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Memorie della

The SRT & (br)other single-dish telescopes

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Abstract. The basic features of a selected subset of the world-class single-dish radiotelescopes are reviewed here, focusing not only on technical aspects but also on scheduling issues. New instruments under development at the various radiotelescopes are also presented. It appears that the new Sardinia Radio Telescope has the capability to successfully compete with the best instruments to provide a high scientific return in many fields of astrophysical interest.

1. Introduction

This paper is a by-product of the work of the SRT Working Group, which was installed in May 2004, by the then-director of the INAF-Istituto di Radioastronomia (INAF-IRA), Prof. G. Tofani, on behalf of the Board of SRT. He 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 consisted of Jan Brand, Paola Caselli, Marcello Felli (chairman), Karl-Heinz Mack, Sergio Poppi, Andrea Possenti, Isabella Prandoni, and Andrea Tarchi. The activity of the WG, as well as many contributions coming from the entire Italian scientific community, resulted in a Report entitled “The Sardinia Radio Telescope (SRT): Science and Technical Requirements” (Brand et al. 2005; hereafter ”the Report”).

During the preparation of the Report, the WG many times faced the necessity to have an updated vision of the operational status and of the new projects running at other important radiotelescopes in the world. Hence the idea to provide the audience of the Workshop *“Science with the SRT”*, with a brief introduction to these themes.

A complete and detailed review of all the publicy available radioastronomical instruments immediately appeared well beyond the scope of such a brief introduction and so the WG decided to focus on a small number of world-class single-dish radiotelescopes selected according to what is contained in the Report. In particular, the WG scanned all the scientific sections in which the Report had been split. Section by section, it determined the list of radiotelescopes with which the new SRT will presumably have to compete. A ranking was thus established, based on the total number of occurrences of the various radiotelescopes in the lists. The first three of the ranking were the 105-m Robert C. Byrd dish, located at Green Bank, in West Virgina (USA), the 100-m dish of Effelsberg (Germany) and the 64-m dish of Parkes (New South Wales, Australia).

Although somewhat arbitrary (and without neglecting the capabilities of radiotelescopes of smaller collecting area: e.g. Nobeyama, Torun and so on), this choice comprises the largest and most modern fully-steerable single-dish in the world (the Robert C.Byrd dish), built with a technology similar to that which will be used for the SRT; the largest single-dish in Europe (the Effelsberg 100-m), having a larger collecting area but an older technology with respect to the SRT; and the most scientifically successful (so far) single-dish in the world (Parkes) among those belonging to the class of 64-m instruments, the same size as the SRT. Provided the SRT will have state-of-the-art detectors (as strongly recommended by the WG in the Summary of the Report), the WG thinks that the most meaningful comparision is between SRT and instruments of the same or larger size.

Finally, it is important to note that the data and the procedures described in Elena Cenacchi's Laurea Thesis (Cenacchi 2005) have been used as a starting point and as reference basis for the comparison between the different telescopes which is presented in the final sections of this paper.

2. The three telescopes in the focus: generalities

2.1. The Robert C. Byrd Green Bank Telescope (GBT)[1]

The GBT is the world's largest fully steerable radio telescope. It is located at the National Radio Astronomy Observatory's site in Green Bank, Pocahontas County, West Virginia (38°25′59.″26 N, 79°50′23.″42 W, altitude: 819.5 m).

The most striking feature of the GBT is its unusual asymmetrical design. Unlike most other telescopes, which have a series of supports protruding from the surface, the aperture of the GBT is unblocked so that all incoming radiation meets the surface directly. This increases the useful area of the telescope and reduces reflection and diffraction that can complicate a telescope's response pattern. In order to accommodate this, an off-axis feed arm cradles the dish, projecting upward at one edge, and the telescope surface is asymmetrical: a 100-by-110 meter section of a conventional, rotationally symmetric 208-meter figure, beginning four meters outward from the vertex of the hypothetical parent structure.

With reference to the 208-m parent paraboloid, the focal ratio of the prime focus is $f/D = 0.29$, whereas the Gregorian focus has a focal ratio $f/D = 1.9$ (with respect to the 100 m effective diameter). The telescope can be pointed in all directions in the sky above 5° elevation. The track has a size of 64 m in diameter, and is level to within a few thousandths of a centimeter in order to provide precise pointing of the structure while bearing 7300 tons of moving weight.

The GBT's lack of circular symmetry greatly increases the complexity of its design and construction. The GBT is also one of the two large radiotelescopes in the world (the other being the 32-m radiotelescope of Noto) that exploit the advantages of an active surface, similar to that which will be mounted on the SRT. The GBT's collecting area is composed of $\sim 2,000$ panels and a series of actuators (little motor-driven pistons) mounted at the corners of each panel with the aim of adjusting the surface shape. Such adjustments are crucial to the high-frequency performance of the telescope, which will nominally operate in the range 100 MHz–110 GHz. However, making the system work at the design specification is not a trivial task: after 5 years since the first light (28 August 2000), the GBT is now operating in the frequency range from 290 MHz up to 50 GHz and most of the Ka- band (26.5-40 GHz) and Q-band (40-50 GHz) observations are scheduled during night-time, when the thermal properties of the dish are stable and thus afford better pointing and beam efficiency.

The Robert C. Byrd telescope is located in a National Radio Quiet Zone (NRQZ) established by the U.S. Federal Communications Commission and by the Interdepartment Radio Advisory Committee since 1958 with the aim of minimizing possible harmful interference to the National Radio Astronomy Observatory at Green Bank. The NRQZ is bounded by NAD-83 meridians of longitude at 78°29′59.″0 W and 80°29′59.″2 W and latitudes of

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[1] `http://www.nrao.edu//GBT/proposals/short_guide.shtml`

37°30′00.″4 N and 39°15′00.″4 N, and encloses a land area of approximately 13,000 square miles near the state border between Virginia and West Virginia.

2.2. *The Effelsberg Telescope*[2]

The 100-m telescope in Effelsberg went into operation already in 1972, but it is still the second largest fully steerable parabolic antenna in the world. It is located not far from Bonn (Germany) at an altitude of 319 m and at coordinates 50° 31′ 30″ N, 06° 53′ 00.″3 E.

The radio telescope rotates on a circular track of 64 m diameter which rests on a solid concrete foundation. The total weight of the steel structure is 3200 tons and it may be pointed for scientific observations from the zenith down to about 8° above the horizon.

It operates in the frequency range from 408 MHz up to 86 GHz (but only receivers for frequency higher than 800 MHz are currently available). No active surface is implemented but observations at short wavelengths can be performed despite the flexing of the steel members of up to 10 cm due to gravity. In fact, because of a special support structure the deviation of the dish surface from the ideal parabolic form is at most 0.5 mm. The shift in the focus position due to surface flexure accompanying the tilting of the dish is compensated by means of an electronic control mechanism.

The receiver systems for astronomical radiation have horn aerials connected to cooled low-noise amplifiers. These are mounted at the focal point of the main reflector (focal ratio $f/D = 0.3$) just beneath the prime focus cabin suspended on four support legs. Alternatively, an elliptically curved second reflector in the light path can focus the incoming radiation towards the central point of the surface. There, in the secondary focus cabin (focal ratio $f/D = 3.85$), it is possible to use many additional receiver systems.

Given the location in one of the most industrialized areas of Western Europe, Radio Frequency Interference (RFI) is unfortunately a major issue.

2.3. *The Parkes Telescope*[3]

The Parkes radiotelescope is located 25 kilometres North of the town of Parkes which is approximately 365 kilometres West of Sydney, in New South Wales (Australia). The latitude is 32°59′59.″8657 S, whereas the Longitude is 148°15′44.″3591 E; the height above sea level is 391.79 m.

The collecting area of the telescope is a paraboloid with a diameter of 64 m. The surface is made of high-precision aluminium millimetre wavepanels to a diameter of 17 m (for operation to 43 GHz), then perforated aluminium plates out to 45 m, and a rectangular galvanised steel 5/16-inch mesh for the remainder of the surface. Only a primary focus is provided, with a focal ratio $f/D = 0.41$ for the full 64 m surface, the focus being located 26 m above the centre. The aerial cabin, which houses feeds and receiver equipment, is supported by a tripod and has been installed in 1996, thus substituting the original much smaller focal cabin, which had been operating for almost 40 years. This major upgrade (as well as the installation of the first example of a multi-beam receiver) allowed the Parkes telescope to keep a very high scientific standard despite its old-style design. Access to the new aerial cabin is either by the lift on one of the tripod legs or by a ladder on one of the other legs. The feed platform translator, which holds up to four receivers, at the base of the aerial cabin has both up/down (focus), lateral, and rotational movement. Given the absence of any active control of the parabolic surface, very high frequency observations are impossible, and the telescope frequency range spans the interval between 300 MHz and 43 GHz.

Another limitation is that only a fraction of the sky above the horizon is visible: in fact, the dish may point between the zenith angle software limits of 1.°5 and 59.°5. There are three structural limits at zenith angles less than 1.°5 and also another three past 59.°5.

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[2] `http://www.mpifr-bonn.mpg.de/index_e.html`

[3] `http://www.parkes.atnf.csiro.au/`

Conversely, a big advantage with respect to most other large radiotelescopes in the world is the location in a comparatively RFI-free site, which allowed the exploitation of very large observational bandwidths even in the low frequency range from 300 MHz to 3 GHz. Only recently, the appearance of cable-TVs started to create trouble with interferences in the 600-700 MHz band.

3. The three telescopes in the focus: news, views, and scheduling

In this section we summarize miscellaneous information about front-end and back-end specific features, about new instruments under development or commissioning, and about the scheduling statistics at the three telescopes. As for the previous section, most of these data are collected from the official web-sites of the telescopes. The selection of what is highlighted (from among a set of many other things in principle worthwhile to be mentioned) is done by the author in the perspective of presenting the most modern and/or innovative systems, which are (or will be) unique to the given telescope.

3.1. Interesting Features

Many spectrometers of a new generation are operating at the **Green Bank radiotelescope**. In particular, the SPIGOT card is a digital spectrometer with up to 800 MHz of bandwidth, sampling the data at a rate which can be chosen in the interval $2.56 - 81.92$ μsec in full Stokes parameters. Lags (between 256-2048), bandwidth (50 MHz or 800 MHz) and sampling time can be programmed according to the constraint of a fixed data rate of 25 MBy/sec. The GBT Spectrometer is a general purpose and flexible machine which can produce up to 8 simultaneous spectra over 800 MHz bandwidth with 391 kHz resolution each or 16 simultaneous spectra over 12.5 MHz bandwidth with up to 48 Hz resolution each. Finally, baseband recording and data processing are accomplished by two different machines, both operating over 128 MHz of bandwidth: CGSR2 (based on the same technology of CPSR2 installed at Parkes, see later) and GASP.

As the first step towards a complete upgrade of the set of available receivers (see Sect. 3.2), two very modern systems have been implemented at the **Effelsberg radiotelescope**. The first is a receiver centred at the wavelength of 1.3 cm with movable horns allowing for very efficient beam switching. It operates at the primary focus. On the contrary in the secondary focus has been installed a receiver at the wavelength of 3.6 cm with 1200 MHz of bandwidth which has a system temperature pushed to the extremes of available tecnology, i.e. less than 25 K (the noise temperature of the receiver itself is 4 K only!).

What has made the **Parkes radiotelescope** unique in last decade is its multi-beam receiver with 13 horns and 300 MHz of bandwidth centred at 1390 MHz. More recently, the telescope has been equipped with a state-of-the-art coaxial receiver, operating simultaneously at the wavelenghts of 50 cm and of 10 cm, with bandwidths of 64 MHz and 1000 MHz, respectively. Baseband recording systems are operating at Parkes since a while, but until recently only with a very small available bandwidth. Two years ago a new machine, called CPSR2, has been installed allowing real-time baseband recording and data processing over 128 MHz of bandwidth. A wideband correlator has also been implemented operating on up to 1024 MHz of bandwidth and 1024 lags for full Stokes parameters.

3.2. Instruments under development or commissioning

At **GBT** a new receiver in the Ka-band has recently been added to the list of the ones available for public use. It is a dual beam, dual polarization, cryogenic receiver in the range 26 to 40 GHz. The front-end operates at the Gregorian focus, and uses cooled HFET amplifiers. With the installation of this receiver, all the frequencies from 290 MHz up to 52 GHz are covered at GBT except for very small gaps in the ranges 2.7-3.9 GHz, 6.0-8.0 GHz, 10.0-12.0 GHz and 15.5-18.0 GHz. With the advent (predicted for 2007?) of observations at frequencies higher than 50 GHz, further receivers which are now under development will be commissioned, notably a receiver in the 68-116 GHz band, whose first module (operating in the range 68-95 GHz) should be ready for observational tests in 2007. A bolometer (the Penn State Bolometer at 80-110 GHz) is also now undergoing engineering tests.

At **Effelsberg** a major refurbishing of the secondary mirror, also implying the installation of an active surface on it, is scheduled for autumn 2006. As far as receivers are concerned, two new multi-beam instruments are about to enter the commissioning phase. One is a seven-horn receiver at 21 cm which will be installed at the prime focus and the other is also a seven-horn receiver at 32 GHz. Notably, the seven-horn receiver at 21 cm is completely funded by ESA for studying space-debris, but 33% of the time will be left to general science. Following the lines of what has been implemented at GBT and planned at Parkes, a new fully digital back-end for both continuum and spectroscopy is also under development.

In fact the **Parkes radiotelescope** will be equipped by 2006 with a fully digital filterbank with a maximum bandwidth of 1024 MHz and a maximum of 2048 channels. Like the aforementioned SPIGOT card at GBT, it is fully programmable with the only limitation of a fixed data rate. Baseband recording will be also improved with a new machine, CPSR3, capable of sampling 512 MHz of bandwidth. Finally, a new multibeam receiver will be installed at the beginning of 2006: it is a seven-horn system operating at a centre frequency of 6.6 GHz with an instantaneous bandwidth of 600 MHz. The predicted system temperature will be about 40 K.

3.3. Scheduling

The **Green Bank telescope** is subjected to a strong observational pressure. Indeed, no very large-scale project (i.e. projects requiring more than 100-200 hrs) has been allocated time so far, probably with the aim of allowing the largest number of proposals to obtain observation time. On average, the percentage ratio between allocated and requested time has been at the level of 58% in 2004. A sizeable fraction of the projects requiring high frequencies remain usually incompleted during the originally scheduled term and has to be moved to next observing terms. This imposes the need of a dynamical scheduling.

The ratio between allocated and requested time at the **Effelsberg radiotelescope** seems less severe (unofficially estimated at about 80%). During the last five years fewer than 10 projects requiring 200-500 hrs (mostly surveys) have been allocated, whereas no project longer than 1000 hrs has been approved. Dynamical scheduling is applied for projects requiring high frequency. A rough estimate indicates that about 30% of the days are useful for observations at more than 10 GHz.

The **Parkes radiotelescope** seems to compensate the smaller collecting area with a longer duration of the running projects. In fact, at least 5 projects during last five years have run for more than 1000 hrs of telescope time and many projects have had 200-500 hrs. Combined with the availability of a sensitive 13-horn multi-beam receiver, this policy turned out to be extremely fruitful, allowing experiments of unprecedented scientific quality to be performed at Parkes. The percentage ratio between allocated and requested time is at the level of 50-60% (estimate).

4. Comparisons

A complete comparison of the capabilities of the three radiotelescopes presented in Sect. 2 with respect to those of the SRT would require a detailed analysis of the technical features of the instruments, of the characteristics of the telescope sites and of the given observing program. Such an analysis is presented for some specific scientific cases in the Report of the Working Group.

Hence, this section is focused on the zeroth-order approximation of any possible comparison between different radiotelescopes, i.e. the comparison of their nominal sensitivity for a given elevation (45° in this case) at different frequencies. The method for calculating the sensitivity is the most commonly used in radio astronomy and its implementation to the instruments under investigation is fully described in Cenacchi (2005). The technical pa-

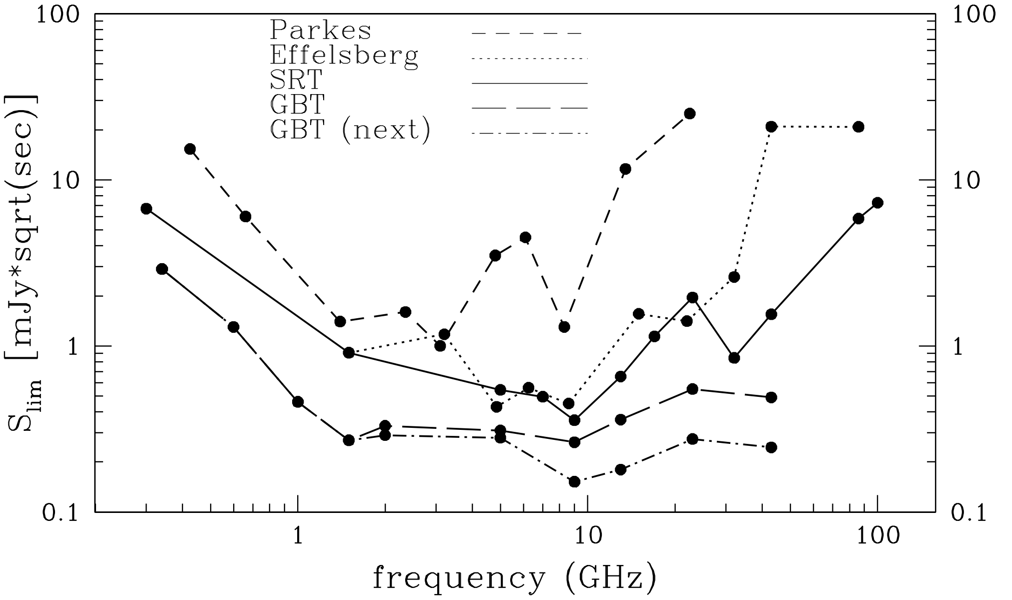

Fig. 1. Sensitivity curves at an elevation of 45° for the the Parkes telescope, the Effelsberg telescope, the Green Bank Telescope and SRT. See text for details about the calculated values. The lower curve is for the Green Bank Telescope when back-ends covering a 3.2 GHz of instantaneous bandwidth at medium and high frequencies will be available.

rameters of the telescopes and of the receivers are those reported on the official web-site of the instruments and are also summarized in a set of tables in Cenacchi (2005).

Figure 1 displays the nominal sensitivity (in units of mJy×sec$^{1/2}$, i.e. the sensitivity reached in 1 sec of observation) of the 4 studied single-dish telescopes at various frequencies. It has been calculated accounting for the maximum bandwidth which is now really used by the different back-ends installed at the GBT, Effelsberg and Parkes radiotelescopes (for the GBT we also plotted the sensitivity which may in principle be attained once back-ends covering 3.2 GHz of instantaneous bandwidth will be operating at medium and high frequencies). In order to calculate the curve for SRT the parameters of Table 3.1 of the Report have been adopted: i.e. it has been assumed that the receivers which will be installed will exploit the maximum instantaneous bandwidth allowed by the system.

Inspection of Fig. 1 shows that, if equipped with state-of-the-art receivers, the SRT may be very competitive. In particular:

- The SRT demonstrates a clear superiority (due to its very modern technology) in instantaneous sensitivity with respect to an older but still very valuable 64-m instrument such as the Parkes radiotelescope. This advantage would be maximally exploited if the SRT will be equipped with many multi-beam systems (beyond the already planned 7-horn receiver in the 18-26.5 GHz range), thus following the same successful policy adopted at Parkes.
- The SRT matches the instantaneous sensitivity of the second largest single-dish in the world (the Effelsberg radiotelescope) over the low and medium frequency range and (thanks to its active surface) can significantly overtake the performances of the 100-m German dish at frequencies higher than 30 GHz. Also the site conditions of the SRT (less airmass due to the higher al-

titude above sea level and less radio interference) help in allowing better science at high frequencies with respect to the largest European antenna. This will be particularly important in the framework of VLBI, which is so far completely lacking instruments of the 64-m class operating at very high frequency.

- The larger collecting area keeps the GBT clearly in advantage with respect to the instantaneous sensitivity of the SRT, but the gap may be partially compensated adopting a policy which favours longer integration times for observations at the SRT with respect to the GBT. Infact, the GBT is largely overscheduled and, as a consequence, the Time Allocation Commitee tends not to allocate time for very large timescale projects. This is the specific sector in which the SRT may be highly competitive also with respect to the US Telescope. Key-programs of long duration will probably not be run ever at the GBT, whereas they may produce high quality science exploiting the expected lighter proposal pressure of the SRT. This is one of the implications of the different sizes of the two (both state-of-the-art) instruments, which will be complementary in their performing different tasks at the frontier of radioastronomical observations.

5. Where SRT can do better?

An almost complete review of the projects which could maximize the scientific output of the SRT and rendering it competitive in the international context is contained in the Report. It can be also complemented with the inclusion of some further experiments proposed during the conference *"Science with the SRT"* and discussed in these Proceedings. Therefore we direct the reader once more to one of the two sources mentioned above for a detailed discussion of the various radioastronomical research where SRT can rival with (or do better than) the best radio antennas in the world.

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