Instruments and Basic Astronomy

A Radiotelescope for Undergraduate Teaching

J.W.V. Storey and J.P. Lloyd, School of Physics
University of New South Wales PO Box 1, Kensington 2033.

Abstract: A fully-steerable 3.7 metre radiotelescope has been developed as an aid to undergraduate teaching. By using commercially available domestic satellite television components, excellent performance can be achieved at very low cost. The telescope is to be fully computer controlled, and has interchangeable feed horns and low-noise amplifiers for 21 cm, *2.5* cm and 7.5 cm. Experiments will include measurement of the surface temperature of the moon and Venus and of the effective temperature of the sun, plus observation of the brightest thermal and non-thermal galactic sources.

1. Introduction

A student pursuing an undergraduate course in physics typically spends an average of several hours per week in the laboratory. Despite the general appeal of astronomy, few students are offered any experiments at all in astronomy during their courses. On the one hand, optical astronomy is inconvenient in that it must be done at night and is at the mercy of prevailing weather conditions. On the other hand, radio astronomy has traditionally required a major engineering investment and the completed telescope usually lacks the sensitivity to see anything but the sun (Lo and Lonc 1986).

With the advent of direct-broadcast satellite television, however, good quality parabolic dishes and feed horns have become available at low cost. In addition, the mass market thus opened up has stimulated rapid development of low-noise receivers and down- converters, with the result that receiving systems now available for a few hundred dollars rival the performance of the best radiotelescope receivers of just a few years ago.

In this paper we describe the construction and operation of a small radio telescope for use in undergraduate teaching laboratories at the University of New South Wales. Three operating wavelengths are available: 2.5 cm, 7.5 cm. and 21 cm (see Table 1). The first two are chosen because they are

Table 1: Operating frequencies currently available

Frequency	Wavelength	fwhm ~ λ/d	Receiver noise temperature
12 GHz	2.5 cm	0.4°	50 K
4 GHz	7.5 cm	1.2°	25 K
1.4 GHz	21 cm	3°	50 K

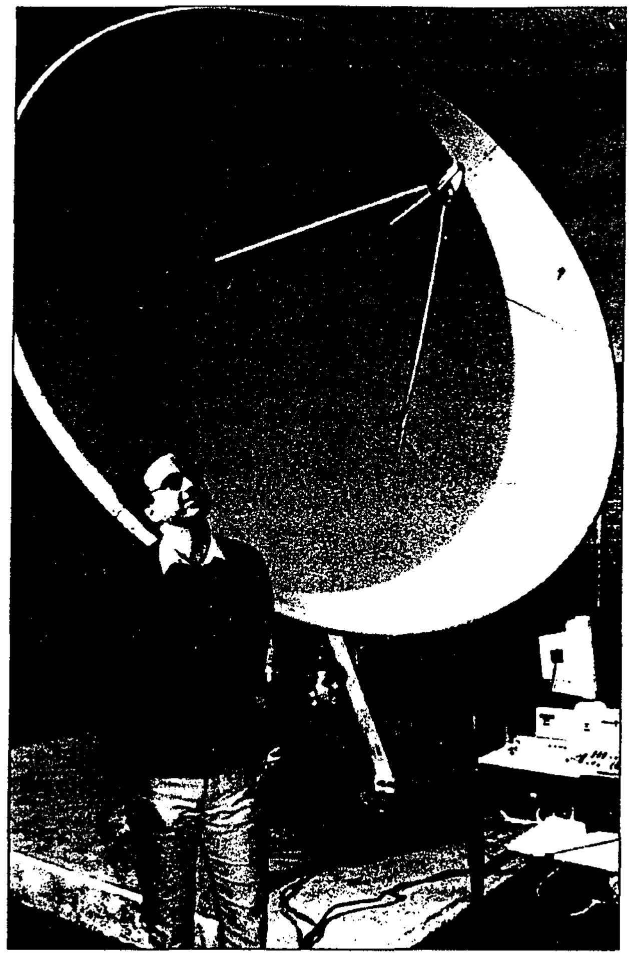


Figure 1: The radiotelescope on the roof of the Physics Building.

commonly used for direct-broadcast satellite television transmissions (e.g. Aussat and Intelsat respectively), and hence very inexpensive, high-performance receiver front-ends are available. The 21 cm band is chosen to allow study of the HI line.

The telescope (see Figure 1) is mounted on the roof of the Physics Building. The feed horns and front-ends for the three wavelengths attach to the telescope focus ring, and are designed to be readily interchangeable. Forty metres of cables bring the intermediate frequency (IF) signal, encoder data, etc. down to the control room, and bring power, motor drive signals. etc. back up.

Control of telescope pointing and receiver tuning is carried out by an 80386-based computer. This same computer houses a 1?-bit A/D converter for data acquisition. Data can be reduced in the 386 machine, or sent via Ethernet to a DECstation 5000 for reduction with standard astronomical packages such as IRAF.

At all three wavelengths the system temperature is 100 K or below. With a 5.5 MHz IF bandwidth and a 1 second integration time. the sensitivity for a 3-sigma detection of a source should be of order 0.1 K. Assuming an aperture efficiency of ~ 65% leads to a minimum detectable source in 1 second of order 100 Jy. This should make several bright thermal sources (e.g. Orion), several non-thermal sources (e.g. Crab nebula) and even bright radio galaxies, such as Centaurus A. readily accessible.

The radio observatory is still under development. It is hoped it will remain that way for many years. as the implementation of new capabilities can be done as higher-year student projects. This paper is therefore partly in the nature of a progress report, with emphasis on the present configuration of the system and the performance already achieved.

2. Antenna

The antenna itself is a 3.7 meter diameter spun aluminium paraboloid with an f/d ratio of 0.375, imported by Acesat Pty. Ltd. The manufacturer quotes a gain of 51.5 dBi at 12.0 GHz, which implies an aperture efficiency at that frequency of 65%. Hybrid-mode feeds for the two higher frequencies, matched to the antenna f/d ratio, are inexpensive and readily available. Polarization selection can be done via either a motor-driven probe or via a Faraday-rotation switch (or, of course, manually). At 1.4 GHz, a simple feed can be constructed from 150 mm copper water pipe. (See, for example, ***The ARRL Antenna Handbook***, 1990.)

3. Mount and Drive System

The telescope mount and drive system must be designed, like the dish itself, to survive (but not necessarily operate in) winds of up to 45 metres/second. This wind speed is expected once every century in Sydney. Because of the very high torques that such winds can generate on a 3.7 m solid dish, both axes incorporate non-reversible gearing. The telescope cannot therefore be blown around by the wind even when powered-down.

The azimuth tower is a thick-walled 150 mm diameter pipe, and stands 2 metres high. At the lower end a 45 mm deep-groove ball race takes out both the radial loads (due to wind) and the thrust load (due to the weight). At the upper end, a plain bearing of high molecular weight polyethylene is used to avoid the cost and complication of a large-diameter ball race. Azimuth drive is via a 60:1 worm and wormwheel, driven through a toothed belt drive by a dc servo motor. To cope with an estimated possible wind-generated torque of 1200 Nm, the worm and wormwheel must be of large diameter and strongly made. They are the only expensive items in the mount and drive system.

The elevation axis is a simple cross-piece atop the azimuth tower, with deep-groove ball races mounted in self-aligning pillow blocks at each end. The drive is via a lead-screw, with a maximum throw of 900 mm and a pitch of 4 mm/turn. The lead-screw is driven via a 6:1 toothed belt reduction and a dc servo motor similar to that used in the azimuth drive.

Each drive motor is fitted with a 900 count/turn incremental encoder, giving 4″ /count on the azimuth axis, and a varying rate of approximately 0.25″/count on the elevation axis. An optical interrupter on each axis allows the counters to be reset at a particular index position. The servo cards (one for each axis) are the MC1000 made by Omnitech Robotics Inc., and are based on the Hewlett Packard HCTL-1000 digital servo control chip. Small power amplifiers (± 15 **V** @ 6A) have been constructed to drive each axis. At the present time the servo control is yet to be implemented, and manual pointing of the telescope via a push-button box is used.

Each axis incorporates two inner and **two** outer limit switches. The inner, or soft limits, send a signal to the servo cards, which incorporate appropriate interrupt lines to halt the telescope and alert the 386 computer. The outer, or hard limits, which should only act in the event of a system failure, are directly in series with the drive motors. A power diode is wired across each outer limit switch to enable the telescope to be driven out of the limit.

4. Receiver

Very low noise block down converters (BDC) for 4 and 12 GHz can be obtained through commercial channels for a few hundred dollars. Each incorporates a high electron mobility transistor amplifier. dielectric resonator oscillator (DRO), mixer, and filter. to produce an IF output of 950 to 1450 MHz. The DRO has a quoted stability of ± 2.5 MHz, adequate for continuum studies but insufficient for spectral line work or for convenient calibration with a cw local oscillator source when narrow receiver bandwidths are used. Power to the BDC (+ 18 V) is supplied via the inner conductor of the **IF** cable.

At 21 cm it is not possible to obtain commercially-built low noise amplifiers at moderate cost. However it is reasonably straight forward to build one: we have constructed a 3-stage room temperature amplifier with a gain of 30 dB and a noise figure of 50K using MGF1402 GaAs FETs and the circuit of Williams et al (1980).

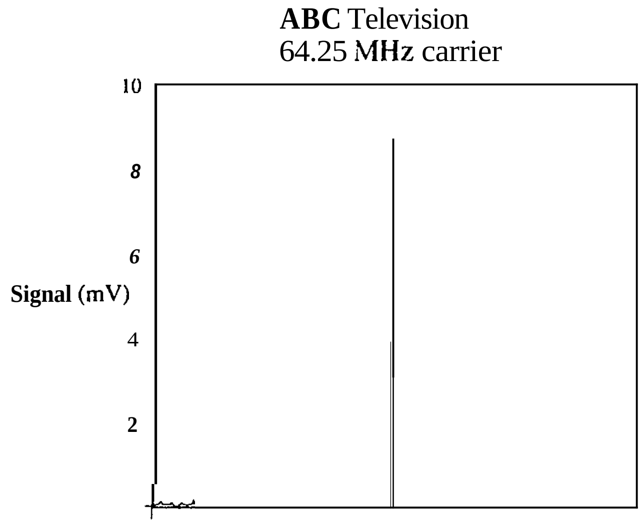
The IF, at 950–1450 MHz, is brought down to the control room where an Icom R7000 communications receiver acts as a back end. This receiver incorporates a frequency synthesizer in the local oscillator, and can be computer controlled via the RS232 serial bus. The only modification required to the receiver is to bring the agc voltage out, via a buffer, to the 12 bit A/D converter in the computer. **A** look-up table, previously generated with a calibrated signal source, is then used to convert agc voltage to equivalent signal power. For continuum work, the maximum available IF bandwidth is used (150 kHz). For spectral line work (see later), narrower IF bandwidths (2.4 kHz, 6kHz, 15kHz) can be selected by choosing the appropriate receiver mode **(ssb,** am, fm narrow, respectively). A 10.7 MHz IF output is also available from the receiver. In future, it is planned to build a 5.5 MHz wide filter centred at this frequency to take advantage of the maximum bandwidth allowed by the other receiver stages when performing continuum measurements.

5. Spectral Line Analysis

An important future project for the radiotelescope is the study of line profiles of the 21 cm HI line. The simplest approach to measuring a line profile is to scan the receiver step by step across the appropriate frequency range. noting the signal intensity at each step. This, in fact, is how the 21 cm line was first detected (Ewen and Purcell, 1951).

The Icom receiver is particularly well suited to this type of operation, as both the IF bandwidth and the received frequency can be computer controlled. Software has been written which selects one of the four available IF bandwidths, then steps the receiver repeatedly across the frequency range of interest. Both the number of "channels" (or frequency steps) and the centre frequency can be selected by the computer.

An example of the output of this system is shown in figure 2. Here the receiver has made a single scan, at 2.4 kHz resolution (1.2 kHz step size) across the video carrier of ABC TV as received at Kensington. As expected for an amplitude-modulated signal, the carrier itself is at full strength, and symmetrically placed sidebands are visible either side of the carrier spaced at harmonics of the television scan-line frequency (15.625 kHz). Such analysis can,



of course, form the basis of an interesting laboratory experiment in itself!

Scanning the receiver in this way incurs a signal/noise penalty equal to the square root of the number of channels. A 16-channel filter-bank is therefore under construction to allow faster measurement of HI profiles. When fully operational, the complete HI experiment will bear a satisfying resemblance to the system built at Murraybank in the late fifties, and used by McGee, Murray and Milton (1961) and McGee and Murray (1963) to survey HI emission in the southern sky. That system used a slightly larger dish (6 m) but with a receiver noise temperature of 800 K.

6. Observations

First observations with the telescope have been carried out at 12 GHz. Figure 3 shows a drift scan of the sun. while Figure 4 is a similar drift scan of the moon. In each case the telescope was moved to point at the Applied Science building after the celestial object had passed out of the beam. These plots were made with the system still in a very primitive form. Optimization of the sampling rate. and use of the 5.5 MHz IF bandwidth, should result in a signal-to-noise increase of at least a factor of six.

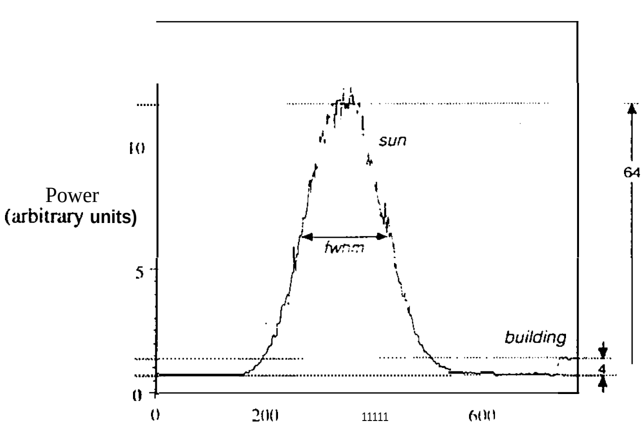


Figure 3: Drift scan of the sun at 12 GHz. The receiver agc voltage is sampled once every 2 seconds and converted to equivalent input power.

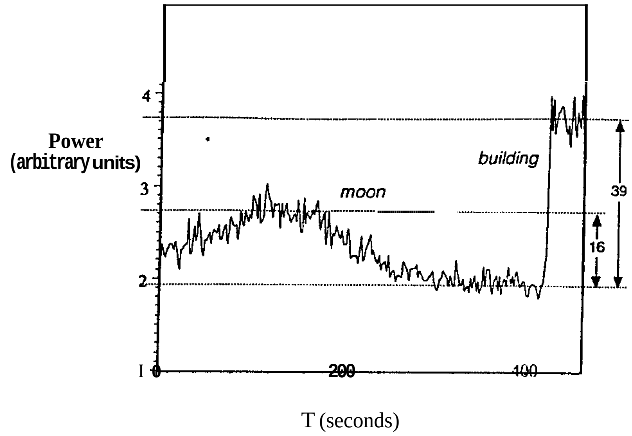


Figure 4: Drift scan of **the** moon at 12 GHz.

Calibration of the results, however, is not straightforward. One rigorous approach (e.g. Kraus, 1966) would be to map the antenna pattern $P_n(\theta,\Phi)$ using a distant point source. The same distant source, if of known flux, S, would allow measurement of the total beam solid angle, Ω_A, from

$\Omega_A = \frac{k_0 \lambda^2 S}{2k\ T_A}$ where k_0 is the ohmic-loss factor (≈ 1), k is Boltzman's constant, and T_A the observed antenna temperature. The observed brightness, B, **from** an extended object (such as the sun) with brightness distribution $B(\theta,\Phi)$ is then

$$B = \frac{\iint B(\theta,\Phi)\, P_n(\theta,\Phi)\, d\Omega}{\iint P_n(\theta,\Phi)\, d\Omega}$$

At 12 **GHz,** however, there is no convenient point source of sufficient intensity. (At a later stage it is hoped to make use of an Aussat beacon for this purpose.)

Hence we adopt a different approach, deriving Ω_A from the quoted antenna gain, G, via

$$\Omega_A - \frac{4\pi}{G} = 8.94 \times 10^{-5}\ sr.$$

The main beam solid angle, Ω_M, will be less than this, and is in fact approximately equal to Ω_S, the source solid angle, for both the moon and the sun.

Measurement of the signal from a nearby building, which fills the main beam and much of the sidelobe pattern, gives at least a fair estimate of the receiver response to a 290K source, while measurement of the sky should give a temperature close to zero, assuming that the contribution from ground radiation at small zenith angles is negligible. (The manufacturer of a similar antenna and feed system quotes 20K.)

The temperature of the sun (or moon) can then be estimated from the ratio of signal received to that received from the building, times Ω_A/Ω_S, times 290K.

From figures 3 and 4 this gives

$$T_{sun} \approx 7000\ K$$

$$T_{moon} \approx 180\ K$$

which agree reasonably well with the accepted values of about 8000K and 200K respectively.

7. Future **Work**

As previously noted, the most important development currently underway is the 21 cm spectral line system for HI studies. At a future stage, it is planned to phase-lock the DRO in the 12 GHz BDC. This will enable studies of the $2_0 \rightarrow 3_{-1}$ E maser transition of methanol at 12.2 GHz to be carried out. The brightest source has an intensity of 1200 Jy in this line, easily visible at short integration times. Another important development will be the installation of a front-end switch, and improved calibration facilities. This will increase the rigour with which measurements can be carried out, and introduce several important new concepts to the students.

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