To appear in proceedings of *Workshop on Multi-feed Systems for Radio Telescopes*, Tucson, Arizona May 16-18, 1994 (ASP conference series).

THE PARKES 21CM MULTIBEAM RECEIVER

L. STAVELEY-SMITH, W.E. WILSON, T.S. BIRD[1], M.W. SINCLAIR AND R.D. EKERS
Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 2121, Australia

R.L. WEBSTER
School of Physics, University of Melbourne, Victoria 3052, Australia

ABSTRACT An extensive extragalactic HI survey using a λ21-cm 3×3 focal plane array will begin in 1996 on the Parkes 64-m telescope. This survey is designed to detect large numbers of galaxies that have failed to be identified optically because of low surface brightness or high optical extinction. We discuss scientific and technical aspects of the system including astronomical objectives, feed design, receiver design, data acquisition and the correlator design required to handle the large data rate (2.3×10^9 samples s^{-1}). A comparison with other telescopes shows that the Parkes multibeam receiver will have significant speed advantages for a large-area λ21-cm galaxy survey in the velocity range range 0–14000 km s^{-1}.

SCIENTIFIC RATIONALE

The primary motivation for a λ21-cm multibeam receiver[2] on the Parkes 64-m telescope is to undertake deep, large-area surveys for neutral hydrogen emission from external galaxies. The system has nine feeds, each detecting orthogonal linear polarizations, arranged in a 3×3 element grid. The key scientific objectives are:

1. a survey for optically obscured galaxies behind the southern Galactic Plane. This region is vital for the study of large-scale structure and deviations from the Hubble flow due to the location of the Hydra-Centaurus-Pavo (Lynden-Bell et al. 1988) and Shapley (Scaramella et al. 1989; Allen et al. 1990) superclusters. Such a study will give us an unbiased view of the local distribution of matter and a better estimator of the peculiar acceleration field. Optical and infrared studies are limited by obscuration and selection problems at low Galactic latitudes.

2. a Southern Hemisphere HI survey for galaxies which have been missed

[1] CSIRO Division of Radiophysics.

[2] The Parkes multibeam receiver is a collaborative venture between the CSIRO Australia Telescope National Facility (ATNF), the University of Melbourne, Mount Stromlo and Siding Spring Observatories and the University of Western Sydney.

in previous surveys due to optical selection effects (Disney & Phillips 1983). These include faint dwarf galaxies and low surface brightness ('failed') Malin-1 type galaxies. This survey will give us a view of the Universe unbiased by the energy emitted from stars. For example, the detecting of large numbers of high mass, low surface brightness galaxies ('crouching giants') would have important implications for galaxy formation theories (e.g. Hoffman et al. 1992). Because of the small field size of large single-beam radio telescopes, only $\sim 1\%$ of the λ21-cm sky has been observed to a modest redshift depth of $z \sim 0.01$ (see Briggs 1990 for a review). Most λ21-cm observations have been aimed at 'bright' optically identified galaxies. The few serendipitous discoveries (e.g. the Leo Ring, Schneider 1989; Malin-1, Bothun et al. 1987; and the Virgo 'protogalaxy', Giovanelli & Haynes 1989) have proved to be highly interesting objects.

3. a deep HI survey aimed at high-latitude fields and nearby southern groups. This will enable us to extend the mass function of galaxies beyond the optically accessible range. It will provide insight into fundamental processes of galaxy formation, giving clues to the mechanisms responsible for triggering and inhibiting global star formation. Through the large numbers of HI-rich dwarf galaxies expected (Staveley-Smith et al. 1992), we will be able to study the dynamics of small groups of galaxies and infer mass-to-luminosity ratios and dark matter content over an important range of scale size.

In addition, there are many projects, such as fully sampled high-resolution HI surveys of the southern Galactic Plane, the Magellanic Clouds and Stream, and a sensitive Galactic Plane pulsar survey which are feasible with a multibeam system.

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 power to handle the 18 (9 beams $\times$ 2 polarizations) wideband 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 VLA do not approach the required surface brightness sensitivity. The VLA and GMRT in *incoherent* mode are closer but, as discussed later, still do not match the sensitivity of the Parkes multibeam system for an extragalactic λ21-cm survey.

THE FEED ARRAY

The proposed feed is a 3×3 square array of circular horns as shown in Figure I. 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 losses. A horn spacing of 1.2λ was chosen, giving a beam spacing of approximately two FWHP

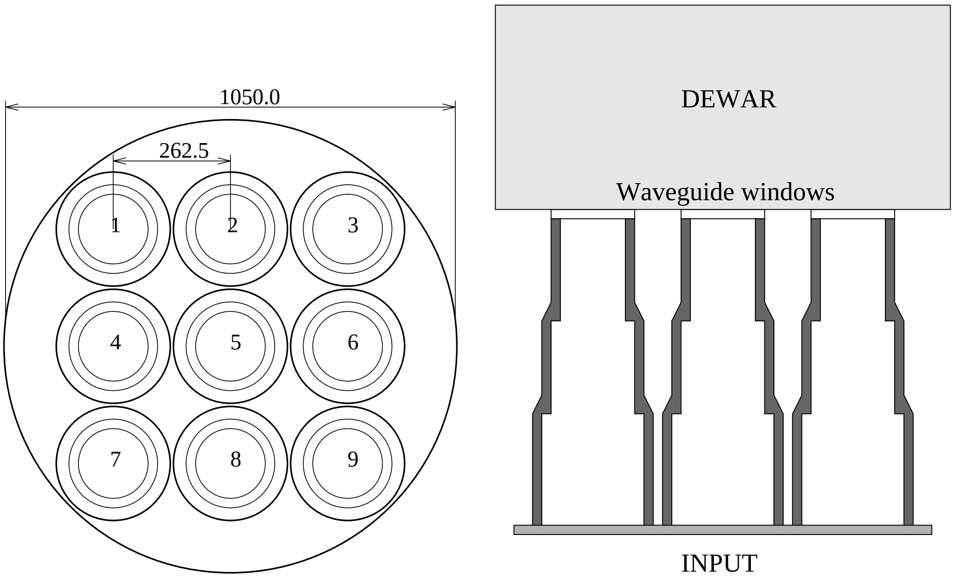

FIGURE I   A view of the feed array (left) and a cross-section (right) of the Parkes 3×3 λ21-cm multibeam system. Dimensions are in mm.

beamwidths. Therefore, a contiguous survey region requires an interleave factor of two (per angular coordinate) for uniform sensitivity, and a factor of about five 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 the two-step horn configuration shown in Figure I, with an aperture diameter of 0.240 m and ending in an 0.153 m diameter circular waveguide. This design is optimized to reduce the effects on the cross-polar performance of unwanted modes caused by coupling between horns. The calculated reflection coefficient of the horn is -36 dB mid-band, increasing to -20 dB at ± 100 MHz (1.27 and 1.47 GHz). The insertion loss of the horn at mid-band is negligible, and is ~ 0.06 dB at ± 100 MHz. The cross-polar illumination is less than -36 dB at the centre frequency, degrading to -27 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 II for the central and corner beams. For a 5-m blockage, the efficiency of the central beam is 70.9% relative to an ideal, uniformly illuminated aperture and neglecting reflector surface errors. This decreases at the band edges (69% at 1.27 GHz, 67% at 1.47 GHz). The mid-band efficiency of the corner beam is 62.6%. The FWHP beamwidth for all beams is about $14'.4$. The coma sidelobe for the corner beam is 16 dB below the peak value. Spillover efficiency is approximately 96% for all beams, and rises slightly with frequency due to the narrowing of the feed horn pattern. Cross-coupling between beams due to the reflector diffraction limit and feed mutual coupling is always less than -25 dB, and typically -40 dB.

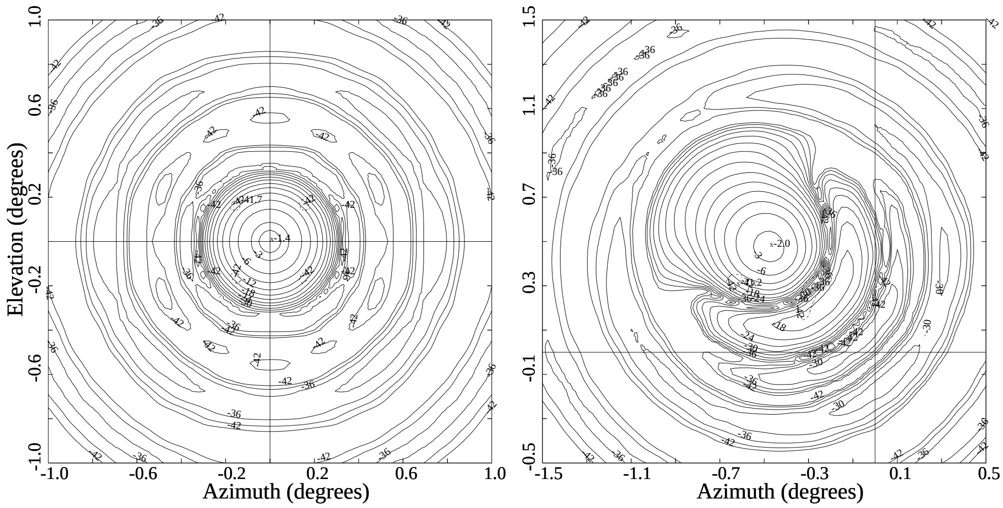

FIGURE II Beam pattern of the central beam (left) and corner beam (right). Contours are every 3dB. The peak values are -1.49 dB and -2.03 dB for the two beams, respectively (this represents the gain relative to an ideal, uniformly illuminated aperture).

THE RECEIVER

The primary design aim of the receiver is to achieve as low a system temperature as possible. To this end simple total-power receivers will be used. Much of the front-end system, including the first-stage amplifiers, will be cooled by a closed-cycle cryogenic refrigerator. The size of the feed array, and its mass, precludes its inclusion in the refrigerator dewar, but the orthomode tranducers, which provide coaxial outputs from the input circular waveguide at two orthogonal linear polarizations, will be cooled to 70 K. Hence the dewar will have nine circular waveguide windows matching the layout of the feed array. The 18 coaxial outputs of the orthomode tranducers will connect to low-noise HEMT amplifiers cooled to approximately 20 K. This defines a dewar diameter of 1.1 m, with a total cooled mass of aproximately 8 kg at the 20 K station, and 13 kg at the 70 K station.

The HEMT amplifiers will have a gain of 40 dB. The noise temperature at the input to the amplifiers is expected to be approximately 3 K, mid-band and at the circular waveguide input to the dewar, $\sim$ 10 K. The overall system temperature, including spillover, is expected to be 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 into both polarizations.

As shown in Figure III the outputs of the low-noise amplifiers will be fed out of the dewar into 18 identical conversion systems where they will be further amplified, filtered and then mixed to an intermediate frequency, where the final accurate band determining filters will limit the band to 64 MHz, which defines

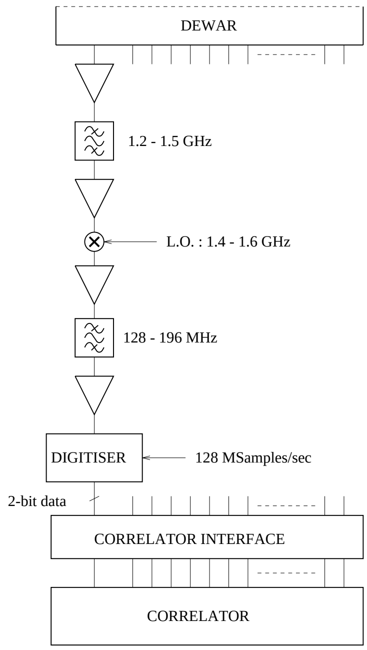

FIGURE III   Block diagram of the IF system.

the instantaneously accessible velocity range of 14000 km s^{-1}.

THE INTERMEDIATE FREQUENCY (IF) SYSTEM

There are two options under investigation for the IF system. The first is the traditional approach, where the IFs are fed via 18 low-loss coaxial cables from the focus cabin to the correlator room, where they are digitized and passed on to the correlator. The other option is to digitize the IFs in the focus cabin and feed the digital data via fibre-optic cables to the correlator room.

The advantage of the coaxial cable option is its simplicity. The disadvantages are the bulk of the cable itself, and the variations in the overall system bandpass caused by changes in reflections along the cables as they are twisted during the telescope motion, or because of temperature effects. The fibre-optic cable option places the samplers close to the receivers and so should eliminate the variations in bandpass. This is the approach used for the Australia Telescope Compact Array and the Mopra telescope. However, there is a significant danger of interference entering the receivers from the high-frequency digital signals in the sampler and fibre-optic transmitter systems. Relative cost is also an important factor, but initial investigations show that the costs are similar for the two options. It is more likely that the final decision will be made based on performance tests.

The digitizers will provide 2-bit, 4-level, digital data at a sample rate of 128×10^6 samples s^{-1} on an input signal covering the frequency range 128 to

196 MHz. They will include automatic control of the sampler levels aimed at reducing any zero-level offset and maintaining the magnitude levels at the point which gives optimum signal-to-noise ratio. They will also include total-power detectors and synchronous demodulators which will be used in conjunction with a switched noise source injected in the input waveguides to measure the system temperature.

THE CORRELATOR

The correlator will use the standard ATNF correlator blocks designed originally for the Compact Array correlator (Wilson et al. 1992) and now used as an autocorrelator at Parkes and in the Long Baseline Array (LBA) VLBI correlator. Each correlator block provides a total of 512 frequency channels in autocorrelation mode on a 2-bit, digitized 64-MHz bandwidth input signal. Hence to achieve the required 512 channel resolution on each of the 18 IFs, 18 correlator blocks will be required. This is a large correlator system requiring six standard equipment racks and 144 correlator boards containing 2600 special-purpose VLSI correlator chips. The total number of correlator elements will be 147,456, each operating at 8 million correlations per second. The new correlator will be assembled mainly from parts 'borrowed' from other ATNF facilities for the duration of the observations. The LBA correlator will provide 8 blocks, the Mopra autocorrelator 4 blocks, the Parkes autocorrelator 2 blocks and 4 new blocks will be constructed. The modular construction of the ATNF correlator systems, where each correlator block is self-contained and can be easily transported, makes this approach feasible. The resultant channel spacing corresponds to 26 km s^{-1}.

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 $\tau \propto (N_b A_t N_a)^{-1}$, where N_b is the number of independent beams in the focal plane, A_t is the total telescope (or array) area, and N_a is the number of antennas. 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 IV shows that the Parkes multibeam system is comparable in power to the VLA (mainly because the VLA has only a limited bandwidth in dual-channel spectral-line mode). That is the time taken to survey fully a given region of sky with the same redshift coverage and noise level is about the same. However, interferometers such as the VLA have poor surface brightness sensitivity, and rapidly become inferior to single dishes for extended sources. For the present scientific purpose, the Parkes multibeam system is superior to either the VLA or the ATCA, including the most compact 122-m 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 a useful survey instrument, and is marginally faster than the multibeam system for compact sources. However, because of the small Arecibo beam size, it is inferior to the Parkes multibeam system for sources

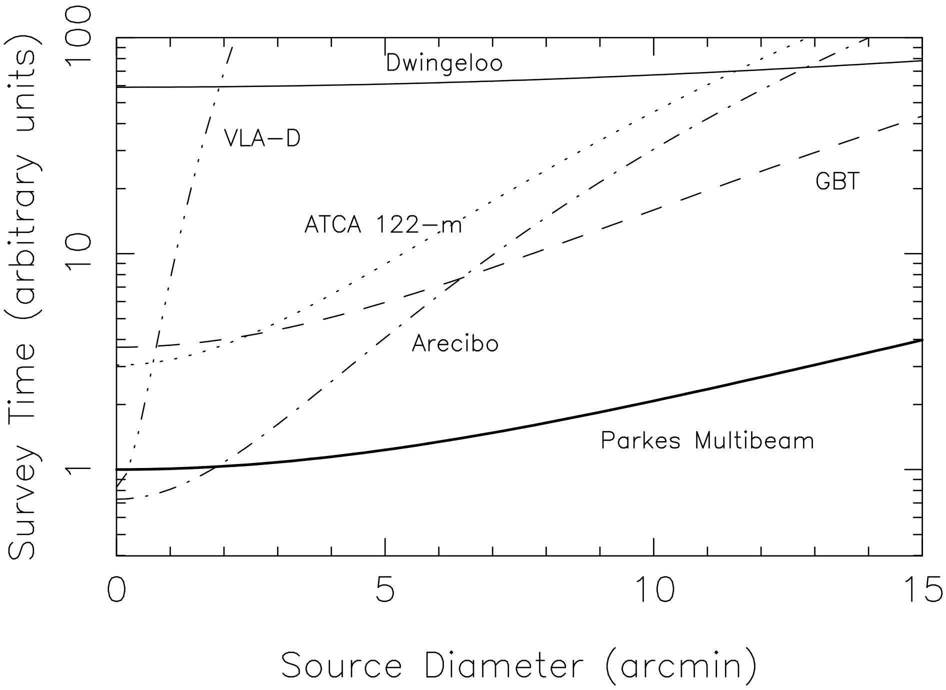

FIGURE IV Comparison of the time taken for various telescopes to fully survey a region of sky to a given sensitivity as a function of source diameter. Identical system temperatures are assumed for all telescopes. Identical 64 MHz bandwidth capability is assumed for all telescopes, except for the VLA which is limited to 6.25 MHz. See text for other details.

with diameters $> 1'.8$. 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 ~ 2 slower (i.e. $\sqrt{2}$ 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, but will probably be rather worse than the VLA due to low λ21-cm telescope efficiency and a low instantaneous bandwidth.

ACKNOWLEDGMENTS

We would like to thank Mike Disney, Raymond Haynes, Otto Richter and Alan Wright for their contributions to the Parkes multibeam project.

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