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Future 3-mm receivers for the SRT

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Abstract. A fundamental design goal of the Sardinia Radio Telescope is efficient operation in the 3-mm wavelength band. In fact, a lot of design effort is currently being expended to ensure that the telescope will function well at this wavelength. Despite this effort, no receivers for the 3-mm band have yet been specified owing to the pressure of work on other aspects of the SRT project and to the development of receivers for lower-frequency bands. To address this need, I will briefly re-examine the scientific drivers for the SRT and will also review the capabilities of the SRT and other new-generation millimeter-wave telescopes in order to discuss which strategy will be needed to exploit the full potential of the SRT at 3 mm.

1. Introduction

A fundamental design goal of the Sardinia Radio Telescope is efficient operation in the 3-mm wavelength band, which is astronomically very important. In fact, a lot of design effort is currently being expended to ensure that the telescope will function well at this wavelength. The individual surface panels have been specified to have sufficiently small manufacturing errors, a system of actuators on each panel has been developed for adjusting its position on the primary reflector, and a system to control the active surface is being studied to form a real-time, closed loop with the actuators.

A 64-m diameter telescope operating with good efficiency in the 3-mm band will give a dramatic, new scientific capability to the Italian and European astronomical community. Although the SRT will have about 2.4 times less collecting area than the largest telescope operating in this band, the Green Bank Telescope (GBT), it will be competitive with the GBT in many scientific areas, as will be shown later. Furthermore, a better surface RMS could efficiently compensate the gap to the GBT in terms of geometrical area, if not in angular resolution. As will be described in the following section, the SRT can attack a rich variety of projects in the 3-mm band, particularly if we will be able to achieve an efficient use of the telescope. This implies that the large collecting area, and thus the great sensitivity to point-sources, should be fully exploited; furthermore, the use of focal plane arrays (FPA) should be considered and optimized.

Although much effort is being expended in making the antenna work at 3 mm, no receivers have been specified owing to the work load in other aspects of the SRT project, and to the development of receivers in lower frequency-bands. To address this need, I will briefly re-examine the scientific drivers for the SRT and will also review the capabilities of the SRT and other new-generation millimeter-wave telescopes in order to discuss what strategy will be needed to exploit the full potential of the SRT at 3 mm. This analysis will allow us to chart a long-term course for a first receiver in the 3-mm band or eventually for a family of instruments in this band.

2. Scientific drivers and other criteria

Continuum and spectral line observations should be considered equally important. Clearly, we cannot build a receiver, or a family of receivers, that would satisfy the demands of all the potential scientific users of the SRT. Spectral-line work requires a receiver optimized for broad bandwidth, low noise, good point source sensitivity, and possibly a $\sim$ 10 – 30 pixel FPA. For competitive continuum work on extended sources we would certainly need a bolometer camera, preferably something similar to that now being built for the GBT.

There are definitely some worries about the atmospheric transparency and sky noise and how they may affect the quality of the calibration and of the data. Though sky noise is not usually considered to be a problem for a heterodyne system in spectroscopic mode, suitable switching schemes must be planned for the continuum observation mode where cancellation of sky noise is fundamental. Another major concern is the pointing accuracy: with a FWHM of about $12''$, one needs a pointing accuracy of about $1''$ or better. Most of the science discussed below should be possible during winter (especially at night time) and in benign low-wind conditions, if we can achieve an RMS pointing of $\lesssim 2''$.

The SRT could certainly do unique science in almost every area of observational astronomy in the 3-mm band. Below we briefly summarize different areas, for both spectroscopy and continuum observations, where the SRT can make a contribution:

- Solar system (e.g., comets, asteroids, ...)
- Interstellar medium
- Low- and high-mass star forming regions (astrochemistry, infall, outflows, pre-stellar cores, ...)
- Nearby stars (giants, supergiants, AGB-stars, ...)
- Masers (OH, SiO, CH_3OH, H_2CO, ...)
- Extragalactic sources (galaxies, clusters, starbursts, mergers, ...)
- High-z objects

Clearly, some of these observations require a high point-source sensitivity, whereas others require mapping. *However, the big investements required to design and develop arrays of receivers can only be justified if the scientific goals of the SRT, as defined by the astronomical community, require mapping over a consistent fraction of telescope time.*

Aside from scientific drivers, the criteria that will lead to the selection and development of receivers for the 3-mm band should also take into account the following issues:

- final operational antenna parameters;
- site properties;
- availability of amplifiers for the 3-mm band;
- available funds for instrumentation;
- know-how and human resources in engineering;
- scientific and technical achievements during the next 5-10 years;

The last point is very important and though it is quite difficult to predict, it should not be ignored. In fact, while similar instruments and telescopes either being built or becoming fully operational shortly (e.g., GBT, LMT) have well-defined specs and scientific objectives, it is less obvious what the requirements for future telescope frontends will become during the next decade. In fact, the next generation of large single-dish telescopes with multibeam heterodyne receivers and bolometer cameras will certainly break new grounds in such areas as the survey and study of early galaxies. It would then definitely be less interesting for the SRT to plan and develop instruments that could only mimic earlier results rather than pursuing frontier science.

3. Focal plane arrays

As shown in Table 1 there are only three FPA being either tested or already in operation at 3 mm, one of which is currently the only bolometer camera operating in this wavelength band. Continuum observations will also be possible with other types of receivers (e.g., correlation type, dual-horn receivers) with a

Table 1. Current focal plane arrays at 3 mm

Antenna	Array type	Technology	N. of pixels	Operational status
NRO-45m	Heterodyne	SIS	5×5	functional
LMT-50m	Heterodyne	MMIC	2 modules 4×4	functional
GBT-100m	Heterodyne	MMIC	~ 30	planned
GBT-100m	Bolometer	TES	8×8	testing

Table 2. Point-source continuum sensitivity. NEFD is the Noise Equivalent Flux Density (for a review of this and other bolometer-related parameters see, e.g., Richards 1994). For the sake of comparison, bolometers are assumed to have the same properties (bandwidth, optical efficiency, etc.) on all telescopes, and thus the NEFD depends on the telescope and site characteristics only (besides on the wavelength of operation). The last column represents the SNR that would be achieved in a five minutes ON-source integration.

Antenna	Altitude [m]	λ [mm]	Surface RMS [μm]	NEFD [mJy $\sqrt{s}$]	SNR
JCMT-15m	4000	0.85	25	116	3.6
IRAM-30m	2700	1.2	80	37	3.9
LMT-50m	4600	1.2	75	13	10.2
SRT-64m	700	3	220	2.6	1.7
GBT-100m	800	3	300	2.2	2.0

point-source sensitivity comparable to that of bolometers. However, they would have to concentrate on compact sources since mapping extended sources would be very inefficient.

Given the properties of the telescopes and associated instruments in Table 1, quite naturally one would like to ask the question whether a 3-mm FPA operating on the SRT would be competitive. The answer depends on the telescope/frontend system and on the site characteristics. Here, I will consider two main criteria to compare different telescopes: first, I will evaluate the signal-to-noise ratio (SNR) expected for point source observations, which depends mainly on the effective area of the telescope, and then I will consider the mapping speed, which strongly depends on the telescope field-of-view (FOV).

To estimate the point-source sensitivity in the continuum I used a dusty source, with a 1″ diameter (pointlike for all telescopes considered here), a spectral index of 2 and a dust temperature of 15 K. Telescope, site and bolometer characteristics were all taken into account to calculate the SNR that would be achieved in a five minutes ON-source integration time. The results are shown in Table 2, and it is interesting to note that the GBT and SRT sensitivities are quite similar. Since for these two telescopes I used the same bolometer and site parameters, this result is mainly dependent on the primary surface RMS, and shows that with a surface RMS $\lesssim$ 200 μm the SRT continuum sensitivity would be competitive with (or even better than) that of the larger GBT.

For extended sources with respect to the beam, the appropriate parameter for a comparison between different telescope/frontend sys-

Table 3. Mapping speed for bolometer arrays in the 3-mm band (see text).

Antenna	Array	Δt_{lim} [s]	Mapping speed [arcmin^{2}s^{-1}]
SRT-64m	5×5	6.7	0.16
GBT-100m	8×8	4.8	0.16
GBT-100m	1000	4.8	2.5

Table 4. Mapping speed for heterodyne arrays in the 3-mm band. The last column shows the time required to map a $10' \times 10'$ region at a 0.1 K sensitivity level, using a 0.25 MHz resolution bandwidth and position switching. Receiver parameters are the same for all cases considered.

Antenna	Altitude [m]	Array	T_{sys} [K]	Mapping time [hr]
LMT-50m	4600	2 modules 4×4	160	0.8
SRT-64m	700	3×3	245	11.3
SRT-64m	700	4×4	245	6.4
SRT-64m	700	5×5	245	4.1
SRT-64m	700	6×6	190	1.7
GBT-100m	800	2 modules 4×4	245	7.8

tems is the mapping speed. This can be calculated as

$$\dot{\Omega}_{map} = \Omega_{inst}/\Delta t_{lim} \quad (1)$$

where Ω_{inst} is the instantaneous sky coverage of the whole bolometer array and Δt_{lim} represents the time required for $1\,\sigma$ detection of a given limiting flux density, e.g. $S_{lim} = 1$mJy, in one individual pixel of the array.

The *maximum* instantaneous sky coverage is determined by the acceptable FOV of the telescope optics. In the case of the SRT, the *shaped* primary and secondary surfaces determine a FOV which is much smaller than what would be obtained with a classical Gregorian configuration. In fact, the angular diameter of the FOV corresponding to a standard 95% of the peak gain on-axis is $2\rlap{.}'0$, or about 10 beams (the FOV would become about $2\rlap{.}'8$ or 15 beams at 90% of the peak gain). This figure must be compared with the FOV of a classical Gregorian with the same focal ratio and aperture of the SRT, which would be about $12\rlap{.}'3$, or 64 beams, at 95% of the peak gain. This corresponds to an area on the sky which is almost 40 times larger than that of the shaped SRT. However, the limiting size of the FOV is truly important only if the *whole* FOV is filled with receivers.

This is illustrated in Table 3 where both Δt_{lim} and $\dot{\Omega}_{map}$ are shown. We note that incidentally the GBT and SRT turn out to have the same mapping speed with these specific parameters. However, bolometer arrays can now be designed and built to have 100s or even 1000s of pixels (e.g., using TES technology). Thus, if we fill the GBT focal plane with bolometers, e.g. with 1000 pixels, the mapping speed becomes more than an order of magnitude bigger than $\dot{\Omega}_{map}$ estimated for the 8×8 TES array currently under testing. However, in the SRT this operation cannot be performed because, as earlier mentioned, its FOV is much more limited due to the use of shaped surfaces.

Next, we consider the mapping speed for heterodyne focal plane arrays on the three new-generation large single-dish telescopes, the LMT, SRT and GBT (see Olmi 2003 for a review). The mapping speed has been evaluated by calculating the time required to map at a given sensitivity level a $10' \times 10'$ region of the sky. A larger telescope with a smaller beam FWHM will intrinsically take a longer time to map a given area of the sky, all other array and site parameters being equal, though with a better angular resolution. This result is clearly shown in Table 4, where the LMT takes less than an hour to map a $10' \times 10'$ region as a combination of (mainly) better site characteristics, a larger beam and many pixels. Once again, however, it is interesting to compare the performance of the GBT and SRT. I have thus considered several array sizes for the SRT, and Table 4 shows that a 4×4 pixel array would already be competitive compared to a twice as large array on the GBT. In the extreme case of a large 6×6 pixel array and during very dry weather conditions, the SRT might also become competitive with the LMT (which will observe in the 3-mm band mainly during "standard" weather conditions).

4. Conclusions

The 3-mm wavelength band is astronomically very important and also represents a fundamental design goal of the SRT. Since we cannot build a family of receivers that would satisfy the demands of all future scientific users of the SRT, a set of criteria must be devised to select 3-mm instrumentation for both continuum and spectral line work. The SRT has a continuum sensitivity to point-sources which is almost the same as that of the GBT: to ensure that the SRT will be competitive with the GBT it is fundamental to achieve the highest possible surface accuracy, and it will also be important to characterize the site. The FOV of the SRT is much more limited compared to classical Cassegrain and Gregorian configurations. However, while this may be a limitation to the development of large-format bolometer arrays that would fill the whole focal plane, it is *not* a limitation to the development of much smaller heterodyne arrays, which are likely to be limited to a few tens of pixels even in the near future.

References

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