (these parts were copies of pieces already produced for SRT K-band multi-feed). This has also been the case for the MED Clow-band for which it took almost four years for the firm to deliver the passive parts of the front-end. On the contrary, the outsourcing of the design, construction and measures of the front-end of the SRT X/Ka-band helped in completing it within two years.
- A few words are due to explain the apparent 'black out' in the production of receivers for the period 1995-1998. In those four years, the IRA antenna group was forced to pause the front-end design and manufacturing because they were engaged in many other telescope-related activities. IRA matured plans about a new generation antenna system (frequency agility, automation and remote control, new receivers, continuous frequency coverage, upgrade at higher frequencies) to offer enhanced observing capabilities so to increase the scientific exploitation of the telescopes. To this aim, in these years the IRA antenna group took care of the implementation of a new driving system for the MED subreflector (first step toward the installation of the frequency agility system), the substitution of the MED rail track (old version) together with the four azimuth wheels and the design of a new rail track system (still today in place at MED and NOTO), the development of the very first prototype of a mechanical actuator for the NOTO active surface and finally the development of an analogue back-end for polarimetric observations at MED.

Fig. 6.12 also shows the life of the receivers at each radio telescope form their construction to the dismissal. It can be also noticed that some receivers (like for example the K-band currently at SRT) have been available at other radio telescopes for a certain period.

Dismissed (old), in operation and under development (new) receivers

Year	SRT P/L	SRT S (new)	SRT Clow (new)	SRT Chigh	SRT K	SRT X/Ka	SRT Q (new)	SRT W (new)	MED L	*MED L (old)*	MED S/X	MED Clow	*MED Clow (old)*	MED Chigh	*MED Chigh (old)*	MED K	*MED K (old)*	MED Ku (new)	*NOTO L (old)*	NOTO S/X	NOTO Clow	NOTO Chigh	NOTO K	NOTO Q	Year
1983																				⬛					1983
1984										⬛			⬛							⬛					1984
1985										⬛			⬛							MED					1985
1986										🟩			🟩							▨					1986
1987										🟦			🟦							▨					1987
1988										🟦			🟦							▨	⬛		⬛		1988
1989										🟦	⬛		🟦				⬛			▨	⬛		⬛		1989
1990										🟦	⬛		🟦				⬛			▨	🟩		🟩		1990
1991									⬛	🟦	⬛		🟦		⬛		⬛		⬛	▨	🟦		🟦		1991
1992									⬛	🟦	🟩		🟦		⬛		🟩		⬛		🟦		🟦		1992
1993									⬛	🟦	🟦		🟦		🟩		🟦		🟩	🟩	🟦		🟦		1993
1994									🟩	🟥	🟦		🟦		🟦		🟦		🟦	🟦	🟦		🟦		1994
1995									🟦		🟦		🟦		🟦		🟦		🟦	🟦	🟦		🟦		1995
1996									🟦		🟦		🟦		🟦		🟦		🟦	🟦	🟦		🟦		1996
1997									🟦		🟦		🟦		🟦		🟦		🟦	🟦	🟦		🟦		1997
1998									🟦		🟦		🟦		🟦		🟦		🟦	🟦	🟦		🟦		1998
1999									🟦		🟦		🟦		🟦		🟦		🟦	🟦	🟦	⬛	🟦		1999
2000									🟦		🟦	⬛	🟦	⬛	🟦		🟦		🟦	🟦	🟦	⬛	🟦		2000
2001						⬛			🟦		🟦	⬛	🟦	⬛	🟦		🟦		🟦	🟦	🟦	🟩	🟦		2001
2002					⬛	NOTO			🟦		🟦	⬛	🟦	⬛	🟦		🟦		🟦	🟦	🟦	🟦	🟦	⬛	2002
2003					⬛				🟦		🟦	⬛	🟦	🟩	🟥		🟦		🟦	🟦	🟦	🟦	🟦	⬛	2003
2004					⬛				🟦		🟦	⬛	🟦	🟦			🟦		🟦	🟦	🟦	🟦	🟦	🟩	2004
2005					⬛				🟦		🟦	⬛	🟦	🟦			🟦		🟦	🟦	🟦	🟦	🟦	🟦	2005
2006				⬛	⬛				🟦		🟦	🟩	🟥	🟦			🟦		🟦	🟦	🟦	🟦	🟦	🟦	2006
2007	⬛			⬛	⬛				🟦		🟦	🟦		🟦			🟥		🟦	🟦	🟦	🟦	🟦	🟦	2007
2008	⬛			⬛	MED				🟦		🟦	🟦		🟦					🟦	🟦	🟦	🟦	🟦	🟦	2008
2009	⬛			⬛	▨				🟦		🟦	🟦		🟦					🟦	🟦	🟦	🟦	🟦	🟦	2009
2010	⬛			⬛	▨				🟦		🟦	🟦		🟦		⬛			🟦	🟦	🟦	🟦	🟦	🟦	2010
2011	⬛			⬛	▨				🟦		🟦	🟦		🟦		⬛			🟦	🟦	🟦	🟦	🟦	🟦	2011
2012	⬛			🟩	🟩		⬛		🟦		🟦	🟦		🟦		⬛			🟦	🟦	🟦	🟦	🟦	🟦	2012
2013	🟩	⬛		🟦	🟦		⬛		🟦		🟦	🟦		🟦		🟩			🟦	🟦	🟦	🟦	🟦	🟦	2013
2014	🟦	⬛	⬛	🟦	🟦		⬛	⬛	🟦		🟦	🟦		🟦		🟦		⬛	🟥	🟦	🟦	🟦	🟦	🟦	2014
2015	🟦	⬛	⬛	🟦	🟦	🟩	⬛	⬛	🟦		🟦	🟦		🟦		🟦		⬛		🟦	🟦	🟦	🟦	🟦	2015
2016	🟦	⬛	⬛	🟦	🟦	🟦	⬛	⬛	🟦		🟦	🟦		🟦		🟦		⬛		🟦	🟦	🟦	🟦	🟦	2016

Figure 6.12 – Development time for receivers in operation, under development, and dismissed. Under development front-ends are indicated with 'new' while the dismissed ones are indicated with 'old'. Black cells indicate the development period, the green cells the year of installation in its current radio telescope, the red cells the removal year, the light blue cells the operational period in its current radio telescope, and the pink cells the operational period in a different radio telescope

From a financial point of view, we plot in Fig. 6.13 in blue the total budget allocated to the more recent receivers in operation (since 2010). It can be seen that for the P/L- and the K-band receivers, which are more complex from a technological point of view, around 300 K€ each have been invested. The Chigh- for the SRT and the K-band for MED had a lower cost, being respectively a mono-feed solution and a *replica* of the multi-feed K-band for SRT.

With respect to the receivers under development (red and green bars in Fig. 6.13), we notice that the cost of the 7-feed S-band for SRT is comparable to that of the K-band multi-feed. The higher cost of the SRT Clow- in respect of SRT Chigh- results from two contributions: *i)* the Clow- is equipped with two high temperature superconductor filters, this adding approximately 20 K€ extra cost for developing, prototyping, and production and *ii)* the size of the passive components of the front-end impact almost proportionally on price. In fact, the ratio between the Chigh and Clow frequencies is 1.37, similar to the cost ratio of their passive parts (equal to 1.3). Note that the cost of passive parts for both receivers accounts for 35-37% of the total cost.

Additionally Fig 6.13 shows that the MED Ku-band dual feed costs 1.5 times the MED K-band dual-feed. This is due to the fact that the former receiver required a new design while the latter is a small-scale copy of an already existing receiver (the SRT K-band multi-feed). Moreover, the MED Ku-band front-end has an instantaneous bandwidth twice that of the MED K-band, thus implying a doubling of the down conversion boards and relative costs.

However, what is really evident from Fig. 6.13 is the SRT Q-band receiver cost, which is well above the average cost of all the other receivers, produced or under construction, basically due to its state-of-the-art characteristics. The SRT Q-band is a mid-density multi-feed receiver (19 feed with double polarization), offering a huge amount of instantaneous bandwidth (about 280 GHz total) and a built-in continuum full-Stokes back-end together with baseband bands for spectroscopic observations. The large amount of components in the cryogenic chamber, the dimension constraints, thermal considerations, and performance call for expensive integrated electronic modules and connections via waveguides. Approximately 29% of the overall cost comes from the LNAs (cost projection for 40 pcs), 22% from the passive parts of the front ends (19 feed systems), and 13% from the first down-conversion modules (40 pcs). Finally, the second conversion boards with the full band continuum back-end integrated inside, processing the thirty-eight outputs from the first down conversion, account for 14%. The main source of cost is therefore the number of components needed to make 19 double polarization receiving chains, while the high frequency range involved (33-50 GHz) has a negligible financial impact. At the beginning of this development the original request was for a 7-beam multi-feed for which MIUR provided 410 K€, even if INAF made available only 250 K€ of this amount. Then the request changed to a 19-beam multi-feed when a funding opportunity coming from Lombardia-Sardegna Regions opened, but eventually the time schedule for the construction did not meet with the expiry of this contract and the foreseen money vanished. It is interesting to note that if one correctly scales the cost for a 19-beam multi-feed to a 7-beam system the amount is around 500 K€, almost matching with the figure originally provided by MIUR. Anyway, the current situation is that 320 K€ has been already spent and 2/3 of the total cost is not available.

Finally, the percentage of involvement of the three INAF structures (OAA, IRA and OAC) in the design and fabrication of the front-end is described in Fig. 6.14 both for the receivers in operation

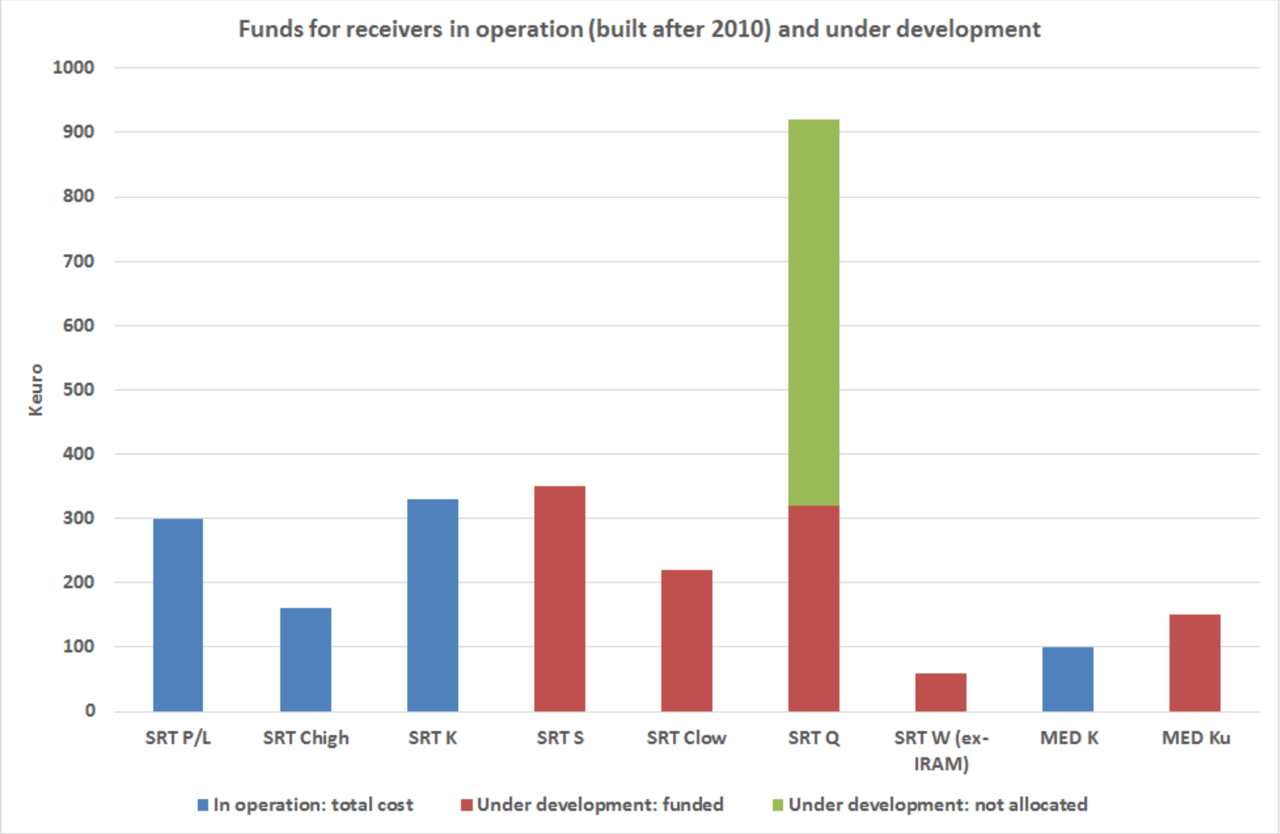
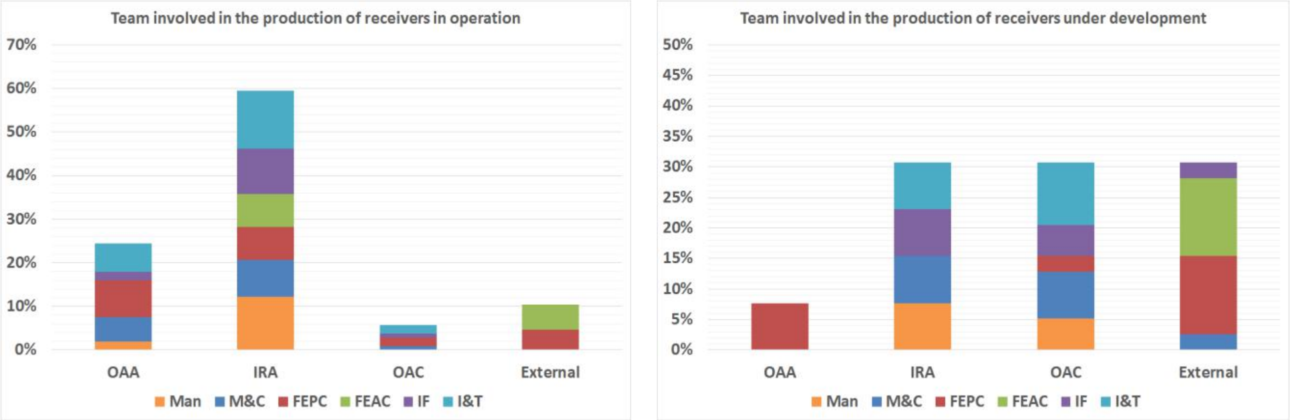


Figure 6.13 – Funds invested in the receivers in operation (since 2010) and under development

and for the new ones. In these plots, we have used the same roles for the activity as defined in Section 3.2. Comparing the period 1990-2013 (Fig. 6.14a) and the present represented by under development receivers (Fig. 6.14b), we see a decrease in the contribution both of OAA, which is now oriented exclusively at the development of front-end passive components, and IRA, which is no more involved in front-end active/passive components. These reductions are balanced by the significant increase, from 5% to 30%, registered in the involvement of OAC. Finally, the contribution from external partners (research institutes, Universities and industries) has increased as well: for instance all the new receivers will use front-end active components externally produced.



(a) (b)

Figure 6.14 – Teams involved in the receivers distributed as OAA, IRA, OAC and external: (a) receivers in operation and (b) receivers under development. Legend for the activities FEPC: Front-end Passive Components; FEAC: Front-end Active Components; M&C: Mechanics and Cooling; IF: Intermediate Frequency section; I&T: Integration and Test

6.4 Status of the receivers in operation and under development

In this last Section we survey the present status of the receivers both in operation and under development. Regarding the former, two different aspects are reported: their degree of operational readiness; and whether some upgrades are expected for the near future. Regarding the latter group, we mention the degree of development reached and practical difficulties encountered.

The operational receivers at the SRT are working well, showing only two weaknesses: the P/L receiver has to be recurrently pumped, so there is a suspect of vacuum loss to be fixed. The K-band receiver shows poor reliability in some cryogenic Low Noise Amplifiers, recurrently repaired. Unfortunately, no spares are available so the intervention needs to dismount the component and wait for its recovery. This problem was waiting for a second release of LNAs, never put under production; this should have also solved an unexpected higher noise in the upper part of the band (25.5 to 26.5 GHz). Today a substitution of all fourteen amplifiers is possible commercially, with a considerable mechanical effort inside the dewar in order to fit the different dimension of the LNA chassis.

The current efforts in NOTO are mainly concentrated in completing the frequency agility in the secondary focus room, essentially making some important modifications to the present mechanical receiver supports and providing each receiver with an appropriate mechanical flange to place it in one of the nine dedicated holes. The implementation of the new mechanical arrangement in the secondary focus room, exactly the same as installed in Medicina in 2003, will allow the contemporary coexistence of nine cooled receiving systems. However, it is required to remove the L-band from the secondary focus. At the present time, no new L-band has been designed for primary focus (even if one is still under evaluation), and thus NOTO is not covering this important frequency band.

As far as the Medicina receivers are concerned, no important inconveniences are reported.

A major upgrade under consideration for the three telescopes is to enlarge the instantaneous bandwidth in the K-band receivers up to the whole band available (8 GHz at MED and SRT and 1.5 GHz at NOTO). This will be done providing sub-bands 1 GHz wide by using new down conversion boards. The prototypes for this upgrade are the down conversion boards presently used in the receivers under development, which also provide a built-in full Stokes back-end.

The five receivers under development, plus the four under evaluation at NOTO, require a considerable effort of people involved. At the SRT a lot of work is now focused on the primary focus S-band receiver. Preliminary tests on a un-cooled, mono-feed receiver have been done on the SRT, confirming the expected specifications in terms of beam pattern. The front-end receiver chain and the down conversion section are defined and fixed, as for the mechanical design of the 7-beams multi-feed receiver. The cryostat construction is in a very advanced phase, and the money for acquiring all the components for building the entire S-band multi-feed is available.

The Clow-band receiver waits for the design of the dewar, whereas the feed-system parts, the HTS filters, the down conversion boards and the control/power supply modules are already available or at an advanced stage. The cryogenic LNAs are promptly commercially available and will be purchased at the proper time in order to avoid the one-year warranty expiration.

The Q-band multi-feed has important parts available and purchased, but key modules are still in the development phase, namely first down conversion, calibration noise injection and thermal gap block. Because the mechanical rotator in the multi-feed K-band is proven to work properly, the same system will be replicated. The receiver will integrate a continuum back-end, as an evolution of the down conversion boards mentioned before: each polarization output will be subdivided into 8 sub-bands, 1.8 GHz wide, so the instantaneous bandwidth available for each of the 38 outputs will be about 15 GHz.

The W-band mono-feed single polarization purchased from IRAM shows difficulties in refurbishing the receiver with a cooling system able to lower the temperature to 4 K using liquid Helium. Current activity is now focused on testing a new cold head from ARS technologies for getting the 4 K necessary for the SIS mixer. The upgrading of the old control system of the receiver is ready and suited to be used in the SRT.

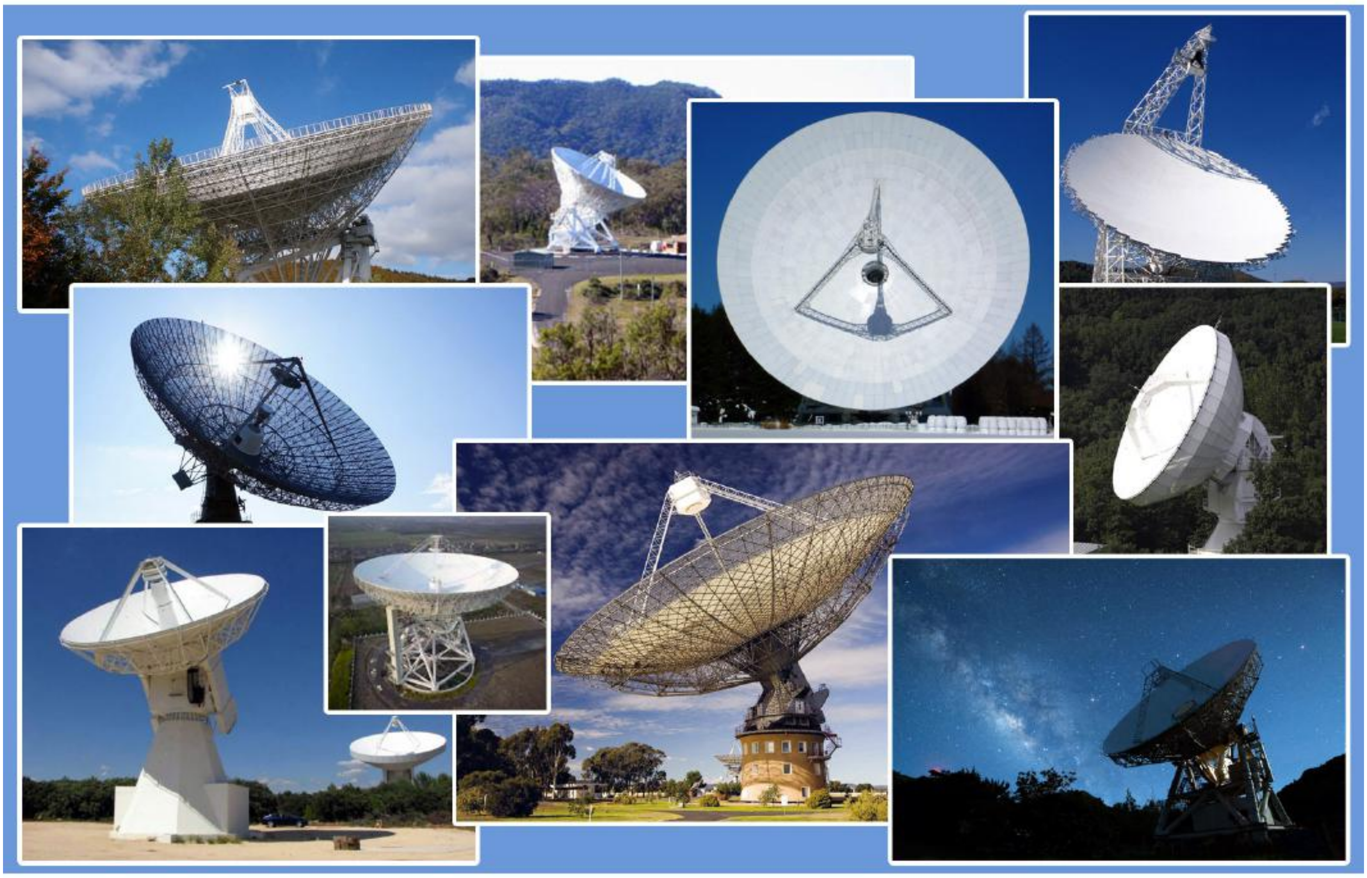
The MED Ku-band development is still at the beginning regarding the feed system and dewar, whereas the conversion boards are under construction. Priority has been given to the development of the SRT receivers.

The most important system under evaluation for NOTO is the L/S/X-band receiver. Started twenty years ago at the Noto Observatory, it was never finalized, showing complications due to its weight, impossibility to be cooled, and defective positioning on the primary focus. Some key electronic components of the receiving chains are broken or defective.

At NOTO, there are three different W-band mono-feed single polarization receivers. Two come from IRAM and are identical to the one purchased for the SRT, so its implementation could take advantage by the work done at OAC. The reason why two identical receivers were bought at NOTO is due to the fact that each of them has a single-linear polarization and the original idea was to merge two receivers to get a double-linear polarization. The third W-band receiver was produced by MPIfR for primary focus operation. This latter receiver has been already installed at different times in the NOTO antenna, without a complete and successful commissioning. In particular, during a laboratory verification in 2008, a technical issue in the receiver noise temperature was found. Therefore, the receiver was shipped to MPIfR for repair. The operation was successfully completed and the receiver was sent back to NOTO. Recently, a design study has been conducted to replace the horn and mount it in the secondary focus.

The current main issue for observing at 3 mm at NOTO is the overall surface accuracy, mainly due to the deformed surface of the subreflector. Investigations are currently in progress aimed at compensating these deformations by using the active surface of the primary mirror.

7. The International context



In order to benchmark the performance of the Italian antennas against recognized top-class worldwide radio astronomy facilities, a review of the characteristics of some of the major international radio telescopes has been made. In this Chapter, we analyze the data collected during this international survey on the receivers (both in operation and under development) at many radio telescopes throughout the world, and compare them with the characteristics of the Italian antennas.

Tab. 7.I lists the twelve radio telescopes included in the international survey, whereas their geographical location is displayed in Fig. 7.1. The Tab. 7.I reports also the class of the radio telescopes according to the following definition: large antennas are those with diameter ≥ 64 m, whereas medium antennas have diameter < 64 m. This division is useful for comparing performance of different size radio telescopes.

The selection criteria aimed to include those facilities that are mainly used for single-dish observations and of similar class, in terms of size, to the Italian antennas. We also included a couple of interferometers (KVN and VERA) for the following reasons: *(i)* KVN is also used as single-dish facility and *(ii)* both are regularly used in combination with the Italian radio telescopes for interferometric observations. Many other telescopes could have been added, but we believe that the amount of data coming from those examined plus the three Italian antennas is sufficient to give a realistic picture of radio astronomy worldwide, for the aims of this review.

Additionally, the comparison of characteristics and performance has been made for the receivers whose frequency range overlaps with that of the Italian radio telescopes (300 MHz up to 116 GHz).

Radio telescope (diameter)	**Abbreviation**	**Class**	**Nation**
Green Bank Telecope (100m)	GBT	Large	USA
Effelsberg (100m)	Effelsberg	Large	Germany
Onsala (20m)	Onsala20	Medium	Sweden
Onsala (25m)	Onsala25	Medium	Sweden
Yebes (40m)	Yebes	Medium	Spain
Pico Veleta (30m)	Pico Veleta	Medium	Spain
Tianma (65m)	Tianma	Large	China
Korean VLBI Network (21m)	KVN	Medium	Korea
VLBI Exploration of Radio Astrometry (20m)	VERA	Medium	Japan
Nobeyama (45m)	Nobeyama	Medium	Japan
Parkes (64m)	Parkes	Large	Australia
Mopra (22m)	Mopra	Medium	Australia
Sardinia Radio Telescope (64m)	SRT	Large	Italy
Medicina (32m)	MED	Medium	Italy
Noto (32m)	NOTO	Medium	Italy

Table 7.I – Radio telescopes contacted for the International survey. In the bottom part, the green cells list the Italian radio telescopes

Among the parameters that were tabulated for the survey of INAF radio astronomy receivers (see Tab. 6.I) we identified a subset of data to be collected for the international facilities. Tab. 7.II lists these parameters divided in technical performance, scientific, and operational data for the receiving systems. To collect data for the International table, which is reported in Appendix B, we first looked at the information available on the websites (see references for this Chapter) and then we contacted local staff asking for both a review of the table and the completion of missing information.

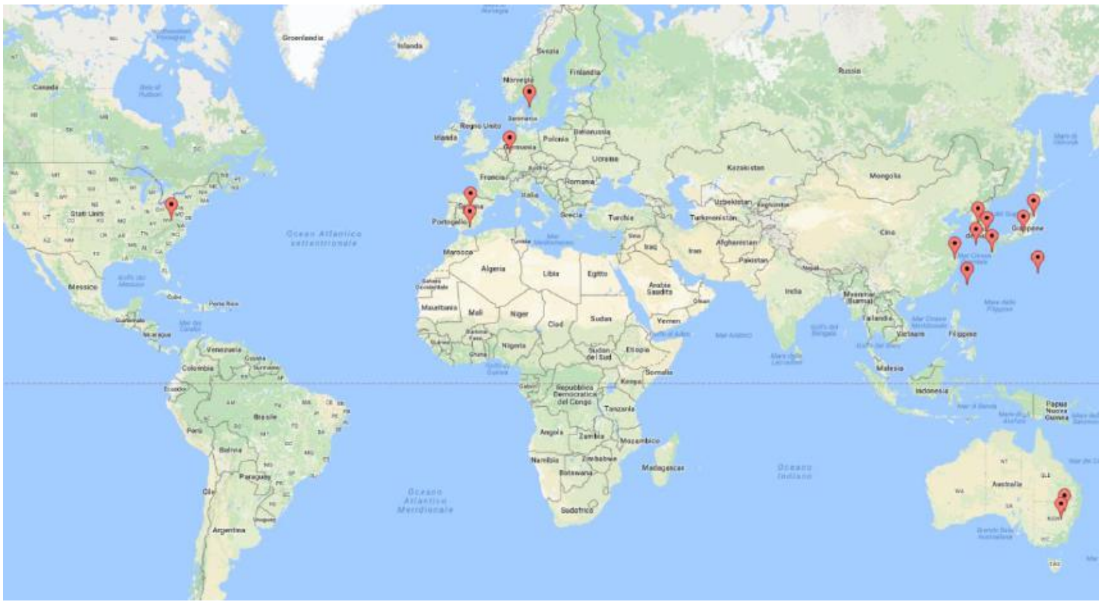
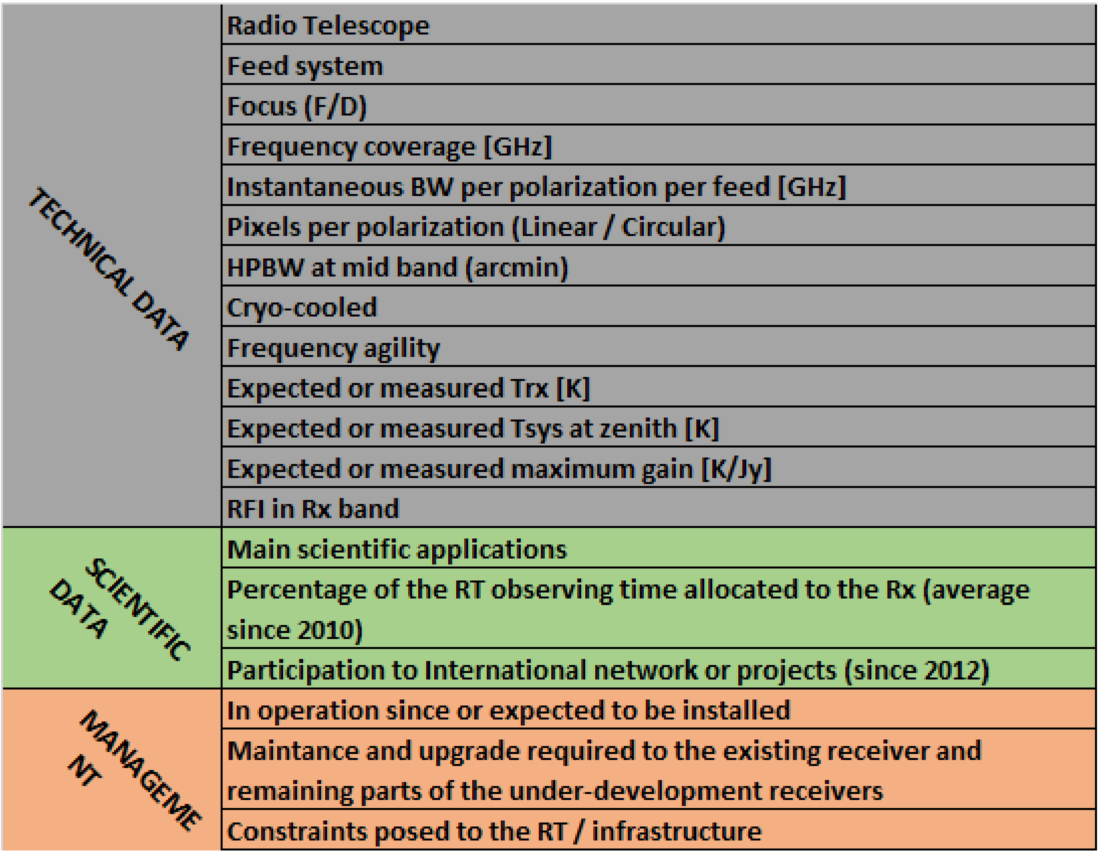


Figure 7.1 – Geographical location of the radio telescopes involved in the International survey



TECHNICAL DATA	Radio Telescope
	Feed system
	Focus (F/D)
	Frequency coverage [GHz]
	Instantaneous BW per polarization per feed [GHz]
	Pixels per polarization (Linear / Circular)
	HPBW at mid band (arcmin)
	Cryo-cooled
	Frequency agility
	Expected or measured Trx [K]
	Expected or measured Tsys at zenith [K]
	Expected or measured maximum gain [K/Jy]
	RFI in Rx band
SCIENTIFIC DATA	Main scientific applications
	Percentage of the RT observing time allocated to the Rx (average since 2010)
	Participation to International network or projects (since 2012)
MANAGEMENT	In operation since or expected to be installed
	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers
	Constraints posed to the RT / infrastructure

Table 7.II – Information collected for each receiver during the International survey. Expected values refer to receivers under development

7.1 Radio telescope characteristics

In the following sub-sections, we introduce each radio telescope with a brief description and information concerning the number of bands available, feed system type (mono-, dual-, multi-feed or dual-frequency systems), frequency coverage, frequency agility, and RFI as gathered by the data of the survey.

7.1.1 Green Bank Telescope

The GBT is an offset antenna, 100 m in diameter with Gregorian optics, placed at 807 m altitude and able to operate between 300 MHz and 115 GHz [1]. At present, the GBT operates 13 receivers, whereas 2 are under development and 4 are planned.

The feed types of the operational receivers are: crossed dipoles or linear taper for frequencies up to 900 MHz (PF1), mono-feed from 900 MHz to 10 GHz (PF2, L, S, C, X) and dual-feed from 12 to 100 GHz (Ku, Ka, Q, W) except for the K-band (18-27.5 GHz) that is a 7-beam multi-feed. All the operational receivers output dual polarization, either linear or circular. Additionally, a bolometer array at 3 mm (called MUSTANG2) and a 16-beam feed horn array in the same band (Argus) have been commissioned at the time of writing this report; therefore, in the following data analysis they are still included in the receiver under development category.

The receivers under development are the 19-element phased array in L-band (FLAG) and the X-band replacement.

Moreover, the L-band replacement, the ultra-wideband mono-feed up to 3 GHz of operating frequency, the 256-element phased array at K-band and the 50-beam multi-feed at W-band are definitely planned, and, even if not fully funded, some level of initial design work and development has been done for all of them.

The operational receivers are located either on the primary focus or on the Gregorian focus. Switching among Gregorian receivers (L-band frequency and higher) takes less than one minute. To switch to and from prime focus takes about ten minutes, necessary to extend (or retract) the prime focus boom. To switch between prime focus feeds takes about two hours, and to remove one Gregorian receiver and replace it with another one takes about half a day (they are swapped over while still cold, so no cool-down is required after installation). Since eight Gregorian receiver slots are available, one can usually swap a receiver in advance of when it is needed, so the one-minute changeover is all that is required.

RFI is present up to 3 GHz, then becoming rare up to 10 GHz and disappearing above this frequency.

7.1.2 Effelsberg

The Effelsberg telescope is a Gregorian antenna 100 m in diameter placed at 319 m altitude, currently operating 21 receivers between 300 MHz and 95 GHz [2]. All frequency bands use feed horns: 15 of them are mono-feed, 4 are dual-feed (basically at frequencies above 5 GHz), and there are two 7-beam multi-feed systems; one in the 21 cm-band, a second one at Ka-band (9mm). One system (300-900 MHz receiver) uses an eleven-feed typology Most receivers offer double circular polarization, some are double linearly polarized, a few old systems have just one polarization.

Remarkable is the wide-band of the last receiver produced, a 4-9.3 GHz mono-feed double linear polarization. A second feed for this last receiver is under development, as well as new dual-feeds in the 12-18 GHz and in the 38-50 GHz bands.

Receivers are located among the primary focus and the Gregorian focus. The switching time among primary and secondary foci is 30 minutes, performed by moving the receiver box in or out of the focus cabin through flaps in the center of the subreflector. Some frequency agility in the primary focus is obtained by using a *multibox system* technique, i.e. inserting more than one band in each box: at present, the primary focus has two “multiboxes” (one including 18/21 cm, 1.9 cm and 1 cm bands and a second one including 30 cm, 5 cm, 2.2 cm and 3 mm bands). Changes within a multibox are done by rotating the box and shifting the subreflector, which takes about 1 minute. Frequency changes among secondary focus receivers are performed by changing pointing offset positions and it takes about 30 seconds.

RFI is indicated as ‘fatal’, ‘high’ and ‘moderate’ as the frequency increases up to 19 GHz. RFI is labelled ‘low’ in Ka band and absent at 40 GHz and higher.

7.1.3 Tianma

The Tianma telescope is a 65-m shaped Cassegrain antenna placed at 7 m altitude, operating from 1.25 to 50 GHz [3]. At present, it is equipped with 7 receivers covering this frequency range. It uses mono-feed front ends up to 18 GHz, two dual frequency systems (S/X and X/Ka bands) mainly for geodesy, and two dual-feed receivers for the K- and Q-bands. All of these are double circular polarization. One dual-feed receiver is under construction in the Ka-band (26-40 GHz).

Tianma has no receivers located in the primary focus and the agility among those in the secondary focus is realized by adopting a combination frequency switching scheme. The L-band receiver, which is big in size is placed offset from the second focus; thus, the L-band observation is performed by tilting the subreflector to it. All the other receivers are placed at a turret of 2 m in diameter, and frequency switching is achieved by rotating the turret. The switching time is less than 1 minute.

RFI is present up to 9 GHz and absent at 12 GHz and higher.

7.1.4 Yebes

The Yebes antenna is 40 m in diameter placed at 931 m altitude with a Nasmyth-Cassegrain optics operating at frequencies up to 116 GHz [4]. It has seven receivers in operation, from 2 to 116 GHz, and three under development aimed at enlarging the band of the current K- and Q-band front ends and at doubling the outputs of the W-band receiver. All receivers are mono-feed with dual circular polarization (except the operational W-band receiver offering only the RCP). The dual-frequency system is the S/X receiver for geodesy. Recently, a quasi-optic system has been provided allowing simultaneous observations in K- and Q-band.

Yebes has no receivers in primary focus and the agility among those in the secondary focus is made by mirrors redirecting the beam coming from the pair primary mirror / subreflector.

RFI is indicated up to K-band, absent in Q-and W- band.

7.1.5 Korean VLBI Network

The KVN consists of three antennas 21 m in diameter (Yonsei, Tamna and Ulsan placed respectively at 260, 320 and 120m of altitude) with shaped Cassegrain optics, capable of operating up to 140 GHz [5, 6, 7, 8]. The network includes one more antenna of the same class, called Sejong. The KVN 3-antennas is the first interferometer able of simultaneously observing with all four available receivers, in K-, Q-, W- and D-band. All of them are mono-feed with dual circular polarization. Additionally, Sejong observes with a dual frequency S/X for geodesy.

The three antennas of KVN do not have receivers located in primary focus and the agility among those in the secondary focus is made by a quasi-optic system of filters and mirrors able to deviate the beam coming from the pair primary mirror / subreflector to four different positions. With such a system, observations at different frequencies are performed simultaneously.

Due to the high frequencies used, the RFI environment is not an issue.

The construction of one more antenna and the installation of 230 GHz receiver at one of the existing KVN antennas is under discussion.

7.1.6 VLBI Exploration of Radio Astrometry

The VERA project consists of four Cassegrain antennas 20 m in diameter, able of operating up to 50 GHz [9, 10]. Currently, VERA observes as dual beam at K- and Q-band. An upgrade is under development to make these two frequencies simultaneously observable. VERA can also observe with a dual-frequency system in the S/X bands for geodesy and in the 6.5-7 GHz band. All receivers are mono-feed with single circular polarization. A development is in progress to add the second polarization output.

There is no frequency agility system available. RFI is present in the S-, X- and C-bands.

7.1.7 Onsala

The Onsala observatory, placed at 20 m altitude, consists of two antennas: one 25-m dish operating up to 7 GHz, mainly used for VLBI observations, and one 20-m dish with Cassegrain reflector operating up to 116 GHz and typically used for single-dish observations [11, 12]. Four receivers are in operation at the 25-m antenna and seven at the 20-m antenna. All are mono-feed dual circular polarization, with the exception of the 26-36 GHz band and the two highest frequency bands (67-87 and 85-116 GHz) which offer dual linear polarization. An under development 4-12 GHz single-feed receiver is reported.

The two antennas mount all the receivers in the secondary focus.

RFI is present up to the S-band (2.4 GHz) and in the 18-26 GHz one. The C- and X-band together with the highest frequency bands, Ka-, Q-, V- and W-band are free from RFI.

There is frequency agility for the 20m from seconds to 30 minutes depending on receiver to receiver switching. The 25-m antenna can switch from seconds up to 1 hour (this last possible only daytime).

7.1.8 Nobeyama

The Nobeyama telescope is a 45-m Coude antenna placed at 1349 m altitude, equipped with a beam-waveguide system and operating from 20 to 116 GHz [13]. It operates six mono-feed receivers, one with double circular polarization, one with single circular polarization and four, at the highest frequencies, with double linear polarization. As far as new receivers, there is a discussion underway to realize a 4-beam wideband (67-116 GHz), dual-polarized, sideband-separating receiver as well as to realize simultaneous observations with H22, H40, and TZ, especially for the VLBI observations at 22, 43, and 86 GHz.

Remotely controlled mirrors are used to switch the beam among these six receivers.

Presence of RFI produced by automotive radar at 76 GHz was confirmed in the field experiment. Automotive radar will be potential RFI issues in the 76-81 GHz band in the near future.

7.1.9 Pico Veleta

The Pico Veleta radio telescope is a 30-m paraboloid operating from 73 to 350 GHz placed at 2850 m altitude [14]. It observes at very high frequencies and its 3mm receiver (73-117GHz) overlaps with the frequency range of the Italian radio telescopes. It has in operation four mono-feed receivers with double linear polarization.

Switching among receivers is possible by using mirrors and dichroics. Dual frequency simultaneous observations are possible.

RFI is absent at the moment with a warning on possible automotive radar interference in the future.

7.1.10 Parkes

The Parkes telescope is a 64-m paraboloid operating from 700 MHz to 26 GHz placed at 415 m altitude [15, 16]. It has nine operational mono-feed receivers with dual polarization, mostly linear, one dual frequency and one multifeed both providing linear polarization. An exception is the 4.5-5.1 GHz C-band receiver offering single polarization. Combined S/X observations are possible.

Receivers are located at the primary focus only, over which packages can be mounted. Each package contains up to four receivers that can be moved with three degrees of freedom (focus, translation, rotation), with receivers put on focus via remote control. The positioning takes about 2 minutes.

Currently, Parkes produced for Effelsberg an ASKAP-type PAF, i.e. a checkerboard with 94 dual-polarization elements producing 188 IFs. It uses the ASKAP digital back-end to produce up to 36 beams (using 27 at present) each up to 384 MHz BW (current system achieves about 300 MHz).

The plans are for Ultra-Wide Band systems to replace many narrow band single pixel feeds. The UWB-Low will be commissioned in 2017.

RFI affects data up to 7 GHz.

7.1.11 Mopra

Mopra is a 22-m antenna operating at frequencies between 1.2 and 117 GHz placed at 860 m altitude [17]. It has in operation seven mono-feed double polarization receivers, allowing both linear and circular polarization. No new receiver developments have been reported.

The receiver changeover is within minutes remotely.

RFI is present in the two lower bands, from 1.2 to 3 GHz.

7.2 Technical data analysis: in operation receivers

In this Section, we give a comprehensive overview of radio telescope performance by comparing their receiver characteristics. Some factors may affect such an analysis and have to be properly taken into account:

1. The relative gain of two antennas with different collecting area scales as the squared ratio of the antenna diameters. Therefore, a very well-designed front-end with excellent noise performance may have a moderate SEFD simply due to the limited collecting area of the radio telescope on which it is mounted. For example, the same receiver shows a peak antenna gain four times higher if mounted at SRT than if mounted at MED or NOTO (assuming the same match to optics).
2. The overall surface accuracy may deteriorate the gain. For example, the peak gain of the 22 GHz multi-feed receiver is 0.66 K/Jy if mounted on SRT, while at MED it would be as low as 0.11 K/Jy. The ratio is higher than the ratio of the collecting areas because at that frequency the SRT has a better overall surface accuracy than MED.
3. The computed values do not take into account the different age of the receivers, which is a key parameter affecting performance.
4. In some cases the performance at the mid-band frequency is taken as representative of the whole band. In some others, the values at the band edges are plotted, because the performance can vary considerably inside the band itself.

Keeping in mind all these known issues, in the following we show some graphs giving an overall picture of the international survey. Graphs for SEFD (ratio between system noise temperature in Kelvin and antenna gain in Kelvin/Jansky) and sensitivity (1-sigma RMS noise in mJy, detectable with the nominal instantaneous bandwidth using 1 second integration time) are given for all telescopes together, then the antennas are subdivided into the two groups large and medium class.

7.2.1 Frequency Coverage

In Fig. 7.2, the bands covered in the whole range 0.3-116 GHz are shown. Inside each block it is also reported the feed system used. Still today mono-feed receivers are the most common: 77 out of 109 in total. Multi-feed (more than two beams) front-ends are a minority, counting five systems only, while thirteen are dual-feed. Eleven receivers are dual-frequency systems, six of which are the usual S/X-band ones used in geodetic observations. Only three crossed dipoles are used, all of them at the GBT.

From Fig. 7.2, we notice that only large antennas observe at frequencies below 1 GHz (partial exception is Onsala25 in the band 0.8-1.2 GHz). The GBT and Effelsberg are the only two telescopes offering practically complete frequency coverage between 300 MHz and 115 GHz by using many receivers.

For the GBT, Effelsberg and Parkes, it happens that some frequency bands are covered by more than one receiver. This is due to the fact that either state-of-the-art receivers have been developed partially replacing the previous ones or they have been developed for different scientific cases. Several telescopes were originally designed to operate in the cm range up to K-band; then, some of them have been upgraded in order to significantly enhance their capabilities above the K-band (NOTO) or the Q-band (Effelsberg) by installing an active surface. On the other hand, there are antennas, which operate in the near-mm range, like Nobeyama (from 20 GHz) and Pico Veleta (from 70 GHz). The younger antennas are specifically designed to operate in the whole range from cm to near-mm (Yebes, Tianma, SRT, GBT).

Tab. 7.III summarizes the number of bands offered in three different frequency ranges below 1 GHz, from 1 to 18 GHz, and higher than 18 GHz. The total number of bands can be different from the number of receivers because sometimes a receiver band crosses the frequency range chosen or more receivers can observe in the same band.

TELESCOPES	f ≤ 1GHz	f = 1÷18 GHz	f = 18÷100 GHz	Total
SRT	1	3	2	6
MED	0	6	1	7
NOTO	0	4	2	6
TOTAL Italy	1	13	5	19
GBT	5	6	4	15
Effelsberg	3	17	6	26
Tianma	0	6	3	9
Yebes	0	5	3	8
KVN	0	2	3	5
VERA	0	3	2	5
Onsala25 + Onsala20	1	6	5	12
Nobeyama	0	0	6	6
Pico Veleta	0	0	1	1
Mopra	0	5	3	8
Parkes	1	10	1	12
TOTAL bands	**11**	**73**	**42**	**126**

Table 7.III – Number of receiver bands in operation

Notes with respect to Italian antennas on frequency coverage

As far as the frequency coverage is concerned, the Italian antennas show a complete frequency coverage for EVN-VLBI and Geo-VLBI observations at MED: L-, S-, C-, X-, and K-band. At NOTO the coverage is almost complete (L-band excluded), whereas at SRT more bands are currently missing (S-, X- and the low part of C-band). The gap between X- and K-band, which is evident in the Italian radio telescopes, is on the contrary filled in some radio telescopes with Ku-band receivers (like at Parkes, GBT, Effelsberg and Tianma). Receivers to fill some of these gaps are under development in Italy as discussed in Chapter 6.

The current maximum frequency in Italy is offered by NOTO with the Q-band (sometimes used for observations within the GMVA array). However, compared to the other countries, the lack of a receiver operating in Italy in W-band is evident, especially if we consider that both SRT and NOTO have been respectively designed and upgraded to reach this frequency band.

Due to the limited resources available for developing many receivers for the continuous frequency coverage, in Italy this could be reached by adopting modern ultra-wide band receivers.

The Italian network of antennas is equipped with all types of feed systems and offer a number of receivers comparable to the other facilities both for medium and high frequency range.

7.2.2 Frequency Agility

Tab. 7.IV summarizes the information on frequency agility, showing that most of the antennas offer this feature, although some telescopes provide also intermediate solutions as a compromise between frequency agility and a complete frequency coverage (GBT, Effelsberg). Eight telescopes locate receivers at the secondary focus only (we include here also Yebes to simplify, though the focus is technically a beam-waveguide), one on primary focus only, whereas five use both. SRT is the only antenna using also beam-waveguide foci and the switching time is the same as for secondary focus. NOTO needs to complete the agility in secondary focus by refurbishing the receivers there located with suitable anchor plates. Currently VERA does not provide frequency agility but an upgrade to make simultaneous K- and Q-band by a quasi-optic system is under development.

TELESCOPES	Switching time from Primary to Secondary focus receivers	Switching time within Primary focus receivers	Switching time within Secondary focus receivers
MED	4 min	≤ 45 sec	≤ 14 sec
NOTO	4 min	10 sec	4 Hours (manual change)
SRT	4 min	2 min	2 min
GBT	10 min	2 hours	1 min; manual change in specific cases
Effelsberg	30 min	1 min; manual change between multi-receiver boxes	30 sec
Tianma	Not applicable	Not applicable	seconds
Yebes	Not applicable	Not applicable	-
KVN	Not applicable	Not applicable	Simultaneity
VERA	Not applicable	Not applicable	No agility
Onsala20	Not applicable	Not applicable	seconds to 30 min
Onsala 25	Not applicable	Not applicable	seconds to 1 hour
Pico Veleta	Not applicable	Not applicable	2-bands simultaneous
Nobeyama	Not applicable	Not applicable	1 min
Parkes	Not applicable	2 min; manual change between multi-receiver boxes	Not applicable
Mopra	Not applicable	Not applicable	Some min for high frequency receivers

Table 7.IV – Survey of the frequency agility at the telescopes

Notes with respect to Italian antennas on frequency agility

Compared to the other radio telescopes, we can conclude that the frequency agility implemented on the Italian antennas offers excellent performance, especially once NOTO will complete the upgrade of the secondary focus cabin. Frequency agility has been demonstrated to be a very important feature for a telescope, because it allows the maximization of the telescope efficiency in terms of observing time and the possibility of dynamic scheduling. Changing receivers without manual intervention improves also the overall reliability of the system, because no disconnection of cables and removal of receivers are necessary. This facility should be held in due consideration when planning a receiver fleet at an observatory and we recommend avoiding receiving systems that ruin this capability.

7.2.3 Radio Frequency Interferences

RFI affects observations in the low/medium frequency ranges at all telescope sites. However, a direct comparison among the various Observatories is not possible due to the qualitative nature of the available information. Italy is strongly affected by the RFI problem and the future landscape is expected to further deteriorate. From this point of view, Observatories mainly devoted to observations at higher frequencies have probably still some years to operate quietly, exploiting at best this favorable condition.

7.2.4 Performance

The receiver SEFDs for all the antennas and then divided for medium-sized and large antennas are shown respectively in Fig. 7.3, 7.4 and 7.5. The bulk of performance ranges between 100 and 2000 Jy for the former and 10 and 200 Jy for the latter. As already stated, the SEFD is strongly dependent on the collecting area. Therefore, in Fig. 7.6 and 7.7 we plot the distribution of the SEFD normalized with respect to a reference antenna of diameter 32 m. In other words, each SEFD value has been multiplied by the ratio:

$$\left(\frac{diameter}{32}\right)^2$$

where *diameter* is the actual diameter of the telescope hosting that receiver.

If an antenna has a diameter larger than 32 m its normalized SEFD increase, while the opposite happens if the diameter is lower than 32 m. In the normalized SEFD graph, the medium-sized antennas show a bulk of values ranging from 200 to 2000 Jy while values for the big antennas range from 100 to 2000 Jy, indicating that the main reason for different performance is the different collecting area, with a lower effect of other characteristics (like better surface accuracy, offset antenna type, better noise temperature receivers). However, it can be noted that even in the normalized plot GBT confirms to be the telescope characterized by the lowest values of SEFD.

For frequencies above 5 GHz it must be taken also into account that, for different telescopes, the measured system temperatures are affected by different atmospheric contributions at the same frequency due to the diverse sky opacity and/or site altitude.

The sensitivity is then plotted in Fig. 7.8, 7.9 and 7.10. A comparison between the SEFD for medium-sized antennas in Fig. 7.4 and the corresponding sensitivity in Fig. 7.9 allows to check whether the instantaneous bandwidth delivered to the continuum back-end is so wide to increase the “rank” of that receiver. Looking at the two graphs we note that in general this is not the case, since each antenna trend in sensitivity at all frequencies is the same as that of the SEFD. A similar consideration holds for large antennas (compare Fig. 7.5 and Fig. 7.10).

SEFD values for the Italian antennas are set at a medium-low figure of Jy for MED and SRT, whereas medium-high for NOTO. Basically, NOTO pays the reckoning of older receivers, half of which are not cooled.

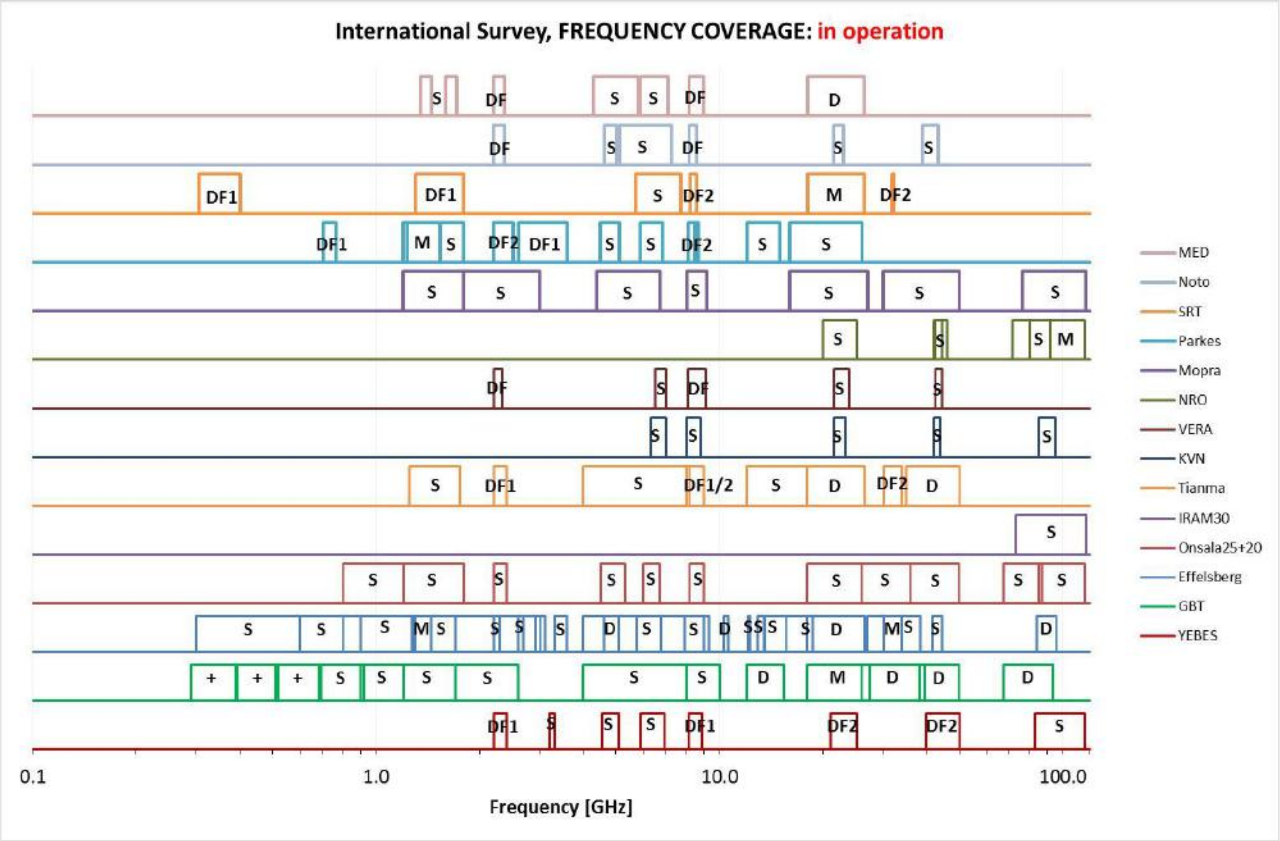


Figure 7.2 – Frequency coverage for operational receivers. The following legend holds: S = mono-feed; D = dual-feed; M = multi-feed; DF = dual frequency; + = crossed dipoles. Bands belonging to the same dual frequency receiver are identified with the same number.

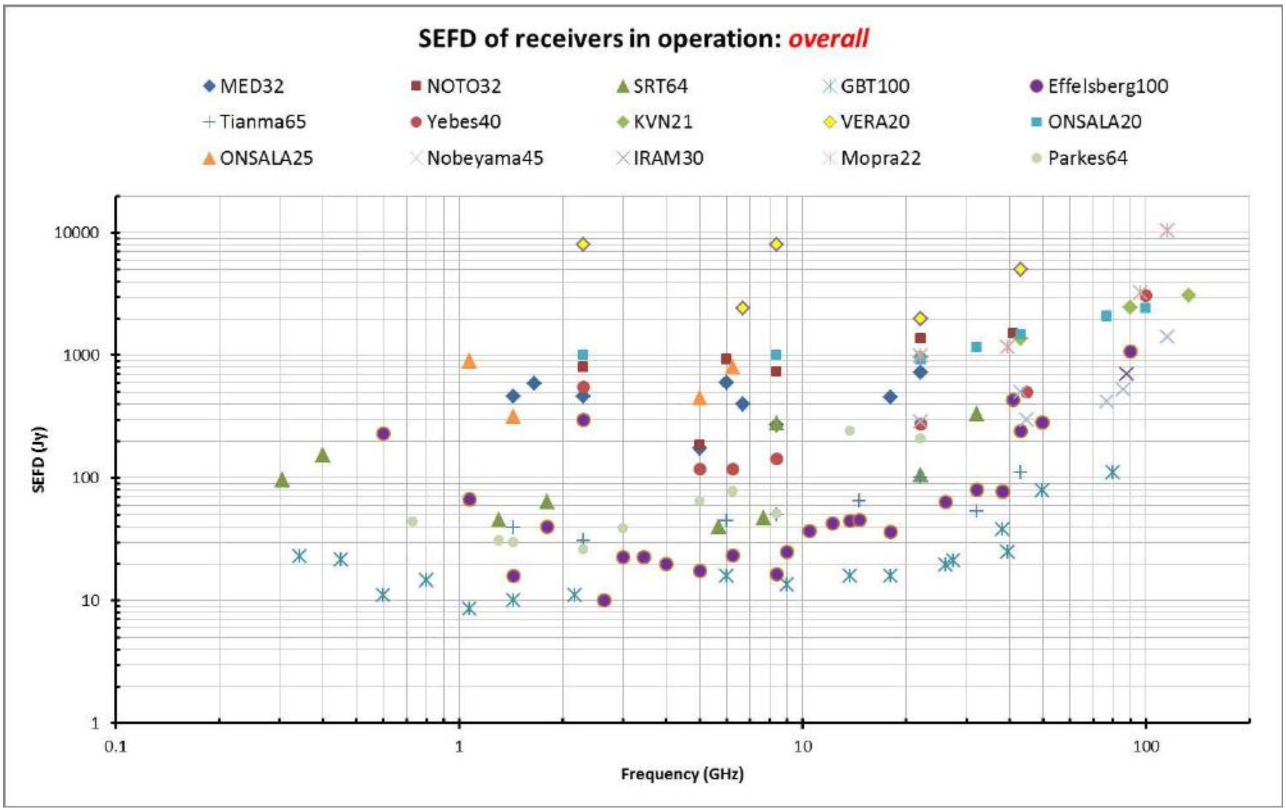


Figure 7.3 – SEFD for operational receivers

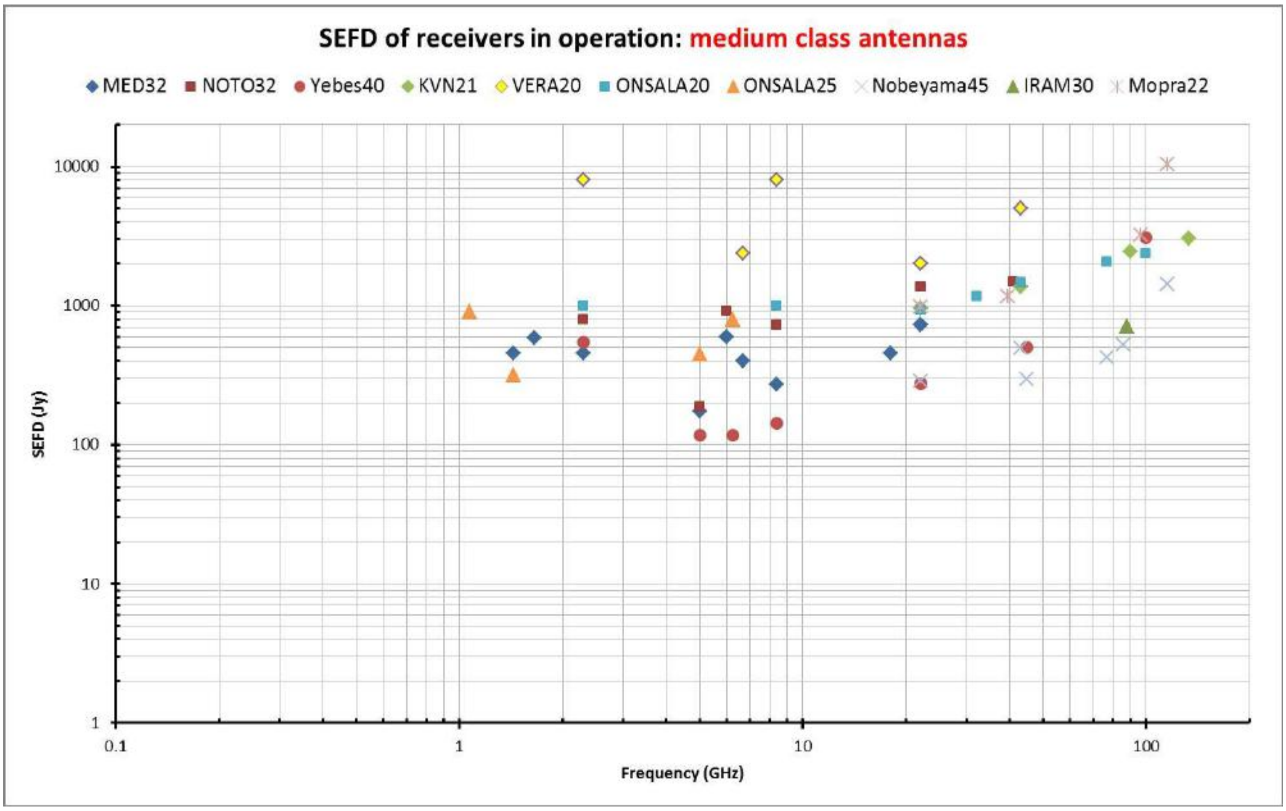


Figure 7.4 – SEFD for operational receivers at medium-class radio telescopes

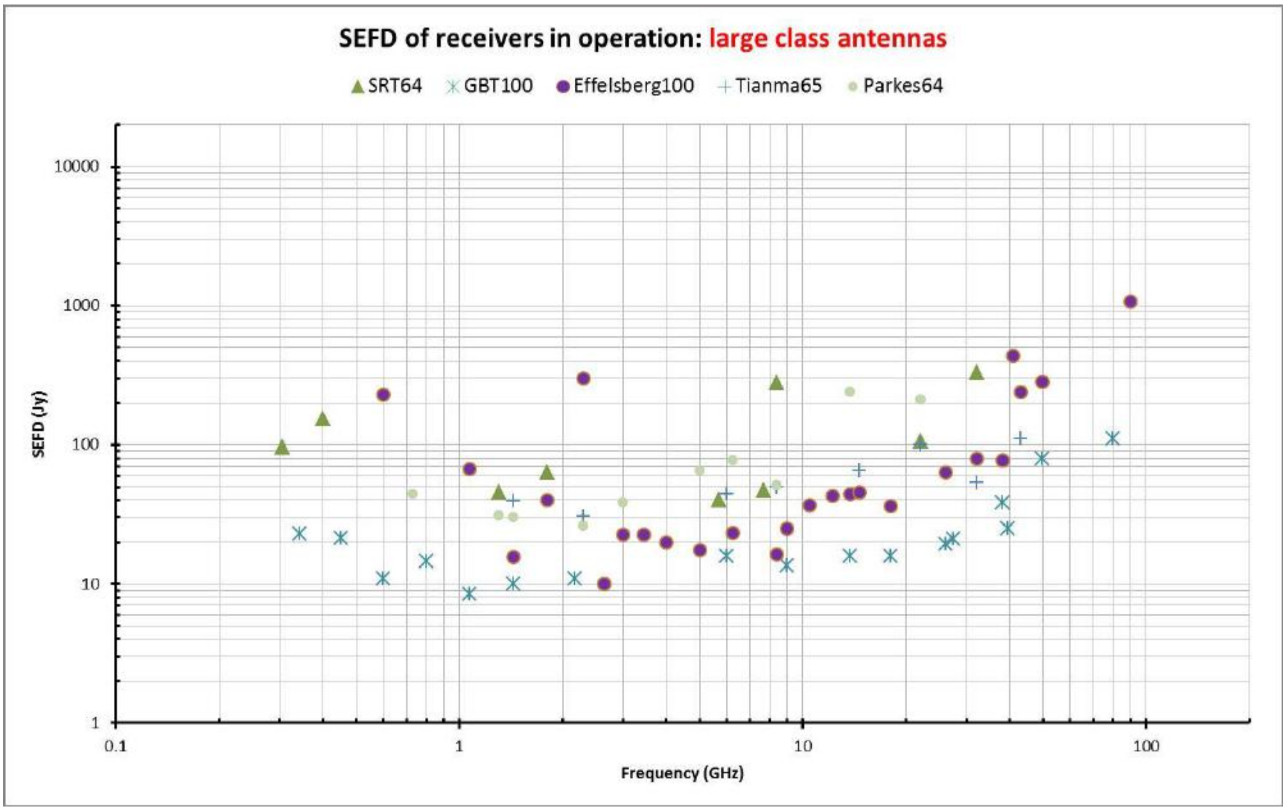


Figure 7.5 – SEFD for operational receivers at large-class radio telescopes

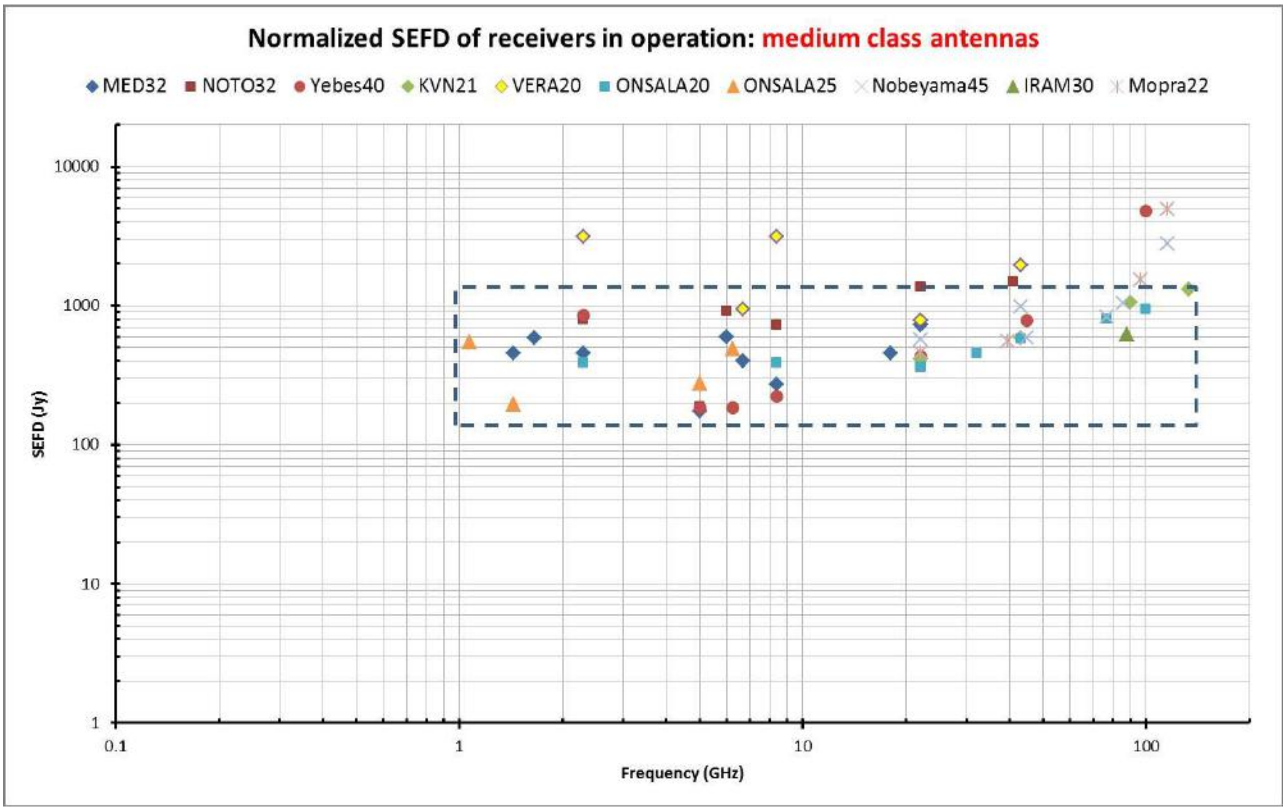


Figure 7.6 – Normalized SEFD for operational receivers at medium-class radio telescopes

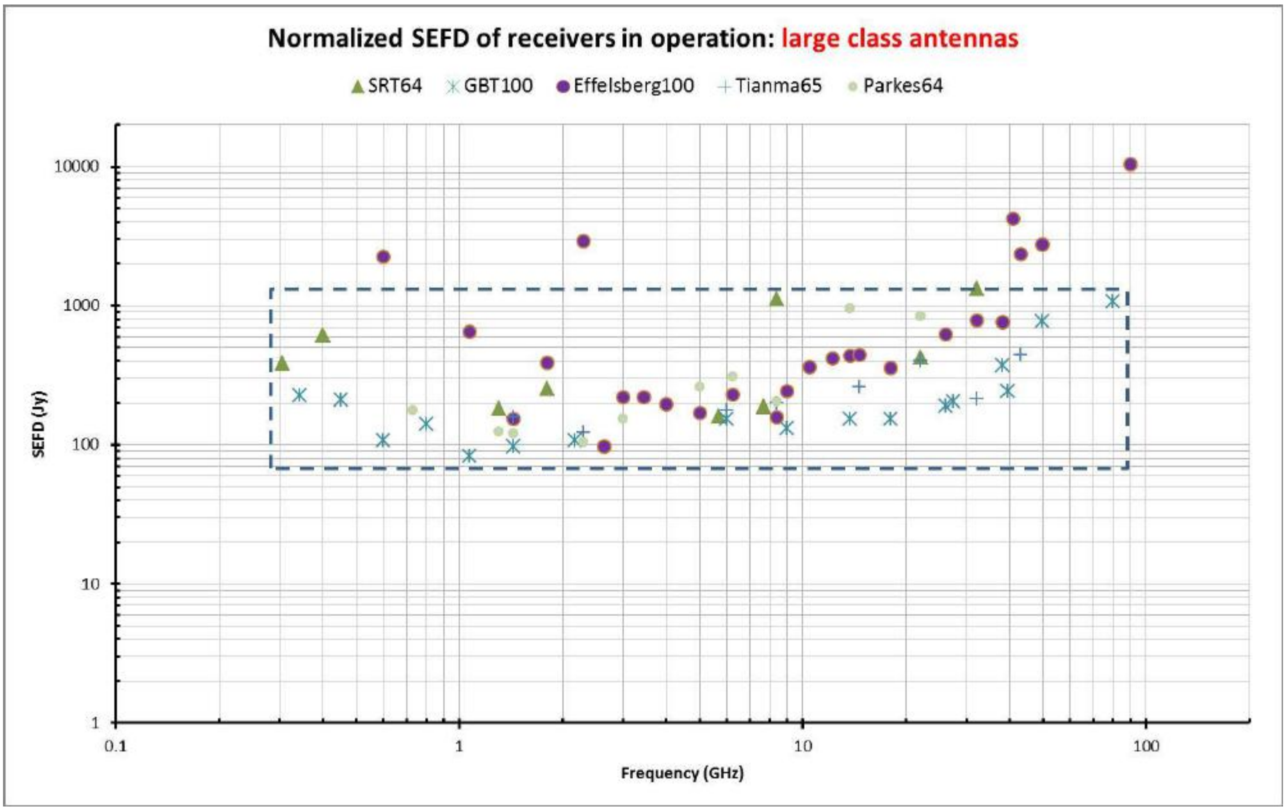


Figure 7.7 – Normalized SEFD for operational receivers at large-class radio telescopes

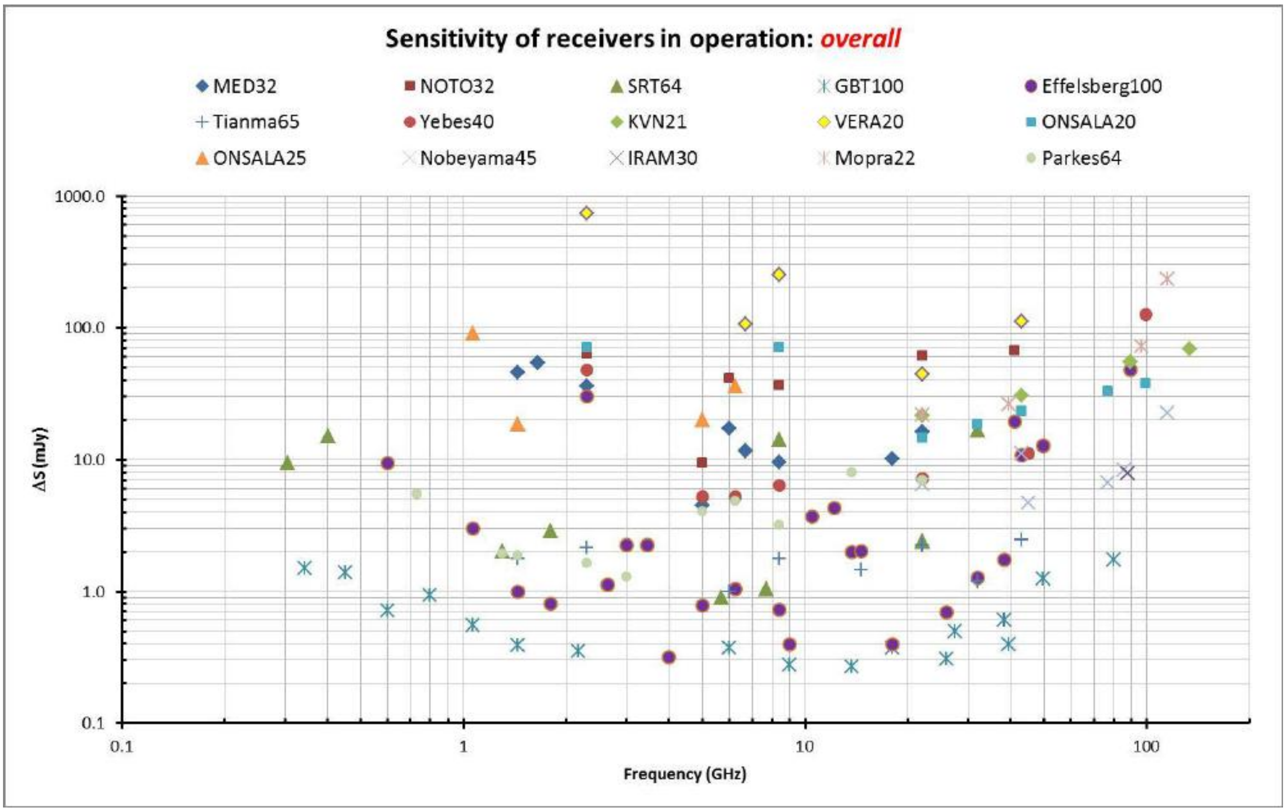


Figure 7.8 – Sensitivity for operational receivers

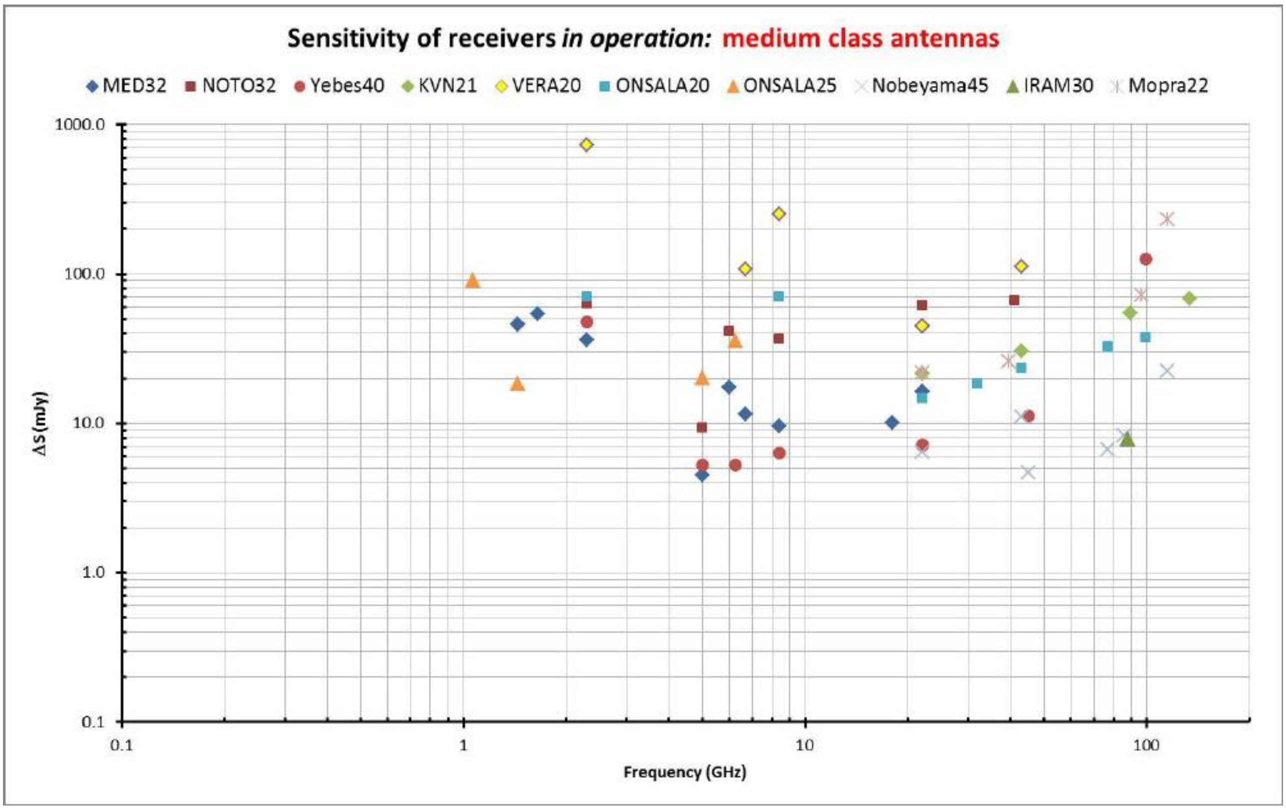


Figure 7.9 – Sensitivity for operational receivers at medium-class radio telescopes

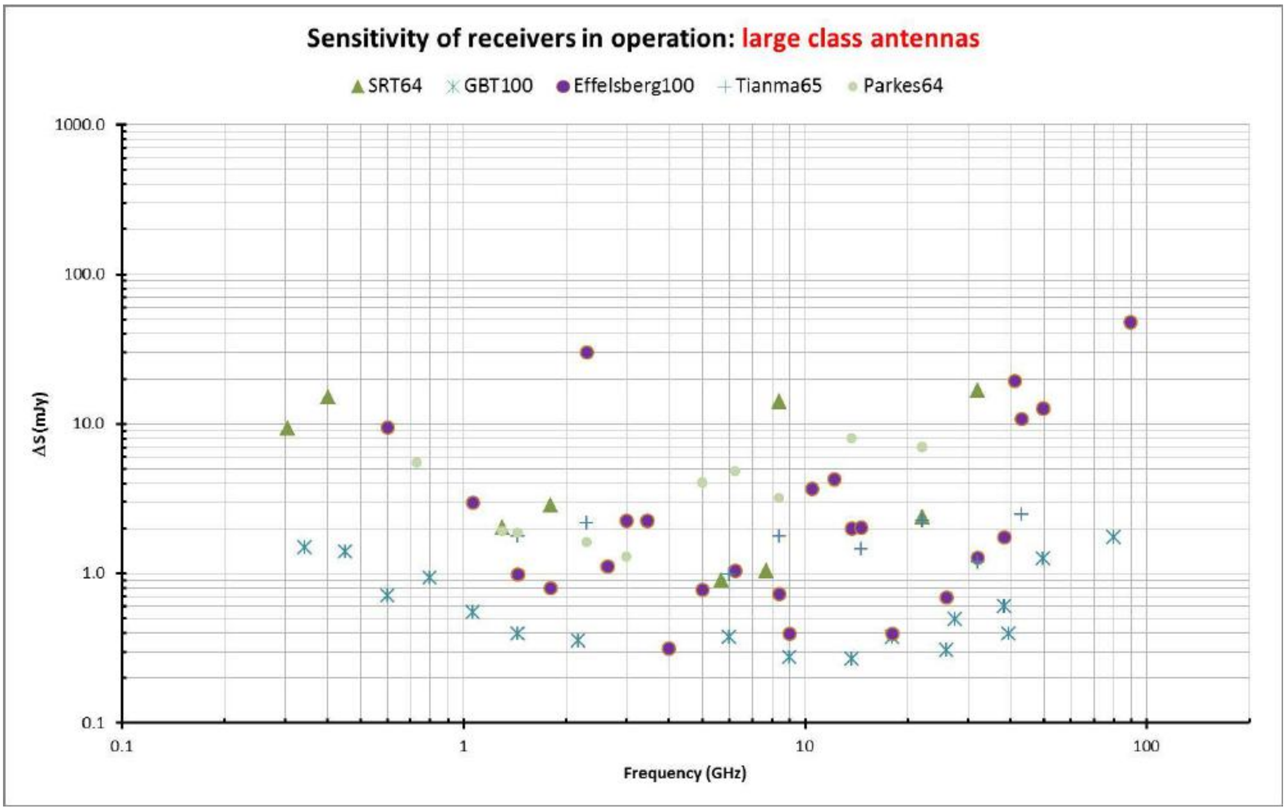


Figure 7.10 – Sensitivity for operational receivers at large-class radio telescopes

7.3 Technical data analysis: receivers under development

In this Section we report information on receivers under development at the international telescopes considered in this survey. The number of such receivers divided for each radio telescope is reported in Tab. 7.V and their frequency coverage is plotted in Fig. 7.11. As it happened for the operational receivers, the sum of the bands covered is different than the number of receivers, amounting to 21. Also in this case there are ultra wide band systems under development, which cross two different frequency ranges of the table.

The majority of new developments are in the 1 to 18 GHz range offering wide or ultra wide band. Twelve receivers are mono-feed (Yebes, GBT, Onsala, Parkes, SRT), four dual-feed (Tianma, Effelsberg, MED), three multi-feed (GBT, SRT). A new development regards low frequency PAF systems (GBT 1.1-1.7 GHz, Parkes 0.6-1.8 GHz).

Italian antennas have five front ends under construction, four at the SRT (we do not include the under evaluation receivers at NOTO). Fig. 7.11 shows that the SRT and GBT are the only radio telescopes developing high frequency multi-feed receivers. Additionally, the SRT is also developing a second multi-feed system at low frequency.

The GBT and Parkes are the only radio telescopes involved in the production of PAF systems at present. We also notice that the GBT is strongly pushing toward the W-band with different concepts: bolometer, 16x multi-feed and 50x multi-feed (this last still under discussion). Actually, the first two receivers (MUSTANG2 and Argus) have completed their commissioning early 2017, during the writing of the report, and they are now operational.

The expected performance of the receivers under development will benefit from state-of-the-art technology and, above all, from the very wide band which can be delivered to the back-ends thus allowing also the medium-sized antennas to reach a considerable sensitivity (Fig. 7.12 and 7.13).

TELESCOPES	**f ≤ 1GHz**	**f = 1÷18 GHz**	**f = 18÷100 GHz**	**Total**
SRT	0	2	2	4
MED	0	1	0	1
NOTO	0	0	0	0
TOTAL Italy	0	3	2	5
GBT	1	3	2	6
Effelsberg	0	1	1	2
Tianma	0	0	1	1
Yebes	0	0	3	3
KVN	0	0	0	0
VERA	0	0	0	0
Onsala25 + Onsala20	0	1	0	1
Nobeyama	0	0	0	0
Pico Veleta	0	0	0	0
Mopra	0	0	0	0
Parkes	1	3	1	5
TOTAL bands	**2**	**11**	**10**	**23**

Table 7.V – Number of under development receiver bands

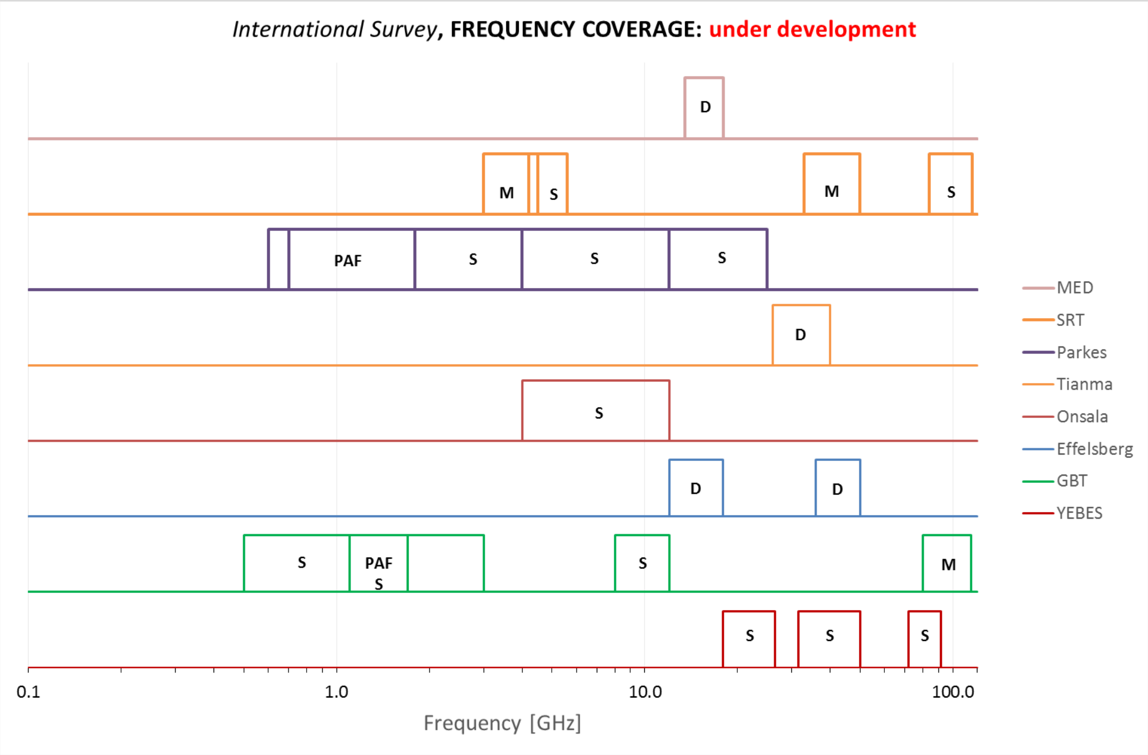


Figure 7.11 – Frequency bands of receivers under development at the International facilities. The following legend holds: S = mono-feed; D = dual-feed; M = multi-feed; PAF = phased array feed

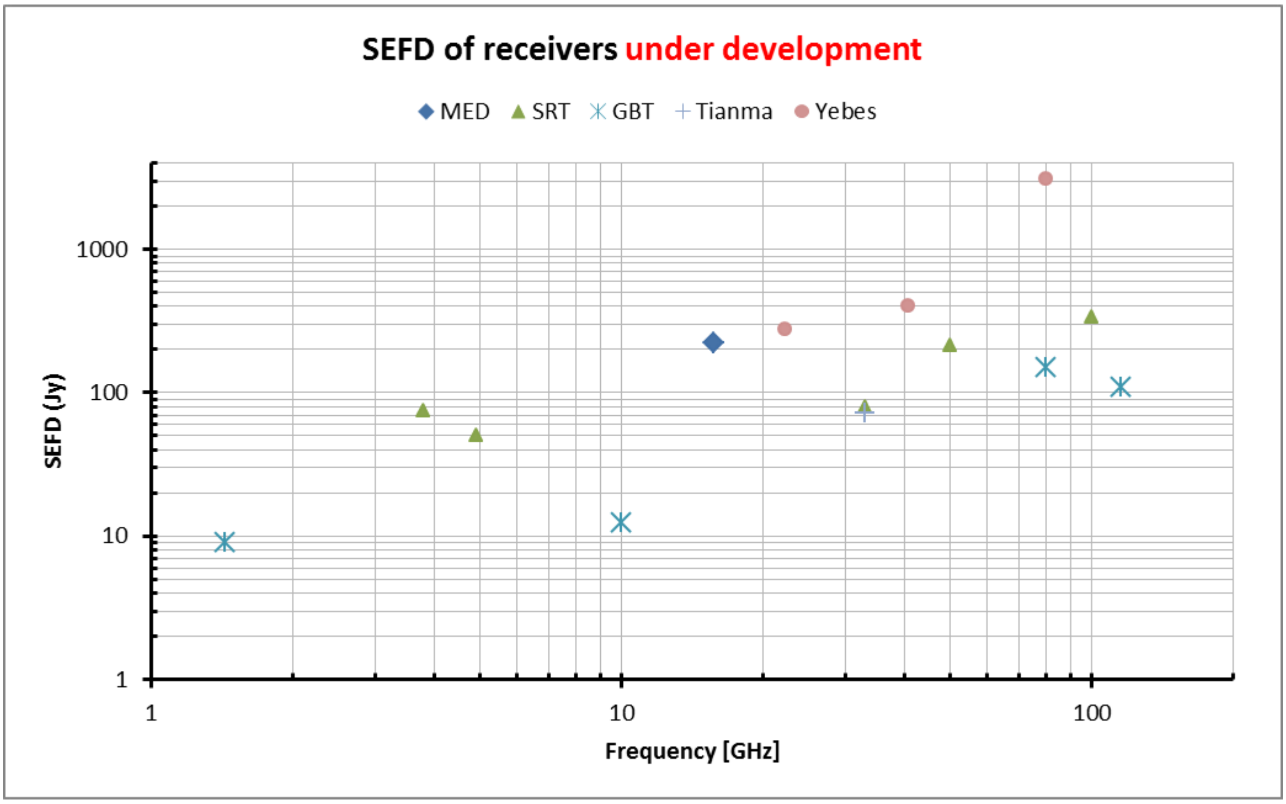


Figure 7.12 – SEFD for receivers under development

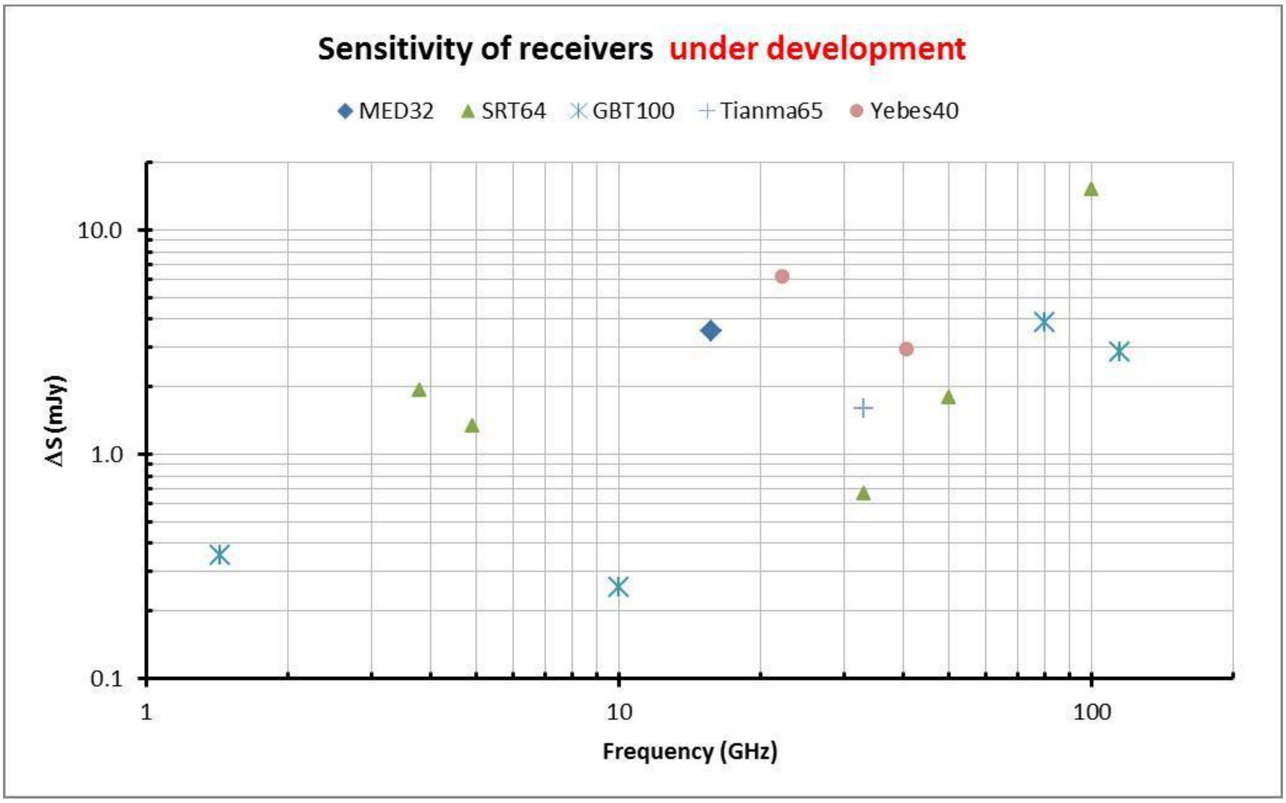


Figure 7.13 – Sensitivity for receivers under development

7.4 Observing time and science cases

From the general table of the international survey in Appendix B some information can be extracted both on the percentage of observing time for operational receivers and on the scientific projects undertaken.

As a preliminary consideration, we note that the international facilities show a large variety of equipment and also that the provided data are not homogeneous, thus preventing a direct comparison among the telescopes. For instance, the description of the scientific applications varies significantly among telescopes; additionally, at some facilities a given band can be covered with a set of different receivers which does not hold true for all the telescopes. Also, the number of receivers available at different telescopes varies significantly, from >20 (Effelsberg) to <10 (f.i. Yebes, VERA and the Italian antennas) hence the percentage of observing time dedicated to each band is likely lower in the former cases than in the latter ones. Despite such caveats, some qualitative consideration can be drawn that may be helpful to the purposes of this report.

Fig. 7.14 shows for the seven Observatories, which provided data, the distribution of the observing time of receivers versus the frequency bands. We notice that even for radio telescopes equipped with many receivers, usually four/five receivers take the majority of the total observing time (for instance, four/five receivers of GBT and Effelsberg are used for 70% of the available time). Even when less receivers are available, the distribution of their use is not uniform, as for example shown in VERA and Yebes where the most used receivers reach peaks up to 70% and 50% respectively. We can also notice that the VLBI technique looks more used than the single-dish.

The smaller Italian antennas MED and NOTO are more used for S/X and C band observations with respect to other single-dish telescopes, with the exception of Tianma which has a comparable percentage of observing time for the C band.

With the exception of VERA which quotes a percentage as high as 70%, within the international context MED and SRT are antennas dedicating a high fraction of their observing time to the K-band. This is possibly due also to the availability of dual- or multi-feed receivers allowing to correct for atmospheric variations even in single-dish mode.

Information regarding the L-band is very inhomogeneous, showing similar values for the 32-m Italian telescopes and Tianma while Effelsberg reports a much higher percentage of observing time for this band with respect to other Observatories. SRT reports a usage percentage for the L band of the order of 27% (considering both L and L+P observations), which is halfway between what quoted for Tianma and Effelsberg.

Apart from SRT, the only telescopes equipped with a P-band receiver and providing info on its usage are Effelsberg and GBT, the former reporting a very low percentage use. SRT and GBT quote comparable values.

NOTO has demonstrated to be quite efficient in observing with the Q-band receiver with respect to the other international facilities, with the remarkable exception of Yebes dedicating 51% of the observing time to this frequency.

Concerning scientific applications, it is not possible to make a direct comparison with the research topics investigated with the Italian radio telescopes and discussed in Chapter 6. In fact, some international facilities focused on the observing techniques (VLBI, single-dish, etc.) while some others listed the science topics (e.g. AGN, line spectroscopy, etc.), at a different level of detail.

Not surprisingly, both the international and national radio telescopes indicate the participation in the same international networks and projects, like for instance EVN and global VLBI, IVS, GMVA, EPTA, LEAP. Together with Tianma, the Italian radio telescopes indicate also their participation in RadioAstron experiments.

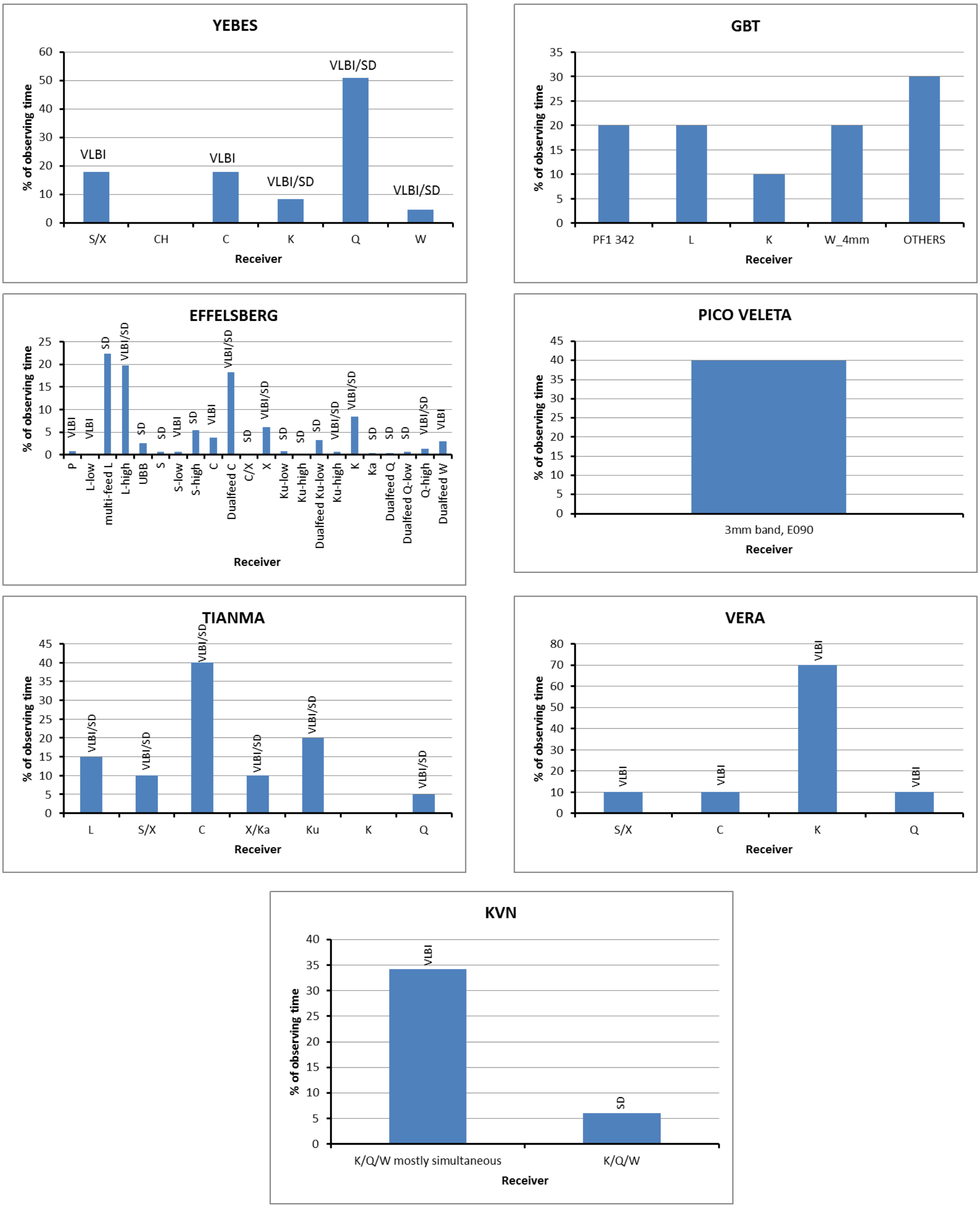


Figure 7.14 – Observing time versus frequency bandsand, if available, the radio astronomical usage of the receiver

7.5 Age of operational receivers

Most of the telescopes surveyed reported the year when their receivers went into operation. Thus it is possible to show their ages for each site. Fig. 7.15, deduced from data of Appendix B, describes the information on the ages of the receivers for each telescope.

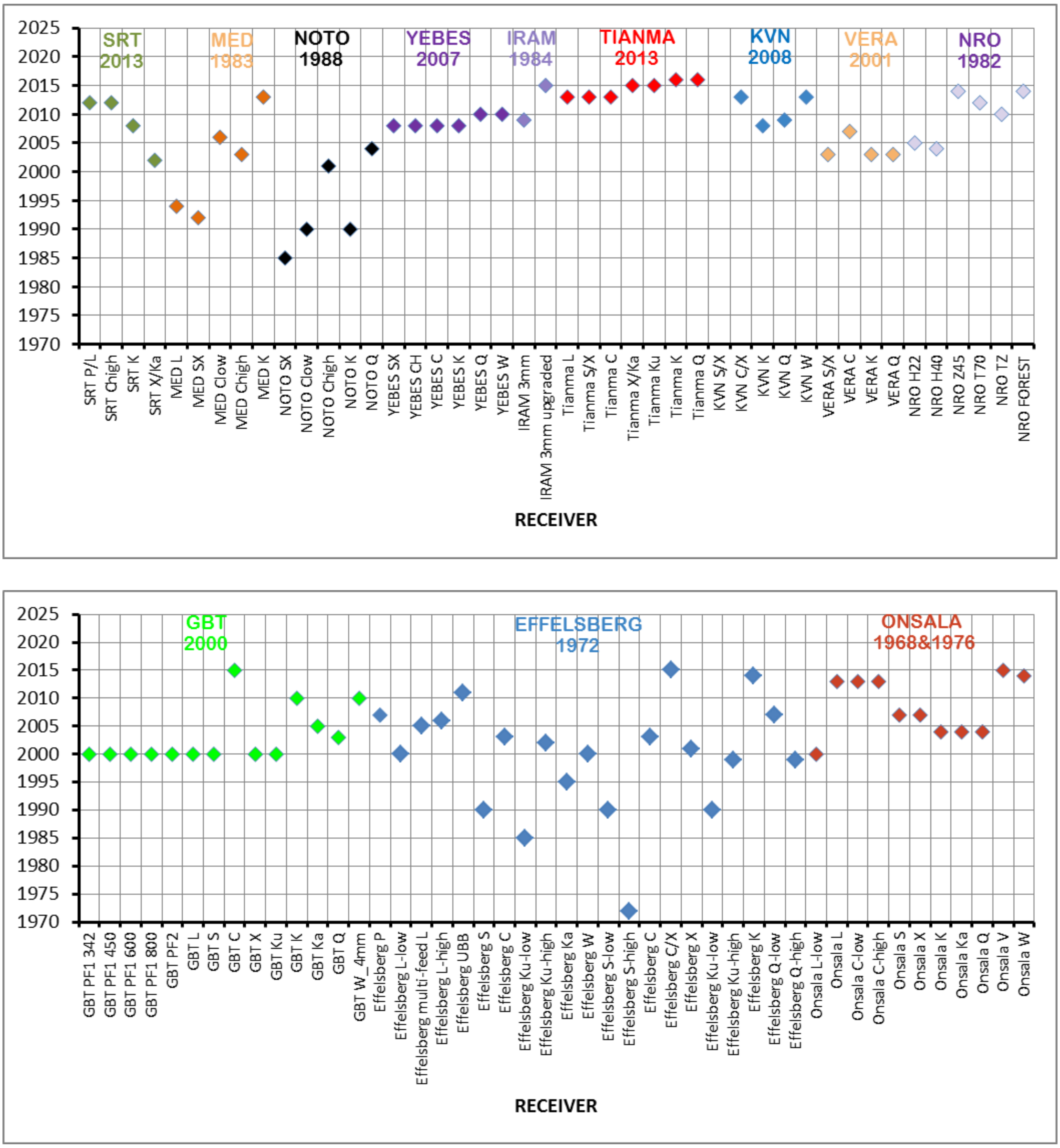
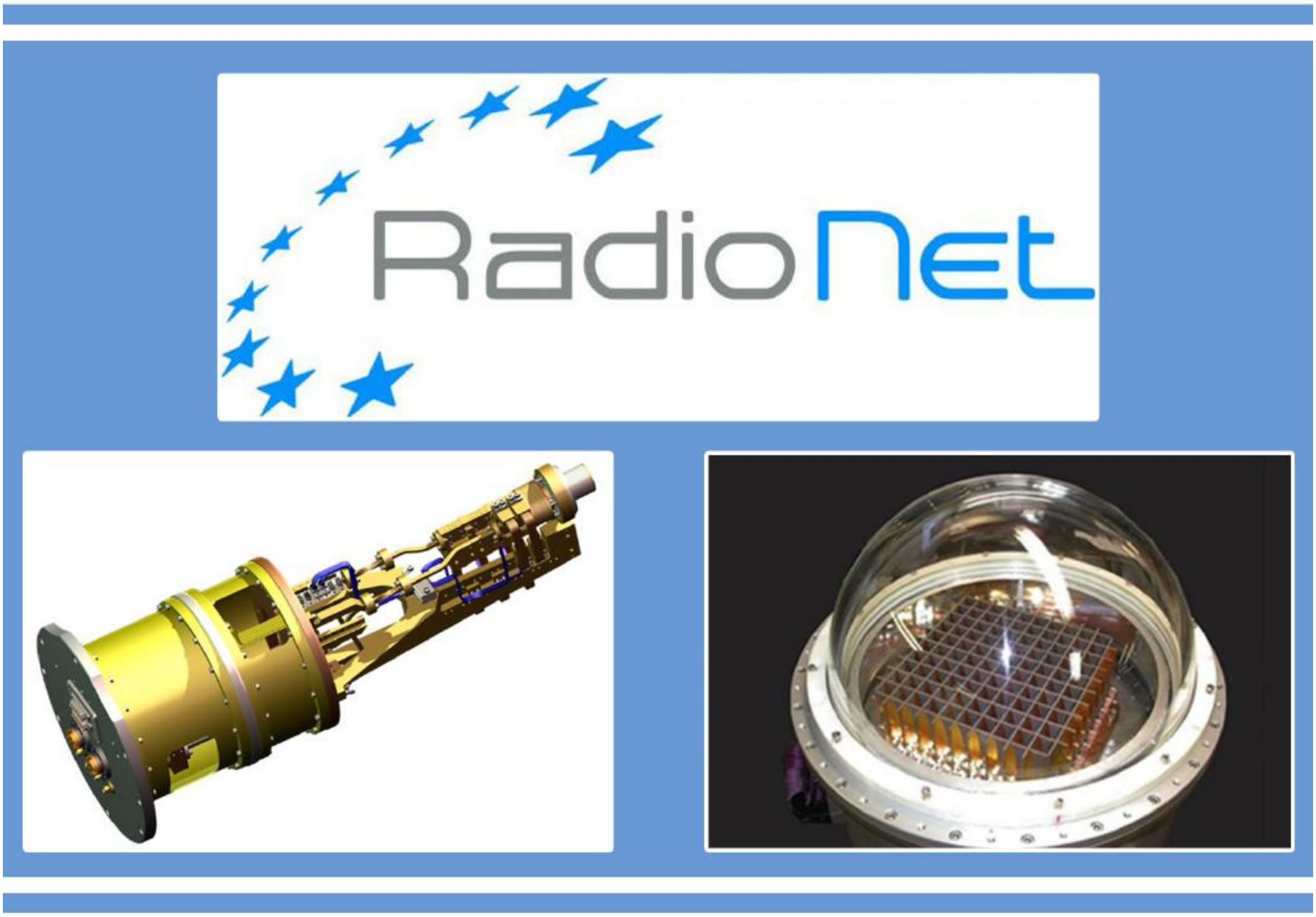


Figure 7.15 – Age of operational receivers. The years on top of the plots indicates the radio telescope inauguration date

In the upper part of each plot the indication of the beginning of the antenna operation has been shown allowing to link the age of each receiver to the age of the antenna. For the Italian antennas, some receivers are older than the radio telescopes inauguration. This is due to the fact that these receivers were designed and manufactured for other Italian antennas already operational.

The GBT, Tianma and Yebes receivers were all operational with full frequency coverage at the same time as the antenna, this illustrates a very professional receiver and system development plan and execution. Effelsberg is an old antenna but shows continuous upgrades and receiver development that keeps the antenna scientifically active.

8. International front-end projects: possible links with the Italian radio telescopes



In this Chapter, we discuss three projects not directly linked to the development of the Italian front-ends but with some possible connections. These future receivers, where INAF is actively involved, have been developed for other International telescopes, but INAF could take into account to negotiate/discuss their installation on the Italian antennas.

8.1 ALMA Band 2+3 receiver

The ALMA Band 2+3 receiver being developed by a group of European Institutes under the coordination of ESO will cover the entire frequency range from 67 GHz to 116 GHz, encompassing ALMA bands 2 (67-90 GHz) and 3 (90-116 GHz) in a single receiver cartridge.

From a scientific point of view, the installation of the ALMA Band 2+3 receiver on the Sardinia Radio Telescope would open a poorly investigated but extremely interesting spectral window to the Italian community. Right now, only a few antennas such as GBT or Onsala have a receiver operating in the band 2 window. Pico Veleta has a receiver that partially covers band 2 because its minimum frequency is 73 GHz. The importance of such a band has been largely discussed in a couple of White Papers [1, 2]. As discussed in Section 8.1.2, the band 2+3 is crucial for both Galactic and Extragalactic studies. Another advantage of installing such a receiver on SRT, would be the possibility of connecting SRT to the mm-VLBI networks (together with ALMA and GBT) for observations in bands 2 and 3.

From a technical point of view, the installation of such a receiver on SRT would allow the test of a state-of-the-art receiver on an Italian facility. The Band 2+3 receiver cannot be tested on APEX, the ALMA Pathfinder, because the beam gets truncated for frequencies lower than about 150 GHz due to the APEX optical system design. The installation of such a receiver at the SRT would allow the maximum observing frequencies (up to 115 GHz) originally planned for the SRT to be reached with a very large effective bandwidth (at least 8 GHz).

From a political point of view, the installation of such a prototype on an Italian antenna would be of crucial importance because it would give more international visibility to the SRT and would allow the Italian radio astronomy community to have a privileged position in this future ALMA upgrade.

On the other hand, the advantage for the Band 2+3 consortium would be the possibility of testing the prototype on a real antenna.

8.1.1 Technical design

The ALMA interferometer is nearing completion and within the next three years will likely be equipped with three receivers currently under construction in Band 1 (35-50 GHz), Band 2 and Band 5 (163-211 GHz).

Regarding Band 2, a group of international research institutes coordinated by ESO, including INAF through IASF-Bologna and OAA, is developing a receiver in band 2+3 (67-116 GHz). The interest in such a broadband receiver is particularly high for ALMA. This would free up space inside the ALMA cryostat that could be used, for example, to install a new receiver in Band 11 (1.0-1.6 THz) or to develop, in one of the bands already in use, a receiver with different observational characteristics, such as a focal plane array. The cryostat has in fact a maximum of 10 different positions initially allocated to 10 different bands (overall coverage from 35 to 900 GHz) and the merging of Band 2 with Band 3 would release a position.

The spectral coverage of the Band 2+3 receiver could also be interesting for SRT, as it would reach the maximum frequency to be observed with this radio telescope. Furthermore, the concept of the cartridge developed for the various ALMA receivers would make the installation of such a receiver in the SRT receiver system easier, with minimal complications in terms of electrical, thermal, and mechanical interfaces, and in terms of ancillary parts to be expressly developed.

The optical performance of the prototype was measured to be in line with ALMA specifications during an extensive test campaign carried out at ESO [3]. The state-of-the-art detectors inside the prototype have been integrated at INAF-IASF-Bologna. A cryogenic test campaign with the aim of verifying and characterizing the prototype at operational condition is on-going (as of April 2017).

The ALMA Band 2+3 receiver as mounted in the cartridge is shown Fig. 8.1.

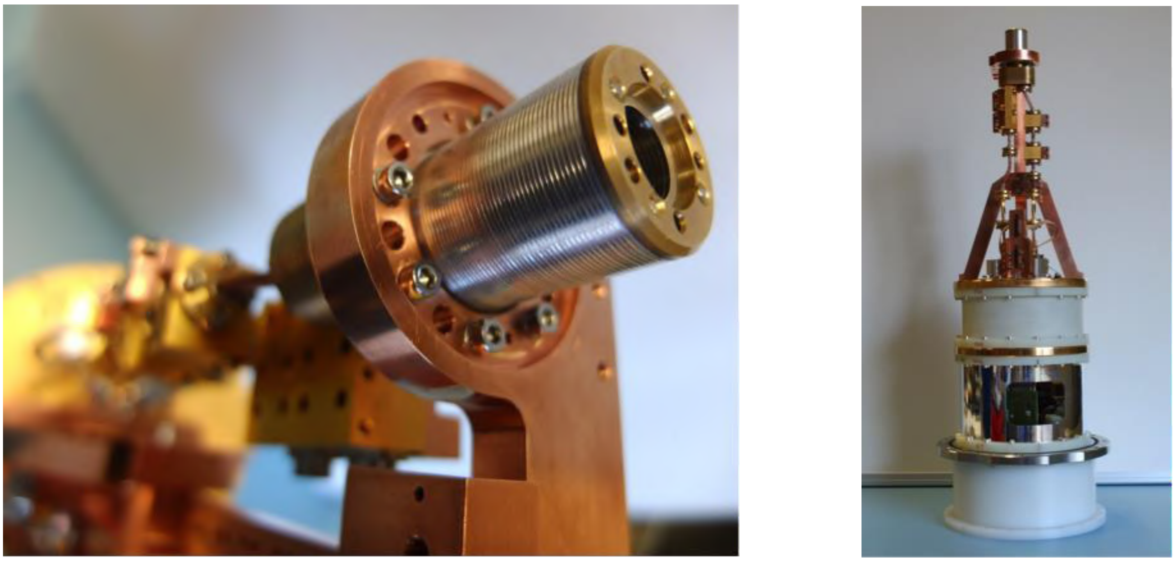

(a) (b)

Figure 8.1 – ALMA Band 2+3 receiver: (a) detailed view of the INAF-OAA feed-horn integrated into the Cold Cartridge Assembly, (b) Cold Cartridge Assembly as integrated at INAF-IASF-Bologna on January 2017.

Such a cartridge, some mechanical characteristics of which are shown in Fig. 8.2, will be installed on ALMA inside a cryostat that also hosts the other 9 receivers. In case of using such a prototype on the SRT, it will be necessary to develop a suitable cryostat, as well as to optimize, if needed, the optical match with the SRT antenna. The thermal architecture of the cartridge is arranged with two thermal links and shield respectively at 110 K and 15 K and, taking into account the extremely small size of the cartridge, it is compatible with the thermo-mechanical interface systems available on the SRT.

Even the electrical interface with the cartridge is characterized by simplicity, with the presence of an extremely reduced number of I/O channels (Fig. 8.3). The inputs are DC power, two reference signals (optical and radio), and control and sensor monitoring lines.

Four output IF signals are present in the 4-12 GHz band that correspond to the LSB-USB pair of each of the two orthogonal linear polarizations (Pol-0 and Pol-1) in which the received signal is separated.

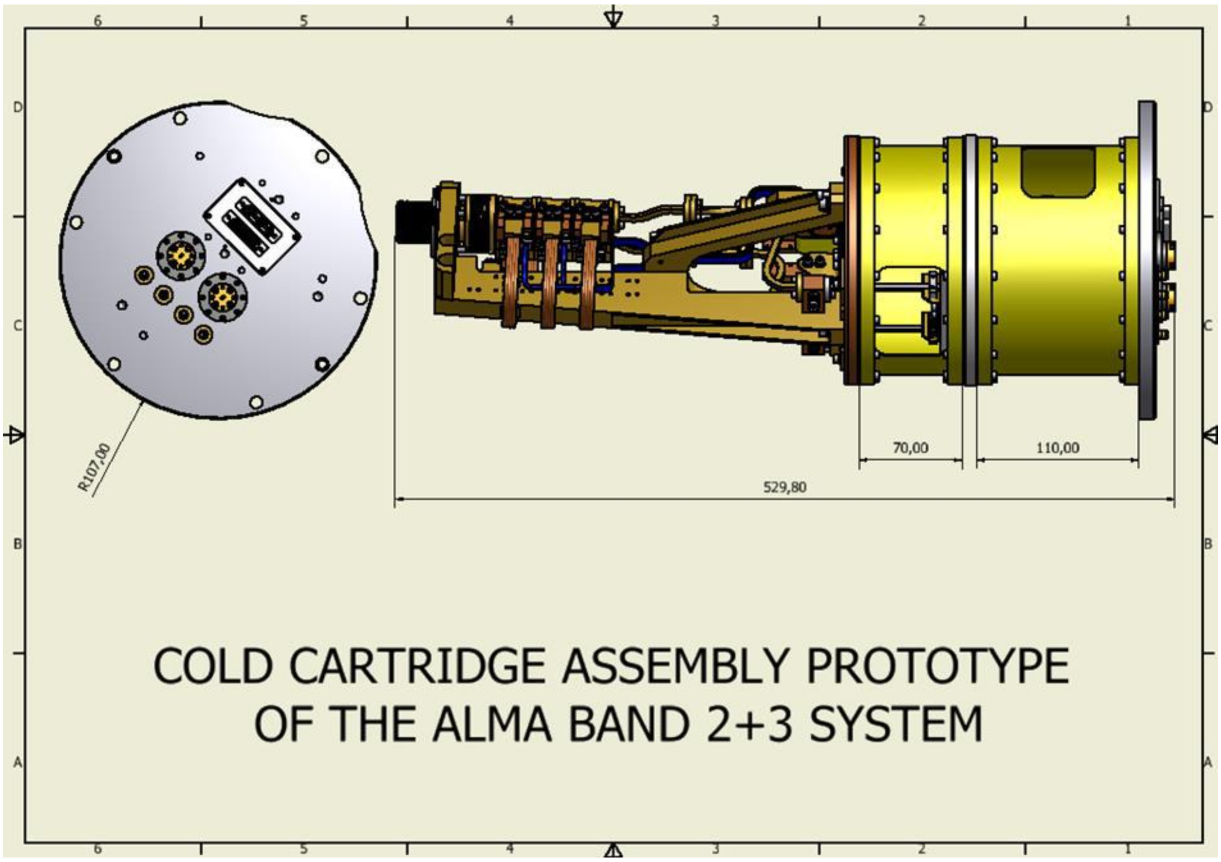


Figure 8.2 – ALMA Band 2+3 prototype: Cold Cartridge Assembly main dimensions

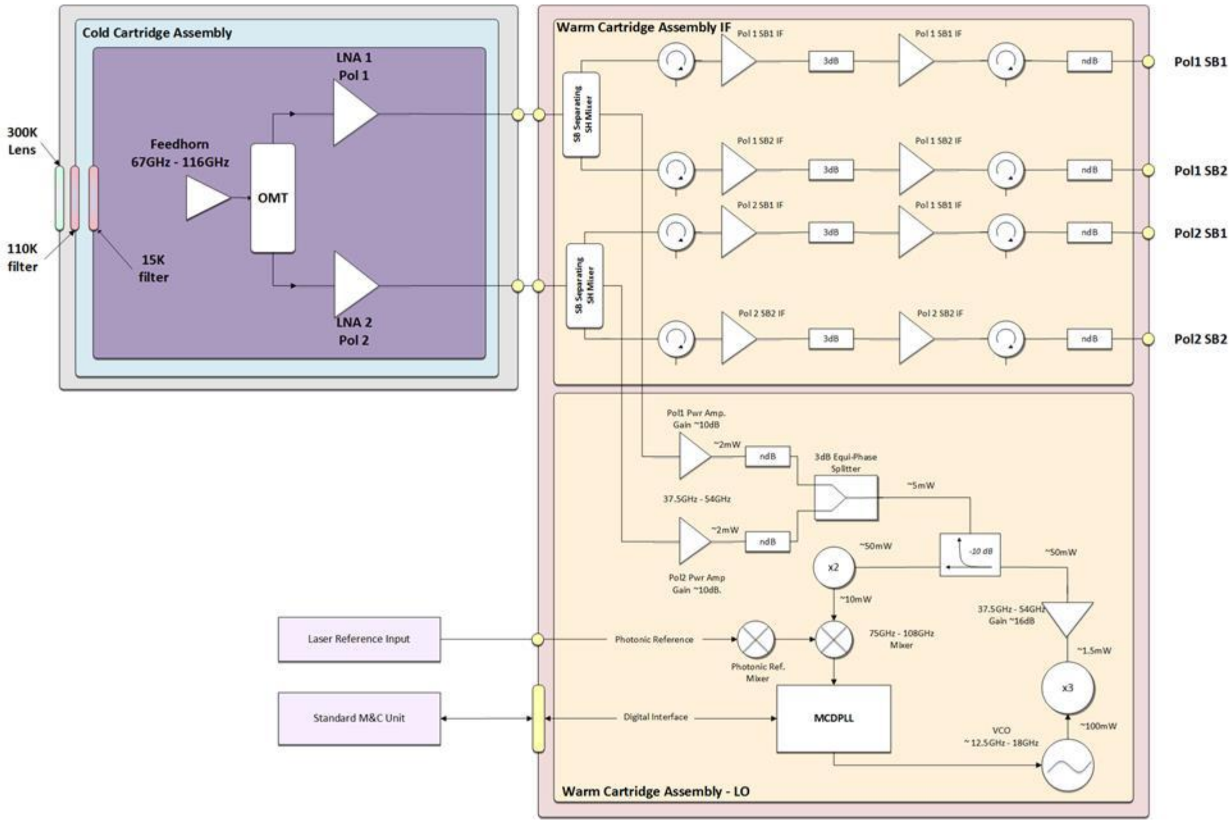


Figure 8.3 – Receiver scheme of the ALMA Band 2+3 prototype

8.1.2 Scientific drivers

The scientific drivers discussed in this Section are specific to the Band 2+3 and are independent of the radio telescope used to carry out the observations (single-dish or interferometer) in the sense that they do not request, as a first step, the high-angular resolution and sensitivity provided by an interferometer. Note that for detection projects, preliminary single-dish observations are usually requested.

The ALMA Band 2+3 Science case has been extensively documented in the White Papers [1, 2]. The science cases developed in these documents and summarized below discuss the advantages of encompassing Band 2 and Band 3 in a single receiver cartridge, in the so called Band 2+3 system. The Band 2 science is obviously covered by the band 2+3 science but the simultaneous frequency coverage allows one to perform critical measurements that cannot be done (or can only be done in a sub-optimal way) with the two bands separated.

Galactic Science

The main Galactic science driver for Band 2+3 is the ability of tracing the ground rotational transitions of deuterated species such as HDO, DCO^+, DCN, DNC, CCD, N_2D^+, orto-NH_2D, simultaneously with the fundamental transitions of their hydrogenated species. Thanks to the low excitation temperature, the (1–0) transition is certainly the most sensitive probe of the physical conditions because it is the most easily excited even at very low temperature. The enhancement of deuterated molecules is one of the most important chemical processes occurring in the cold ($T \leq 20$ K) and dense ($\geq 10^4$ cm^{-3}) pre–stellar phase, and the observation of deuterated species is crucial to derive the kinematics and other chemical/physical properties of pristine dense cores. Deuterated species are also important probes of the heavily shielded mid-plane of proto-planetary disks, and N_2D^+ and DCO^+ can identify the location of the ‘CO snowline’, where volatiles freeze-out onto the icy mantles of dust grains. The water distribution and deuteration ratio (HDO/H_2O) in proto-planetary disks can also help us to understand the origin of water on Earth and test the scenario of water delivery by asteroids and comets.

Another important science case is the formation of COMs of astrobiological interest, such as glycine, glycolaldehyde, ethylene glycol, etc., in star-forming regions and proto-planetary disks. These molecules play a central role in interstellar pre-biotic chemistry and may be directly linked to the origin of life. The advantage of Band 2+3 is the fact that the number of molecular rotational lines excited at these frequencies (67–116 GHz) is significantly lower than at higher frequencies, and hence the transitions of COMs suffer less from line blending with other species, with the added advantage that the broad frequency coverage of Band 2+3 will allow us to detect multiple transitions of COMs with different excitation energies, which is needed to confirm robustly the detections and to derive the physical parameters (column densities and temperatures). The study of pre-biotic molecules, in particular in Band 2+3, is one of the ALMA Major Science Themes in the 2020-2030 decade in the field of Astrochemistry and Astrobiology.

Other Galactic drivers of Band 2+3 include the study of: circumstellar disks around high-mass protostars, taking advantage of the fact that at low frequencies the line emission is less affected by dust opacity; flaring emission from young stars, because the wide frequency range will allow to derive quasi-instantaneous spectral indexes of the flares and thus, to constrain their nature; the earliest ionized gas during massive star formation by observing simultaneously different recombination lines; the dust evolution from grains to planets, which is one of the brainstorming ideas raised in the ALMA Major Science Themes in the 2020-2030 decade document; and silicon monoxide, methanol and formaldehyde maser emission in galactic regions.

Extragalactic Science

The main Extragalactic science driver of Band 2+3 is the study of redshifted CO for both a more efficient redshift determination and characterization of the cool gas content of galaxies over the epoch of galaxy formation, characterized by a dramatic decline of cosmic star-formation rate density of the Universe, from $z \gtrsim 8$ down to nearby galaxies in the Local Universe. The lowest excitation CO lines available in Band 2+3 are the best suited for redshift determination, in particular in the “redshift desert” ranges $0.37 < z < 0.99$ and $1.74 < z < 2.00$. The low-J transitions are also fundamental to accurately estimate the cool molecular gas mass and make a complete assessment of excitation conditions and the CO spectral line energy distribution possible. Band 2+3 will also allow the study of the properties and evolution of the dense gas, of molecular outflows and AGN feedback by observing high-velocity wings in low-J CO transitions and the ground state transition of high-density tracers, such as HCN, HNC, and HCO^+ in the crucial redshift range $0.4 \lesssim z \lesssim 2$, where the cosmic star-formation density is rapidly declining. Redshift determination and study of cool gas at all redshifts are part of the ALMA Major Science Themes in the 2020-2030 decade.

Other Extragalactic drivers of Band 2+3 include the study of: the radio-loud AGN duty cycle, from AGN fueling to jet-induced feedback; the evolutionary history of galaxy environments; deuterated molecules in nearby galaxies by observing the fundamental (1-0) transition of HDO, N_2D^+, DCN, DNC, and DCO^+; super-massive black holes, even on event horizon scales, origin and polarization of AGN jets, and high-z absorption kinematics, and fundamental constants by using mm VLBI techniques; and the Sunyaev-Zel’dovich effect in Galaxy clusters, taking advantage of the lower dust contamination by early-type galaxies at ~70 GHz.

8.2 PHAROS/PHAROS2 receiver

PHAROS is a C-band cryogenically cooled low noise Focal Plane Array system, which has been developed as part of a European technology demonstrator project. Within the framework of the SKA PAF AIP, of which INAF is part, PHAROS will be upgraded to a new instrument, named PHAROS2, that will re-use most part of the existing PHAROS hardware [4]. The PAF AIP partners include the following institutions: CSIRO (Australia, PI of the program), ASTRON (The Netherlands), University of Manchester (UK), Onsala Space Observatory (Sweden) and JLRAT (China).

In the framework of the SKA AIP, it is not currently planned to install PHAROS2 on the SRT, nor on the other Italian dishes. Instead, it is planned to install it on the Lovell Telescope at Jodrell Bank. The timeline is very tight, so there would be no time to carry out the installation and testing on the SRT. There is however an agreement, at the time informal, that after installation on Jodrell Bank, PHAROS2 could also be installed on the SRT. This would take place outside the PAF program of the SKA AIP. The PAF program is expected to be complete by the end of 2018.

8.2.1 Technical design

PHAROS2 is designed for the primary focus of a large parabolic reflector to perform radio astronomy observation across the 4-8 GHz range. Fig. 8.4 illustrates the system diagram of

PHAROS. The phased array feed consists of a 220 element Vivaldi array cooled to 20 K along with 24 low noise amplifiers (LNAs) mounted directly behind the active antenna elements. The LNAs are followed by low-loss low thermal conduction RF connections to the analog beam forming system designed to operate at 77 K. The RF signals of the active elements are distributed to the beam formers by passive splitters, while the non-active elements are terminated into 50 Ω loads. Four beam former modules are available, each with 13 RF inputs and 13 individually controllable phase and amplitude control units, along with 13 amplifiers to make up for system losses. The last stage of beam forming is a 16-way Wilkinson combiner (three inputs terminated). Each analog beam former is responsible for the amplitude and phase weightings of 13 elements in order to produce a single (compound) one-polarization beam.

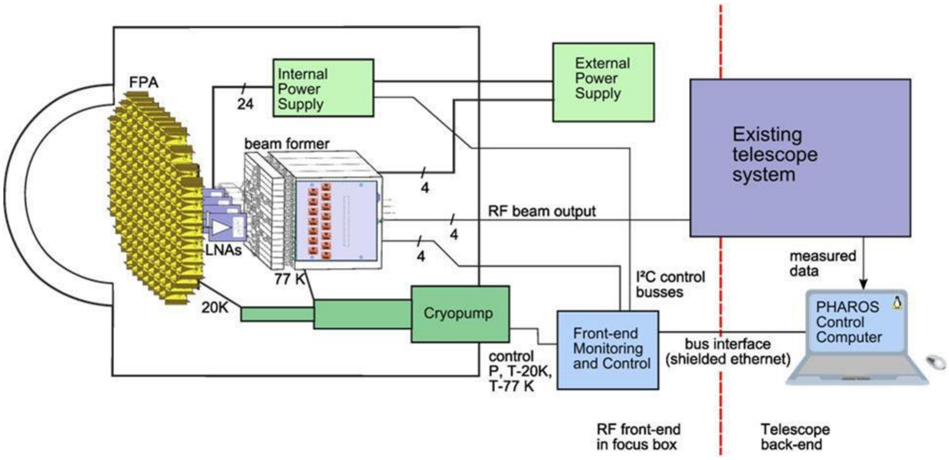


Figure 8.4 – PHAROS system diagram showing the main parts of the instrument

PHAROS2 will be a cryogenically cooled C-band PAF demonstrator with digital beamformer with the following features:

- new focal plane array of antennas (possibly with extended RF frequency coverage, beyond the current 4-8 GHz band); antennas will be optimized for a new type of cryogenic LNAs;
- new cryogenic LNAs with state-of-the-art performance to replace the existing ones. Goal is to integrate low-power consumption ultra-low noise LNAs with antennas in a compact module without coaxial interconnections;
- a down conversion system from RF to baseband;
- signal transportation with analog Radio Frequency over Fiber optical links;
- iTPM digital back-end (LFAA digital beamformer based on FPGAs) to perform digitization, coarse frequency channelization and pre-beamforming. Beamforming in GPU boards, mounted in high class PCs;
- 4 independent beams digitally formed using 24 active elements (baseline design). 9 independent beams digitally formed using 37 active elements (goal);

A preliminary PHAROS2 baseline architecture that would deliver 4 independent digitally formed beams is shown in Fig. 8.5. A design concept based on RF signal direct digitization (as opposed to signal downconversion in baseband) will also be considered for PHAROS2.

8.2.2 Scientific drivers

The PHAROS2 project is a technology demonstrator project and has no scientific drivers associated to it.

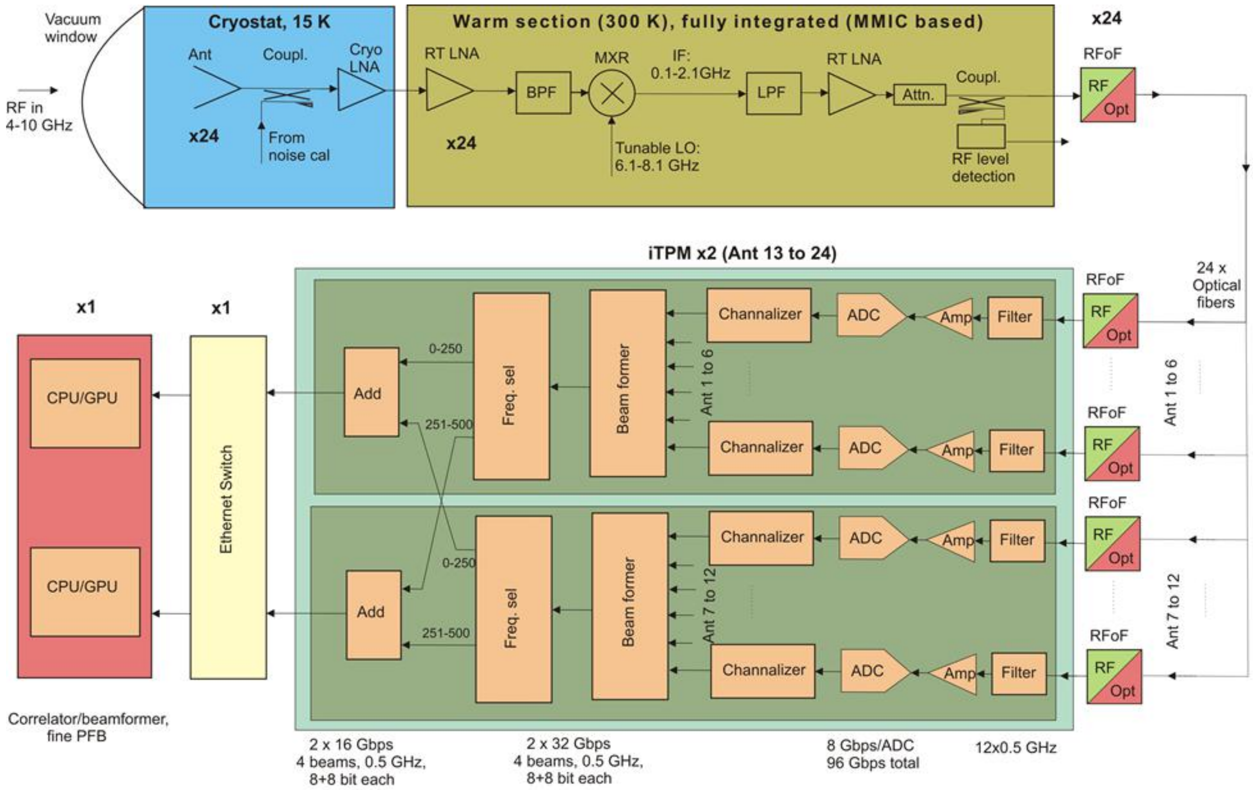


Figure 8.5 – Top level schematic diagram of a possible design concept for PHAROS2

8.3 BRAND receiver

The BRoad-bAND EVN receiver, which is under development in the framework of the Radionet4 Project, will cover a very wide band, from 1.5 to 15.5 GHz [5, 6]. It will be a receiver devoted to astronomical observations in the EVN consortium and will be installed at all the EVN antennas. Still today some EVN stations lack a frequency agility system, so the switching time among different wavelengths take from seconds to hours, depending on the station. The EVN has fast-frequency switching as a high priority goal for the next 15 years. Moreover, a system such this could provide multi-band simultaneous observations in the 18 to 2 cm range.

BRAND aims to spread through the EVN stations this new kind of receiver, taking into account mechanical constraints at each station in order to allow its installation.

8.3.1 Technical design

Technical development will start from an already available 2-12 GHz linear polarization feed designs. A feed system design for the primary focus will be the main aim of the project (to be tested on the Effelsberg antenna), as well as an investigation of secondary focus mounting (by adding a lens).The receiver will be cooled and its analogue part will consist of cooled LNA, post-amplifiers and HTS RFI filters. Then the chain will be processed digitally (no frequency conversion; digital polarization conversion from linear to circular; additional digital RFI mitigation; local RFI ‘fingerprint’ determination at stations; multi-band total power detector; multi-band polarimeter and spectrometer).

At its very beginning BRAND shows two weaknesses; first, it does not provide 21 cm observations, still a standard in the EVN consortium. Second, the feed performance in the designs today available in term of cross-polarization are poor, about 18 dB, while EVN has always requested 28-30 dB for its antennas. It is hoped that this Joint Research Activity can overcome these.

On the other hand, providing by one receiver only the entire frequency span, and more, used today inside the EVN is very attractive: only one receiver to maintain; same receiver type at all stations; more observing time due to no equipment dismounting issues.

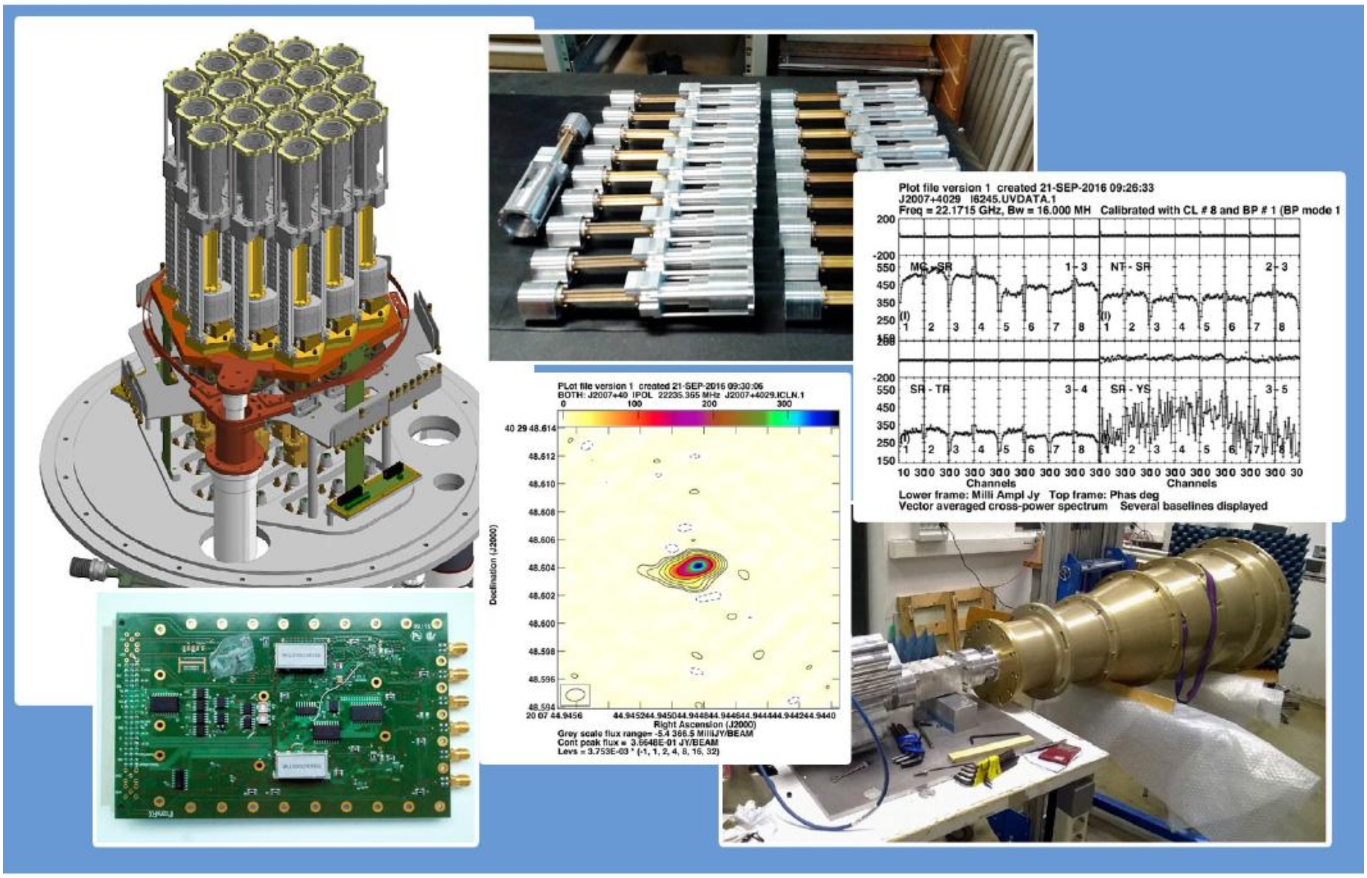
8.3.2 Scientific drivers

From a scientific point of view such a system could allow the following opportunities:

- multi-wavelength VLBI mapping: simultaneous multi-frequency observations but superior to VGOS due to continuous frequency coverage (RFI filters); fringe-fitting over very wide frequency range; determination of the ionosphere; precise registration of simultaneous images at different frequencies; superior to fast switching;
- multi-wavelength spectroscopy: study several different maser types in different frequency bands simultaneously; alignment of different maser species, e.g. determine conditions in complex flow patterns;
- multi-wavelength polarimetry: variations of polarized emission as a function of frequency over a very wide frequency range; precise unambiguous rotation measures; improve studies of physical conditions of various astronomical objects;
- multi-wavelength single-dish: flux variation studies in several bands simultaneously especially interesting for intraday variability; rotation measures over large bandwidths; pulsar observations over a wide frequency range with no timing ambiguities;
- geodetic VGOS compatibility: joint observations with geodetic VGOS antennas would be possible; precise positions of astronomical antennas celestial reference frame; huge arrays for astronomical observations if needed.

Part III - Scientific perspectives of the Italian Radio Telescopes

9. Scientific cases for receivers under development



In this Chapter we summarize the main scientific cases that were identified for the receivers under development or under evaluation at the Italian radio telescopes. The science cases presented here are not intended to be an exhaustive list of all the possible applications for the various receivers, the aim being to give an overview of the main astronomical drivers at the various frequencies for both single-dish and VLBI observations, as well as for continuum and spectroscopic techniques.

For each receiver we report the key science cases that were identified at the time of the proposal/design phase, whenever this information is available. This is typically not the case for the older front-ends, for which the documentation related to their scientific motivation was not (or is no longer) available. For such receivers, but more in general whenever some information could be added for a given front-end, additional science drivers have been identified also with contribution from INAF radio astronomers outside this Working Group (see Acknowledgements Section). For the SRT, we also referred to the Proceedings of the Workshop “Science with the Sardinia Radio Telescope” held in 2005 [1].

The scientific output of a front-end strongly depends on the telescope observing capabilities and the available back-end equipment. Some of the science cases mentioned in the following Sections need On-The-Fly observing capabilities and, on the back-end side, high spectral resolution. Both these requirements are met at the Italian antennas thanks to the ESCS/Nuraghe telescope control system and the new generation of digital back-ends.

There are four receivers under development for the SRT: the multi-feed systems in the S- and Q-bands, the mono-feed in the Clow-band and the ex-IRAM mono-feed W-band. Currently there is a Ku-band dual-feed receiver under development for the 32-m Medicina telescope. For Noto the receivers currently under evaluation, namely the ex-IRAM and ex-MPIfR receivers in the W band as well as the L/S/X-band one, have been taken into consideration.

9.1 SRT S-band receiver

The frequency range of the S-band receiver is different from that of the typical S-band front-ends at the EVN telescopes, therefore its usage for VLBI applications is not foreseen.

A number of scientific goals for the SRT S-band 7-beams receiver have been identified at the time of writing the proposal for its funding. They can be summarized as follows:

a) To probe, through the discovery of new highly relativistic binary systems including a radio pulsar, alternative Gravity theories whose measurable effects are marginally different from those predicted by Relativistic Gravity, but whose impact on fundamental cosmology is very high, and in general enlarge the available pulsar sample.
b) To monitor the sample of pulsars of the European Pulsar Timing Array experiment aimed at the detection of the gravitational wave background in the nanoHertz regime. S-band observations have the potential to allow higher precision measurements of pulses times of arrival and to improve the limits on the GW background in order to possibly lead to a detection.
c) To map the large scale properties of magnetic fields in clusters of galaxies, which have strong implications in our understanding of cosmological magnetic fields.
d) To understand the polarized synchrotron emission of our Galaxy in order to infer the galactic contribution to the polarized Cosmic Microwave Background.

e) To produce calibrated images of SNR and improve the knowledge of their spectra.

Also, the multi-feed properties of the S-band receiver make it suitable for the realization of large-area sky surveys.

9.2 SRT Clow-band receiver

SRT first light instrumentation includes a Chigh-band receiver. The decision to subsequently build also a Clow-band front-end has been motivated mainly by the possibility to join EVN/global VLBI observations at this frequency. All the EVN antennas are in fact equipped with Clow-band receivers, only a minority having a Chigh-band one. EVN continuum observations in the C band are thus usually done at 5 GHz in order to maximize the UV coverage and sensitivity of the network.

The availability of both Clow- and Chigh-band receivers at the SRT will be of importance for polarization studies, since a wide and contiguous spectral coverage permits to sample the variation of the polarization angle and to derive accurate and reliable estimates of the Faraday Rotation Measure (RM).

Typical science cases for Clow-band VLBI observations are related to:

a) The study of continuum emission from optically thin emission regions. The C band frequency range offers the best combination of angular resolution and dynamic range for such studies. At lower frequency, the resolution becomes too poor and the depolarization is stronger; at higher frequency, the emission is fainter and the noise is higher, so that the dynamic range is affected significantly.

b) Jets of radio loud AGN, such as radio galaxies and blazars, can be studied in great detail to infer many important properties of the relativistic flow, which in turn are fundamental to understand the jet formation mechanism: jet collimation profile, transverse brightness distribution, proper motion of jet knots, polarization and magnetic field, rotation measure and presence of Faraday screens.

c) Jets from compact binaries are also ideally studied at this frequency, with the advantage that the much smaller physical scales determine shorter evolution time scales and the above described studies can be carried out in weeks, rather than years. This could have tremendous importance for the study and understanding of the accretion/ejection coupling.

d) In young radio sources, it is possible to monitor the advance velocity of hot spots and thus obtain kinematic age estimates, to be compared against radiative ages estimated from lower angular resolution multi-frequency studies.

e) The study of transient phenomena, which can in particular benefit from the exploitation of the real-time capabilities of the e-EVN [2]. Possible studies include: the nature of Fast Radio Bursts (FRB); explosive extragalactic phenomena (SN and γ-ray bursts, tidal disruption events and black holes); and galactic transients (black-hole X-ray binaries, accretion events in isolated black holes, cataclysmic variables).

f) The study of continuum emission from compact Galactic and extragalactic sources (e. g. AGN and SN remnants).

g) Polarization properties of AGN and compact sources; VLBI studies of polarization in young compact radio sources like CSO and CSS, and VLBI studies of Rotation Measure properties in quasar and blazar jets.

h) Spectroscopic observations of some molecular transitions like the OH line at 4660.42 and 4765.562 MHz, and the formaldehyde (H_2CO) line at 4829.66 MHz.

Finally but not less important, being MED and NOTO already equipped with Clow band receivers, there is also great potential for Italian VLBI network coordination in this band, with much higher sensitivity than at Chigh or K bands (due to the much higher system temperature of those receivers). For instance, the search of counterparts to gamma-ray unidentified sources would be ideally carried out at Clow band frequencies.

Among the possible single-dish applications of the Clow-band receiver, we mention:

a) Study of the interstellar gas properties by means of recombination lines (in particular Hydrogen ones) both galactic (e.g. Ultra-Compact HII regions) and extragalactic (e.g. in starburst galaxies). In the latter case, a synergy exists with interferometric observations for the follow up of the detected emission.
b) Study of galactic and extragalactic emission/absorption and – possibly – maser emission produced by the formaldehyde molecule. Currently some detections of extragalactic CH_2O masers have been claimed but their reliability is still debated. A confirmation of formaldehyde as a molecular tracer would be of great interest for studies of gas kinematics in star forming regions and/or AGN.
c) Single-dish total intensity and polarization studies of extended sources (> 10 arcmin) like Galactic emission, giant radio galaxies or radio relics in galaxy clusters, not detectable in C band interferometric experiments that would resolve out their diffuse emission.
d) Study of background point-like sources in nearby galaxy clusters (RM grid) to measure the cluster magnetic field.
e) Formaldehyde absorption line ratios can be used as gas density tracers if both the 4829.66 MHz and the 14.470–14.500 GHz transition lines can be observed. This last case study highlights a possible synergy with the Medicina telescope, for which a Ku-band receiver in the 13-18 GHz frequency domain is under development.

Other science drivers for a Clow-band receiver at the SRT have been identified during the Workshop "Science with the Sardinia Radio Telescope" and were related to the study of active binary stars, polarization of the CMB and SETI experiments.

9.3 SRT Q-band receiver

The Q-band and W-band receivers share a number of possible science cases to be addressed by observations with the VLBI network (see also Section 9.4). Among them we mention:

a) Physics of supermassive black holes and tests of general relativity.
b) Physics of relativistic jets. The high spatial resolution achievable in the Q band permits to observe the most compact parts of the jet, residing in the proximity of the γ-ray emitting regions and typically self-absorbed at lower frequencies. In synergy with very high energy data this would allow to study the origin of γ-ray emission in relativistic outflows and the surrounding of supermassive black holes [3]. Q-band observations are complementary to Clow band ones, which are more suited to investigate jets on scales >10 pc.
c) Young Stellar Objects, star forming regions in our Galaxy and Supernovae Remnants.

d) During the Workshop “Science with the Sardinia Radio Telescope” a science case requiring VLBI observations in both the Q and W bands has been presented, aimed at the detection of SiO masers in Mira variables and other evolved stars in order to investigate the kinematics of the surrounding gas and to probe the circumstellar envelopes at different depths.

We point out the synergy with international arrays like VERA and KVN, operating in the Q band as well, which would be ideal partners also for real-time VLBI observation.

Among the main scientific goals that can be exploited with single-dish observations using the multi-feed SRT Q-band receiver we mention:

a) Mapping Galactic filaments by means of SiO, CH3OH and high density tracer observations to investigate the nature and possible formation mechanism of such structures, and to infer their physical properties.
b) Survey of COMs in high-mass star-forming regions. Centimeter-wavelength studies of these molecules are favorable with respect to (sub)millimeter observations which are severely affected by line blending.
c) Galactic maser surveys. Class I methanol masers at 36 and 44 GHz in star-forming regions can be observed to investigate their distribution, morphology and the kinematics of maser emission. Also, the detection of SiO masers at 43 GHz in evolved stars (supergiants and AGB stars) allows the study of stellar atmospheres and the circumstellar environment.
d) Study of methanol megamasers in starbursts and AGN are useful to probe their demographics and to investigate the possible link with feedback mechanisms in galaxies. A 36.2 GHz survey with the SRT could also be included in a VLBI initiative for maser proper motions.

9.4 SRT and NOTO W-band receivers

A number of scientific goals for the W-band receivers under development at both the SRT and NOTO have been identified, some of them mentioned as drivers for 3mm receiver development in the Proceedings of the Workshop “Science with the Sardinia Radio Telescope”. Their effective exploitation at the two telescopes depends mostly on sensitivity considerations. The SRT can play a major role in W-band observations also in single-dish mode thanks to its sensitivity. It is reasonable to expect that the Noto telescope will be best exploited in the W-band by fully joining the global VLBI experiments at millimeter frequency performed by the GMVA, while its actual efficiency in single-dish programs may be limited to studies of our Galaxy and the nearby Universe. A new subreflector for NOTO would be in any case necessary to perform observations in the W band.

Among the main science cases that can be investigated with mm-VLBI observations we mention:

a) The study of the physical properties, formation, structure and kinematics of relativistic jets: the relation between the jet and the central black hole; the jet polarization properties and the connection with the surrounding magnetic field.
b) Physical properties of regions affected by scatter broadening, such as SgrA*, which cannot be efficiently studied at lower frequency. Given the low declination of the galactic center,

the geographical position of both SRT and NOTO would make the installation of a W-band receiver particularly important for the study of SgrA*.

c) (Binary) supermassive black holes.
d) Monitoring of flares and outbursts in AGN.
e) Kinematics, distribution, polarization and variability of SiO masers in evolved stars.
f) A science case on Mira variable stars requiring Q- and W-band observations with the SRT has been already reported in Section 9.3.

Concerning single-dish applications, we mention:

a) Science cases based on the study of CO transitions, for instance:
    - Mapping of Galactic filaments in CO and isotopologues as well as in N_2H^+(1-0) to estimate velocity field, column density, mass and characteristic width of such structures and compare their properties with those estimated from the dust continuum emission.
    - Multi-line studies of methanol Class I and II Galactic masers in star-forming regions to investigate the distribution, morphology and kinematics of the maser emission.
    - Observations of CO in local galaxies to compare molecular gas mass profiles with dust mass and atomic/HI gas mass profiles obtained with other telescopes. This analysis may also be useful to define gas/dust scaling relations that will serve as local benchmarks in future SKA studies. Coupled with other multi-wavelength diagnostics, mapping the CO in local galaxies over a wide range of metallicities and star formation rates gives insight into the influence of physical conditions on the conversion of H_2 into stars.
    - CO emission in intermediate z starbursts can probe a crucial phase in galaxy evolution, covering almost half the age of the Universe and the most dramatic change in star-formation activity.
    - Molecular gas in HI-selected galaxies can be used to estimate the total gas content. CO(1-0) follow-up surveys of such samples in the local Universe ($z \leq 0.3$) would be useful especially in view of the SKA telescope, which will revolutionize HI surveys out to $z \approx 1$.
    - SRT mapping could be used in charting molecular outflows in AGN with broad CO(1-0) emission.
    - Observations of molecular tracers (CO and other mm-wavelenght probes) in low-metallicity dwarf galaxies, although difficult, can be potentially rewarding especially in terms of isotopologues and the possibility of estimating column densities through optically thin emission.
b) By means of 3 mm observations in nearby galaxies and starbursts several isotopologues (including $H^{13}CO^+$(1–0), $H^{13}CN$(1–0) and $HN^{13}C$(1–0)) may be detected to compute accurate line ratios and reveal a wealth of chemistry as a diagnostic of source obscuration and excitation.
c) Dense-gas tracers such as HCN(1–0), HCO^+(1–0), HNC(1–0), or CS(2–1) may be used to study the dense gas distribution in nearby galaxies, including AGN, starbursts, Luminous and Ultra-Luminous Infrared Galaxies.
d) The SiO(2–1) transition at 86.85 GHz can be observed to probe shocks in AGN, and to disentangle the physics of dense outflows around the AGN itself.

e) The Sunyaev-Zeldovich effect in galaxy clusters can be detected and used to investigate the properties of cluster galaxies and the intra cluster medium, as well as the cosmological parameters.

9.5 MED Ku-band receiver

A number of single-dish science cases for the Ku-band receiver at MED were identified at the time of the construction proposal, namely:

a) Continuum and polarization studies of galactic and extragalactic radio sources; detection and spectral energy distribution of GPS/CSS populations.
b) Blind, large-area surveys of the sky. The spatial resolution achievable in the Ku band with MED is such to avoid severe limitations from confusion noise, and makes it possible to start resolving the structure of extragalactic radio sources.
c) Source variability monitoring, also in synergy with projects at other frequencies. Among such collaborations, it is worth mentioning the monitoring of Planck sources (the Simultaneous Medicina-Planck Experiment [4]) and the ongoing participation in the GLAST-AGILE Support Program for the long-term continuous monitoring of gamma-ray blazars (e.g. [5]).

Also, spectral line studies (both Galactic and extragalactic) will benefit by the continuous coverage of the radio band from 12 to 26 GHz at MED that will be achieved by the construction of the Ku-band receiver in addition to the already existing K-band front-end. In particular, the Clow- and Ku-band receivers at MED may be exploited to detect the formaldehyde molecule at both 4829.66 MHz and 14.470–14.500 GHz. For such observations a synergy will exist with the SRT, once the Clow-band receiver for that telescope will be available.

With respect to VLBI observations, currently only a sub-array of the EVN is used for observations at 2 cm since this wavelength is available at very few of the European telescopes. Observations in the Ku band are possible with the VLBA and GBT. A recommendation to the EVN Board for the expansion of the EVN capabilities in the 12-15 GHz domain was issued in the Vision document EVN2015 “The Future of European VLBI Network” [6]. The addition of the Medicina telescope to the VLBA or the EVN sub-array at 2 cm will improve the observations in terms of UV coverage, resolution and sensitivity.

VLBI science cases in the Ku band include studies on:

a) Physics and kinematics of radio jets.
b) Evolution of black hole systems.
c) Magnetic field and polarization properties of blazars and connection with multi-frequency (gamma-ray) observations.
d) Spectroscopic studies include methanol maser studies of collapsing gas clouds at stellar birthplaces and protoplanetary discs.

It is worth mentioning that 15 GHz is the observing frequency of the MOJAVE project [7], one of the VLBA Key Science Projects. MOJAVE is a long-term program to monitor radio brightness and polarization variations in active galaxies jets, aimed at understanding their parsec-scale evolution and magnetic structure, and the correlation with gamma-ray emission detected by NASA's Fermi Observatory. The availability of a Ku-band receiver at MED would in principle give the opportunity to join the VLBA for MOJAVE observations. The addition of MED could be of interest for the MOJAVE project, since it would imply a significant increase in angular resolution, translating in a considerable decrease of the project duration or, for equal length, a decrease in the measurement uncertainties and in the number of upper limits.

9.6 NOTO L/S/X-band receiver

At the moment, an evaluation of the possible refurbishment of this already existing receiver is ongoing. With respect to the currently installed S/X at NOTO, the L/S/X front end would offer the advantage of permitting observations in the L band, and to have a larger S/X bandwidth. The scientific cases that can be addressed in the L and S/X bands with this receiver are discussed in the following.

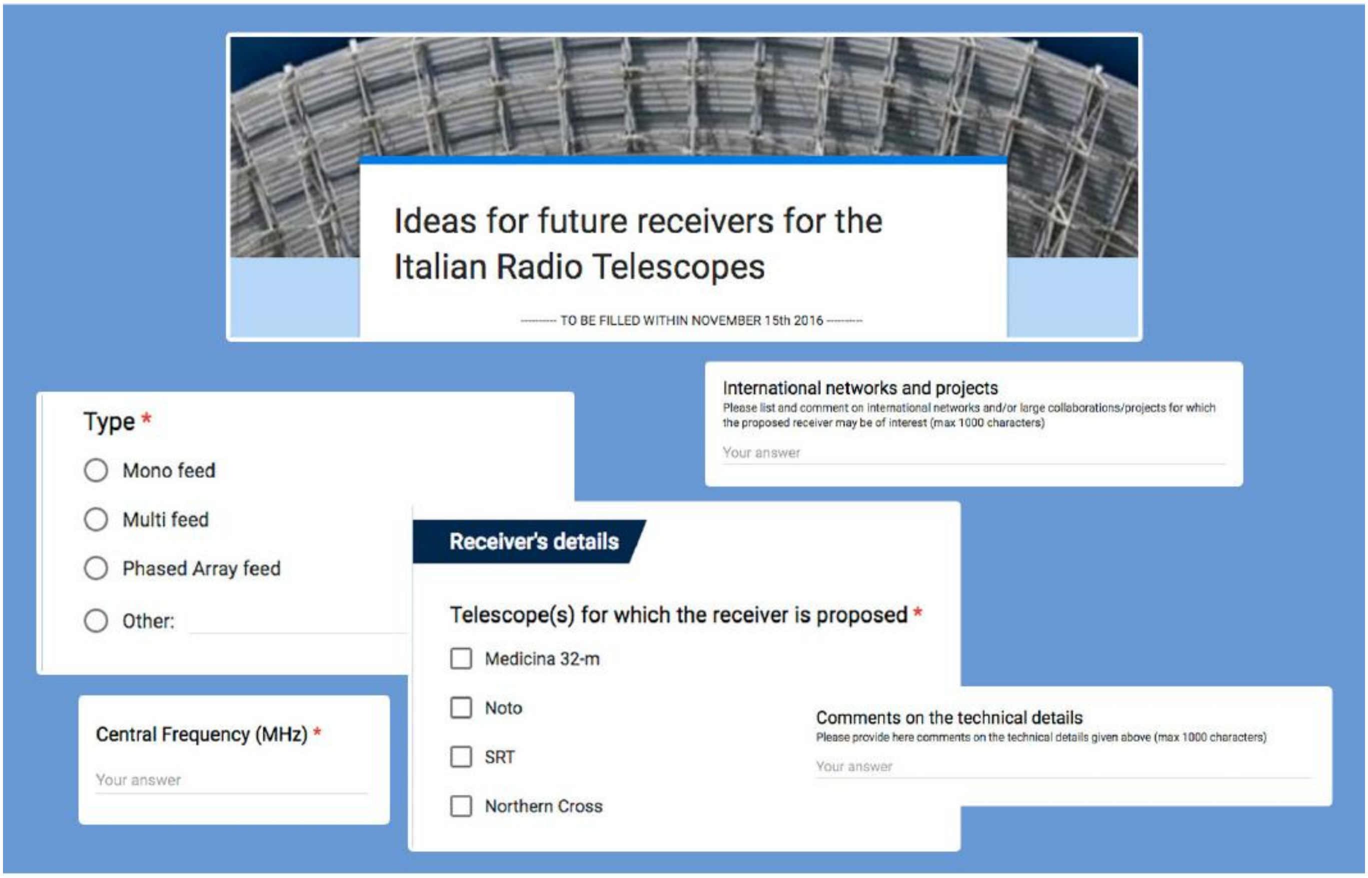
L band: this frequency band has a very limited interest in single-dish mode for a 32-m class telescope like NOTO, due to the large beam size and limited sensitivity. However, as demonstrated by the significantly high publication rate of the old L-band Noto receiver dismounted in 2014, this band is of great interest for VLBI observations, for both continuum and spectroscopy studies. VLBI in fact allows for higher sensitivity through a larger collecting area, better RFI rejection and great temporal and spectral resolution as supported by DBBC back-ends. Possible VLBI scientific applications include spectroscopic observations of OH galactic masers, OH maser distribution in low redshifts galaxies and HI distribution in nearby galaxies. The L band is also extensively used in the continuum for AGN studies with the EVN array. Finally, other two science cases can be considered of importance also in the international context, namely:

a) FRBs. The discovery frequency of these sources is generally ≤ 1 GHz, so the L-band receiver is well suited for such studies.
b) SETI project. L-band is the traditional search band for SETI and the VLBI potential in this context, even with small arrays, has already been demonstrated [8].

It is worth noting that, since accurate imaging is not in general required in neither FRB or SETI searches, even a simple three-stations array (MED, NOTO, SRT) could be adequate for these, and similar, studies.

S/X band: this coaxial receiver will be mostly used for geodetic observations within the IVS network, similarly to what is happening with the currently available S/X receiver at the Noto telescope. The larger bandwidth available with the new S/X receiver would allow the participation of NOTO in a wider range of geodetic experiments, coming from the well-established IVS regular sessions to the near-field target experiments that are being developed recently, allowing observations of GNSS satellites. With respect to single-dish studies, the X band can be used for continuum observations of strong radio sources, mostly aiming at variability monitoring campaigns. The S band receiver suffers from the same limitations as the L band (poor resolution and sensitivity) and it is thus considered to have a limited efficiency for single-dish observations at NOTO.

10. Ideas for future receivers



Ideas for future receivers for the Italian Radio Telescopes

--------- TO BE FILLED WITHIN NOVEMBER 15th 2016 ---------

Type *

○ Mono feed

○ Multi feed

○ Phased Array feed

○ Other:

International networks and projects

Please list and comment on international networks and/or large collaborations/projects for which the proposed receiver may be of interest (max 1000 characters)

Your answer

Receiver's details

Telescope(s) for which the receiver is proposed *

☐ Medicina 32-m

☐ Noto

☐ SRT

☐ Northern Cross

Central Frequency (MHz) *

Your answer

Comments on the technical details

Please provide here comments on the technical details given above (max 1000 characters)

Your answer

In this Chapter the results of the Call for Ideas are reported. The Call for Ideas aimed at the production of a roadmap for future receiver developments at INAF. This roadmap represents an opportunity for the whole Italian astronomical community to play an active role in the definition of the priorities for future instrumental and scientific developments. Thus, it has been asked to the whole Italian astronomical community at large (not only astronomers, and not only in the radio domain) to express their ideas by compiling the online web survey form. The scope of the questionnaire was to survey the interest of the community in the development of new receivers and as such, it was just a Call for Ideas and not a formal call to develop new receivers.

The Call for Ideas was successfully concluded with fifteen proposals. For convenience of the reader the various ideas were subdivided into two groups, requests in low-medium frequency bands (< 18 GHz) and requests in high frequency bands (> 18 GHz). Moreover, the ideas within each group are listed with increasing frequency bands.

10.1 Low-mid frequency bands

Receiver for SRT at 1.4 GHz
proposed by Isabella Prandoni, IRA
freq: 1400MHz
bandwidth: 750 MHz
Single frequency, Mono feed

International networks and projects
The idea is to establish a VLBI network including MeerKAT, HartRAO and SRT (plus perhaps other antennas). This idea was developed in the context of the MIGHTEE & LADUMA MeerKAT key projects, as joint MeerKAT-VLBI observations are thought to provide added-value science products. Large dishes like the SRT are clearly crucial for getting matched sensitivity Meerkat-alone and MeerKAT-VLBI observations, but the more antennas join the better in terms of UV coverage. The current MeerKAT-VLBI project envisages the use on all antennas of the same L-band receivers (the state-of-the-art MeerKAT receiver). If I understood correctly, SKA-SA would provide such receivers for all antennas.
I think this could be a good opportunity for Italian antennas (or SRT alone). At the It/SA AVN workshop held in Bologna in October 2016, it emerged a clear scope for a It/SA technical collaboration on the AVN. This initiative may be more helpful to establish a scientific collaboration based on It/SA VLBI observations.

Short science case(s)
The science case for high-sensitivity VLBI networks can be wide and diverse. We plan to organize a dedicated workshop in 2017 to discuss science cases in more detail. Here I briefly report a couple of paragraphs produced in the framework of the MIGHTEE/LADUMA key projects, mainly focusing on AGNs:

a) feedback and feeding mechanisms in low-power AGNs. MeerKAT's high sensitivity and wide field-of-view surveys will be limited to ~5 arcsec angular resolution (at 1.4 GHz), limiting our ability to separate RQ-AGN and SFGs on morphological grounds, although the wealth of multi-wavelength data available in the target fields can address this to a certain extent. VLBI would add another piece of information to the problem, not only allowing evermore robust separation of AGN and SFGs, but also to explore the incidence of AGN radio cores in RQ-AGNs,

and possibly resolving sub-kpc/kpc AGN-driven radio structures (radio jets/outflows) in low-power AGNs (both RL and RQ). This will allow us to get insights on radio-jet duty cycles and related feedback to much lower luminosities than probed today.
In addition VLBI will play an important role in the HI absorption components of MIGHTEE, contributing unique morphological insights to the interpretation of gas inflows and outflows, associated to AGNs in particular [1].

b) AGN jet physics VLBI polarimetry will not only provide detailed information on sub-kpc magnetic fields and jet physics, but also enable comparison with (and separation from) the larger scale polarisation properties to be probed by MeerKAT [2].

Other comments
None

Receiver for SRT at 5 GHz
proposed by Marcello Giroletti, IRA
freq: 4900 MHz
bandwidth: 1400 MHz
Single frequency, Mono feed

Technical details
A relatively straightforward mono-feed, mid-frequency receiver. It needs to be cooled, with low Tsys (SEFD < 30K), full polarisation, to be operated in VLBI mode. It is fundamental to work with Medicina and Noto in a common frequency range for a national network.

International networks and projects
This is the main frequency for the EVN and the Global VLBI arrays, as well as for Radioastron. It will be one of the first frequencies available to African stations in the context of AVN activity. It will also be one of the main frequencies at which the SKA will participate to VLBI operations. It is mandatory that the SRT is able to participate in these networks.
On a national basis, 5 GHz will be the frequency at which the Mc-Nt-Sr array achieves the best sensitivity making it a strong and reliable facility (e.g. in comparison to 7 GHz where only bright sources can be studied, or 22 GHz which are severely weather dependent).

Short science case(s)
The science case is very heterogeneous and largely overlaps with all is being done in continuum by VLBI arrays such as the EVN and the VLBA. It is only sketched here: physics of relativistic jets in extragalactic and galactic sources (AGN, X-ray and gamma-ray binaries), transients (novae, supernovae, gamma-ray bursts), characterization and identification of gamma-ray sources.

Other comments
I understand that this is a receiver already under development so this form is mostly to express my feeling of a high priority for this receiver, as also expressed by the EVN and its Program Committee.

PAF receiver at 6 GHz for SRT
proposed by Paolo Serra, OAC
freq: 6000 MHz

bandwidth: 4000 MHz
Single frequency, Phased Array feed

Technical details

A PAF in C band on SRT represents a good compromise between angular resolution and sky coverage. At lower frequency the resolution would be too coarse for the science case below; at higher frequency the field of view would be too small for good survey speed (and the radio emission too faint).

International networks and projects

This could be part of a push for PAFs on SKA as part of existing collaborations or within the Advanced Instrumentation Program. L band PAFs are sufficiently covered at other institutes, so it seems to make sense to work on a different band which is also of interest for our newest telescope.

Short science case(s)

Large surveys of diffuse emission from nearby galaxy clusters. Coupled with surveys of the cold ISM of galaxies in clusters (e.g., HI with APERTIF, CO with SRT itself), this would give a picture of the interaction between the galaxies and the intra-cluster medium. This interaction may be one of the keys for the emergence of the Hubble sequence and the transformation of galaxies from blue star-forming to red passive in high-density environments.

Other comments

None

PAF receiver at 6 GHz for Medicina, Noto and SRT

proposed by Francesco Schillirò, OACt
freq: 6000 MHz
bandwidth: 4000 MHz
Single frequency, Phased Array feed

Technical details

Crio-cooled 24 elements with double polarization , completely digital down-converted and with automatically setting into antenna position. Design for Digital software de-rotation and tools for calibration and data reduction.

International networks and projects

SKA Phased Array Feed Consortium - ASKAP project - PHAROS project

Short science case(s)

1) Mapping of bright Galactic Extended Radio Sources (Supernova Remnant, HII regions): aims of the project is to recover the extended diffused emission not detectable with interferometer, do to the LAS (Largest Angular Scale) problem;
2) Galactic Center monitoring for search of highly circularly polarized transients.

Other comments

None

PAF receiver at 6 GHz for SRT
proposed by Ettore Carretti, OAC
freq: 6000 MHz
bandwidth: 4000 MHz
Single frequency, Phased Array feed

Technical details

1) It is a 4-8 GHz PAF system. The back-end BW could not be necessarily that broad (1 GHz IF could be sufficient - goal: 2 GHz), the detected band to be set within that 4-8 GHz range.
2) Cryogenic (the signal is low, needs highest possible intrinsic sensitivity).
3) Minimum 50 formed beams, essential to detect diffuse emission (total intensity and polarisation) and spectral lines on all-sky class surveys on human affordable observing time scales.
4) 2:1 high-to-low frequency end ratio is indicative. Exact bandwidth can be adjusted following manufacturing details or technological development constraints.

International networks and projects

1) All projects related to cosmic magnetism or search survey of methanol masers.
2) Legacy projects for large scale emission missed by the SKA at those frequencies, or any interferometric array. (Interferometry has no sensitivity to scale larger than the minimum array baseline.)
3) Essential for CMB foreground characterisation toward the search for the Inflation footprint on the CMB B-Mode.

Short science case(s)

1) Fast C-band continuum/polarisation surveys (spectropolarimetry), in particular in the Galactic Plane to improve existing surveys from ~60' to ~2.5’ resolution. Essential to beat depolarisation in the Galactic plane and study Galactic magnetism and Galactic structure in the spiral arms (even the closest arm, Sagittarius, is depolarized at 2.3 GHz). Essential to cover all angular scales needed for CMB foregrounds investigations. The latter requires the high Galactic latitudes where the signal is low and cryogenic systems with tens of beams are essential to cover at least half a sky.
2) CMB foregrounds. The CMB community has realized that it is essential to map the CMB foregrounds at as many frequencies as possible with the highest possible sensitivity and accuracy. S-band is covered, the next step is the C-band (C-BASS, with 1 deg resolution, is not sufficient), that requires a leap in sensitivity to reach the same S/N ratio reached by, e.g., S-PASS in S-band. A cryogenic PAF with, say, 50 formed beams is essential.
3) GRB and GW event follow-ups.
4) FRB search: the larger the number of beams the better.
5) High Dispersion Measure pulsar searches toward the Galactic Centre.
6) Excited rotational states of OH at 6.0 GHz: Zeeman effect, star formation.
7) Methanol (6.7 GHz): survey of methanol masers, gas kinematics, Ultra Compact HII regions.
8) Hydrogen recombination lines around 5 GHz, to study the environment conditions in star forming regions.
9) Flat spectra transients/pulsars, like magnetars.

10) This receiver will also be a learning ground to establish foundation for PAF technology and then move to higher frequencies. The ultimate goal is to have a PAF cameras with large number of pixels and broad band (minimum 2:1 max/min frequency ratio) in K-band (20 GHz) and W-band (100 GHz), the only reasonable way to get a high speed survey instrument at high frequency for blind surveys that covers a wide range of science cases (continuum, spectro-polarimetry, spectroscopy, pulsar).

Other comments
None

Receiver for SRT at 2.3 and 8.4 GHz

proposed by Monia Negusini, IRA
freq: 2.3 and 8.3 GHz
freq. range: 2.2-2.36 and 8.18-8.98
Dual Frequency, Mono feed

Technical details
The proposed receiver is a well-established S/X receiver that allows SRT to be included in the present global geodetic network, coordinated by IVS.

International networks and projects
The proposed receiver is of interest for the VLBI community that operates in a collaboration within the International VLBI Service for Geodesy and Astrometry (IVS) and the Associations linked to it: IAG, IERS and IAU. It is well-known that the future network will be constituted by small, fast-moving, continuously observing antennas (VGOS), but the legacy antennas will serve even more other years.

Short science case(s)
The Sardinia Radio Telescope is the fourth Italian radio telescope, together with the Medicina, Noto and Matera. It is already taking part at the astronomical European VLBI Network (EVN) observations and in the future, if the geodetic receivers should be installed, it might give its contribution to geodesy, being situated in a stable portion of the European continental domain and consequently a very convenient reference for studying the kinematic of the Central Mediterranean area.

VLBI is the fundamental technique for defining and realizing the ICRF, contributes at the realization of the ITRF, in particular of its scale, is able to estimate the EOP, and contribute to different research studies, together with the other geodetic techniques (crustal deformations, water vapor content in the atmosphere, sea level variation, ionospheric total electron content, etc.).

For regional and global issues, the contribution of SRT to geodesy should be preferred. At national level, the geodetic VLBI antennas may integrate the Italian GNSS network and constitute the fundamental nodes, thanks to the co-located instruments. The Italian VLBI network is able to support any application of the fundamental GNSS network, giving its external control and the framing of the GNSS network into ITRF. A contribution to the National Geodetic Reference Datum should be achievable. To this end, the presence of SRT could strengthen the Italian VLBI network.

Other comments
This proposal could meet a second one I will submit soon, related to BRAND-EVN receiver.

Receiver for SRT at 10 GHz

proposed by Tiziana Venturi, IRA
freq: 10 GHz
bandwidth: 4000 MHz
Single frequency, Mono feed

Technical details

The proposed receiver would fill the frequency range 8-12 GHz at the SRT. The idea is to equip the three Italian antennas with broad band receivers in the X-band region, for participation in SKA-VLBI observations in SKA Band 5 (5-15 GHz). Medicina is already equipped with a X-band received with a reasonably broad band, and as far as I understand, an upgrade of the X-band receiver in Noto is feasible and does not require a new receiver.

International networks and projects

The main motivation for this proposal is the suitability of the three Italian antennas for SKA-VLBI observations in Bands 5A (5-8 GHz) and 5b (8-15 GHz). It is important to point out that due to their favorable location, the three Italian antennas are those primarily involved in such a project.

Short science case(s)

The scientific cases are many, as we are talking of a participation in a super sensitive VLBI array. The science case would range from planetary science to transients, from near starburst galaxies to primordial SMBHs. The approval of Band 5 has renewed the interest in the possibility that the SKA (or a subset of it) may be phased up to provide an extremely sensitive "station" in a VLBI array, to complement the range of possible science. It is also worth pointing out that the VLBI capabilities in the Southern Hemisphere are poor compared to the Northern Hemisphere, and the Southern sky is still largely unknown. Being in the privileged position to take part in such array is an opportunity which should not be ignored.

Other comments

None

Broadband receiver for Medicina, Noto and SRT

proposed by Monia Negusini, IRA
frequency range: 1500 to 15000 MHz
Broadband receiver, Mono feed

Technical details

A VGOS-like wideband receiver is under development in the framework of RadioNet Project (Brand-EVN) to be installed at all the EVN antennas and it should be the link in between geodetic and astronomical observations.

International networks and projects

The proposed receivers are of interest for the VLBI community that operates in a collaboration within the International VLBI Service for Geodesy and Astrometry and the Associations linked to it: IAG, IERS and IAU. The Italian radio telescopes could be equipped with this new receiver that could link EVN and IVS networks.

Short science case(s)

The Sardinia Radio Telescope is the fourth Italian radio telescope, together with the Medicina, Noto and Matera. It is already taking part at the astronomical European VLBI Network observations and in the future, if the geodetic receivers should be installed, it might give its contribution to geodesy, being situated in a stable portion of the European continental domain and consequently a very convenient reference for studying the kinematic of the Central Mediterranean area.

VLBI is the fundamental technique for defining and realizing the ICRF, contributes at the realization of the ITRF, in particular of its scale, is able to estimate the EOP, and contribute to different research studies, together with the other geodetic techniques (crustal deformations, water vapor content in the atmosphere, sea level variation, ionospheric total electron content, etc.).

For regional and global issues, the contribution of SRT to geodesy should be preferred. At national level, the geodetic VLBI antennas may integrate the Italian GNSS network and constitute the fundamental nodes, thanks to the co-located instruments: The Italian VLBI network is able to support any application of the fundamental GNSS network, giving its external control and the framing of the GNSS network into ITRF. A contribution to the National Geodetic Reference Datum should be achievable. To this end, the presence of SRT could strengthen the Italian network.

Other comments

The S/X receiver, that I have already proposed, could allow SRT to be included in the present global geodetic network, coordinated by IVS, and to work together with the other 3 Italian antennas.

It is well-known that the future network will be constituted by small, fast-moving, continuously observing antennas (VGOS), but the legacy antennas will serve even more other years.

However, a VGOS-like wideband receiver is under development in the framework of RadioNet Project (Brand-EVN) to be installed at all the EVN antennas and it should be the link in between geodetic and astronomical observations.

It should be critical providing the receiver to SRT, first, but in the future also Medicina and Noto should benefit of this new opportunity.

10.2 High frequency bands

Receiver for SRT at 8.4 GHz

proposed by Paolo Tortora, University of Bologna
freq: 8400/32000 MHz
bandwidth: 2MHz
Dual Frequency

Comments on the technical details

A dual/frequency receiver at X- and Ka-band would enable three-way tracking of Deep Space probes, using a Mark V receiver, appropriate frequency prediction and steering and data preprocessing and formatting tools. Data would then be processed using a precision Orbit Determination S/W tool (like NASA/JPL ODP/MONTE codes).

International networks and projects

Deep Space Tracking for radio science experiments is a technique used since the 70' for most missions flown by NASA and ESA in the solar system. Current interest for using SRT as a receiving antenna is related to the NASA-Juno mission, ESA-BepiColombo and ESA-JUICE, with a wide network of international scientists.

Short science case(s)

Radio science is a discipline where radio links between spacecraft and Earth or between spacecraft are used to examine changes in the phase/frequency, amplitude, line-width, and polarization, as well as round-trip light time of radio signals to investigate neutral atmospheres and ionospheres, rings and tori, surfaces, shapes, gravitational fields, orbital motion and dynamics of solar system planets, satellites, asteroids, and comets.

In addition to planetary exploration objectives, the tools and techniques of Radio Science on deep space missions are applied to investigations of the solar wind, corona and magnetic field, as well as tests of fundamental physics including the theory of General Relativity.

Current RS investigations include radio occultations by planetary rings, ionospheres, and neutral atmospheres, propagation through the solar corona, reflection from surfaces, and distance/velocity measurements leading to determinations of mass and density distribution and construction of models for gravity fields and interior structure. The investigations can be grouped into two classes: propagation and gravitation. The first investigates the effects of media on the signals and treats the effects of spacecraft motion as noise to be calibrated out of the data, while the second investigates the effects of forces on the spacecraft causing shifts in the signal and treats the effects of media as noise to be calibrated out of the data.

Acquisition of radio science data is a service provided by networks of ground-based tracking stations (e.g. NASA’s DSN and ESA’s ESTRACK) used to support all space missions by providing communications, and tracking and RS services. Deep Space ground stations support communications in various modes. In the two-way coherent mode, the station transmits an uplink signal to the spacecraft that is then coherently transmitted back as downlink to the same station. If the receiving station is different from the transmitting one, the mode is called three-way. In the one-way non-coherent mode, the station receives a downlink referenced to an oscillator on-board the spacecraft, such as an auxiliary oscillator in the transponder or a stand-alone Ultra-Stable Oscillator (USO). Two-way (or three-way) coherent mode, which can also be implemented between spacecraft, is used for gravitation investigations, while one-way signals are the observables for propagation science.

The characterization of gravity fields, atmospheres/ionospheres and surfaces are the three most interesting investigations to improve the knowledge of a planetary object in space.

Other comments

None

Super-Resolution receiver Platform for Medicina and SRT

proposed by Luca Olmi, OAA

freq. K-band

Technical details

Super-resolution, i.e. an angular resolution beyond the classical diffraction limit, on a telescope could be achieved with variable transmittance filters, also known as “Toraldo Pupils”. At OAA we have started a project devoted to a more exhaustive analysis of TPs and how they could be implemented on a radio tele- scope. We have carried out full-wave electromagnetic numerical simulations [3], extensive microwave laboratory measurements [4] and also designed a preliminary “Toraldo Pupils” system for the K-band receiver of the Medicina antenna [5].

International networks and projects
Our current working group includes IFAC-CNR, University of Salerno and also Cardiff University. We also have other potential interested collaborators at the Photonics Center of the Universidad Metropolitana and Arecibo Observatory in Puerto Rico (USA).

Short science case(s)
The SRP would be appropriate to improve the angular resolution of the telescope/receiver system on compact (not pointlike) or extended bright sources. In fact, initially the SRP is expected to have a reasonable gain resolution (~1.5) but low-efficiency, which will be able to be improved with the use of meta-materials. Likely high sidelobes will be removed using deconvolution techniques.

Other comments
Although the SRP is not a real receiver we think it is important to discuss its potential applications with the Italian radio astronomical community, particularly with the radio receivers designers. The SRP has currently no counterpart on any other telescope (radio or otherwise) and represents a novel application which needs support. We are still in the development phase, but collaboration with all interested parties would be important for future applications on the Italian antennas. The project is also expected to lead to the development of devices using meta-materials.

Receiver for Noto at 43 GHz

proposed by Francesco Schilliro', OACt
freq: 43 GHz
freq. Range: 38-48 GHz
Single frequency, Dual-feed

Technical details
Dual feed cryogenic receiver with 2-4 GHz of baseband with digital back-end.

International networks and projects
None

Short science case(s)
Radio Recombination lines - Spectral lines (SiO2 for ex) - Continuum

Other comments
None

Receivers for Medicina, Noto and SRT at high frequencies

proposed by Marcello Giroletti and many others
freq.: Simultaneous 22, 43, 90 GHz
freq. Range: 18-26 + 33-50 + 80-110 GHz
multi-frequency, Mono feed

Technical details
Wide-band, multi-wavelengths receivers are recognized as essential elements for a leap forward in the 20-100 GHz domain. As demonstrated in [6] it is possible to transfer calibration data from 22

GHz up to 130 GHz, greatly extending coherence time at high frequency, even in modest weather conditions. The 5:1 frequency ratio is overall modest, compare to the 10:1 ratio that will be achieved in the 1.5-15 GHz band in the RadioNet BRAND project. The 20-100 GHZ and the BRAND receivers will make it possible to cover quasi continuously the 1.5 to 100 GHz frequency range. The solution should be installed at the three Italian stations, which would permit INAF to achieve international leadership in mm-VLBI. Noto and SRT are relatively ready for the operations, while a full exploitation at the highest bands in Medicina requires an active surface. A single-feed multi-lambda receiver would then be relatively easy to install also outside Italy.

International networks and projects

The international community is rushing to improve the accessibility of high frequency and large band observations: new national networks have been built and operate up to 7mm (VERA, in Japan) and 2mm (KVN, in Korea). The VLBA has enforced an agreement with the LMT in Mexico to include it in its 3mm sessions, and even ALMA will participate in VLBI experiments at 3, 2, and 1 mm, with the GMVA and the event horizon telescope (EHT). INAF will be a main GMVA partner with three stations at all frequencies (Noto already participated to 7mm test observations). The SRT will be part of the High Sensitive Array coordinated by NRAO. A strong collaboration is already present with the KVN and VERA arrays (KAVA) and the future eastern array including China and Australia. Collaboration with the African VLBI Network (AVN) is already a possibility in the 1.5-15 GHz; the 20-100 GHz receiver could become a standard solution easy to export to other stations.

Short science case(s)

The high frequency range, and in particular through VLBI observations, is fundamental as it allows simultaneously high angular resolution and the possibility to work above the synchrotron self-absorption frequency even in the most compact regions. This is of great importance primarily in the study of transient sources and of the jet base in active galactic nuclei. In a complementary area, K, Q, and W bands host molecular transitions of great importance in the study of star formation in our Galaxy and gas dynamics in extragalactic sources (H2O, SiO, CO). The capability to observe simultaneously from 20 (or even 1.5) to 100 GHz will allow a strong (unique) presence of the Italian astrophysics at international level in several fields:

1) programs in strong collaboration with (Very) High Energy studies (AGILE, Fermi, MAGIC, CTA) as single-dish survey and monitors as well as pilot VLBI observations of peculiar and variable objects. These observations are necessary for a proper study of SMBHs at the center of galaxies and on the origin of high energy emission and cosmic rays. A combination of single-dish and interferometric observations will disentangle the contribution from very compact and more diffuse regions e.g. star-burst or AGN.
2) studies of SgrA* and of extragalactic low luminosity AGN, in which the emission mechanisms are still poorly constrained. VLBI observations in the 20-100 GHz frequency range are fundamental to discriminate at the parsec scales between emission from the jet (synchrotron) and the advection-dominated accretion flows (ADAFs, thermal), which cannot be achieved at lower resolution due to contamination by circum-nuclear emission
3) study of galactic and extragalactic transients, which are initially optically thick. This is for example the case of gamma-ray bursts and tidal disruption events, in which models predict a much higher peak at 20-100 GHz frequencies rather than in the GHz domain
4) many other scientific topics as e.g.: a) Faraday Rotation studies to increase our knowledge of magnetic fields in nuclear regions; b) Opacity and core-shifts; c)The nature of the VLBI core; d)

gamma-ray flares; e) maser emission in evolved stars. Some of these projects might be carried out as a national VLBI facility or in single-dish mode, while other will require global facilities where INAF would play a prominent role.

Other comments

Given the aim of this request (to provide input) we have preferred to send a single suggestion which includes many but not all interested people. This request have been submitted by: M.Giroletti, M. Orienti, L. Feretti, G. Giovannini, T. Venturi, F. D'Ammando, R. Lico. We know that other people at IRA, Bologna University, Arcetri, Cagliari, Torino, Trieste, Milano, Roma and Perugia are interested. Because of the strong interaction with the high energy community (e.g. Fermi, CTA) a large part of the Italian community is interested to this development. A large international collaboration is already active involving EVN NRAO KASI NAOJ AVN and more.

Receiver for SRT at 90 GHz

proposed by Paolo de Bernardis, Università di Roma
freq: 90 GHz
bandwidth: 20 GHz
Dual Frequency, Multi feed

Technical details

We propose the development of a W-band, dual color (80-90 GHz and 90-100 GHz) camera for the SRT. The camera will host a cold reimaging optics and an array of about 400 independent pixels, Nyquist sampling simultaneously a field of view of 2’ x 2’. Each pixel will consist of a kinetic inductance detector, derived from our D-band KIDs [7, 8]. The array must be cooled by a dry cryogenic system (pulse-tube + 3He fridge). The beams of different pixels are separated by a few tens of arcsec and, starting from the primary mirror of SRT, share basically the same arimass, up to tens of km. For this reason, common-mode rejection algorithms across the array can remove most of the atmospheric noise, and we expect a noise per diffraction limited beam around 0.2 fW/sqrt(Hz), i.e. below 100 microJy in 1 hour of integration (5 sigma).

International networks and projects

This activity naturally complements similar activities carried out at the IRAM 30m (NIKA, NIKA2 projects) and at the Green Bank radio Telescope (MUSTANG). Sinergies with the groups working at those projects can be found and common proposals can be setup.

Short science case(s)

Several Galactic sources have been widely observed from mid-infrared through centimeter wavelengths; however, there is a general gap in the observations of an order of magnitude in wavelength in the millimeter spectrum. The W-band is widely unexplored with regard to continuum observations with high angular resolution. The natural targets for this instrument at the SRT will be:

1) Measurements of dust emission in collapsing interstellar clouds and protostars: Continuum mm high resolution (~10'') maps of star forming regions, when paired to higher frequencies maps, allow to determine the spectral index of dust emission, considered an excellent tracer of mass within star-forming regions, and thus to disentangle among theoretical models describing the hydrodynamic collapse of proto-stellar envelopes, and the flow of material from the dense

molecular clouds core through the disk.

2) Measurements of free-free and dust emission in Galaxies to study the star formation rate at high redshift: Continuum mm emission from star-forming galaxies is expected to be dominated by free-free emission. High resolution observations, combined with lower frequency (eg. 1.4 GHz) interferometric data, provide useful insights into the star formation rate allowing to efficiently disentangle thermal and non-thermal emission. In general, in order to weight the relative importance of dust emission, free-free emission and synchrotron emission, continuum high angular resolution observations at mm wavelengths are of fundamental importance.
3) Measurements of the Sunyaev-Zeldovich in nearby galaxy clusters, to study the internal structure of the clusters all the way to the periphery of the cluster: Galaxy clusters can be used as powerful probes of cosmology, provided systematic errors are under control. In addition to exquisite instrumentation, cluster cosmology requires understanding intracluster medium astrophysics. This requires high resolution observations, complementing those of X-ray telescopes, which are sensitive to the bremsstrahlung emission from the highest density regions. The Sunyaev¨CZel'dovich (SZ) effect is a complementary probe of the ICM, with an amplitude proportional to the line-of-sight integral of the ICM pressure. This means that sensitive SZ measurements can access tenuous gas outside the cluster core and directly measure pressure variations, due to e.g. shocked gas from mergers, or bubbles, or cooling flows.
4) Measurements of the Sunyaev-Zeldovich effect in distant galaxy clusters: The amplitude of the SZ does not depend on the distance of the cluster. This means that with sufficient angular resolution early clusters can be observed, providing an additional tool to test the paradigm of structure formation on the Universe. Moreover, the combination of SZ measurements and X-ray measurements on distance clusters provides an independent Hubble diagram and the determination of the Hubble constant.

Other comments

This instrument requires a large (diameter around 1 m, height around 1.5m) heavy (around 500 kg) cryostat in the receiver cabin.

Receiver for SRT at 100 GHz

proposed by Viviana Casasola & Simone Bianchi, OAA
freq: 100 GHz
bandwidth: 30 GHz, Single frequency, Multi feed

Technical details

The proposed scientific case has the technical aim to support the development of the receiver for SRT at 100 GHz. This would represent a new, important opportunity for the Italian millimeter community that is growing even thanks to the activity of the ALMA Regional Center at the INAF-IRA.

International networks and projects

The proposed observations at 100 GHz are located in the context of the European FP7 project DustPedia. It is a collaboration of six European Institutes (INAF-OAA is one of these), with the primary goal of exploiting existing data coming from Herschel and Planck satellites. These data at far infrared wavelengths are providing us the unprecedented opportunity to study the dust in local galaxies. They are and will be combined with available data from other telescopes to make the most extensive and intensive study of galaxies in the nearby Universe. The receiver for SRT at 100 GHz would play the role of leader with detections of emission lines of the molecular gas, another important component -in addition to the dust- of the interstellar medium in galaxies.

Short science case(s)
We propose to map in ^{12}CO(1-0) emission line at 115 GHz (rest frame) a sample of local galaxies (within ~40 Mpc) extracted from the DustPedia sample, without available CO maps, to compare molecular gas mass profiles with dust mass profiles given by Herschel observations and atomic/HI gas mass profiles obtained with different telescopes (e.g., VLA) aiming at solving for CO-to-H_2 conversion factor for single galaxies. This approach, already successfully performed for some DustPedia galaxies, will allow us to better constraint the poorly-known CO-to-H_2 conversion factor, that is the major uncertainty in the derivation of the molecular gas content in a galaxy. It will also serve to define the gas/dust scaling relations that will serve as local benchmarks in future SKA studies. Data on dust (Herschel) and atomic (SKA) and molecular gas (SRT) will provide us with an opportunity to study the interstellar medium in galaxies to answer fundamental questions about physical processes in the interstellar medium, its effect on stellar radiation, and the relation of its components with the star formation.

Other comments
Because of different reasons (e.g., international agreements) Italian astronomers are disadvantaged in Calls of Proposals at the available single-dish antennas (e.g., IRAM-30m). SRT operating at 100 GHz would therefore offer an unique opportunity for the present and future Italian millimeter community, taking into account the long life of ALMA and our need to be always more competitive.

Receiver for SRT at 100 GHz

proposed by Fabrizio Massi, OAA
freq: 100 GHz
bandwidth: >8000 MHz
Single frequency Multi feed

Technical details
According to the most recent radiometric measurements at the SRT site, we expect at least 1000 hours to be achievable with opacity < 0.2 at 100 GHz in the January-April period. We estimated that this makes T*_ant ~ 0.1 K (at a 0.2 km/s resolution) in 1 min quite feasible at 110 GHz [13CO(1-0) and C18O(1-0)] in this time slot. The basic goal should be mapping 1 square arcmin in 1 min with T*_ant ~ 0.1 K, meaning that an array of at least 6x6 or 5x5 elements is needed. Considering that the antenna efficiency of the beams is expected to degrade outwards, one can envisage 19-30 elements. Based on the band 2/3 i-ALMA receiver currently under development, this would provide a 67-116 GHz coverage and lower design (and possibly construction) cost. Given the high opacity at 67 GHz, a slightly narrower band (70-116 or even 72-116 GHz) could help to reduce cost. The instantaneous bandwidth should be at least state-of-the-art, i.e. 8 GHz, and double polarization should be provided.

A wide-band back-end (> 30-35 GHz) would allow using the central pixel for searching High-Z CO during the lowest opacity time slots. Fast switching (target-reference signal) techniques (like frequency switching) should be implemented in OTF mode, as well.

International networks and projects

The HiGal consortium is led by INAF-IAPS and has already obtained complete maps of dust emission with Herschel over the whole Galactic plane at several infrared wavelengths with 5-36 arcsec spatial resolution.

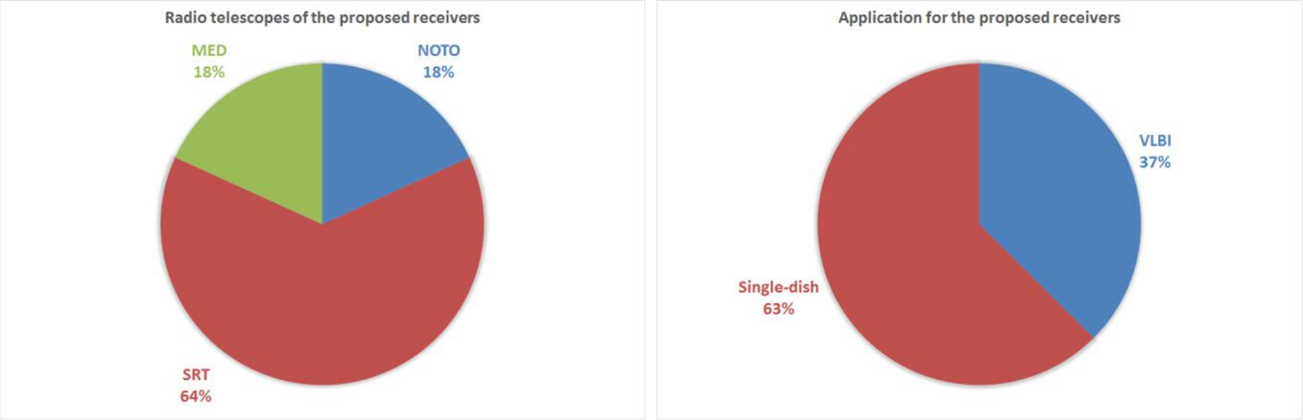
The Italian astronomical community involved in the search for Complex Organic Molecules, or COMs (the subject of progetto premiale iALMA); IRAM/NOEMA interferometric programmes could also exploit 3 mm receivers at SRT to obtain the so-called zero (and short) spacing data for lower frequency projects.

Short science case(s)

1) Complementing the HiGal data-set by mapping C18O(1-0) and 13CO(1-0) in a fraction of the Galactic plane. Mapping large fractions of the Galactic plane in a number of molecular transitions with a spatial resolution of ~12 arcsec (which would be achieved by SRT at the proposed frequencies) would add much valuable information, particularly on the dynamics and physics of gas-dust filaments that have proven to be ubiquitous in the ISM. This has been recognised as a fundamental topic in the final report following the MACROAREA 2 2016 meeting in Bologna and could drive a valuable large programme.
2) Studying dynamics and physics of the nearest gas filaments in the ISM by mapping various molecular transitions of: CS, C34S, N2H+, CH3OH, HCO+, HCN, and HNC.
3) Studying dynamics and physics of local filaments in the Gould belt.
4) Large scale surveys searching for complex organic molecules. Complex Organic Molecules in the ISM is indeed a major topic; an array operating in the range 70-116 GHz would allow searching large areas of the Galaxy for COM-emitting regions, which is unfeasible to an interferometer.
5) Large scale chemistry in molecular clouds (e.g., observations in HC3N and HC5N transitions).
6) Relatively intense (> 1-10 Jy) methanol maser emissions are observed at 85.6, 86.6, 86.9, 107.0 and 108.9 GHz, in regions of massive star formation. SRT with a 3mm array receiver would allow surveying these, still pretty unexplored, maser emissions.
7) Maps of intensity ratios of these lines, interpreted with the aid of maser excitation models, would provide information on the density and temperature of the masing gas.

Other comments

This "proposal" is based on discussions with and is supported by: S. Casu, S. Leurini, A. Melis, A. Navarrini (OA Cagliari); L. Moscadelli, R. Nesti, L. Olmi (OA-Arcetri); D. Elia, S. Molinari, E. Schisano (INAF-IAPS Roma); A. Giannetti, J. Brand (INAF-IRA Bologna).



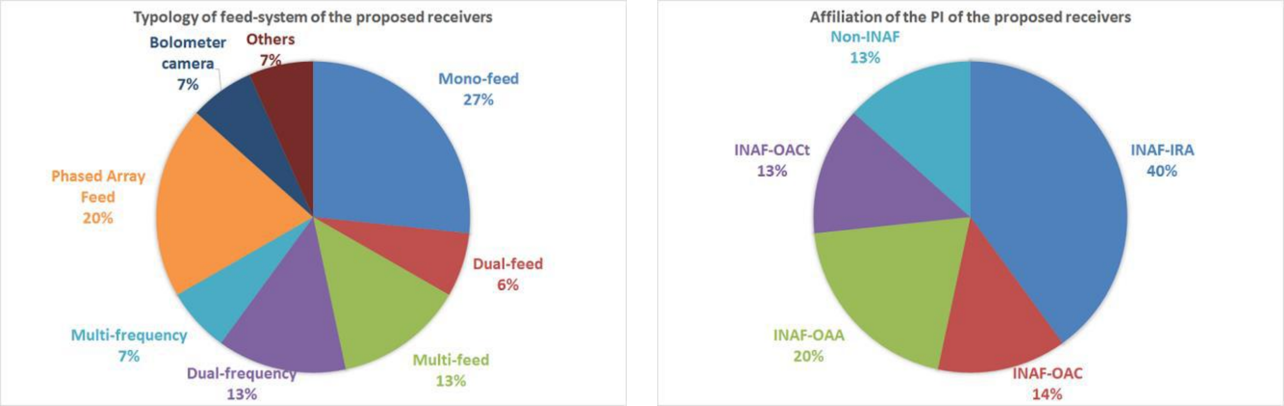
(a) (b)

Figure 10.1 – Telescope and observing mode for the proposed receivers: (a) percentage of proposed receivers for the various radio telescopes, (b) percentage of observing modes (single-dish or VLBI) mostly associated with the scientific goals of the proposed receivers

10.3 Comments and considerations on the ideas for future receivers

In this Section, we perform some basic analysis on the output of the Call for Ideas for future receivers. In Fig. 10.1 and 10.2 we summarize some characteristics of the proposed front-ends, the telescopes and observing modes for which they have been conceived and the affiliation of the proposers. In particular in Fig. 10.1a, it is evident that many ideas were addressed to the SRT, whereas MED and NOTO have been required in four proposals each. Among the scientific projects associated to the proposed receivers, a slightly higher number is requiring single-dish observing modes rather than VLBI, as can be seen in Fig. 10.1b. A quite uniform distribution of receiver typology is evident in Fig. 10.2a, with the standard mono-feed and advanced PAF front-ends being the more required ones with four and three proposals, respectively. Multi-feed and dual-frequency follow with two proposals each. In Fig. 10.2b the distribution of the affiliations of the proposers clearly shows that a significant contribution to the Call for Ideas has been given by researchers from IRA. Remarkably, in a number of cases it is clearly stated that the proposed receiver is the expression of a large community, sometimes involving many INAF and non-INAF institutions. It should also be noted that two projects have non-INAF proposers, namely from the University of Rome “La Sapienza” and the University of Bologna. These results on one hand point out that the interest in Italian radio astronomical instrumentation is widespread across the many national research institutions, an on the other hand further stress the high degree of interaction and synergies already present in the Italian (radio)astronomical community.

Fig. 10.3 shows the distribution of the required frequency bands after having grouped the fourteen proposals (the proposal by L. Olmi is not considered in Fig. 10.3 and 10.4 being an optical system) by similar projects or typologies, namely the C-band PAF (E. Carretti, F. Schillirò and P. Serra), the W-band multi-feeds (V. Casasola, F. Massi) and the two dual-frequency (M. Negusini, P. Tortora). Three projects, M. Negusini (BRAND), M. Negusini + P. Tortora and M. Giroletti (sim. freq.), occupy several frequency bands since they are wide-band or multi-frequency receivers.



(a) (b)

Figure 10.2 – Characteristics of the proposed receivers: (a) percentage of feed systems typology requested in the Call for Ideas, (b) affiliation of the proposer

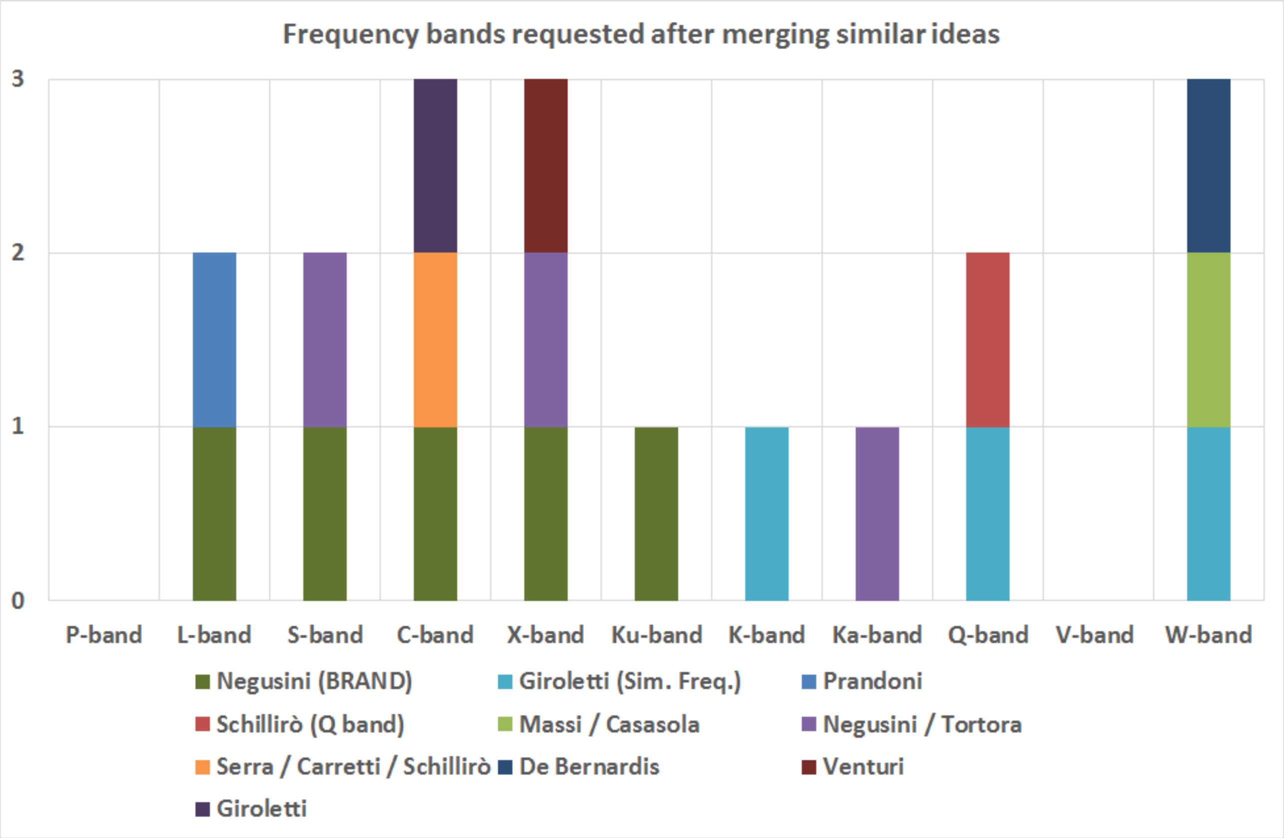


Figure 10.3 – Distribution of the frequency bands requested for the proposed receivers

Finally, the frequency coverage of the fourteen proposals is given in Fig. 10.4 divided by typology of receiver. We notice that all the proposed ideas are at frequencies above 1 GHz and the distribution is quite uniform over the frequency range, with peaks at C, X and W bands. Looking at Fig. 10.4 and starting from the bottom, we can notice that the four proposed mono-feed front-ends are at frequencies below 18 GHz, whereas the two dual-frequency projects are in the standard bands for geodesy and space science. The proposal for a dual-feed receiver cover the Q band, while a bolometer camera is for the W band. All the proposed PAFs are intended for the C band and both the multi-feed receivers are for the W band. Finally, the multi-frequency receiver for simultaneous observation covers the K, Q and W bands.

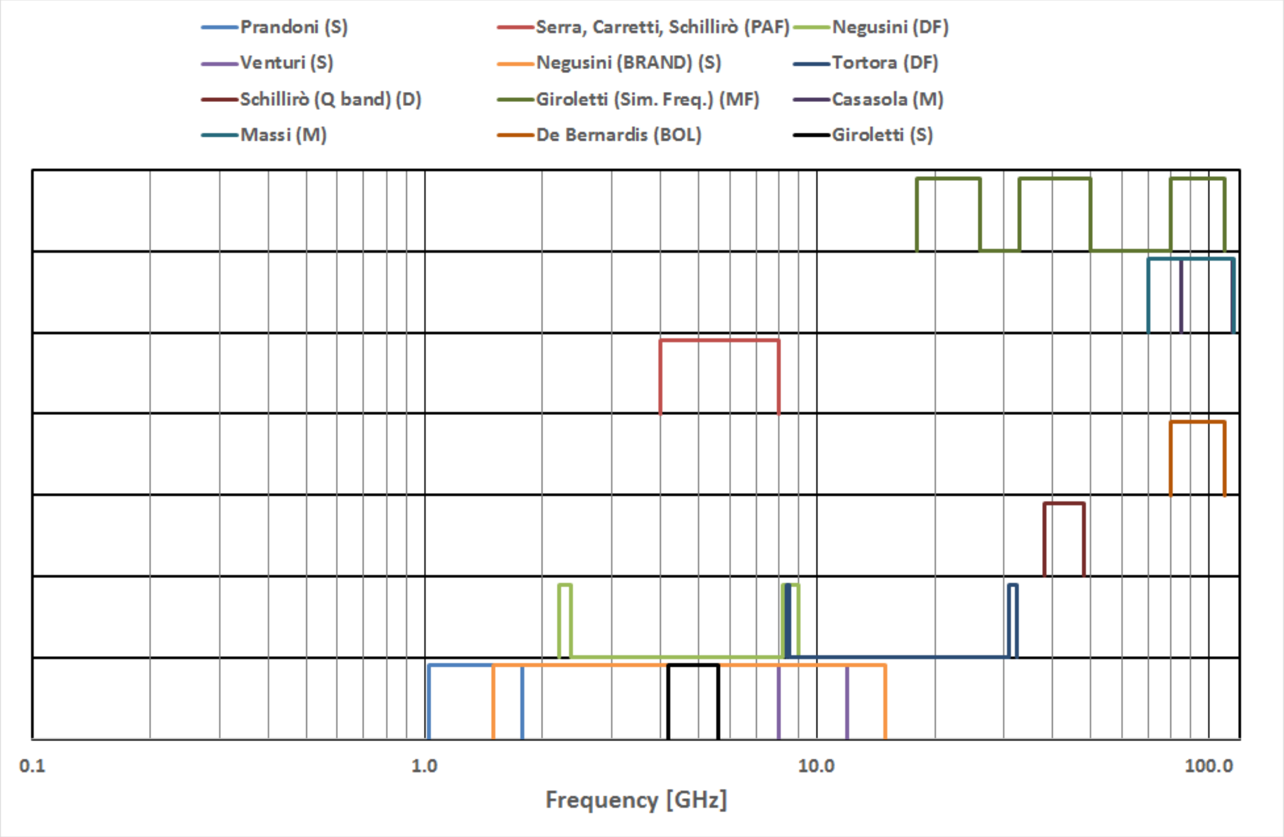


Figure 10.4 – Frequency coverage of the proposed receivers. Each line includes receivers with equal concept, from the bottom to the top: mono-feed (S), dual-frequency (DF), dual-feed (D), bolometer (BOL), phased array feed (PAF), multi-feed (M) and multi-frequency (MF)

In conclusion, the interest of the radioastronomical community is focused on two main development areas: high-frequency and PAF receivers.

Among the proposed ideas, some refer to or can be associated with existing receivers, being under development or still in a design phase. The C-band receiver proposed for the SRT by M. Giroletti belongs to the first category, while the wide-band receiver proposed by M. Negusini is basically the BRAND project, that will be completed in the next few years and could probably be purchased. The idea for an X-band receiver from T. Venturi can be fulfilled by the BRAND project as well.

As anticipated in some of the figures at the beginning of this Section, among the fifteen answers to the Call for Ideas there are some projects that can be merged in a single proposal. For instance, the ideas presented by V. Casasola and F. Massi can be merged into one receiver working in the 70-116 GHz, overlapping the frequency range of band 2+3 system for ALMA, but with a multi-feed solution. Also the three C-band PAF proposals by E. Carretti, F. Schillirò and P. Serra can be considered as a unique project. A challenging project would be to merge the proposal by F. Schillirò for a Q-band dual-feed receiver and the M. Giroletti idea for a simultaneous frequency front-end working in the K, Q and W bands, to make a dual-feed receiver in the 18-100 GHz domain serving both purposes.

The ideas for dual-frequency receivers by M. Negusini and P. Tortora could be grouped to build one triple-frequency coaxial feed for observations in the S, X and Ka bands. A similar receiver has been built for the Yebes radio telescope in order to perform observations within the VGOS project [9].

In a minority of cases, the proposed receivers could be purchased or built by non-INAF staff. It is the case, for instance, for the L-band front-end proposed by I. Prandoni for the SRT. This receiver has a larger bandwidth with respect to the one currently in use and it is devised for combined VLBI observations in particular with MeerKat. These can also be accomplished with the current P/L-band receiver at the SRT even if with a smaller bandwidth. It could be verified if such MeerKat-like receiver could be purchased for the SRT. However, it must be noted that, since the currently available SRT L-band receiver coexist with the P-band one and both share some mechanical parts, its replacement with a new one would not be an easy task.

The proposal by P. de Bernardis is quite different from the others, being relative to a bolometer device. This is in principle an interesting idea that could possibly be developed by the group at the University of Rome “La Sapienza”. However, some concerns on the feasibility of such a receiver installed on the SRT arise, mainly related to size and weight considerations.

Finally, the proposal by L. Olmi is a peculiar one since it is not a classical microwave receiver. However it represents an interesting project deserving further attention. It is developed within a collaboration among national and international research Institutes and has some innovative aspects related to diffraction-limited optics and the use of meta-materials.

Part IV - Conclusions

11. Recommendations

After significant financial and human efforts, which took more than two decades, an Italian network of radio telescopes is almost finalized. Within the year 2019 it is expected that the SRT will reach full operation after the refurbishment of the active surface system, currently underway. In the meantime, the NOTO antenna must complete the restructuring of the observatory operations and management. The MED telescope is demonstrated to be a reliable facility even during the prolonged and demanding engagement of the Medicina staff in the construction of SRT and now calls for further exploitation of its instrumental capabilities and staff expertise.

The equipment of the 32-m Italian radio telescopes allowed past and present participation in international VLBI networks as well as single-dish observations for various science projects. The Early Science Program recently completed at the SRT is delivering very promising results for the full exploitation of its scientific capabilities.

The overall performance and services offered by the Italian radio telescopes are comparable to antennas of similar dimension in the international context. The scientific production of MED and NOTO in terms of refereed publications in the last five years is relevant. Extending the participation of the Italian telescopes both in existing and in new international networks could further increase this production and is therefore highly recommended. A natural step in this direction is the finalization of a national VLBI network, following the path already traced by a number of successful experiments (also involving a subset of foreign EVN antennas) and the considerable effort already invested in the Italian software correlator DifX. To this purpose, it is highly desirable to continue in the direction started with the development of a common telescope control software. This would allow a high level of automation of the observing sessions and consequently an optimization of human resources requirements. Such a goal can be pursued for instance by means of standardized procedures at any stage of the scientific usage of the telescopes, including proposal preparation, schedule creation, observation setup and shift organization, etc. Also, remote observing and/or unattended runs are technically possible with a minimum effort as well as distributed operations control. It is for instance possible to imagine a Virtual Control Centre common to the three telescopes and managed in turn by the staff at the involved Observatories to execute and supervise the observing runs at the three facilities simultaneously.

As an overall consideration, within this WG there is a general consensus that the main lines for future development, as evinced from the Call for Ideas, are related to the development of receivers at high frequencies (typologies: simultaneous frequency and multi-beams), and PAFs. There is also a consensus that almost all the receivers under construction should be completed within 2018, and that the development of future state-of-the-art front-ends should start from 2019.

In Sections 11.1, 11.2 and 11.3 the WG recommendations on future receiver implementation at each Italian radio telescope are described identifying two periods: 2017-2018, and 2019 and beyond. Some proposed projects to be further investigated and possible major upgrades on existing receivers are illustrated respectively in Sections 11.4 and 11.5. Timeline and financial considerations are described in Section 11.6. Section 11.7 illustrates some suggestions for the organization, management and development of future radio astronomical instrumentation within INAF. Finally, in Section 11.8 some considerations on the use of SRT for space science and on the Northern Cross are presented.

11.1 Sardinia Rario Telescope

The suite of frequencies used in the astronomical VLBI networks (EVN, Global VLBI, Space VLBI/RadioAstron) should be completed with high priority at the SRT.

The SRT should be also equipped with high-frequency receivers for a number of reasons. Considerable interest in such front-ends emerged from the Call for Ideas also from non-INAF research groups. Also, almost all the international radio telescope facilities considered in this report are equipped with receivers for observations in the W-band domain. Moreover, significant financial effort is being made by INAF to restore the active surface of SRT to its best performance, opacity conditions at the SRT site are acceptable (see Section 2.3), and RFI is not expected to be a concern in the coming years at such frequencies. Finally, the original motivation for the construction of SRT was to make it possible to address science cases in the high frequency domain.

In the last twenty years, the receiver group participated in many radio astronomical research programs devoted to technological developments at high frequency, for which funds have been allocated and state-of-the-art equipment has been developed (e.g. the 7-beam K-band receiver and key prototypes in the 7-mm band). It is thus recommended to complete the Q-band multi-feed receiver even if some financial concerns arise. This receiver will allow an efficient use of SRT as a single-dish telescope and also the participation in VLBI experiments together with other international radio telescopes working at this frequency.

Similar considerations stand in favor of the availability of receivers in the W-band. In the last years considerable effort was devoted by the OAC technological staff to the refurbishment and finalization of the ex-IRAM W-band receiver. Its adaptation for the SRT is now challenged by the opportunity to equip the telescope with the ALMA Band 2+3 mono-feed receiver prototype, whose time schedule is compatible with the planned SRT maintenance period. The ALMA receiver is alternative to the ex-IRAM one, but has a remarkably higher interest from a scientific point of view and allows for more advanced technical performance.

It must be stressed that from the Call for Ideas a considerable interest of the scientific community for multi-feed and very wide band receivers at high frequencies emerged: a technological challenge to be addressed in the near future. The INAF community expressing interest for such receivers is already involved in international collaborations like the HiGal Consortium and the DustPedia FP7 project. Synergies with observations at other wavelengths (like the ones from the Herschel and Planck satellites*)* can be seen as an added value to the proposed studies. It must be also emphasized that at such frequencies a lot of work has to be done in the field of antenna metrology and active surface modeling in order to get accurate and reliable pointing and good sensitivity.

At lower frequencies, we identify two main achievements for the SRT: the 7-beam multi-feed S-band receiver under development, and a future C-band PAF receiver as suggested by the Call for Ideas. The development of a PAF receiver seems currently appropriate for SRT only, being the most sensitive among the Italian antennas and providing also a good compromise between angular resolution and sky coverage. PAF technological development is an ambitious and long-term project, mostly benefiting by its deployment on the more performing among the Italian antennas.

We point out that such developments at lower frequencies would make the SRT primary focus somewhat crowded: the simultaneous presence of the current dual frequency P/L-bands, the S-band multi-feed and the mentioned PAF system is not mechanically possible, thus the frequency agility facility at primary focus would be compromised. The possibility to locate also a BRAND receiver will increase the problem. However, the timeline planned for the availability of a PAF receiver and the BRAND prototype is such that the scientific exploitation of the P/L and S-band prime focus receivers will be possible for a significant number of years.

Period 2017 – 2018

- **Clow-band receiver**. This front-end 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 (possibly extended to some EVN antennas) VLBI array. The science cases illustrated for this receiver include some of the hottest topics in today's radio astronomy (e.g. transient sources), also strengthened by tight links with multi-wavelength observations outside the radio domain. A proposal to support the development of such a receiver has been submitted in the Call for Ideas (see Chapter 10), further stressing the interest of the community in this front-end.
- **S-band receiver**. A multi-feed front-end at this frequency would be almost unique in the international scenario. Despite usage for VLBI applications not being foreseen, a number of high-level science topics can be addressed with single-dish observations at this frequency. The receiver is very close to final construction, it is fully funded and it is expected to be ready by the end of 2018.
- **Q-band receiver**. Currently under-development, it represents a good opportunity to start testing SRT metrology at relatively high frequency keeping at the same time a receiver with a high impact from a scientific point of view. It must be stressed that no other multi-feeds covering this band are available at foreign radio telescopes. We recommend to complete its construction by 2018 and to have it installed at the telescope in 2019 for technical commissioning after the SRT planned maintenance.

  Some financial issues exist for this front-end. Among the receivers under development, the Q-band is the only one for which the availability of funds may be a concern (see Fig. 6.13). The amount of money still needed for the completion of the current design is of the order of 600 K€, mainly related to the high number of feed chains to be built. The science cases described in Chapter 9 for the Q-band receiver do not clearly highlight the need for a 19-feed system. If budget allocation is a concern, the reduction of the number of feeds from 19 to 7 is a possibility still allowing the fulfillment of the main science goals. However, the realization of the original design would represent an opportunity to gain experience in view of the more challenging construction of a dense multi-feed receiver at 100 GHz recommended for the SRT. The expertise developed for the SRT Q-band receiver could be later exploited at Noto, but see also the considerations regarding the development of simultaneous-frequency receivers.
- **ALMA 2+3-band receiver**. In parallel to the developments described above it is advisable to start working on the modifications needed to install this receiver on the SRT in 2019. Indeed, several changes to the receiver are necessary, involving the cryogenic system, electrical interfaces, horn, mechanical support, etc. The IASF-Bologna group is interested in

taking responsibility of this task, thus there should be no additional workload on the receiver group at IRA/OAC/OAA.

Period 2019 and beyond

- **Phased Array Feed**. This project is of relevant interest both as a technological demonstrator and as a new receiver to perform cutting-edge science. Three proposals presented in the Call for Ideas ask for PAF front-ends, highlighting the strong interest of the Italian scientific community. The interest for a PAF receiver at the SRT matches with the involvement of INAF in the SKA AIP project. Within a few years, the efforts coordinated by A. Navarrini in the PHAROS2 project will allow INAF to gain sufficient expertise to start building a new generation PAF receiver. We thus support this project and, at the end of PHAROS2, we encourage the receiver group to be involved in the development of a new PAF in the C band with state-of-the-art performance to satisfy the scientific interests that emerged in the Call for Ideas.
- **Multi–feed receiver at high frequency.** Starting from 2019, the efforts of the receiver group should also concentrate on developing a receiver in W band with several pixels. It should be noted that some goals emerging from the Call for Ideas require relatively dense arrays, up to a number comparable or higher than the one foreseen in the current Q-band receiver design. The availability of a dense feed system at high frequency could put the SRT in a leading position for studies of our Galaxy and the overall galactic population by exploiting the telescope resolution and sensitivity as well as the mapping efficiency guaranteed by the multi-feed design. The experience in the ALMA Band 2+3 can be exploited also for this new receiver.

11.2 Medicina Radio Telescope

The Medicina 32-m telescope has proved to be a reliable instrument throughout its life. Past and ongoing maintenance is expected to guarantee the antenna reliability also for the coming years. MED is currently the best equipped Italian antenna in terms of frequency bands offered for VLBI observations. It has also been the first one equipped with the ESCS software system, which allowed the full exploitation of the telescope single-dish capabilities with hitherto unprecedented sensitivity in both continuum and spectroscopic observations (including polarization).

The completion of the Ku-band receiver under development is advisable particularly in view of the expansion of the EVN capabilities in this frequency range, as recently recommended by the EVN Board. Also, the participation of MED in joint observations with international facilities like the VLBA would represent a significant improvement in terms of UV coverage, resolution and also sensitivity. MED (and NOTO as well) can play out its strengths at frequencies above 10 GHz also as a single-dish telescope. Being an intermediate-size facility it offers a suited compromise between sufficiently large beam size to cover quickly large areas of sky and sensitivity. MED can thus be seen as a niche instrument offering the best conditions for large-area blind surveys and monitoring programs at moderate to high frequencies.

The development of simultaneous frequency receivers is another scientific and technological niche in which MED and the skills in receiver construction owned by the IRA staff could be best exploited in the coming years. Indeed, from the Call for Ideas the interest of a large part of the Italian astronomical community (both inside and outside INAF) for simultaneous frequency observations at all the three Italian radio telescopes emerged. Strong collaborations are already in place with the KVN and VERA arrays, and could be reinforced by adding MED (and possibly NOTO) to simultaneous high-frequency experiments. Besides, the availability of similar equipment at all the three Italian radio telescopes would also put INAF in a leading position in the international context of mm-VLBI. The multi-wavelength aspect related to the synergy with projects like FERMI and CTA are an added value to this project, allowing participation in these important international collaborations to be strengthened. A valuable aspect of the proposed K/Q/W-band receiver is its relevance for both VLBI and single-dish applications on some of the current hot topics for modern radio astronomy. In particular, this development would be a significant step forward in the exploitation of the Italian VLBI network.

A full use of MED in the Q and W bands would require an antenna refurbishment. As detailed in Appendix D, a solution exists for the upgrade of MED in order to make it work with reasonable efficiency up to 86 GHz also without the installation of an active surface system. Some considerations on the financial aspects related the MED refurbishment for high frequency observations are given in Section 11.6. Furthermore, an added value to pursuing the development of high frequency receivers for MED would be the increase of the knowledge in metrology techniques needed to compensate non-systematic sources of pointing errors.

Period 2017 – 2018

- **Ku-band receiver**. The completion of this receiver, together with the existing K-band one, will result in a continuous coverage of the radio band from 12 to 26 GHz at MED. This is of great interest for the already mentioned continuum studies and also for spectral line analysis. The relevance of this receiver in the International context is clear, and will also open the possibility of fruitful and continuative collaborations in long term monitoring programs like the VLBA MOJAVE. It is worth noting that this is one of the few receivers documenting a number of science cases at the moment of the design phase.

Period 2019 and beyond

- **Simultaneous frequency receiver for K/Q/W-band observations**. This front-end gives the opportunity to promote the interest in MED and represents a niche in which also the smaller Italian radio telescopes can give a substantial contribution. We believe that the reliability of the Medicina telescope operations in the last two decades guarantees the successful exploitation of such an ambitious project. This project should start immediately after the completion of the Ku-band receiver. However, since it requires a major upgrade of MED, we recommend that the feasibility study and design phase necessary for the refurbishment of the telescope mirrors will start in advance of the simultaneous frequency receiver development.

11.3 Noto Radio Telescope

The Noto antenna requires significant effort to regain its observing efficiency and solve operations issues. To this aim, works to be done on the technological side include: the completion of the frequency agility; the refurbishment of the mechanical and electronic parts of the actuators; the replacement of the electronic part of the subreflector motion system. To fully exploit the potential of the active surface at 86 GHz, a new subreflector with better surface accuracy is advisable.

It is also recommended to finish the upgrade of the telescope control software by completing the ESCS commissioning. This will in particular allow for a proper tracking of the subreflector (necessary above 22 GHz) so to perform better pointing and gain calibration campaigns, and enhance the sensitivity of single-dish observations.

It is recommended that NOTO restarts its observations in the L band, a traditional one for VLBI (e.g. EVN, RadioAstron). The importance of NOTO as an EVN station resides also in its geographical location. Together with the C and K bands, the L band is also a frequency range common to the three Italian antennas and is thus relevant for the Italian VLBI, within which it could be exploited for some scientific hot topics (e.g. transients and SETI). Furthermore, an improvement of the operability in the S/X band is of interest for IVS observations. The refurbishment of the L/S/X-band receiver is thus a recommendation of this WG.

After the optimization of the telescope performance at 43 GHz we recommend to proceed with the development of receivers in the 3 mm band, a frequency of great interest for the participation in the observations of the GMVA network. In the recent past, NOTO joined some 7 mm GMVA test experiments. In an initial phase, the ex-MPIfR W-band receiver is preferable to the ex-IRAM for easier installation and financial reasons (the involved cost for the ex-IRAM receiver adaptation is a factor of ten higher than that for the ex-MPIfR). However, since considerable effort has been invested on the ex-IRAM solution at OAC, the knowledge acquired in adapting this receiver for the SRT may be in a second phase transferred to NOTO to benefit from its better performance. The installation of the ex-MPIfR W-band receiver would permit to test the suitability of Noto (both telescope and site) at such frequency and it will also indicate if a new subreflector is useful/necessary.

Period 2017 – 2018

- **Status of the antenna**. NOTO needs to perform at its nominal technical capabilities with also full operability of the frequency agility, as well as to reach stable operational procedures.
- **L/S/X-band receiver**. The hardware evaluation of this front-end by the Medicina staff concludes that its completion could be done by means of a number of modifications/refurbishments with reasonable cost. We thus recommend to finalize this receiver whose scientific interest is high especially for VLBI and IVS observations.
- **W-band receiver.** With lower priority, such a receiver should be installed. Given the very limited cost of the adaptation of the ex-MPIfR receiver for the secondary focus, mainly consisting in a new feed horn, we would recommend to proceed with this solution. At a later stage, it could be worth to adapt the ex-IRAM W-band receiver at NOTO by means of the knowledge gained at OAC.

Period 2019 and beyond

- Even if the Call for Ideas expressed interest in simultaneous high frequency observations at NOTO, the criticalities at this telescope both in terms of observing efficiency and management make it difficult to foresee a realistic plan for future receiver developments.

11.4 Valuable projects for future evaluation

From the Call for Ideas two additional proposals emerged that are of high interest for the Italian radio telescopes. The management of these projects is in charge of non-INAF groups and their applicability on the Italian antennas is still not well defined. Also, some technical issues related to their deployment arise. However, their scientific value motivates us to recommend further interaction and discussion with the related teams.

- **BRAND**. This project foresees the involvement of INAF and it aims at building a new generation UWB receiver for VLBI, suited also for geodetic studies. The UWB solution seems to be the preferred one for the future of the 64-m Parkes telescope and also of other large radio telescopes. This challenging project pushes for advanced digital acquisition system especially to handle RFI issues. Having BRAND installed at the SRT could be a good opportunity in particular to perform geodetic studies since a classical S/X-band receiver is neither available nor planned. However, the critical issues pointed out in Chapter 8 (21 cm not available, high cross polarization) raise some concern to the possible scientific usage of the BRAND prototype. Also, the appeal of this receiver remains high if it will be able of satisfying the requirements of both single-dish and VLBI observations. Thus, the actual interest of BRAND in terms of a single receiver covering an extremely wide band and suited for all observing modes will depend on its final design and capabilities. Finally, we note that BRAND could be an interesting possibility also for the other two 32-m radio telescopes given their successful and long-standing participation in international VLBI and geodetic observations.

- **W-band bolometer**. This receiver has been proposed by the de Bernardis' group and it is a very challenging project promising to increase the scientific applications of the SRT and to widen the astronomical community interested in the use of the Italian radio astronomical facilities. With regard to a bolometer array operating in the W band, a similar project has been recently developed at GBT. However, due to the technical complexity of the camera, it should be developed under the responsibility of the proposing group. Its integration at the SRT, as proposed, seems challenging due to dimensional and mechanical constraints and would need a close interaction with the SRT staff during the design phase.

11.5 Major upgrades on operational receivers

The mandate of the WG included also a priority list of works to undertake on existing receivers that require major upgrades. The multi-feed K-band receiver at the SRT is the only one that has been classified as belonging to this category. This front-end would largely benefit from the replacement of its LNA and from the upgrade of the instantaneous bandwidth, as discussed in Section 6.4.

In respect of the LNAs, due to the different dimensions their substitution with commercial components would imply that some mechanical work is to be done on the receiver dewar. The upgrade of the instantaneous bandwidth would in principle be technologically easier, as it involves only the warm part of the receiver and some electronic board developments are already ongoing for the Q-band receiver.

Due to the remarkable scientific value of the K-band front-end, we recognize the importance of this improvement. The feasibility and timeline for this upgrade will strongly depend on the availability of human resources within the receiver group, given the very tight schedule foreseen for the completion of receivers under development.

11.6 Timeline and financial considerations

This Section addresses the timeline proposed for the development of new receivers as well as the completion of existing ones (see Tab. 11.I), according with the priorities detailed in the previous Sections. Then in Tab. 11.II a possible scheme for the workload in charge of the INAF involved Structures is defined. The objective of this analysis is to verify whether the science-driven recommendations proposed in the previous Sections are compatible with the human resources available at INAF.

Looking at Tab. 11.II we notice that in the years 2017 and 2018 a significant number of receivers have to be finalized both at IRA and OAC. However, we believe this plan is affordable given that the construction of receivers is in a quite advanced stage and the workload is efficiently distributed in the receiver group.

In the period 2017-2018, we see also the possibility to increase the involvement of the IASF group in developing receivers for the Italian radio telescopes. This collaboration would add skills and resources to the *classical* receiver group formed by OAC, IRA and OAA. We also encourage a similar approach with the de Bernardis’ group in order to explore possible synergies.

For the period 2019 and beyond, we recommend reconsideration of the development strategy concentrating the efforts in a smaller number of ambitious projects. We believe that the responsibility and implementation of each project should be located in a specific INAF Structure (see Section 11.7 for further discussion on this topic). Therefore, we recommend that the proposed new projects will be assigned to the two structures mainly dealing with receiver development according to the following scheme: OAC takes the responsibility of the multi-feed in W-band and the C-band PAF, while IRA takes the responsibility of the simultaneous frequency project. Assigning two large projects of receiver development at OAC is still reasonable in terms of human resources since experience in W-band have been already gathered during the activity done for the ex-IRAM and multi-feed skills have been acquired during the development of the S-band receiver. Moreover, the PAF front-end will require a strong contribution in the field of digital engineering thus the involved human resources will include also people other than those in the OAC receiver group, like for instance the SKA group in Medicina for what concerns various fields inherent to PAF development (e.g. fiber optics links).

In the period 2019 and beyond, it is also desirable that the groups at OAA and IASF continue the collaboration with OAC and/or IRA in the realization of these new-generation receivers.

Finally, in this Section we also provide a tentative budget estimate for receiver development in the next years taking into account what has been recommended in the previous Sections (Tab. 11.III). The given figures consider the cost of each specific project recommended either in the period 2017-2018 or in 2019 and beyond. For receivers under development, we give the residual cost still to be allocated for their completion.

Status	RT	Receiver	2017	2018	2019 and beyond
Receivers under development	SRT	S-band	OAC	OAC	
	SRT	Clow-band	IRA OAC OAA		
	SRT	Q-band	IRA OAC	IRA	
	SRT	ALMA 2+3 Band	IASF	IASF	
	MED	Ku-band	IRA OAA	IRA	
	NOTO	L/S/X-band	IRA		
	NOTO	W-band (ex-MPIfR)		IRA	
New receivers	SRT	Multi-feed W-band			OAC
	SRT	PAF C-band			OAC
	MED	Simultaneous frequency K/Q/W-bands			IRA

Table 11.I – Proposed scheme for receiver development in the next years

INAF structure	2017	2018	2019 and beyond
IRA	Q-band Clow-band Ku-band L/S/X-band	Q-band Ku-band W-band	Sim. freq. K/Q/W-bands
OAC	S-band Clow-band Q-band	S-band	Multi-feed W-band PAF C-band
OAA	Clow-band Ku-band		
IASF	ALMA 2+3 Band	ALMA 2+3 Band	

Table 11.II – Workload distribution for receiver development among the INAF structures. Considered periods are: 2017, 2018 as well as year 2019 and beyond. Colors indicate the radio telescopes for which the receiver is under development: SRT (black), MED (blue), NOTO (red)

With regard to receiver under development/evaluation and international projects, the cost for the development of the SRT Q-band receiver recalls what was indicated in Fig. 6.13, while the cost for the NOTO L/S/X-band one reports what was indicated in [1, Chapter 6]. The estimated budget for the implementation of the ALMA 2+3 Band prototype at the SRT includes the cryostat; the vacuum system; the cold head; the differential phase shifter; some components for the frequency down-conversion and the mechanics to install the receiver at the Gregorian focus. Since the Band 2+3 is specifically developed to satisfy ALMA interfaces, a dedicated implementation plan for the SRT should be envisaged and studied including needed resources and requested budget. The implementation cost for the ex-MPIfR W-band receiver at NOTO is negligible compared to the total budget.

Status	RT	Receiver	k€ (2017-2018)	k€ (2019 and beyond)
Receivers under development	SRT	S-band	Fully funded	
	SRT	Clow-band	Fully funded	
	SRT	Q-band	600 (19 feeds) 180 (7 feeds)	
	SRT	ALMA 2+3 Band	100	
	MED	Ku-band	Fully funded	
	NOTO	L/S/X-band	80	
	NOTO	W-band (ex-MPIfR)	Negligible	
New receivers	SRT	Multi-feed W-band		~ 1700
	SRT	PAF C-band		~ 2700
	MED	Simultaneous frequency K/Q/W-bands		~ 2400 (w AS) ~ 1600 (w/o AS)
TOTAL			**780 (19 feeds)** **360 (7 feeds)**	**~ 6800 (w AS)** **~ 6000 (w/o AS)**

Table 11.III – Budget estimate (k€) for the receivers proposed in the recommendations

The total amount for the finalization of the receivers under development/evaluation is around 780 k€, 3/4 of which related to the Q-band receiver (600 k€). Note that we are indicating here the cost for the completion of the Q-band front-end in its full configuration. In the case of a downgrade to a 7-feed configuration the needed budget to complete the Q-band would be of the order of 180 k€ (see also Section 6.3) and therefore the overall budget for the period 2017-2018 would become 360 k€.

The development scheme for the period 2019 and beyond concerns three projects, two of them to be undertaken for the SRT (a W-band multi-feed receiver with 19 elements, and a PAF front-end in the C band) and one for MED (simultaneous frequency in K, Q and W bands).

The simultaneous frequency receiver needs at least the upgrade of the MED surface (primary mirror panels and subreflector) accounting for 1.2 M€. A second option including also the active surface system (actuators and their control network) would imply additional 800 k€ but nevertheless determines a significant improvement of the antenna efficiency (see Appendix D) allowing the best exploitation of its scientific capabilities.

The budget necessary for the production of a tri-feed system is quoted as 300 k€. The cost of the quasi-optic system for simultaneous observing in the three bands should not exceed 100 k€, but this could be contracted within the already existing Italy-Korea collaboration. In fact we mention that, within a similar collaboration, the Yebes Observatory got for free a simultaneous K/Q-band system by exchanging it with antenna time for observations. It should also be interesting to investigate the feasibility of a UWB mono-feed, which would not need a quasi-optic system.

In respect of the multi-feed W-band receiver for the SRT, we estimate an indicative cost under the hypothesis of constructing a 19 element array, which is the minimum request among the technical specifications detailed in the Call for Ideas for such a front-end. The estimated budget for such a development is 1.7 M€.

With regard to the C-band PAF receiver, an indicative budget estimate of 2.7 M€ results from considering the technical specifications described in the proposals of the Call for Ideas. The three main PAF components are: the cryostat, which includes the vacuum window, the focal plane array and the cryogenic LNAs (approximate cost 1 M€); the Warm Section, which includes the down-conversion system, filtering, signal amplification and transportation (700 k€); the digital backend (1 M€).

11.7 Suggestions for future receiver development within INAF

Currently, the INAF staff FTE dedicated to the development of receivers for radio astronomy amounts to approximately 10 FTE characterized by a **wide spectrum of skills and expertise**, with considerable experience in many different technological aspects including antenna-related subjects. Nowadays, the receiver group is mainly composed by personnel from OAC and IRA, with a factor of two lower contribution from OAA. Additional contribution from two other INAF groups at IASF-Bologna and IRA-Medicina (SKA group) should be further encouraged to improve the already existing synergies. Besides that, the construction of a new front-end often involves also third-party Institutions and commercial industries.

This complex landscape, the results already obtained and the challenges posed by future development call for the definition of common rules to maximize the output from the available resources and to guarantee that INAF, and Italian radio astronomy in particular, maintain a leading position within the international context.

These considerations motivate this WG to suggest some general guidelines that could be adopted for future receiver development.

Periodically, a survey of the interest of the astronomical community in new instrumentation should be conducted by INAF by means of open **Call for Projects**. Each receiver proposal must illustrate the science cases to be addressed and its evaluation should **involve astronomers as well as technologists** to ensure that both scientific exploitation and technical feasibility are properly accounted for.

Most importantly, the design and development of future state-of-the-art projects is to be made within the framework of a **coordinated national plan for the development of radio astronomical instrumentation**, under the supervision of Section II 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, we believe that **each project should be in charge of a specific group and locally managed**. Interactions and scientific collaborations between the groups are strongly encouraged, but the receiver responsibility should be clearly identified at the site where it is designed and built.

Each new receiver should thus be seen as a separate project, with a well-designed management scheme and definition of roles to avoid or limit delays in the completion of tasks and of the project itself. This includes assigning a **Project Scientist** and **dedicated human resources** to each project. The existence of a well defined management structure should also help in overcoming the difficulties sometimes encountered in handling bureaucratic/administrative issues.

A more structured approach may be adopted by applying **system engineering** methodologies to the various phases of a project. For instance, the implementation of detailed scheduling and regular reviews to monitor the development of a receiver should become the standard procedure.

It can also be envisaged the creation of a **permanent Commission composed by astronomers and technologists** who will regularly meet to review the status of the ongoing projects and issue recommendations. This Commission should start its operations as soon as possible in order to gain experience in aspects related to project management before 2019, when the development of new receivers will start.

11.8 Developments related to space science at SRT and to Northern Cross

Finally, we mention some considerations on the following aspects:

- Regarding the shared use of the SRT as a receiving antenna for radio astronomical and space science applications, we recommend the involved institutions (INAF and ASI) to define best practices for the use of common spaces and facilities. With a good level of financial and technical planning and coordination, these activities can coexist and an efficient and rapid switching between the two system configurations for the use of the antenna can be made. A critical issue is related to the RFI generated by ASI devices. This aspect should be seriously considered keeping in mind the extremely sensitive radio astronomical receivers. The most relevant compatibility issue for radio astronomy and space science services at the SRT is related to the installation of high-power transmitters operating in X and Ka bands. Such an installation needs a very detailed and accurate analysis to prevent damages to the INAF receivers and equipment as well as to the safety of the staff. Recommendations regarding future ASI development of receivers dedicated to space science activities are out of the scope of this working group. However, we would like to point out the existence of an idea for a future receiver (see Paolo Tortora's contribution to the Call for Ideas) which could be connected to ASI interest in the SRT.

- The conditions for a possible refurbishment of the Northern Cross are quite different than for the other Italian radio telescopes for a number of reasons. The use of the NC in the next years will be focused more on space science applications than on classical radio astronomical studies. Not less important, the NC is a propriety of the University of Bologna which should be involved in any discussion on possible upgrades. Finally, no specific interests raised from the Call for Ideas on exploiting the NC for astronomical purposes. Very likely a significant refurbishment of the NC, like for example increasing the frequency band or the sensitivity, could make it very interesting for the low-frequency astronomical community. Nevertheless, given the aforementioned reasons we believe that such decisions on possible upgrades of the NC are not of pertinence of this WG and are not further discussed in this report.

12. Workshop

As one of the final steps of the activities of the Working Group defined in the Terms of Reference, a Workshop was held on March 21st 2017 at the INAF Headquarters in Rome. Aims of the Workshop were on one hand to present to the community the results of the WG activities summarized in this report, and on the other to start a discussion and get feedback on the report itself and in particular on the WG reccomendations.

In the words of Prof. Steven Tingay, Head of Section II (Radio Astronomy) of the INAF Science Directorate, who sponsored this review on receiver development within INAF and who opened the works, “this workshop is a big step forward in the direction of finding out what the community wants and starting to have some discussion about the next decade and what receivers we want to see on the different Italian radio telescopes”.

The points raised either during the Workshop final discussion or collected as feedback before/after the Workshop completion have been taken into consideration by the WG and, wherever deemed important, have been integrated in this report.

12.1 Program

The entire Workshop is visible on the INAF SEDECENTRALE YouTube channel at the following address: https://www.youtube.com/watch?v=wpcV8YdV6HQ.

Links to the pdf files of the presentations can be found on the Workshop web page: http://rx2017.inaf.it/RX2017/prog.html

The Workshop programme is outlined below. The YouTube video start times for each presentation are given in the first column.

Opening

- 12'47" - Opening and motivations (S. Tingay and P. Bolli)

Part I: Present - Chairs: M. Beltrán/ A. Zanichelli

- 35'50" - Infrastructures (A. Zacchiroli)
- 56'06" - International context (A. Orfei)

Part II: Future - Chairs: A. Orfei/ T. Pisanu

- 1h16'37" - International projects of receivers of interest for italian antennas (M. Beltrán)
- 1h44'03" - Science cases of the receivers under development (C. Stanghellini)
- 2h03'36" - Ideas for new receivers (A. Zanichelli)
- 2h29'38" - Receivers at the italian radio telescopes (T. Pisanu)*
- 2h53'57" - Recommendations from the working group (P. Bolli)

Lunch break

Part III: General discussion - Chairs: P. Bolli/ M. Burgay

- 4h36'41" - Summary (M. Burgay)
- 4:43'50" - General discussion

* originally planned at the end of Part I

12.2 Participants

Tab. 12.I lists the Workshop participants as evinced from the signatures on the attendance sheet (see Fig. 12.1). The distribution of attendant affiliations is plotted in Fig. 12.2.

Name	Affiiation
Maite Beltrán	INAF - OAArcetri
Germano Bianchi	INAF - IRA Bologna
Pietro Bolli	INAF - OAArcetri
Marta Burgay	INAF - OACagliari
Ettore Carretti	INAF - OACagliari
Viviana Casasola	INAF - OAArcetri
Pietro Cassaro	INAF - IRA Noto
Silvia Casu	INAF - OACagliari
Giovanni Comoretto	INAF - OAArcetri
Corrado Contavalle	INAF - IRA Noto
Cristian Franceschet	Università di Milano
Stefano Giovannini	INAF - IRA Bologna
Maria Noemi, Iacolina	ASI, Roma
Adelaide Ladu	INAF - OACagliari
Andrea Maccaferri	INAF - IRA Bologna
Sergio Mariotti	INAF - IRA Bologna
Pasqualino Marongiu	INAF - OACagliari
Jacopo Martelli	Università di Milano
Fabrizio Massi	INAF - OAArcetri
Andrea Melis	INAF - OACagliari
Carlo Migoni	INAF - OACagliari
Marco Morsiani	INAF - IRA Bologna
Alessandro Navarrini	INAF - OACagliari
Monia Negusini	INAF - IRA Bologna
Alessandro Orfei	INAF - IRA Bologna
Andrea Orlati	INAF - IRA Bologna
Dario Panella	INAF - OAArcetri
Delphine Perrodin	INAF - OACagliari
Tonino Pisanu	INAF - OACagliari
Sergio Poppi	INAF - OACagliari
Andrea Possenti	INAF - OACagliari
Isabella Prandoni	INAF - IRA Bologna
Francesco Schillirò	INAF - OACatania
Paolo Serra	INAF - OACagliari
Carlo Stanghellini	INAF - IRA Bologna
Vincenza Tornatore	Politecnico di Milano
Corrado Trigilio	INAF - OACatania
Giuseppe Valente	ASI, Roma
Fabrizio Villa	INAF - IASF Bologna
Salvatore Viviano	ASI, Roma
Giampaolo Zacchiroli	INAF - IRA Bologna
Alessandra Zanichelli	INAF - IRA Bologna

Table 12.I – List of Workshop participants

WORKSHOP

“Receivers for Radio Astronomy:
current status and future developments at the Italian radio telescopes”
Rome, Tuesday 21 March 2017

Participants List

	Last Name	Affiliation	Signature
Roberto	Ambrosini	INAF-IRA Bologna	
Elia	Battistelli	Università la Sapienza, Roma	
Maite	Beltran	INAF - OAArcetri	
Germano	Bianchi	INAF - IRA Bologna	
Pietro	Bolli	INAF - OAArcetri	
Marta	Burgay	INAF - OACagliari	
Ettore	Carretti	INAF - OACagliari	
Viviana	Casasola	INAF - OAArcetri	
Pietro	Cassaro	INAF - IRA Noto	
Alessandro	Cattani	INAF - IRA Bologna	
Silvia	Casu	INAF - OACagliari	
Giovanni	Comoretto	INAF - OAArcetri	
Corrado	Contavalle	INAF - IRA Noto	
Cristian	Franceschet	Università di Milano	
Stefano	Giovannini	INAF - IRA Bologna	
Maria Noemi	Iacolina	ASI, Roma	
Adelaide	Ladu	INAF - OACagliari	
Andrea	Maccaferri	INAF - IRA Bologna	
Aniello	Mannella	Università di Milano	
Sergio	Mariotti	INAF - IRA Bologna	
Pasqualino	Marongiu	INAF - OACagliari	
Jacopo	Martelli	Università di Milano	
Fabrizio	Massi	INAF - OAArcetri	
Andrea	Melis	INAF - OACagliari	
Andrei	Mesinger	Scuola Normale Superiore, Pisa	
Carlo	Migoni	INAF - OACagliari	
Marco	Morsiani	INAF - IRA Bologna	

	Last Name	Affiliation	Signature
Alessandro	Navarrini	INAF - OACagliari	
Monia	Negusini	INAF - IRA Bologna	
Alessandro	Orfei	INAF - IRA Bologna	
Andrea	Orlati	INAF - IRA Bologna	
Dario	Panella	INAF - OAArcetri	
Gioirgia	Parca	ASI, Roma	
Delphine	Perrodin	INAF - OACagliari	
Tonino	Pisanu	INAF - OACagliari	
Sergio	Poppi	INAF - OACagliari	
Ignazio	Porceddu	INAF - OACagliari	
Andrea	Possenti	INAF - OACagliari	
Isabella	Prandoni	INAF - IRA Bologna	
Francesco	Schillirò	INAF - OACatania	
Giampaolo	Serra	INAF - OACagliari	
Paolo	Serra	INAF - OACagliari	
Carlo	Stanghellini	INAF - IRA Bologna	
Corrado	Trigilio	INAF - OACatania	
Giuseppe	Valente	ASI, Roma	
Fabrizio	Villa	INAF - IASF Bologna	
Salvatore	Viviano	ASI, Roma	
Giampaolo	Zacchiroli	INAF - IRA Bologna	
Alessandra	Zanichelli	INAF - IRA Bologna	
Mario	Zannoni	Università di Milano Bicocca	
Vincenzo	Torustori	Politecnico di Milano	

Figure 12.1 – Copy of the attendance sheet

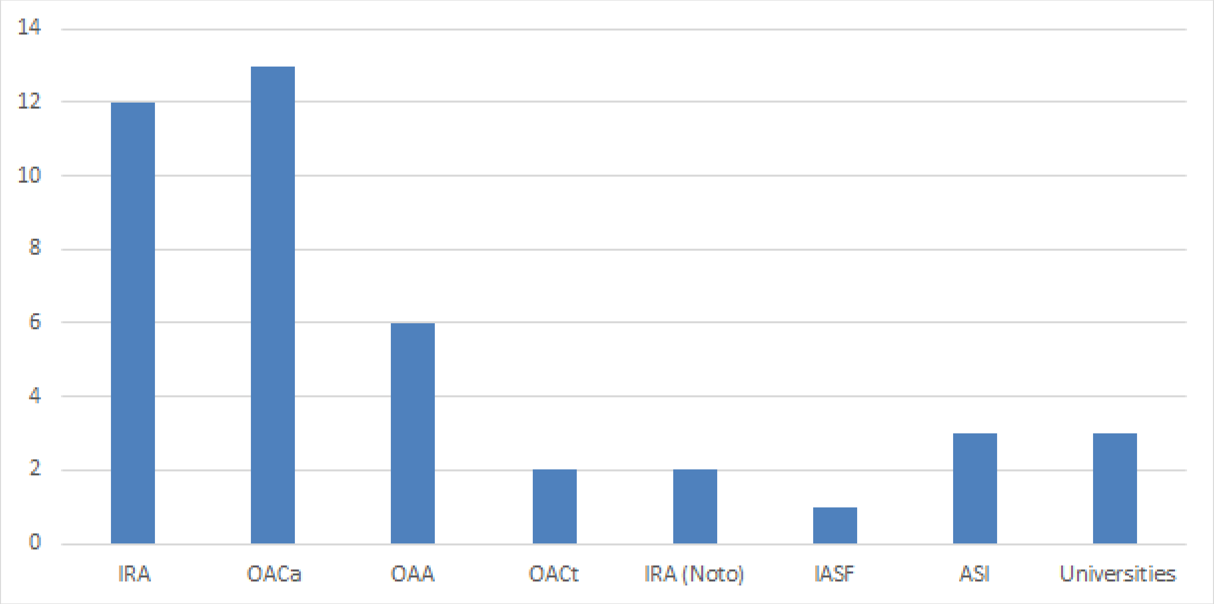


Figure 12.2 – Distribution of the affiliation of the Workshop participants

12.3 Discussion

Before the Workshop, some WG members held local presentations of this report at the INAF institutes involved in receiver development, in order to gather preliminary comments and suggestions. Several important issues were raised during the discussion at the Workshop. Finally, the WG invited the community to send comments in written form also after the conclusion of the Workshop itself. The more relevant among the collected feedbacks are listed below and may represent starting points for future discussion:

- Several comments were made about the best policies to be followed when proposing or designing a new receiver. There has been general consensus that the project of a receiver has to be approached in a systematic way and managed in an integrated manner. Besides the requirement for the receiver itself, many other ingredients must be taken into account for scientific, budgetary and timeline evaluation, such as back-ends, control software, metrology, impact on existing infrastructures (space, cabling, power consumption, computing needs, etc.). Another relevant aspect that must be continuously pursued is the involvement of micro-, small- and medium-sized enterprises in the receiver development process.

- To properly schedule the completion of the receivers under development for the SRT the time needed for their commissioning must be taken into account. It would be advisable to space out the finalization of these receivers so that there will not be overlap in their commissioning.

- ALMA Band 2+3 receiver: from a formal point of view, to make this receiver available for its installation at the SRT it will be necessary to formalize an agreement between ESO and INAF. On the technical side, the project looks feasible provided the execution of some adaptations (optical part, cryogenics and others) that IASF-Bologna is willing to implement. Boards for down-conversion are under development at the Medicina laboratories and could be used to connect this receiver to the available SRT back-ends. Completion and adaptation of the ALMA Band 2+3 receiver for its use at the SRT should be possibly done by the end of 2018. However, the tight schedule of the SRT together with the time required to meet the metrology and pointing accuracy specifications may postpone at a later date the installation of this receiver at the telescope. The possibility to place the cryo-components of the ALMA Band 2+3 receiver in a newly-built cryostat instead of adapting the ALMA cartridge for the SRT has been discussed. This would however imply a specific agreement with ESO as owner of the receiver components. Moreover, installing the Band 2+3 cartridge with its own dedicated cryostat offers the possibility to develop a compatibily of SRT with the ALMA receivers. Anyway, the technical details of the receiver adaptation to SRT will be discussed and defined within the group that will have in charge this activity. From a scientific point of view, the community showed great interest for the ALMA Band 2+3 receiver, which could also be seen as an advanced test bed for high-frequency observations at the SRT in view of the construction of a multi-beam receiver in W band.

- The possibility to downgrade the 19-beams Q-band receiver under development for SRT to a 7-beam receiver was lengthily discussed. At the moment of funding the 19-beams version of this receiver no science case was presented. During the Workshop, the community has been further invited to submit compelling scientific cases whose exploitation would be prevented or strongly limited by a 7-beams configuration. The scientific relevance of this receiver would be particularly high if coupled with a spectrometer capable of handling all the 19 beams. Currently, the existing SARDARA back-end can handle the 7-beams configuration (with maximum bandwidth 2 GHz) with no additional cost. A further 500 k€ approximately would be needed to equip the receiver with a spectrometer for the 19-beams configuration. It has also been suggested the possibility to invest in expanding the bandwidth available on the SARDARA spectropolarimetric back-end rather than in completing the 19 beams for the Q-band receiver.

- Further science cases for single-dish continuum applications of the Q-band receiver have been provided after the Workshop. Q-band observations could represent a crucial tool aimed at looking for electron energy distribution cut-off/breaks in the synchrotron spectra of many classes of bright Galactic sources (e.g. SNRs, PWNe, Compact binaries), typically expected at cm wavelengths or less. Through multi-feed Q-band OTF mapping and/or cross-scan combined to full-stokes Total-Power back-ends, it could be possible to determine which is the maximum energy of particle accelerated in relativistic shocks like those provided by a SNR interacting with molecular/atomic clouds, from a PWN interacting with the interstellar medium or from a microquasar jet. Furthermore, a better characterization (synchrotron spectral indexes and breaks) of spatially-resolved radio spectra is necessary to constrain the high-energy spectra in the frame of IC/Bremsstrahlung leptonic models in gamma-rays/TeV (and eventually probe them versus hadronic models), serving a wide part the high-energy scientific community. Solar Physics-Space Weather applications involving single-dish observation of the Solar Chromosphere are a new challeging field suitable as scientific/technological case for the SRT in next years. Quick mapping of the solar disk through a very dense Q-band multi-feed configuration is crucial to avoid long exposures of the solar disk, which would be biased by solar rotation.

- A request for VLBI observations of GNSS satellites has been presented. In order to take advantage from VLBI techniques for the combination of space geodetic techniques to determine ITRF and to realize the connection to the ICRF in space, L-band observations of GNSS satellite signals by radio telescopes play a major role. Simultaneous observations of frequencies in the 1.5-1.7 GHz and the 1.1-1.3 GHz ranges are necessary to correct the ionospheric effects, which highly degrade the quality of the results. Given the very high pollution of the L band at lower frequencies, the use of narrow filters around the needed frequencies is suggested. It is highly recommended to install the L-band receiver in the primary focus at all the telescopes to enable phase referencing observations that would allow to connect satellites (dynamic frame) directly to ICRF (kinematic, or quasi-inertial frame). A coaxial L/S/X design or, alternatively, a broadband receiver (e.g. BRAND or VGOS with added the capability to receive GNSS frequencies) are preferrable with respect to a L-band receiver alone. A multiband configuration would allow joint observations of both GNSS satellites and radio sources normally used in standard geodetic VLBI experiments. Finally, a request of continuous tracking of the satellites at all the antennas was also presented.

- With regard to the simultaneous K/Q/W-band receiver, it has been pointed out that a possible design is already available based on quasi-optical systems. However, it has been suggested that a technologically challenging design based on an UWB feed could be investigated. The capabilities of high frequency observations at Medicina have been presented with some slides describing the expected performance of MED with a refurbished surface. The possibility to have a simultaneous K/Q/W-band receiver at all the three Italian antennas on a longer time-scale has been raised.

- The possibility to develop a PAF receiver at 100 GHz instead of a multifeed in W-band has been discussed. Due to the shaped design of the SRT antenna, such a receiver should be mounted on the secondary focus. This in turn raises some PAF-related technological challenges due to the need of more directive beams than would be required by primary focus positioning. However, some international facilities are developing PAFs for the secondary focus position, like for instance the C-band PAF developed for the Canadian SKA prototype reflector antenna.

- It has been suggested to extend the frequency range of the proposed C-band PAF for the SRT down to 3 GHz to partially solve the overcrowding of the primary focus. Such a PAF would serve as an upgrade of the 7-beams S-band receiver under development. Also, a suggestion to extend the band at higher frequency has been made in order to reach a ratio between the maximum and minimum frequency of about 3.

- The L-band MeerKat-like receiver proposed in the Call for Ideas for the SRT could represent an interesting opportunity for establishing further scientifically valuable collaborations in the VLBI field also in view of the SKA telescope. The time scale for such a development would possibly be compatible with the lifetime exploitation of the existing P/L-band receiver.

12.4 Concluding remarks

The recommendations described in Chapter 11 as the result of almost one year of activity of the WG have been extensively discussed with the national astronomical community. The discussion highlighted that for some receivers further investigation is needed. For instance, the technical details of the ALMA Band 2+3 receiver adaptation to SRT and the quantitative analysis to assess the optimal multi-feed configuration for the Q-band SRT receiver. Such aspects are beyond the mandate of this WG and should be discussed and defined within executive projects specifically targeted for the development of each recommended receiver.

Overall, the general consensus expressed by the technological and scientific communities both at the Workshop and during other interactions demonstrates that the WG successfully identified a mid- and long-term plan for receiver development. Such a consensus, together with the coordinating role of the INAF Section II – Radioastronomy, will facilitate the implementation phase in future receiver development. In order to adopt a more systematic and comprehensive approach to the activities at the Italian radio astronomical facilities, the review process that has been applied for the development of receivers should be repeated also in other technological sectors (e.g. back-ends, software development, infrastructure).

12.5 Final remarks from the sponsor (Prof. Steven Tingay)

As sponsor of the Working Group and this report, I would like to deeply thank the members of the Working Group for their intense and high quality work over the last 12 months. The Working Group has spent many hours gathering information and constructing the report; more importantly, they have applied their decades of experience and wisdom connected with the Italian radio telescopes to the task. In particular, I wish to express my deepest thanks to Pietro Bolli, acting as Chair of the Working Group, providing highly expert direction to the activity and a very systematic and thoughtful guidance.

This report shows the depth of potential that exists within the Italian radio telescopes and the Italian radio astronomy community. While considerable work is required to realise three fully operational and efficient telescopes, this report shows that the scientific reward is likely to be high and that the technical experience exists withn INAF and its partners.

I hope that this report will form a very stong basis for Section II of the INAF Science Directorate 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. A key set of recommendations from this report regard how receiver development projects within INAF should be structured and controlled. These recommendations are key to realising the benefits that are identfied in this report and I hope that Section II will be able to take charge of these recommendations in the future.

Acknowledgements and Credits

This report was the results of contributions received from many people to whom we devote our thanks.

Chapter 2

Andrea Orlati (INAF-IRA), Sergio Poppi, Carlo Migoni, Andrea Melis and Alessandro Corongiu (INAF-OAC) for providing information about back-ends.

Matteo Stagni (INAF-IRA) for contribution on the DiFX software correlator.

Claudio Bortolotti, Mauro Roma (INAF-IRA), Francesco Gaudiomonte, Giampaolo Serra (INAF-OAC) and Gaetano Nicotra (INAF-IRA) for giving information about the RFI at each site.

Franco Buffa (INAF-OAC) for providing opacity data at SRT.

Chapter 3

Sergio Mariotti (INAF-IRA), Adelaide Ladu (INAF-OAC) and Giuseppe Valente (ASI) and finally Dario Panella and Renzo Nesti (INAF-OAA) for information about the laboratory facilities at INAF-IRA (Bologna and Medicina), at INAF-OAC and at INAF-OAA respectively.

Jader Monari (INAF-IRA) and Fabrizio Villa (INAF-IASF-Bologna) for information about other groups inside INAF taking care of receiver development.

Chapter 4

Germano Bianchi (INAF-IRA) for the information on the Northern Cross.

Chapter 6

Marco Poloni and Marco Morsiani (INAF-IRA) for providing the status of the L/S/X-band Noto receiver under evaluation.

Jan Brand (INAF-IRA) and Luca Moscadelli (INAF-OAA) for useful discussion on the scientific use of the Chigh-band receiver.

Ettore Carretti, Paola Castangia, Silvia Casu, Elise Egron, Federica Govoni, Matteo Murgia, Alberto Pellizzoni, Andrea Tarchi (INAF-OAC) for contributing to the compilation of scientific keywords for SRT.

Chapter 7

The foreign colleagues providing lot of information, including pictures on the front page, about their telescopes and revising this Chapter:

Richard Prestage (USA), Alex Kraus (Germany), Zhiqiang Shen (China), Jose A. Lopez-Perez, Pablo de Vicente and Carsten Kramer (Spain), Bong Won Sohn (Korea), Mareki Honma and Tetsuiro Minamidani (Japan), Michael Lindqvist (Sweden) and Tasso Tzioumis (Australia).

Chapter 8

Alessandro Navarrini (INAF-OAC) for information on PHAROS/PHAROS2.

Figure credits:

Front page – INAF-OAA and Radionet FP6 Pharos Joint Research Activity; ALMA Band 2+3 Consortium.

Figure 8.1 – INAF IASF-Bologna, INAF-OAA (ALMA Band 2+3 Consortium).

Figure 8.2 – Chalmers-GARD, INAF IASF-Bologna (ALMA Band 2+3 Consortium).

Figure 8.3 – STFC-RAL (ALMA Band 2+3 Consortium).
Figure 8.4 – Astron / Radionet FP6 Pharos Joint Research Activity (presentation by Jan Geralt Bij De Vaate, Frascati, Italy, September 2008).
Figure 8.5 – Alessandro Navarrini (INAF-OAC).

Chapter 9
All the colleagues providing input to describe the science cases for the receivers under development: Marco Bondi, Marcello Giroletti, Karl-Heinz Mack, Monia Negusini, Isabella Prandoni, Tiziana Venturi (INAF-IRA), Simone Bianchi, Viviana Casasola, Leslie Hunt (INAF-OAA), Paola Castangia, Federica Govoni, Maria Noemi Iacolina, Silvia Leurini, Matteo Murgia (INAF-OAC), Corrado Trigilio (INAF-OACt).

Chapter 10
All the colleagues answering the Call for Ideas: Simone Bianchi, Viviana Casasola, Fabrizio Massi, Luca Olmi (INAF-OAA), Paolo de Bernardis (University of Rome "La Sapienza"), Paolo Tortora (University of Bologna), Marcello Giroletti, Monia Negusini, Isabella Prandoni, Tiziana Venturi (INAF-IRA), Francesco Schillirò (INAF-OACt), Ettore Carretti, Paolo Serra (INAF-OAC)

Chapter 11
Alessandro Navarrini (INAF-OAC) for useful information on budget estimates for PAF receivers.

Chapter 12
All the colleagues who participated in the discussion during the Workshop and who sent us their comments and feedback after having read the preliminary version of this Report.

Appendix C
Monia Negusini, Marcello Giroletti and Jan Brand (INAF-IRA) for contributing to complete the publication list.

Graphics and Photography
Simona Righini (INAF-IRA) for the report graphics.

Web support
Antonio Poddighe (INAF-OAC) and Franco Tinarelli (INAF-IRA) for the realization of the Workshop web site.

Workshop Organization
Federico Gualano and Chiara Giorgieri (INAF-HQ) for the local support to the organization of the Workshop.

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APPENDICES

A. National receivers table

Status	Receiver ID	TECHNICAL DATA																	
		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Down-conversion & IF band [GHz]	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	Allocated RAS bands and status of protection [GHz]	RFI in Rx band	Back-End connected to the receiver	Technological pubblications since 2010
					Min	Max													
In operation	SRT P/L	64m SRT	Dual-frequency coaxial feed	Primary (0,33)	0,305	0,410	0,105	1 x 2 (L&C)	48	Yes	No: 0,305-0,405 or 0,305-0,355	Yes	17-22	50-80	0,52	0,322-0,3286 (d) 0,4061-0,41 (b)	**	TP DBBC ROACH-1 DFB SARDARA	10
					1,3	1,8	0,5	1 x 2 (L&C)	11.4	Yes	No: 1,3-1,8 or 1,34-1,46 or 1,595-1,715		13	25-35	0,55	1,33-1,4 (c) 1,4-1,427 (e) 1,6106-1,6138 (b) 1,66-1,67 (b) 1,7188-1,7222 (c)	***	TP DBBC ROACH-1 DFB SARDARA	
	SRT Chigh	64m SRT	Mono-feed	BWG F3 (1,37)	5,7	7,7	2	1 x 2 (C)	2,7	Yes	Yes: 0,1-2,1	Yes	6.5-9	24-28	0,6	6,65-6,6752 (c)	*****	TP DBBC DFB SARDARA	5
	SRT K	64m SRT	Multi-feed	Gregorian (2,34)	18,0	26,5	2	7 x 2 (C)	0,8	Yes	Yes: 0,1-2,1	Yes	20-40 (18-24 GHz)	40-70	0,45-0,66	22,0-22,5 (b) 22,81-22,86 (c) 23,6-24,0 (e)	*****	TP DBBC DFB XARCOS SARDARA	4
	SRT X/Ka	64m SRT	Dual-frequency coaxial feed	Primary (0,33)	8,2	8,6	0,4	1 x 1 (LCP)	2,35	No	Yes: 0,1-0,5	Yes	150	180	0,64	8,4-8,5 (a)	*****	Spectrum analyzer	3
					31,85	32,25	0,4	1 x 1 (LCP)	0,61	No	Yes: 0,1-0,5		130	190	0,57	31-32,3 (a)	*****	Spectrum analyzer	
	MED L	32m Med	Dual-channel mono-feed	Primary (0,32)	1,35	1,45	0,1	1 x 2 (C)	27,5	No	Yes: 0,314-0,414	Yes	50	55	0,12	1,33-1,4 (c) 1,4-1,427 (e)	****	TP DBBC XARCOS	Not applicable
					1,595	1,715	0,12	1 x 2 (C)	31,2	No	Yes: 0,3-0,42		60	65	0,11	1,6106-1,6138 (b) 1,66-1,67 (b)	***	TP DBBC XARCOS	
	MED S/X	32m Med	Dual-frequency coaxial feed	Primary (0,32)	2,2	2,36	0,16	1 x 2 (C)	18	Yes	Yes: 0,18-0,34	Yes	40	55	0,12	2,2-2,3 (a)	*** / **	TP DBBC XARCOS	Not applicable
					8,18	8,98	0,8	1 x 2 (C)	4,9	Yes	Yes: 0,1-0,9		25	38	0,14	8,4-8,5 (a)	***** / ****	TP DBBC XARCOS	

Status	Receiver ID	TECHNICAL DATA																	
		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Down-conversion & IF band [GHz]	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	Allocated RAS bands and status of protection [GHz]	RFI in Rx band	Back-End connected to the receiver	Technological pubblications since 2010
					Min	Max													
In operation	MED Clow	32m Med	Mono-feed	Cassegrain (3,04)	4,3	5,8	1,5	1 x 2 (C)	7,4	Yes	Yes: 0,1-0,5 or 0,1-0,9	Yes	12-15	28	0,16	4,825-4,835 (c) 4,95-4,99 (c) 4,99-5,00 (d)	*** / **	TP DBBC XARCOS	Not applicable
	MED Chigh	32m Med	Mono-feed	Cassegrain (3,04)	5,9	7,1	1,2	1 x 2 (C)	5,4	No	Yes: 0,1-0,5 or 0,1-0,9	Yes	70-50	90-60	0,15	6,65-6,6752 (c)	**** / ***	TP DBBC XARCOS	Not applicable
	MED K	32m Med	Bi-feed	Cassegrain (3,04)	18	26,5	2	2 x 2 (C)	1,85	Yes	Yes: 0,1-2,1	Yes	20-50	50-80	0,11	22,0 - 22,5 (b) 22,81 - 22,86 (c) 23,6 - 24,0 (e)	***** / ****	TP DBBC XARCOS	0
	NOTO S/X	32m Nt	Dual-frequency coaxial feed	Primary (0,32)	2,2	2,36	0,16	1 x 1 (C)	20	No	Yes: 0,18-0,34	Yes	Not available	120	0,15	2,2-2,3 (a)	***	DBBC	Not applicable
					8,18	8,58	0,4	1 x 1 (C)	4,8	No	Yes: 0,1-0,5		Not available	110	0,15	8,4-8,5 (a)	*****	DBBC	
	NOTO Clow	32m Nt	Mono-feed	Cassegrain (3,04)	4,62	5,02	0,4	1 x 2 (C)	8	Yes	Yes: 0,1-0,5	No	15	30	0,16	4,825-4,835 (c) 4,95-4,99 (c) 4,99-5,00 (d)	****	DBBC	Not applicable
	NOTO Chigh	32m Nt	Mono-feed	Cassegrain (3,04)	5,1	7,25	0,5	1 x 2 (C)	7,8	No	Yes: 0,1-0,5	No	Not available	120	0,13	6,65-6,6752 (c)	*****	DBBC	Not applicable
	NOTO K	32m Nt	Mono-feed	Cassegrain (3,04)	21,5	23	0,5	1 x 2 (C)	1,7	Yes	Yes: 0,1-0,5	No	70	110	0,08	22-22,5 (b) 22,81 - 22,86 (c)	*****	DBBC	Not applicable
	NOTO Q	32m Nt	Mono-feed	Cassegrain (3,04)	39	43,5	0,5	1 x 2 (C)	0,9	Yes	Yes: 0,1-0,5	No	35	120	0,08	42,5-43,5 (b)	*****	DBBC	Not applicable
	8 NS NC BEST-2	NC	Array feed	0,256	0,4	0,416	0,014	24 (L)	104' (RA) x 31,1' (DEC) FoV = 6,6° (RA) x 5,7° (DEC)	No	Yes: 0,022-0,038	Not applicable	51	86	0,36	0,4061-0,41 (b)	***	Roach	7

Status	Receiver ID	TECHNICAL DATA																	Technological pubblications since 2010
		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Down-conversion & IF band [GHz]	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	Allocated RAS bands and status of protection [GHz]	RFI in Rx band	Back-End connected to the receiver	
					Min	Max													
Under-development	SRT S	64m SRT	Multi-feed	Primary (0,33)	3	4,5	1,5	7 x 2 (L)	5,25	Yes	Yes: 0,3-0,8	Yes	15	30	0,75	3,260-3,267 (c) 3,332-3,339 (c) 3,3458-3,3525 (c)	****	TP DBBC DFB SARDARA	3
	SRT Clow	64m SRT	Mono-feed	BWG F4 (2,81)	4,2	5,6	1,4	1 x 2 (C)	4	Yes	Yes: 0,1-1,5	Yes	10	23-35	0,7	4,825-4,835 (c) 4,95-4,99 (c) 4,99-5,00 (d)	****	TP DBBC DFB SARDARA	0
	SRT Q	64m SRT	Multi-feed	Gregorian (2,34)	33	50	14,4	19 x 2 (C)	0,48	Yes	Yes: 1-18	Yes	22-35	45-120	0,56	34,7-35,20 (a) 36-36,43 (a) 36,43-36,5 (c) 36,5-38 (a) 42,5-43,5 (b) 48,94-49,04 (b)	***** (up to 40 GHz)	TP DBBC SARDARA	2
	SRT W (ex-IRAM)	64m SRT	Mono-feed	Gregorian (2,34)	84	116	0,5	1 x 1 (C)	0,2	Yes @4K	Yes: 0,3-0,8	Yes	30-45	115	0,34	86-92 (e) 92-94 (b) 94-94,1 (d) 94,1-100 (b) 100-102 (e) 102-105 (b) 105-109,5 (b) 109,5-111,8 (e) 111,8-114,25 (b) 114,25-116 (e)	Not available	TP DBBC SARDARA	2
	MED Ku	32m Med	Bi-feed	Cassegrain (3,04)	13,5	18	4	2 x 2 (C)	2,5	Yes	Yes: 0,1-2,1	Yes	12-15	30-36	0,12-0,16	12,75-13,25 (a) 3,75-14,3 (a) 14,40-14,47 (a) 14,47-14,5 (d) 14,5-15,3 (a) 15,35-15,4 (e)	***** / ****	TP XARCOS	0
	16 NS NC BEST-4	NC	Array feed	0,256	0,4	0,416	0,014	48	104' (RA) x 15,6' (DEC) FoV = 6,6° (RA) x 5,7° (DEC)	NO	Yes: 0,022-0,038	Not applicable	51	86	0,72	0,4061-0,41 (b)	***	Roach	0

Status	Receiver ID	TECHNICAL DATA																	
		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Down-conversion & IF band [GHz]	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	Allocated RAS bands and status of protection [GHz]	RFI in Rx band	Back-End connected to the receiver	Technological pubblications since 2010
					Min	Max													
Under-evaluation	NOTO L	32m Nt	Mono-feed	Primary (0,32)	1,3	1,8	0,5	1 x 2 (C)	30	No	No	Yes	Not available	Not available	Not available	1,33-1,4 (c) 1,4-1,427 (e) 1,6106-1,6138 (b) 1,66-1,67 (b) 1,7188-1,7222 (c)	***	DBBC	0
	NOTO S/X	32m Nt	Dual-frequency coaxial feed	Primary (0,32)	2,2	2,36	0,16	1 x 2 (C)	20	No	No	Yes	Not available	Not available	Not available	2,2-2,3 (a)	***	DBBC	0
					8,18	8,98	0,4	1 x 2 (C)	4,8	No	Yes: 0,1-0,9		Not available	Not available	Not available	8,4-8,5 (a)	*****	DBBC	
	NOTO W (ex-MPIFR)	32m Nt	Mono-feed	Cassegrain (3,04)	85,945	86,545	0,1	1 x 1 (C)	0,5	Yes	Yes: 0,1-0,2	No	300	Not available	Not available	86-92 (e)	Not available	DBBC	0
	NOTO W (ex-IRAM)	32m Nt	Mono-feed	Cassegrain (3,04)	84	116	0,5	1 x 1 (C)	0,2	Yes @4K	Yes: 0,3-0,8	No	30-45	115	Not available	86-92 (e) 92-94 (b) 94-94,1 (d) 94,1-100 (b) 100-102 (e) 102-105 (b) 105-109,5 (b) 109,5-111,8 (e) 111,8-114,25 (b) 114,25-116 (e)	Not available	DBBC	0

Status	Receiver ID	SCIENTIFIC DATA				MANAGEMENT											
		Main scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Scientific pubblications since 2012	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Real or expected cost (k€) for receivers developped after 2010	Real or expected duration of the development (year)	Technlogical team involved in the Rx development						Contact person	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure
									Management	Mechanics and cooling	FE passive components	FE active component (LNA)	IF section	Integration and test			
In operation	SRT P/L	Pulsar, ISM, polarized diffuse emission, all sky-survey (e.g. GIMMS-north), galactic magnetism	0% P-only 12,5% in parallel with L-band	1	EPTA IPTA	2013	300 (SRT)	5,5	IRA	OAC	OAC IRA	IRA	OAC	OAC IRA	Valente	Suspected vacuum loss	Cryogenic ON
		Pulsar, ISM, galactic magnetism, VLBI, HI, thermal Mol. Lines and Maser (e.g. OH), Active Binaries, Galaxy Clusters, AGN, Cosmic web filaments, Galactic foreground, SNRs, PWN, X-ray binaries and galactic transients	14,7% L-only 12,5% in parallel with P-band	4	LEAP EPTA IPTA VLBI RadioAstron	2012										Suspected vacuum loss	Active surface ON
	SRT Chigh	VLBI, thermal molecular lines and masers (e.g. methanol), Active Binaries. AGN, Galaxy Clusters, Recombination lines, SNRs, PWN, X-ray binaries and galactic transients, pulsars (in GalC)	38,40%	10	VLBI	2012	160 (SRT)	5,5	IRA	IRA	OAA IRA CNR-IEIIT	Commercial: LNF	IRA	IRA	Valente	None	Active surface ON
	SRT K	VLBI, thermal molecular lines & maser (e.g. H20, NH3), Survey, X-ray Binaries, Extr. GRG, Blazar, Protostar, Sun. Z.vich, Comets, Anomalous Dust Emission, AGN (spectral ageing), SNRs, PWN	34,40%	2	VLBI RadioAstron	2012 (2008-2011 at 32m Med)	330 (SRT)	5,5	IRA	OAA	OAA IRA	IRA	IRA	OAA IRA	Valente	Problem with two chain at Cryo LNA No new spare cryo LNA Back-end 1GHzx8x14 basebands and full Stokes detected outputs	Active surface ON
	SRT X/Ka	space science (ASI)	0%	0	None	2015 (2002 at 32m Nt)	Not applicable	1	IRA	IRA	L.T. Calcoli TILAB	Commercial: MITEQ	IRA	IRA	Valente	None	Active surface ON
		space science (ASI)	0%	0	None	2015 (2002 at 32m Nt)										None	Active surface ON
	MED L	AGNs; galaxy formation and evolution; Galaxy structure; HI (parallaxes and proper motions)	12%	3	EVN e-VLBI RadioAstron	1994	Not applicable	2,5	IRA	IRA	IRA FPM Space	IRA	IRA	IRA	Orfei	None	None
		galaxy formation and evolution; AGNs; pulsar; X-ray binaries; black hole physics; supernovae and SN remnants; masers; star formation and evolution; ISM structure; radio line emission; physics of radio sources; gravitational lensing		46	EVN e-VLBI RadioAstron	1994										None	None
	MED S/X	galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; extragalactic surveys; variability monitoring; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames	29%	35	EVN IVS	1992	Not applicable	2,5	IRA	IRA	IRA	IRA	IRA	IRA	Orfei	None	None
		galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; extragalactic surveys; variability monitoring; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames		66	EVN e-VLBI IVS	1992										None	None

Status	Receiver ID	SCIENTIFIC DATA				MANAGEMENT											
		Main scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Scientific pubblications since 2012	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Real or expected cost (k€) for receivers developped after 2010	Real or expected duration of the development (year)	Technlogical team involved in the Rx development						Contact person	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure
									Management	Mechanics and cooling	FE passive components	FE active component (LNA)	IF section	Integration and test			
In operation	MED Clow	galaxy formation and evolution; AGN; physics of radio sources; black hole physics; pulsar (parallaxes and proper motions); X-ray binaries; variability monitoring; supernovae and SN remnants; ISM structure; extragalactic surveys; polarization properties (agn); radar astronomy	29%	70	EVN e-VLBI RadioAstron	2006	Not applicable	6	IRA	IRA	OAA TILAB IRA	IRA	IRA	OAA IRA	Orfei	None	None
	MED Chigh	masers; ISM structure; star formation and evolution; radio line emission; Galaxy structure, kinematics and dynamics; astrometry; magnetic fields and polarization (masers and protostars)	5%	20	EVN e-VLBI	2003	Not applicable	3	IRA	IRA	OAA IRA OAC	Commercial: MITEQ	IRA	OAA IRA OAC	Orfei	None	None
	MED K	masers; ISM molecules; surveys; galaxy formation and evolution; AGN; variability monitoring; radio line emission; polarization properties (agn); Galaxy structure, kinematics and dynamics; star formation and evolution, astrometry; comets	25%	26	EVN e-VLBI RadioAstron VERA	2013	100 (INAF)	3	IRA	OAA	OAA	Commercial: NRAO	IRA	OAA IRA	Orfei	Back-end 1.GHzx8x4 basebands and full Stokes detected outputs	None
	NOTO S/X	galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames	21%	31	EVN IVS	1993 (1985-1991 at 32m Med)	Not applicable	2	IRA	IRA	IRA	IRA	IRA	IRA	Contavalle Platania	None	None
		galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames		41	EVN e-VLBI IVS	1993 (1985-1991 at 32m Med)										None	None
	NOTO Clow	galaxy formation and evolution; AGN; physics of radio sources; black hole physics; pulsar; X-ray binaries; polarization properties (agn); supernovae; SN remnants; ISM	25%	42	EVN e-VLBI RadioAstron	1990	Not applicable	2	IRA	OAA IRA	OAA	IRA	IRA	OAA IRA	Contavalle	Upgrade for the frequency agility	None
	NOTO Chigh	masers; ISM molecules; ISM kinematics and dynamics; star formation and evolution; Galaxy structure, kinematics and dynamics; astrometry; magnetic fields and polarization (maser)	8%	16	EVN e-VLBI	2001	Not applicable	1,5	OAA IRA	OAA	OAA	Commercial: MITEQ	OAA	OAA IRA	Contavalle Nocita	New feed & upgrade for the frequency agility	None
	NOTO K	masers; ISM molecules; galaxy formation and evolution; AGN; radio line emission; Galaxy structure, kinematics and dynamics; star formation and evolution; astrometry	14%	11	EVN e-VLBI RadioAstron VERA	1990	Not applicable	2	IRA	OAA IRA	OAA	IRA	IRA	OAA IRA	Contavalle	Upgrade for the frequency agility	None
	NOTO Q	galaxy formation and evolution; AGN; masers; galaxy clusters and ICM (SZ)?	20%	12	GMVA VERA	2004	Not applicable	2	OAA	OAA	OAA	Commercial: NRAO	OAA	IRA	Contavalle	Upgrade for the frequency agility	New subreflector if the current one can not be recovered by the active surface
	8 NS NC BEST-2	Space debris, pulsar, radiosurce survey, carbon radio recombination lines, monitoring of supernova remnants secular flux decrease	100%	0	SST IADC SKADS	2007	Not applicable	Not applicable	IRA	IRA	IRA	IRA	IRA	IRA	Bianchi, Perini	Needed an user friendly interface	None

		SCIENTIFIC DATA				MANAGEMENT											
Status	Receiver ID	Main scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Scientific pubblications since 2012	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Real or expected cost (k€) for receivers developped after 2010	Real or expected duration of the development (year)	Technological team involved in the Rx development						Contact person	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure
									Management	Mechanics and cooling	FE passive components	FE active component (LNA)	IF section	Integration and test			
Under-development	SRT S	Pulsar, Galactic foreground for CMB studies, Galaxy clusters, galactic magnetism, evolution with z of ex.gal magnetism, ISM, ISM turbulence, Galaxy structure, new SNRs, syncrotron cosmic web, thermal molecular lines and masers (e.g. HC5N, CH)	Not applicable	Not applicable	None	2018	300 = 200 (RAS) + 100 (not yet available)	4	OAC	OAC	OAC	Commercial: TTI	OAC	OAC	Valente	Dewar Control and powering system Mounting system Cabling	Active surface ON
	SRT Clow	VLBI, Extr. RM, Mol. Lines and masers (e.g. formaldehide), Active Binaries, Pulsars, AGN, SNRs, PWN	Not applicable	Not applicable	VLBI RadioAstron EPTA	2017	220 (MIUR), fully available	3,5	IRA	IRA OAC	OAA CNR-IEIIT	Commercial: LNF	IRA	OAC IRA	Orfei	Dewar HTS filter LNA purchase Mounting framework	Active surface ON Cryogenic ON
	SRT Q	Thermal molecluar lines and masers (e.g. SiO); mm-VLBI, Extr.CO, Extr. Survey, Blazar, Sun. Z.vich, Protostar, AGN, SNRs, PWN	Not applicable	Not applicable	ALMA NOEMA	2018	920 = 320 (EU+MIUR+ UniMi) + 600 (not yet available)	6	IRA	IRA	OAA Uni. Manchester CNR-IEIIT	Commercial: Under consideration	IRA OAC	IRA OAC	Orfei	Dewar; 1st down conversion; LNA; Cal circuit; Rotator; Back-end 1.8GHzx8x38 basebands and full Stokes detected outputs	Active surface ON
	SRT W (ex-IRAM)	molecular lines (e.g. CO), Sun-Zeldovich, mm-VLBI	Not applicable	Not applicable	GMVA ALMA NOEMA	2017	60 (SRT), fully available	Not applicable	OAC	IRAM Modified at OAC	IRAM	IRAM	IRAM	OAC	Valente	Cryogenic cooler at 4 K Mechanics Installation	Active surface ON Metrology ON Total RMS < 200 µm
	MED Ku	galaxy formation and evolution; AGNs; physics of radio sources; extragalactic surveys; variability monitoring	Not applicable	Not applicable	None	2018	150 (MIUR), fully available	4	IRA	IRA	OAA CNR-IEIIT	Commercial: LNF	IRA	IRA	Orfei	Dewar Passive components LNA purchase	None
	16 NS NC BEST-4	Space debris, pulsar, radiosurce survey, carbon radio recombination lines, monitoring of supernova remnants secular flux decrease	Not applicable	0	SST IADC	2016	235 (EU), fully available	Not applicable	IRA	IRA	IRA	IRA	IRA	IRA	Bianchi, Perini	Back-end upgrade Installation of analogue components, optical fibers and cables Focal lines modification	None

		SCIENTIFIC DATA				MANAGEMENT											
Status	Receiver ID	Main scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Scientific pubblications since 2012	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Real or expected cost (k€) for receivers developped after 2010	Real or expected duration of the development (year)	Technological team involved in the Rx development						Contact person	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure
									Management	Mechanics and cooling	FE passive components	FE active component (LNA)	IF section	Integration and test			
Under-evaluation	NOTO L	***Llow:*** AGNs; galaxy formation and evolution; Galaxy structure; HI (parallaxes and proper motions). ***Lhigh:*** galaxy formation and evolution; AGNs; pulsar; X-ray binaries; black hole physics; supernvae and SN remnants; masers; star formation and evolution; ISM; radio line emission; physics of radio sources; gravitational lensing	Not applicable (12% for the old L band receiver)	Not applicable (35 for the old L-high and 3 for the old L-low	EVN e-VLBI RadioAstron IVS	Not applicable	Not applicable	Not applicable	IRA	IRA	TILAB	Commercial: MITEQ	IRA	IRA	Under evaluation	Under evaluation	None
	NOTO S/X	galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames	Not applicable	Not applicable	EVN e-VLBI RadioAstron IVS	Not applicable											None
		galaxy formation and evolution; AGNs; ISM structure; physics of radio sources; supernovae; gravitational lensing; astrometry; geodesy; International Celestial and Terrestrial Reference Frames	Not applicable	Not applicable	EVN e-VLBI RadioAstron IVS	Not applicable											None
	NOTO W (ex-MPIFR)	star formation and evolution; ISM molecules; galaxy clusters and ICM (SZ)?	Not applicable	Not applicable	GMVA VERA	Not applicable	Not applicable	Not applicable	IRA	IRA	MPIFR	MPIFR	MPIFR	Under evaluation	Contavalle Nocita	Need modification for Cassagrain focus	New subreflector if the current one can not be recovered by the active surface
	NOTO W (ex-IRAM)	star formation and evolution; ISM molecules; galaxy clusters and ICM (SZ)?	Not applicable	Not applicable	GMVA / VERA	Not applicable	Not applicable	Not applicable	IRA	IRAM Under evaluation	IRAM	IRAM	IRAM	Under evaluation	Contavalle Nocita	Under evaluation	New subreflector if the current one can not be recovered by the active surface

B. International receivers table

		TECHNICAL DATA														SCIENTIFIC DATA			MANAGEMENT			
	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
					Min	Max																
In operation	YEBES S/X	40 m YEBES	Mono-feed simultaneous operation	7,909	2,2	2,4	0,13	1 x 2 (C)	12,3	Yes	No	<50	170	0,31	Yes	VLBI	18	IVS	2008			
					8,15	8,9	0,5	1 x 2 (C)	3,8	Yes	No	<10	40	0,28	No	VLBI		EVN/IVS				
	YEBES CH	40 m YEBES	Mono-feed	7,909	3,2	3,3	0,17	1 x 2 (C)	9,3	Yes	Yes	<50	NA	NA	Yes	single-dish	NA		2008			
	YEBES C	40 m YEBES	Mono-feed (not simultaneous)	7,909	4,56	5,1	0,5	1 x 2 (C)	6	Yes	Yes	<10	40	0,34	Yes	VLBI	18	EVN	2008			
					5,9	6,9	0,5	1 x 2 (C)	4,7	Yes	Yes	<10			Yes	VLBI		EVN				
	YEBES K	40 m YEBES	Mono-feed simultaneous operation	7,909	21	25,0	1,5	1 x 2 (C)	1,25	Yes	Yes	<20	80	0,29	Yes	VLBI/single-dish	8,4	EVN/KASI	2008			
	YEBES Q			7,909	40	50,0	2	1 x 2 (C)	0,6	Yes	Yes	50-60	100	0,2	No	VLBI/single-dish	51	EVN/KASI	2010			
	YEBES W	40 m YEBES	Mono-feed	7,909	83	116,0	0,6	1 x 1 (L or C)	0,28	Yes	Yes	50-60	170	0,055	No	VLBI/single-dish	4,6	GMVA	2010			
	GBT PF1 342	100 m GBT	X Dipole	Prime (0,6)	0,290	0,395	0,24	1 x 2 (L&C)	36	LNA	Yes	12	46	2	Yes	Pulsars, Radio Transients	20		2000	Routine cryogenic maintenance, two hours to install feed	None	
	GBT PF1 450	100 m GBT	X Dipole	Prime (0,6)	0,39	0,52	0,24	1 x 2 (L&C)	27	LNA	Yes	22	43	2	Yes	Rarely Used				N/A	None	
	GBT PF1 600	100 m GBT	X Dipole	Prime (0,6)	0,51	0,69	0,24	1 x 2 (L&C)	21	LNA	Yes	12	22	2	Yes	Rarely Used				N/A	None	
	GBT PF1 800	100 m GBT	Linear Taper	Prime (0,6)	0,68	0,92	0,24	1 x 2 (L&C)	15	LNA	Yes	21	29	2	Yes	Rarely Used				Routine cryogenic maintenance, two hours to install feed	None	
	GBT PF2	100m GBT	Mono-feed	Prime (0,6)	0,9	1,2	0,24	1x2 (L&C)	12	LNA	Yes	10	17	2	Yes	Pulsars, Radio Transients, Rdshifted HI			2000	N/A	None	
	GBT L	100 m GBT	Mono-feed	Gregorian (1,9)	1,2	1,7	0,65	1 x 2 (L&C)	9	LNA	Yes	6	20	2	Yes	Pulsars, Radio Transients, galactiv HI, nearby Galaxies	20		2000	Routine cryogenic maintnenance, baselines deteriorating, will be replaced.	None	
	GBT S	100 m GBT	Mono-feed	Gregorian (1,9)	1,7	2,6	0,97	1 x 2 (L&C)	5,8	LNA	Yes	10	22	2	Yes	Pulsars (esp.globular clusters), repeating FRB			2000	Routine cryogenic maintenance	None	
	GBT C	100 m GBT	Mono-feed	Gregorian (1,9)	4,0	8,0	3,8	1 x 2 (L&C)	2,5	LNA	Yes	5	18	2	Some	Radio Recombination Lines, Magnetars			2015	Routine crogenic maintenance (upgraded 2015)	None	
	GBT X	100 m GBT	Mono-feed	Gregorian (1,9)	8,0	10,0	2,4	1 x 2 (C)	1,4	LNA	Yes	13	27	2	Rare	Radio Recombination Lines, Magnetars, VLBI			2000	Routine cryogenic maintenance; bandwidth/cryogenics upgrade planned	None	

	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
			TECHNICAL DATA													SCIENTIFIC DATA			MANAGEMENT			
					Min	Max																
In operation	GBT Ku	100 m GBT	Bi-feed	Gregorian (1,9)	12,0	15,4	3,5	2 x 2 (C)	0,9	LNA	Yes	14	30	1,9	No	Radio Recombination Lines, line surveys, chemistry			2000	Routine cryogenic maintenance	None	
	GBT K	100 m GBT	Multi-feed 7 pixels	Gregorian (1,9)	18,0	27,5	7	7 x 2 (C)	0,53	LNA	Yes	21	30-40	1,9	No	Star formation (ammonia), Megamasers, high redshift CO, chemistry	10		2010	Routine cryogenic maintenance	None	
	GBT Ka	100 m GBT	Three-channel dual-feed	Gregorian (1,9)	26,0	39,5	3x4	2 x 1 (C)	0,38	LNA	Yes	20	35-45	1,8	No	CMB (continuum point source subtraction), high redshift CO			2005	Routine cryogenic maintenance	None	
	GBT Q	100 m GBT	Bi-feed	Gregorian (1,9)	38,2	49,8	4	2 x 2 (C)	0,27	Yes	Yes	40-70	65-135	1,7	No	Molecular line surveys, chemistry			2003	Routine cryogemic maintenance	None	
	GBT W_4mm	100 m GBT	Four-channel bi-feed	Gregorian (1,9)	67,0	93,3	4x4	2 x 2 (C)	0,17	Yes	Yes	30-70	110	1	No	Star formation, chemistry	20		2010	Routine cryogenic maintenance	None	
	GBT MUSTANG2	100 m GBT	Bolometer Array	Gregorian (1,9)	80,0	100,0	20	200	0,17	Yes			N/A	N/A	No	Cosmic microwave background, S-Z effect, cluster dynamics	N/A		2017		None	
	GBT Argus	100 m GBT	16x single-pol feed horn array	Gregorian (1,9)	80,0	115,3	1,5	16 x 1 (C)	0,13	Yes		35-60	90-110	0,6-1	No	Star formation, ISM, chemistry filamentry structure in molecular clouds, comets	N/A		2017		None	
	Effelsberg P	100 m Effelsberg	Mono-feed	Primary (0,3)	0,3	0,9	0,6	1 x 2 (C)	25	No	Yes	150	300	1,3	partly fatal	VLBI	0,8	EVN, global VLBI	2007			
	Effelsberg L-low	100 m Effelsberg	Mono-feed	Primary (0,3)	0,8	1,3	0,5	1 x 2 (C)	10	No	Yes	50-95	100	1,5	partly fatal	VLBI	0,1		2000			
	Effelsberg multi-feed L	100 m Effelsberg	Multi-feed 7 beam	Primary (0,3)	1,27	1,45	0,25	1 x 2 (C) 6 x 2 (L)	9	Yes	Yes	10-20	22	1,4	high	Pulsars, Spectroscopy	22,4	EPTA, LEAP	2005			
	Effelsberg L-high	100 m Effelsberg	Mono-feed	Primary (0,3)	1,29	1,7	0,14	1 x 2 (C)	8-9	Yes	Yes	10	20	1,5	high	VLBI, Continuum, Pulsars, Spectroscopy	19,7	EVN, global VLBI	2006			
	Effelsberg UBB	100 m Effelsberg	Mono-feed	Primary (0,3)	0,6	3,0	2,5	1 x 2 (L)	7-15	Yes	Yes	20	50	1,25	partly fatal	Pulsars	2,6		2011			
	Effelsberg S	100 m Effelsberg	Dual-channel mono-feed	Primary (0,3)	2,9 3,3	3,1 3,6	0,1	1 x 1 (L)	4	Yes	Yes	30	35	1,55	moderate - high	Spectroscopy	0,7		1990			
	Effelsberg C	100 m Effelsberg	Mono-feed	Primary (0,3)	5,75	6,75	0,5	1 x 2 (C)	2	Yes	Yes	8	35	1,5	moderate	VLBI	3,8	EVN, global VLBI	2003			
	Effelsberg Ku-low	100 m Effelsberg	Dual-channel mono-feed	Primary (0,3)	12,1 12,9	12,3 13,6	0,1	1 x 2 (C)	1	Yes	Yes	40-50	60-100	1,4	partly bad, parlty moderate	Spectroscopy	0,8		1985			

		TECHNICAL DATA														SCIENTIFIC DATA			MANAGEMENT			
	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
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In operation	Effelsberg Ku-high	100 m Effelsberg	Mono-feed	Primary (0,3)	13,5	18,7	0,5	1 x 1 (L)	0,8-1	Yes	Yes	35	40	0,9 - 1,2	moderate	Spectroscopy	0,3		2002			
	Effelsberg Ka	100 m Effelsberg	Mono-feed	Primary (0,3)	27,0	38,5	2	1 x 1 (L)	0,5	Yes	Yes	10-40	70	0,6 - 0,9	low	Spectroscopy	0,4		1995			
	Effelsberg W	100 m Effelsberg	Bi-feed	Primary (0,3)	84,0	95,5	0,5	2 x 2 (C)	0,2	Yes	Yes	~100	160	0,15	no	VLBI	3	mm-VLBI (GMVA)	2000			
	Effelsberg S-low	100 m Effelsberg	Mono-feed	Secondary (3,85)	2,2	2,3	0,1	1 x 1 (C)	6	No	Yes	80	150	0,5	high	VLBI	0,6 (used only together with the X-band receiver)	EVN, geodetic VLBI	1990			
	Effelsberg S-high	100 m Effelsberg	Mono-feed	Secondary (3,85)	2,6	2,68	0,08	1 x 2 (C)	4	Yes	Yes	4	15	1,5	high	Continuum, Pulsars	5,4	EPTA	1972			
	Effelsberg C	100 m Effelsberg	Bi-feed	Secondary (3,85)	4,6	5,1	0,5	2 x 2 (C)	2,5	Yes	Yes	9	27	1,55	moderate	VLBI, Continuum, Pulsars, Spectroscopy	18,3	EVN, global VLBI, EPTA	2003			
	Effelsberg C/X	100 m Effelsberg	Mono-feed	Secondary (3,85)	4,0	9,3	4	1 x 2 (L)	1,2	Yes	Yes	10	30-40	1,5-1,6	high	Continuum, Spectroscopy, Pulsars	0,3		2015	2nd feed 2018		
	Effelsberg X	100 m Effelsberg	Mono-feed	Secondary (3,85)	7,9	9,0	0,5	1 x 2 (C)	1,2	Yes	Yes	4	22	1,35	moderate	VLBI, Continuum, Pulsars, Spectroscopy	6,1	EVN, global VLBI, geodetic VLBI, EPTA	2001			
	Effelsberg Ku-low	100 m Effelsberg	Bi-feed	Secondary (3,85)	10,3	10,6	0,1	2 x 2 (C)	1	Yes	Yes	50	50	1,35	moderate	Continuum	3,3		1990			
	Effelsberg Ku-high	100 m Effelsberg	Mono-feed	Secondary (3,85)	13,6	15,6	0,5	1 x 2 (C)	0,8	Yes	Yes	30	50	1,1	low	VLBI, Continuum	0,7	global VLBI	1999	new dual feed RX under construction 12 - 18 GHz 2017		
	Effelsberg K	100 m Effelsberg	Bi-feed	Secondary (3,85)	18,0	26,5	8,5	2 x 2 (C)	0,6	Yes	Yes	20	40-70	1,1	moderate - high at 18-19 GHz, otherwise low	VLBI, Continuum, Pulsars, Spectroscopy	8,5	EVN, global VLBI	2014			
	Effelsberg Ka	100 m Effelsberg	Multi-feed 7 beam	Secondary (3,85)	30,0	34,0	4	2 x 2 (L,C)	0,5	Yes	Yes	18-24	60	0,75		Continuum, no IF	0,6		2007			
	Effelsberg Q	100 m Effelsberg	Mono-feed	Secondary (3,85)	41,6	44,4	0,5	1 x 2 (C)	0,3	Yes	Yes	73	120	0,5		VLBI, Continuum, Spectroscopy	1,4	EVN, global VLBI	1999	new dual feed RX under construction 38 - 50 GHz 2017		
	Onsala L-low	25 m Onsala	Broadband-feed	0,3	0,8	1,2	0,1	1 x 2 (C)	49,15	No	Yes	100	900 Jy (SEFD)		Yes	Astro VLBI	NA	EVN	2000			
	Onsala L	25 m Onsala	Broadband-feed	0,3	1,2	1,8	0,3	1 x 2 (C)	32,77	Yes	Yes	30	320 Jy (SEFD)		Yes	Astro VLBI	NA	EVN	2013			
	Onsala C-low	25 m Onsala	Broadband-feed	0,3	4,5	5,3	0,5	1 x 2 (C)	10,03	Yes	Yes	80	450 Jy (SEFD)		No	Astro VLBI	NA	EVN	2013			
	Onsala C-high	25 m Onsala	Broadband-feed	0,3	6,0	6,7	0,5	1 x 2 (C)	7,74	Yes	Yes	80	800 Jy (SEFD)		No	Astro VLBI	NA	EVN	2013			
	Onsala S	20 m Onsala	Mono-feed	0,44	2,2	2,4	0,2	1 x 1 (C)	21,37	Yes	Yes	60	1000 Jy (SEFD)		Yes	Geodetic VLBI, Astro VLBI	NA	IVS, EVN	2007			

	Receiver ID	TECHNICAL DATA														SCIENTIFIC DATA			MANAGEMENT			
		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
					Min	Max																
In operation	Onsala X	20 m Onsala	Mono-feed	0,44	8,2	9,0	0,8	1 x 2 (C)	5,92	Yes	Yes	80	1000 Jy (SEFD)		No	Geodetic VLBI, Astro VLBI	NA	IVS, EVN	2007			
	Onsala K	20 m Onsala	Mono-feed	0,44	18,0	26,0	2x4	1 x 2 (C)	2,58	Yes	Yes	30	55	0,06	Yes	Astro VLBI, Single dish	NA	EVN	2004			
	Onsala Ka	20 m Onsala	Mono-feed	0,44	26,0	36,0	1x4	1 x 1 (L)	1,88	Yes	Yes	50	65	0,056	No?	Single dish	NA		2004			
	Onsala Q	20 m Onsala	Mono-feed	0,44	36,0	49,8	2x4	1 x 2 (C)	1,44	Yes	Yes	50	75	0,051	No?	Astro VLBI, Single dish	NA	EVN	2004			
	Onsala V	20 m Onsala	Mono-feed	0,44	67,0	87,0	2x4	1 x 2 (L)	0,802	Yes	Yes	50-60	95	0,046	No	Astro VLBI, Single dish	NA	GMVA	2015			
	Onsala W	20 m Onsala	Mono-feed	0,44	85,0	116,0	2x4	1 x 2 (L)	0,615	Yes	Yes	50-60	110	0,046	No	Astro VLBI, Single dish	NA	GMVA	2014			
	IRAM EMIR Band 1 (3mm band, E090)	30 m IRAM	Ortho-mode transducer	9,7	73,0	117,0	2 x 8	1 x 2 (L)	0,5	Yes	Yes	35	120K (90GHz, 4mm pwv)	0,17 (@ 86 GHz)	none (in the future possibly car radars)	Ground transition of CO and its isotopomers, and of dense gas tracers HCN, HCO+, HNC, HOC+, deuterated species like DCN, DCO+, N2D+, bright redshifted lines	About 40% of the observed time (2015)	GMVA, EHT	Since 2009. The 3mm band was upgraded in 12/2015 to include the frequency range 73-81GHz.			
	Tianma L	65m Tianma	Monofeed	shaped Cass. (2,19)	1,25	1,75	0,5	1 x 2 (L&C)	10,8	Yes	Yes	14	26	0,66	Yes	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Ssingle-Dish (pulsar, spectroscopy)	15	VLBA, EVN, RadioAstron	2013	No	RFI	
	Tianma S/X	65m Tianma	Dual-frequency coaxial feed	shaped Cass. (2,19)	2,2	2,4	0,2	1 x 2 (C)	7	Yes	Yes	12	22	0,72	Yes	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Ssingle-Dish (pulsar, spectroscopy)	10	EVN, IVS, CVN	2013	No	RFI	
					8,2	9	0,8		1,9		Yes	21	33	0,66	Yes	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Ssingle-Dish (pulsar, spectroscopy)				No	RFI	
	Tianma C	65m Tianma	Monofeed	shaped Cass. (2,19)	4	8	4	1 x 2 (C)	2,7	Yes	Yes	22	32	0,72	Yes	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Ssingle-Dish (pulsar, spectroscopy)	40	VLBA, EVN, RadioAstron, East Asian VLBI	2013	No	RFI	
	Tianma X/Ka	65m Tianma	Dual-frequency coaxial feed	shaped Cass. (2,19)	8	9	1	1 x 2 (C)	1,9	Yes	Yes	15	27	0,66	Yes	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Ssingle-Dish (pulsar, spectroscopy)	10	IVS	2015	No	RFI	
					30	34	4		0,5		Yes	22	32	0,6	No	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Single-Dish (pulsar, spectroscopy)				No	No	

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	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
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In operation	Tianma Ku	65m Tianma	Monofeed	shaped Cass. (2,19)	12	18	6	1 x 2 (C)	1,1	Yes	Yes	30	43	0,66	No	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Single-Dish (pulsar, spectroscopy)	20		2015	No	No	
	Tianma K	65m Tianma	Dualfeed	shaped Cass. (2,19)	18	26,5	8,5	2 x 2 (C)	0,7	Yes	Yes	35	60	0,6	No	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Single-Dish (pulsar, spectroscopy)	0		2016	Upgrade to 7-Pixel	Atmosphere	
	Tianma Q	65m Tianma	Dualfeed	shaped Cass. (2,19)	35	50	8	2 x 2 (C)	0,4	Yes	Yes	40	66	0,6	No	VLBI (Astrophysics, Astrometry/geodesy, space navigation); Single-Dish (pulsar, spectroscopy)	5	East Asian VLBI	2016	No	Atmosphere	
	KVN S/X	22m Sejong	Dual frequency coaxial feed	shaped Cass. (4)														IVS, (EAVN, KaVA)		Wider band backend system		
	KVN C/X	21m KVN Ulsan	Monofeed	shaped Cass. (4)	6,3	7	0,7	1 x 2 (C)		No						Maser		EAVN	2013	Wider band backend system with dual pol support	summer maintanance from June to August; humidity between June to August	
					8	8,8	0,8															
	KVN K	3 x 21m KVN; 1 x 22m Sejong	Monofeed	shaped Cass. (4)	21,25	23,25	2	1 x 2 (C)	2,1	Yes	Yes (simultaneous)	35	70	0,073		AGN, Astrometry Galactic center, Star formation	3000 hours; mostly more than two frequencies simulataneously	EVN, EAVN, KaVA, Radioastron	2008	Wider band backend system	summer maintanance from June to August	
	KVN Q	3 x 21m KVN; 1 x 22m Sejong	Monofeed	shaped Cass. (4)	42,11	44,11	2	1 x 2 (C)	1,1	Yes		75	100	0,073				EVN, EAVN, KaVA, Radioastron	2009	Wider band backend system	summer maintanance from June to August	
	KVN W	3 x 21m KVN	Monofeed	shaped Cass. (4)	85	95	2	1 x 2 (C)	0,5	Yes		90	150	0,061				GMVA, KVN-Nobeyama, (EHT,KVN-Yebes)	2013	Wider band backend system	summer maintanance from June to August; humidity between June to August	
	VERA S/X	4 x 20m VERA	Dual frequency	Cass.	2,21	2,33	0,12	1 X 1 RCP	30	No	Yes (simultaneous)	300	320	0,04	Yes	Geodesy	10	AOV (Asia-Oceania VLBI for Geodesy and Astrometry)	2003			
					8,1	9,1	1	1 X 1 RCP	8	No												
	VERA C	4 x 20m VERA	Monofeed	Cass.	6,5	7	0,5	1 X 1 LCP	10	No	No	100	120	0,05	Yes	AGN, SFR, Maser	10	EAVN, JVN, KaVA,VERA	2007	RCP to be installed		
	VERA K	4 x 20m VERA	Monofeed	Cass.	21,5	23,8	2	1 x 1 LCP	2,5	Yes	Simultaneous optics under develop..	40	100	0,05	No	AGN, SFR, Maser	70	EAVN, JVN, KaVA,VERA	2003	RCP to be installed		
	VERA Q	4 x 20m VERA	Monofeed	Cass.	42,5	44,5	2	1 X 1 LCP	1,3	Yes		80	200	0,04	No	AGN, SFR, Maser	10	EAVN, JVN, KaVA,VERA	2003	RCP to be installed		
	NRO H22	45 m NRO	Mono-feed		20	25	2	1 x 2 (C)	1,2	Yes (15K)			100	0,3477		- H2O maser lines - NH3 lines - VLBI			2005	Yearly Maintenance - Cryro-coole	No Blocker	

TECHNICAL DATA																SCIENTIFIC DATA			MANAGEMENT			
	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
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In operation	NRO H40	45 m NRO	Mono-feed		42,5	44,5	2	1 x 1 (C)	0,62	Yes (15K)			150	0,3021		- SiO maser lines - VLBI			2004	Yearly Maintenance - Cryro-coole	No Blocker	
	NRO Z45	45 m NRO	Mono-feed		42	46	4	1 x 2 (L)	0,61	Yes (15K)		50	100	0,3363		- Zeeman effect - CCS line			2014	Yearly Maintenance - Cryro-coole	No Blocker	Nakamura et al. 2015, PASJ, 67, 117
	NRO T70	45 m NRO	Mono-feed		71,5	92	4	1 x 2 (L)	0,33	Yes (4K)			120-170	0,285-0,2451	Automotive radar (potential)	- Deuterated molecules			2012	Yearly Maintenance - Cryro-coole	No Blocker	
	NRO TZ	45 m NRO	Bi-feed		80	116	4	2 x 2 (L)	0,27	Yes (4K)		40-70	150-300	0,2052-0,1938		- Simultaneous multi-line observation toward point-like sources - Deep integration obseration toward point-like sources			2010	Yearly Maintenance - Cryro-coole	No Blocker	Nakajima et al. 2013, PASP, 125, 252
	NRO FOREST	45 m NRO	Multi-feed		80	116	4	4 x 2 (L)	0,27	Yes (4K)		40-70	150-300	0,285-0,2109		- Large-area mapping - Simultaneous multi-line observation			2014	Yearly Maintenance - Cryro-coole	No Blocker	Minamidani et al. 2016, Proc. SPIE, 9914, 99141Z
	Parkes 10/50	64m Parkes	Dual-frequency coaxial feed	Primary (0,41)	0,7	0,764		2 x 2 (L)			Yes (commutation time 2min)		40	0,909	RFI isues							
					2,6	3,6							35	0,909	RFI isues							
	Parkes MB20	64m Parkes	Multi-feed	Primary (0,41)	1,23	1,53		13 x 2 (L)					28	0,909	RFI isues							
	Parkes H-OH	64m Parkes	Mono-feed	Primary (0,41)	1,2	1,8		1 x 2 (L)					25	0,833	RFI issues							
	Parkes GALILEO	64m Parkes	Mono-feed	Primary (0,41)	2,2	2,5		1 x 2 (C)					20	0,769	RFI issues							
	Parkes S-band	64m Parkes	Mono-feed	Primary (0,41)	2,2	2,5		1 x 2 (L)					79	0,526	RFI issues							
	Parkes C-band	64m Parkes	Mono-feed	Primary (0,41)	4,5	5,1		Single circular with 1/4 of wave					50	0,769	not 100% reliable							
	Parkes METH6	64m Parkes	Mono-feed	Primary (0,41)	5,9	6,8		1 x 2 (C)					55	0,714	not 100% reliable							
	Parkes MARS	64m Parkes	Mono-feed	Primary (0,41)	8,1	8,5		1 x 2 (C)					30	0,588								
	Parkes X-BAND	64m Parkes	Mono-feed	Primary (0,41)	8,1	8,7		1 x 2 (L/C)					110	0,833								
	Parkes Ku	64m Parkes	Mono-feed	Primary (0,41)	12	15		1 x 2 (L)					150	0,625								
	Parkes 13-mm	64m Parkes	Mono-feed	Primary (0,41)	16	26		1 x 2 (L/C)					95	0,455								

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		RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
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In operation	Mopra 20-cm	22m Mopra	Mono-feed	Cassegrain	1,2	1,8	0,128	2 x 2		Yes			35	0,1	RFI							
	Mopra 12-cm	22m Mopra	Mono-feed	Cassegrain	1,8	3	0,128	2 x 2		Yes			35	0,1	RFI							
	Mopra 5-cm	22m Mopra	Mono-feed	Cassegrain	4,4	6,7	0,128	2 x 2		Yes			35	0,1								
	Mopra 3-cm	22m Mopra	Mono-feed	Cassegrain	8	9,2	0,128	2 x 2		Yes			35	0,1								
	Mopra 12-mm	22m Mopra	Mono-feed		16	27	2	1 x 2	1		Yes (change over within minutes remotely)		70	0,0712								
	Mopra 7-mm	22m Mopra	Mono-feed		30	50	2	1 x 2	0,7				80	0,0685								
	Mopra 3-mm	22m Mopra	Mono-feed		76	117	2	1 x 2	0,3				200-600	0,0616								

		TECHNICAL DATA														SCIENTIFIC DATA			MANAGEMENT			
	Receiver ID	RT	Feed system	Focus (F/D)	Frequency coverage [GHz]		Inst.eous BW per Pol. per feed [GHz]	Pixels per pol. (L/C)	HPBW at mid band (arcmin)	Cryo-cooled	Frequency agility	Expected or measured Trx [K]	Expected or measured Tsys at zenith [K]	Expected or measured maximum gain [K/Jy]	RFI in Rx band	Scientific applications	Percentage of the RT observing time allocated to the Rx (average since 2010)	Participation to International network or projects (since 2012)	In operation since or expected to be installed	Maintance and upgrade required to the existing receiver and remaining parts of the under-development receivers	Constraints posed to the RT / infrastructure	Other info
					Min	Max																
Under development	YEBES New K-band	40 m YEBES	Mono-feed	7,909	18	26,5	2GHz	1 x 2 (C)	1,25	Yes	Yes	<20	80	0,29		VLBI/single-dish	N/A	EVN/NanoCosmos/KASI	2017			
	YEBES Q-band Nanocosmos	40 m YEBES	Mono-feed	7,909	31,5	50	18,5GHz	1 x 2 (C/L)	0,6	Yes	Yes	<40	80	0,2		VLBI/single-dish	N/A	EVN/NanoCosmos/KASI	2017			
	YEBES W-band Nanocosmos	40 m YEBES	Mono-feed	7,909	72	91,5	18,5GHz	1 x 2 (C/L)	0,28	Yes	Yes	<60	170	0,55		VLBI/single-dish	N/A	GMVA/NanoCosmos/KASI	2018			
	GBT FLAG Phased-Array Feed	100 m GBT	19x dual pol phased array feed	Prime (0,6)	1,1	1,7	0.155 (future: 0.3)	7x2 (L)	9	LNA		17	25-30 (meas)	N/A	Yes	Galactic HI, nearby galaxies, pulsar / transient searches	N/A		2016	Under development	None	
	GBT L-band replacement	100 m GBT	Mono-feed	Gregorian (1,9)	1,2	1,7	0,65	1 x 2 (L&C)	9	LNA		5 (est)	18 (est)	2	Yes	Pulsars, Radio Transients, galactiv HI, nearby Galaxies	N/A		2017	Planned	None	
	GBT X-band replacement	100 m GBT	Mono-feed	Gregorian (1,9)	8,0	12,0	2,4	1 x 2 (C)	1,4	LNA		11 (est)	25 (est)	2	No	Radio Recombination Lines, Magnetars, VLBI	N/A		2017	Under development	None	
	GBT UWB feed	100 m GBT	Mono-feed	Prime (0,6)	0,5	3,0	2,5	1x2 (?)	0,6	LNA				2	Yes	Pulsar /Radio Transient Seacrhing, pulsar timing	N/A		2018?	Planned	None	
	GBT KPAF Phased Array Feed	100 m GBT	256x single pol phased-array feed	Gregorian (1,9)						Yes				1,8	No	Ammonia mapping	N/A		2020?	Future	None	
	GBT 50 pixel W-band receiver	100 m GBT	50x single pol feed horn array	Gregorian (1,9)						Yes				1	No	Star formation, ISM, chemistry filamentry structure in molecular clouds, comets	N/A		2020?	Future	None	
	Onsala Broad-band	20 m Onsala	Broadband-feed	0,44	4	12				Yes						Astro VLBI, Geodetic VLBI, Single dish	N/A	EVN, IVS				
	Tianma Ka	65m Tianma	Dual-feed	shaped Cass. (2,19)	26	40	8	2 x 2 (C)	0,5	Yes	Yes	14	26	0,6	No	VLBI	N/A		2017	Building	Atmosphere	
	Parkes UWB (low)	64m Parkes	Mono-feed	Primary	0,7	4,0		1 x 2 (L)									N/A			Prototyped		
	Parkes Rocket PAF	64m Parkes	94 elements; 36 beams	Primary	0,6	1,8											N/A			Under discussion		
	Parkes UWB (mid)	64m Parkes	Mono-feed	Primary	4,0	12,0	2x2	1 x 2 (L)									N/A			Under discussion		
	Parkes UWB (high)	64m Parkes	Mono-feed	Primary	12,0	25,0	2x2	1 x 2 (L)									N/A			Under discussion		

C. Publications using the Italian radio telescopes

This Appendix reports on the efficiency, in terms of scientific and technological publications, of the use of the receivers installed at the four Italian radio telescopes. **Scientific publications** are listed for the period Jan 2012 - Dec 2016 assuming that they should be representative of observations made in 2010 or later. For MED and NOTO only refereed publications are included. This restriction has not been applied to SRT given the very recent start of its scientific operations. For SRT and NC, **technological publications** related to radio astronomy receivers at the Italian radio telescopes in the period Jan 2010 - Dec 2016 have been considered, including also non-refereed papers. Almost all the receivers at MED and NOTO have been built before 2010, thus the technological publications for these two telescopes have not been included in this report.

The list of scientific publications and statistics for both MED and NOTO are grouped in Section C.1 and C.2, due to the similar characteristics of these telescopes, their operations dating back to the '80 and their common participation to most of the EVN and geodetic experiments.

As already discussed in Sections 1.4 and 1.5, there were some considerably long stops in telescope operations (as well as the unavailability of some receivers/back-ends) at Medicina and Noto in the considered time period. The impact of such aspects on the publication rate should be taken into account for a correct interpretation of the following statistics and is briefly discussed in the next Section. In the following, the definition “observing mode” refers to single-dish or VLBI.

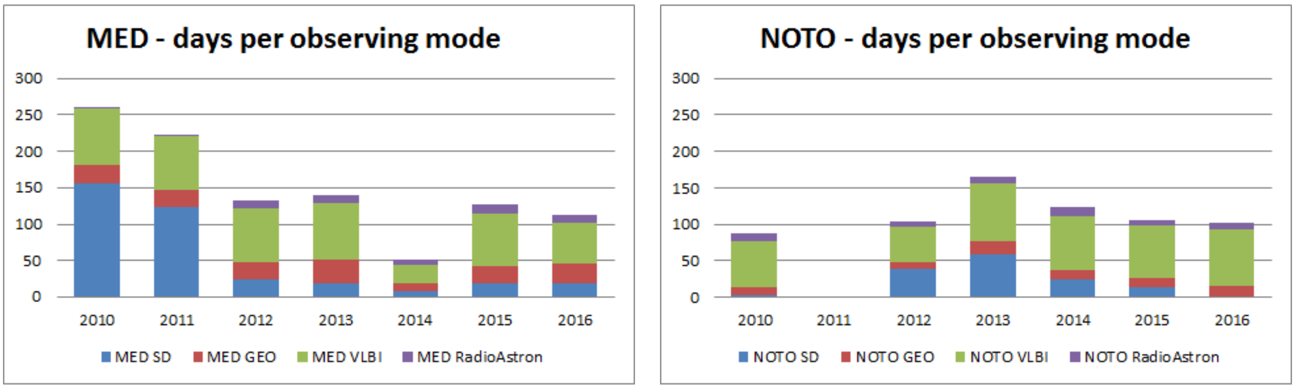
C.1 Medicina and Noto radio telescopes

In Fig. C.1 the number of days (full-day equivalents) dedicated to each observing mode at MED and NOTO in the years 2010-2016 is shown. Tab. C.I lists the number of publications using data taken with the receivers installed on these telescopes in the years 2012-2016. Two publications use both single-dish and VLBI data (Orienti et al., 2016 and Orienti et al., 2014) and have been counted only once in this Section among the single-dish publications. The Norris et al. (2013) paper does not specify the frequency used and has not been included in the statistics. Finally, some publications report the use of both antennas, each at a different frequency (e.g. Duev et al., 2015). To avoid losing the information on which receiver has been used at which telescope, such publications have been included in both the “Medicina only” and the “Noto only” entries in Tab. C.II.

The comparison of Fig. C.1 and Tab. C.I shows that the number of days dedicated to VLBI observations, as well as the number of VLBI refereed publications, remains almost constant in the considered period. On the contrary, the decrease in the number of single-dish publications is delayed by about two years with respect to the decrease in the number of single-dish observing days. This difference can be explained by the availability of well tested and widely used software for interferometric data reduction, allowing a shorter period between the acquisition and the scientific exploitation of the data, while single-dish processing still largely relies on custom-made programs often developed ad-hoc. Similarly, the prolonged stop of the Medicina telescope in 2014 reflects in a very low rate of publications in the year 2015 for VLBI and in 2016 for single-dish.

Other factors that likely affected the publication rate are related to the availability of receivers and modern observing tools. A significant fraction of the single-dish observing time at MED in 2010 and 2011 was devoted to multi-feed K-band observations and almost all the single-dish publications listed in this report make use of ESCS, available at Medicina since 2008. The K-band 7-

horn receiver currently at SRT has been available for observations at MED until May 2011, while the new dual-feed K-band receiver has been available starting from February 2013. Between 2011 and 2013 Medicina was equipped with the old K-band mono-feed receiver, which was however not usable for observations with the new ESCS observing software. NOTO started the commissioning of the ESCS software at the end of 2016. The unavailability of an observing system suited for single-dish observations affected the single-dish publication rate of NOTO with respect to MED.



(a) (b)

Figure C.1 – Observing days (full-day equivalents) for the various observing modes in the period 2010-2016: (a) MED and (b) NOTO

Year	VLBI	Single-Dish	Total
2016	39	1	40
2015	22	6	28
2014	36	5	41
2013	37	6	43
2012	42	14	56
Total	**176**	**32**	**208**

Table C.I – VLBI and single-dish scientific publications in the period 2012-2016

Total single-dish publications using Medicina only	20
Total single-dish publications using Noto only	1
Total single-dish publications using both telescopes	11
Total VLBI publications using Medicina only	39
Total VLBI publications using Noto only	4
Total VLBI publications using both telescopes	133

Table C.II – Scientific publications as a function of telescope and observing mode

C.1.1 Statistics on scientific publications

In Tab. C.III the same publication has been counted more than once if it is related to the use of more than one receiver/telescope/observing mode. The label GEO refers to publications from geodetic observations using VLBI techniques. The label VLBI refers to radio astronomical observations using VLBI techniques (including RadioAstron).

There are two publications that use both single-dish and VLBI data: Orienti et al. (2016) and Orienti et al. (2014). With respect to receivers statistics in Tab. C.III and C.IV, each observing frequency used in these two publications has been properly counted and associated to its observing technique.

Receiver	**VLBI (*) (**)**		**SD**	**GEO (**)**	**TOT**
Medicina K	3	7	16	0	26
Medicina X	7	11	21	39	78
Medicina Chigh	4	16	0	0	20
Medicina Clow	15	43	17	0	75
Medicina S	0	5	0	39	44
Medicina Lhigh	15	35	0	1	51
Medicina Llow	1	3	0	0	4
TOTAL	*45*	*120*	*54*	*79*	*298*
	165				

Table C.III – Scientific publications as a function of MED receiver and observing mode

Receiver	**VLBI (*) (**)**		**SD**	**GEO (**)**	**TOT**
Noto Q	2	0	10	0	12
Noto K	0	7	4	0	11
Noto X	0	11	5	34	50
Noto Chigh	0	16	0	0	16
Noto Clow	6	43	1	0	50
Noto S	0	5	0	34	39
Noto Lhigh	2	35	0	0	37
Noto Llow	0	3	0	0	3
TOTAL	*10*	*120*	*20*	*68*	*218*
	130				

Table C.IV – Scientific publications as a function of NOTO receiver and observing mode

(*) First column refers to VLBI publications using only MED (or only NOTO), second column refers to VLBI publications using both antennas.
(**) Publications labeled as "EVN/VLBI/GEO/IVS" that do not specify the antenna names have been attributed to both MED and NOTO (if the receiver is available at that telescope).
Detailed tables with the number of publications for a given receiver and observing mode for each one of the years considered in this report can be found in Section C.5.

C.1.2 Authorship statistics

Authorship of Medicina and Noto publications has been investigated according to the presence of Italian co-author(s) with particular regard to IRA staff scientists. A number of codes have been defined, as detailed in Tab. C.V, and have been used in the publication list in Section C.2.

Authorship	**List code**	**VLBI**	**SD**
Italian first author	FIRST	6	3
IRA first author	FIRST IRA	13	9
Italian co-author	YES	8	6
IRA co-author	YES IRA	11	7
no Italian (co-)author	NO	130	3
Italian first author + IRA co-author	FIRST/YES IRA	2	4

Table C.V – Sceintific publications authorship

C.2 Medicina and Noto radio telescopes: list of scientific publications

For each refereed scientific paper the telescope(s) used, frequency, authorship and the scientific keywords in the paper are listed. For papers based on inteferometric observations the array name quoted in the publication is given. The label GEO is added to the telescope name whenever the VLBI technique has been used for geodetic studies.

2016

NOTE: Orienti et al. (2016) use both single-dish and EVN data. It is listed among single-dish publications but it has been counted also among VLBI ones for statistical purposes in Section C.1.

1) Altamimi, Z., et al., 2016. J. Geophys. Res. Solid Earth 121, 6109. “ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions”

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: n/a.

2) An, T., et al., 2016. PASJ 68, 77. "VLBI observations of flared optical quasar CGRaBS J0809+5341"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Noto	5 GHz	NO

Keywords: galaxies: active, radio continuum: galaxies, quasars: individual (CGRaBS J0809+5341), techniques: interferometric.

3) Akiyama, K., Johnson, M. D., 2016. ApJ 824, 3. "Interstellar Scintillation and the Radio Counterpart of the Fast Radio Burst FRB 150418"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	NO

Keywords: galaxies: individual (WISE J071634.59-190039.2), galaxies: jets, Galaxy: nucleus, radio continuum: galaxies, radio continuum: ISM, scattering.

NOTE: it uses data from Marcote et al 2016, ATel 8959

4) Akiyama, K., et al., 2016. ApJ 823, 26. "EVN Observations of HESS J1943+213: Evidence for an Extreme TeV BL Lac Object"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.6 GHz	YES IRA

Keywords: galaxies: active, galaxies: individual: HESS J1943+213, galaxies: jets, radio continuum: galaxies, techniques: high angular resolution, techniques: interferometric.

5) Bachmann, S., et al., 2016. Journal of Geodesy 90, 631. "IVS contribution to ITRF2014"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	IVS (GEO)	S/X	NO

Keywords: ITRF2014, VLBI, Intra-technique combination, Station coordinates, Terrestrial reference frame, Earth orientation parameters, Base-line interferometry, Celestial Reference Frame, atmospheric gradients, VLBI terrestrial, realization, geodesy, tides.

6) Bartkiewicz, A., Szymczak, M., van Langevelde, H. J. , 2016. A&A 587, 104. "European VLBI Network imaging of 6.7 GHz methanol masers"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	6.7 GHz	NO

Keywords: masers, stars: massive, instrumentation: interferometers, stars: formation.

7) Beltrán, M. T., de Wit, W. J., 2016. A&ARv 24, 6. "Accretion disks in luminous young stellar objects"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	6.7 GHz	NO

Keywords: accretion: accretion disks, techniques: high angular resolution, techniques: interferometric, stars: formation.

8) Biggs, A.,D., et al., 2016. MNRAS 462, 2819. "Parsec-scale H I absorption structure in a low-redshift galaxy seen against a compact symmetric object"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.38 GHz	NO

Keywords: galaxies: active, galaxies: individual: J0855+5751, galaxies: individual: SDSS J085519.05+575140.7, galaxies: ISM, radio lines: galaxies.

9) Boccardi, B., et al., 2016. A&A 585, 33. "The stratified two-sided jet of Cygnus A. Acceleration and collimation"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Noto	43 GHz	NO

Keywords: galaxies: jets, galaxies: active, instrumentation: high angular resolution.

10) Bondi, M., et al., 2016. A&A 588, 102. "Unveiling the radio counterparts of two binary AGN candidates: J1108+0659 and J1131-0204"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: nuclei, galaxies: interactions, radio continuum: galaxies, techniques: interferometric.

11) Bruni, G., et al., 2016. AN 337, 180. "Fast outflows in broad absorption line quasars and their connection with CSS/GPS sources"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: evolution, galaxies: jets, quasars: absorption lines.

NB: it uses data from Bruni et al., 2013.

12) Burke-Spolaor, S., et a., 2016. ApJ 826, 223. "Limits on Fast Radio Bursts from Four Years of the V-FASTR Experiment"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	8.4 GHz	NO

Keywords: pulsars: general, radio continuum: general.

13) Coppejans, R., et al., 2016. MNRAS 463, 3260. "On the nature of bright compact radio sources at $z > 4.5$ "

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7 GHz (Medicina), 5 GHz (Noto)	NO

Keywords: galaxies: active, galaxies: high-redshift, radio continuum: galaxies.

14) Coppejans, R., et al., 2016. MNRAS 459, 2455. "What are the megahertz peaked-spectrum sources?"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.66 GHz	NO

Keywords: techniques: high angular resolution, techniques: interferometric, galaxies: active, galaxies: high-redshift, radio continuum: galaxies.

15) Covino, S., Gotz, D., 2016. Astronomical & Astrophysical Transactions 29, 205. "Polarization of prompt and afterglow emission of Gamma-Ray Bursts"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	FIRST

Keywords: polarization, gamma-ray burst: general.

NB: it uses data from van der Horst et al., 2014.

16) Duev, D. A., et al., 2016. A&A 593, 34. "Planetary Radio Interferometry and Doppler Experiment (PRIDE) technique: A test case of the Mars Express Phobos fly-by"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	8.4 GHz	YES IRA

Keywords: techniques: interferometric, techniques: miscellaneous, methods: data analysis, astrometry.

17) Frey, S., et al., 2016. MNRAS 455, 2058. "Four hot DOGs in the microwave"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7 GHz	NO

Keywords: techniques: interferometric, galaxies: active, galaxies: high-redshift, galaxies: starburst, radio continuum: galaxies.

18) Giroletti, M., et al., 2016. A&A 593, 16. "FRB 150418: clues to its nature from European VLBI

Network and e-MERLIN observations"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: individual: WISE J071634.59-190039.2, radio continuum: galaxies, scattering.

19) Gomez, J. L., et al., 2016. ApJ 817, 96. "Probing the Innermost Regions of AGN Jets and Their Magnetic Fields with RadioAstron. I. Imaging BL Lacertae at 21 Microarcsecond Resolution"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	22 GHz	NO

Keywords: galaxies: active, galaxies: individual: BL Lac, galaxies: jets, polarization, radio continuum: galaxies.

20) Hees, A., et al., 2016. Universe 2, 30. "Tests of Lorentz Symmetry in the Gravitational Sector"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	IVS (GEO)	S/X	NO

Keywords: general relativity and quantum cosmology, high energy physics – phenomenology.

21) Kraszewska, K., Jagoda, M., Rutkowska, M., 2016. Acta Geophysica, 64, 1495. “Tectonic Plate Parameters Estimated in the International Terrestrial Reference Frame ITRF2008 Based on SLR Stations”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	GEO	S/X	NO

Keywords: tectonic plate motion, ITRF2008, SLR stations.

22) Le Bail, K., et al., 2016. AJ 151, 79. "IVS Observation of ICRF2-Gaia Transfer Sources"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina (GEO)	S/X	NO

Keywords: astrometry, catalogs, quasars: general, reference systems, techniques: interferometric.

23) Le Poncin-Lafitte, C., Hees, A., Lambert, S., 2016. Phys. Rev. D 94, 125030. “Lorentz symmetry and very long baseline interferometry”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: n/a.

24) Madzak, M., et al., 2016. Journal of Geodesy 90, 1237. "High-frequency Earth rotation variations deduced from altimetry-based ocean tides".

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: Earth rotation variations, empirical ocean tides, tidal currents, angular momentum changes, VLBI.

25) Mertens, F., et al., 2016. A&A 595, 54."Kinematics of the jet in M 87 on scales of 100-1000 Schwarzschild radii"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	1.7 GHz	NO

Keywords: galaxies: active, galaxies: individual: M 87,galaxies: jets,magnetohydrodynamics (MHD).
NB: it uses data from Giroletti et al. (2012) and Asada et al.(2014)

26) Orienti, M., et al., 2016. Galaxies 4, 26. "Flaring γ-Ray Emission from High Redshift Blazars"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, EVN	8.4, 24 GHz	FIRST IRA

Keywords: galaxies: active, gamma-rays: general, radiation mechanisms: non-thermal.
NB: this paper uses also EVN, it is not clearly said which telescope (EVN or MED) at which frequency. Both frequencies are attributed to Med and EVN (MED+NOTO) in the statistics.

27) Plank, L., et al., 2016. MNRAS 455, 343. "On the estimation of a celestial reference frame in the presence of source structure"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: techniques: interferometric, astrometry, reference systems, quasars: general.

28) Radcliffe, J. F., et al., 2016. A&A 587, 85. "Multi-source self-calibration: Unveiling the microJy population of compact radio sources"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	1.6 GHz	NO

Keywords: techniques: interferometric, radio continuum: galaxies, instrumentation: interferometers.

29) Reid, M. J., et al., 2016. ApJ 823, 77. "A Parallax-based Distance Estimator for Spiral Arm Sources"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	1.4, 6.7	NO

Keywords: Galaxy: structure, parallaxes, stars: formation.
NB: frequencies inferred from paper description (study of HI and CO).

30) Romero-Canizales, C., et al., 2016. ApJ 832, 10. "The TDE ASASSN-14li and Its Host Resolved at Parsec Scales with the EVN"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz (Medicina), 5 GHz (Noto)	NO

Keywords: galaxies: active, galaxies: individual (PGC 043234), galaxies: nuclei, radio continuum: galaxies.

31) Russell, T. D., et al. 2016. MNRAS 460, 3720. "The reproducible radio outbursts of SS Cygni"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	NO

Keywords: stars: individual: (SS Cygni), stars: jets, novae, cataclysmic variables, radio continuum: stars, X-rays: stars.

32) Schindelegger, M., et al., 2016. Surv Geophys 37, 643. "The Global S1 Tide in Earth's Nutation"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: Earth rotation variations, nutation, geophysical excitation, atmospheric tides, ocean tides, nonrigid earth, forced nutations, open-ocean, pressure, models, dissipation, interferometry, precession, excitation, rotation.

33) Soja, B., et al., 2016. Journal of Geodesy 90, 1311. "Determination of a terrestrial reference frame via Kalman filtering of very long baseline interferometry data"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: terrestrial reference frame, VLBI, Kalman filter, seismic events, seasonal signal.

34) Straal, S. M., et al., 2016. ApJ 822, 117. "HESS J1943+213: A Non-classical High-frequency-peaked BL Lac Object"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.6 GHz	NO

Keywords: BL Lacertae objects: individual: HESS J1943+213, pulsars: general.
NB: it uses data from Gabanyi et al., 2013

35) Szymczak, M., et al., 2016. MNRAS 459, 56. "Discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	6.7 GHz	NO

Keywords: masers, stars: formation, stars: individual: G107.298+5.639, ISM: clouds, radio lines: ISM.

36) Tornatore, V., Tanır Kayıkçı, E., Roggero, M., 2016. Adv. Space Res. 58, 2742. " Comparison of ITRF2014 station coordinate input time series of DORIS, VLBI and GNSS"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	FIRST

Keywords: DORIS, VLBI, GNSS, ITRF2014, time series modeling, harmonic analysis.

37) Tseng, C., et al., 2016. ApJ 833, 288. "Structural Transition in the NGC 6251 Jet: an Interplay with the Supermassive Black Hole and Its Host Galaxy"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords:galaxies: active, galaxies: individual (NGC 6251), galaxies: jets,radio continuum: galaxies.

38) Wielgosz, A., Brzezinski, A., Bohm, S., 2016. Artificial Satellites 51, 135. “Complex Demodulation in Monitoring Earth Rotation by VLBI: Testing the Algorithm by Analysis of Long Periodic EOP Components”

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: Earth orientation parameters, Earth rotation, Very Long Baseline Interferometry, complex demodulation.

39) Wielgosz, A., Tercjak, M., Brzezinski, A., 2016. Reports on Geodesy and Geoinformatics 101, 1 “Testing impact of the strategy of VLBI data analysis on the estimation of Earth Orientation Parameters and station coordinates”

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina (GEO)	S/X	NO

Keywords: VLBI, weighting strategy, EOP, station coordinates.

40) Yang, J., et al., 2016. MNRAS 462, 66. "No apparent superluminal motion in the first-known jetted tidal disruption event Swift J1644+5734"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: galaxies: individual: Swift J1644+5734, galaxies: jets, radio continuum: galaxies.

2015

1) Aleksic, J., et al., 2015. A&A 573, 50. “Multiwavelength observations of Mrk 501 in 2008”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8.4 GHz (Medicina); 43 GHz (Noto)	YES IRA

Keywords: astroparticle physics, BL Lacertae objects: individual: Mrk 501, gamma rays: general.

2) Aleksic J. et al., 2015. A&A 576, 126. “The 2009 multiwavelength campaign on Mrk 421: Variability and correlation studies”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8.4 GHz (Medicina); 8.4, 22.3 GHz (Noto)	YES IRA

Keywords: BL Lacertae objects: individual: Mrk 421.

3) Argo, M. K., et al., 2015. MNRAS 452, 1081. "A new period of activity in the core of NGC 660"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.4 GHz	NO

Keywords: techniques: high angular resolution, galaxies: individual: NGC 660, radio continuum: galaxies.

4) Bobylev, V. V., 2015. AstL 41, 156. "Residual HCRF rotation relative to the inertial coordinate system"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7, 22 GHz	NO

Keywords: astronomical catalogs, astrometry, radio stars, VLBI observations, masers.

5) Bobylev, V. V., Bajkova, A. T., 2015. MNRAS 447, 50. "Detection of periodic variations in the vertical velocities of Galactic masers"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	NO

Keywords: masers, stars: formation, Galaxy: stellar content.

6) Bogdanov, S., et al., 2015. ApJ 806, 148. "Coordinated X-Ray, Ultraviolet, Optical, and Radio Observations of the PSR J1023+0038 System in a Low-mass X-Ray Binary State"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: pulsars: general, pulsars: individual: PSR J1023+0038, stars: neutron, X-rays: binaries.

7) Boucher, C., Pearlman, M., Sarti, P., 2015. AdSpR 55, 24. “Global geodetic observatories”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	IVS (GEO)	S/X	YES IRA

Keywords: global geodetic observatories, GGOS, space geodesy, space geodetic techniques, co-locations, tie vectors.

8) Carnerero, M. I., et al., 2015. MNRAS 450, 2677. “Multiwavelength behaviour of the blazar OJ 248 from radio to gamma-rays”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	5,8,22 GHz (Medicina); 43 GHz (Noto)	YES IRA

Keywords: galaxies: active, galaxies: jets, quasars: general, quasars: individual: OJ 248.

9) Ceglowski, M., Kunert-Bajraszewska, M., Roskowinski, C., 2015. MNRAS 450, 1123. "VLBI survey of compact broad absorption line quasars with balnicity index BI = 0"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7 GHz	NO

Keywords: galaxies: active, galaxies: evolution, quasars: absorption lines.

10) Cseh, D., et al., 2015. MNRAS 452, 24. "The evolution of a jet ejection of the ultraluminous X-ray source Holmberg II X-1"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz (Medicina, Noto); 5 GHz (Noto)	NO

Keywords: accretion, accretion discs, black hole physics, X-rays: binaries.

11) de Bruyn, A. G., & Macquart, J.-P., 2015. A&A 574, 125. "The intra-hour variable quasar J1819+3845: 13-year evolution, jet polarization structure, and interstellar scattering screen properties"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	8.4 GHz	NO

Keywords: techniques: high angular resolution, quasars: individual:, J1819+3845, radiation mechanisms: non-thermal, scattering, galaxies: active, ISM: clouds.

12) Deller, A. T., Moldon, J., Miller-Jones, J. C. A., 2015. ApJ 809, 13. "Radio Imaging Observations of PSR J1023+0038 in an LMX B State"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: accretion, accretion disks, pulsars: individual: PSR J1023+0038, radio continuum: stars, X-rays: binaries

13) Duev, D. A., et al., 2015. A&A 573, 99. "RadioAstron as a target and as an instrument: Enhancing the Space VLBI mission's scientific output"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz (Noto); 8.4 GHz (Medicina)	NO

Keywords: astrometry, techniques: interferometric, instrumentation: interferometers, instrumentation: miscellaneous.

14) Faggi S., et al., 2015. Planetary & Space Science 118, 173. "Search for ammonia in comet C/2012 S1 (ISON)"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
SD	Medicina	23.7 GHz	FIRST

Keywords: comets: individual: C/2012 S1 (ISON), techniques: radio observations, ISM: molecules.

15) Frey, S., et al., 2015. MNRAS 446 2921. "The first estimate of radio jet proper motion at z > 5"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	NO

Keywords: techniques: interferometric, galaxies: active, quasars: individual: SDSS J102623.61+254259.5, radio continuum: galaxies.

16) Gubanov, V. S., Kurdubov, S. L., 2015. Astronomy Letters 41, 225. "Influence of Ocean Tides on the Diurnal and Semidiurnal Earth Rotation Variations from VLBI Observations"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	IVS (GEO)	S/X	NO

Keywords: Earth's rotation, tidal deformations, VLBI observations.

17) Gubanov, V. S., Kurdubov, S. L., 2015. Astronomy Letters 41, 232. "Resonances in Solid Earth Tides from VLBI Observations"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	IVS (GEO)	S/X	NO

Keywords: Earth's tidal deformations, VLBI observations.

18) Kirsten, F., et al., 2015. A&A 577, 111. "Revisiting the birth locations of pulsars B1929+10, B2020+28, and B2021+51"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	5 GHz	NO

Keywords: pulsars: individual: B1929+10, pulsars: individual: B2020+28, pulsars: individual: B2021+51, parallaxes, techniques: interferometric, proper motions.

19) Kunert-Bajraszewska, et al., 2015. A&A 579, 109. "A VLBI survey of compact broad absorption line quasars with balnicity index BI > 0"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	NO

Keywords: galaxies: active, galaxies: evolution, quasars: absorption lines.

20) Lobanov, A. P., t al., 2015. A&A 583, 100. "RadioAstron space VLBI imaging of polarized radio emission in the high-redshift quasar 0642+449 at 1.6 GHz"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Noto	1.6 GHz	NO

Keywords: galaxies: jets, galaxies: nuclei, quasars: individual: 0642+449.

21) Mantovani, F., et al., 2015. A&A 577, 36. "A sample of weak blazars at milli-arcsecond resolution"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	FIRST IRA

Keywords: galaxies: active, quasars: general, BL Lacertae objects: general.

22) Nechaeva, M. B., et al.,2015. R&QE 57, 691. "VLBI Radar of the 2012 DA14 Asteroid"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	YES IRA

Keywords: n/a

23) Plank, L,, et al., 2015. AdSpR 56, 304. "Challenges for geodetic VLBI in the southern hemisphere"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina (GEO)	S/X	NO

Keywords: VLBI, Southern hemisphere reference frames, source uncertainties, IVS.

24) Raiteri C.M., et al., 2015. MNRAS 454, 353. “The WEBT campaign on the BL Lac object PG 1553+113 in 2013. An analysis of the enigmatic synchrotron emission”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8 GHz (Medicina); 43 GHz (Noto)	FIRST/ YES IRA

Keywords: galaxies: active, BL Lacertae objects: general, BL Lacertae objects: individual: PG 1553+113

25) Rampadarath, H., et al., 2015. MNRAS 452, 32. "A high-resolution wide-field radio survey of M51"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	1.6 GHz	NO

Keywords: instrumentation: interferometers, galaxies: individual: (M51), galaxies: Seyfert, radio continuum: general, X-rays: general.

26) Seitz, M., 2015. 1st International Workshop on the Quality of Geodetic Observation and Monitoring Systems 2015, International Association of Geodesy Symposia 140, 57. Ed: Kutterer, H., Seitz, F., Alkhatib, H., et al. "Comparison of Different Combination Strategies Applied for the Computation of Terrestrial Reference Frames and Geodetic Parameter Series"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	IVS (GEO)	S/X	NO

Keywords: n/a

NB: from Springer: peer-reviewed proceedings.

27) Sulentic J.W., et al., 2015. MNRAS 450, 1916. “3C 57 as an atypical radio-loud quasar: implications for the radio-loud/radio-quiet dichotomy”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5 GHz	YES

Keywords: line: profiles, quasars: emission lines, quasars: general, quasars: individual: 3C 57.

28) Surcis, G., et al., 2015. A&A 578, 102. "EVN observations of 6.7 GHz methanol maser polarization in massive star-forming regions. III. The flux-limited sample"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	YES

Keywords: stars: formation, masers, polarization, magnetic fields.

2014

NOTE: Orienti et al. (2014) uses both single-dish and EVN data. It is listed among single-dish publications but it has been counted also among VLBI ones for statistical purposes in Section C1.

1) Ackermann, M., et al., 2014. ApJ 786, 157. “Multifrequency Studies of the Peculiar Quasar 4C +21.35 During the 2010 Flaring Activity”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 22 GHz	YES IRA

Keywords: galaxies: active, gamma rays: general, quasars: general, quasars: individual: 4C +21.35, radiation mechanisms: non-thermal.

2) Aleksic, J., et al., 2014. A&A 569, 46. “MAGIC gamma-ray and multi-frequency observations of flat spectrum radio quasar PKS 1510-089 in early 2012”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	YES

Keywords: galaxies: active, galaxies: jets, gamma rays:, galaxies, quasars: individual: PKS 1510-089.

3) Aleksic, J., et al., 2014. Science 346, 1080. "Black hole lightning due to particle acceleration at subhorizon scales"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	YES

Keywords: n/a

4) Asada, K., et al., 2014. ApJ 781, 2. "Discovery of Sub- to Superluminal Motions in the M87 Jet: An Implication of Acceleration from Sub-relativistic to Relativistic Speeds"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: galaxies: active, galaxies: individual: M87, galaxies: jets.

5) Azulay, R., et al., 2014. A&A 561, 38. "Radio detection of the young binary HD 160934"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: stars: pre-main sequence, binaries: general, radio continuum: stars, stars: individual: HD 160934.

6) Bartkiewicz, A., Szymczak, M., van Langevelde, H. J., 2014. A&A 564, 110. "European VLBI Network observations of 6.7 GHz methanol masers in clusters of massive young stellar objects"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	6.7 GHz	NO

Keywords: stars: formation, ISM: molecules, masers, instrumentation: high angular resolution.

7) Bietenholz, M. F., 2014. PASA 31, 2. "VLBI Constraints on Type I b/c Supernovae"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI	8.4 GHz	NO

Keywords: supernovae, radio continuum.

8) Blossfeld, M., Seitz, M., Angermann, D., 2014. Journal of Geodesy 88, 45. "Non-linear station motions in epoch and multi-year reference frames"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: ITRF, Epoch reference frame, multi-year reference frame, inter-technique combination, EOP, non-linear station motions, center of mass, center of network, Terrestrial Reference Frame, space geodetic observations, geocenter motion, computations, system.

9) Bobylev, V. V., & Bajkova, A. T., 2014. MNRAS 441, 142. "The local standard of rest from data on young objects with account for the Galactic spiral density wave"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	6.7 GHz	NO

Keywords: masers, Galaxy: kinematics and dynamics, galaxies: individual: local standard of rest.

10) Bosy, J., 2014. Pure and Applied Geophysics 171, 783 . "Global, Regional and National Geodetic Reference Frames for Geodesy and Geodynamics"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: geodetic reference frame, ITRS, ETRS89, GGOS, navigation satellite systems, laser ranging service, VLBI, astrometry, ITRF2008, Poland.
NB: from Springer: peer reviewed journal.

11) Cao, H. -M., et al., 2014. A&A 563, 111. "VLBI observations of the radio quasar J2228+0110 at z = 5.95 and other field sources in multiple-phase-centre mode"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	1.6 GHz	NO

Keywords: techniques: interferometric, radio continuum: galaxies, galaxies: active.

12) Chomiuk, L., et al., 2014. Nature 514, 339. "Binary orbits as the driver of gamma-ray emission and mass ejection in classical novae"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: n/a.

13) Cosmovici, C. B., et al., 2014. Planetary and Space Science 96, 22 . “Search for the 22 GHz water maser emission in selected comets”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	22 GHz	FIRST/YES IRA

Keywords: n/a.

14) D'Ammando F., et al., 2014. MNRAS 438, 3521. “Multiwavelength observations of the gamma-ray-emitting narrow-line Seyfert 1 PMN J0948+0022 in 2011”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: individual: (PMN J0948+0022), galaxies: nuclei, galaxies: Seyfert, gamma-rays: galaxies, gamma-rays: general.

15) Deane, R. P., et al., 2014. Nature 511, 57. "A close-pair binary in a distant triple supermassive black hole system"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.7 GHz (Med, Noto); 5 GHz (Medicina)	NO

Keywords: n/a.

16) Du, Y., et al., 2014. ApJ 782, 38. "Very Long Baseline Interferometry Measured Proper Motion and Parallax of the gamma-Ray Millisecond Pulsar PSR J0218+4232"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: astrometry, pulsars: general, pulsars: individual: PSR J0218+4232.

17) Gabanyi, K. E., et al., 2014. MNRAS 443, 1509. "A single radio-emitting nucleus in the dual AGN candidate NGC 5515"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.7, 5 GHz	NO

Keywords: techniques: interferometric, techniques: spectroscopic, galaxies: individual: NGC 5515, galaxies: Seyfert, radio continuum: galaxies.

18) Gordon, D., et al., 2014, Earth on the Edge: Science for a Sustainable Planet - IAG 25th General Assembly of the International Union of Geodesy and Geophysics, International Association of Geodesy Symposia 139,185. Ed.: Rizos, C., Willis, P. "The Construction of ICRF2 and Its Impact on the Terrestrial Reference Frame"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: ICRF2, VLBI, terrestrial reference frame, Earth orientation parameters, celestial reference frame, quasars, VLBA calibrator survey, Celestial Reference Frame.
NB: from Springer: peer-reviewed proceedings.

19) Hada, K., et al., 2014. ApJ 788, 165. "A Strong Radio Brightening at the Jet Base of M 87 during the Elevated Very High Energy Gamma-Ray State in 2012"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	EVN	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: individual: M 87, galaxies: jets, gamma rays: galaxies, radio continuum: galaxies.

20) King, M. A., Watson, C. S., 2014. Geophysical Journal International 199, 1161. "Geodetic vertical velocities affected by recent rapid changes in polar motion"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: reference systems, sea level change, space geodetic surveys, Earth rotation variations, dynamics of lithosphere and mantle.

21) Kirsten, F., et al., 2014. A&A 565, 43. "Precision astrometry of pulsars and other compact radio sources in the globular cluster M15"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: globular clusters: individual: M15 (NGC 7078), pulsars: individual: M15A, pulsars: individual: M15C, astrometry, X-rays: individuals: 4U 2129+12 (AC211), techniques:

interferometric.

22) Lambert, S., 2014. A&A 570, 108 . "Comparison of VLBI radio source catalogs"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: astrometry, reference systems.

23) Marti-Vidal, I., Marcaide, J. M., 2014. A&A 561, 40. "Limit to the radio emission from a putative central compact source in SN1993J"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	2.3, 5, 8.4, 15, 22 GHz	NO

Keywords: acceleration of particles, radiation mechanisms: non-thermal, ISM: supernova remnants, supernovae:general, supernovae: individual: SN1993J, galaxies:clusters:individual: M81.
NB: coupling freq-antenna unclear, assign all frequencies to both antennas.

24) Mezcua, M., et al., 2014. ApJ 785, 121. "Revealing the Nature of the ULX and X-Ray Population of the Spiral Galaxy NGC 4088"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6, 5 GHz	NO

Keywords: accretion, accretion disks, black hole physics, ISM: jets and outflows, radio continuum: general, X-rays: binaries.

25) Molera Calves, G., et al., 2014. A&A 564, 4. "Observations and analysis of phase scintillation of spacecraft signal on the interplanetary plasma"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	8.4 GHz	YES IRA

Keywords: scattering, plasmas, interplanetary medium, Sun: heliosphere, techniques: interferometric, astrometry.

26) Moscadelli, L., Goddi, C., 2014. A&A 566, 150. "A multiple system of high-mass YSOs surrounded by disks in NGC 7538 IRS1. Gas dynamics on scales of 10-700 AU from CH3OH maser and NH3 thermal lines"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	FIRST

Keywords: ISM: jets and outflows, ISM: molecules, masers, accretion, accretion disks, techniques: interferometric.

27) Orienti, M., et al., 2014. MNRAS 444, 3040. “Exploring the multiband emission of TXS 0536+145: the most distant gamma-ray flaring blazar”

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz (Medicina); 22 GHz Medicina, Noto (EVN)	FIRST IRA

Keywords: radiation mechanisms: non-thermal, galaxies: quasars: individual: TXS 0536+145, gamma-rays: general, radio continuum: general.
NB: this paper uses both single-dish data with Medicina and VLBI data from MED+NOTO at 22 GHz (EVN).

28) Paragi, Z., et al., 2014. ApJ 791, 2. "Probing the Active Massive Black Hole Candidate in the Center of NGC 404 with VLBI"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: black hole physics, galaxies: active, galaxies: individual: NGC 404, radio continuum: galaxies, X-rays: galaxies.

29) Parijskij, Yu. N., et al., 2014. MNRAS 439, 2314. "Observations of the z = 4.514 radio galaxy RC J0311+0507"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.6 GHz	NO

Keywords: galaxies: active, early Universe, radio continuum: galaxies.

30) Pavlovskaya, N. S., Titov, O. A., 2014. ARep 58, 563. "The accuracy with which coordinates of radio telescopes can be estimated using VLBI observations"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto (GEO)	2.7, 8.4 GHz	NO

Keywords: n/a.

31) Perez-Torres, M. A., et al., 2014. ApJ 792, 38. "Constraints on the Progenitor System and the Environs of SN 2014J from Deep Radio Observations"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.66 GHz	NO

Keywords: stars: mass-loss, Supernovae: individual: SN2011fe SN2014J.

32) Pollet, A., et al., 2014. Journal of Geodesy 88, 1095. "Comparison of individual and combined zenith tropospheric delay estimations during CONT08 campaign"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	VLBI (GEO)	S/X	NO

Keywords: combination of space geodetic measurements, ZTD, CONT08, meteorological model, corrective model, GPS data, DORIS, VLBI, combination.

33) Reid, M. J., Honma, M., 2014. ARA&A 52, 339. "Microarcsecond Radio Astrometry"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	EVN	1.6, 6.7, 22 GHz	NO

Keywords: n/a.

34) Romero-Canizales, C., et al., 2014. MNRAS 440, 1067. "The nature of supernovae 2010O and 2010P in Arp 299 - II. Radio emission"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6, 5, 8 GHz	NO

Keywords: supernovae: general, supernovae: individual: SN 2010O, supernovae: individual: SN 2010P, galaxies: individual: Arp 299, galaxies: starburst, radio continuum: galaxies.

35) Seitz, M., Steigenberger, P., Artz, T., 2014. Earth on the Edge: Science for a Sustainable Planet - IAG 25th General Assembly of the International Union of Geodesy and Geophysics, International Association of Geodesy Symposia 139, 215. Edited by: Rizos, C., Willis, P. "Consistent Adjustment of Combined Terrestrial and Celestial Reference Frames"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: International Terrestrial Reference Frame, International Celestial Reference Frame, EOP, VLBI, SLR, GNSS, local ties, combination of normal equations.

NB: from Springer: peer-reviewed proceedings.

36) Surcis, G., et al., 2014. A&A 563, 30. "The magnetic field at milliarcsecond resolution around IRAS 20126+4104"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	6.7 GHz	YES

Keywords: stars: formation, masers, polarization, magnetic fields, ISM: individual objects: IRAS 20126+4104.

37) Tilanus, R. P. J., et al., 2014. arXiv:1406.4650. "Future mmVLBI Research with ALMA: A European vision"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Noto	43 GHz	YES IRA

Keywords: astrophysics - instrumentation and methods for astrophysics.

NB: EVN observations above 30 GHz; 43 GHz is relevant for this report.

38) Tornatore V., et al., 2014. In: Earth on the Edge: Science for a Sustainable Planet, IAG Symposia 139, C. Rizos, P. Willis, Pascal (Eds), ISBN 978-3-642-37221-6 (Print), ISSN 978-3-642-37222-3 (Online), pp. 247-252. "Direct VLBI observations of Global Navigation Satellite System signals"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina (GEO)	Lhigh	FIRST

Keywords: GNSS, local ties, reference frames, space ties, VLBI.

39) van der Horst, A. J., et al., 2014. MNRAS 444, 3151. "A comprehensive radio view of the extremely bright gamma-ray burst 130427A"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: gamma-ray burst: individual: GRB 130427A.

40) Varenius, E., et al., 2014. A&A 566, 15. "The radio core structure of the luminous infrared galaxy NGC 4418. A young clustered starburst revealed?"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: galaxies: Seyfert, galaxies: star formation, galaxies: individual: NGC 4418.

41) Zhang, Z., Liu, X., 2014. AdSpR 54, 1563. "A VLBI baseline post-adjustment approach for station velocity estimation in Eurasian continent"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	IVS (GEO)	S/X	NO

Keywords: n/a.

2013

1) An, T., Paragi, et al., 2013. MNRAS 433, 1161. "The radio structure of 3C 316, a galaxy with double-peaked narrow optical emission lines"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	5 GHz	NO

Keywords: galaxies: active, galaxies: individual: 3C 316, galaxies: ISM, galaxies: jets, radio continuum: galaxies.

2) Argo, M. K., et al., 2013. MNRAS 431, 58. "Probing the nature of compact ultrasteep spectrum radio sources with the e-EVN and e-MERLIN"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.6 GHz	NO

Keywords: galaxies: active, radio continuum: galaxies.

3) Bianchi, S., Piconcelli, E., Perez-Torres, M., 2013. MNRAS 435, 2335. "The NGC 3341 minor merger: a panchromatic view of the active galactic nucleus in a dwarf companion"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.7 GHz (Medicina); 5 GHz (Noto)	FIRST

Keywords: galaxies: active, galaxies: interactions, galaxies: Seyfert, X-rays: individual: NGC 3341.

4) Bobylev, V. V., Bajkova, A. T., 2013. AstL 39, 809. "Galactic rotation curve and spiral density wave parameters from 73 masers"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	6.7, 22 GHz	NO

Keywords: galactic kinematics and dynamics, spiral density waves, masers.

5) Brocksopp, C., et al., 2013. MNRAS 432, 931. "XTE J1752-223 in outburst: a persistent radio jet, dramatic flaring, multiple ejections and linear polarization"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	NO

Keywords: accretion, accretion discs, stars: individual: XTE J1752-223, radio continuum: stars, X-rays: binaries.

6) Bruni, G., et al., 2013. A&A 554, 94. "The parsec-scale structure of radio-loud broad absorption line quasars"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	FIRST IRA

Keywords: quasars: absorption lines, galaxies: active, galaxies: evolution, radio continuum: galaxies.

7) Chi, S., Barthel, P. D., Garrett, M. A., 2013. A&A 550, 68. "Deep, wide-field, global VLBI observations of the Hubble deep field north (HDF-N) and flanking fields (HFF)"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	EVN	1.4 GHz	NO

Keywords: galaxies: active, radio continuum: galaxies, galaxies: starburst.

8) Dallacasa, D., et al., 2013. MNRAS 433, 147. "A sample of small-sized compact steep-spectrum radio sources: VLBI images and VLA polarization at 5 GHz"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Noto	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: jets, galaxies: nuclei, quasars: general, radio continuum: galaxies, radio continuum: general.

9) D'Ammando F., et al., 2013. MNRAS 436, 191. "Multifrequency studies of the narrow-line Seyfert 1 galaxy SBS 0846+513"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
SD	Medicina	5, 8.4 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: individual: SBS 0846+513, galaxies: nuclei, galaxies: Seyfert, gamma-rays: general.

10) Deane, R. P., et al., 2013. MNRAS 434, 3322. "The preferentially magnified active nucleus in IRAS F10214+4724 - III. VLBI observations of the radio core"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.7 GHz	NO

Keywords: gravitational lensing: strong, galaxies: active, galaxies: individual: IRAS F10214+4724.

11) Doi, A., et al., 2013. PASJ 65, 57. "Multifrequency VLBI Observations of the Broad Absorption Line Quasar J1020+4320: Recently Restarted Jet Activity?"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: galaxies: active, galaxies: jets, galaxies: quasars: absorption lines, galaxies: quasars: individual (SDSS J102027.20+432056.2), radio continuum: galaxies.

12) Frey, S., et al., 2013. A&A 552, 109. “A compact radio source in the high-redshift soft gamma-ray blazar IGR J12319-0749”

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	NO

Keywords: techniques: interferometric, radio continuum: galaxies, galaxies: active, quasars: individual: IGR J12319-0749.

13) Gabanyi, K. E., et al., 2013. ApJ 762, 63. "Very Long Baseline Interferometry Search for the Radio Counterpart of HESS J1943+213"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina	1.6 GHz	NO

Keywords: ISM: supernova remnants, radio continuum: general, radio lines: ISM, techniques: interferometric, X-rays: individuals: CXOU J194356.2+211823.

14) Gitti, M., et al., 2013. A&A 557, 14. "A candidate supermassive binary black hole system in the brightest cluster galaxy of RBS 797"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
VLBI	Medicina, Noto	5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: clusters: individual: RBS 797, radio continuum: galaxies.

15) Imai, H., et al., 2013. ApJ 771, 47. "Exploration of a Relic Circumstellar Envelope in the 'Water

Fountain' Source IRAS 18286-0959"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: masers, stars: AGB and post-AGB, stars: individual: IRAS 18286-20130959, stars: mass-loss, stars: winds, outflows.

16) Imai, H., et al., 2013. ApJ 773, 182. "The Spatiokinematical Structure of H2O and OH Masers in the 'Water Fountain' Source IRAS 18460-0151"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: masers, stars: AGB and post-AGB, stars: individual: IRAS 18460-20130151, stars: kinematics and dynamics, stars: mass-loss, stars: winds, outflows.

17) Kardashev, N. S., et al., 2013. ARep 57, 153. "RadioAstron"-A telescope with a size of 300 000 km: Main parameters and first observational results"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	YES IRA

Keywords: n/a.

18) Krasna, H., et al., 2013. Acta Geodaetica et Geophysica 48, 389. "Investigation of crustal motion in Europe by analysing the European VLBI sessions"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: crustal motion, geodetic VLBI, reference frame, plate tectonics, european geodetic VLBI network, current plate motions, interferometry, constraints, astrometry, network, bifrost, geodesy.

19) Levshakov S.A., et al., 2013. A&A 559, 91. "Limits on the spatial variations of the electron-to-proton mass ratio in the Galactic plane"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	18, 23 GHz	YES IRA

Keywords: line: profiles, ISM: molecules, radio lines:, ISM, techniques: radial velocities, elementary particles.

NB: frequencies as from Levshakov 2010 AA 512, 44.

20) Lopez-Caniego M., et al., 2013. MNRAS 430, 1566. "Mining the Herschel-Astrophysical Terahertz Large Area Survey: submillimetre-selected blazars in equatorial fields"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5 GHz	YES IRA

Keywords: BL Lacertae objects: general, quasars: general, submillimetre: general.

21) MacLeod, C. L., et al., 2013. ApJ 773, 35. "Detection of Substructure in the Gravitationally Lensed Quasar MG0414+0534 Using Mid-infrared and Radio VLBI Observations"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	8.4 GHz	NO

Keywords: galaxies: structure, gravitational lensing: strong.

22) Malkin, Z., 2013. A&A 558, 29. "A new approach to the assessment of stochastic errors of radio source position catalogues"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: astrometry, reference systems, methods: data analysis.

23) Mezcua, M., et al., 2013. MNRAS 436, 1546. "Milliarcsec-scale radio emission of ultraluminous X-ray sources: steady jet emission from an intermediate-mass black hole?"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: accretion, accretion discs, black hole physics, ISM: jets and outflows, radio continuum: general, X-rays: binaries.

24) Mezcua, M., Lobanov, A. P., Martí-Vidal, I., 2013. MNRAS 436, 2454. "The resolved structure of the extragalactic supernova remnant SNR 4449-1"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: supernovae: individual: SNR 4449-1, ISM: supernova remnants, radio continuum: general.

25) Miller-Jones, J. C. A., et al., 2013. Science 340, 950. "An Accurate Geometric Distance to the Compact Binary SS Cygni Vindicates Accretion Disc Theory"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	NO

Keywords: n/a.

26) Moscadelli, L., et al., 2013. A&A 549, 122. "A double-jet system in the G31.41 + 0.31 hot molecular core"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	FIRST

Keywords: techniques: interferometric, masers, ISM: kinematics and dynamics.

27) Nechaeva, M., al., 2013. BaltA 22, 341. "First Results of the VLBI Experiment on Radar Location of the Asteroid 2012 DA14"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	YES IRA

Keywords: instrumentation: interferometers, Very Long Baseline Interferometry, methods: observational, techniques: interferometric, radar astronomy, ephemeris, asteroid 2012 DA14.

28) Nechaeva, M., et al., 2013. BaltA 22, 35. "A experiment on radio location of objects in the near-Earth space with VLBI in 2012"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	YES IRA

Keywords: instrumentation: interferometers, Very Long Baseline Interferometry, techniques: interferometric, radar astronomy, ephemeris.

29) Norris, R. P., et al., 2013. PASA 30, 20. "Radio Continuum Surveys with Square Kilometre Array Pathfinders"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	?	YES IRA

Keywords: radiotelescopes, surveys, galaxy evolution, cosmology.

NB: listed for completeness but not used in the statistics, as no frequency is specified in this paper.

30) Panessa, F., Giroletti, M., 2013. MNRAS 432, 1138. "Sub-parsec radio cores in nearby Seyfert galaxies"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz	FIRST/YES IRA

Keywords: galaxies: active, galaxies: jets, galaxies: nuclei, galaxies: Seyfert, radio continuum: galaxies, X-rays: galaxies.

31) Orienti M., et al., 2013. MNRAS 428, 2418. "Radio and gamma-ray follow-up of the exceptionally high-activity state of PKS 1510-089 in 2011"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	FIRST IRA

Keywords: radiation mechanisms: non-thermal, galaxies quasars: individual: PKS 1510-089, radio continuum: general.

32) Paragi, Z., et al., 2013. MNRAS 432, 1319. "VLBI observations of the shortest orbital period black hole binary, MAXI J1659-152"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	YES

Keywords: stars: individual: MAXI J1659-152, ISM: jets and outflows, X-rays: binaries.

33) Petrov, L., 2013. AJ 146, 5. "The Catalog of Positions of Optically Bright Extragalactic Radio Sources OBRS-2"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	2.7, 8.4 GHz	NO

Keywords: astrometry, catalogs, surveys.

34) Rani, B., et al., 2013. A&A 552, 11. "Radio to gamma-ray variability study of blazar S5 0716+714"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Noto	5, 8, 22, 43 GHz	YES

Keywords: galaxies: active, BL Lacertae objects: individual: S5 0716+714, gamma rays: galaxies, X-rays: galaxies, radio continuum: galaxies.

35) Ricci R., et al., 2013. MNRAS 435, 2793. "A 20 GHz bright sample for DEC > 72d - II. Multifrequency follow-up"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8 GHz	FIRST IRA

Keywords: galaxies: active, radio continuum: galaxies, radio continuum: general.

36) Sarti, P., Abbondanza, C., Altamimi, Z., 2013. Reference Frames for Applications in Geosciences - IAG Symposium on Reference Frames for Applications in Geosciences, International Association of Geodesy Symposia 138, 75. Ed.: Altamimi, Z., Collilieux, X. "Local Ties and Co-Location Sites: Some Considerations After the Release of ITRF2008"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	GEO	S/X	FIRST IRA

Keywords: Tie vector, Local tie, Co-location site, ITRF, Combination residuals, Point, VLBI.

NB: from Springer: peer-reviewed proceedings.

37) Sarti, P., et al., 2013. Geophysical Journal International 192, 1042. "Intrasite motions and monument instabilities at Medicina ITRF co-location site"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina (GEO)	S/X	FIRST IRA

Keywords: time-series analysis, reference systems, space geodetic surveys, intraplate processes, Europe.

38) Schaap, R. G., et al., 2013. MNRAS 434, 585. "Scintillation is an indicator of astrometric stability"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	IVS (GEO)	S/X	NO

Keywords: scattering, astrometry, reference systems, ISM: structure, quasars: general.

39) Seitz, M., Angermann, D., Drewes, H., 2013. Reference Frames for Applications in Geosciences - IAG Symposium on Reference Frames for Applications in Geosciences , International Association of Geodesy Symposia 138, 87. Ed.: Altamimi, Z., Collilieux, X. "Accuracy Assessment of the ITRS 2008 Realization of DGFI: DTRF2008"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: International terrestrial reference frame, ITRF2008, DTRF2008, Combination, GPS, SLR, VLBI, DORIS, Datum parameters.

NB: from Springer: peer-reviewed proceedings.

40) Spencer, R. E., et al., 2013. MNRAS 435, 48. "Radio and X-ray observations of jet ejection in Cygnus X-2"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: acceleration of particles, accretion: accretion discs, stars: neutron, X-rays: binaries, X-rays: individual: Cygnus X-2.

41) Surcis, G., et al., 2013. A&A 556, 73. "EVN observations of 6.7 GHz methanol maser polarization in massive star-forming regions. II. First statistical results"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	6.7 GHz	NO

Keywords: stars: formation, masers, polarization, magnetic fields.

42) Teke, K., et al., 2013. Journal of Geodesy 87, 981. "Troposphere delays from space geodetic techniques, water vapor radiometers, and numerical weather models over a series of continuous VLBI campaigns"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: Troposphere delays, Space geodetic techniques, Numerical weather models, Water vapor radiometers, Base-line interferometry, zenith delays, time-series, GPS, gradients, DORIS, improvements, terrestrial, systems, errors.

43) Wu, F., et al., 2013. A&A 550, 113. "Kinematics of the compact symmetric object OQ 208 revisited"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	2.3, 8.4 GHz	YES IRA

Keywords: radio continuum: galaxies, galaxies: active.

2012

1) Abramowski, A., et al., 2012. ApJ 746, 151. "The 2010 Very High Energy gamma-Ray Flare and 10 Years of Multi-wavelength Observations of M 87"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	YES

Keywords: galaxies: active, galaxies: individual: M 87, galaxies: jets, galaxies: nuclei, gamma rays: galaxies, radiation mechanisms: non-thermal.

2) Ackermann M., et al., 2012. ApJ 751, 159. "Multi-wavelength Observations of Blazar AO 0235+164 in the 2008-2009 Flaring State"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	5, 8, 22 (Medicina); 43 GHz (Noto)	YES IRA

Keywords: BL Lacertae objects: individual: AO 0235+164, galaxies: active, galaxies: jets, gamma rays: galaxies, radiation mechanisms: non-thermal.

3) Alexandroff, R., et al., 2012. MNRAS 423, 1325. "A search for active galactic nuclei in the most extreme UV-selected starbursts using the European VLBI Network"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz	NO

Keywords: techniques: interferometric, galaxies: active, galaxies: ISM, galaxies: starburst, radio continuum: galaxies.

4) Altamimi, Z., Metivier, L., Collilieux, X., 2012. Journal of Geophysical Research - Solid Earth 117, 7402. "ITRF2008 plate motion model"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: glacial isostatic-adjustment, reference frame, space geodesy, ICE-5G VM2, Earth, velocity, deformation, viscosity, surface, impact.

5) An, T., Baan, W. A., 2012. ApJ 760, 77. "The Dynamic Evolution of Young Extragalactic Radio Sources"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	1.6 GHz	NO

Keywords: galaxies: active, galaxies: evolution, galaxies: jets.
NB: data from five bands in the range 1.6-15 GHz, but frequencies are not specified. Consider only 1.6 GHz.

6) An, T., et al., 2012. ApJS 198, 5. "VLBI Observations of 10 Compact Symmetric Object

Candidates: Expansion Velocities of Hot Spots"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	8.4 GHz	NO

Keywords: galaxies: active, galaxies: evolution, galaxies: jets, galaxies: nuclei, radio continuum: galaxies.

7) Asada, K., Nakamura, M., 2012. ApJ 745, 28. "The Structure of the M87 Jet: A Transition from Parabolic to Conical Streamlines"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: galaxies: active, galaxies: individual: M87, galaxies: jets.

8) Bartkiewicz, A., Szymczak, M., van Langevelde, H. J., 2012. A&A 541, 72. "Milliarcsecond structure of water maser emission in two young high-mass stellar objects associated with methanol masers"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	22 GHz	NO

Keywords: stars: formation, ISM: molecules, masers, instrumentation: high angular resolution.

9) Batejat, F., et al., 2012. A&A 542, 24. "Rapid variability of the compact radio sources in Arp220. Evidence for a population of microblazars?"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	NO

Keywords: galaxies: nuclei, galaxies: starburst, galaxies: individual: Arp220, radio continuum: stars, X-rays: binaries.

10) Bondi, M., et al., 2012. A&A 539, 134. "The nuclear starburst in Arp 299-A: from the 5.0 GHz VLBI radio light-curves to its core-collapse supernova rate"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6, 5 GHz	FIRST IRA

Keywords: galaxies: starburst, galaxies: luminosity function, mass function, galaxies: individual: Arp 299, supernovae: general, radiation mechanisms: non-thermal, radio continuum: stars.

11) Bontempi, P., et al., 2012. MNRAS 426, 588. "Physical properties of the nuclear region in Seyfert galaxies derived from observations with the European VLBI Network"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: nuclei, galaxies: Seyfert, radio continuum: galaxies.

12) Brand J., et al., 2012. A&A 547, 85. "Molecular gas and stars in the translucent cloud MBM18 (LDN1569)"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	22 GHz	FIRST IRA

Keywords: stars: formation, stars: emission-line, Be, ISM: clouds, ISM: individual objects: MBM 18 (LDN 1569).

13) Cseh, D., et al., 2012. ApJ 749, 17. "Black Hole Powered Nebulae and a Case Study of the Ultraluminous X-Ray Source IC 342 X-1"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: accretion, accretion disks, black hole physics, ISM: bubbles, ISM: jets and outflows, X-rays: binaries.

14) D'Ammando F., et al., 2012. MNRAS 426, 317. "SBS 0846+513: a new gamma-ray-emitting narrow-line Seyfert 1 galaxy"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	FIRST IRA

Keywords: galaxies: active, galaxies: individual: SBS 0846+513, galaxies: nuclei, galaxies: Seyfert, gamma-rays: general.

15) De Lotto, B., Magic Collaboration, 2012. Journal of Physics: Conference Series Volume 375 Issue 5 id. 052021. "The MAGIC telescopes: performance, results and future perspectives"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8.4 GHz (Medicina); 8.4, 22.3 GHz (Noto)	FIRST

Keywords: n/a.

16) Donnarumma, I., AGILE Team, 2012. Journal of Physics: Conference Series Volume 355 Issue 1 id. 012004. "A review of the multiwavelength studies on the blazars detected by AGILE"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	5, 8, 22 (Medicina); 43 GHz (Noto)	FIRST

Keywords: n/a.

17) Duev, D. A., et al., 2012. A&A 541, 43. "Spacecraft VLBI and Doppler tracking: algorithms and implementation"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	8 GHz	NO

Keywords: instrumentation: interferometers, instrumentation: miscellaneous, techniques: interferometric, astrometry.

18) Fok T. K.T., et al., 2012. ApJ 760, 65. "Maser Observations of Westerlund 1 and Comprehensive Considerations on Maser Properties of Red Supergiants Associated with Massive Clusters"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	22 GHz	NO

Keywords: masers, open clusters and associations: individual: Westerlund 1, stars: late-type, stars: mass-loss, supergiants, radio lines: stars.

19) Foschini, L., et al., 2012. A&A 548, 106. "Radio-to-gamma-ray Monitoring of the Narrow-Line Seyfert 1 Galaxy PMN J0948+0022 from 2008 to 2011"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	FIRST/YES IRA

Keywords: galaxies: jets, galaxies: Seyfert, gamma rays: galaxies, galaxies: individual: PMN J0948+0022.

20) Foster, J. B., et al., 2012. ApJ 751, 157. "Distances to Dark Clouds: Comparing Extinction

Distances to Maser Parallax Distances"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	6.7 GHz	NO

Keywords: dust, extinction, Galaxy: structure, ISM: clouds, masers.

21) Frey, S., et al., 2012. MNRAS 425, 1185. "Two in one? A possible dual radio-emitting nucleus in the quasar SDSS J1425+3231"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	1.7, 5 GHz	NO

Keywords: techniques: interferometric, galaxies: active, quasars: individual: SDSS J1425+3231, radio continuum: galaxies.

22) Giommi, P., et al., 2012. A&A 541, 160. "Simultaneous Planck, Swift, and Fermi observations of X-ray and gamma-ray selected blazars"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	5, 8.4 GHz	FIRST/YES IRA

Keywords: relativistic processes, BL Lacertae objects: general, quasars: general, galaxies: active.

23) Giroletti, M., et al., 2012. A&A 538, 10. "The kinematic of HST-1 in the jet of M 87"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	FIRST IRA

Keywords: galaxies: jets, radio continuum: galaxies, galaxies: nuclei.

24) Hayashida M., et al., 2012. ApJ 754, 114. "The Structure and Emission Model of the Relativistic Jet in the Quasar 3C 279 Inferred from Radio to High-energy gamma-Ray Observations in 2008-2010"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	5,8,22 GHz (Medicina); 43 GHz (Noto)	YES

Keywords: galaxies: active, galaxies: jets, gamma rays: galaxies, quasars: individual: 3C 279, radiation mechanisms: non-thermal, X-rays: galaxies.

25) Herrero-Illana, R., Perez-Torres, M. A., Alberdi, A., 2012. A&A 540, 5. "Evidence of nuclear disks in starburst galaxies from their radial distribution of supernovae"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6, 5 GHz	NO

Keywords: galaxies: starburst, galaxies: luminosity function, mass function, galaxies: individual: Arp 299-A, supernovae: general, radiation mechanisms: non-thermal, radio continuum: stars.

26) Honma, M., et al., 2012. PASJ 64, 136. "Fundamental Parameters of the Milky Way Galaxy Based on VLBI astrometry"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	6.7, 22 GHz	NO

Keywords: astrometry, Galaxy: Galactic parameters, VLBI.
NB: frequencies presumed on the basis of the observed masers.

27) Kirsten, F., Vlemmings, W. H. T., 2012. A&A 542, 44. "No evidence for a central IMBH in M 15"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6 GHz	NO

Keywords: globular clusters: individual: M 15 (NGC 7078), black hole physics, techniques: interferometric, radio continuum: general.

28) La Delfa, S., et al., 2012. International Journal of Earth Sciences 101, 1065. "Geodetic techniques applied to the study of the Etna volcano area (Italy)"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto (GEO)	S/X	FIRST/YES IRA

Keywords: Mt. Etna, VLBI, GPS, mantle, crust, earthquakes, eruptions, mount-Etna, Mt-Etna, triggering mechanisms, ground deformation, flank eruptions, magma, interferometry, evolution, extension, crust.

29) Landau, S. J., et al., 2012. Astroparticle Physics 35, 377. "Space-time variation of the electron-to-proton mass ratio in a Weyl model"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	18, 23 GHz	NO

Keywords: n/a.

NB: frequencies as from Levshakov 2010 AA 512, 44.

30) Li, J. J., et al., 2012. ApJ 749, 47. "Massive Star Formation toward G28.87+0.07 (IRAS 18411-0338) Investigated by Means of Maser Kinematics and Radio to Infrared Continuum Observations"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	YES

Keywords: ISM: individual objects: G28.87+0.07, ISM: kinematics and dynamics, masers, techniques: interferometric.

31) Lindfors, E., MAGIC Collaboration, 2012. Journal of Physics: Conference Series Volume 355 Issue 1 id. 012003. "Recent results from MAGIC observations of AGN"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8.4, 22.3GHz (Med); 8.4,22.3, 43GHz (Noto)	YES

Keywords: n/a.

32) Mesler, R. A., et al., 2012. ApJ 759, 4. "VLBI and Archival VLA and WSRT Observations of the GRB 030329 Radio Afterglow"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: gamma-ray burst: general, gamma-ray burst: individual: GRB 030329.

33) Moldon, J., et al., 2012. A&A 543, 26. "On the origin of LS 5039 and PSR J1825-1446"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	8.4, 5 GHz	NO

Keywords: stars: individual: LS 5039, pulsars: individual: PSR J1825-1446, radio continuum: stars, proper motions, X-rays: binaries, gamma rays: stars.

34) Moldon, J., Ribo, M., Paredes, J. M. , 2012. A&A 548, 103. "Periodic morphological changes in the radio structure of the gamma-ray binary LS 5039"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz	NO

Keywords: stars: individual: LS 5039, radio continuum: stars, binaries: close, gamma rays: stars, X-rays: binaries, radiation mechanisms: non-thermal.

35) Nafisi, V., et al., 2012. RaSc 47, 2020. "Ray-traced tropospheric delays in VLBI analysis"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina (GEO)	S/X	NO

Keywords: numerical weather models, radio refractive-index, interferometry, atmosphere, equation, geodesy, air.

36) O'Sullivan, S. P., et al., 2012. MNRAS 421, 3300. "Complex Faraday depth structure of active galactic nuclei as revealed by broad-band radio polarimetry"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: techniques: polarimetric, galaxies: magnetic fields, radio continuum: galaxies.

37) Perucho, M., et al., 2012. ApJ 749, 55. "Anatomy of Helical Extragalactic Jets: The Case of S5 0836+710"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6, 2, 5, 8 GHz	NO

Keywords: galaxies: jets, magnetohydrodynamics, quasars: individual: S5-0836+710, radio continuum: galaxies, relativistic processes.

38) Perucho, M., et al., 2012. A&A 545, 65. "S5 0836+710: An FRII jet disrupted by the growth of a helical instability?"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.6, 5 GHz	NO

Keywords: galaxies: jets, hydrodynamics, instabilities, quasars: individual: S5 0836+710.

39) Petrov, L., 2012. MNRAS 419, 1097. "The EVN Galactic Plane Survey - EGaPS"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	22 GHz	NO

Keywords: instrumentation: interferometers, catalogues, surveys, astrometry.

40) Piner, B. G., et al., 2012. ApJ 758, 84. "Relativistic Jets in the Radio Reference Frame Image Database. II. Blazar Jet Accelerations from the First 10 Years of Data (1994-2003)"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	8 GHz	NO

Keywords: BL Lacertae objects: general, galaxies: active, galaxies: jets, quasars: general, radio continuum: galaxies.

41) Pushkarev, A. B., Kovalev, Y. Y. , 2012. A&A 544, 34. "Single-epoch VLBI imaging study of bright active galactic nuclei at 2 GHz and 8 GHz"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	2, 8 GHz	NO

Keywords: galaxies: active, galaxies: jets, quasars: general, radio continuum: galaxies.

42) Raiteri C. M., et al., 2012. A&A 545, 48. "Variability of the blazar 4C 38.41 (B3 1633+382) from GHz frequencies to GeV energies"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	5, 8, 22 GHz (Med); 38, 43 GHz (Noto)	YES

Keywords: galaxies: active, quasars: general, quasars: individual: 4C 38.41, galaxies: jets
NB: it uses also 5, 8, 22 GHz archival data.

43) Richter, S., Spanier, F., 2012. International Journal of Modern Physics: Conference Series Volume 8, 392. "A spatially resolved SSC Shock-In-Jet Model"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina, Noto	8.4, 22.3 (Medicina); 8.4, 43 GHz (Noto)	NO

Keywords: active galaxies, jets, Mrk501.

44) Righini S., et al., 2012. MNRAS 426, 2107. "A 20 GHz bright sample for DEC > +72d - I. Catalogue"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	Medicina	22 GHz	FIRST IRA

Keywords: methods: observational, galaxies: active, radio continuum: general.

45) Romero-Canizales, C., et al., 2012. A&A 543, 72. "e-MERLIN and VLBI observations of the luminous infrared galaxy IC 883: a nuclear starburst and an AGN candidate revealed"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	5 GHz	NO

Keywords: galaxies: starburst, galaxies: individual: IC 883, radio lines: stars, radiation mechanisms: non-thermal.

46) Romero-Canizales, C., Perez-Torres, M. A., Alberdi, A., 2012. MNRAS 422, 510. "EVN observations of the farthest and brightest ULIRGs in the local Universe: the case of IRAS 23365+3604"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	1.7, 5 GHz	NO

Keywords: galaxies: individual: IRAS 23365+3604, galaxies: starburst, radio continuum: general.

47) Rushton, A., et al., 2012. MNRAS 419, 3194. "A weak compact jet in a soft state of Cygnus X-1"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	YES

Keywords: stars: individual: Cygnus X-1, ISM: jets and outflows, X-rays: binaries.

48) Rygl, K. L. J., et al., 2012. A&A 539, A79. "Parallaxes and proper motions of interstellar masers toward the Cygnus X star-forming complex. I. Membership of the Cygnus X region"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	6.7 GHz	NO

Keywords: stars: formation, astrometry, techniques: interferometric, ISM: general, masers, ISM: kinematics and dynamics.

49) Schuh, H., Behrend, D., 2012. Journal of Geodynamics 61, 68. "VLBI: A fascinating technique for geodesy and astrometry"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	VLBI (GEO)	S/X	NO

Keywords: Very Long Baseline Interferometry (VLBI), IVS, VLBI2010, CRF, TRF, Earth orientation, Global Geodetic Observing System (GGOS), Base-line interferometry.

50) Souchay, J., et al., 2012. A&A 537, 99. "The second release of the Large Quasar Astrometric Catalog (LQAC-2)"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	2, 8 GHz	YES

Keywords: cosmological parameters, astrometry, quasars: general, catalogs.

51) Surcis, G., et al., 2012. A&A 541, 47. "EVN observations of 6.7 GHz methanol maser polarization in massive star-forming regions"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina, Noto	6.7 GHz	NO

Keywords: stars: formation, masers, polarization, magnetic fields.

52) Suyu, S. H., et al., 2012. ApJ 750, 10. "Disentangling Baryons and Dark Matter in the Spiral Gravitational Lens B1933+503"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	1.7 GHz	NO

Keywords: galaxies: halos, galaxies: individual: B1933+503, galaxies: kinematics and dynamics, galaxies: spiral, gravitational lensing: strong.

53) Wu, Z., Jiang, D. R., Gu, M., 2012. MNRAS 424, 2733. "The radio structure of ultra-high-energy synchrotron-peak BL Lacs"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	EVN	5 GHz	NO

Keywords: galaxies: active, BL Lacertae objects: general, quasars: general.

54) Yang, J., et al., 2012. MNRAS 426, 66. "Very long baseline interferometry detection of the Galactic black hole binary candidate MAXI J1836-194"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	5 GHz	NO

Keywords: stars: individual: MAXI J1836-194, radio continuum: stars, X-rays: binaries.

55) Yang, J., et al., 2012. MNRAS 419, 74. "The radio core and jet in the broad absorption-line quasar PG 1700+518"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	1.6 GHz	NO

Keywords: galaxies: active, galaxies: individual: PG 1700+518, galaxies: jets, radio continuum: galaxies.

56) Zuther, J., Fischer, S., Eckart, A., 2012. A&A 543, 57. "Compact radio emission from z ~ 0.2 X-ray bright AGN"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
VLBI	Medicina	1.6, 5 GHz	NO

Keywords: galaxies: nuclei, radio continuum: galaxies, techniques: interferometric.

C.3 Sardinia Radio Telescope

Given the relatively recent start of the scientific activity at the Sardinia Radio Telescope, we report both the refereed and non-refereed scientific papers based on data taken with the SRT receivers. Technological contribution dealing with the SRT receivers development and performance are listed as well. The observing proposals approved for the Early Science Program and the required receivers are listed as well.

C.3.1 Scientific publications

2016

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1) Bassa, C.G., et al., 2016. MNRAS 456, 2196. "LEAP: the Large European Array for Pulsars"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	L	YES OAC

Keywords: gravitational waves, methods: data analysis, techniques: interferometric, pulsars: general.

2) Egron, E., et al., 2016. The Astronomer's Telegram #9508. "Monitoring of Cyg X-3 giant flare with Medicina and the Sardinia Radio Telescope"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC + YES IRA

Keywords: binary, black hole, neutron star.

3) Egron, E., et al., 2016. The Astronomer's Telegram #9087. "Detection of a bright radio flare of Cygnus X-1 at 7.2 GHz with the Sardinia Radio Telescope"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC

Keywords: binary, black hole.

4) Egron, E., et al., 2016. The Astronomer's Telegram #8921. "Detection of GRS 1915+105 and SS 433 at 7.2 GHz and 21.4 GHz with the Sardinia Radio Telescope"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh, K	FIRST OAC

Keywords: binary, black hole, neutron star, transient.

5) Egron, E., et al., 2016. The Astronomer's Telegram #8849. "Observations of H1743-322 with the Sardinia Radio Telescope: upper limits"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC

Keywords: binary, black hole, transient.

6) Egron, E., et al., 2016. The Astronomer's Telegram #8821. "Sardinia Radio Telescope observations of IGR J17091-3624 - upper limit"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC

Keywords: black hole.

7) Egron, E., et al., 2016. arXiv:1609.03882. Proc. of: Supernova Remnants: An Odyssey in Space after Stellar death, 2016. "Observations of Supernova Remnants with the Sardinia Radio Telescope"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC

Keywords: n/a.

8) Keane, E. F., et al., 2016. Nature 530, 453. "The host galaxy of a fast radio burst"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	L	YES OAC

Keywords: n/a.

9) Loru, S., et al., 2016. arXiv:1609.03875. Proc. of: Supernova Remnants: an Odyssey in Space after Stellar Death, 2016. "Modelling high-resolution spatially-resolved Supernova Remnant spectra with the Sardinia Radio Telescope"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	L, Chigh	FIRST OAC

Keywords: n/a.

10) Murgia, M., et al., 2016. MNRAS 461, 3516. "Sardinia Radio Telescope wide-band spectral-polarimetric observations of the galaxy cluster 3C129".

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	Chigh	FIRST OAC

Keywords: polarization, techniques: polarimetric, galaxies: clusters: individual: 3C 129, radio continuum: galaxies.

11) Perrodin, D., et al., 2016. arXiv:1608.01839. Proc. of: 14th Marcel Grossmann Meeting on General Relativity (MG 14), 2015. "Pulsar observations with European telescopes for testing gravity and detecting gravitational waves "

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD	SRT	L	FIRST OAC

Keywords: n/a.

2014

1) Prandoni et al., 2014. Proc. of 12th European VLBI Network Symposium and Users Meeting (EVN 2014). https://pos.sissa.it/archive/conferences/230/046/EVN%202014_046.pdf "The SRT in the Context of European Networks: Astronomical Validation & Future Perspectives"

Obs. Mode	Telescope	Frequency/Receiver	Italian authorship
SD, VLBI	SRT	P, L, C, K	FIRST IRA

Keywords: n/a.

2013

1) Buttu, M., et al., 2013. The Astronomer's Telegram #5053. "Detection by Sardinia Radio Telescope of radio pulses at 7 GHz from the Magnetar PSR J1745-2900 in the Galactic center region"

Obs. Mode	**Telescope**	**Frequency/Receiver**	**Italian authorship**
SD	SRT	Chigh	FIRST OAC

Keywords: radio, neutron star, soft gamma-ray repeater, pulsar.

C.3.2 Front-end technological publications

2016

1) Ladu, A., et al., 2016. Proceedings of SPIE 9914, Millimeter, Submillimeter, And Far-Infrared Detectors And Instrumentation For Astronomy VIII. "The control system of the 3 mm band SIS receiver for theSardinia Radio Telescope"
Receiver: W.

2) Ladu, A., et al., 2016. Journal of Electromagnetic Waves and Appications 30, 1207. "A wideband quadruple-ridged horn antenna for the multifeed S-band receiver of the Sardinia radio telescope"
Receiver: S.

3) Navarrini, A., et al., 2016. In: 27th International Symposium on Space Terahertz Technology. "The Sardinia Radio Telescope Front-Ends"
Receiver: P/L, Chigh, X/Ka, K.

4) Valente, G., et al., 2016. Proceedings of SPIE, 9914, Millimeter, Submillimeter, And Far-Infrared Detectors And Instrumentation For Astronomy VIII. "The 7-beam S-band cryogenic receiver for the SRT primary focus: project status"
Receiver: S.

5) Valente, G., et al., 2016. Proceedings of SPIE, 9914, Millimeter, Submillimeter, And Far-Infrared Detectors And Instrumentation For Astronomy VIII. "Status of the Radio Receiver System of the Sardinia Radio Telescope"
Receiver: P/L, Chigh, X/Ka, K.

2015

1) Bolli, P., et al., 2015. Journal of Astronomical Instrum., 4(3-4). "Sardinia Radio Telescope: General Description, Technical Commissioning and First Light"
Receiver: P/L, Chigh, K.

2) Pisanu, T., et al., 2015. Proceeding of the 36th ESA Antenna Workshop on Antennas and RF Systems for Space Science. "Installation and characterization of an X-Ka receiver on the Sardinia Radio Telescope"
Receiver: X/Ka.

3) Valente, G., et al., 2015. IEEE Transactions on Microwave Theory and Techniques, 63, 3218. "A Compact L-Band Orthomode Transducer for Radio Astronomical Receivers at Cryogenic Temperature"

Receiver: P/L.

2014

1) Ambrosini R., et a., 2014. 29th URSI General Assembly and Scientific Symposium 2014 16-23 August 2014 Beijing, China. “Commissioning of the Sardinia Radio telescope in Italy: results and perspective”
Receiver: P/L, Chigh, K (NB: commissioning paper, assume it uses these receivers).

2) Bolli, P., et al., 2014. Journal of Astronomical Instrumentation, 3(1). “A high temperature superconductor microwave filter working in C-band for the Sardinia Radio Telescope”
Receiver: Chigh.

3) Ladu, A., et al., 2014. Proceedings of SPIE, 9153,Millimeter, Submillimeter, And Far-Infrared Detectors And Instrumentation For Astronomy VII. “A 3mm band SIS receiver for the Sardinia Radio Telescope”
Receiver: W.

4) Valente, G. Montisci, G., Mariotti, S., 2014. Electronics Letters 50(6). "High-performance microstrip directional coupler for radio-astronomical receivers at cryogenic temperature"
Receiver: P/L.

5) Valente, G., et al., 2014. Proceedings of SPIE, 9153, Millimeter, Submillimeter, And Far-Infrared Detectors And Instrumentation For Astronomy VII. "A multifeed S-band cryogenic receiver for the Sardinia Radio Telescope primary focus”
Receiver: S.

2013

1) Ambrosini, R., et al., 2013. International Conference on Electromagnetics in Advanced Applications (ICEAA), 2013 9-13 Sept 2013 Torino, p. 82-85, ISBN 978-1-4673-5705-0, DOI 10.1109/ICEAA.2013.6632194. “The Sardinia Radio Telescope: overview and status”
Receiver: P/L, Chigh, K.

2012

1) Bolli, P., Huang, F., 2012. Experimental Astronomy 33, 225. “Superconducting Filter for Radio Astronomy Using Interdigitated Spirals”
Receiver: P/L.

2) Pisano, G., et al., 2012. Journal of Electromagnetic Waves and Applications 26, 707. “A Novel Broadband Q-band Polariser with Very Flat Phase Response”
Receiver: Q.

2011

1) Ambrosini, R., Asmar, S.W., Bolli, P., 2011. Proceedings of the IEEE 99, 875. “The Planned Space Science Utilizations of the New Sardinia 64-m Radio Telescope”
Receiver: X/Ka.

2) Peverini, O.A., et al., 2011. IET Microwaves, Antennas & Propagation 5, 1008. "Development of passive microwave antenna-feed systems for wide-band dual-polarisation receivers"
Receiver: Chigh.

3) Valente, G., Navarrini, A., Pisanu, T., 2011. IEEE Microwave and Wireless Components Letters 21, 13. "Double Ridged 180deg Hybrid Power Divider with Integrated Band Pass Filter"
Receiver: P/L.

2010

1) Orfei, A., et al., 2010. IEEE Antennas and Propagation Magazine 52, 62. "A Multifeed Receiver in the 18-26.5 GHz Band for Radioastronomy”
Receiver: K.

2) Pisanu, T., Marongiu, P., Navarrini, A., 2010. Proceedings of SPIE, 7741, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. “A compact L-band Ortho Mode Junction”
Receiver: P/L.

3) Valente, G., Navarrini, A., Pisanu, T., 2010. Proceedings of SPIE, 7741, “Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V”.
“A novel 180° hybrid power divider”
Receiver: P/L.

4) Valente, G., et al., 2010. Proceedings of SPIE, 7741, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy V. “The dual-band LP feed system for the Sardinia Radio Telescope prime focus”
Receiver: P/L.

C.3.3 Early Science Program

The following proposals for the Early Science Program have been approved for observation with the SRT in the first half of 2016.

1) S0001: “SRT Multi-frequency Observations of Galaxy Clusters”.
Receiver: L, Chigh, K.

2) S0003: “Proper motions and star formation activity of Local Group dwarf galaxies”.
Receiver: Chigh, K.

3) S0004: “Class I methanol masers: shock tracers in deeply embedded sources”.
Receiver: K.

4) S0005: “A new view on the family of the eclipsing pulsars”.
Receiver: P/L.

5) S0006: “Radio follow-up of gravitational radiation sources with SRT”.
Receiver: Chigh.

6) S0007: “Mapping the microwave emission of Andromeda: filling the gap between radio and IR emission”.
Receiver: Chigh.

7) S0008: “Searching for pulsars at high frequency in the Galactic Center region”
Receiver: Chigh.

8) S0009: “Constraining Cosmic Rays Production in Supernova Remnants with SRT”.
Receiver: L, Chigh, K.

9) S0010: “The Large European Array for Pulsars”.
Receiver: L.

10) S0011: “Determining the kinetic temperature of star-forming molecular clouds across the outer Galaxy”.
Receiver: K.

11) S0013: “Monitoring of neutron star and black hole X-ray binaries with the SRT”.
Receiver: L, Chigh, K.

12) S0014: “Polarimetric multi-frequency observations of a complete sample of radio sources”.
Receiver: Chigh, K.

13) S0015: “Launching a radio pulsar timing program at SRT”.
Receiver: P/L.

C.4 Northern Cross radio telescope

The following list includes the technological publications related to the Northern Cross Radio Telescope in the period 2010 – 2016.

1) Montebugnoli, S., et al., 2015. Acta Astronautica 116, 382. DOI: 10.1016/j.actaastro.2015.07.030. “Project of a multibeam UHF receiver to improve survey capabilities”.
http://www.scopus.com/inward/record.url?eid=2-s2.0-84944153094&partnerID=MN8TOARS

2) Morselli, A., et al., 2015. Proceedings of 2nd IEEE International Workshop on Metrology for Aerospace, Benevento, Italy June 3-5, 2015. IEEE Catalog Number: CFP1532W-USB; ISBN: 978-1-4799-7568-6. “A new high sensitivity radar sensor for space debris detection and accurate orbit determination”

3) Morselli, A., et al., 2014. 65th International Astronautical Congress, 29 September 2014, Toronto, Canada. IAC-14-A6.9.4. “Orbit Determination of Space Debris Using a Bi-static Radar Configuration with a Multiple-Beam Receiver”, http://eprints.soton.ac.uk/372082/1/Article-formatted.pdf

4) Foster, G., et al., 2014. MNRAS 439, 3180. DOI:10.1093/mnras/stu188. “Implementation of a direct-imaging and FX correlator for the BEST-2 array”

5) Magro, A., Hickish J., Zarb Adami, K., 2013. Journal of Astronomical Instrumentation 2, 1350008. DOI: 10.1142/S2251171713500086. “Multibeam GPU transient pipeline for the Medicina BEST-2 Array”

6) Montebugnoli, S., et al., 2010. Acta Astronautica 66, 610. “The next steps in SETI-ITALIA science and technology”. http://dx.doi.org/10.1016/j.actaastro.2009.07.015

7) Montebugnoli, S., et al., 2010. Acta Astronautica 67, 1350. “SETI-ITALIA 2008: On-going searches and future prospects”.

C.5 Medicina and Noto radio telescopes: detailed tables

In the following tables the number of scientific publications for each MED and NOTO receiver and observing mode (VLBI, Geodesy and Single-Dish) is given for the years considered in this report.

<table>
<tr><th>2016</th><th colspan="6">VLBI</th></tr>
<tr><th>Receiver</th><th colspan="2">Medicina</th><th colspan="2">Noto</th><th colspan="2">Both</th></tr>
<tr><td></td><td>GEO</td><td>Non-GEO</td><td>GEO</td><td>Non-GEO</td><td>GEO</td><td>Non-GEO</td></tr>
<tr><td>Q</td><td>n/a</td><td>n/a</td><td></td><td>1</td><td>n/a</td><td>n/a</td></tr>
<tr><td>K</td><td></td><td>2</td><td></td><td></td><td></td><td></td></tr>
<tr><td>X</td><td>2</td><td>2</td><td></td><td></td><td>11</td><td>1</td></tr>
<tr><td>Chigh</td><td></td><td>1</td><td></td><td></td><td></td><td>3</td></tr>
<tr><td>Clow</td><td></td><td>2</td><td></td><td>3</td><td></td><td>6</td></tr>
<tr><td>S</td><td>2</td><td></td><td></td><td></td><td>11</td><td></td></tr>
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<tr><td>Llow</td><td></td><td>1</td><td></td><td></td><td></td><td>1</td></tr>
<tr><th colspan="7">SD</th></tr>
<tr><th>Receiver</th><th colspan="2">Medicina</th><th colspan="2">Noto</th><th colspan="2">---</th></tr>
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Table C.VI – Year 2016 publications as a function of telescope, receiver and observing mode

2015	**VLBI**					
Receiver	**Medicina**		**Noto**		**Both**	
	GEO	Non-GEO	GEO	Non-GEO	GEO	Non-GEO
Q	n/a	n/a			n/a	n/a
K						1
X	1	1			4	1
Chigh						3
Clow		2		1		5
S	1				4	
Lhigh		1		2		2
Llow						1

SD			
Receiver	**Medicina**	**Noto**	**---**
Q	n/a	3	
K	2	1	
X	4	1	
Chigh			
Clow	2		
S			
Lhigh			
Llow			

Table C.VII – Year 2015 publications as a function of telescope, receiver and observing mode

2014	**VLBI**					
Receiver	**Medicina**		**Noto**		**Both**	
	GEO	Non-GEO	GEO	Non-GEO	GEO	Non-GEO
Q	n/a	n/a		1	n/a	n/a
K						3
X					9	4
Chigh		2				3
Clow		2				9
S					9	1
Lhigh	1	3				9
Llow						

SD			
Receiver	**Medicina**	**Noto**	**---**
Q	n/a		
K	2		
X	3		
Chigh			
Clow	4		
S			
Lhigh			
Llow			

Table C.VIII – Year 2014 publications as a function of telescope, receiver and observing mode

2013			**VLBI**			
Receiver	**Medicina**		**Noto**		**Both**	
	GEO	Non-GEO	GEO	Non-GEO	GEO	Non-GEO
Q	n/a	n/a			n/a	n/a
K						1
X	1				7	2
Chigh		1				2
Clow		4		2		8
S	1				7	1
Lhigh		4				6
Llow						1
			SD			
Receiver	**Medicina**		**Noto**		**---**	
Q	n/a		1			
K	1		1			
X	3		1			
Chigh						
Clow	4		1			
S						
Lhigh						
Llow						

Table C.IX – Year 2013 publications as a function of telescope, receiver and observing mode

2012			**VLBI**			
Receiver	**Medicina**		**Noto**		**Both**	
	GEO	Non-GEO	GEO	Non-GEO	GEO	Non-GEO
Q	n/a	n/a			n/a	n/a
K		1				2
X	1	4			3	3
Chigh						5
Clow		5				15
S	1				3	3
Lhigh		3				13
Llow						
			SD			
Receiver	**Medicina**		**Noto**		---	
Q	n/a		6			
K	10		2			
X	10		3			
Chigh						
Clow	7					
S						
Lhigh						
Llow						

Table C.X – Year 2012 publications as a function of telescope, receiver and observing mode

D. Surface refurbishment of the Medicina Radio Telescope

In this Appendix, two possible options for the MED upgrade to efficiently observe at high frequencies are described. The improved antenna gain at different frequencies up to 100 GHz are shown and compared to the current one. The calculations of realistic performance of a W-band receiver achievable today and a comparison with the sensitivity of the GMVA antennas are also given.

D.1 Current situation and effects of upgrades

The gravity deformations of the 32-m Medicina antenna are well established by measurements performed on 1989. Additionally, the manufacturing accuracy of the current main primary mirror panels and of the subreflector surface are also known. The panels manufacturing accuracy and the precision in the alignment of the panels are the main components affecting the overall surface accuracy and consequently the antenna gain (or aperture efficiency). For completeness, it is however convenient to also add other minor parameters.

Tab. D.I lists all the parameters affecting the surface accuracy as a function of the elevation. These are Root Sum Squared (RSS) in order to get the overall surface accuracies reported in the last line of the table.

ALL UNITS IN μm	El=20°	El=30°	El=45°	El=60°	El=90°
Error Source	RMS				
Panels manufacturing accuracy	**570**	**570**	**570**	**570**	**570**
Panels measurement error	25	25	25	25	25
Panel thermal effect	15	15	15	15	15
Panel gravity deformation	30	30	30	30	30
Panel wind effect	30	30	30	30	30
Structure field alignment	**200**	**200**	**200**	**200**	**200**
Structure gravity deformation	400	250	0	190	580
Structure thermal+wind effect	48	48	48	48	48
Subreflector manufacturing error	**350**	**350**	**350**	**350**	**350**
Subreflector thermal effect	15	15	15	15	15
Subreflector wind effect	15	15	15	15	15
overall RSS	***808.0***	***745.2***	***702.0***	***727.3***	***910.6***

Table D.I – Components affecting the overall surface accuracy of MED

By using the Ruze formula, it is possible to calculate how much the theoretical antenna gain, i.e. the gain due to a proper illumination of the mirrors, is decreased by surface accuracy effects. This is shown for various frequencies in Fig. D.1, which describes the current situation of the Medicina antenna gain at 5, 22 and 43GHz (values at 100 GHz are not shown since they are zero at any elevation). Atmospheric effects, not considered for the moment, would further decrease the gain values.

In order to test the likelihood of this simulation we compare it with true measurements routinely performed with MED. In Fig. D.2a and D.2b, measured gain values at 22 and 5 GHz are shown respectively.

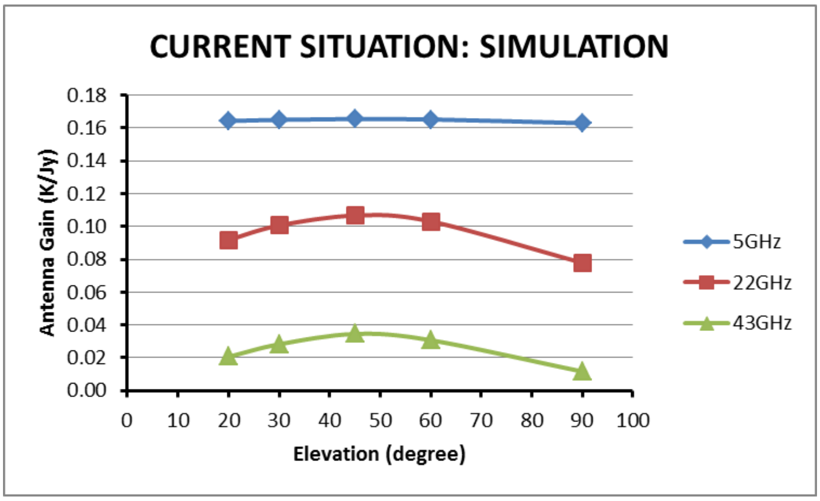
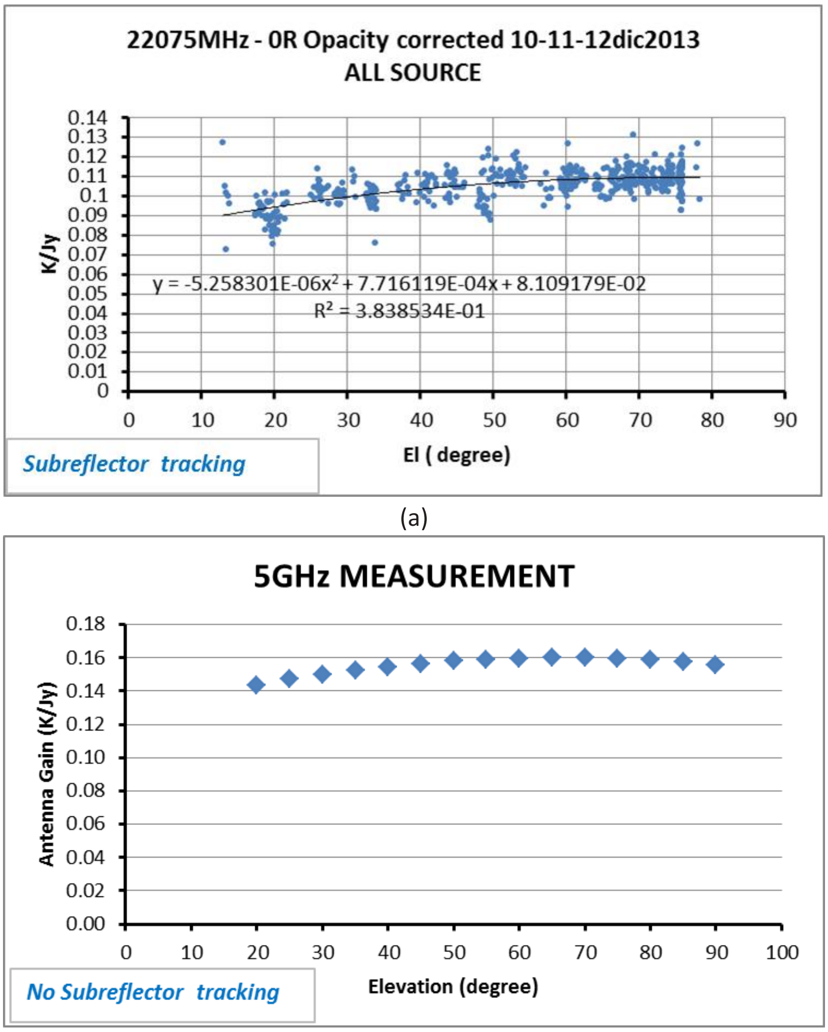


Figure D.1 – Simulated antenna gain at MED



(a)

(b)

Figure D.2 – MED measured gain values at: (a) 22 GHz and (b) 5 GHz

Both experimental results of Fig. D.2 match very closely the simulated values of Fig. D.1, the curve at 22 GHz being actually better than the simulation. This discrepancy is due to the beneficial effect of optimizing the position of the subreflector on varying the elevation and shows that the Ruze formula, which assumes the deviations to be small scale and randomly distributed, is actually underestimating the surface error efficiency. The subreflector optimization allows to recover a good beam shape and to compensate the deformations due to gravity. This is confirmed at 5 GHz where the tracking of the secondary mirror is disabled and the curve is not perfectly flat, but the effects of the deformations are nevertheless practically negligible because the observing wavelength is high compared to the RSS surface accuracy value.

Having "validated" the model at low frequencies, it is possible to calculate the impact of a refurbishment of the telescope surfaces on the antenna gain. The upgrade of the antenna for high frequency observations can be made in two ways:

1) by replacing both main primary mirror panels and subreflector surface with new, more accurate ones;
2) by adding to 1) the installation of actuators to realize an active surface system.

A conservative value for the manufacturing accuracy of panels with the same dimension as those used for the MED primary mirror is 60 μm. The secondary mirror could reach an accuracy of 50 μm, again a conservative value.

The real challenge resides in the request of a very good alignment of the corners of four converging panels and of all panels as a whole. This is a mandatory requirement for high frequency observations. A realistic value obtainable by using photogrammetry and then holography techniques is an accuracy of 100 μm.

By applying the refurbishment option 1) to MED, the parameters in Tab. D.I would be modified according to Tab. D.II.

ALL UNITS IN μm	El=20°	El=30°	El=45°	El=60°	El=90°
Error Source	RMS				
Panels manufacturing accuracy	**60**	**60**	**60**	**60**	**60**
Panels measurement error	25	25	25	25	25
Panel thermal effect	15	15	15	15	15
Panel gravity deformation	30	30	30	30	30
Panel wind effect	30	30	30	30	30
Structure field alignment	**100**	**100**	**100**	**100**	**100**
Structure gravity deformation	400	250	0	190	580
Structure thermal+wind effect	48	48	48	48	48
Subreflector manufacturing error	**50**	**50**	**50**	**50**	**50**
Subreflector thermal effect	15	15	15	15	15
Subreflector wind effect	15	15	15	15	15
overall RSS	***426.0***	***289.8***	***146.6***	***240.0***	***598.3***

Table D.II – Components affecting the overall surface accuracy in case of refurbishment option 1)

Fig. D.3 shows the resultant antenna gain values calculated by applying the Ruze formula with the figures in Tab. D.II at various frequencies up to 100 GHz.

Note here the large improvement of the gain at 22 and 43 GHz and, above all, the presence of reasonable values for the gain even at the highest frequencies. Again, these curves do not take into account the beneficial effect of moving the subreflector on varying the elevation, thus it is expected that the real 22 GHz curve would flatten and, to a certain degree, also the 43, 86 and 100 GHz ones. At the moment, the amount of improvement due to subreflector tracking is known for the 22 GHz case only.

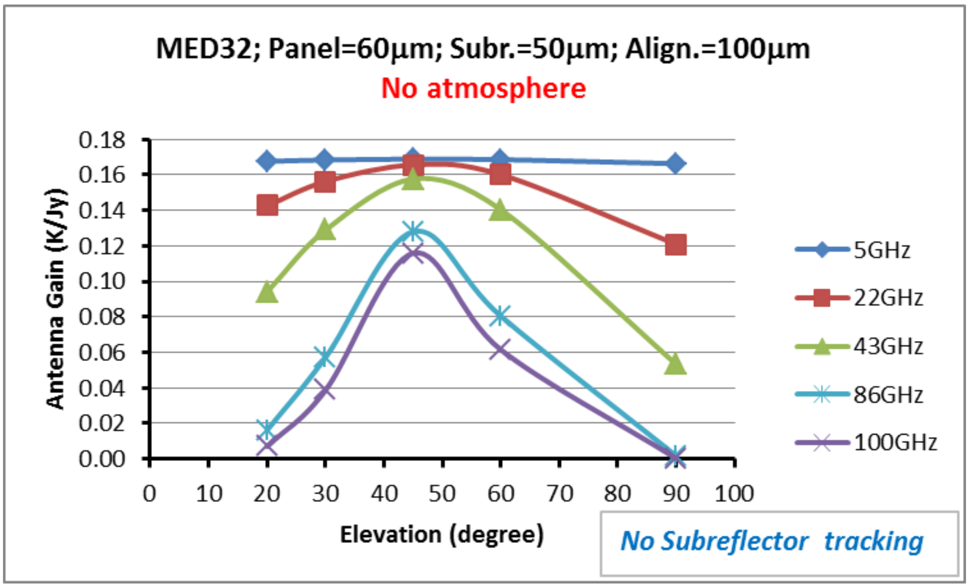


Figure D.3 – Simulated antenna gains in case of refurbishment option 1)

We can evaluate what would happen if an active surface system is realized, according to option 2) above. Actuators totally compensate the gravitational deformations (refer to *Structure gravity deformations* values in the tables), thus those terms could be set to zero at any elevation. However, to be conservative, it is better to consider residuals effects, such as residuals misalignment, poor stiffness of actuators support on the back-up structure or other. A realistic landscape is depicted in Tab. D.III.

ALL UNITS IN µm	El=20°	El=30°	El=45°	El=60°	El=90°
Error Source	RMS				
Panels manufacturing accuracy	**60**	**60**	**60**	**60**	**60**
Panels measurement error	25	25	25	25	25
Panel thermal effect	15	15	15	15	15
Panel gravity deformation	30	30	30	30	30
Panel wind effect	30	30	30	30	30
Structure field alignment	**100**	**100**	**100**	**100**	**100**
Structure gravity deformation	80	50	0	40	100
Structure thermal+wind effect	48	48	48	48	48
Subreflector manufacturing error	**50**	**50**	**50**	**50**	**50**
Subreflector thermal effect	15	15	15	15	15
Subreflector wind effect	15	15	15	15	15
overall RSS	***167.0***	***154.9***	***146.6***	***152.0***	***177.5***

Table D.III – Components affecting the overall surface accuracy in case of refurbishment option 2)

In case of option 2 of the refurbishment, Fig. D.3 transforms in Fig. D.4. At 22 GHz, the beneficial effect of the subreflector is produced by the active surface and the gain curve is practically flat at 43 GHz as well. The active surface shows its best performance at the highest frequencies, 86 and

100 GHz, by improving the gain values even at the lowest and the highest elevations. Again, the movement of the secondary mirror could improve a bit the flatness of these two curves.

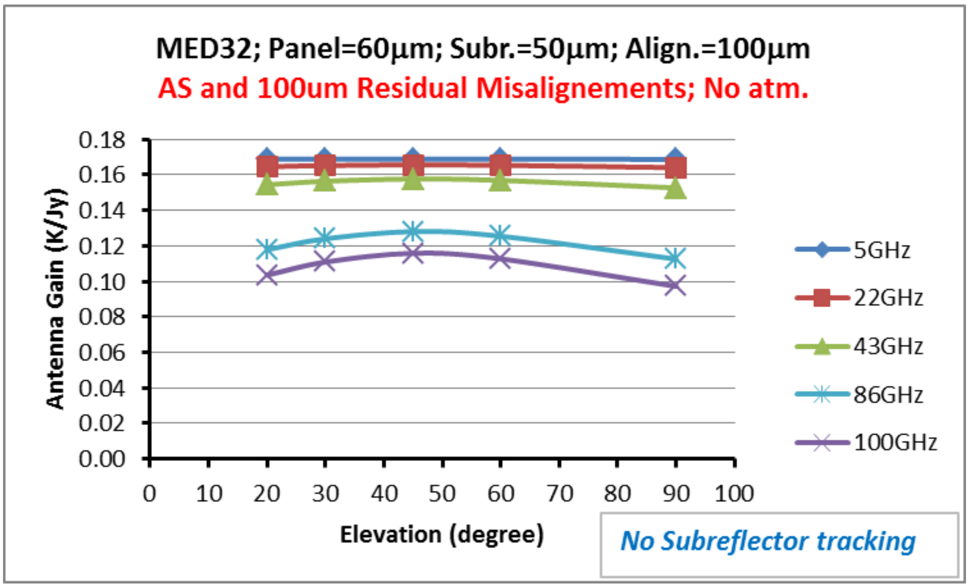


Figure D.4 – Simulated antenna gains in case of refurbishment option 2)

D.2 Comparison with other antennas operating at 86 GHz

In order to properly place the results of previous analysis, it is necessary to make a comparison with the performance quoted by other telescopes. Also, it is necessary to calculate MED performance taking also into account the noise temperature of a receiver and the atmospheric effects that contribute on both the overall system temperature and the antenna gain attenuation. Tab. D.IV reports values for a number of radio telescopes from the GMVA web site (http://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/).

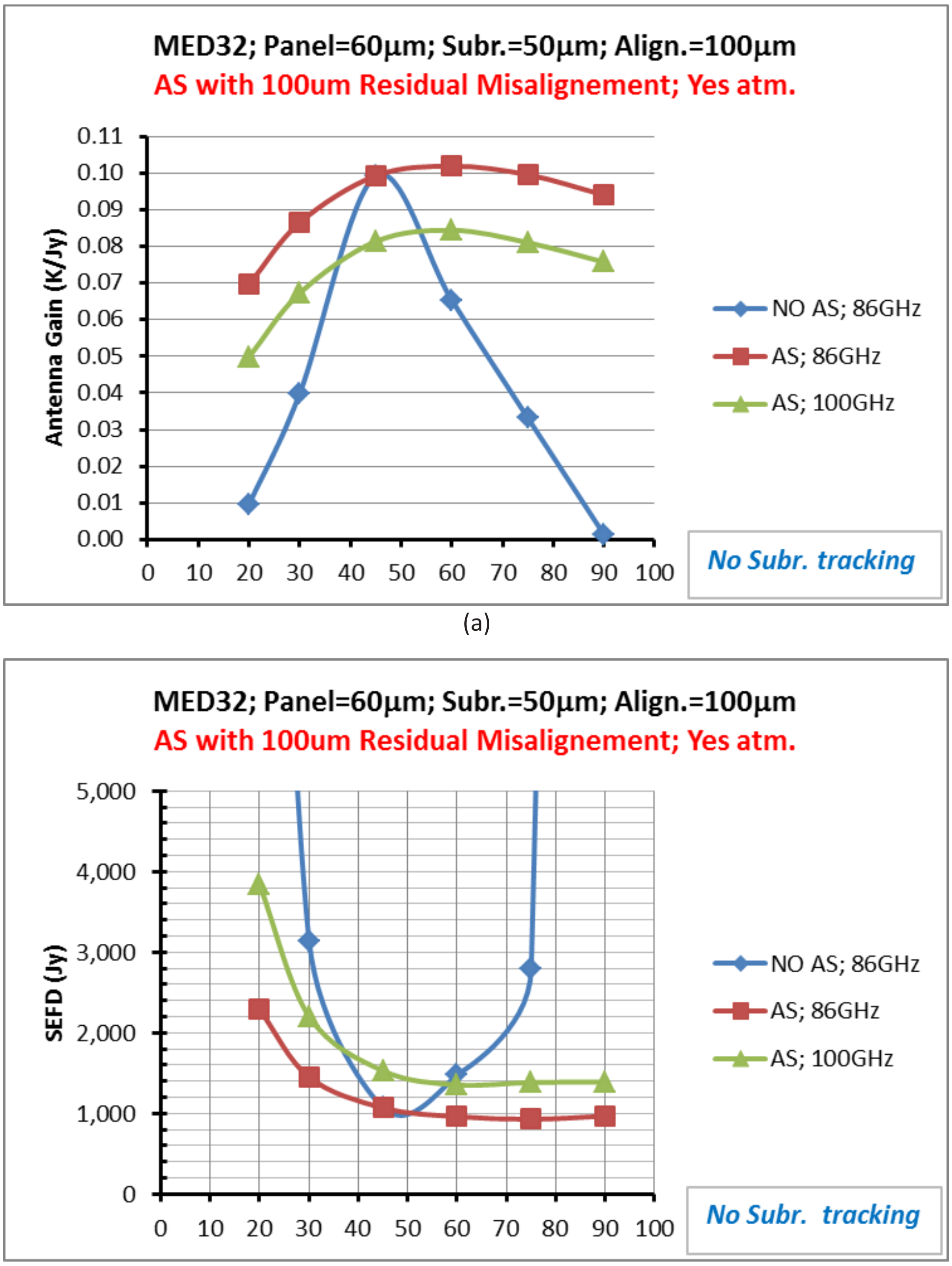
Station	Diameter (m)	Zenith Tsys (K)	Gain (K/Jy)	Eta (%)	SEFD (Jy)	Comment
GBT	100.0	100.0	0.73	26	137	for nighttime observing
Effelsberg	80.0 (eff.)	140.0	0.14	7.7	1000	-
Plateau de Bure	33.2	180.0*	0.22	70	818	* for 1 Gbps
Pico Veleta	30.0	100.0	0.15	60	654	-
Yebes	40.0	150.0	0.09	20	1667	-
VLBA	25.0	100.0	0.040	22	2500	average, range is: 0.02-0.04 K/Jy
KVN (3x21m)	21.0	200.0	0.062	49	3226	for one 21m antenna
Onsala	20.0	250.0	0.049	43	5102	-
Metsähovi	14.0	300.0	0.017	30	17647	-
LMT (prelim)	32.5	240.0*	0.14	48	1714	* DSB receiver
ALMA	79.7 (eff.)	90.0	1.32	73	68.0	50x12m

Table D.IV – Antenna and receiver properties at 86 GHz of GMVA network

The GMVA values are accompanied with the following important note: “Here we assume optimum weather conditions (low opacity, τ at zenith < 0.1, no clouds). Important: Depending on weather, the zenith Tsys and the SEFD could be considerably higher!”.

Commercially available LNAs nowadays show very flat noise response at a level of 30 K throughout the band 63-116 GHz with a power gain spanning 20-25 dB. Consequently a state-of-the-art W-band receiver can reach a noise of 50 K.

Considering at the Medicina site an opacity at the zenith equal to 0.18 at 86 GHz and 0.25 at 100 GHz (see Section 2.3.2), and no clouds, Fig. D.5 shows the antenna gain and the SEFD at 86 GHz and 100 GHz, for both solution 1) and solution 2).



(a)

(b)

Figure D.5 – (a) Antenna gain and (b) SEFD, at 86 and 100 GHz including atmosphere effects. 86 GHz curves are given with and without active surface

From these curves, the following conclusions can be extracted:

- In case of solution 1), i.e. surface refurbishment with no active surface system, MED would show acceptable gain and SEFD compared to some other telescopes of the GMVA network in the 30 - 75 degrees elevation range only. The performance in this case would be up to three times worst than those obtainable with an active surface. At present, the amount of beneficial effects by subreflector optimization is unknown, especially outside this elevation range. Moreover, the antenna elevation range with acceptable performance at 100 GHz should be further restricted. On the other hand, this solution allows very good antenna efficiency on both K and Q bands. Limiting the development to these wavelengths only, time and money for the refurbishment would be saved, while permitting to make valuable observations up to 6 mm.

- In case of solution 2), i.e. active surface system in place, MED would show SEFD values comparable or better than most of GMVA antennas (for example MED would have similar performance as Effelsberg). Obvious exceptions are GBT, ALMA, Plateau de Bure and Pico Veleta, but these last three antennas are placed at very high altitude and 100 GHz is their lowest operating frequency, not the highest.

Finito di stampare
per Edizioni Helicon (Arezzo)
nel mese di Marzo 2018
Digital Team - Fano (PU)

ISBN 978-88-9898-504-3

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