The Parkes 21-cm Multibeam Receiver

L. Staveley-Smith[1], W. E. Wilson[1], T. S. Bird[2], M. J. Disney[3], R. D. Ekers[1], K. C. Freeman[4], R. F. Haynes[1], M. W. Sinclair[1], R. A. Vaile[5], R. L. Webster[6] and A. E. Wright[1]

[1] Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121.

[2] Division of Radiophysics, CSIRO, PO Box 76, Epping, NSW 2121.

[3] Department of Physics and Astronomy, University of Wales College of Cardiff, PO Box 913, Cardiff CF2 3YB, U.K.

[4] Mount Stromlo and Siding Spring Observatories, Weston Creek PO, Canberra, ACT 2611.

[5] University of Western Sydney, Macarthur, PO Box 555, Campbelltown, NSW 2560.

[6] School of Physics, University of Melbourne, Parkville, Victoria 3052

Abstract

Several extragalactic H I surveys using a λ21-cm 13-beam focal plane array will begin in late 1996 using the Parkes 64-m telescope. These surveys are designed to detect efficiently nearby galaxies that have failed to be identified optically because of low optical surface brightness or high optical extinction. We discuss scientific and technical aspects of the multibeam receiver including astronomical objectives, feed, receiver and correlator design and data acquisition. A comparison with other telescopes shows that the Parkes multibeam receiver has significant speed advantages for any large-area λ21-cm galaxy survey in the velocity range range 0–14000 km s^{-1}.

Keywords: instrumentation: miscellaneous – telescopes – surveys – galaxies: distances and redshifts – galaxies: luminosity function, mass function – radio lines: galaxies

1 Introduction

A focal plane array is essential for mapping large areas of sky efficiently. For radio spectroscopy, however, such systems are in their infancy. Goldsmith (1995) describes four arrays which are in operation plus nine which are being being developed for astronomical spectroscopy. Most of these are designed to operate in the millimetre regime, where telescope beam sizes are typically small ($0'.2 \sim 1'$) and large numbers of pointings may be required to map sources. However, a similar situation arises at lower frequencies where large areas of sky are to be mapped. This paper describes a new λ21-cm focal plane array, or multibeam receiver, for use on the Parkes 64-m telescope. The λ21-cm multibeam receiver consists of 13 independent beams, each detecting orthogonal linear polarisations, arranged in a hexagonal grid. Each beam has a FWHP angular resolution of $14.'4$. The instantanous bandwidth, defined by the correlator, is 64 MHz, and the frequency resolution is 62.5 kHz (13 km s^{-1}). An earlier version of this system, with a smaller number of beams, is described by Staveley-Smith et al. (1995).

The primary aim is to make deep, large-area surveys for neutral hydrogen emission from external galaxies. The key scientific objectives are to undertake:

- a deep H I survey for optically obscured galaxies in the Zone of Avoidance covering the latitude range $|b| \leq 5°$ and the longitude range $\ell = 213°$ to $33°$. The southern Galactic Plane obscures a part of the sky that is vital for a complete understanding of the distribution and dynamics of nearby galaxies. The Galaxy obscures the southern crossing of the Local Supercluster and its probable connection with the Fornax-Dorado complex. It also obscures the connection between the Hydra-Centaurus supercluster and the Pavo-Indus-Telescopium supercluster (Lahav 1994). The latter two superclusters appear to dominate the dynamics of galaxies within $70h^{-1}$ Mpc,[1] and appear to be responsible for a large part of velocity of the Local Group of galaxies with respect to the Cosmic Microwave Background radiation. However, there are large unexplained discrepancies between the observed motions of galaxies, and motions predicted on the basis of the observed galaxy distribution and linear gravity theory. This discrepancy may be caused by optical selection effects in the vicinity of the Galactic Plane, or the presence of a large obscured supercluster. On a smaller scale ($\sim 4h^{-1}$ Mpc), the discovery of any large nearby galaxies such as Dwingeloo-1 (Kraan-Korteweg et al. 1994) would also have an effect on timing arguments on which estimates of the mass of the Local Group and the present density of the universe are based (e.g. Peebles 1994).
- an extragalactic H I survey of the entire southern sky. Such a survey will be sensitive to a volume of $6 \times 10^6 h^{-3}$ Mpc^3 and will contain valuable information on the distribution of galaxies, the power spectrum, the H I mass function, the dynamics of groups and superclusters, the frequency of dwarf galaxies, the space density of giant low-surface-brightness

[1] h is the Hubble Constant in units of 100 km s^{-1} Mpc^{-1}, $h = H_\circ/(100$ km s^{-1} Mpc$^{-1})$.

galaxies, and information relevant to the density parameter $\Omega_\circ$. This wavelength regime is probably one of the least 'biased' in terms of tracing large-scale structure and will increase the size of existing H I-selected samples (Szomoru et al. 1994; Henning 1995) by two orders of magnitude. Such a survey will be sensitive to low-surface-brightness objects absent from existing catalogues because of optical selection effects (McGaugh 1994; Disney & Phillipps 1983) and will include giant Malin-1-type galaxies (Bothun et al. 1987). The frequency of such objects is presently subject to some uncertainty (see Rao & Briggs 1993 and Schneider 1996).

For an integration time of 600 s, the $5-\sigma$ detection limit will be $\sim$ 20 mJy per 13 km s^{-1} (62.5 kHz) channel which, for a spatially unresolved galaxy with a velocity width of 200 km s^{-1} , corresponds to an H I mass limit of $\sim 10^6 d^2$ M$_\odot$, where d is the distance in Mpc.

The multibeam project involves a feed system designed to ensure minimal beam cross-coupling, relatively large-scale cryogenic engineering and amplifier construction and relies on the availability in Australia of sufficient correlator capacity to handle the 26 (13 beams $\times$ 2 polarisations) wide-band signal channels. These features, combined with the relatively wide field of view afforded by the prime focus on the Parkes telescope means that the proposed large-area survey cannot easily be undertaken by other telescopes, including the upgraded Arecibo telescope and the new Green Bank telescope (GBT). Interferometers such as the Australia Telescope Compact Array (ATCA) and the Very Large Array (VLA) do not approach the required surface brightness sensitivity. The VLA and the Giant Metre Wave Radio Telescope (GMRT) in *incoherent* mode are more comparable but, as discussed later, still do not match the sensitivity of the Parkes multibeam system for an extragalactic λ21-cm survey.

2 The Feed Array

The feed is an array of 13 circular horns as shown in Figure 1. Circular horns were chosen in preference to square horns because of their excellent pattern symmetry, lower spillover and improved cross-polar performance (Bird 1994). Efficient illumination of the Parkes 64-m telescope calls for a feed horn of approximately one wavelength diameter. Dielectric loading of the horns would allow for a smaller diameter, and hence a closer spacing in the array, but this approach was rejected because of the attendant feed losses. A horn spacing of 1.2λ was chosen, giving a

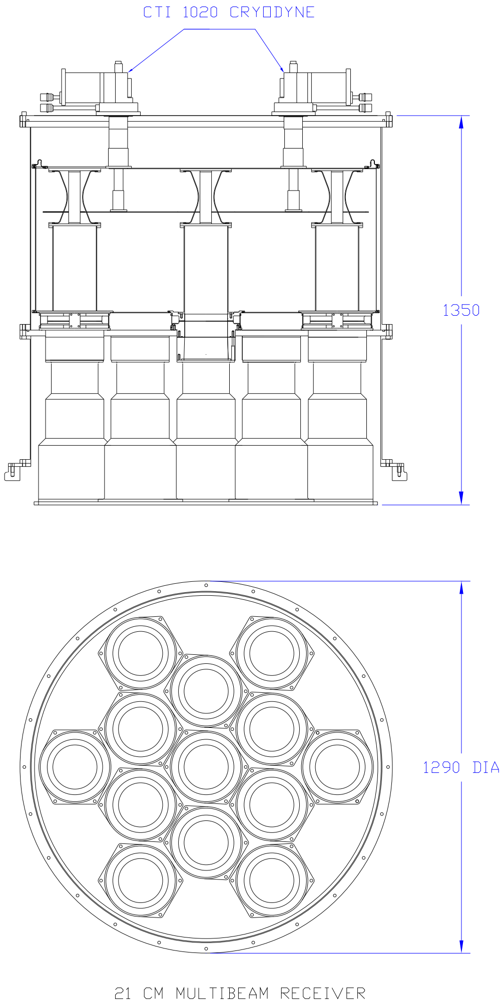

Figure 1: A diagrammatic view of the feed array and dewar

beam spacing of approximately two FWHP beamwidths. Therefore, in point-and-shoot mode, a contiguous survey region requires an interleave factor of two (per angular coordinate) for uniform sensitivity, and more to map continuous structure at the Nyquist rate.

The feed-horn array was designed using mode-matching software for circular stepped horns. This software (Bird 1979, 1991) includes the effects of mutual coupling between the horns. The final design uses a two-step horn configuration, with an aperture diameter of 0.240 m and ending in a 0.153-m-diameter circular waveguide. This design is optimised to reduce the effects on the cross-polar performance of unwanted modes caused by coupling between horns. Measurements with the fabricated horns confirm the original design predictions. The reflection coefficient of a horn in the array is -30 dB mid-band, increasing to -20 dB at ± 100 MHz (1.27 and 1.47 GHz). The insertion loss at mid-band is negligible, and is ~ 0.06 dB at ± 100 MHz. The peak cross-polar

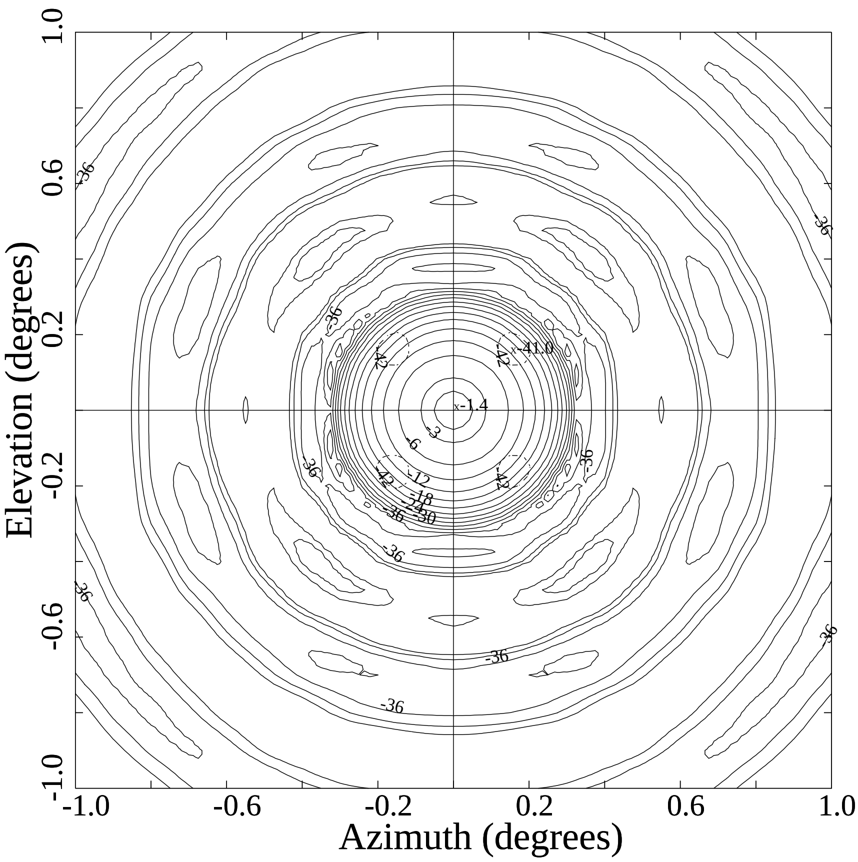

Figure 2: Beam pattern for the central feed of the array. Contours are every 3 dB. The peak value is -1.59 dB relative to a uniformly illuminated aperture, corresponding to an efficiency of 69.3%. Cross-polar lobes, which are shown dotted, peak at -39.6 dB relative to peak co-polar.

illumination is less than -25 dB at the centre frequency, degrading to -22 dB at the lower band edge.

The array-feed software was combined with CSIRO's reflector analysis software to compute the radiation pattern of the overall antenna. This is shown in Figure 2 for the central beam and Figure 3 for one of the beams most displaced from the axial focus. For a 5-m blockage, the efficiency of the central beam is 69.3% relative to an ideal, uniformly illuminated aperture and neglecting reflector surface errors. This decreases at the band edges (68% at 1.27 GHz, 66% at 1.47 GHz). The mid-band efficiency of the most extreme beam is 59.8%. The FWHP beamwidth for all beams is about $14'.4$. The coma sidelobe for the extreme beam is 14 dB below the peak value. The spillover efficiency is approximately 96% for all beams, and rises slightly with frequency because of the narrowing of the feed horn pattern. Cross-coupling between beams due to the reflector

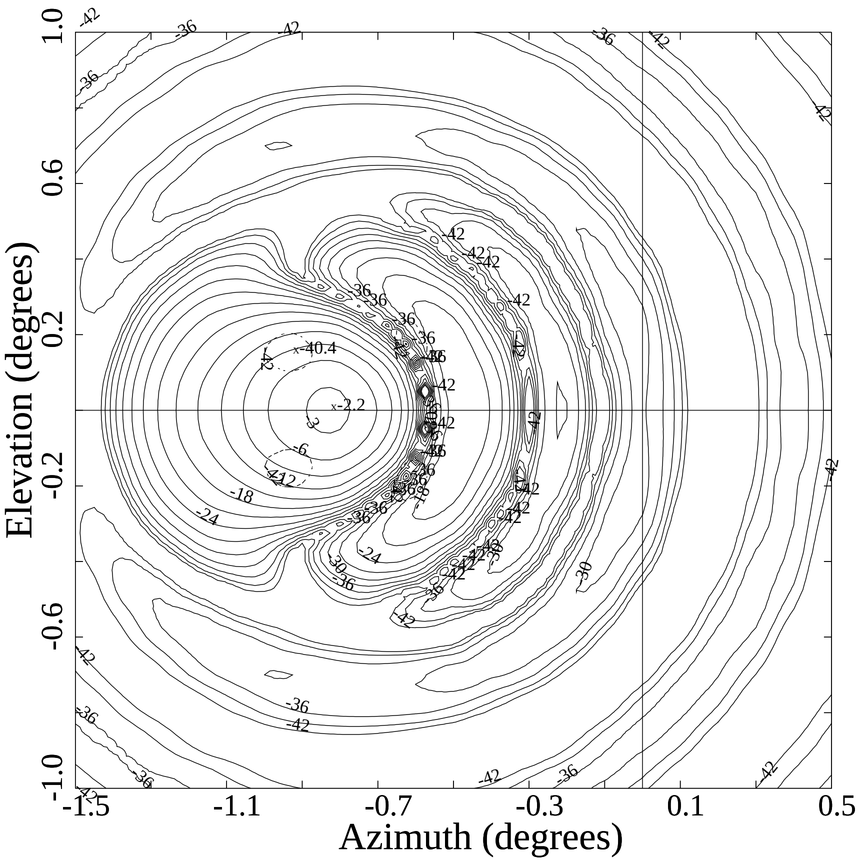

Figure 3: Beam pattern for one of the circumferential feeds (beam 9) in the array. Contours are every 3 dB. The peak value is -2.23 dB relative to a uniformly illuminated aperture, corresponding to an efficiency of 59.8%. Cross-polar lobes, which are shown dotted, peak at -38.2 dB relative to peak co-polar.

diffraction limit and feed mutual coupling is always less than -21 dB, and typically less than -35 dB, while cross-polar isolation is greater than 40 dB.

3 The Receiver

The primary aim of the receiver design is to achieve as low a system noise temperature as possible. To this end simple total-power receivers are being used. Much of the front-end system, including the first-stage amplifiers, is to be cooled by two closed-cycle cryogenic refrigerators. The size of the feed array, and its mass, precludes its inclusion in the cryogenic dewar, but the orthomode transducers, which provide coaxial outputs from the input circular waveguide at two orthogonal linear polarisations, will be cooled to $\sim$ 70 K. Hence the dewar will have 13 circular waveguide windows matching the layout of the feed array. The 26 coaxial outputs of the orthomode transducers will connect to low-noise HEMT amplifiers cooled to $\sim$ 20 K. The dewar diameter is 1.2 m, with a total cooled mass of $\sim$ 25 kg at the 20-K station and a cool-down time of $\sim$ 24 h.

The HEMT amplifiers, built at Jodrell Bank, will have a nominal gain of 40 dB. The noise temperature at the input to the amplifiers is expected to be $\sim$ 3 K at mid-band and $\sim$ 10 K at the circular waveguide input to the dewar. The overall system temperature, including spillover, is expected to be $\sim$ 25 K. A -35 dB directional coupler will be mounted on each of the circular waveguides just before entering the dewar. Positioned at 45° to both outputs of the orthomode transducer, it will provide a means of injecting a low-level switched calibration signal equally into both polarisations.

The outputs of the low-noise amplifiers will be fed out of the dewar into 26 identical conversion systems where they will be further amplified, filtered and then mixed to an intermediate frequency covering the frequency range 50 to 350 MHz. These signals will be fed from the focus cabin to the control room via 26 low-loss coaxial cables. After passing through equalisation filters, which serve to compensate for the frequency-dependent loss in the cable, the signals will enter the final, accurate, band-determining filters which will limit the bandwidth to 64 MHz. This defines the instantaneously accessible velocity range of 14000 km s^{-1}.

4 The Digitisers and Correlator

The digitiser units provide 2-bit, 4-level digital data at a sample rate of 128×10^6 samples s^{-1} from an input signal covering the frequency range 128 to 192 MHz. They include automatic control of the sampler decision levels aimed at reducing any zero-level offset and maintaining the magnitude levels at the point which gives optimum signal-to-noise ratio. They also include total-power detectors and synchronous demodulators which are used in conjunction with the switched noise source injected in the input waveguides to measure the system temperature.

The correlator uses the NASA SERC High Performance Correlator chip (Canaris 1993). This chip is a 1024-lag, 3-level correlator. The data are converted from four levels to three at the correlator input. The correlator board contains two of these chips and is capable of forming two 1024-lag auto-correlations or one 1024-lag cross-correlation. Thirteen of these boards will be required to form a 1024-channel auto-correlation spectrum for each of the 26 sampled data streams. The resultant channel spacing corresponds to 13 km s^{-1}.

5 Data Analysis

With 5-s integration cycles, the data rate from the correlator is reduced to $\sim$ 20 kB s^{-1}. This remains a substantial data rate and excludes the possibility of inspecting individual spectra. We will automate a substantial part of the data reduction using an on-line aips++ object-oriented approach. Interference will be a major problem confronting this survey. The GPS L3 beacon at 1385 MHz has been particularly prominent during recent observations at Parkes. The main form of interference suppression will be to make use of the substantial redundancy in the data in time and position. Instead of assuming that the signal is characterised by a normal distribution of residuals, we will use non-parametric statistics (medians instead of means and least median-of-squares instead of least squares) in order to estimate the form of the sky spectrum at each position, and to form data cubes. We hope to investigate cross-correlation techniques in a further bid to suppress interference, by using the fact that man-made interference is usually highly polarized. The on-line data-reduction system will also include facilities such as "on-the-fly" mapping. The reductions will be carried out using a DEC Alphaserver 1000 running Unix.

6 Comparison with Other Facilities

A comparison with other telescopes is illuminating. We can show that, to achieve a given sensitivity above the confusion limit, the time taken to survey a region of sky fully for point sources is $\tau \propto (N_b A_t N_a \Delta\nu)^{-1}$, where N_b is the number of independent beams in the focal plane, A_t is the total telescope (or array) area, N_a is the number of antennas, and $\Delta\nu$ is the available spectral bandwidth (assumed to be 64 MHz except for the VLA and GMRT which have correlator and hardware limitations). This applies as long as other factors such as system temperature and aperture illumination are constant, and applies equally to a single dish or a coherent interferometer array ($N_a \gg 1$) which has the ability to image its entire primary beam. For a large-scale survey of point sources, Figure 4 shows that the Parkes multibeam system is faster than the VLA (the

VLA correlator has a bandwidth which is about a factor of 10 smaller in dual-channel spectral-line mode), and only slightly slower than the compact GMRT. However, the GMRT, like other interferometers, has poor surface brightness sensitivity, and rapidly becomes inferior to Parkes for sources more extended than $17''$, such as nearby galaxies. For the present scientific purpose, the Parkes multibeam system is therefore superior to any existing interferometer array. For single dishes, we find that a single beam on the upgraded Arecibo telescope (an illuminated area of 237×213 m^2 is assumed) is slower than the Parkes multibeam system for sources of any size. An interesting Northern Hemisphere equivalent to the multibeam system is the VLA in incoherent mode (equivalent to a 27-beam system on a 25-m telescope). This would be only a factor of ~ 3 slower (i.e. $\sqrt{3}$ less sensitive) than the Parkes system for sources $< 12'$ in diameter, assuming that a bandwidth close to the Parkes 64-MHz system can be achieved with a useful resolution. Similarly, the GMRT in incoherent mode will be a reasonably sensitive survey instrument, though it may suffer from low λ21-cm telescope efficiency. However, the most useful northern equivalent is likely to be the Lovell telescope, for which a more limited four-beam array is planned.

7 Documentation

Documentation on the Parkes multibeam receiver, including more details on scientific goals, observing and data-reduction techniques can be found on the World Wide Web. The address (as of July 1996) is http://www.atnf.csiro.au/Research/multibeam/multibeam.html.

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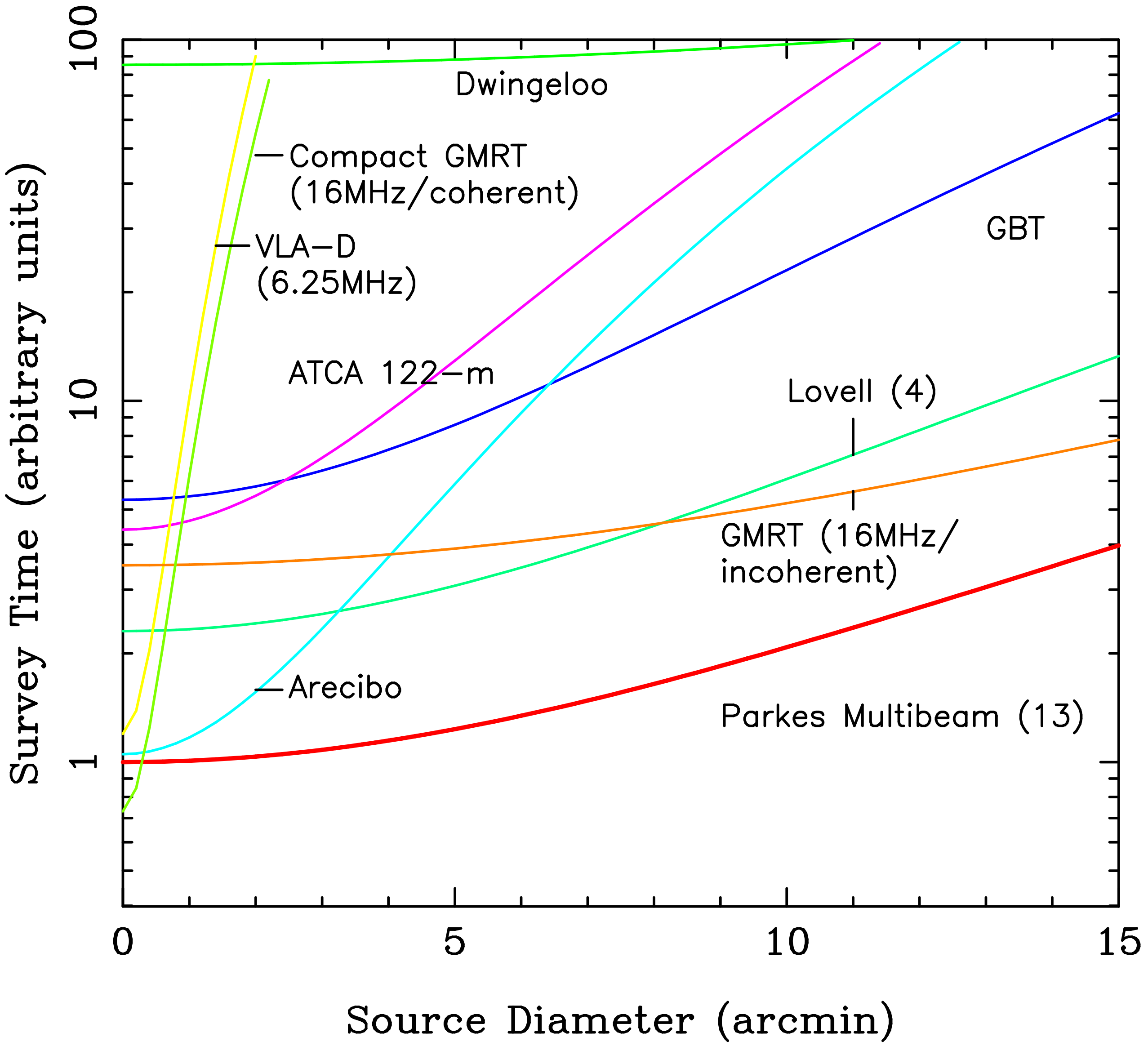

Figure 4: Comparison of the time taken for various telescopes to fully survey a region of sky to a given sensitivity, as a function of source size (FWHP Gaussian). Identical system temperatures are assumed for all telescopes. Identical 64 MHz bandwidth capability is assumed for all telescopes, except for the VLA and the GMRT which are limited by their hardware to 6.25 MHz and 16 MHz respectively, for such a survey.