The Sardinia Radio Telescope (SRT) Science and Technical Requirements

Report of the SRT Working Group

IRA 371/05

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Chapter 1

Introduction

In May 2004, the director of the Istituto di Radioastronomia (IRA), Prof. G. Tofani, on behalf of the Board of SRT, asked eight researchers - active in a variety of fields of astronomical research - to form a working group (WG) which was given the task to outline scientific programs that could be carried out with the Sardinia Radio Telescope (SRT), and to describe the technical requirements necessary to lead these projects to a successful outcome. The WG consists of Jan Brand, Paola Caselli, Marcello Felli (chairman), Karl-Heinz Mack, Sergio Poppi, Andrea Possenti, Isabella Prandoni and Andrea Tarchi.
The installation of a WG was deemed necessary by the Board of the SRT, three years after the SRT Symposium held in Cagliari on November 2001 (*SRT: the impact of large antennas on Radio Astronomy and Space Science*, eds. D'Amico, Fusi Pecci, Porceddu & Tofani, published by SIF), in order to provide further input from the potential user community in the early phases of the SRT's development, and to present projects that maximize the scientific output of the SRT and which renders it competitive in an international context. This input (as well as the results of the aforementioned Symposium) will allow the Board to take decisions about the first phase focal plane instrumentation and to anticipate future developments and requirements.
This report includes contributions from outside groups, the particular areas of interest of which were not adequately represented within the WG (e.g. planetary astronomy, VLBI, Geodesy and Radio Science). The emphasis is on scientific themes and on the general features of the equipment necessary for successfully investigating them. In particular, sensitivity and observation time requirements are outlined, whereas technical details of the antenna performance and focal plane instruments are beyond the scope of the present report and are described only in rather general terms. Direct interaction between the scientific community and those who are responsible for the realization of the hardware and software will be coordinated by the Board of the SRT at a later stage.
Right from the start, it was felt by the WG that the report should **not** describe **all** possible scientific uses of the SRT, but only those that reflect **real** interests in the Italian scientific community. Behind each scientific project presented here, there is a group of researchers ready to actively work with the SRT once it has become operational.
We have omitted the names of the people who have prepared the various sections to be consistent with the philosophy that wants this report to be the result of the participation of the entire Italian scientific community. Nevertheless, the WG wishes to express its gratitude to the following persons outside the WG for their contributions and useful comments during the writing of this report: Roberto Ambrosini, Uwe Bach, Marco Bondi, Maria Teresa Capria, Ettore Carretti, Elena Cenacchi, Claudio Codella, Gianni Comoretto, Gianfranco De Zotti, Mario Di Martino, Luigina Feretti, Lars Fuhrmann, Carlo Giovanardi, Gabriele Giovannini, Federica Govoni, Matteo Murgia, Simone Migliari, Luca Moscadelli, Stelio Montebugnoli, Enzo Natale, Luca Olmi, Alessandro Orfei, Francesco Palagi, Paola Parma, Pierguido Sarti, Gian Paolo Tozzi, Corrado Trigilio, Grazia Umana, Tiziana Venturi, and Mario Vigotti.
In order to obtain input for this report its first draft was sent in November 2004 to more than 240 potentially interested scientist of the Italian astronomical community. The accompanying letter can be found in http://www.ira.cnr.it/∼mack/SRT/, an electronic copy of this report can be downloaded from http://www.ira.cnr.it/∼mack/SRT/srt_report_all.ps .

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Chapter 2

Summary

The report is organized as follows:

- A section where we provide general requirements, with particular attention to the software issues, useful for an optimum use of the SRT.
- A large section is devoted to the single-dish use of the SRT, divided into classical astronomical sections: solar system, galactic and extra-galactic, each one divided in turn into continuum and line.
- Four separate sections describe the projects and requirements for VLBI, Geodesy, Radar Astronomy and Space Science..

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New competitive opportunities for the SRT can be opened only following these general criteria:

- for single-dish applications:
  - use of the SRT at the highest possible frequency,
  - implementation of multi-beam arrays,
  - use of bandwidths as large as possible, for the continuum and for spectral line work, so that more lines can be observed simultaneously, either over a large bandwidth at low resolution or at higher resolution by centering several smaller bandwidths around different frequencies,
  - spectroscopy (galactic and extragalactic) in non-standard bands,
  - lower-frequency projects (as for instance pulsars, polarimetry) with ad hoc hardware.
- for VLBI
  - non-standard frequencies
  - frequency agility
  - Mark V
- for Geodesy: SX receiver systems, Mark V, co-located GPS
- for Radar: radar transmitter
- for Space Science: Doppler tracker

Chapter 3

General Requirements

This chapter deals with some hardware and software requirements necessary for a proper and efficient use of the SRT. Furthermore we discuss a series of observational programs that need to be carried out both *before* and *during* regular SRT operations, in order to guarantee the collection of 'clean' and well-calibrated data.

We would like to stress that software requirements are often underestimated in the development of a new instrument. Our experience indicates that good software packages for operating the radio telescope and managing the data flow is essential and of the same importance as a good performance of the antenna and the focal plane instruments.

3.1 Hardware Requirements

For the operation of the multi-beam receivers we strongly recommend the employment of a built-in mechanical derotator. During the observations the telescope's field-of-view rotates as it tracks objects across the sky. While this does not pose a problem in case of single beam (feed) observations, it affects multi-beam 'grid mapping' of extended sources because the sky position seen by each of the off-axis beams changes systematically during the observation. A derotator would compensate for this effect, thus permitting simultaneous (long-integration) observations of as many positions as the number of beams in the receiving system. This is of particular importance in spectral line studies (especially extragalactic ones) where long integrations are required on each position in a map in order to obtain spectra with high enough signal-to-noise ratio.

For continuum mapping it often suffices when the derotation of the field of view w.r.t. to the multi-beam array can be recovered via software producing an (almost) full spatial coverage of a region of interests.

3.2 Software Requirements

All SRT operations are carried out by special software. Below we give a list of what we think is needed to ensure proper functioning of the telescope.

1. A telescope drive programme that allows the SRT to point, focus, and to perform skydips ('antenna tippings'). This software package should also be capable of executing the various observing modes requested by the scientific projects outlined in this report, such as total power, position -, beam - , and frequency switching, cross scans, raster scans, coverage of a matrix of points in any type of coordinates and On-The-Fly maps.
   A software package that is able to handle both continuum and line observations within the same environment would be desirable.

2. Software that constitutes the interface between the observer and the telescope drive programme, i.e. some template in which to set observational parameters, mapping mode, integration times, resolutions, bandwidths etc.

3. Data acquisition software that reads out the backends and puts the data into a file, adds a header, and writes the result to disk. Output files have to be written in a standard format (e.g. FITS, CLASS)

and the header should contain all the keywords needed by the various data reduction packages (e.g. AIPS, Miriad, IDL, GILDAS).

4. On-line data monitoring and -reduction software (for example the acquired data could be written into a second file, that can be accessed during the observations from a separate workstation). This would allow the observer to monitor the data in real-time, and hence, to check the general performance of the system. For this purpose it would also be useful to have several monitors on which the output of various receiver/backend combinations are shown, so that one can immediately see if for instance the backends are positioned correctly around the spectral line.
   The on-line reduction software should preferably be of a type that allows one to write additional modules that can be integrated into the main software package (e.g. IDL, GILDAS). Ideally several reduction software packages could be available at the SRT; in this case software is needed to transform the (say) FITS-files written by the data acquisition software package to the format required by the specific data reduction software packages.

5. Remote observing capabilities: although the complexity of the SRT renders completely remote observations (almost) impossible and the presence of a team of trained operators at the telescope site mandatory, the possibility for the observer to check remotely (i.e. from his/her home desk) the flow of data for standard observations (e.g. long-integration spectroscopic observations), should be pursued.

6. Creation of a telescope archive. In this archive one would store information on all observed targets (name, coordinates, observing modes, frequencies) to avoid unnecessary repeat observations and thus to optimize the efficiency of the use of the SRT.

   A backup archive of all observational data should be kept at the telescope. With time (taking into account a certain proprietary period), certain parts of the data archive should be made publicly accessible.

3.3 Monitoring campaigns

Before regular SRT operations can start, test observing campaigns are needed, to assure that useful science data can be obtained. Once operations have started, continued monitoring of several parameters and phenomena is required. Below we give an overview of what is needed.

1. The telescope must be able to accurately point to celestial sources. The pointing accuracy required depends on the observing frequency. We therefore need to have a list of suitable pointing sources at all operational frequencies. 'Suitable' means continuum (or maser) sources, strong enough to be detected in a short-integration cross-scan; the sources have to be point-like for the SRT at the relevant frequency, and their distribution on the sky should be as uniform as possible (i.e. at every time of the day at every azimuth and elevation there should be a pointing source nearby).

   Likewise there is the need for continuum and line calibration sources, with known flux density at the observing frequencies available at the SRT, and these should therefore be non-variable. These sources are to be used to calibrate the bandpass and polarization (continuum observations). For spectral line observations strong line sources are needed to verify the correct tuning of the receivers and to check the centering of the backends.

   Before beginning SRT operations, an extensive 'pointing' and 'calibration' campaign should be carried out, to construct a pointing model and to establish the reference flux density values for the SRT at all operational frequencies. During normal operations pointing and calibration sources should be observed regularly to update the pointing model and to check the reference flux values.

   As a start we could utilize the pointing and calibration source catalogues that are in use at the Effelsberg 100-m and IRAM 30-m telescopes.

2. The SRT is located in a 'Radio-quiet zone': within a radius of 3 km around the telescope, no structures can be erected that might adversely influence the observations, without prior consent of the IRA.

Unfortunately there remains the distinct possibility that observations may suffer interference from transmitters that are well outside this radius (e.g. satellites!).

Periodic monitoring of radio interference at certain frequencies at which this is known to be a potential problem is therefore needed. Software could then be created to either eliminate interference from the scientific observations by inserting into the receiver a signal similar to the interference signal but with opposite phase, or that shuts down the receiver temporarily.

Given the increasing problems of 'in-house-made interference', caused by the electronic equipment of modern radio observatories, adequate shielding, e.g. in the form of a dedicated 'Faraday room' which contains the strongest radio emitters, is essential.

3. In order to explore the possibility to use the SRT at higher frequencies (up to 100 GHz), it is very important to start *as soon as possible* radiometer measurements at the SRT site of the sky transparency at various frequencies of astronomical interest.

3.4 VLBI Requirements

With its large collecting area and the suite of planned receiver frequencies the SRT will be a powerful addition to the various existing VLBI networks.

- For the participation in the European VLBI Network (EVN) frequency agility is very important. In a possible priority list of the receivers to be built, the most requested EVN frequencies should be considered first. On the other hand, the EVN performance at frequencies ≥ 8.4 GHz and < 1.4 GHz is still limited. The addition of the SRT capable to observe at these non-standard frequencies will yield a significant increase of sensitivity (factor 1.5 at 1.4 GHz, factor up to 4 at 86 GHz). Also the upcoming launch of the Japanese VSOP2 should be taken into account when prioritising the receiver list.
- The SRT should be inserted in the Global mm-Array for high-frequency (> 40 GHz) VLBI.
- It should be attempted to establish a special relationship between the SRT and the VLBA similar to the one already existing between the Effelsberg 100-m telescope and the VLBA.
- To facilitate any 'national VLBI' observations (using the three IRA telescopes) an agreement with the correlator facilities either at JIVE or the MPIfR should be formalised. Alternatively, the construction of a small national correlator could be considered.

3.5 The SRT Reference Parameters

Reference values for the relevant telescope parameters are listed in Table 3.1. These values, unless stated otherwise, have been used to compute the time estimates in the scientific projects collected in the present report. The maximum instantaneous bandwidth (IF_{max}) of each receiver, reported in the third column of Table 3.1 is at most 2 GHz; obviously, the actually usable maximum value depends on the frequency-range of each receiver. In addition, where the frequency-range of the receiver allows this, one can select IF-values of 80, 400, and 800 MHz. Note that each receiver has 2 polarisation channels, for which the IF can be selected individually. Depending on whether the backend allows this, spectral line observers could simultaneously observe lines at different frequencies, while continuum observers may have a bandwidth of $2\times$IF at their disposition. Note that SEFD (Col. 8) stands for System Equivalent Flux Density.

Table 3.1: Reference values for relevant parameters of SRT receivers*

Receiver number⊤	RF Band (GHz)	IF_{max} (MHz)	Rx Noise T (K)	Sys Noise T (K)	Ant eff (%)	Ant Gain (K/Jy)	SEFD (Jy)	HPBW arcmin
1P	0.31-0.35	40	30	52	59	0.68	76	59.1
2P#	0.58-0.62	40						
3P#	0.7-1.3	600						
4P	1.3-1.8	500	5	20	59	0.69	29	12.6
5P#	2.2-2.36	160						
6P#	2.36-3.22	860						
7P#	3.22-4.3	1100						
8P#	8.18-8.98	800						
1BW	4.3-5.8	1500	15	20	58	0.67	30	3.9
2BW	5.7-7.7	2000	15	21	58	0.67	31	2.9
1G	7.5-10.4	2000	10	16	61	0.70	23	2.2
2G	10.3-14.4	2000	14	29	60	0.70	41	1.6
3G	14.4-19.8	2000	18	48	57	0.66	72	1.1
4G†	18-26.5	2000	21	81	56	0.65	124	0.88
5G	26-36	2000	14	34	54	0.63	54	0.63
6G	35-48	2000	40	60	52	0.61	98	0.47
7G	70-90	2000	91	171	40	0.46	370	0.24
8G	90-115	2000	106	186	35	0.40	460	0.19

* From E. Cenacchi, Laurea thesis, Univ. Bologna. Values refer to an elevation of 45°.

⊤ Letters added to the receiver numbers indicate at which focus they will be mounted, and have the following meaning: 'P'='Primary'; 'G'='Gregorian'; 'BW'='Beam Waveguide'.

\# Parameters not yet assessed.

† This is the only receiver already under construction and is a 7-horn system.

Chapter 4

Single-dish observations

4.1 Solar system

4.1.1 Line observations

4.1.1.1 Radio spectroscopic observation of comets

Scientific Background

The knowledge of the composition of cometary ices and of their physical properties is one of the main issues of comet science. It is thought that cometary ices keep trace of the molecular composition of the solar nebula in the giant planet region where they formed, as well as of the temperature environment in which they condensed. In the last years, more than 22 molecules, radicals, ions and isotopologues were detected from radio spectroscopic observations of comets; most of these new species were found due to the coming of two extraordinary long period comets, C/1996 B2 (Hykutake) and C/1995 O1 (Hale-Bopp). From the analysis of the new data available it seems that the ices found in C/1995 Hale-Bopp have many similarities with the ices present in the star forming regions (Bockelée-Morvand & Crovisier 2002), thus suggesting that the outer parts of the solar system inherited to a large extent the composition of the protosolar cloud, but more data are needed.

The analysis of spectra from radio observations of comets is a mature field; kinetic temperature and gas outflow velocity, derived from the velocity at half-maximum of the lines, are used to estimate the production rates of the sublimating gases. This is commonly done, for example, for OH (used in turn to derive water production rate) and for NH_3 (Bird et al. 1997; Gerard et al. 1998; Colom et al. 1999). It must be stressed that it is not enough to measure the production rate in one or few points close to the perihelion of the orbit, but it would be highly desirable to obtain production rates spread along the orbit as much as possible. This requires a reasonably easy access to a suitable radiotelescope like the SRT for short time intervals at selected heliocentric distances.

Of the many subjects that could be investigated in a comet with a radiotelescope such as SRT, two are listed hereafter as an example. It is clear that the opportunity to use SRT will give birth to many new ideas in the cometary community.

- **Search for new molecules**. There are certainly unidentified lines in the radio domain and new molecules to be detected at an abundance level with respect to water of $10^{-3} - 10^{-5}$ (Crovisier et al. 2004): we could cite, for example, water dimer (transition $2_0E^- - 1_0E^+$ at 24.284 GHz), deuterated water (transition $1_{10} - 1_{11}$ at 80.578 GHz) and cyanodiacetylene (HC_5N, transition 34 - 33 at 90.526 GHz; Bockelée-Morvan & Crovisier 2002). It is also thought that most of the organic molecules identified in the interstellar medium could be found also on comets; new complex molecules could even be searched for. The possible links between the formation of organic molecules on interstellar grains, their incorporation in comets and their possible spreading in the solar system are some of the most interesting subjects in cometary science.

- **The ratio HCN/HNC**. This ratio, regarded as an indicator for the origin of the ices, has been measured for few comets. It seems to be very similar to that measured in warm quiescent molecular clouds (Bockelée & Crovisier 2002): this is suggesting that cometary nuclei can be composed by relatively unprocessed interstellar ices. Anyway, the strong variations of this ratio along the orbit, measured in C/1995 Hale-Bopp, cast some doubts on the true significance of this ratio. More data are needed.

Although it is true that the Italian community working on such kind of observations is much smaller than, for example, the one working on stellar formation, this community is nevertheless well-inserted in the international community. The availability of SRT time would be a wonderful occasion to strengthen and enlarge our community and to establish cooperations with other communities, sharing knowledge and expertise.

Technical requirements

Cometary lines are narrow and rotational temperatures are low, so there is no problem of spectral confusion. As a general requirement for the observations detailed above, in particular the search for low abundance molecules, high sensitivity and good spectral resolution ($\sim$ 0.1 km/s) are needed, along with a comet close and bright enough.
The search for new molecules requires a continuous frequency coverage by the SRT receivers in the high-frequency range above 10 GHz (excluding the atmospheric O_2 line region around 50 GHz). The HCN/HNC ratio is measured at 90 GHz. A spectrometer with standard bandwidths of 10 MHz would be sufficient for both projects. While the sensitivities for the search for new molecules cannot be predicted, typical HCN/HNC ratio measurements require sensitivities of about 50 mK. A potential problem could be that, as in other spectral domains, good molecular databases are necessary but are not always available.
Anyway, most important in order to carry out comet observations is that a kind of "target of opportunity" policy should exist: usually bright comets arrive unexpectedly and approach Earth at high speed. Moreover, even usually "quiet" comets can be subjected to unpredictable outbursts, during which their magnitude increases by several times. It should be possible for our community to make observations on short notice.

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4.2 Galactic astronomy

4.2.1 Line observations

4.2.1.1 Galactic Masers with the SRT

Scientific Background for water masers

Maser emission from the $6_{16} - 5_{23}$ rotational transition of water at 22.2 GHz is a common feature in both circumstellar shells and in star-forming regions (hereafter SFRs). In both types of sources the maser emission is highly variable. For the masers associated with Young Stellar Objects this variation is mostly erratic, while those associated with late-type stars sometimes vary in phase with the luminosity of the central star, and at other times may show highly irregular behaviour, including spectacular burst events.

During the last 15 years a unique monitoring program has been carried out at Medicina, in which water masers in ca. 20 late-type stars and ca. 55 SFRs have been observed 3 − 4 times a year. These programs have provided useful insights in the workings of the maser mechanism in both environments, and allowed the recognition of correlations between parameters of the maser emission and the source properties. While these observations have proven to be extremely useful for variation studies, it has also become clear that the sensitivity, the spatial- and spectral resolution, and the velocity coverage offered by the Medicina telescope and instrumentation does not favour the study of maser line profiles and maser-burst events.
The SRT has a smaller beam size ($\sim 53''$ versus $1\farcm9$ for Medicina), which helps in separating different maser sites, which is especially useful in SFRs. The SRT also has a superior quality of the surface of the dish, and a 'cleaner' beam, which results in a higher sensitivity and more efficient observations. The SRT will therefore allow the detection of maser emission of lower luminosity objects, thus enabling to more accurately set the threshold luminosity at which the maser emission can be triggered.
The mere presence of the SRT will permit more frequent observations and therefore provides a denser time-coverage, which will result in a higher probability of capturing maser bursts.

Scientific Background for other masers

A further advantage of the SRT for galactic maser research is the possibility to observe maser emission of different molecules at various frequencies. For instance OH (1612−1712 MHz) and (eventually) SiO (43 GHz). This is especially useful for circumstellar masers, as different parts of the expanding envelope are sampled at these frequencies, thus allowing the determination of, e.g., the mass loss history. For SFRs there is the possibility to observe masers from various inversion transitions of $^{15}NH_3$ (22−24 GHz), CH_3OH (12, 20, 23, 36−38, 44 GHz and higher), which would be impossible to do with Medicina/Noto.

The SRT as part of a VLBI network for water maser observations

A particularly exciting prospect is that the presence of the SRT will allow one to observe masers with an all-Italian VLBI network (SRT-Medicina-Noto). Such a combination of telescopes has a maximum baseline of ∼894 km, resulting in a synthesized beam size of ca. 2.5 mas. Thus, "in-house" pilot observations of maser sites in SFRs can be performed, which serve as preparation for proposals to observe these sites with the VLA or VLBI/EVN. The coverage of the *u*-*v* plane provided by the 3 Italian telescopes is shown in Fig. 4.1.

Technical Requirements

At Medicina, with a system temperature $T_{\rm sys}$, one reaches an rms of ΔS Jy in a spectrum with a velocity-resolution of Δv km s^{-1}, in $t_{\rm ON}$ minutes of ON-source integration time (with an equal amount of time spent on an OFF-position, in position-switching mode), given by the expression:

$$\Delta S(Jy) = 1.32(\frac{0.178}{KtJ})(\frac{T_{sys}}{350\ K})(\frac{1\ kms^{-1}}{\Delta v})^{\frac{1}{2}}(\frac{1\ min}{t_{ON}})^{\frac{1}{2}}.$$

Here KtJ is the Kelvin-to-Jansky conversion factor, which for Medicina is 0.178 at 22 GHz. Thus, the rms reachable in a 5 minute ON-source integration, with a spectral resolution of 0.1 km s^{-1}, and a typical $T_{\rm sys}$ of 350 K, is ∼1.9 Jy per channel.
For the SRT we have:

$$\Delta S(Jy) = 8.36 \times 10^{-2}(\frac{0.65}{KtJ})(\frac{T_{sys}}{81\ K})(\frac{1\ kms^{-1}}{\Delta v})^{\frac{1}{2}}(\frac{1\ min}{t_{ON}})^{\frac{1}{2}}.$$

Following Table 3.1 we assume $T_{\rm sys} \approx 81$ K and $KtJ \approx 0.65$, and therefore we expect to reach an rms of ~ 0.12 Jy per channel of 0.1 km s^{-1} in a 5 minute ON-source integration, an order of magnitude improvement over Medicina, enormously facilitating the detection of fainter maser components. See also Table 4.1 for different spectral resolutions.
For water maser observations a range of spectral resolutions is needed, depending on the specific type of study one wants to undertake: from 0.25 km s^{-1} with a coverage of $\lesssim 500$ km s^{-1} for detection of weak outlying features (in SFRs; at large velocity-offset from the velocity of the cloud in which the maser is embedded), to 0.01 km s^{-1} for detailed studies of line profiles. An autocorrelator similar in its setup to VESPA

Table 4.1: R.m.s. noise in mJy reachable with the SRT †

$t_{\rm ON}$ (minutes)	Δv 0.01	0.10	0.25 km s^{-1}
5	374	118	75
10	264	83	53
30	152	48	30
60	108	34	22

† Assuming $T_{\rm sys} = 81$ K (see Table 3.1)

at the IRAM 30-m would be a good solution, as it allows for a large range of instantaneous bandwidths and spectral resolutions to be used simultaneously.
Regarding the time requirement, the goal of the water maser patrol can be achieved only if a minimum of 5-6 observing runs per year are granted, each one of 2-3 days.
A very high spectral resolution will be useful for Zeeman measurements of H_2O masers, where typical magnetic field strengths ($\sim$ 50mG) lead to line splitting of the order of 50 Hz. A backend such as Montebugnoli's MSPEC0 would be very useful for this work (64,000 channels in an 8 MHz band, thus a resolution of 125 Hz at 22 GHz). The possibility to do circular polarization observations is required for this.

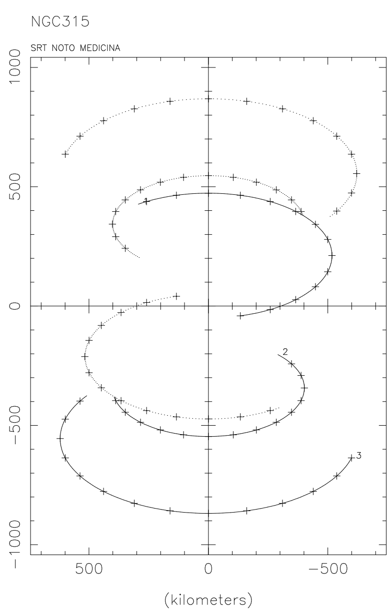

Figure 4.1: Simulation of u-v-plane coverage for a VLBI water maser experiment with the Medicina, Noto, and SRT telescopes. The simulation is for a 12-hour observation of a source at $\delta = 30°$; track labels are for the SRT-Noto (1), SRT-Med (2), and Med-Noto (3) baselines, respectively. *(Figure prepared by D. Dallacasa, Dip.to di Astronomia, Univ. Bologna and IRA, Bologna)*

Most recent publications of the water maser group

Brand J., Cesaroni R., Comoretto G., Felli M., Palagi F., Palla F., Valdettaro R. 2003, A&A 407, 573

Valdettaro R., Palla F., Brand J., Cesaroni R., Comoretto G., Felli M., Palagi F. 2002, A&A 383, 244

4.2.1.2 Unbiased Surveys of Cloud Cores in NH_3(1,1) and (2,2) and other molecules

Scientific Background

Stars form in gaseous condensations (the so-called dense cores) within molecular clouds. The column density ($N_{\rm H_2} \geq 10^{22}$ cm^{-2}) and gas density ($n_{\rm H_2} \geq 10^4$ cm^{-3}) toward these regions are so high that they are opaque both in the visible and to the radiation from CO(1–0) transition, which is the common tracer of diffuse material in molecular clouds ($n_{H_2} \sim 10^2$–10^3 cm^{-3}).

The spectral lines of the inversion transitions of NH_3 at 24 GHz are good tracers of the material in dense cores of molecular clouds, particularly of those which form low-mass stars (e.g. Ho & Townes 1983; Benson & Myers 1989). The transition (J,K) = (1,1) has 18 hyperfine components separated into five spectral groups, thus allowing the determination of the optical depth. Moreover, the frequency separation of the inversion transition (J,K) = (2,2) is less than 1 GHz from the (J,K) = (1,1) lines, so that both transitions can be observed with the same telescope and receiver configuration, allowing one to make a more accurate determination of the kinetic and excitation temperatures.

So far, most of the cores observed in the NH_3(1,1) and (2,2) transitions were selected from the photographic plates of the Palomar Sky Survey (Myers & Benson 1983) or through the association with embedded YSOs detected by the Infrared Astronomical Satellite (IRAS; e.g. Harju et al. 1993; Ladd et al. 1995). Only few unbiased searches of cores have been done using the high density tracers CS (Lada et al. 1991; Tatematsu et al. 1993) and in $H^{13}CO^+$ (Onishi et al. 2002), but from these species it is difficult to derive physical parameters of the detected dense cores mainly because of the line optical depth and the fact that both tracers are likely to deplete within the condensations, when the volume densities become larger than a few $\times 10^4$ cm^{-3} (e.g. Tafalla et al. 2004; Lee et al. 2003). On the other hand, NH_3 is known to trace densities as large as $\sim 10^6$ cm^{-3} (e.g. Tafalla et al. 2002), so that its observations will give us information on the whole core material. Moreover, the simultaneous observation of the two inversion transitions gives us the unique opportunity of determining the gas temperature in different regions of the same molecular cloud, extremely important to test the current calculation of the dust and gas temperature (e.g. Galli et al. 2002). Finally, a detailed study of the ammonia line profiles will shed light on the kinematics of the dense gas and the molecular cloud complex as a whole, very useful to test the validity of current turbulent cloud models (e.g. Ballesteros-Paredes et al. 2003).

Although they do not have the same potential as interstellar thermometers as does ammonia, also cyanopolyynes ($HC_{2n+1}N$, n=1–4) are useful tracers for cloud cores. Several molecules and transitions are easily observable, as demonstrated by recent detections of HC_3N(5–4) (45 GHz; Noto), HC_5N(9–8) and HC_7N(21–20) (24 GHz; Medicina; Codella, priv. comm.), and can thus be used for unbiased surveys of cloud cores.

Technical Requirements

The SRT antenna, equipped with a multi-element receiver array, a high spectral resolution autocorrelator and the possibility of using the frequency switching technique, will be the best instrument to carry out the unbiased surveys described above. Considering that typical line widths of high density tracers in molecular cloud cores are around 0.3-0.4 km s^{-1}, we will need velocity resolutions of at least 0.1 km s^{-1} (or 8 kHz at 24 GHz). For the unbiased survey, we can however consider a 20 kHz spectral resolution which will allow us to detect the dense cores. These objects will then be successively mapped with a finer grid and higher spectral resolution. Assuming a system temperature of 81 K at 24 GHz, a 20-kHz resolution and a total bandwidth of $\sim$ 20 MHz, we will need about 5 minutes per position to reach a rms of 0.05 K (76 mJy) in antenna temperature units (or about 0.1 K in brightness temperature units), needed to detect well all the ammonia cores already known in regions such as Taurus. Considering a Half Power Beam Width (HPBW) of 50$''$ and the multi-beam array, we will need about 5 minutes to beam sample an area of about 20000 arcsec^2, or $\sim$ 50 hours to cover 1 square degree. Therefore, large portions of molecular cloud complexes such as Taurus, Ophiuchus, Perseus, and Orion can be studied in a few days of telescope time. Future SRT ammonia surveys will thus be compared with recent surveys performed in the millimeter and submillimeter continuum dust emission (made with SCUBA, the Submillimetre Common-User Bolometer Array at JCMT, the James Clerk Maxwell Telescope; MAMBO, the Max-Planck Millimeter Bolometer array at the 30m-IRAM antenna; the Spitzer satellite; and in the future by Herschel PACS – the Photodetector Array Camera & Spectrometer – and SPIRE – the Spectral and Photometric Imaging Receiver). We should point out that surveys in the Far Infra Red and mm continuum (i) are limited in sensitivity to the densest and more centrally concentrated structures (e.g. Johnstone et al. 2004), (ii) have difficulties in detecting extended emission because of the chopping technique (e.g. Bacmann et al. 2000) and, of course, (iii) do not furnish any information on the gas temperature and kinematics.

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4.2.1.3 Detection of DCO^+(1–0) and N_2D^+(1–0) to trace the kinematics of high-density molecular cores

Scientific Background

In the past few years it has been realized that abundant species such as CO and CS disappear from the densest regions of molecular cloud cores, where protostars will soon form or are just formed (e.g. Caselli et al. 1999; Tafalla et al. 2002; Belloche & André 2004). On the other hand, nitrogen-bearing species (in particular NH_3 and N_2H^+) survive in the gas phase until densities of about 10^6 cm^{-3} because of the volatility of the parent species N_2 (e.g. Bergin et al. 2001; Caselli et al. 2002a; Tafalla et al. 2004). For this reason, N_2H^+ has been extensively used in recent work to trace the kinematics of the innermost regions of dense cores and to search for the initial conditions of the star formation process (e.g. Caselli et al. 2002b; Crapsi et al. 2004).

Even more interesting are the deuterated forms of species such as N_2H^+ and HCO^+ (N_2D^+ and DCO^+, respectively), because their abundances are highly enhanced, relatively to the main isotopomers, in the dense regions where CO is frozen onto dust grains (e.g. Dalgarno & Lepp 1984; Roberts & Millar 2000). Thus, they better sample the core nucleus, giving us information on the chemistry (in particular the electron fraction; e.g. Caselli et al. 1998) and kinematics (contraction motions) of core centers (e.g. Caselli et al. 2002b). We point out that this applies not just to low-mass star forming regions, but also to high-mass pre-stellar cores, recently detected by the Midcourse Space Experiment (MSX; e.g. Carey et al. 2000), and several projects are currently under way to extend the observations of deuterated species in more massive and quiescent cores (Caselli et al., in prep.).

Previous studies, carried out at the IRAM-30m antenna with bandwidths up to 40 MHz, are based on observations of the N_2D^+(2–1) and DCO^+(2–1) lines, given that so far it was not possible to extend the 3-mm receiver to below 80 GHz (where the J=1–0 transitions of the above two species are found: 72 and 77 GHz for DCO^+ and N_2H^+, respectively) and also because of angular resolution problems (the half power beam width (HPBW) of the 30-m antenna at 80 GHz is about 30$''$, comparable to the size of a nearby (D $\leq$ 200 pc) dense core nucleus). Unfortunately, the DCO^+(2–1) line is optically thick and the N_2D^+(2–1) line has 18 hyperfine components heavily blended, from which it is difficult to extract detailed information on internal motions. On the other hand, the N_2D^+(1–0) line has seven hyperfine components and three well separated groups of hyperfines, one of which consists of one single component. DCO^+(1–0) also has hyperfine structure detectable with high spectral resolution ($\lesssim$ 5 kHz; Caselli & Dore, subm.). This is crucial to study the line profile, to determine the infall velocity, and to unveil the radial velocity profile across the core. Observations of the J=1–0 rotational transition lines will be important to trace the deuteration process across the core and, together with the available J=2–1 lines, the gas density.

Technical Requirements

The frequency range between 70 and 80 GHz is typically not covered by millimeter antennas, such as IRAM (although they are now exploring the possibility to extend the 3-mm receiver to 70 GHz). The only antenna currently able to cover this range with reasonable angular resolution (but not with good sensitivity and spectral resolution) is the 45-m Nobeyama antenna. The SRT-HPBW between 70 and 80 GHz will be $\sim$ $15''$, close to the angular resolution of the IRAM 30-m antenna at 2mm, where studies of the DCO^+(2–1) and N_2D^+(2–1) lines have been performed. Therefore, future SRT observations will be extremely useful to carry out the proposed observations and to make an important step forward in our understanding of the kinematics of star forming regions. For these studies, high sensitivities ($\sim$ 20 mK, 31 mJy) and high spectral resolutions ($\sim$ 3–10 kHz) will be required to resolve well the line profiles and put stringent constraints on available models of the radiative transfer in contracting clouds. Moreover, we strongly recommend the possibility of using the frequency switching technique in particular for low-mass star forming regions, where the lines are narrow and relatively simple, and the wobbler switching technique for more massive regions. A multi-beam receiver will be ideal to make quick maps and easily extend the kinematic study from core center to edge (necessary for a detailed comparison with current theories of core and star formation). To map a minimum number of selected cores we estimate several weeks of telescope time, in good weather conditions.

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4.2.1.4 Complex Molecules in the Interstellar Medium

Scientific Background

There are over 130 molecular species identified to date in interstellar space and a large fraction of them are organic in nature. Among those with biochemical significance are H_2CO (formaldehyde), CH_4 (methane), HCOOH (formic acid), H_2C_2O (ketene), CH_3OH (methanol), NH_2CHO (formamide), CH_3CHO (acetaldehyde), CH_2CHOH (vinyl alcohol), CH_3COOH (acetic acid), $HCOOCH_3$ (methyl formate), CH_2OHCHO (glycol aldehyde), C_2H_5OH (ethanol), $(CH_3)_2CO$ (acetone), and C_6H_6 (benzene). The simplest members of several homologous series which are important in terrestrial biochemistry – aldehydes, acids, ketones, and sugars – are also known interstellar molecules. Thus, there is potentially a strong link between interstellar organics and prebiotic synthesis (Ehrenfreund & Charnley 2000). However, there is still much to be done before we can answer crucial questions such as: (i) how much of the organic material in primitive Solar System bodies, such as comets and asteroids, is pristine interstellar material?, (ii) to what extent does it reflect chemical processing within the primordial nebula?

The search for new complex molecules and the abundance of organic species in different astrophysical environments is a challenge for astrochemistry and awaits sensitive antennas and high spectral resolution receivers able to span the whole range of frequencies from 1 GHz to the millimeter range, within which many transitions of the above mentioned asymmetric rotors are present. This implies that the SRT will be particularly suitable for this search and can be used: (i) to look for complex molecules in cold clouds, (ii) to search for new species, whose spectra have been recently measured in the laboratory (e.g. Chen et al. 1998; McCarthy et al. 2004), and (iii) to try to identify some of the carriers of the Diffuse Interstellar Bands (DIBs) in the diffuse medium.

In the first case, we will learn how important dust grains are in the production of organic species (the current view is that organic species are mostly formed on the surface of dust grains until a heating event – such as the formation of a protostar – will release the icy mantles in the gas phase; e.g. Caselli et al. 1993; Nomura & Millar 2004). The second project will definitely put stringent limits on the current chemical models and shed light on the crucial questions mentioned above. For the last project, we point out that the identity and nature of the DIBs have remained undetermined for over 70 yr (Herbig 1995). There are suggestions that complex molecules may play an important role (e.g. Tulej et al. 1998; Ruffle et al. 1999), although no definitive conclusions have been reached. Therefore, it will be a very attractive program to carry out with the SRT. We point out that this ambitious project requires a continuous information exchange with chemical research groups, and this is possible thanks to the active collaboration between the Arcetri group and distinguished researchers and professors at the European Laboratory for Non-linear Spectroscopy (LENS), associated with the University of Florence, at the Ciamincian Institute of Chemistry (University of Bologna), at the Department of Physics and Astronomy of The Ohio-State University (Columbus, USA), and at the Geo- and Radio-Astronomy Division and the Division of Engineering and Applied Sciences of the Harvard-Smithsonian Center for Astrophysics (Cambridge, USA).

Technical Requirements

High sensitivity (10mK, 15 mJy), large bandwidths (up to 500 MHz) and spectral resolution ($\sim$ 0.1 km/s) are required to carry out these projects. Larger spectral coverage is required for the search of new species and the identification of DIBs (see the recent discovery of complex molecules (propenal and propanal) by the GBT in the 16 - 26 GHz band. A possibility, at least in the frequency range between 8.8 and 50 GHz, could be to follow the prescription of the 45-m mm-wave radio telescope of the Nobeyama Radio Observatory, as described in Table 1 of Kaifu et al. (2004), but a significantly better backend is required to resolve well molecular line profiles in quiescent regions.
Time requirements: at this stage we can only estimate a minimum of one month of telescope time, in good weather conditions, to give significance to the project. But a search will be proposed any time new frequencies will be measured in the laboratory.

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4.2.1.5 The Evolution of Low-Mass Protostars and their Bipolar Outflows

Scientific Background

Studying the early evolution of stars is difficult because protostars form in regions which are deeply hidden in molecular clouds and are surrounded by thick envelopes. As the circumstellar material is dispersed around a young stellar object (YSO) by the action of its outflows, the spectral energy distribution (SED) of the YSO evolves systematically. This process allowed the classification of YSOs in Classes 0, I, II, and III (e.g. André et al. 1993). However, it is clear that this classification is too schematic, and it results, for instance, that under the label of Class 0 sources (e.g. sub-millimeter protostars) we find a rather heterogeneous collection of YSOs. Indeed the main obstacle when studying the evolution of YSOs is the identification of a reliable age indicator.

Outflows could have the key to refine the classification of YSOs, especially at low luminosities where the flow geometry can be relatively simple. Mm-wave observations, mainly with the IRAM instruments, have put in evidence the properties of outflows from Class 0 sources, which are highly collimated (see e.g. Bachiller 1996). Outflows from Class I sources are much less collimated and have a much lower mechanical power efficiency (Bontemps et al. 1996). The most recent observations show that there is also a kind of time sequence for low-mass outflows based on well known objects and on the chemical changes that are expected to be induced in the surrounding molecular outflows. In fact, the propagation of outflows lead to shock waves which heat the surrounding medium and trigger chemical reactions, including also dust grains that do not operate in more quiescient environments. Consequently, the abundance of some species (such as SiO, CH_3OH, H_2O and several S-bearing molecules) can be strongly enhanced (e.g. Bachiller 1996, Bachiller et al. 2001, Codella et al. 2005). Also a direct injection into the gas phase from the dust grains through sputtering can play a major role (e.g. Caselli et al. 1997). Bachiller & Tafalla (1999) proposed a preliminary scheme based on a limited number of objects. The empirical time sequence can be summarised as follows (see also Santiago Garcia et al. 2005): (i) Jet-like outflows driven by Class 0 YSOs and associated with extremely high velocities (EHV) molecular bullets that appear as secondary components in the spectra, (ii) Chemically active outflows which are driven by a Class-0 object, show no bullets, but are associated with very strong chemical anomalies with large abundance enhancements and prominent wings in several shocked gas tracers, and (iii) Class I outflows with no chemical anomalies and associated with evacuated cavities and HH objects. In other words, the chemically rich stage should be able to refine the low-mass protostar classification. In particular, the abundances of several molecules at the high velocities of the outflows can be used to further specify the characteristics of the Class 0 YSOs.

Unfortunately, the above classification is based on only a few objects, and further unbiased observations are necessary to make it more firm and detailed. Thus, the chemical anomalies have to be characterised in a sample of outflows from sources of similar low luminosity ($\leq 10\ L_\odot$), covering all of this empirical sequence. The challenge is to find molecular species (i) whose production is exclusively associated with the high-temperature shocked gas, and (ii) whose abundance is clearly time-dependent to discern definitely the Chemical Active Stage from the 1st and 3rd evolutionary phases. The answer can be found thanks to standard shock tracers such as SiO, CH_3OH, and HDO as well as to products of the S-bearing chemistry such as SO, HCS^+, OCS, H_2CS, and SO_2. Actually, Sulphur chemistry can be seriously affected by grain surface reactions: shock waves can inject H_2S into the gas phase with a consequent fast production of SO and SO_2 (e.g. Pineau des Forêts et al. 1993; Charnley 1997). Later on, some S-bearing species such as H_2CS, OCS, and HCS^+ are expected to definitely increase their abundances as a consequence of the injection of sulphur into the gas phase.

Finally, it is worth to stress the importance of studying the line profiles in detail. In the case of molecular outflows, different excitation conditions as well as different gas compositions at different velocities are expected (Codella et al. 1999, 2003, 2005). This makes essential surveys aimed at studying the chemical and physical characteristics of the material flowing from YSOs as a function of velocity.

Technical Requirements

The strategy of this project is to observe a sample of outflows in the lines of shock tracers as well as a tracer of the ambient medium, like CS, to well define the rest velocity. The selected molecules emit almost all at frequencies larger than 20 GHz. When possible, two or three lines of each species will be needed to discern between excitation and chemistry. The SRT HPBWs will be about 30″–48″ in the 20-50 GHz range and about 12″ at frequencies above 70 GHz. These values allow one to map different positions located along the outflow: for instance the size of the typical chemically rich outflow, L1157, is about 5 arcmin, whereas the outflow associated with the typical Class 0 source, L1448, is ∼4 arcmin.

The final list of the lines to observe will be selected in the next years and will be based on the results of forthcoming projects. In any case, examples of suitable lines can be found in the 20–50 GHz range, observable with 4G, 5G, and 6G receivers: CS(1–0), SiO(1–0), $CH_3OH(1_K–0_K)$, $HCS^+(1–0)$, OCS(2–1), and $H_2CS(1_{01}–0_{00})$. On the other hand, by using the 7G and 8G receivers in the 70-110 GHz range it is possible to observe higher excitation lines: CS(2–1), SiO(2–1), $CH_3OH(2_K–1_K)$, $HCS^+(2–1)$, OCS(6–5), $H_2CS(3_{13}–2_{12})$, $SO(3_2–2_{02})$, $HDO(1_{10}–1_{11})$, and $SO_2(3_{13}–2_{02})$. In order to: (i) carefully investigate the line profile at high velocities, and (ii) detect EHV bullets, velocity resolutions of at least 0.2 km s^{-1} (i.e. $\leq$ 13 kHz) and bandwidths larger than 100 – 200 km s^{-1} (6.7 to 13.4 MHz) are needed.

At this stage, only very preliminary time estimates can be made by using the values reported in Table 3.1. By assuming a system temperature of ∼70 K at 40 GHz, an rms of 0.02 (0.04) K should be reached in about 30 (5) minutes on-source. At 90 GHz, assuming a system temperature of 180 K one should have an rms of 0.03 (0.08) K again in 30 (5) minutes on-source. The derived rms values are low enough to detect the proposed lines with a good S/N ratio, since we expect brightness temperatures larger than 1 K for the CS, SO, and CH_3OH lines, and about 0.1–0.5 K for the emission due to the other selected tracers (Codella & Bachiller 1999, Bachiller et al. 2001, Codella et al. 2003, 2005).

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4.2.2 Continuum observations

4.2.2.1 Active Binaries

Scientific Background

RS CVn type systems are close binaries that share a number of common features. In particular, they display all the manifestations of solar activity (spots, chromospheric active regions, X-ray and radio coronal emission, flares) but to a greater degree because of the presence of strong magnetic fields generated by efficient dynamo action. Those systems have been found to be conspicuous stellar radio sources. The interest to study them comes from the opportunity to investigate stellar coronae at radio wavelengths and relate to the radio emission with other activity diagnostics, in solar-like magnetic structures.

The statistical properties of a large sample of RS CVn have led to a self-consistent picture for the radio emission mechanism interpreted in terms of gyrosynchrotron radiation by electrons of a few MeV or less, spiraling in fields of 10 to 1000 Gauss. This conclusion is based mainly on the high variability of the radio flux and the observed moderate circular polarization (which excludes a synchrotron regime) in combination with the derived brightness temperature, $T_B \sim 10^{9\pm1}\ K$. In particular the radio flux density usually shows two different regimes: active periods, characterized by a continuous strong flaring which can last for several days, and quiescent periods, during which the flux density goes down to a few mJy.

Although these stars have been studied very extensively in the radio since their discovery, only during the past few years radio multi-frequency observations were carried out. Due to the erratic nature of the radio flares most of the radio observations were carried out during quiescent periods (Jones et al. 1994; White & Franciosini, 1995). Only very recently Osten et al. (2004) reported on 4-epoch multi-wavelength (radio, UV, X-ray and EUV) observations of HR1099, including an active period (up to 200 mJy at 6 cm). Still, the complete evolution of the radio flare, from its onset to its decline, is not well documented. In particular, information on the trend at higher frequencies, where most of the energy releases as well as radiative and collisional losses are evident, is missing.

VLBI observations with their high-resolution capability are, at present, the only technique capable of probing the topology of coronal magnetic fields confining the hot coronae of these systems. Recently, VLBA has provided maps of the radio coronae of RS CVns with unprecedented detail, obtained in both active and quiescent periods (Beasley & Güdel, 2000).

The presence of magnetic activity on both K and G stars in the RS CVns and their proximity led to theories involving the existence of a system of loops, connecting the two components, due to the interactions of magnetic structures of both stars (Uchida, 1986). However it is still not possible to discriminate between the possibility that the radio emission during flares originates from a magnetic structure surrounding the binary system and probably formed by the interaction of the magnetic field of the individual stars, or that it is originating from large loops connected to only one of the stars.

Since 1991 single-dish 6-cm monitoring of active binary systems, carried out using the 32-m telescope at Noto, has been conducted. Even if the principal aim of this monitoring program was to activate ad-hoc VLBI observations once an active period has been detected, the collection of a quite large database has allowed us to study the variability of radio emission from active binaries on short as well as long timescales.

In the following we will summarize results achieved so far with the single-dish monitoring at Noto to evaluate the impact of the SRT on the study of the radio emission from active binaries. If we compare the actual performance of the Noto telescope at 5 GHz, with those expected for the SRT, an improvement of at least a factor of 5 in the theoretical sensitivity is foreseen. Therefore, it should be possible not only to extend the sample of sources to be monitored, which are now limited to the brightest systems, but also to follow, with high time-resolution, the development of the most energetic events. Furthermore, the frequency agility will allow us to gather the spectral information, both in quiescence and in flaring state, necessary to fully understand the physics of coronal plasma.

One of the main scientific results of Noto active binaries monitoring was to assess the existence of extended periods of activity, during which flares occur one after the other and the radio flux never reaches its quiescent value.

These kinds of flaring events have been observed in HR 1099 (Trigilio et al. 1993, Umana et al. 1995) and UX Ari (Trigilio et al. 1998). The active periods can last from a few days up to several months, and are characterized by a sequence of multiple 4-5 hour flares of variable intensity. The existence of very long quiescent periods is a piece of observational evidence against recent models of the quiescent radio emission from active binaries (Chiuderi et al. 1993), which foresee very high flaring rate. Systematic radio observations will also shed light on open questions such as morphology of radio emitting regions and possible correlation with other diagnostics of magnetic activity.

UX Ari has been observed, with a good temporal coverage, in different epochs during strong active periods. During a very active period, with a continuous series of radio flares of flux densities up to 350 mJy, the radio emission consists of two different components: a long-term modulation with an amplitude of $200 \div 300$ mJy and time-scale of few days and a succession of flaring events. The amplitude of the radio flares and their time of occurrence do not depend on the orbital phase, suggesting that the region where they originate is always visible from Earth. Such a behaviour has been modelled in terms of a polar spot as origin of the radio flares plus an active region, located in the corona of the K star and systematically occulted by the K star itself, as the source of the modulated component (Trigilio et al. 1998).

While a rapid succession of intense radio flares is always visible during active periods, the modulated emission is not always present. It was not observed during another epoch of UX Ari observations in 1995, but was present again in 2000 with a minimum at similar phase as in 1993. This seems to indicate that coronal magnetic structures, large enough to determine a rotational modulation, are not always present in the corona of UX Ari; however, during strong flaring periods, they appear to form always in the same part of the K star hemisphere, where they are regularly occulted by the star itself at orbital phase 0.4. This does not support the hypothesis that the emitting regions are related to interbinary magnetospheres.

Radio observations of active binaries offer the opportunity to study the coronal plasma and to relate the radio emission with other activity diagnostics, in solar-like magnetic structures.

The decay phase of a giant flare was followed, for the first time, in $H\alpha$ and in the radio (6 cm) in UX Ari (Catalano et al. 2003). Since $H\alpha$ is formed in the chromosphere this result indicates that the flare involves the whole stellar atmosphere.
With this kind of observations the non-thermal energy emitted by the radio corona, signature of high-energy non-thermal electrons, and the chromospheric thermal Hα-losses can be computed, providing important constraints on energy release models operating during flares.

Technical Requirements

- **Development of specific acquisition software:**
  - **Scanning technique:** The study of highly variable events requires high sensitivity. The rms of the flux density with the Noto telescope at 5 GHz (with a $T_{sys} \approx 35$ K at zenith), obtained observing with the on-off technique, is about 20–30 mJy. Preliminary results of a prototype of an acquisition software, based on the raster scan technique, at Noto indicate an rms even better of 10 mJy in less than 30 min of integration time. This promises a rms of about 2 mJy with the SRT, which makes the SRT a powerful telescope for this kind of study.
  - **Frequency agility:** The acquisition software packages should give the possibility to analyze the data on-line in order to recognize the onset of a flare event. In this case, the construction of dynamic spectra is very important. This requires the possibility to switch quickly receivers in order to obtain microwave spectra in the range from 1.6 to 45 GHz in less than 30 min.
- **Multi-Beam receivers:** The sensitivity would be clearly improved in the case of multi-beam receivers, that eliminate the uncertainty due to the fluctuations of the atmospheric brightness. This is particularly important at high frequencies ($\nu > 15$ GHz).

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4.2.2.2 Measurements of Polarized Diffuse Emission with the SRT

Scientific Background

The polarized diffuse emission of our Galaxy provides us with information of the large-scale structure of the galactic magnetic field. Moreover, it allows the investigation of structures typical of the polarized emission like Faraday screens and regions with rapid magnetic field changes, which generate structures only in polarized emission.

The study of the diffuse polarized emission is of great importance also for Cosmic Microwave Background Polarization (CMBP) investigations. The galactic synchrotron radiation is expected to be the leading contaminant for CMBP experiments and its study at radio frequencies, where it is dominant, allows a clearer view of its contribution.

The diffuse polarized emission has been explored mainly around the galactic plane and at frequencies lower than 2.7 GHz. The high galactic latitudes are less explored: to-date the investigation has been carried out only up to 1.4 GHz, at which a complete mapping of the sky is almost completed by Wolleben et al. (2004) and Testori et al. (2004). These data, not yet released, will allow the exploration of the large-scale structure of the polarized emission down to the degree scale with a sensitivity of 15 mK.

However, at this low frequency the Faraday effects are still significant, and surveys at higher frequencies are desirable to investigate the galactic synchrotron emission in a condition of negligible Faraday effects. Bernardi et al. (2003) show how this situation should be realized starting from about 5 GHz.

A large survey at 4.8 GHz, starting from the galactic plane, can thus significantly enhance our knowledge and provide significant input to the study of both the galactic magnetic field structure and the contamination of the CMBP by synchrotron emission. The survey will consist of about $10^\circ \times 10^\circ$ maps, measuring the relative values of the Stokes parameters within the observed patch (mean values in each patch are lost, as is typical of this type of surveys). In combination with 1.4- and 2.4-GHz results it would allow the evaluation of Faraday rotation effects and other important features like the frequency behavior of the polarized galactic synchrotron emission.

The high sensitivities of the SRT receivers make the telescope suitable for this project.

Technical Requirements

The technical requirements can be summarized as follows:

- **Polarimetric backend**. A correlation polarimeter is needed for the realization of this project. In particular, it has to perform the correlation between the Right- and Left-Handed circular polarizations to allow the simultaneous measurement of both the Stokes Q and U parameters.

- **Sensitivity**. Assuming the mean spectral index $\beta = -2.8$ of the diffuse synchrotron emission in the 1.4-10 GHz range (Platania et al. 1998), a survey at 4.8 GHz requires sensitivity of $\sigma_{\rm px}^{4.8} = 0.5$ mK (0.74 mJy), well achievable in 1 second by a receiver having $T_{\rm sys} = 20$ K and 1500 MHz bandwidth. A wider band would, in any case, be preferable. Sensitivity requirement is thus $\sigma_0^{4.8} = 0.29$ mKs$^{1/2}$ (0.43 mJys$^{1/2}$);

- **Instrumental polarization**. On-axis instrumental polarization should be less than 1%; Off-axis instrumental polarization should be less than 1%, achievable with a cross-polarization pattern of the optics better than 35 dB.;
- **Scanning capability**. With a single-dish antenna the maps are made by scanning the sky in orthogonal directions. This requires antenna software and hardware allowing precise pointing during the scans (10–20 arcsec). The polarimeter would also acquire the data at an appropriate rate: considering a sampling better than two pixels per beam, a FWHM = $3.9'$ beam size at 5 GHz, and an antenna speed of $240''$/s, the proper sampling rate frequency is ν_{SMP} >40 Hz (as for the device installed at Medicina). High antenna speed allows a fast coverage of the sky to be mapped.
- **Data Reduction Software**. Maps of both diffuse emission and discrete sources require calibration and map-making software. The one currently under development for the Medicina telescope will satisfy the requirements of a SRT-like telescope.
- **Time necessary**. To map the Northern Sky, about 530 hours at 1.5 GHz bandwidth) of effective integration time are necessary. As typical of such large surveys the project can be carried out in 2–3 years.

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4.2.3 Pulsar observations

Scientific Background

After nearly 40 years since the original discovery the pulsars − rapidly rotating highly magnetized neutron stars − keep on having many exciting scientific applications, in fields ranging from ultra-dense matter physics to relativistic gravity, cosmology and stellar evolution. A striking example has been the confirmation of the existence of gravitational radiation, as predicted by Einstein's general theory of relativity. In the last 10 years, the Italian Pulsar group has carried out a series of successful pulsar experiments using the Parkes 64-m dish in Australia. In 1996 a large-scale survey of the southern hemisphere at 430 MHz (Manchester et al. 1996, D'Amico et al. 1998) discovered more than 100 new pulsars, including 20 millisecond pulsars. More recently, using a new generation 1.4-GHz multi-beam receiver, the Italian group has been involved in an unprecedented boom of radio pulsar counting, doubling the number of known objects in the galactic field (D'Amico et al. 2001a; Manchester et al. 2001; Kramer et al. 2003). A deep search of the Globular Cluster (GC) system has found 12 millisecond pulsars in 6 GCs for which no associated pulsars were previously known, contributing a 25% to the number of clusters containing known pulsars (Possenti et al. 2003). A high latitude survey for millisecond pulsars has found many new interesting objects, including the first ever known double-pulsar (Burgay et al. 2003; Lyne et al. 2004). In fact, increasing the pulsar counting allows the discovery of many objects which are intrinsically rare in the population, but very interesting for their physical applications. The Italian group has identified several young energetic pulsars, relativistic binary systems, binary pulsars with a massive star companion and millisecond pulsars in tiny orbits with a body of planetary mass. Future deep searches with similar equipment would eventually open the possibility of detecting a pulsar orbiting a black hole.

In this scientific scenario, the Italian pulsar group proposes to use the SRT with two initial aims.

A) Search for and modelling of millisecond pulsars in the Galaxy and in the GC system. In fact millisecond pulsars can be considered as test masses for probing gravitational effects and most of them are also extremely stable clocks, allowing for accurate measurements of their rotational parameters, position and apparent motion in the sky. Discovering more millisecond pulsars will allow one to address many interesting (astro-)physical issues, ranging from the neutron star Equation of State (Cook et al. 1994) to the binary evolution (with emphasis on the eclipsing millisecond pulsars, Nice et al. 2000; D'Amico et al. 2001b), to the population statistic of this kind of sources (Lyne et al. 1998). When detected in GCs, millisecond pulsars prove to be valuable tools for studying the GC-potential well (D'Amico et al. 2002), the dynamical interaction in the GC-core (Colpi, Possenti & Gualandris 2002), the neutron star retention (Rappaport et al. 2001) and the gas content in a GC (Freire et al. 2001).

B) Understanding gravity and gravitational waves. On the one hand, this can be done with the search and follow-up of highly relativistic binary systems, similar to (or even more extreme than) the double-pulsar; on the other hand with the timing of millisecond pulsars on the long term. In particular a *timing array* of many millisecond pulsars can be used for detecting gravitational waves (Hellings & Downs 1983).

Technical Requirements

Given the aforementioned scientific framework and accounting for the pulsar projects ongoing at other major radio-telescopes, the Italian pulsar group believes that a development plan for a competitive pulsar research activity with the SRT on a short-medium term should be based on systems operating at the three frequencies described in the following:

System 1: 325-MHz (low frequency) observations: The Radio Frequency Interference (RFI) environment at the SRT site indicates that the 325-MHz band is relatively free of interferences (much more than the 408-MHz band) and that a relatively large clean bandwidth is available. Depending on the dynamic range and robustness of the receiver system, a bandwidth up to 80 or even 100 mHz could be exploited. A 325-MHz low noise cooled receiver system would be ideal in order to undertake large scale surveys at high galactic latitude. Such a survey would probe the population of millisecond pulsars with unprecedented sensitivity in ~ 100 days of observation. The system should be equipped with a 1024,2048 or even 4096$\times$32-kHz filter-bank for each polarization (the amount of channel depending on the actual RFI situation). The same receiver, equipped with a coherent de-dispersing system (like those developed at CalTech and Swinburne), can also provide excellent performance in high precision timing observations.

System 2: 1.3–1.8 GHz (intermediate frequency) observations: As a short-term plan for a 21-cm pulsar system, we propose to build a high resolution (2$\times$1024$\times$0.50 MHz) de-dispersing system to be used with the 1.3–1.8 GHz receiver already planned. Such a system can be very well suited for a deep search of the GC system (requiring some tens of days of observations) and other selected targets (for instance SNRs), and can be used for regular timing observations of non-millisecond pulsars. The outstanding results obtained at Parkes at 21 cm, strongly suggest that this is a prime frequency for pulsar search. However, the key-feature of the success of the 21-cm Parkes experiments was the availability of a 13-element multi-beam receiver. The slightly shorter focal ratio of the SRT (f/0.34) compared to that of Parkes (f/0.4) constraints a multi-beam receiver to probably no more than 7 beams: for covering a given sky area, the typical integration time would then probably be reduced by a factor of 2 compared to that adopted in the Parkes survey (35 min). Thus, in order to keep the same sensitivity, a bandwidth twice as large as the Parkes' one (288 MHz) should be considered. The 1300–1800 MHz frequency interval in Sardinia is nominally relatively interference-free, but the lower end of the band is very close to the frequency of a civil aviation radar system. This is the typical situation that needs to be checked with a systematic RFI campaign, rather than a single shot, as the effective impact of these spurious effects might strongly depend on azimuth, and on the time of the day. Furthermore, we are now convinced that a state-of-the art 21-cm pulsar system should be equipped with a much higher frequency resolution than adopted at Parkes (3 MHz), which strongly limited the discovery of millisecond pulsars. With a double band per beam and a much larger number of frequency channels in the de-dispersing system, such a system would require the development of a major backend. In summary a careful analysis of the effective RFI environment and a comparative evaluation of the scientific interest of other groups should be considered here before taking a decision about a 21-cm multi-beam receiver.

System 1+2: The case for a dual frequency receiver: The state-of-the-art for observations in the context of the pulsar timing is represented by dual band receivers: infact they provide the large frequency baseline ($\gtrsim 60\%$ of the upper frequency) and simultaneity necessary to measure with high accuracy the dispersion delay of most millisecond pulsars, and estimate with ultra-high precision (rms 0.1–1.0 μsec) any secular or transient effect affecting their pulse arrival times at infinite frequency. These receivers are also unrivalled instruments for studying the class of the so-called eclipsing pulsars (Nice et al. 2000), the emission of giant pulses (Cairns 2004) and the insterstellar medium along the line-of-sight to a radiopulsar (Bhat et al. 2002). Recent technology allows to minimize the loss of efficiency (few percent at worst) with respect to single band receivers operating at the same frequencies and hence dual band systems also optimise observation times and telescope scheduling: a given sensitivity in both the bands can be attained in a much shorter observation time than that required if observing at the two frequencies separately.

In particular the availability of a dual frequency receiver for performing pulsar timing observations has become of paramount importance in recent years, within the framework of the international programme called Pulsar Timing Array, for which there is a strong pressure for SRT to be involved in. Other big radiotelescopes collaborating with this project have been already equipped (or are going to be equipped) with dual band systems: at Parkes has been recently installed a 10cm/50cm receiver whose performances are significantly better than those of the two receivers previously available at those frequencies (and comparable with the best single band receivers at 10 cm or 50cm installed elsewhere). At GBT the construction of a dual 340MHz/820MHz feed capable of performing *simultaneous observations at both bands* has been highly recommended, being *extremely useful scientifically* (Report from the NRAO-GBT Pulsar Workshop of November 2004) and largely preferable over other kinds of dual feed systems (Report from the NRAO-GBT Pulsar Workshop of November 2004). In view of this, a natural configuration for SRT would be that of a 90cm/21cm receiver, which would allow unique investigations by itself but might in turn overlap with the Parkes (and future GBT) systems in term of frequency baseline, significantly improving the overall precision of the international Pulsar Timing Array. Of course this dual band receiver would replace the two systems (System 1 & System 2) mentioned before.

System 3: 3 GHz (high frequency) observations: Relatively high frequency (~ 3 GHz) is also very useful to undertake a program (typically requiring 6 hrs every 2 weeks, for a total of 6 days a year) of extremely high precision timing observations like those carried out in the case of millisecond pulsars, or in the measurements of relativistic effects in double neutron star systems. This frequency choice requires a rather large bandwidth ($\gtrsim 1$ GHz), in order to compensate the lack of flux due to the steep spectra of pulsars. According to the RFI environment, a relatively clean bandwidth is available at the SRT site in the frequency interval 3–4 GHz. This is a bit higher than the typical centre frequency (~ 3 GHz) adopted for these applications, but still well-suited. The pulsar backend necessary for these applications should be a digital filter bank (1024×1 MHz) similar to that developed at Parkes. The decision of the focal location of such a receiver is a matter of compromise with other scientific interests. For pulsar applications, side-lobe suppression and spill-over are not of paramount importance, while the key parameter is the effective antenna gain; so concerning pulsar research, this receiver with mono-feed could be better accommodated in the primary focus. On the other hand, should the SRT Board decide for the construction of a BW focus receiver operating at a similar frequency, the Italian pulsar group could cope with that.

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4.3 Extragalactic astronomy

4.3.1 Line observations

4.3.1.1 Extragalactic HI Blind Searches with the SRT

Scientific Background

These years have seen the completion of the whole-sky HI (21 cm line) blind surveys performed at 70-m class antennas equipped with state of the art multi-beam receivers. This remarkable effort was aimed, mainly, at determining the shape of the HI mass function. In fact, one of the principal discrepancies between Cold Dark Matter (CDM) structure formation theory and the real world is the large difference between the large predicted abundance of satellite halos around giant galaxies and the scantly observed satellite population. In other words, there is no agreement on the logarithmic slope of the faint end of the galaxy mass function. Since this is hard to measure directly, efforts have concentrated mainly on the optical luminosity function, and on the HI mass function. In this way limits can be put at least on halos with sizeable contents of stars and/or gas.

Another difficulty of the 'missing satellite problem' is to determine the possible changes of the mass function with the environment. Recent studies on the optical luminosity function show definite variations of the faint end in differing environments: steeper faint ends (more dwarfs) are found in dense clusters. On the contrary, the results on the HI mass function indicate that the population below $10^8\,\mathrm{M}_\odot$ is depressed in clusters respect to the field environment. Obviously, we are still far from a comprehensive understanding of the building process of the galaxy population.

Anyway, even the most extended, in terms of sampled volume, of the available HI surveys (HIPASS, Parkes + HIJASS, Jodrell Bank) sample a lower mass limit just below $M(\mathrm{HI}) = 10^8\,\mathrm{M}_\odot$ and no galaxies have been reliably detected with $M(\mathrm{HI}) < 10^7\,\mathrm{M}_\odot$, independently of distance. A vast improvement in the statistics below $10^8\,\mathrm{M}_\odot$ is necessary to resolve the controversy over the faint end slope of the HI mass function.

Presently, even for a dedicated antenna, it would be too demanding, in terms of telescope time, to embark on whole-sky surveys deeper than those just completed. The projects in this area are therefore focusing on deep blind surveys in selected areas. There is therefore a good chance for instruments of the 70-m class to produce interesting science by scanning with long integration times restricted areas with a focused rationale.

Technical Requirements

The instrumentation required is quite standard nowadays: a spectral backend capable of a coverage of $\sim 15000\,\mathrm{km\,s^{-1}}$, that is 70 MHz, and a resolution of $\sim 20\,\mathrm{km\,s^{-1}}$, that is 1000 channels per polarization. With modern frontends ($T_{sys} \sim 20\,\mathrm{K}$), the noise expected at a 65-m antenna would be about $\sim 3\,\mathrm{mJy}$ (channel to channel) with 5000 s of integration time. In practice this translates to a 2-σ detection limit of $\sim 2.5 \cdot 10^7\,\mathrm{M}_\odot$ of HI in the Virgo cluster (17 Mpc), that is a large distance for the problem at hand.

This would be a remarkable result if it could be pursued in an area of some square degrees. No time would be lost in off-scans since these would be acquired in adjacent fields as part of the project. The observations should of course be coordinated with the other teams working on the subject AND, as in all blind surveys, it could greatly profit of the availability of a multi-beam 1.4-GHz receiver like those presently used at Parkes, Jodrell Bank and Arecibo, just to cite a few.

References
For more info on the subject and related references see for example the extragalactic white-paper at http://alfa.naic.edu/.

4.3.1.2 H_2O Megamasers

Scientific Background
This project aims at using the SRT to detect 22-GHz H_2O masers within the nuclei of galaxies. In some nuclei, the water masers populate accretion disks around the super-massive black holes (SMBHs), lying as close as 0.1 pc to the nuclear 'monster'. Once discovered, Very Long Baseline Interferometry (VLBI) can be used to map the angular distribution of maser features throughout individual disks, and hence, to obtain a direct imaging of disk structures typically obscured or not resolved by optical and infrared observations (e. g. Miyoshi et al. 1995; Greenhill et al. 1995). So far, no other astronomical technique can provide images of accretion disks in such a proximity to the SMBHs. Depending on the properties of the galactic nucleus (e.g., orientation to the line of sight and black hole mass), from such images important physical quantities can be derived with extreme accuracy, for example: accretion rate, degrees of disk warping and orientation, and the cosmic distance. The latter is particularly important because the technique used to obtain the distance is entirely geometric and thereby independent of the luminosity calibrations that affect almost all other distance measurement techniques. A 'geometric distance' is available for the galaxy NGC 4258 (see Herrnstein et al. 1999), and it represents the most accurate distance measurement so far. Hopefully, geometric distances to NGC 4258 and several more galaxies will ultimately provide anchors in the local universe, against which calibration of the extragalactic distance scale can be checked.

Technical Requirements
For the project previously outlined we can profit by the 22 GHz multi-beam receiver option, planned for the SRT, performing internal beam switching observations without losing time on the off position. We recommend a spectrometer that (at least) supports simultaneously two 200 MHz bands in two polarizations with 8192 spectral channels each. Alternatively, the SRT could be provided with a digital correlation spectrometer (e. g. that the CfA SAO4K; http://cfa-www.harvard.edu/ lincoln/swis/sao1k/html) with bandwidths of up to 400 MHz and 4096 spectral channels. This corresponds to about 1.3 km/s at the rest frequency of the H_2O line (22.2 GHz), enough for detection purposes.

Such unusually wide bandwidth capabilities are necessary because known H_2O masers in active galactic nuclei (AGN) display typically sub-Jy spectral lines distributed over a frequency interval of about 500 to 2000 km s^{-1}, where the interval is dictated by the rotation speed of the disk at radii where the maser action is excited. Because it is impossible to predict such interval, the widest possible instantaneous bandwidth is critical for efficient surveys of large numbers of galaxies.

The isotropic luminosities $L_{\rm iso}$ of water megamasers range from 20 $L_\odot$ to 6000 $L_\odot$ (the 'gigamaser' in TXFS2226-184; Koekemoer et al. 1995). The maser features widths are also very different, normally between 0.5 to tens of km s^{-1}. For pure detection purposes, we can take a prototypical line with linewidth of dv = 30 km s^{-1} at a redshift z of 0.03 (the most distant maser detected, in the radio galaxy 3C 403, is at z = 0.06; Tarchi et al. 2003). The isotropic luminosity of a maser line is given by the equation:

$$\frac{L_{\rm iso}}{[\rm L_\odot]} = 0.023 \cdot \frac{D^2}{[\rm Mpc]} \cdot \int \frac{S}{[\rm Jy]} \cdot \frac{{\rm d}v}{[\rm km\,s^{-1}]}$$

Hence, 20 and 6000 $L_\odot$ features at $z = 0.03$ (D = 120 Mpc, assuming H_0 = 75 km s^{-1} Mpc^{-1}) will have a peak flux density of 2 and 600 mJy, respectively. Therefore, in a survey the possibility to detect als the weakest megamasers ($L_{\rm iso} = 20\,L_\odot$) imply a sensitivity per channel not worse than 0.7 mJy (3σ). With the 80 K system temperature and an antenna efficiency of 56 % at 22 GHz (Table 3.1), the SRT should be able to obtain a sensitivity of 0.7 mJy in 60 and 25 hours, for a channel width of 1.3 and 5 km s^{-1}, respectively. Such huge integration times and the large number of AGN that need to be searched for maser emission force us to conclude that the outlined SRT survey will necessarily focus on high-luminosity megamasers (with isotropic luminosities $> 50\ L_\odot$), with integration times of (only) about 5 to 10 hours per target (dependin on the channel width required).

Cosmological water megamasers: Standard 22-GHz receivers have nominal frequency bandwidths between 18 and 26 GHz. However, if the object that emits the water maser line(s) has a redshift z greater than 0.25 the maser line falls outside the receiver bandwidth, at frequencies < 18 GHz. Hence, to extend our survey to cosmologically-relevant water megamasers it would be necessary to extend the low-frequency coverage o the 22-GHz receiver and/or to build an *ad hoc* receiver capable to work between 16 and 20 GHz. So far, such a receiver is not yet available in any of the other large antennas (e.g. GBT and Effelsberg). The SRT would then be able to perform the first high-redshift water megamasers survey ever tried. Of course, the integration times computed for $z = 0.25$ would rise by huge factors, limiting the possible survey detections only to very luminous objects ($L_{\rm iso} > 500 - 100 L_\odot$). However, as recently speculated, the number of such objects might be higher in the 'earlier' Universe (e. g. Townsend et al. 2001), because of enhanced AGN activity and merging phenomena. The result of such a survey might be used as a pathfinder for similar studie that will be performed in the future by the Square Kilometer Array (SKA).

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4.3.1.3 A Redshift Machine for the SRT

Science Background

(adapted from the science case for the Large Millimeter Telescope [LMT] redshift machine, http://www.lmtgtm.org/overview/sci/node4.html)

Current surveys are unable to associate unambiguously sub-mm sources to their optical/IR/radio counterparts. Thus, the redshift distribution, luminosities and star-formation history of submm-selected galaxies at redshifts > 1 is still unclear.

Using a stable, sensitive, very broad-band mm-wave receiver with an instantaneous bandwidth of ~ 35 GHz (the Redshift Machine) it will be possible to determine CO spectroscopic redshifts of mm-/submm sources without the need of optical/IR spectroscopy, a task that may even be impossible to carry out at very high redshifts: at $z > 6$ the redshifted Lyα passes into the near-IR band and the intervening neutral hydrogen clouds along the line of sight completely absorb the UV light of galaxies. Near-IR (NIR) spectra, obtained with the new generation NIR multi-object spectrographs on 10-m class telescopes, will help somewhat to elucidate the nature of star-forming galaxies at $z > 6$, but only for those systems that are not heavily dust-extinguished or even quiescent. For these sub-mm/mm sources, molecular or atomic emission lines in the mm bands (1 and 3 mm) may be the only means to obtain reliable redshifts. The distances between two adjacent J-transitions of the CO molecule shrink to $\Delta\nu < 35$ GHz (the approximate width of the mm-wave atmospheric windows) at $z > 2$. This means that a 35-GHz bandwidth spectrometer is virtually guaranteed of covering (if not detecting) at least one CO line for any galaxy with $z > 2$. Some redshifts will allow more than one line to fall in the bandwidth. If the same object is observed by two (or more) of such spectrometers covering adjacent wavelength bands, there is always the chance to detect at least two lines and determine the object's redshift, even if (or in particular when) optical spectroscopy is not possible.

Given the initial redshift from the Redshift Machine it will then be possible to accurately tune more 'conventional' narrower-bandwidth heterodyne systems, that cover higher or lower frequency passbands, to the

appropriate redshifted frequency of additional CO transitions. The higher velocity resolution of the more conventional receivers, and additional line ratios, will provide important kinematic and chemical information. Apart from the above specific considerations, a broad-band facility would also offer the possibility to search for new lines in extragalactic sources.
As an example of what one can expect, we refer to the various line surveys carried out toward Orion-KL, in various bands between 70 and 857 GHz. Thousands of molecular emission lines were found in these surveys – many will be too weak to detect in external galaxies, but lines of e.g. CO, CS, SO, CH_3OH, H_2CO, SO_2 may be detectable. More precise detectability estimates for the SRT have to await a careful analysis of expected line strengths, required redshift, receiver sensitivity, and available backends and bandwidth.

Technical Requirements

Observations at frequencies $\gtrsim 100$ GHz with the SRT are not possible. Hence, we can think of a lower-frequency Redshift Machine composed of several spectrometers covering the 1 cm and the 3 mm bands. It is conventionally assumed that the largest continuum band technically feasible can be at most as large as $\sim 40\%$ of its central frequency (still a challenging task). The SRT could then be equipped with a 35 GHz wide-band spectrometer (central frequency 86 GHz) in the 3 mm band and two narrower-band spectrometers continuously covering the 1-cm band (for instance two 10 GHz wide-band spectrometers centred at 43 and 32 GHz respectively).
Another issue is the sensitivity-feasibility of such high-z line measurements. Olmi (2003) has demonstrated, using a simple model for the high-z galaxy ISM (Olmi & Mauskopf 1998) and correcting for cosmological effects, beam dilution, telescope/receiver performance and atmospheric absorption estimated at the SRT site, that the strongest CO transitions can be detected (5σ) in the 3-mm band in a time of $\lesssim 1$ hr at $z \sim 2.5 - 5$. However, in the 1-cm band detections may take much longer, from a few to tens of hours. For a detailed discussion of this issue we refer to Olmi (2001).

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4.3.2 Continuum observations

4.3.2.1 High-Frequency Extra-Galactic Sky Surveys with the SRT

Scientific Background

The recent development of multi-beam receivers will enable single-dish telescopes, like the SRT, to survey large areas of sky at high radio frequencies (≥ 15 GHz). High-frequency extragalactic sky surveys are expected to have a major impact on astrophysics. Some of the key topics that can be addressed by such surveys are listed below.

- They provide adequate samples to get a really unbiased view of rare, but very interesting, classes of sources with flat spectrum up to high frequencies, that, at low frequencies, are swamped by more numerous populations which fade away as the frequency increases. One example are flat-spectrum radio quasars (FSRQ), for which much more extended samples are required to properly cover their parameter space. A second example are BL Lac objects: it is still debated whether radio selected and X-ray selected BL Lacs are the extremes of a single class of objects whose properties are determined by the beam orientation or have intrinsically different properties.

- They open a window on new classes of sources, such as those with strong synchrotron or free-free self-absorption corresponding to both very early phases of nuclear radio-activity (extreme GHz Peaked Spectrum - GPS - sources or high-frequency peakers - HFP) and late phases of the evolution of Active Galactic Nuclei (AGNs), characterized by low accretion/radiative efficiency (ADAF/ADIOS sources), as well as to early phases of the evolution of radio afterglows of gamma-ray bursts (GRB).

- They produce surveys of the Sunyaev-Zeldovich effect in distant clusters of galaxies and perhaps on galactic scales, extremely important both to understand the formation of large scale structure and the heating of the intergalactic medium.
- They play a vital role in the interpretation of temperature and polarization maps of the Cosmic Microwave Background (CMB), by allowing us to characterize and remove the contamination by astrophysical foregrounds.

A census of the expected contribution from different source populations in high frequency extragalactic samples is listed in the Table below.

Table 4.2: Expected number density (per sq. degr.) for various source populations at 20 GHz. Based on the model described in De Zotti et al. 2004.

	N(> 1 mJy)	N(> 10 mJy)
FSRQ	2.7	0.57
BL Lac	2.5	0.2
Steep-spectrum	26	2
ADAF	0.12	0.0042
GRB Afterglows	0.0045	0.0034

In the following we focus on a particular topic: the study of the very early phase of nuclear radio-activity. The nature of the mechanism that causes the triggering of extragalactic radio sources is an open question. To answer it a large sample of young sources is needed. Current models of radio source growth that consider the effects of self absorption on the source synchrotron emission indicate that very young radio sources should have radio spectra which peak at frequencies > 1 GHz, with younger sources peaking at higher frequencies than older sources (O'Dea 1998; Snellen et al. 2000).

This is due to a well-known relation between linear size of a radio source and turnover frequency: the younger the source, the smaller the size, the thicker the optical depth, the stronger the self-absorption effects, the higher the turnover frequency. Typically, sources with linear sizes < 1 kpc have turnover frequencies > 1 GHz.

This class of extragalactic radio sources (assumed to be hundreds of years old) is called Gigahertz Peaked Spectrum (GPS) population. Extreme GPS sources with turnover frequencies > 10 GHz (called High Frequency Peakers, HFP) would have linear sizes < 10 pc and should be the youngest sources (tens of years old). GPS sources are rare ($\sim 20\%$ of sources are GPS in 2.7-GHz samples and $\sim 3\%$ are HFP in 5-GHz samples). Today we know a total of a hundred of such sources. To obtain a better census and understanding of the initial stages of the radio source physical evolution, high frequency extragalactic sky surveys are of crucial importance.

Any blind radio survey is biased toward sources with spectra peaking close to the selection frequency, hence blind surveys at frequencies > 10 GHz provide a means of effectively generating a sample rich in HFPs and thereby testing the models of source growth in very young sources. On the other hand, high-frequency sky surveys have started to become feasible only very recently. If we focus on surveys at frequencies $10 - 100$ GHz (which are the relevant ones for the study of very young radio sources), the most interesting one is the so-called 9th Cambridge survey (9C) carried out at 15 GHz with the Ryle Telescope (Waldram et al. 2003). This survey has covered 520 deg^2 to 25 mJy, 190 deg^2 to 10 mJy and 12 deg^2 to 5 mJy (the deepest survey currently available at $\nu > 10$ GHz). A follow-up on a sub-sample at other radio frequencies is currently under way to select flat- and/or inverted-spectrum sources (eg. GPS/HFP candidates). Preliminary results indicate that the fraction of HFP candidates decreases from 33% at fluxes > 100 mJy to 20% at fluxes > 25 mJy, to 10% at fluxes > 5 mJy (Waldram & Pooley 2004).

Another survey which could give a contribution to this topic in the future is the planned all-sky ATCA 18 GHz survey which will be undertaken in the southern hemisphere to a few hundred mJy (a pilot survey covers about 1200 deg^2 to 100 mJy, Ricci et al. 2004).

High frequency sky surveys could also give a very important contribution in investigating the so-called faint radio population (mJy and sub-mJy fluxes at 1.4 GHz), a mixture of different kinds of sources (mainly low luminosity AGNs and star-forming galaxies), which is still quite elusive. The possibility of reaching in the near future (sub-)mJy flux detection limits at frequencies > 10 GHz will allow the study of the spectral properties of such sources and the test of different accreting models proposed for low-luminosity AGN (eg. advection dominated accretion flows - ADAF - vs core-jet models).

Technical Requirements

The SRT could give an important contribution to the topics discussed above. We can profit of the 22 GHz multi-beam receiver (7 elements, 2 polarizations) which is already under development for the SRT to carry out extragalactic surveys. The multi-beam option is crucial to efficiently conduct extensive surveys with the SRT due to the very small primary beam of the 64-m antenna ($\sim 54''$ FWHM at 22 GHz, see Tab. 3.1). In absence of a derotator mounted at the telescope, a derotation software should be made available at the SRT to correctly align all the beams (see Chapter 3).

Assuming an instantaneous bandwidth of 2 GHz for continuum observations, 2 polarizations and the antenna sensitivity parameters provided so far for the SRT at 22 GHz (see Sect 3.5 and Tab. 3.1), it is possible to estimate that a 1 s exposure would provide an rms noise of $\sim$ 2 mJy/beam, whereas a 1 min exposure would give an rms noise of $\sim$ 0.25 mJy/beam. This translates to an observing campaign of, say, 20 days to map either (A) an area of 500 deg^2 to 2 mJy/beam (rms), or (B) an area of 10 deg^2 to 0.25 mJy/beam (rms), driving the telescope in raster scanning mode (as necessary for blind surveys).

Case (A) would be more suitable to pick up rare objects like the GPS/HFPs. From the existing counts at 15 GHz, we estimate that we would detect about 1300 extragalactic radio sources at 5σ ($\sim$ 10 mJy), about 20% of them ($\sim$ 260) being HFPs candidates (see Waldram & Pooley 2004). Such a survey alone could provide nearly three times the number of GPS/HPF sources currently known. Case (B), on the other hand, would be very suitable to study the faint radio population, providing $\sim$ 280 sources above $\sim$ 1.3 mJy (5σ).

To fully exploit the SRT capability, a survey should reach the SRT confusion limit, which is $50-70$ μJy/beam (rms) at 22 GHz (as estimated by extrapolating to lower fluxes the 15 GHz number counts of Waldram et al. 2003). A noise level of 60 μJy can be reached by the SRT with 18 min long exposures. This means an observing campaign of 40 days to map an area of 0.5 deg^2 and detect 75 sources at $S > 0.3$ mJy (5σ). While still feasible with the SRT, such a campaign is very long, and bad atmospheric conditions could make it even longer. In this respect a multi-beam receiver with more than 7 elements would be very useful. Allowing for a response loss of $\sim$ 25% for the external elements, we can accommodate a grid of 5×5 feeds in the SRT 22-GHz focal plane. With a 25-element multi-beam system the observing time necessary for the survey mentioned above would be reduced to 15 days.

In a future perspective, it would be also very interesting to equip the SRT with a 30 or 40-GHz multi-beam receiver, suited for deep continuum observations (largest instantaneous bandwidth). Indeed, extragalactic sky mapping is very scarce at these higher frequencies. The only existing surveys are the few very bright surveys associated with recent CMB experiments: for instance the VSA at 34 GHz ($S_{lim} \sim 100$ mJy) and the WMAP at 41 GHz ($S_{lim} > 1$ Jy). Possible other surveys will be performed during the Planck mission. From Tab. 3.1 we can see that the SRT sensitivity at 30 GHz is a factor of two better than at 40 GHz. In addition, the beamsize decreases with increasing frequency, making sky surveys increasingly challenging.

Nonetheless, since a 30-GHz multi-beam receiver is already being developed for the Torun 32-m single-dish, a 40-GHz multi-beam receiver could be considered preferable for the SRT. In this respect we notice that the smaller beamsize at 40 GHz could be counterbalanced by a larger number of beams that can be accommodated in the multi-feed array.

Another important issue to be taken into account before establishing the best frequency for a high-frequency sky survey with the SRT is the atmospheric transparency at ≥ 30 GHz and its seasonal variations which should be monitored at the SRT site.

A tentative estimate of the confusion limit of the SRT at 30/40 GHz can be obtained from the 15 GHz number counts of Waldram et al. (2003), by assuming flat-spectrum sources ($\alpha = 0$). This yields rms limits of $20 - 30$ μJy at 32 GHz and of $10 - 15$ μJy at 43 GHz. Given the sensitivity parameters tabulated in Tab. 3.1, to achieve the confusion limit for statistically relevant samples (> 100 sources) in a reasonable time (< 30 days), we need multi-feed receivers with at least 3×3 elements at 30 GHz and 10x10 elements at 40 GHz.

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4.3.2.2 Search for Sources with High Rotation Measures

Scientific Background

The measurement of rotation measures (RMs) of extragalactic sources is a powerful instrument in several respects. The RM is proportional to the product of the magnetic field and the electron density along the line of sight and thus bears considerable information on physical conditions in the source and along the line-of-sight towards us. The measured RM is composed of a galactic (GRM) and an extragalactic (RRM) contribution. The separation of these two parts can be done by the observation of neighbouring sources. Since the galactic contribution is expected to vary on much larger scales than the extragalactic part, the mean RM of neighbouring sources at similar galactic latitude is a reliable measure of the galactic part (Oren & Wolfe 1995). Observing large samples with high source densities is therefore essential to guarantee a separation of GRM and RRM. The extragalactic component RRM can provide information on any gaseous material along the line-of-sight to the source (intervening galaxies, intergalactic clouds or protogalaxies, intracluster gas of material associated with the radio source itself).
The unambiguous determination of RMs in such samples will push forward our knowledge in several aspects:

- characteristics of the medium in groups and clusters. A RM study will disclose the conditions of the medium in galaxy clusters and groups, in particular at higher redshifts. Carilli et al. (1997) presented evidence that most sources with detected RM have the Faraday screen local to the source. The simplest interpretation would be that these sources are situated in dense, cluster-type environments, as has been found at lower redshifts. E.g. Pentericci et al. (1997) and Athreya et al. (1998) reported observations of a radio galaxy with a high RM at a redshift of 2.2, which is evolving to become a cD galaxy.
- At high redshifts the correlation between high RM and the existence of damped Lyα clouds can be studied. It has been claimed that large RM screens are neither galactic nor associated with the source, but cosmologically intervening material (Kronberg & Perry 1982; Wolfe et al. 1992; Oren & Wolfe 1995). There is some indication that high-redshift sources with high RMs are also good candidates to find damped Lyα systems. The main problem of these studies is the poor statistics.
- With sufficiently closely sampled RM measurements it is also possible to 'map' the GRM distribution over large parts of the sky. These data are of great interest for galactic halo research.

Technical Requirements

As eventually at least three measurements at different well-spaced frequencies are required for an unambiguous determination of the RM, all broad-band continuum receivers should be equipped with polarimeters for Stokes Q and U.

As an example the following time estimate is given for the planned 5-GHz receiver system (1BW in Tab. 3.1). For the calculation a single horn is assumed, although a double-horn system would warrant a more efficient cancellation of atmospheric effects at frequencies ≥ 5 GHz (more important for total-intensity measurements). Assuming an aperture efficiency of 58% for 5 GHz, a system temperature of about 20 K and a receiver bandwidth of 400 MHz a total power flux density limit of 1.1 mJy/beam can be reached within 1 second of integration time. Given that the confusion limit at this frequency is estimated to be around 0.7 mJy/beam and 0.24 mJy/beam in total power and polarisation, respectively, this would be reached in about 2.5 s pure on-source observing time. In cross-scan mode the total telescope time would then sum up to about 90 s, if four subscans for better statistics and redundancy are made. This means that a sample of, say, 1000 sources with flux densities $>$ 40 mJy and assumed fractional polarisation of 3% can be observed down to the confusion noise limit in polarisation in about 35 hours on a 5σ level in each polarisation channel. This observing mode requires driving software for cross-scans (as will be required also for standard pointing checks).

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4.3.2.3 High-Frequency Follow-up to Surveys

Science Background

It is well-known that radio sources undergo intermittent activity. This is e.g. reflected in numerous high-resolution images of radio galaxies which exhibit different components obviously produced at different epochs. The final exhaustion of engines in radio galaxies is followed by rapid synchrotron cooling of the hotspots and lobes, which is the reason why only very few relic radio sources are observed at the present epoch. In order to explore the evolution of radio sources it is hence mandatory to investigate the spectral evolution of a large and complete sample of radio sources. One of the best suited samples to explore the spectral characteristics of sources over a wide frequency range is the B3 VLA survey (Vigotti et al. 1989). It consists of a subset of 1049 sources selected from the B3 survey (Ficarra et al. 1985) in five flux bins by narrowing the survey strip in declination and restricting it to high galactic latitudes so that the completeness is very carefully controlled. This survey, some 30 times deeper in flux density than the 3C has measured flux densities between 74 MHz and 10 GHz (Vigotti et al. 1999). It is now essential to extend the flux measurements to radio frequencies beyond 10 GHz as it is here where either possible ageing (and thus convex curvatures of the spectra) or the influence of new synchrotron components (and thus high-frequency flattening) are visible first.

Taking the B3 VLA survey as example we have extrapolated the known broad-band continuum spectra to probable future continuum frequencies at the SRT at 20, 32, 43, and 86 GHz. In order to give an idea which noise levels ought to be reached we have estimated the median flux densities at these four frequencies for the 1049-source B3 VLA survey: 20 GHz: 13.4 mJy; 32 GHz: 8.0 mJy, 43 GHz: 5.7 mJy and 86 GHz: 2.5 mJy.

Technical Requirements

This observing programme requires broad-band (multi-beam) receivers at typical continuum frequencies greater than 10 GHz (e.g. 20 GHz, 32 GHz, 43 GHz, 86 GHz, preferably with polarimeters). Assuming the values reported in Tab. 3.1 at 20 and 32 GHz show that it is well possible to observe the majority of the sample in relatively little time at three lower frequencies, while measurements at 86 GHz would be taken for a suitable subsample only. The time-consuming factor will be the deep mapping of extended sources, which will be increasingly necessary with decreasing beam sizes at higher frequencies. The employment of multi-beam arrays should be of great help to accelerate the latter observations. Both cross-scanning and raster-scanning modes would be required.

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4.3.2.4 High-Frequency Mapping of Extended Sources

Science Background

The class of giant radio galaxies (GRGs) is formed by radio galaxies with linear sizes exceeding 1 Mpc. Some 130 mostly nearby ($z < 0.2$) GRGs are known today, most of which were discovered serendipitously (http://www.astro.uni-bonn.de/∼mjamrozy/grglist1.html). Their angular sizes range from a few arcminutes to more than a degree. The aims of studying GRGs are twofold: Firstly, since their radio properties are extreme, they are an ideal laboratory for studying the physics of radio sources. Due to their large angular sizes, even single-dish observations with their relatively low resolutions reveal a wealth of detail in these sources. Secondly, these are the only sources that can probe their environment and the intergalactic medium (IGM) over such a large scale. Studying these sources can therefore constrain physical parameters of the IGM. While most of these sources have been thoroughly studied at frequencies up to 10 GHz (e.g. Mack et al. 1997, Schoenmakers et al. 2000), their characteristics at shorter wavelengths have not been observed yet. Mapping of GRGs with the SRT should therefore be done at frequencies > 10 GHz. The use of single-dish instruments is mandatory at such high frequencies due to increased missing spacing effects of interferometers.

Technical Requirements

This project depends on the availability of multi-beam receivers (for beam-switching to remove weather effects) or better even horn arrays, large bandwidths (e.g. 2 GHz at 32 GHz) and polarimeters. The SRT at 20 GHz would offer a beam size of $56''$, ideal for mapping the largest GRGs. From extrapolation of intensities found in the 10 GHz maps obtained with the 100-m Effelsberg telescope an rms noise level of less than 0.3 mJy/beam seems mandatory for a significant progress of high-frequency studies of these sources. Assuming a system temperature of 81 K and a bandwidth of 2 GHz, we expect to reach a noise level of 1.7 mJy in 1 s. 0.3 mJy/beam are therefore reached in a pure observing time of about 32 s. Further assuming a raster-scanning mode **with one horn** only, one would therefore require about 12 coverages. Typical durations for one coverage **for the largest sources** would be about 6.5 hours (assuming a pixel size of $15''$, scan speed of $20'$/min and total map sizes of $60' \times 30'$), thus summing up to almost 78 hrs per source. Obviously the employment of multi-beam receivers can greatly reduce this time.

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4.3.2.5 Multi-frequency Monitoring of long- and short-term Blazar Variability

Scientific Background

One of the outstanding characteristics of blazars is the frequently observed strong variability (often by a factor of two or more) across the whole electromagnetic spectrum on time scales of months to years. The mechanisms of this variability are still not well understood. Possibilities discussed so far include shocks in jets (e.g. Marscher & Gear 1985, Aller et al. 1985, Marscher 1986) and changes in the direction of forward beaming e.g. due to helical trajectories of plasma elements in the jets (Camenzind & Krockenberger 1992) or a precessing binary black-hole system introducing flux-density outbursts (lighthouse effect, Begelman et al. 1980; Sillanpaa et al. 1988). Thus, variability studies furnish important clues into size, structure, physics and dynamics of the radiating region in these sources. The wide variety of models calls for new and ongoing long-term as well as multi-frequency flux-density campaigns capable of providing the necessary observational constraints.

About 20 years ago, a new type of variability in extragalactic radio sources could be established: variations on time scales of hours up to two days were found as a frequent phenomenon in compact blazar cores (Witzel et al. 1986, Heeschen et al. 1987). There is still a debate about the physical origin of such rapid, IntraDay Variability (IDV) in total flux density as well as polarization. IDV has been found to be present in about 30% of these compact objects (Quirrenbach et al. 1992) and reveal extremely tiny dimensions of the emitting region (∼ light-hours) with brightness temperatures of up to $T_B \simeq 10^{21}$ K, far in excess of the allowed inverse Compton limit of $T_B^{\max} \simeq 10^{12}$ K. The cause of the variations seen in these sources is currently controversial with claims being made for either: 1) a source-intrinsic or 2) extrinsic origin due to scattering in the interstellar medium (ISM) similar to the phenomenon of pulsar scintillation (e.g. Wagner & Witzel 1995 and ref. therein). While an intrinsic interpretation requires excessive Doppler boosting or shock-in-jet models with uncomfortable special source geometries, interstellar scintillation (ISS) must contribute to the cm-radio IDV due to the involved small source structures with sizes smaller or comparable to the scattering size set by the ISM. In order to disentangle both effects, intensive new multi-frequency and polarization observations are essential. In particular, the discovery of a seasonal dependence of the variability time scale throughout the year has attracted a lot of attention. A scintillation model, which takes the Earth's motion with respect to the scattering medium into account, can fully explain the effect and clearly identifies ISS as origin of the rapid variations (e.g. Dennett-Thorpe & de Bruyn 2000, 2003). At present, an annual modulation has been detected only in the two most extreme IDV sources (time scales ∼ 0.5 hours). The detection of such seasonal cycles in a larger number of IDVs will help to disentangle between an intrinsic or extrinsic origin of the IDV phenomenon. In particular, the discovery of seasonal cycles in the "classical" type-II IDV sources (type II: IDV on time scales ∼ 0.5–2 days; type I: > 2 days; Heeschen et al. 1987) is important to investigate the role of ISS also in this class of objects (Fuhrmann 2004, Fuhrmann et al. 2002). As a by-product, the modeling of seasonal cycles constrains important properties of the scattering medium and thus is an important new tool to study the ISM. Furthermore, the size of the scintillating compact source component can be constrained to angular scales presently not accessible with any radio interferometer (a few tens of μas).

Technical Requirements

The multi-frequency and polarization capabilities of the SRT will provide a great new tool to investigate the above mentioned topics. Radio outbursts in the long-term light curves of blazars usually show time delays (days to weeks) between higher and lower frequencies due to a combination of optical-depth effects and plasma motion. Dedicated multi-frequency, flux-density monitoring campaigns with the SRT over months and years (e.g. simultaneous with observations in the IR, optical and at higher energies as well as VLBI) will allow one e.g. to search for time delays, correlated variability over a wide range of frequencies, follow the spectral shape evolution and therewith constrain jet models. Furthermore, an italian long-term radio monitoring of blazars would be highly desirable in view of the next launch of the italian γ-ray-satellite AGILE as well as the Large Area Telescope (LAT) γ-ray-detector on the GLAST satellite, which both will likely detect many of these blazars in the GeV energy band. Among important blazar identification and coordinated multi-wavelength monitoring campaigns of newly detected sources, e.g. the combination of a SRT radio monitoring with optical observations (e.g. within the WEBT collaboration[1]) will allow to detect flaring states which might trigger further ToO observations by these satellites. However, a broad and good sampled frequency coverage of the SRT (between 1–100 GHz, as planned and shown in Table 3.1) will be important to obtain simultaneous broad-band radio spectra, in particular towards higher frequencies (≥ 10 GHz). In order to obtain a good time coverage, the sources should be monitored frequently over the year (e.g. bi-monthly) during observing runs lasting for about 24 hours (depending on the number of sources and frequency coverage).

As far as IDV studies are concerned, typically longer observing runs are essential to detect the rapid variability and to determine the variability time scales with high accuracy. The total as well as polarized flux density of "classical" IDV sources showing time scales of about 1–2 days should then be observed with

[1] http://www.to.astro.it/blazars/webt

a very fast duty cycle of about one measurement per hour over a continuous period of ~ 5 days. In order to detect seasonal cycles in the variability time scale and model the variations with a scintillation model, this procedure should be repeated frequently over the year (ideally monthly or more often).

The observations discussed here require precise total flux-density measurements and thus broad-band (as given in Table 3.1), multi-beam receivers (preferably at all continuum frequencies). The final measurement accuracy will mainly be affected by the local weather conditions, receiver performance/stability, pointing accuracy and focus stability/accuracy. The possibility of multi-beam (double-horn) observations are of particular importance to reduce the atmospheric contribution, especially towards higher frequencies. The frequent observations of a set of suitable secondary calibrators (nearby, non-IDV sources) with the same duty cycle as the target sources will allow one to trace the receiver/system and weather conditions during a run. This data can subsequently be used to correct for telescope gain as well as systematic time-dependent effects in the IDV light curves. The typical peak-to-peak variations seen in IDV sources are of the order 5–20%. In order to detect even the modest variability amplitudes on a $3\,\sigma$-level, the final scatter in the secondary calibrator light curves due to the afore mentioned effects should be of the order ≤ 1.5–$2\,\%$.

The sources are usually point-like and sufficiently strong (≥ 0.5 Jy) at the considered frequencies. Taking the SRT receiver characteristics as given earlier, all sources will be detectable with a sufficient signal-to-noise ratio. Thus, cross-scans are the method of choice as ideal compromise between sufficient accuracy and a fast enough duty cycle. As by-product, the pointing deviation of the telescope can be determined and corrected simultaneously during the observations.

At frequencies ≥ 10 GHz, the frequent measurement of secondary calibrators as well as opacity corrections are of particular importance to minimize the strong influence of atmospherical effects. Since a Sky-Dip procedure of frequent τ-measurements is not possible in a densely time-sampled IDV experiment, a radiometer will be very usefull (as suggested in section 3.2). However, excellent weather conditions during the observations are essential. In order to study polarization and polarization angle variations the receivers should be equipped with correlation polarimeters providing the simultaneous information of Stokes Q and U. The instrumental polarization should be not greater than $1\,\%$. The extremely fast duty cycle requires the possibility to switch quickly between receivers. Switching times of $\leq$ one minute will allow fast duty cycles for a sufficient number of sources (1 scan per source and frequency in about one hour).

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4.3.2.6 SRT and the Sunyaev-Zel'dovich effect

Scientific Background The Sunyaev-Zel'dovich (SZ) effect is the modification of the spectrum of the Cosmic Microwave Background radiation (CMB) as it transverse a cluster of galaxies or any other reservoir of hot plasma. Photons interact with free electrons in the ionized medium through the inverse Compton process resulting in a distortion in the spectrum of the outgoing radiation. The observed fractional change in antenna temperature is proportional, in the first approximation (i.e. neglecting the peculiar velocity of the cluster and the relativistic correction), to the Comptonization parameter $y \propto \int n_e T_e dl$, a line-of-sight integral of the electron density and temperature through the cluster.

Measurements of the effect yield directly the properties of the hot gas, and the total dynamical mass of the cluster. An extremely valuable property of the SZ effect is its redshift independence that makes it a useful cosmological probe (Zel'dovich & Sunyaev, 1969). As matter of fact the SZ can be used for the determination of the Hubble constant without the sistematic error due to the source evolution as is the case of other methods.

The SZ effect was measured for the first time with single-dish radiometers. More recently, the best images of the effect (Carlstrom et al. 2002) has been obtained for about 50 clusters, mostly with ground-based interferometric arrays (BIMA and OVRO) operating at low microwave frequencies (30 GHz). The use of single-dish radiometers in the study of the SZ effect is less used since early 1990s with the exception perhaps of 45m dish of Nobeyama Observatory. The combined results of Nobeyama observations, for instance, at 21 and 43 GHz and JCMT observations at 350 GHz allowed for the first time in 1999 an unambiguos detection of the effect in the Wien region of the spectrum (Komatsu et al. 1999). The advent of the generation of large single-dish telescopes operating up to millimeter wavelenghts, such as GBT and SRT, open new opportunities.

Measured typical values of the Compton parameter y at 32 GHz (Mason et al. 2001) is of few units in 10^{-5}. It turns out that the antenna temperature decrement is of the order of 90 - 200 μK at this frequency. Slightly lower or higher values of y are expected respectively at 20 GHz and 40 GHz.

The best frequencies for SRT should be 20, 30 and 40 GHz. Unfortunately, the 90-GHz band might not be useful due the large amount of the water vapour. At this frequency, the estimated atmospheric transparency in the best conditions at SRT is of the order of 90%; however more stringent limitation will come from atmospheric absorption fluctuation which will induce an increase of the $(1/f)^n$ noise. This will also prevent the use of high performance, large bandwidth, bolometer arrays. It is worth noting that the frequency band centred around the water vapour line at 22 GHz can be easily eliminated at the SRT owing to the large receiver bandwidth. In this case, the atmospheric opacity becomes about a factor of 2, in optical depth, less than the opacity at 90 GHz.

Technical Requirements

The angular extents of clusters are of several arcmin (e.g. a linear size of 1 Mpc is 9.5′ at z=0.1, 3.2′ at z=0.5 and 2.7′ at z=1, with WMAP cosmology). Indeed, images of the SZ effect in clusters over a wide redshift range show cluster sizes of about 2′ - 5′ (see e.g. Carlstrom et al. 2002). Thus, given the SRT beam of 52″ at 20 GHz, the multibeam will be crucial in mapping the nearby clusters, but it will be needed also for the clusters at redshift ≥ 0.5.

The technical requirements can be summarized as follows:

- **Receiver:** Multibeam receivers for 20 GHz and 40 GHz band
- **Backend:** total power
- **Sensitivity :** The expected sensitivity of SRT at 20 and 40 GHz, assuming for the receiver noise temperatures and for antenna efficiencies the values reported in Table 1 of this Report, and an IF instantaneous bandwidth of 2 GHz, are respectively about $3.2mKs^{-0.5}$ and $2.5mKs^{-0.5}$; for a cluster with $y = 5 \times 10^{-5}$, the expected signal is of the order of 0.1 mK which imply an integration time of about 1000 sec at 1 sigma. An IF bandwidth larger than 2 GHz would be, in any case, preferable.

  The half power beamwidths at 20 and 40 GHz are 52″ and 28″, respectively. To observe a region $5' \times 5'$ with the 20 GHz receiver focal plane array (7 double polarization receiver) at 0.1 mK sensibility, the observing time would be about 50 hours. The beam separation in the sky between two adiacent receivers is about 82″, so an undersampling factor of about 10 must be considered.

- **Scanning capability:** Beam switching is required. Likely raster scan and/or on-the-fly techniques will be used for the map acquisition.

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Chapter 5

VLBI

5.1 Galactic astronomy

5.1.1 Line observations

5.1.1.1 An Italian VLBI array for the 6.7 GHz CH_3OH masers

Scientific Background

The formation of high-mass stars is still a poorly known process. Main open problems are: 1) the accretion mechanism, whether massive stars form primarily via an accretion disk, or by accretion onto lower mass cores followed by coalescence to form a more massive object; 2) the determination of the evolutionary sequence of high-mass star formation; 3) the cause(s) terminating mass accretion. Present millimeter (and submillimeter) interferometers lack the necessary angular resolution to study the physical conditions and the gas motions in the proximity of the high-mass protostars. However, such a region can be studied with very high angular resolution ($\sim$ 1 mas) by means of VLBI (Very Long Baseline Interferometry) observations at centimeter wavelengths of maser sources. In fact, H_2O and Class II CH_3OH (methanol) maser transitions are commonly observed toward regions of high-mass star formation, the strongest emission lines (up to thousands of Jy) being those at 22.2 GHz for water and those at 6.7 and 12.2 GHz for methanol.

The astrophysical environment traced by the 6.7 GHz CH_3OH masers is still to be more precisely determined. Single-dish and interferometric surveys (Walsh et al. 1997; Szymczak et al. 2000; Codella and Moscadelli 2000) seem to indicate that, like the water masers at 22.2 GHz, the methanol 6.7 GHz maser emission may trace a pre-UC HII phase. VLBI observations have shown that the 6.7 GHz maser spots (the individual maser emission centers) are often distributed along lines or arcs (of sizes from 100 mas to 1 arcsec) with, occasionally, a monotonic velocity trend along these structures (Norris et al. 1998; Minier et al. 2000). This strongly suggests that the methanol masers trace ordered motions, and some authors have proposed that they originate from circumstellar accretion disks.

Presently, the only VLBI array capable to observe at 6.7 GHz is the European VLBI Network (EVN), but observations of the CH_3OH masers have been hampered by poor knowledge (only a few arcmins) of their absolute positions. The SRT together with the other two Italian antennae at Medicina and Noto, will constitute a small, yet sensitive, array, which will be able to determine both the absolute position and the space-velocity structure of the strong 6.7 GHz masers. The achievable angular resolution at the maser frequency of 6.7 GHz is $\approx$10 mas, implying that relative positions of compact maser features detected with signal-to-noise ratio $\geq$10 are obtainable with accuracy $\leq$1 mas. The main advantage with respect to the EVN is that, observing with only three baselines it allows to use very short ($\leq$ 0.5 sec) integration times for correlating the visibilities, making the instantaneous field of view of the array sufficiently wide to compensate for the uncertainty in the target position.

In the Spring of 2003 and 2004, we have carried out two exploratory VLBI runs at 6.7 GHz using the single-baseline Medicina-Noto. In order to derive the absolute maser positions we applied the phase reference technique, referring the visibility phase of the maser target to a closeby reference continuum source, whose position is known with milliarcsec accuracy. The results are encouraging: with only two antennae, absolute positions accurate to within a few tenths of an arcsec are obtained for maser sources with peak flux densities in the range of 10 – 100 Jy. The SRT will bring two major improvements to these measurements: 1) working with three antennae will allow selfcalibration of the visibility phase, removing the atmospheric phase fluctuations; 2) the SRT 64-m dish will significantly lower the sensitivity threshold for maser detection. We are confident that the Italian 6.7 GHz array will be able to determine positions with an accuracy of tens of mas and space-velocity structures for maser sources with fluxes as weak as a few Jy.

Technical Requirements

One of the main justifications of the SRT project is to build a big antenna in a strategical position (in the middle of the Mediterranean Sea) to provide sensitive, long, North-South oriented baselines for the EVN array. Conceivably, VLBI operability should be a primary goal for the SRT already at 'first light'. In the following, we indicate the main requirements for the 6.7 GHz VLBI operation:

1. Hydrogen maser to set the time of the VLBI station
2. MkV (or MKIV) VLBI recorder
3. Superheterodyne, cooled receiver, working in double circular polarization at the CH_3OH maser frequency of 6669 MHz

The correlator is obviously a fundamental component for VLBI. Our 6.7 GHz Medicina-Noto experiments have been so far correlated at the Max-Planck-Institut für Radioastronomie (Bonn, Germany). We do not doubt that the Bonn correlator will be available for correlating the 'Italian' 6.7 GHz experiments also in future years. However it is predictable that, in the immediate future, the cross-correlation of a small number of baselines can also be performed using a cluster of fast PCs. Then, at a relatively modest cost, we might be totally independent in the correlation process, too.

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5.1.2 Continuum observations

5.1.2.1 Radio Emission from Galactic X-ray Binaries

Scientific Background

Relativistic jets, collimated bipolar outflows of matter travelling at a significant fraction of the speed of light, appears to be a common feature of accreting supermassive black holes in the centres of active galaxies, in some cases completely dominating the power output of such systems (Ghisellini & Celotti 2001). However, the mechanisms of jet formation, their acceleration and collimation, the way in which they couple to the accretion process and also their matter and total energy content are yet to be well understood. In the past decade it has become apparent that such jets are also commonly associated with stellar-mass black hole and neutron star X-ray binary systems within our own galaxy: since the characteristic timescales of accretion and jet formation should be proportional to the accretor size, and hence mass, then by observing X-ray binaries on timescales of days to decades we are probing the equivalent of otherwise unobservable timescales of tens of thousands to millions of years or more for active galactic nuclei.

The key observational aspect of X-ray binary (XRBs) jets lies in their synchrotron radio emission. Such jets appear to come in two types: milliarcsec-scale[1] continuous jets with flat radio-mm spectra, and arcsec-scale optically thin jets resolved into discrete plasmons moving away from the binary core with highly relativistic velocities (see Fender 2004 for a review).

[1] corresponding to $\sim$1 AU at 1 kpc

In the past decade or so, thanks to coordinated multi-wavelength campaigns, considerable progress has been made in our understanding of the link between the production of jets and the inflow of matter in XRBs. Specifically, by means of simultaneous radio/X-ray observations, a quantitative correlation has been established between accretion and the production of steady jets in *black hole* XRB systems displaying hard X-ray spectra, in terms of a tight non-linear scaling between the radio and the X-ray luminosities (Hannikainen et al. 1998; Corbel et al. 2000; Gallo, Fender & Pooley 2003). Probably the most notable consequence of this finding is that, in spite of their low radiative efficiency, these jets may carry away a dominant fraction of the dissipated accretion power, requiring a substantial modification of the existing models (Gallo, Fender & Pooley 2003). Our knowledge about jets in X-ray binaries is mostly based on observations of black hole candidates; this is because, in general, neutron star X-ray binaries appear to be less radio loud than black holes (Fender & Kuulkers 2001; Migliari et al. 2003). However, recent deep coordinated radio and X-ray studies of neutron stars have shown an overall pattern of behaviour very similar to that of black holes (Migliari et al. 2003, 2004; Muno et al. 2004). By comparing these two systems we can gather important information on the driving mechanism for the production of jets and on the role played by the characteristics typical of the compact object involved, as e.g. the spin, the presence of an event horizon in black holes or of a solid surface and a magnetic field in neutron stars.

A number of key questions in XRB jet physics need to be addressed, with a broader relevance for the study of the time-variable jet/accretion coupling on all mass scales; among others:

What are the conditions for a collimated outflow to exist? Specifically: Does the presence of a jet require a geometrically thick accretion disc? Does the jet production mechanism switch off at very low accretion rates?

The high-energy spectrum of compact objects accreting matter at low rates, from the active nuclei to XRBs, are successfully modelled in terms of advection-dominated accretion flows (e.g. Narayan et al. 1997), i.e. geometrically thick two-temperature inflows in which most of the released accretion power, instead of being radiated, is stored in the ions and advected towards the accretor. Advection-dominated solutions are highly unstable to convection and large entropy gradients; as such, they are expected to power strong winds, possibly collimated (Blandford & Begelman 1999). Gallo, Fender & Hynes 2004 have argued that relativistic outflows in stellar mass black holes exist down to Eddington luminosities[2] as low as $10^{-6} L_{\rm Edd}$. However, the collimated nature of such outflows remains a matter of speculation, and so does the mere existence of relativistic outflows below $L_{\rm X}/L_{\rm Edd} = 10^{-6}$. In fact, the minimum Eddington ratio at which a steady jet has been resolved on milliarcsec scales is $L_{\rm X}/L_{\rm Edd} = 10^{-2}$ (in the 10 solar mass black hole XRB Cyg X-1, with a flux density of 15 mJy; Stirling et al. 2001). *Sensitive VLBI observations are needed in order to address this issue.*

What is the role of the magnetic field/event horizon? Specifically: Do high-magnetic field neutron star XRB host jets? Is advection across an event horizon needed in order to reproduce the observed luminosity difference between black hole and neutron star XRBs, or can the jets account for it?

A possible explanation for the fact that XRBs hosting neutron stars seem to be less radio loud than black hole XRBs is that the presence of a magnetic field anchored to the neutron star surface might somehow inhibit the jet production. A systematic investigation of high-magnetic field neutron star XRBs is needed to address this issue (note that none of the XRB pulsars has ever been convincingly detected as an incoherent synchrotron radio source; however, the existing upper limits are not conclusive, as they are actually compatible with radio detections of some low-magnetic field neutron star XRBs).

On the other hand, 'quiescent' ($L_{\rm X}/L_{\rm Edd} < 10^{-5}$) black hole X-ray binaries are significantly less luminous – in the X-ray band – than the neutron stars. This has been interpreted as the single strongest evidence for the existence of an event horizon in accreting black holes, as the advected power would be realised when it impacts the neutron star surface, while it would cross the horizon and be lost forever in the case of a black hole (see Narayan et al. 1997). An alternative explanation, which does not require advection across an event horizon, is the existence of 'jet-dominated' states in XRBs

[2] The Eddington X-ray luminosity is the maximum luminosity for a spherically accreting object, corresponding to 1.3×10^{38} erg/sec per solar mass of the accreting object

(Fender, Gallo & Jonker 2003), i.e. states in which the dominant fraction of the accretion power is carried away by the radiatively inefficient jet. Crucial to this interpretation is the steepness of the radio/X-ray correlation in neutron star XRBs (Migliari et al. 2003), for which confirmation is sought after.

Technical Requirements
The SRT can help in solving the above questions by means of, respectively:

VLBI observations of low luminosity XRBs would have a major impact in the field of XRB jet research. In particular, achieving milliarcsec resolution for micro-Jy sources would give us the possibility, for the first time, to resolve the radio emission region of 'quiescent' sources, representing the *majority* of the XRB population.

Single-dish observations of neutron star XRBs to be possibly coordinated with X-ray observations. The required rms noise level for this kind of study is of ∼0.01 mJy/beam, achievable by SRT at 22 GHz in 12 hours.

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5.2 Extragalactic astronomy

5.2.1 Line observations

5.2.1.1 Mapping of HI absorption regions in extragalactic sources

Scientific Background
A critical ingredient of any orientation unification scheme of radio-loud Active Galactic Nuclei (AGN) is an obscuring region of atomic or molecular gas surrounding the central engine. This circum-nuclear material, which is believed to be in a disk or torus, effectively shields the inner few parsecs from view, if the axis of the radio source lies at a large angle to the line of sight (e.g. Antonucci 1993). It is likely that this gas also plays an important role as fuel for the central engine and in collimating the bipolar outflow in the radio jets. It therefore forms a vital element of our understanding of AGN.

Although the composition of the obscuring material in the torus may be varied, it seems likely that at some radii and scale heights, there will be significant amounts of neutral atomic hydrogen gas (Neufeld

& Maloney 1995). Young radio-loud AGN, known as Compact Symmetric Objects (CSO) and Gigahertz-Peaked Spectrum (GPS) sources, provide a unique opportunity to study this gas. In contrast to other types of compact radio sources, they are not dominated by emission coming from Doppler-boosted components at the base of a nearly face-on radio jet, but from isotropically radiating hot-spots or mini-lobes mostly seen with the radio axis at a large angle to the line of sight. Since this makes it likely that a large fraction of the radio-emitting plasma is located behind obscuring material, it makes them ideal probes to study HI in absorption.

Indeed, observations show a large incidence of HI in absorption against young radio sources ($\sim$ 50%: Conway 1996, Vermeulen, in press, astro-ph/0012352, Mack et al. in prep.). Unfortunately, since most of the redshifted HI absorption frequencies fall outside the standard frequency bands, follow-up observations at high spatial resolution using VLBI-arrays are only rarely possible. This while VLBI observations are found critical for our understanding of the location and distribution of the absorbing gas, and subsequently for the interpretation as a possible torus. It is therefore important to increase the number of instruments which can be tuned to detect redshifted HI.

Technical Requirements

At present, only 6 EVN telescopes are equipped with an UHF receiver, i.e. Eb, Wb, On, Tr, Jb1 and Ar. For this reason, the addition of another large antenna, such as SRT, would significantly contribute to the performance of the EVN array. To accurately map the HI absorption, in particular to image different parts of the line profile separately, and obtain kinematic information at a reasonable dynamic range, the requested sensitivity is $\sim$ 1 mJy/beam/channel. Such values could be achieved by the EVN with the addition of SRT, if we consider for instance a channel width of 15 kHz, and an integration time of two hours. At a more general level, the inclusion of SRT in the UHF EVN array improves image (and channel) sensitivity by a factor of $\sim$ 1.5. The instantaneous bandwidths required for typical extragalactic HI absorption features is about 3 MHz at 750 MHz and 10 MHz at 1400 MHz. At least 3 channels should cover the absorption features, thus at least 256 channels might be necessary. As the planned programme is not a blind survey but based on previous detection measurements the redshift and the expected line widths will be well-known. It is important, however, to point out that a wide band is necessary for this receiver in order to warrant a continuous coverage in redshift. The UHF band is in the range 750 - 1400 MHz, however the frequency coverage is different for the various antennas, and the above mentioned performance holds only in the frequency range 1000 - 1200 MHz. Outside this range, the number of available telescopes decreases, and for this reason the addition of a large telescope in the EVN is even more important.

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5.2.2 Continuum observations

5.2.2.1 Millimeter VLBI Observations

Scientific Background

Nowadays, mm-VLBI observations are regularly performed at 86 GHz (3.5 mm), where images with an angular resolution of up to about 50 microarcsec are obtained, but are still limited in sensitivity. For this reason, only a few dozen compact objects with typical flux densities S(86 GHz)> 0.5-1 Jy can be reliably imaged. This limitation can be overcome by (i) adding more collecting area, (ii) increasing the observing bandwidth and data recording rate, (iii) correcting phase fluctuations introduced by the atmosphere (water vapour radiometry, dual VLBI). Another important limitation is the sparse and non-uniform uv-coverage of mm-VLBI observations (to date limited to 4 European antennas), and in particular the lack of short interferometer baselines. The implementation of the SRT in the European VLBI network will improve the high-frequency sensitivity of the network by a factor of up to 4. In order to fully exploit the capabilities of a 64m antenna, the 86 GHz receiver should allow to record data with large bandwidth ($\sim$ 1 GHz), and possibly in dual polarisation. In this context, with its large collecting area, high-frequency performance and appropriate location within Europe, the SRT can make a significant contribution to the scientific research of compact galactic and extragalactic radio sources.

Technical Requirements

Receiver at 86 GHz, large bandwith ($\sim$ 1 GHz), dual polarisation.

5.2.2.2 Wide-Field VLBI Imaging and Surveys

Scientific Background

The steadily increasing sensitivity of the VLBI arrays is opening up new areas of VLBI research such as the study of the sub-mJy radio source population using deep wide-field VLBI surveys. What is currently routine for the VLA is becoming possible for the VLBI arrays, thanks to the improved performance of the antennas (new receivers and improved surfaces) and of the correlators. VLBI observations of the sub-mJy radio source population have sufficient resolution to distinguish between AGN and starburst activity in these optically faint radio sources (e.g. the EVN observations of the Hubble Deep Field). New telescopes in the near future (the SRT is one of them), and upgrades of the existing ones (in terms of better surface and/or new receivers) are planned. In particular, new receivers must have low system temperatures (possibly less than 30 K) and large bandwidth in order to reach the highest sensitivity despite the radio interferences present mostly at the lower frequencies. The target is to perform continuum observations with r.m.s noise levels of a few microJy, imaging a large fraction of the primary beam of the largest antenna in the array (several arcminutes). Dozens of faint sub-mJy and microJy radio sources will thus be simultaneously imaged with milliarcsecond resolution, full uv-coverage and micro-Jy sensitivity.

Technical Requirements

Receivers at 1.4 and 5 GHz, largest possible bandwidth, dual polarisation

5.2.2.3 A Study of Faint Extragalactic Radio Sources

Scientific Background

The radio sky at metre to centimetre wavelengths is dominated by extragalactic radio sources. At flux densities ranging from tens of mJy to Jy or more most of them are active galactic nuclei (AGN). At lower flux densities radio sources associated with starburst galaxies are the dominant population in the source count statistics (Condon 2004). Most of the faint sources have radio luminosities $L_{1.4} < 10^{23}$ W/Hz, steep spectra and angular sizes comparable to, or smaller than, their parent galaxies.

A number of new radio surveys covering large parts of the sky down to low flux densities are now available, in particular: the NRAO VLA Sky Survey (NVSS) and Faint Images of the Radio Sky (FIRST) were both carried out at 1.4 GHz, but with different resolutions (Condon et al. 1998; Becker et al. 1995). A parallel survey was carried out at 325 MHz with the Westerbork Radio Synthesis Telescope (WSRT), the WENSS, which is similar in terms of sky coverage and resolution to the VLA survey NVSS (Rengelink et al. 1997). In the optical band, the Sloan Digitised Sky Survey is providing a wealth of information, which is an invaluable support to the radio surveys.

With these new surveys, covering large sky regions and reaching flux density limits much lower than previously available, it is now possible to study the population of low luminosity radio galaxies, which were very rare in the less sensitive surveys carried out before the 1990s. In particular, it is now possible to study the nature of faint radio sources, associated with elliptical galaxies with radio power $\leq 10^{23}$ W/Hz. This value is an order of magnitude lower than the radio power typically found in the samples obtained from the B2 catalogue, and may be suggestive of a different population of radio galaxies.

In the entire WENSS we expect to find about 70 elliptical galaxies with radio power $\leq 10^{23}$ W/Hz. This number is large enough to perform a statistical analysis on the properties of elliptical galaxies with very low radio power. The main questions to be addressed by such studies are the following:

1) Is the jet phenomenon still present in low power radio sources? If so, how do their inner jets compare to those in radio galaxies of intermediate to high power?

2) Do the well known correlations found in intermediate and high power objects still hold at low radio powers? An example of such correlations is for instance the ratio between the nuclear and the extended radio power.

3) Which is the dominant radio emission mechanism in these objects? Is the radio emission still driven by a central AGN, or is it dominated by starburst emission? Or both?

In order to tackle these issues it is necessary to look into the very inner region of these radio galaxies, and this implies the need of the angular resolution provided by the Very Long Baseline Interferometry (VLBI) technique.

Imaging at parsec-scale resolution will enable us to distinguish between AGN radio activity (if compact cores and radio jets are detected) and starburst emission (which is usually characterised by extended and diffuse emission). Furthermore it will allow one to study the properties of both classes of radio sources.

The selected sample The WENSS is used as a starting point to construct a sample of radio sources identified with bright elliptical galaxies, i.e. $m_r < 16.5$ (de Ruiter et al., in preparation). We expect to find about 70 bright elliptical galaxies with radio power $\leq 10^{23}$ W/Hz. Inspection of the FIRST survey (20 cm, resolution of ~ 5 arcsec) will allow us to select the most compact sources on the arcsecond scale, i.e. best suited for follow-up VLBI studies. As an indication, the bulk of the faint sources selected from the WENSS, have flux densities of a few tens of mJy on the FIRST survey, corresponding to surface brightness of the order of a fraction of mJy/arcsec^2 (0.2 - 1 mJy/arcsec^2).

Technical requirements and feasibility

The EVN is currently the most sensitive VLBI array in the world, its best performances being reached at 1.4 and 5 GHz. This is possible especially thanks to the new MK5 recording system, which already allows recording rates up to 1 Gbps (corresponding to up to 128 MHz bandwidth). Using the very sophisticated calibration and imaging techniques developed at JIVE (Garrett et al. 2001), i.e. phase referencing and wide field imaging, it is possible to reach detection levels of the order of 40 μJy/beam in few hours of observations. The beam of the EVN at 1.4 GHz is of the order of 5 - 15 mas, depending on the array. This means that radio sources with surface brightness of 1 mJy/arcsec^2 are already detectable.

The addition of SRT will have the following major impacts on the EVN: 1) it will improve the uv–coverage at short baselines, and this is crucial for the detection of extended nuclear features; 2) it will improve the number of very large telescopes, reflecting on the whole array sensitivity. For instance, at the frequencies requested to carry out this project, the presence of SRT in the EVN would improve the image sensitivity (i.e. the thermal noise) by a factor of ~ 2, going down to a value of $\sim 20 - 25$ μJy/beam for a 256 Mbps recording, 2-bit sampling and a total time on-source of 2.5 hours.

In order to carry out this project it is essential that the SRT is equipped with the most updated recording technique for VLBI observations, and with 1.4-GHz and 5-GHz receivers.

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Chapter 6

Geodesy with the SRT

Scientific Background

1) Science with geodetic VLBI

Geodetic VLBI is a useful and powerful tool for acquiring precise space geodetic observations and enhancing scientific knowledge of the Earth and its dynamics. This technique plays a unique role in determining the International Celestial Reference Frame (ICRF) (Gontier et al. 2002; Fey et al. 2004) and, constraining the scale of the frame, strongly contributes to the definition and realization of the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2002). VLBI also contributes to Earth Orientation Parameters (EOP) determination: it is the only space geodetic technique capable of accurately and simultaneously measuring Universal Time (UT1) (Capitaine et al. 2003), polar motion (Ma 1978), precession and nutation (Herring et al, 2002). These products are important for geophysical applications as well as for astronomy and astrophysics. Geodetic VLBI can also be applied to investigate Earth's surface deformation, troposphere water vapour content (e.g. Negusini and Tomasi 2004; Schuh et al. 2004) and ionosphere Total Electron Content (TEC). A complete review of geophysical applications of VLBI technique can be found in Robertson (1991).

2) Geodesy with co-located techniques

The impact of the SRT on geophysics and its performance in astronomy would be greatly enhanced by realizing a co-location with other space geodetic techniques. The scientific perspectives would considerably increase and the role of the observatory within the geodetic networks would be of greater importance. A very easy, efficient and rewarding way to co-locate a VLBI telescope is realized by means of the Global Positioning System (GPS): it is based on cheap, easy-to-use and easy-to-manage devices with a wide range of scientific, engineering and commercial applications (e.g. Hoffman-Wellenhof et al. 2001). A co-location with the Galileo system and its different services must also be evaluated (http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm).

a - International scenario

Simultaneous observations of different space geodetic techniques can independently study the same geophysical phenomena and estimate related parameters. Integrated Precipitable Water Vapour (IPWV) and TEC can be determined by GPS data and can be used to model and improve astronomical VLBI observations (e.g. Ros et al. 2000; Erickson et al. 2001). Final EOP values are estimated combining VLBI with other space geodetic observations. Integration of techniques and observations is the scientific strategy that has recently been adopted by the International Association of Geodesy (IAG) for defining its future policy: space geodesy as a tool and a service for other sciences by means of Integrated Global Geodetic Observing System (Beutler 2004). Combination and integration of space geodetic observations are mandatory in order to investigate technique-dependent biases and improve the accuracy of the products (Ray 2000). Within this international frame, co-location of different space geodetic instruments are important and must be realized and maintained (Altamimi 2004).

b - National scenario

The intense seismicity that interests Italy is an expression of the complex tectonic features that characterize the Mediterranean region (Mantovani et al. 2002). Earth's surface deformations are strictly related to the geodynamical evolution of the area. Italian VLBI telescopes have proved to be very important in studying crustal motion in the Mediterranean and in Europe (e.g. Campbell et al. 2002). The SRT will have a key role in the evolution of Italian space geodesy: it can form a polyhedron of four national VLBI telescopes, which would represent a unique facility in Europe. Scientific perspectives are similar to those of Japan or USA, where analogous national interferometers can be found. A local VLBI-based crustal deformation monitoring will be possible, simultaneously ensuring a global framing of the phenomena with very high accuracy (Key Stone Project: http://ksp.nict.go.jp/). Furthermore, the activity of the national GPS reference network (Biagi et al. 2001) will be preciously supported by the four Italian VLBI telescopes. A better framing into ITRF can be ensured, a link to ICRF can be provided and long-term technique-dependent trends can be monitored (Imakiiere et al. 2004). A complete integration between national VLBI and GPS networks will be possible only if the SRT is co-located with a GPS system. This is already the case for Medicina, Noto and Matera observatories.

3) Realization and maintenance of co-locations

Nevertheless, co-locations alone do not solve the problem of integration of space geodetic techniques. Effective co-locations are ensured by provision of accurate local-ties (Rothacher 2000). Their importance has been largely acknowledged by the International Earth rotation and Reference systems Service (IERS) and the IAG. Lately, the attention of the geodetic community has been focused on computation strategies of accurate local ties and Solution INdependent EXchange format (SINEX) files generation (Sarti and Angermann 2004). A few rigorous methods have proved to meet all IERS requirements for space geodetic observations combination and ITRF computation (Dawson et al. 2004, Sarti et al. 2004b). These methods are also consistent to one another (Sarti et al. 2004a) and will allow the computation of a reliable and accurate SRT-GPS connection.

4) Maintenance of a radioastronomical observatory

A local ground control network is an essential infrastructure that must be created at the SRT site. The local network will be used to monitor the stability of the radio telescope structure, to externally monitor the gravitational deformation of the dish, to locate and monitor its geometrical reference point and to monitor the stability of the site. This latter point is particularly important to distinguish between local and global signals in order to enhance data significance (Sarti and Vittuari 2003). If a co-location is present, the local ground control network is an essential tool for monitoring the eccentricity between the reference points of the space geodetic techniques. These tasks are nowadays considered as attractive scientific issues but will be considered as mandatory and challenging maintenance operations in the near future. It is therefore important to carefully design the shape and the geometry of the local network as well as its extension, and carefully consider the position of the ground pillars and the technological solutions adopted for geodetic marker materialization (Sarti and Angermann 2004).

Technical Requirements

Fulfillment of scientific applications described in point 1 will be guaranteed with S and X-band receivers and the Mark V recording system. A co-location with a GPS system (antenna and GPS-GLONASS receiver) will be of enormous advantage for enhancing the SRT role at national and international levels (as described in a previous section). The best implementation of the SRT co-location will be ensured by the results described in 1.3, both for scientific and technical/commercial purposes. Temperature, humidity and pressure sensors (as specified by International GPS Service standards) are also necessary in order to evaluate IPWV and eventually use the SRT data for climate change and environmental studies. As described in a previous section, the design and the realization of a local ground control network is essential. Scientific and technical expertise for a proper evaluation of local requirements and for an optimized design of the ground network, the pillars and the ground markers can be found within the structure of the new INAF.

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Chapter 7

Planetary Radar Astronomy

SRT as Radar for Asteroid and Space Debris Studies

Introduction Among the Solar System bodies, asteroids are the largest population. Most of them orbit around the Sun in a region of space, called the "main belt", located between the orbits of Mars and Jupiter. Two groups (the "Trojans") are located in the L4 and L5 Lagrangian points of Jupiter, while others (belonging to the Aten, Apollo and Amor groups, collectively known as NEAs, Near-Earth Asteroids) follow trajectories that cross the orbits of the terrestrial planets, therefore representing a potential hazard for the Earth. In fact, in the main belt, catastrophic collisions among asteroids can occur, and the fragments which result from these collisions can be "injected", due to complex dynamic processes, in th inner regions of the Solar System. The hazard of a catastrophic impact with a large body is not so unlikely. According to the Torino-scale (defined in 1999 during the international IMPACT congress, held in Turin and regarding the potentially hazardous asteroids), it is estimated that an impact producing sever consequences to the terrestrial ecosystem can occur every few hundred thousand years. The first step toward the "mitigation" of such a threat is space surveillance, in order to determine the orbits of most of the objects whose trajectories are close to the Earth's orbit.

In the last years, the Planetology Group of the Turin Astronomical Observatory, in collaboration with the IRA, started radar observations of NEAs, which is one of the most powerful techniques for the dynamical and physical study of these bodies, offering huge advantages with respect to the traditional optical observations. In fact, from the dynamical point of view it is possible to improve the accuracy of the orbits by orders of magnitude, a key factor to evaluate the impact hazard: unlike the "classical" optical measurements, the radar astrometric observations can make the difference in predicting if an asteroid will hit our planet or not. From the physical characterization point of view, it is possible to obtain some parameters, such as size, shape, rotational state and superficial structure, which cannot be derived with other techniques or are derivable only in a very rough way and with time consuming optical observations.

Asteroid Radar Astronomy A radar observation of an asteroid consists in the transmission of a signal with fixed parameters and in the subsequent registration of the signal echo. The great advantage with respect to other "passive" techniques lies in the observe control of all the characteristics of the coherent signal (especially the wave form, time/frequency modulation, and polarization) used to illuminate the target (Ostro, 1993).

From the echo analysis it is possible to determine the orbital elements of an object very accurately, allowing a very high precision of ephemeri calculation. In fact, measuring the signal propagation time with an accuracy better than 10^{-6} s, the radial distance of the target can be estimated with an error of some tens of meters. Moreover, the component of the asteroid velocity, V_{LOS}, along the "line-of-sight" (connecting the radar antenna with the target), produces a Doppler shift in the frequency of the echo signal, which, measured with a accuracy of $\approx$ 0.01 Hz, allows one an estimate of V_{LOS} with an error of the order of 1 mm/s. Furthermore, the spin of the object generates a Doppler frequency dispersion of the signal; the measurement of the power distribution of the echo signal, as a function of the time delay and of the frequency, allows one to obtain bi-dimensional images with spatial resolutions less than 100 meters if the transmitted signal is strong enough.

Finally, by measuring the polarization properties of the echo signal, radar observations permit one to infer some surface characteristics of the target such as roughness, albedo and abundance of metallic elements, information which cannot be directly derived by using other astronomical techniques. In fact, the reflection due to a single reflecting plane surface reverts the handedness, or helicity of a circularly polarized wave, so single back-reflections from dielectric interfaces, whose sizes and radii of curvature greatly exceed the wavelength, yield echoes almost entirely in the opposite circular (OC) polarization. On the contrary, same circular (SC) echo power can arise from multiple scattering, from single backscattering from interfaces with wavelength-scale radii of curvature (e.g., rocks), or from subsurface refraction effects. Therefore, the circular polarization ratio, that is, the ratio between the radar cross-section (defined as 4π times the reflected power per unit solid angle and per unit flux of incident power) measured in the two opposite polarization ways, σ_{SC} and σ_{OC}, of the reflected signal ($\mu_C = \sigma_{SC}/\sigma_{OC}$), is a useful gauge of the target near-surface wavelength-scale complexity, or "roughness", from which important information about the nature of the surface regolith as well as the radar albedo and also the presence of superficial metallic elements, can be inferred (Ostro 1993).

Consequently, radar observations are a unique, very powerful tool to study the macroscopic physical properties (diameter, shape, rotation period and spatial orientation of the spin axis) and surface properties of the target.

Space Debris Radar Observations Another fundamental application of the radar technique is the study and monitoring of the space debris orbiting around the Earth, and the interaction of meteoroids with the atmosphere. The artificial material orbiting around our planet consists of actually operative structures only to a minimum extent; most of them consist of out-of-use spacecrafts, rocket stages and fragments generated by explosions and collisions of artificial satellites.

Nowadays, optical and radar sensors are used to locate centimeter-sized particles (in Low-Earth Orbit, or LEO) or decimeter-sized objects (in Geostationary Orbits, or GEO). The USA, and, to a lower extent, Russia, have a space surveillance system, while Japan is starting such a survey. So far, Europe does not have these facilities: only one radar (the TIRA of the FGAN Institute, in Germany) an one telescope have been occasionally used by the European Space Agency (ESA) in order to detect and monitor space debris. In particular, in Italy such campaigns have never been undertaken.

The problem of artificial space debris is now analysed in a strict relation with the meteoroid environment. ESA defined the Meteoroid and Space Debri Environment Reference Model (MASTER) to determine the flux originating from the environment of particles following orbits close to those of space shuttles, in the LEO, MEO and GEO regions. The analysis of material coming from space and "in situ" experiments contributed to extending the knowledge on natural particles with millimetre and micron sizes, which are the most abundant. As for spacecrafts in LEO-type orbits, impact velocities range from 5 to 15 km/s with a mean value of about 10 km/s for space debris, and from 12 to 72 km/s with a mean value of 17-20 km/s for meteoroids. Studies on impact residues, carried out on the LDEF, EURECA and HST satellites in order to discriminate between impacts by natural meteoroids and by artificial space debris have not been conclusive, because of the complexity of the targets.

In GEO-type orbits, the flux of natural particles prevails over the flux of artificial particles, whereas it is assumed that collisions in LEO-type orbits are mostly due to artificial objects. Particles coming from meteoroids are dangerous for orbiting structures because their impact energy exceeds 2 kJ, a value corresponding to 3 to 10 g for some meteoroids and to 10 to 30 g for particles belonging to a meteor stream.

Therefore, in order to monitor the natural and artificial debris population and to understand their evolution both on the short and long run, it is absolutely necessary to complete the models through observations carried out from the Earth and from space.

The information provided by a radar system can be exploited to validate current models of debris environment; they can also improve the precision with which we know the orbital parameters of those catalogued debris for which a close encounter with an operative satellite, or a manned space shuttle, is predicted. Finally, they can verify the integrity of big wrecks and update, if possible, the catalogues of big debris being currently tracked.

SRT as Radar for Asteroid and Space Debris Studies Our interest in radar observations has been fostered by the future realization of the Sardinian Radio Telescope (SRT), that can be used both as a receiving antenna of a bistatic system and as an independent (monostatic) system if it would be supplied with a power transmitter. Of course, this second configuration, which provides the best combination of the necessary technical parameters and full independence of the observations, is the most desirable.

In December 2001 the first intercontinental experiment (Italy - Ukraine - USA) for the radar detection of an asteroid took place, involving the Osservatorio Astronomico di Torino, the Istituto di Radioastronomia (IRA) in Bologna and NASA-JPL, under the local supervision of M. Di Martino (Turin) and S. Montebugnoli (Bologna). From the Goldstone (Mojave desert, California) and Evpatoria (Crimea, Ukraine) antennas, monochromatic radio signals were transmitted towards asteroid 1998 WT24, less than 2 million km from the Earth at the time. Echoes from the asteroid were detected by the 32-m VLBI antenna in Medicina, and analyzed by means of a high-resolution, high-efficiency spectral analyzer. After approximately 12 s from first detection, the echo could be sharply resolved on the screen of the receiving station back-end, thus successfully achieving the intended goals of the experiment (Di Martino et al. 2004). This experiment could represent the first step towards an integrated intercontinental network for the monitoring of potentially dangerous NEA's, a network in which SRT could play a key role.

Radar Astronomy with SRT The scientific value of a radar experiment depends mainly on echo strength and receiver sensitivity. The received power P_R inversely scales with the fourth power of the target distance R, and can be computed by means of the radar equation:

$$P_R = \frac{P_T\, G_T\, G_R\, \lambda^2\, \sigma}{(4\pi)^3\, R^4} \tag{7.1}$$

where λ is the transmitted wavelength, P_T the transmitte power, G_T the gain of the transmitting antenna, G_R the gain of the receiving antenna, and σ the radar cross section of the target. The antenna gain is given by:

$$G = \frac{4\pi}{\lambda^2}\, A_e \tag{7.2}$$

where A_e is the effective area of the antenna, obtained by multiplying the geometric area of the antenna by its efficiency.

The power of the received signal can be very small compared to the syste noise power in the receiving system, which is given by:

$$P_n = k\, T_s\, \Delta\nu \tag{7.3}$$

where T_s is the noise temperature in the receiver, k is Boltzmann's constant and $\Delta\nu$ is the bandwidth of the receiver.

The echo signal can be detected when the received power P_R is significantly above the threshold given by the RMS of the noise power. A quantitative measure of the extent to which the signal is stronger than the noise, that is the quality of a radar measurement, is expressed by the SNR. It can be shown that the SNR value expected for a radar observation is given by the following equation:

$$SNR = \frac{P_T\, G_T\, G_R\, \lambda^{2.5}\, \hat{\sigma}\, D^{1.5}\, P^{0.5}\, \sqrt{\Delta t}}{8.96 \cdot 10^3\, k\, T_s\, R^4} \tag{7.4}$$

where $\hat{\sigma}$ is the target radar albedo, defined as the ratio between its radar and geometric cross sections, D is the target diameter, and Δt is the integration time.

SRT as Receiver of a Bistatic Radar We consider two different possibilities for the use of SRT as a planetary radar: SRT as a receiver in a bistatic radar system, and SRT as a monostatic radar.

In the first configuration, SRT would act as the receiving station. The specifications for the receiver presented in Grueff & Ambrosini (1998) provide a highly versatile instrument, covering a frequency range spanning from 300 MHz up to 100 GHz. It is thus certainly possible to receive a signal transmitted, for example, by the DSS14 antenna at Goldstone, operating in the X-band (ν = 8560 MHz, λ = 3.5 cm). In this case, the values for the terms in the radar equation are $P_T \approx 500$ kW, $G_T \approx 75.6$ dB, $\lambda = 3.5$ cm. The gain for SRT in the X-band is approximately 73 dB, T_s is around 30 K, and the diameter is 64 m, for an effective area of 1945 m^2. It is also necessary that the target is in a visibility window common to both antennas, meaning that the target must have a North declination greater than 45 degrees.

SRT as Monostatic Radar For a completely independent radar system, it is necessary to provide the radiotelescope with a power transmitter. If a comparison is made between the sensitivities of SRT and DSS14 in the X-band, it can be seen that SRT is approximately four times less sensitive. A better opportunity is offered by the use of a transmitter operating in the Ka band ($\nu = 34$ GHz , $\lambda = 0.8$ cm $P_T \approx 1$ kW): writing explicitly the effective dependence from the wavelength in the radar equation, one obtains:

$$P_R = \frac{P_T \, \sigma \, A_e^2}{4\pi \, \lambda^2 \, R^4} \tag{7.5}$$

the relative power of the echo signal produced by a transmitte operating in the Ka band is thus given by:

$$\frac{\lambda_X^2}{\lambda_{Ka}^2} = \frac{3.5^2}{0.9^2} \approx 15 \tag{7.6}$$

that is 15 times larger than the one produced by a transmitter operating in the X-band, for the same radiated power. In terms of SNR, the net gain is reduced, because, as can be seen from equation (7.4), it scales as $\lambda^{-1.5}$. Furthermore, it is necessary to take into account the noise temperature of the receiver, which increases with frequency.

The following table illustrates the performance of SRT in the two bands:

Band	G (dB)	T (K)	G/T (dB)
X	73	30	58
Ka	85	50	68

To obtain the net gain in terms of SNR for a Ka-band transmitter over an X-band transmitter, for the same integration time, it is sufficient to substitute the figures listed above in equation (7.4), obtaining that $SNR_{Ka}^2/SNR_X^2 \approx 5$.

SRT and Space Debris The seemingly unstoppable increase in the number of space debris in low orbits, especially below 2000 km of altitude, poses increasingly larger threats to all space activities in that region. Any prediction of the evolution of their population, especially in the long term, and any protection and mitigatio measure requires adequate knowledge of their present distribution, also following peculiar events such as an explosion or a loss of material.

Low-orbiting space debris with a size larger than 10 cm (now around 10,000 in number) are routinely monitored mainly by the US-based USSPACECOM surveillance systems; their orbits are known only in terms of the so-called “two lines elements” (http://www.amsat.org/amsat/keps/formats.html) provided by NASA. To this class belong also space vehicles out of control, especially those who are re-entering the atmosphere: because predictions of place and time of their re-entry are affected by large uncertainties, it is important to have frequent updates of their orbit.

Our knowledge of the smaller debris, in particular those of millimetrer size, is in general indirect and statistical: On the other hand, they are capable of producing significant damage to space systems, and they constitute a large fraction of man-made debris, larger than natural space debris. (The number of debris is inversely proportional to their size.)

The main technique for monitoring them is radar detection, requiring large-size instruments: for this task, the SRT would play an extremely significant role, also in the context of international space policy, especially that of ESA. All major space agencies have in fact initiated ambitious programs for monitoring and prediction of, and protection from, space debris. Italy is a member of the Inter-Agency Space Debris Coordination Committee (IADC); among the four main areas in which the space debris problem is studied (Measurements, Environment and Database, Protection, Mitigation), the Italian contribution is particularly weak (practically absent) in the first one: the only radar observations of space objects performed in Italy are those of natural meteorites. Europe in general is not well equipped in this respect; the main instrument available is the military radar TIRA belonging to the German FGAN institute, which, under ESA control, has occasionally provide important observations. Thus, there is plenty of opportunities for SRT in this field of research.

Conclusions In the light of the above, it is proposed that the SRT antenna be used for planetary radar observations, both in bistatic and in monostatic mode. In the second case, which is deemed to be more efficient both for achieving scientific results and for monitoring circumterrestrial space, it is proposed to provide SRT with a power transmitter and associated auxiliary structures, such as two parallel receiving channels for simultaneous reception of same-sense and opposite-sense circular polarizations. In a study performed at JPL (Interoffice Memorandum 335.1-95-038), the technological feasibility of a transmitter operating in the Ka band with a 1 MW power has been demonstrated, using either a single transmitter or a pair of 500-kW transmitters. The total cost of the device was estimated at 2,000,000 US$, corresponding to about 1.500.000 Euro (exchange rate of 25-11-2004).

This kind of operation requires high stability and accuracy both in time and frequency measurements, and, in the case of a bistatic system, in the synchronization between the transmitting and receiving stations. Furthermore, the availability of such a complete instrument of investigation for both planetary and space debris studies would allow the creation of an entirely national radar network together with the two twin 32-m antennas of Noto and Medicina.

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Chapter 8

Space Science with the SRT

Since the start of the SRT project, 'Space Science' applications have been included among its primary research objectives. The reasons are twofold. Firstly, the Istituto di Radioastronomia has successfully participated in many observational campaigns of Doppler Tracking of interplanetary spacecrafts with the Medicina radio telescope: first with the Ulysses mission and, more recently using the upgraded parabola at Noto, with Cassini, even up to Ka-band (32 GHz). The primary observables in this type of experiments are the phase and the amplitude and polarization of the radio signals making the radiolinks that connect the spacecraft to Earth, both in the up and down-stream interplanetary paths. The extremely high frequencies of these downlinks, now at X-band (8.4 GHz) and Ka-band (32 GHz), and the utilization of an atomic frequency standard at the ground stations, allow the measurement of residual Doppler frequencies at the level of fractions of microHertz over integration times of a thousand seconds. Such a tremendous resolution opens observational windows suitable to make accurate checks of General Relativity like for example the search for an experimental evidence of gravitational waves and the measurement of the Gamma constant with uncertainties two orders of magnitude less than reached before, as recently obtained by the Italian Radio Science team. The name 'Radio Science' is used to identify all classes of scientific applications of the Doppler tracking technique that now includes such diverse topics as:

- Planetary atmospheric profiles and ionospheric compositions (one way, downlink only),
- Structure of planetary rings (one way, downlink only),
- Planetary surface characteristics (in the bistatic radar configuration),
- Planetary gravitational fields, shapes, masses, and ephemerids (two way, full up+down),
- Solar corona and solar wind (two way, full up+down links).

The second reason for doing 'Space Science' with the SRT is related to the interest shown by the Italian Space Agency in using such an antenna for sending uplink commands to spacecraft, if properly equipped with special 'transmitting' hardware. To this end, the SRT was designed for use as a full-tracking ground station with simultaneous receiving and transmitting capability at four bands: X up (7.3 GHz), X down (8.4 GHz), Ka up (34 GHz) and Ka down (32 GHz). The necessary equipment (mirros and electronics) would be installed in the Beam Waveguide cabin, in the tertiary focus of the SRT. This second application of course would have put extremely tight requirements on the operational reliability, compatibility, security of the SRT and the allowance for special transmitting licenses.

At this moment, only the receiving configuration is planned for Space Science with the SRT. The interested scientists, apart from the Radio Science team, are then restricted to those willing to collect downlink data from a spacecraft at a higher data rate (due to the extremely large collecting area of the SRT that gives a higher S/N), and its availability at transit times different from those at other ground stations, normally used for the tracking.

In the years to come the SRT, if equipped with dedicated data acquisition systems suitable for Space Science applications will be able to play a strategic role, in special circumstances due to its much higher sensitivity than the typical 34-m tracking antennas (a factor of between 4 and 8 is expected, both for the larger collecting area and the active surface concept). The double frequency, X + Ka, primary focus receiver, originally designed for and successfully used in Noto, will be easily installed on the SRT which has the same F/D ratio for the main reflector. Its use will open new opportunities in Space Science experiments not only with the last part of the Cassini mission, now supposed to end by 2009, but also with the new NASA - ESA missions like Bepi Colombo and others to come.

Chapter 9

SETI

Scientific Background

Are We Alone in the Universe? This is a fundamental and crucial question, which has haunted mankind since we realized that the points of light in the night sky are other suns. Today we have the technology to seek a definitive answer. This is the aim of the Search For Extra Terrestrial Intelligence (SETI), an international effort to look for artificial radio signals coming from the outer space. A hypothetical result could represent for mankind the biggest discovery of the millennium. This is a very hard challenge for modern physics, technology and philosophy/theology. The Drake formula attempts to give us an estimate of the number of communicative civilisations.

$$N = R f_p n_e f_l f_i f_c L$$

N = The number of civilisations trying to contact us
R = The average rate of star formation
f_p = The fraction of stars that are suitable for planet formation
n_e = Number of Earth-like planets
f_l = Fraction of Earth-like planets where life develops
f_i = Fraction of Earth-like planets where life has intelligence
f_c = Fraction of intelligent species who want to communicate
L = Lifetime of a civilisation

Where Should we look?

- Frequency: Radio from 1 GHz to 10 GHz for the low background noise level and particularly at the HI and OH emission frequencies (the so-called 'waterhole')
- Polarization: Circular, linear, modulated
- Direction: Targeted search, All-Sky survey, Serendipitous mode (piggy-back observation), Radio Leakage (unintentional signals)/RF leakage (Kashunen-Loewe Transformation is requested)
- Narrow band signals – preferably pure continuous wave (CW) – (intentional signals) (Fourier-Transformation is requested)

What signal should we look for?

Intentional radio message (CW):

- A signal with Doppler shift
- A signal with Doppler shift would indicate non-terrestrial. CW signal to get attention
- A CW beacon would stand out from Galactic noise

- Can be seen with low bandwidth receiver

Unintentional radio message:

- A radio signal with a probably unknown modulation.

This will spread the signal over a wide bandwidth and make the signal hard to detect

Technical requirements

We need to look at as much bandwidth as possible and at the same time we need to divide in very narrow channels to increase the sensitivity. This means t operate with an extremely high resolution spectrum analyzer (at least 0.7 Hz). The backend that could be used is the already existing Serendip IV high-resolution spectrometer at present operating at the Medicina 33-m VLBI dish (15 MHz at 24 million channels). With a given Effective Isotropic Radiated Power (EIRP) from an extraterrestrian transmitter, the beacon can be detected at the distance of

$$D = \sqrt{\frac{EIRP \cdot A_{eff}}{4\pi kTB}}$$

where $EIRP$ is beacon power
k is Boltzmann's constant
B is frequency resolution
T is antenna temperature
A_{eff} is the effective aperture of the receiving antenna

Having a larger antenna means the detection of the same signal coming from larger distances. In other words, the distance covered (at a given power) by an extraterrestrial transmitter is dependent also on the square root of the collecting area. For this reason the SRT is more suitable for this search than the present Italian antennas. The starting point for this program is to install the existing high-resolution Serendip IV spectrometer in the SRT. The main characteristics of this spectrometer are:

- Input bandwidth 16 MHz
- Number of channels 24.000.000
- Integration time 1.7 sec.
- Realtime processing.

Appendix A

Appendix

A.1 The SRT Receiving System Plan

In the framework of the planning of the SRT construction, the Board of the SRT has established several working groups with the aim to provide the antenna with specific tools able to obtain a state-of-the-art radioastronomical instrument. One of them is the receiver group, to which the design of the receivers and of the complete receiving system architecture was assigned.

The key points of the receiving system can be summarized as follows:

- Design receivers that can be used for single dish as well as for VLBI, which avoids having more receivers than the available space will permit at all three foci. It will also avoid the need of a manual mounting and dismounting and offer an automatic and remote 'frequency agility'. It should be noted that this accomplishment will allow a receiver change in less than 4 minutes, in the worst case!
- Offer a continuous coverage of the RF (Radio Frequency) band from 300 MHz to 100 GHz. There are exceptions to this in the lower part of the frequency spectrum due to man-made interference. All the receivers will be dual channel.
- Design and construct large bandwidth feed systems (up to about 33% of the nominal frequency), keeping good performance in terms of return loss, cross polarization purity, insertion loss and sidelobes.
- Offer a receiver noise temperature as low as possible by cooling most part of the feed system together with the Low Noise Amplifier (LNA)
- Offer different and selectable instantaneous bandwidths (IF), up to 2 GHz, leaving anyway the possibility to add electronics for particular and 'extreme' receivers aimed at exploiting the full RF band (for example RF polarimetric and/or total power receivers). The IF band will be positioned from 100 MHz to 2100 MHz spanning all the RF bandwidth by tuning a proper value of the local oscillator. Other IF filters available are 80/400/800 MHz wide.
- Organize a receiving architecture and interconnections such that all the bands and bandwidths will be automatically selectable and will provide the signal for backends mounted both on the antenna and in the control room (500 m away, by using fiber optic links).

Table A.1: Instrumentation Requirements for Single-Dish Observations Derived from the WG Report.

	Requirements of Scientific WG									
Project	*Scientific Keywords Reference*	*Backend*	*Monofeed/ Multifeed*	*RXs (GHz)*	*Instantaneous Bandwidth (MHz)*	*Sensitivity*	*Resolution (km/s)\ kHz*	*Feed system*	*Antenna mode*	*Observatio*
1	Comets	Spectrometer	Monofeed	> 10	10	50 mK	0.1\	-	-	
2	Galactic, Masers	Spectrometer	Monofeed	1.612,1.712 12 20,22÷24 36÷38 43	≤ 200	0.12 Jy	0.01 to 0.25 \ ≥ 0.05	-	-	-
3	Galactic, NH_3	Spectrometer	Multifeed	24	20	50 mK, 70 mJy	<0.1\8	-	-	-
4	Galactic, DCO+, N_2D^+	Spectrometer	Multifeed	70÷80	?	20 mK, 30 mJy	\3	-	wobbling	Frequency s
5	Galactic, ISM Molecules	Spectrometer	Monofeed	1÷100	500	10 mK, 15 mJy	0.1\	-	-	-
6	Galactic, Active binaries	Total Power	Monofeed, Dualfeed	1.6 ÷ 45	largest possible	1 mJy	-	-	raster scan	Frequency
7	Galactic, CMBP	Polarimeter	Monofeed	4.8	500÷1500	$0.5\ \mathrm{mK}\cdot\sqrt{s}$	-	≤ 35 dB cross	cross-scan $4'/s$	Mapping s
8	Galactic, Pulsar	Spectrometer	Monofeed & Multifeed	0.325,1.4,3	32,600,1000	8.5,0.9,? mJy $\sqrt{s}$	\32,500,1000	-	-	-
9	Galactic, Protostars	Spectrometer	Monofeed better Multifeed	20, 40, 70, 90	15	20 mK	0.2 \ 10	-	-	Mapping S
10	Galactic, X-Ray Binaries	?	?	22	2000	0.01 mJy	-	-	-	-
11	Extragal. HI blind	Spectrometer	Multifeed	< 1.42	70	3 mJy	20\100	-	-	-
12	Extragal. H_2O Mmaser	Spectrometer	Multifeed	22.2,16÷20	> 200	0.7 mJy	1.3\100	-	-	-
13	Extragal. CO	Spectrometer	Monofeed	27÷37 38÷48 69÷104	10000 10000 35000	0.1 mJy 0.3 mJy 1.1 mJy	20\2000 20\3000 20\8000	-	-	-
14	Extragal. sky survey	Total power	Multifeed Multifeed Multifeed	22 30 40	2000 2000 2000	0.050mJy 0.030mJy 0.015mJy	-	-	raster-scan	-
15	Extragal. RM sources	Polarimeter	Monofeed	5	500	0.24 mJy	-	-	cross-scan	Mapping s
16	Extragal. source survey	Total power & Polarimeter	Monofeed better Multifeed	20 32 43 86	≥2000 ≥2000 ≥2000 ≥2000	13.4 mJy 8 mJy 5.7 mJy 2.5 mJy	-	-	cross-scan raster-scan	Mapping s
17	Extragal., GRG mapping	Total power & Polarimeter	Monofeed Dualfeed Multifeed	20 32	2000 2000	0.3mJy 0.3mJy	-	-	raster-scan $20'/\mathrm{min}$	Mapping s
18	Extragal., Blazar monit.	Total power & Polarimeter	Dual Feed	≥ 10	2000	$\geq$ 5mJy	-	< -35 dBcross	-	Frequency 1 m
19	Extragal., Sunyaev-Zel'd	Total Power	Multifeed	20,40	> 2000	0.1 mK	-	-	beam switch. wobbling raster scan	-
20	Space Science	tone extractor	Dual Frequency	8.4 / 32			-	-	-	-
21	SETI	Spectrometer	Monofeed	1÷10	15 ÷ 20	-	\ ≤0.0007	-	-	-
22	Planetary Radar	Spectrometer	Monofeed	8.5, 34	?	?	?	-	-	-

Table A.2: Instrumentation Requirements for VLBI Observations Derived from the WG Report.

	Requirements of Scientific WG									
Project	*Scientific Keywords Reference*	*Backend*	*Monofeed/ Multifeed*	*RXs (GHz)*	*Instantaneous Recording Rate*	*Sensitivity*	*Resolution (km/s)\ kHz*	*Feed system*	*Antenna mode*	*Observation Mode*
1	Redshifted hydrogen	MK5	Monofeed	0.8 ÷ 1.3		-	-	-	-	Frequency Agility
2	Wide-Field VLBI Imaging and Surveys	MK5	Monofeed	1.4,5	up to 1Gbps	-	-	-	-	Frequency Agility
3	Methanol line	MK5	Monofeed	6.7	up to 1Gbps	-	-	-	-	Frequency Agility
4	AGN	MK5	Monofeed	8.4	up to 1Gbps	-	-	-	-	Frequency Agility
5	AGN, X-ray Binaries	MK5	Monofeed	22	up to 1Gbps	-	-	-	-	Frequency Agility
6	AGN	MK5	Monofeed	43	up to 1Gbps	-	-	-	-	Frequency Agility
7	Millimiter VLBI	MK5	Monofeed	86	up to 1Gbps	-	-	-	-	Frequency Agility
8	High Sensitivity Array	MK5	Monofeed	0.33,0.61,1.4,5 8.4,15,22,43	≥256 Mbps	-	-	-	-	Frequency Agility
9	Geodesy	MK5	Coax Dualfrequency	2.3 /8.4	256Mbps	-	-	-	-	Frequency Agility

Table A.3: Frontend Configurations Planned by the Receiver Group

	Planned by Receiver Group							
Project	Planned RXs (GHz)	Instantaneous Bandwidth (MHz)	Sensitivity (continuum 2ch)	Resolution feasibility (Km/s)\KHz	Feed system feasibility	Antenna mode	Observation Mode	Remarks
1	1.3÷1.8 10.3÷14.4 18÷26 35÷48	80/500 80/400/800/2000 80/400/800/2000 80/400/800/2000	2.3 mJy·$\sqrt{s}$ 0.7 mJy·$\sqrt{s}$ 1.7 mJy·$\sqrt{s}$ 1.6 mJy·$\sqrt{s}$	Yes	-	-	-	
2	18÷26	80/400/800/2000	1.7 mJy·$\sqrt{s}$	Yes	-	-	-	
3	70÷90	80/400/800/2000	5.1 mJy·$\sqrt{s}$	Yes	-	Yes	To be implemented	wobbling time = 0.7 s, off=5*HPBW
4	see planned RF band list	80/400/800/2000	see this column	Yes	-	-	-	
5	see planned RF band list	80/400/800/2000	see this column	-	-	Yes	Yes	
6	4.3÷5.8	80/400/800/1500	0.54 mJy·$\sqrt{s}$	-	Yes	Yes	Previous experience	
7	0.31÷0.35,1.3÷1.8,3.22÷4.3	40,500,1100	8.5/0.9/? mJy·$\sqrt{s}$	Yes	-	-	-	
8	18 ÷26 26 ÷36 35÷48 70÷90	80/400/800/2000 80/400/800/2000 80/400/800/2000 80/400/800/2000	1.7 mJy·$\sqrt{s}$ 0.85mJy·$\sqrt{s}$ 1.6 mJy·$\sqrt{s}$ 5.1mJy·$\sqrt{s}$	Yes	-	-	-	
9	18÷26	80/400/800/2000	1.7 mJy·$\sqrt{s}$	Yes	-	-	-	
10	1.3÷1.8	80	2.3 mJy·$\sqrt{s}$	Yes	-	-	-	
11	18÷26,14.4÷19.8	80/400/800/2000	1.7/1.2 mJy·$\sqrt{s}$	Yes	-	-	-	
12	26÷36 35÷48 70÷90 + 90÷115	2000 2000 2000	0.85 mJy·$\sqrt{s}$ 1.6 mJy·$\sqrt{s}$ 5.1+ 6.4 mJy·$\sqrt{s}$	Yes	-	-	-	Widest BW at 30 and 40 GH possible,in principle, by additions to planned receiver. 69÷104 very problematic.
13	18÷26 26÷36 35÷48	2000 2000 2000	1.7 mJy·$\sqrt{s}$ 0.85 mJy·$\sqrt{s}$ 1.6 mJy·$\sqrt{s}$	-	-	Yes	-	Widest BW at 30 and 40 GH possible, in principle, by additions to planned receiver. Requested sensitivities can be achieved with planned RX.
14	4.3÷5.8	400/1500	1.1/0.54 mJy·$\sqrt{s}$	-	-	Yes	Previous experience	
15	18÷26 26÷36 35÷48 70÷90	2000 2000 2000 2000	1.7 mJy·$\sqrt{s}$ 0.85 mJy·$\sqrt{s}$ 1.6 mJy·$\sqrt{s}$ 5.1 mJy·$\sqrt{s}$	-	-	Yes	Previous experience	BW=10 GHz needs additions planned receiver. Requested sensitivities can be achieved with planned RX.
16	18÷26 26÷36	2000 2000	1.7 mJy·$\sqrt{s}$ 0.85 mJy·$\sqrt{s}$	-	-	Yes	Previous experience	
17	see planned RF bands list	2000	see this column	-	Yes	-	Yes	

Table A.3: Frontend Configurations Planned by the Receiver Group (cont'd)

	Planned by Receiver Group							
Project	Planned RXs (GHz)	Instantaneous Bandwidth (MHz)	Sensitivity (continuum 2ch)	Resolution feasibility (Km/s)\KHz	Feed system feasibility	Antenna mode	Observation Mode	Remarks
18	$18 \div 26$ $35 \div 48$	2000	1.7 mJy$\cdot\sqrt{s}$ 1.6 mJy$\cdot\sqrt{s}$	-	-	Yes	-	Widest BW possible, in principle, by additions to planned receiver.
19	No planning							
20	1.3÷1.8,2.36÷3.22,3.22÷4.3 4.3÷5.8,5.7÷7.7,7.5÷10.4	80/400/800/2000	see this column	Yes	-	-	-	
21	7.5÷10.4,26÷36	80/400/800/2000	see this column		-	-	-	
22	18÷26	80	1.7 mJy$\cdot\sqrt{s}$	Yes	-	-		-

Table A.4: Starting from the planned receivers bands this table identifies which projects use it together with which backend and type of receiver

Planned RXs Bands vs Requested Projects			
Planned RF Bands (GHz)	*Requesting Projects*	*Requested Backend*	*Requested RX*
0.31÷0.35	Pulsar VLBI	Spectrometer MK5	Monofeed
0.58÷0.62	VLBI	MK5	Monofeed
0.7÷1.3	VLBI	MK5	Monofeed
1.3÷1.8	Maser ISM Mol. Active Binaries Pulsar Extragal. HI VLBI SETI	Spectrometer Total Power MK5	Mono/Dual Multifeed
3.22÷4.3	Pulsar Active Binaries SETI	Spectrometer Total Power	Mono/dualfeed
4.3÷5.8	ISM Mol. Active Binaries CMBP Extragal. RM VLBI SETI	Spectrometer Polarimeter Total Power MK5	Monofeed
5.7÷7.7	VLBI Active Binaries SETI	Spectrometer Total Power MK5	Monofeed
2.3/8.4	VLBI Planetary Radar	Spectrometer MK5	Monofeed
10.3÷14.4	Maser ISM Mol. Active Binaries Blazar Monitoring Comets	Spectrometer Total Power Polarimeter	Mono/Dualfeed
14.4÷19.8	ISM Mol. Megamaser H_2O Active Binaries VLBI Blazar Monitoring Comets	Spectrometer Total Power MK5 Polarimeter	Mono/Dual/Multifeed

Table A.4: Starting from the planned receivers bands this table identifies which projects use it together with which backend and type of receiver (cont'd)

Planned RXs Bands vs Requested Projects			
Planned RF Bands (GHz)	*Requesting Projects*	*Requested Backend*	*Requested RX*
18÷26	Maser Gal. NH_3 ISM Mol. Active binaries Megamaser H_2O Extragal. sky survey Extragal. source survey Extragal. GRG VLBI X-RAY Binaries Protostar Blazar Monitoring Sunyaev - Zel'dovic Comets	Spectrometer Total Power Polarimeter MK5	Mono/Dual Multifeed
26÷36	ISM Mol. Active Binaries Extragal. CO Extragal. sky survey Extragal. source survey Extragal. GRG Blazar Monitoring Planetary Radar	Spectrometer Total Power Polarimeter	Mono/Dual/Multifeed
35÷48	Maser ISM Mol. Active Binaries Extragal. CO Extragal. survey Extragal. source survey VLBI Protostar Blazar Monit. Sunyaev-Zel'dovich Comets	Spectrometer Total Power Polarimeter MK5	Mono/Dual/Multifeed
70÷90	DCO^+, N_2D^+ ISM Mol. Extragal. CO Extragal. source survey VLBI Protostar Blazar Monitoring Comets	Spectrometer Total Power Polarimeter MK5	Mono/Dual/Multifeed
90÷115	ISM Mol. Extragal. CO Blazar Monitoring Comets	Spectrometer Total Power Polarimeter	Mono/Dual/ Multifeed

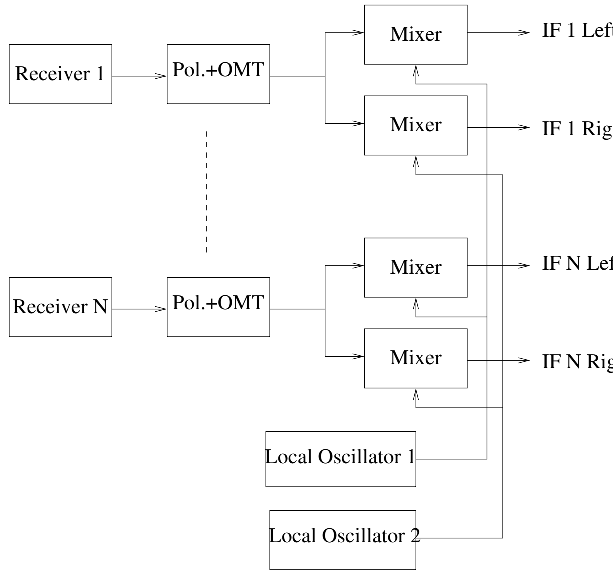

Figure A.1: Conceptual schematics for a multi-beam front-end receiver. Each receiver has two separate polarizations. The two polarizations can be tuned independently within the receiver band.

A.2 A spectroscopic backend for the SRT

A.2.1 Introduction

The SRT will have a frequency coverage from 300 MHz to 86 GHz (up to 115 GHz if the active surface will allow it). The receivers will have a single beam and dual polarization, except for the 18-26.5 GHz band that will have 7 beams with double polarization. Nevertheless, for efficiency considerations, it is advisable that in the future all bands will be equipped with multi-beam receivers. All receivers should be able to operate in three modes: 'VLBI', continuum and spectroscopic.

The planned configurations are:

- VLBI mode: The receiver signal will be sent using a fiber-optic connection to the control room. There will be a total of 6 fibers: 2 for each of the 3 foci: Primary, Gregorian and Beam Waveguide (BW)
- spectroscopic and continuum modes: The backends will be located in the vertex room, to avoid long radio frequency interconnections. Only the integrated data, with a much lower data rate, will be sent to the control building using a digital optical fiber.

Preliminary studies of the receiver systems consider an intermediate frequency bandwidth of 2 GHz. Separate local oscillator could be used for the two polarizations. Moreover, the central pixel of all the multi-beam receivers will be used for VLBI operations. A conceptual schematic for a multi-beam receiver is shown in Fig. A.1.

A.2.2 Spectroscopic backend characteristics

The main feature of the spectroscopic backend must be its flexibility, both for single beam and for multi-beam receiver observations. The operating modes can be summarized as follows:

1. Single beam
    - Dual polarization
    - Single polarization:
        - simultaneous observations of two bands arbitrarily positioned in the full receiver bandwidth

   – observation of the full 2 GHz bandwidth

2. Multi-beam
   - Dual polarization
   - Single polarization: simultaneous observations of two bands, arbitrarily positioned in the receiver instantaneous bandwidth

The minimum velocity resolution should be around 0.03 km/s in any mode.

A possible implementation for the spectrometer consists of 32 channels of 512 spectral points each, that can be combined together as 16 independent channels of 1024 points each (mode A: multi-beam), or as a single channel of up to 16000 points (mode B: single beam). These are described in greater detail in the following section, and in Figs. A.2, and A.3, respectively.

In Table A.5 the required frequency resolution $\delta\nu$, in kHz, is reported as a function of the observing frequency and velocity resolution δv (km/s). For mode A (1024 channels) the corresponding bandwidths can be obtained reading the same values as expressed in MHz. We assume that the sampling frequency will be around 160 MHz, and therefore the maximum instantaneous bandwidth will be 80 MHz. The combinations in italics in Table A.5 denote bandwidths larger than this value, that cannot be obtained with this implementation.

Observing	Velocity resolution δv (km/s)				
frequency	0.03	0.1	0.3	1	3
1 GHz	0.1	0.33	1	3.3	10
5 GHz	0.5	1.66	5	16	50
10 GHz	1	3.3	10	33	*100*
20 GHz	2	6.7	20	67	*200*
45 GHz	4.5	14	45	*140*	*450*
90 GHz	9	30	*90*	*300*	*900*

Table A.5: Frequency resolution, in kHz, as a function of the receiver frequency and of the desired velocity resolution δv, in km/s. Values in italics denote a bandwidth too large for the assumed 160-MHz sampler.

It should be noted that using a 160-MHz correlator we can cover for dual polarization only a fraction of the total 2-GHz instantaneous receiver bandwidth in mode B. It is possible to observe the full 2-GHz instantaneous bandwidth only in single polarization and single-beam mode. To be able to cover a 2-GHz bandwidth with 16 correlators per polarization, a sampling frequency of 250 MHz is required. This would allow one to use a 250-MHz sampler for mode A, thus permitting greater velocity coverage for the higher frequency receivers. However currently available Field Programmable Gate Arrays do not guarantee operations at frequencies above 160 MHz, and thus this lower operating frequency has been assumed.

The possibility of observing two independent frequency bands arbitrarily placed within the full receiver bandwidth requires the use of two independent local oscillators, as shown in Fig. A.1.

A.2.3 Implementation

A possible structure of the SRT correlator would include 32 sections with 512 spectral points each. Dedicated software and a Crossbar Switch will allow to configure the correlator as follows:

- 16 inputs with 80 MHz bandwidth each
- 2 inputs with 1 GHz bandwidth each
- 1 input of 2 GHz bandwidth

In multi-beam operation (Mode A, Fig. A.2), the IF signals from the multi-beam receiver, after down-conversion and anti-aliasing filtering are sampled at 160 MHz and sent to a digital SSB (Single Side Band)

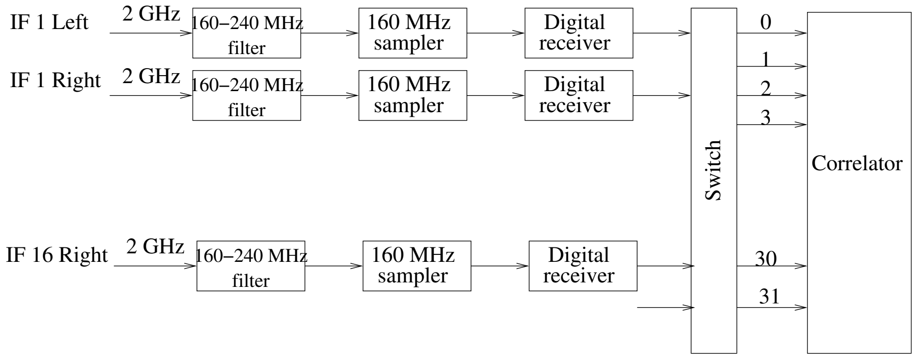

Figure A.2: Multi-beam mode (mode A). Signals from the multi-beam receiver are converted, filtered, and sampled at 160 MHz. The frequency region extracted (up to 80 MHz) is the same for all beams and polarization channels. The bandwidth can be further narrowed by a digital receiver. The 32 correlator channels can be grouped to analyze fewer of the 32 receiver outputs with increased resolution.

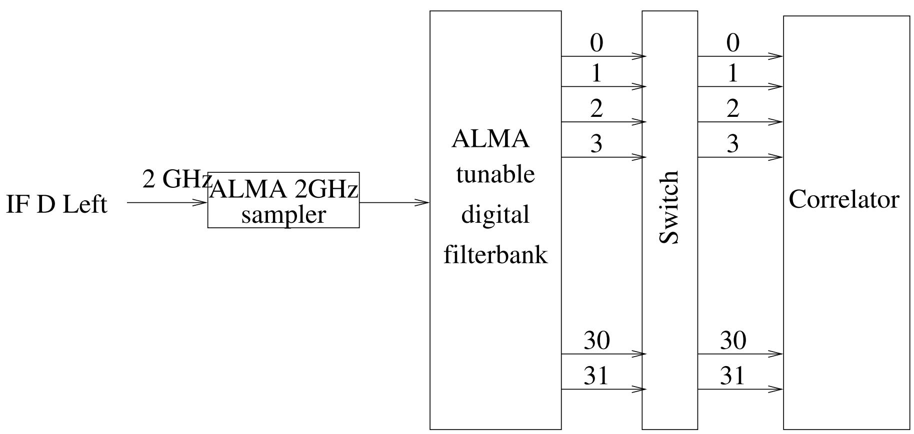

Figure A.3: Single-beam mode (mode B). Signals from the receiver is sampled at 2 GHz, and processed by a tunable digital filter bank derived from the ALMA design. Up to 32 independently tunable channels can be extracted and sent to the correlator

filter for the required bandwidth selection (from 0.1 to 80 MHz). The second local oscillator is the same for all receivers.

These signal are finally sent to the inputs of the correlator. For dual polarization modes, the 32 correlator sections are independently used to analyze up to 16 beams in two polarizations. For single polarization, signals are sent to the even inputs of the correlator, in which two adjacent sections are connected in series to obtain the required 1024 spectral points. The electronic components are at low cost and available commercially; the realization should be flawless.

For large bandwidth, single-beam operation (Mode B, Fig. A.3), the approach developed for ALMA is envisaged. After the sampling, the signal is ‘divided’ in 32, 62.5 MHz wide, sub bands using sophisticated digital filters followed by re-sampling. Each sub-band can be independently tuned across the 2 GHz instantaneous bandwidth, both to synthesize a larger band or to analyze regions of interest. These 32 signals are sent directly to the 32 correlator sections. Sections can be cascaded to increase spectral resolution. This configuration will require components partially not commercially available. Also the realization could be quite complex and expensive.

For operation with much larger instantaneous bandwidth, say 10 GHz, like those required by 90 GHz receivers, the acousto-optic technology must be considered as demonstrated by Acousto-Optic Spectrometers on board of SWAS (Submillimeter Wave Astronomy Satellite) and Herschel.

A.3 Pulsar Facilities

A.3.1 Overview of state-of-art de-dispersion techniques

A.3.1.1 Incoherent de-dispersion using analogue filter-banks

Incoherent de-dispersion techniques are usually adopted in pulsar *search observations*. This technique implies the use of a proper filter-bank system, whose resolution and number of channels depend on the central frequency adopted and the maximum dispersion measure searched. For instance, in the Parkes multi-beam surveys, a filter-bank system with 96 3 MHz-wide channels covering a bandwidth of 288 MHz for each polarization of each beam was used, making a total of 2496 channels. This system was developed by the IRA in collaboration with Jodrell Bank and the ATNF (Sydney). In this case, detected signals from individual frequency channels are added in polarization pairs, high-pass filtered with a cutoff at approximately 0.2 Hz, integrated and 1-bit digitized every 250 or 125 ms, and recorded on magnetic tape (DLT) for subsequent analysis.

It was proven that the 3-MHz choice was successful in terms of the total number of pulsars discovered (more than six hundred), but it also became clear that a relative lack of millisecond pulsars discovered in the Parkes multi-beam survey was due to some extent to the relatively poor frequency resolution adopted. A parallel experiment carried out at Parkes, namely a deep search of the Globular Cluster system, thanks to the small number of pointings required, used the single central beam only of the same multi-beam receiver equipped with a much higher frequency resolution de-dispersing system (2x512x0.5 MHz). The experiment was extremely successful in the discovery of millisecond pulsars.

A.3.1.2 Incoherent de-dispersion using digital filter-banks

An analogue filter-bank does not provide the stability required to achieve the desired accuracy in *high precision timing observations*. If observing at relatively high frequency, say around 3GHz, which is an ideal frequency for achieving high timing precision (because the signal is relatively free from multi-path scattering effects), dispersion can be easily removed using a *digital filter-bank*. The disadvantage of a digital filter-bank with respect to the classical analogue spectrometers used for pulsar searches, is that it produces an intrinsically much higher data rate, but this is not an issue for timing observations which target a limited sample of sources. A good state-of-art example of a digital filter-bank is that under construction at Parkes and planned as the standard backend for timing observations at the 10-cm band of the dual band 50/10cm receiver. The filter-bank spans a total bandwidth of 1 GHz (two polarizations) and has a frequency resolution of 1 MHz. Because the dispersion smearing scales as ν^{-3}, this is almost equivalent to a frequency resolution of 125 kHz at 21cm, which is good enough to provide high timing precision.

A.3.1.3 Coherent de-dispersion

Precise timing observations are also carried out *at relatively low frequency (300-1800 MHz)* at which *coherent de-dispersion is much more efficient*. Although interstellar scattering is much more severe in this case, low frequency observations are necessary and complementary to high frequency observations because they provide the large frequency baseline necessary to measure with high accuracy the dispersion delay, and estimate with high precision the pulse arrival times at infinite frequency. While in incoherent de-dispersors, like in those based on analogue filter-bank, the signals of the individual frequency channels are sampled at post-detection level, in a coherent de-dispersor the baseband radio signal is sampled. The advantage of this technique is that *de-dispersion can be removed totally* by Fourier-transforming the radio signal and applying a proper convolution filter. The disadvantage is that it requires rather high data rates and powerful real-time data processing power. A state-of-the-art coherent de-dispersor, called CPSR-2, has been developed as a joint project between Swinburne University and CalTech. It allows on-line coherent de-dispersion of a 128 MHz band, and it is based on modern DMA cards developed at Caltech and a cluster of 196 fast CPUs available on-line.

A.3.2 A pulsar backend for the SRT

In general, different sets of filter-banks and coherent de-dispersion systems must exist in a versatile equipment for performing pulsar observations: namely analogue filters for survey observations, digital filters for precise timing observations at high frequency and machines for coherently de-dispersing the signal for low and intermediate frequency timing observations.

In particular, following what is described in Sect. 4.2.3 (Pulsar Observations), a state-of-art pulsar system at the SRT should include:

1. A set of analogic filter-banks or digital filter-banks based on FPGA polyphase filters with 2048 channels (1024 per polarization), each of them 32-kHz wide, for a total instantaneous bandwidth of $\sim 32, 64$ or 128 MHz. It will be used for pulsar search at low frequencies (300-400 MHz).

2. An analogic filter-bank with 2048 channels (1024 per polarization), each of them 500 kHz wide, for a total instantaneous bandwidth of $\sim$ 500 MHz. It will be mostly devoted to pulsar search at 1.4 GHz and higher frequencies.

3. If a multi-beam system will be available at 1.4 GHz, each beam should be equipped with a filter-bank like the one described at point 2. This will allow to undertake very large-scale searches for pulsar at 1.4 GHz.

4. A digital filter-bank with a total instantaneous bandwidth of 1 GHz and a frequency resolution of 1 MHz to be exploited in timing observations at high frequency ($>$ 3 GHz).

5. A coherent de-dispersion system, capable of handling up to 512 MHz of instantaneous bandwidth, in order to perform high precision timing observation both at low (300-400 MHz) and intermediate (1.4 GHz) frequencies. Although such a system does not exist yet, it can be easily assembled by the time the SRT will be operational. It will require to combine 8 machines like the already available CPSR-2 machine developed at CalTech and Swinburne University.

A.4 A continuum backend for total intensity and polarization for the SRT

The polarimeter available at the Medicina VLBI radiotelescope, can be considered as a prototype of the continuum backend for the SRT. It consists of an analogue correlator which as inputs has the two circular intermediate frequencies (IF left & IF right, obtained from the RF signal after a down-conversion with one or more local oscillators). It gives 4 channels as outputs which are the two total power channels (left and right) and the 2 Stokes parameters denoting linear polarization (Q & U). The outputs are simultaneously sampled by 4 analogue-to-digital converters working at a maximum rate of 40 Hz. By means of this feature, it has been possible to develop ad-hoc strategies for map-making by the SPOrt team (IASF-CNR Bologna and IRA-CNR), because the output channels are sampled at a proper rate to sample fully the sky, during the raster scanning. Recent measurements (Carretti E., Poppi S., 2004, *Diffuse Polarized Maps with the Medicina Polarimeter: Map-Making Procedure and Observing Tests*, internal report, in prep.) showed the map-making capabilities in continuum for both total intensity and polarization.

The working scheme of a polarimeter is summarized in Fig. A.4, where the Q and U outputs measure the linear polarization, the TP1 and the TP2 are the total power detection of left and right polarization. The advantage of a polarimeter working with the two circular polarizations from the receiver is in terms of stability and time efficiency, as both the Q and U Stokes parameters are directly obtained (Kraus, *Radioastronomy*, 1986). Moreover, the use of the IFs as inputs for the polarimeter satisfies the requests of versatility for the SRT backends (i.e. backends able to work with as as many SRT receivers as possible); otherwise if RF inputs (Radio Frequency signal without any down-conversion) should be used, ad-hoc backends for each receiver would be necessary.

Furthermore, it is worth noting that in designing the receivers particular care must be taken to minimize the instrumental polarization; for an analysis of all the possible sources of spurious polarization see Carretti et al. 2001 (New Astron. 6, 173) and Cortiglioni et al. 2004 (New Astron. 9, 297).

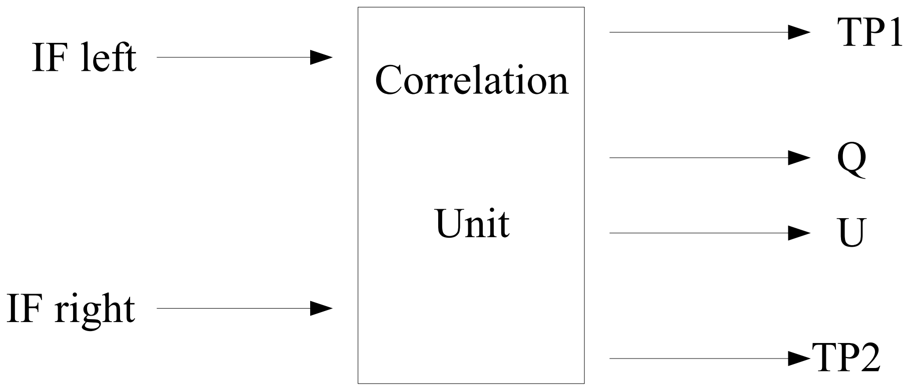

Figure A.4: Polarimeter scheme

The polarimeter for the SRT will work with a large instantaneous bandwidth, at least 1 GHz, in order to give the highest sensitivity. The outputs will be sampled at a rate of 100 Hz, sufficient to have enough points per beam during a raster scan at maximum antenna speed. A possible choice for the correlation unit is a digital correlator, which would be possible if the two input IF are sampled at the proper rate: for a 1-GHz-wide instantaneous bandwidth the sampler will work at a rate greater than 2 Gsamples/s, according to the Nyquist theorem. The sampled signal can be digitally filtered and the IF can be divided into narrower bands, allowing to exclude those affected by interference.