

# 1 The Australia Telescope Compact Array

This chapter gives an overview of the *Australia Telescope Compact Array* (ATCA) and provides the information needed to prepare an observing proposal. As such, this chapter supercedes the *Guide to Observations* that was provided in the past (and which contained a lot of overlap with the previous *User Guide*). The old *User Guide* is still available and is recommended for those reducing pre-CABB data (i.e., observations before April 2009).

The ATCA consists of six 22-m radio antennas which can be configured with antenna spacings of up to 6km, located at the Paul Wild Observatory near Narrabri, some 550 km northwest of Sydney. It is one of the telescopes operated by the Australia Telescope National Facility (ATNF).

## 1.1 The Australia Telescope National Facility

The ATNF is managed as a National Facility by the Commonwealth Scientific and Industrial Research Organisation (CSIRO). Formerly part of the CSIRO Division of Radiophysics, it became a separate division in January 1989. The ATNF became a National Facility in April 1990. In December 2009, ATNF became part of a new Division, CSIRO Astronomy and Space Science (CASS), together with NASA Operations (including the Canberra Deep Space Communication Complex), and CSIRO Space Sciences and Technology. The Australia Telescope continues as a National Facility, providing world-class observing facilities for astronomers at Australian and overseas institutions.

The ATNF employs about 185 staff, including about 40 astronomers, with the majority of staff located at its headquarters in Marsfield, a suburb of Sydney (although Marsfield is sometimes referred to as Epping, a larger neighbouring suburb). The Anglo-Australian Observatory (AAO) headquarters are co-located with ATNF at Marsfield.

Besides the ATCA, the ATNF operates the 64-m radio telescope at the Parkes Observatory (300 km west of Sydney) and a 22-m antenna at Mopra, 120 km south of the ATCA. In addition, the ATNF negotiates time with the CSIRO-administered 70-m and 34-m antennas at the Tidbinbilla Deep Space Tracking station outside Canberra. The ATNF telescopes are used together, in conjunction with the University of Tasmania telescopes at Hobart and Ceduna, as part of the Long Baseline Array for Very Long Baseline Interferometry (VLBI) observations.

The ATNF is currently structured into four themes: Operations, Astrophysics, Technologies, and ASKAP. ASKAP (the Australian SKA Pathfinder), is being constructed by ATNF in Western Australia, will be an array of thirty-six wide-field 12m antennas operating in the 0.7–1.8 GHz range. It is expected to be operational in 2013. More details are available at <http://www.atnf.csiro.au/projects/askap/>.

A biannual newsletter is produced by the ATNF which includes recent news items, scientific articles and time assignment information. It is archived at <http://www.atnf.csiro.au/news/newsletter/>. *ATNF Annual Reports* are available from [http://www.atnf.csiro.au/the\\_atnf/annual\\_reports/](http://www.atnf.csiro.au/the_atnf/annual_reports/).

## 1.2 Overview of the ATCA

The ATCA is an array of six 22m diameter antennas located 237m above sea level at latitude  $-30^{\circ}18'46.385''$  south, longitude  $149^{\circ}33'00.500''$  east. The array has a 3km east-west track with a 214m northern spur. Five antennas can be moved along these tracks, with the sixth antenna at a fixed position 3km to the west of the east-west track. The longest possible baseline is, therefore, 6km. The array can be used for observations in seven wavelength bands between 27cm and (with five antennas only) 3mm, between frequencies of approximately 1.1GHz and 105GHz.

### 1.2.1 Array configurations

The location of six antennas at six stations is called an *array configuration*, or often, simply a *configuration*. The westernmost antenna, CA06, is fixed in position. The other five antennas can be positioned at any of 44 fixed stations. The station posts provide mains power to the antennas and connectors allow commands from the control building to be sent to the antenna, and data from the antenna (both astronomical data

and control & monitor data) to be transferred to the control building. The smallest baseline increment available is 15.306m, and the shortest physical baseline is 30.612m. Five of the six ATCA antennas are shown in Figure 1.1.

A standard set of 17 configurations has been defined, and a subset of these is offered for each semester. These configurations have been designed to give optimum, minimum-redundancy coverage after a 12 hour observing period. Sets of four configurations for the principal arrays (750m, 1.5km and 6km) are offered and form recommended observing sets. Your choice of configuration depends on the extent, brightness and complexity of your source (see below).

The Australia Telescope Compact Array is an earth-rotation aperture synthesis radio interferometer. Earth-rotation aperture synthesis was first used in the 1950s for radio observations of the sun. The technique is comprehensively explained, with a historical perspective, in *Interferometry and Synthesis in Radio Astronomy* by Thompson, Moran & Swenson (Wiley, 1st edition 1986, 2nd edition 2001). Essentially, the array of antennas form pairs of two-element interferometers. The visibility (i.e., the fraction of the signal common to both antennas of a pair) is derived by multiplying the (suitably delayed) signals together. By combining the correlated signals obtained over a long period of time and with a large range of spacings between antennas, the Compact Array measures the spatial coherence function:

$$V = \int I_{\nu}(s) e^{2\pi i s \cdot (r_1 - r_2)} d\Omega$$

where  $I_{\nu}(s)$  is the two dimensional intensity distribution on the sky,  $s$  is the unit vector in the direction of the celestial source,  $(r_1 - r_2)$  is the separation vector between antennas 1 and 2 and  $d\Omega$  indicates integration over the sphere (or, in practice, solid angle of the antenna beam).

The van Cittert–Zernike theorem tells us that the Fourier transformation of the spatial coherence function yields the source brightness distribution, i.e., the Fourier Transform of the visibilities produces an image of a radio source. The image is formed with the same angular resolution (but, of course, lower sensitivity) as for observations with a single antenna of diameter equal to the largest spacing.

By plotting the tracks that the baseline vectors trace out (from the source's perspective) as the earth rotates, astronomers can gauge how good the telescope will be at imaging the source and resolving components in the field of view. This plot is referred to as the  $(u, v)$ -coverage as, by convention, the two orthogonal axes of the plot are  $u$  and  $v$ . These variables have units of the observing wavelength. The  $(u, v)$ -coverage shows where on the Fourier plane the image has been sampled.

In order to obtain the fullest  $(u, v)$  coverage with the ATCA, you need to observe, using many different configurations, and for twelve hours with each configuration. However, almost any program can be successfully carried out with less than complete  $(u, v)$  coverage, and the individual configurations are chosen so as to optimise single configuration imaging characteristics. Sophisticated off-line image processing techniques minimise the effect of missing  $(u, v)$  coverage and allow reasonable images to be made with one configuration. For most programs one to four configurations provide the best compromise between dynamic range,  $(u, v)$  coverage and time.

The smallest synthesized beamwidths in Right Ascension for each observing wavelength are shown in Table 1.1, but bear in mind that, for east-west arrays, the beamwidth in Declination is greater by a factor  $\text{cosec}(\text{Dec})$ . At high angular resolution, the telescope is only useful for observing southern objects. North of Declination  $-24^\circ$ , full  $(u, v)$ -coverage is unobtainable; near Declination zero the beam is highly elongated north-south; and north of Declination  $+48^\circ$  sources are below the telescope's  $+12^\circ$  elevation limit and are inaccessible. For lower angular resolution, the north-south and hybrid arrays improve the  $(u, v)$ -coverage for equatorial sources, but only up to a maximum north-south baseline of 214m.



Figure 1.1: Five of the six ATCA antennas in the H75 array.

The rest of this chapter outlines the structure and operation of the ATCA. The path of the radio signal is traced through the system from the dish to the final data recording. This section is designed to help you understand how the Compact Array operates and provide all the information required to design an appropriate experiment. Detailed technical information about the ATCA can be found in the *Journal of Electrical and Electronics Engineering, Australia*, Special Issue, Vol. 12, No. 2, June 1992, a copy of which is available in the control room at the Narrabri Observatory.

### 1.2.2 Design and Operation of the ATCA

The antennas have a Cassegrain design, i.e., the receivers are located in a turret that protrudes through the main reflector surface (see Figure 1.1). The antennas have an altitude-azimuth mount with wrap limits as shown in the figure. The shaped (i.e., non-parabolic) dish and subreflector surfaces are designed to maximise the gain to antenna noise ratio. The reflecting surface of antennas 1–5 is solid panels that allow observations up to 116 GHz. This is also true of the inner 15.3m of antenna 6. The outer reflecting surface of antenna 6 is perforated panels which are accurate enough to permit observations at frequencies up to 50 GHz.

The subreflector mounted near the prime focus has a specially designed shape, differing slightly from the hyperbolic secondary of standard Cassegrain optics. The feedhorns are mounted on the optic axis – this allows polarisation measurements to be made, with very low ( $\sim 1\%$ ) instrumental polarisation. Subreflector focus is presently chosen to best suit 3mm observations and is adjusted for some antennas at 7mm. This means that the subreflectors positions may be slightly less than ideal for longer wavelengths. If you need better focus settings, discuss your requirements with local staff.

A major feature of the ATCA is its wide bandwidth operation. The feedhorns and front-end electronics operate over a very large range of frequencies, thus allowing  $(u, v)$  coverage to be increased by multi-frequency synthesis and dual frequency observations. The feedhorns are compact, with a corrugated interior surface and are designed for maximum frequency coverage, low noise, low spillover, low reflection and low cross-polarisation sidelobe levels. The feedhorns allow two simultaneous orthogonal linear polarisations to be measured (at frequencies almost an octave apart), and have a main lobe with near-constant, symmetrical beamwidth (James, G.L., 1984, *IEEE Trans. Antennas Propagat.* **AP-22**, pp 1134–1138; Thomas, B.M., James, G.L., Greene, K.J., 1986, *IEEE Trans. Antennas Propagat.* **AP-34**, pp 750–757).

The frequencies at which the Australia Telescope operates are listed in Table 1.1 see also section [Available Frequency Range](#) (page 17).

Each range of frequencies is referred to as a *band*. Bands are referred to by the wavelength of the approximate centre of the band or (especially at higher frequencies) by the frequency (and sometimes by the letter-codes shown over the columns of Table 1.1). There are presently five feedhorns mounted on each antenna (four on antenna 6): a large (2m high) feed-horn that operates in the 16cm band, and a somewhat smaller (50cm high) 6cm/3cm band feedhorn and three (several cm high) feedhorns mounted on the same dewar for the 15mm, 7mm and 3mm wavelengths.

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The feedhorns and the receivers are mounted on a rotating turret. The rotating turret design ensures that all feedhorns, when brought on-axis, are aligned with the optic axis of the antenna, allowing a wide field of view and dual-polarisation observations. The turrets are rotated automatically in accordance with the frequencies selected by the observing file. Rotating the turret orients the desired feed-horn and also ensures that the subsequent electronics suit the frequency at which you are observing. Changing the observing band to or from 7mm requires first rotating the turret to the 15mm position, and then translating the whole mm dewar to bring the 7mm feed on axis. The latter stage takes 2~3 minutes, and so changes to or from 7mm are much slower than any other band change.

The 6cm/3cm band feed-horn is fitted with separate 6cm and 3cm receivers, while the 16cm band feedhorns are fitted with wide-bandwidth receivers that covers the horn's entire usable frequency range. All receivers run continuously and use cooled FET and HEMT amplifiers that provide wide bandwidths and total system temperatures between 20K to 65K, depending on frequency.

The signals collected by the feedhorns are fed to the receiver systems for amplification and conversion to standard intermediate frequencies. During observations each antenna provides four independent intermediate frequency (IF) outputs (two frequency bands, two polarisations). These channels allow simultaneous observations of both polarisations at the two available frequencies in either dual-receiver system. The frequencies can be anywhere in the range covered by the selected feed-horn except at 15, 7 and 3mm where the two frequencies must be less than 6 GHz apart, and not straddle the 7 or 3mm sideband inversions (which are discussed later).

In order to convert the received radio signals to lower frequencies, the radio signals are mixed with a "local oscillator" signal. Four local oscillator signals provide four IF outputs to enable the dual-frequency, dual-polarisation operation. You can also switch frequencies at the end of each integration cycle (typically ten seconds). To change to a pair of frequencies covered by a different feed-horn requires a rotation of the turret and takes about twenty seconds. However, to avoid excessive wear of the turrets, a limit of four rotations per hour is imposed. Thus time sharing between a number of frequencies is limited only by signal to noise ratio, wear and tear on the equipment, your imagination, and the off-line software.

### 1.2.3 Signal Path

The following sections describe the path of the signal from the initial reflection off the antenna surface, through to the data recorded onto export media, in more detail than the introduction above. Some radio-astronomy jargon is also explained, as is some important mathematics. The details of this section are not required by observers, but are included anyway, for the sake of curiosity. A knowledge of the system is however essential if you want to design an experiment that uses the array in a new or unconventional way. Familiarity with the names and functions of some critical components can also be helpful if you need to diagnose faults. Many system components are housed in modules, and repairs can be made quickly by replacing a module once a correct diagnosis has been made.

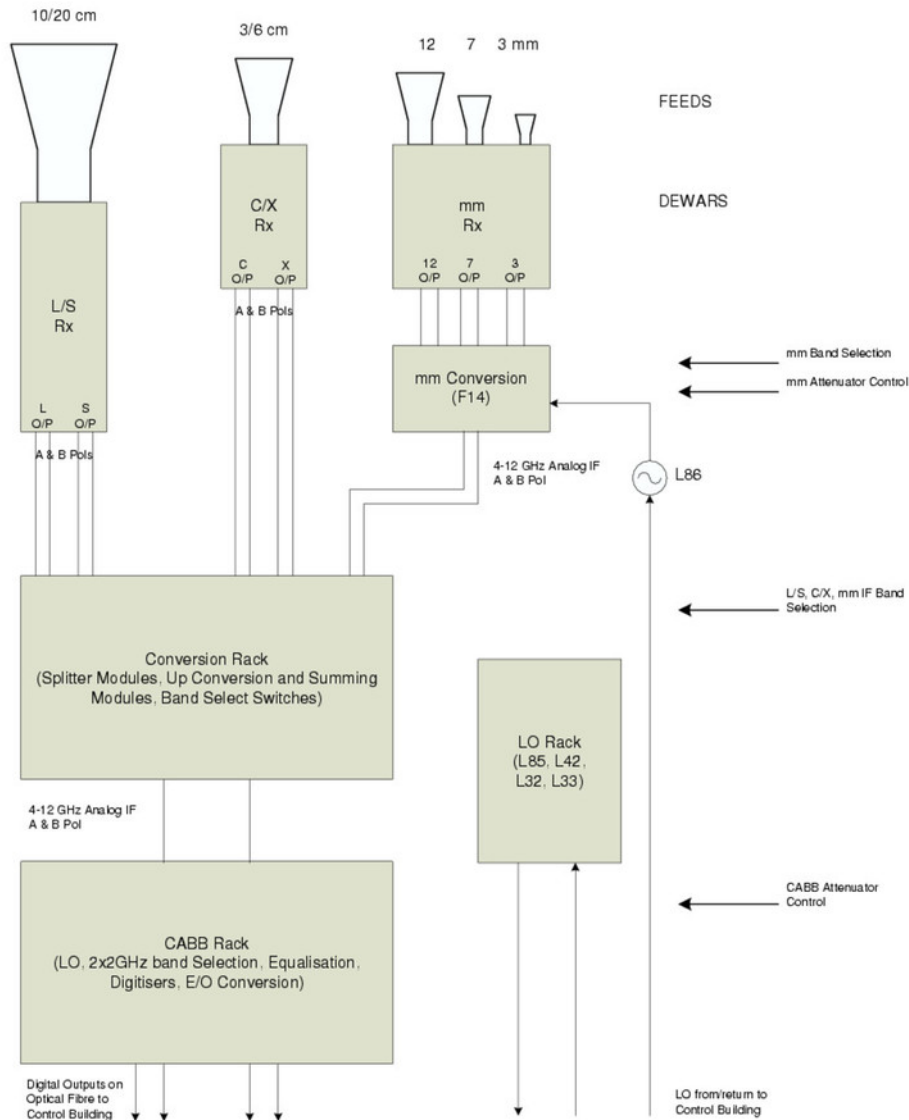


Figure 1.2: Overview of signal paths into CABB (courtesy Brett Hiscock).

### 1.2.4 Sensitivity and System Temperature

Radio waves (approximately within a range of 300 MHz to 120 GHz) are accurately reflected from the primary surface of the main parabolic dish and are re-reflected off a secondary reflector into a feed-horn. At the base of the feed-horn is a directional, coupling waveguide. In this coupler (the *cal coupler*) is a diode that injects a noise signal of known amplitude. This noise signal is used to calibrate the system temperature (Equation 1.1 (page 9)) and gain of the receiving system.

For radiation emitted by a randomly polarised source, the power received by a radio telescope is given by:

$$P_{received} = \frac{1}{2} AS \Delta\nu,$$

where  $A$  is the effective area of the antenna,  $S$  is the spectral power flux density and  $\Delta\nu$  is the range of frequencies observed (the effective bandwidth). The factor of  $\frac{1}{2}$  occurs because a detector can only respond to one polarisation component of the randomly polarised wave. The ATCA overcomes this limitation by

providing separate detectors and electronics for two orthogonal polarisations, thus allowing all the power in the wave to be detected.

Band name	16cm	6cm	3cm	15mm	7mm	3mm
Band code	L / S	C	X	K	Q	W
Frequency range (GHz)	1.1-3.1	4.4-6.7	8.0-10	16-25	30-50	83-105
Fractional frequency range	95%	39%	22%	44%	50%	24%
Number of antennas	6	6	6	6	6	5
Number of baselines	15	15	15	15	15	10
Primary beam [a]	42' - 15'	9'	5'	2'	70"	30"
System temperature (K) [c]	21	40	48	45	72	207
System sensitivity (Jy) [d]	47	70	90	83	145	1108
Strongest confusing source (mJy) [e]	140 - 24	2.3	0.4	—	—	—
Array assumed below	6km	6km	6km	6km	6km	H214
Synthesized beam [b]	9" - 3"	2"	1"	0.5"	0.2"	2"
Bandwidth assumed below (GHz)	2	2	2	2	2	2
Centre frequency assumed below (GHz)	2.1	5.5	9.0	17.0	40.0	95.0
Flux sensitivity (mJy/beam) (10 min) [f]	0.03	0.05	0.06	0.05	0.10	0.73
Brightness sensitivity (K) (10 min) [g]	0.1	0.15	0.19	0.17	0.3	0.02
Flux sensitivity (uJy/beam) (12 hr)	4	5	7	6	11	86
Brightness sensitivity (K) (12 hr)	0.01	0.02	0.02	0.02	0.04	0.002

[a] Field of view (full width at half power).

[b] HPBW in RA for the 6 km array for all bands except 3mm, for which the H214 array is assumed. No taper applied. In Declination, for the 6 km array (and other pure east-west arrays), the HPBW is larger by cosec(Dec). Longer arrays (up to 3 km) are possible at 3mm but only with self-calibration and under favourable weather conditions.

[c] The system temperature at high elevation under reasonable weather conditions. These values, particularly at high frequency, are weather-dependent.

[d] The signal which doubles the system temperature.

[e] Within FWHM primary beam --- see A.H. Bridle, in Perley R.A., Schwab F.A. & Bridle A.H. (1989) 'Synthesis Imaging in Radio Astronomy' Astron. Soc. Pacific Conf. Ser., 6, p.471.

[f] Theoretical rms noise; one frequency; dual orthogonal polarisation; natural weighting. The effect of confusing sources can substantially degrade this number.

[g] For the array listed in the same column:  
see following table for shorter arrays.

Table 1.1: Observing Parameters for the 6km Compact Array

The *sensitivity* of a radio telescope is the minimum signal power that can be distinguished from the random fluctuations at the output of the receiving system which are caused by noise inherent in the system. The

sensitivity is usually defined as the spectral power flux density of a source that would produce the same signal power as the noise power. It is measured in *Janskys* (Jy), with  $1\text{Jy} = 10^{-26}\text{Wm}^{-2}\text{Hz}^{-1}$ .

The *noise power* consists of two main components: the noise power due to the receiving amplifier and other electrical system components, and the noise due to ground radiation, thermal emission from the atmosphere (which varies with elevation, cloud cover, etc.), background radio emission from our Galaxy and other sources detected by the antenna. These noise powers are usually referred to as *equivalent temperatures*, although at no point is a physical temperature measured. The ‘temperature’ due to the noise power is called the *system temperature*,  $T_{sys}$ , and is related to the noise power by:

$$T_{sys} = \frac{P_{noise}}{k\Delta\nu},$$

where  $P_{noise}$  is the noise power and  $k$  is Boltzmann’s constant. As both the source and noise signals are random in nature, measurements of the power levels made at time intervals separated by  $(2\Delta\nu)^{-1}$  can be considered independent (e.g., Thompson, Moran & Swenson 1986, 2001). If the signal level is averaged for  $t$  seconds then  $2\Delta\nu t$  samples have been measured.

The signal to noise ratio is the ratio of the power in the output that is due to the radio source being observed to that caused by the noise, and is given by:

$$\frac{S}{N} = \frac{T_{ant}}{T_{sys}} \times \sqrt{\text{number of independent samples}}.$$

In this expression,  $T_{ant}$  is the *antenna temperature*, the equivalent temperature of the radio source being observed. Note that ‘antenna temperature’ is sometimes also taken to mean the contribution to the noise power from radio noise detected by the antenna, as described above. For typical values for bandwidth (2 GHz) and integration time (12 hours), it is possible to detect a signal for which the power level is less than  $10^{-6}$  times the noise level.

### 1.2.5 Online Calibration

The noise source in the cal coupler injects a signal that is about 5% of the level of the system temperature at a rate of 30 Hz. This noise signal is synchronously demodulated and the following relationship holds:

$$T_{sys} = T_{cal} \times \frac{P_{on}}{P_{on} - P_{off}}.$$

Here,  $T_{cal}$  is the equivalent temperature of the noise source,  $P_{on}$  is the power received while the noise diode is on, and  $P_{off}$  is the power received while the noise diode is off.  $T_{sys}$  is measured accurately once by placing a thermal radiator of known temperature (a microwave absorber at 300K, giving  $300\text{K} + T_{sys}$ ) directly above the feeds. The power received with this load in place is then compared with the power output with the antenna just looking at the sky ( $\sim T_{sys} + 3\text{K}$ ). This measurement is used to establish the level of  $T_{cal}$ , which is assumed not to vary with time. The measurement of system and antenna temperature is described by Sinclair and Gough (1991).

The cal coupler is mounted on another coupler that provides a vacuum seal between the cal coupler and the subsequent receiver system, which is housed in an evacuated, cryogenic cylinder. An air gap thermally isolates the cylinder, the contents of which are cooled by a helium pump to 20K. The second coupler is mounted on the polariser.

The dual function of the polariser is to select the two linear polarisations and the desired band, so it is also known as a *band splitter*. The polariser consists of four strips of metal inside a conical waveguide that ‘guide’ two orthogonal linear polarisations into probes at the narrow end of the polariser. The way in which the metal strips select the linear polarisations can be thought of as analogous to the effect of a ridged waveguide, which constrains a particular mode to propagate along the region between the ridge and the roof of the waveguide. The probes are simply short (with respect to the wavelength) lengths of the

cores of the coaxial cables that take the signal into the first amplifiers. Thus the polariser converts a wave into a voltage: the impedance of the circuit is effectively the same as a waveguide impedance, so it works like a well-matched load. The polariser's official title is quad-ridged *orthomode transducer*, or OMT.

Separate electronics exist for both orthogonal linear polarisations, which are measured simultaneously. The position angle of the polariser is fixed with respect to the antenna. As the antennas have altitude-azimuth mounts, the position angle of the linear probes rotate on the sky during the course of an observation (imagine a circumpolar line on the sky orbiting around a stationary antenna). Measurement of both polarisations is therefore required for polarised sources. The two linear polarisations can be combined to give an accurate total intensity: the Stokes  $I$  parameter. Without additional calibration, the other Stokes parameters (the linear polarisation measures  $Q$ , and  $U$ , and the circularly polarised component  $V$ ) can be in error by about 2% of the value of  $I$ . Measurements of the phase difference of the two linear polarisations (referred to as the X and Y (or A and B) polarisations) at the receiver by on-line hardware may need further off-line calibration.

For an unpolarised source, observing both orthogonal polarisations offers a  $\sqrt{2}$  improvement in signal to noise ratio for an  $I$  image over an image generated from only one polarisation.

For the 6/3cm band, the two polarised outputs from the polariser go into *diplexers* which filter off the 6cm band and 3cm band signals. This stage is not necessary for any of the other bands. Separate IF chains exist for each of the subsequent four signals.

The signal is taken from the feedhorn/diplexer into a low noise, broadband amplifier.

The 16cm receivers use four low-noise amplifiers (LNAs) to amplify the signal by 30–40 dB. All six antennas are fitted with wideband, continuously running, receivers. Cooled gallium-arsenide field effect transistors (GaAs FETs) are used at 16cm, while gallium-arsenide high electron mobility transistors (GaAs HEMTs) are used at 6 and 3cm, and indium-phosphide monolithic microwave integrated circuit (InP MMIC) devices are used at 15mm, 7mm and 3mm. Only the “inner” five antennas (i.e., excluding CA06) have 3mm receivers. The accessible frequency range is given in Table 1.1, and the average system temperatures are given in Table 1.2 and in [Available Frequency Range \(page 17\)](#). Note that frequencies outside these nominal limits may be accessible.

The next step is the conversion to the frequency range that is used by the CABB digitisers. The 3cm and 6cm signals require no conversion, whereas the mm signals require a down-conversion stage, and the 16cm signals require up-conversion to the 4 to 12 GHz band.

The local oscillator signals have a relatively narrow tuning range, lying in the regions between the radio frequency bands (this reduces the likelihood of self-generated interference). The conversion system is flexible, allowing the input signals to be within the same band (e.g., both in the 3cm centred band), or one from each of the two bands simultaneously received by the wide-band feed-horn.

### 1.2.6 CABB Correlator

The final output from the conversion system is sent to the *samplers* for digitisation. The CABB samplers were developed in-house and is capable of 4 gigasamples per second (GS/s), with 10 bit sampling (more information is available in the February 2007 ATNF newsletter: [http://www.atnf.csiro.au/news/newsletter/feb07/CABB\\_upgrade.htm](http://www.atnf.csiro.au/news/newsletter/feb07/CABB_upgrade.htm)).

The samplers, which are also referred to as the CABB digitisers, do two things. First the analog (continuously variable in time and amplitude) signal is sampled into a discrete-time sequence of values. This process does not degrade the signal as it is sampled at the *Nyquist rate* (twice the inverse frequency of the bandwidth of the analog signal). Subsequently, each of the discrete-time, continuously variable values are converted to one of a finite set of values: this is called *quantising*. CABB uses 9-bit sampling, with approximately 6-bits used in sampling the regular data range, and the additional bits providing extra robustness in the case of interference RFI (radio-frequency interference).

The digitised signals from the sampler are sent from each antenna to the correlator along optic fibres at a rate of 160 gigabits per second for each antenna. Optical fibres run from the samplers in each antenna to the correlator, which is housed in the screened room (to prevent RFI generated by the correlator electronics

from affecting the observations) of the central control building. Synchronising code is added to the data stream at the start of each integration cycle to allow each bit to be correctly identified at the correlator irrespective of temporal changes in the length of the fibre.

The *correlator* effectively multiplies simultaneous signals from two samplers: the more similar the signal from both antennas, the larger the degree of correlation. A plane wavefront approaching the ATCA will, in general, arrive at different antennas at different times. The signals from the antennas therefore need to be *delayed* before being presented to the correlator so as to simulate a wavefront arriving at each antenna simultaneously. This was previously achieved by separate *delay units*, but is now included in the CABB boards. The *delay calibration* undertaken at the start of an observation removes other delays caused by return path length differences, instrumental delay variations and the like, so that wavefront samples are presented to the correlator synchronously.

The CABB filterbank/correlator is divided across a number of Digital Signal Processing (DSP) boards. The DSP boards use Virtex-4 Xilinx Field Programmable Gated Arrays (FPGAs) to provide a flexible, programmable hardware correlator (more information is available in the October 2006 ATNF newsletter: <http://www.atnf.csiro.au/news/newsletter/oct06/CABB.htm>).

The output from the correlator is averaged for the period of one *integration cycle*, and sent to the correlator control computer *CACCC* where it is written to hard disk. Integration cycles can be set by the observer, between 2 and 30 seconds, although the default cycle time of 10 seconds is generally recommended for all observers.

More information on the correlator can be found at the CABB webpage at <http://www.narrabri.atnf.csiro.au/observing/CABB.html>. This page is updated frequently, and the current state of correlator development can always be found there.

The CABB correlator can already, or will soon provide a large range of observing modes, including:

- Two always-available 2048 MHz continuum IFs (although an analogue bandpass filter may reduce the usable bandwidth by 32 MHz)
- Up to 6 GHz separation of simultaneous IF centre frequencies (depending on receiver restrictions)
- 8 bit sampling accuracy
- Square, independent channels (ie. no leakage between channels)
- All polarisation parameters for all products (including auto-correlations)
- Up to 16 zoom bands per IF to provide finer spectral resolution
- A pulsar binning mode
- Integration times as fast as 1 second

This design ensures that the user will always get high continuum sensitivity from the wide-bandwidth IFs, while providing very high spectral resolution for line studies at the same time.

### 1.3 Centimetre Observations (16–3 cm bands)

The next two sections describe some necessary considerations for both centimetre and millimetre observations at the ATCA. This section on centimetre observations is also relevant for millimetre observers and should be read by everyone planning to propose for the ATCA. The millimetre section describes some additional requirements specific to millimetre observations.

Array	6km	1.5km	750m	EW352	H214	H75
Band						
16 cm	0.01 K	1 mK	0.4 mK	0.07 mK	0.1 mK	0.01 mK
6 cm	0.02 K	2 mK	0.5 mK	0.1 mK	0.1 mK	0.02 mK
3 cm	0.02 K	3 mK	0.7 mK	0.2 mK	0.2 mK	0.02 mK
15 mm	0.02 K	2 mK	0.6 mK	0.2 mK	0.2 mK	0.02 mK
7 mm	0.04 K	4 mK	1.1 mK	0.2 mK	0.3 mK	0.03 mK
3 mm				1.6 mK	3.0 mK	0.3 mK

Table 1.2: Continuum brightness temperature sensitivity (12 hr integration) for bandwidth specified in Table 1.1, for various arrays.

### 1.3.1 Calibration

There are four classes of data calibration: flux, bandpass, polarization and gain. The ATCA instrumental bandpass, polarization response and gain amplitude are all relatively stable and flux, bandpass and polarization calibration can be done just once during an observation. At centimetre wavelengths these three calibrations can be performed with an observation of B1934-638. This is often called the *primary* flux calibrator. Atmosphere-induced phase and amplitude gains are more variable and brief observations of suitable calibrator sources (*gain* calibrators) are usually interleaved with observations of the target source. In addition, observations are made to calibrate aspects of the instrument's performance: antenna pointing and instrumental delay. Pointing calibration is normally only necessary at short wavelengths 7mm and 3mm, and involves periodic observations of a nearby point source. Differences in signal arrival times at the correlator arise from the geometric delay, which can be calculated, and instrumental delays, which must be measured. Instrumental delays vary slowly and are measured with a single observation of a strong point source at the beginning of an observing session.

#### 1.3.1.1 Flux Calibration

All observations must be ultimately related to a compact source in the southern sky whose flux is constant, unpolarised, and known. For frequencies below 30 GHz, PKS B1934-638 is used; this source should be observed at least once a day. Its flux density (following a revision of the flux density scale in August 1994) is 12.6, 5.0 and 2.7 Jy at 2100, 5500 and 9000 MHz, respectively (Reynolds 1994: <http://www.atnf.csiro.au/observers/memos/d96783~.pdf>) and 1.2 and 1.0 Jy at 17000 and 19000 MHz respectively (Sault 2003: [http://www.narrabri.atnf.csiro.au/calibrators/data/1934-638/1934\\_12mm.pdf](http://www.narrabri.atnf.csiro.au/calibrators/data/1934-638/1934_12mm.pdf)).

The flux densities are incorporated in the on-line calibration routine in CAOBS, and in the MIRIAD calibration software. For frequencies above 30 GHz, observations of a planet (Uranus is recommended, Mars may be an alternative in the most compact arrays) will be required for primary amplitude calibration (in suitably compact configurations). Suitable software exists in MIRIAD for using planetary calibration data.

#### 1.3.1.2 Gain Calibration

The calibrators database gives information on potential sources that may be used to measure the interferometer amplitude/phase calibration. A round-trip phase correction machinery automatically corrects for the changes in electronics path length in real time; therefore, the astronomical gain calibration observations are for taking out the atmospheric path changes and any errors in the baseline parameter determinations. The on-line system temperature calibration takes out the temporal changes in the electronics gain but does not correct for elevation dependence of either antenna (optical) gain or atmospheric opacity.

A series of brief gain calibrator observations are important to correct for these effects. The gain calibrator should be close to the target source. Observers concerned with accurate positions will also need to choose

a gain calibrator whose J2000 position is accurately known. It is preferable to make  $\sim 2$ min calibrator observations once every  $\sim 30$ min. Less-frequent calibration is possible at 16cm and more frequent calibration may be required at 3cm. At 15mm and shorter wavelengths, it is preferable to calibrate as frequently as possible (consistent with not spending too much time off source), unless the array is very compact.

In summer, or during the day, phase stability can be poor. Phase stability can be monitored for bright compact sources with VIS, or with the ATCA seeing monitor. The ATCA Seeing Monitor (<http://www.atnf.csiro.au/observers/docs/7mm/seeing.pdf>) describes the system as initially installed. In 2008 a new satellite beacon was adopted, resulting in a change in the frequency from 30GHz to 21GHz.

Observations requiring maximum phase stability (e.g., at wavelengths less than 6cm) should therefore be made in winter, or at night. Most compact sources are variable, but they can be calibrated for the observation against PKS B1934-638.

The most up-to-date calibrator list is available by position or flux-limited online search: <http://www.narrabri.atnf.csiro.au/calibrators/>.

### 1.3.1.3 Bandpass Calibration

A spectral-line observation will normally require a bandpass calibrator. At low frequencies, the primary calibrator PKS B1934-638 is usually enough, but at wavelengths of 3cm and shorter a source such as 0537-441, 1253-055, or 1921-293 (usually  $>5$ Jy) may be needed. The Compact Array bandpasses are stable, and so a single bandpass calibration is normally sufficient, unless you need high dynamic range.

### 1.3.2 Sensitivity Calculations

The general expressions for the flux and brightness sensitivities are given in the document AT/01.17/025 (<http://www.narrabri.atnf.csiro.au/observing/AT-01.17-025.pdf>), and these general expressions have been used in Table 1.1. The observer has control of the integration time ( $t$ ), bandwidth ( $B$ ), observing wavelength ( $\lambda$ ), number of baselines ( $N$ ) and synthesized beam size ( $\theta$ ) only, and with these variables and the system sensitivity ( $S_{sys}$ ), the expressions reduce approximately to:

rms Flux Sensitivity =  $\Delta S = 7.55 \times 10^{-5} S_{sys} (NtB)^{-1/2}$  (Jy), and

rms Brightness Sensitivity =  $\Delta T = 1.36 \times 10^3 \Delta S \lambda^2 / (\theta_\alpha \theta_\delta)$  (K),

where  $S_{sys}$  is in Jy,  $t$  in min,  $B$  in MHz,  $\lambda$  in cm, and  $\theta$  is in arcsec. For the full 6 km array,  $N=15$ . There is a convenient ATCA sensitivity calculator at <http://www.narrabri.atnf.csiro.au/cgi-bin/obstools/atsen7.pl> which takes into account system temperature, observing frequency, array, correlator configuration and  $(u, v)$ -weighting. It has been updated for CABB observing.

## 1.4 Millimetre-wave observations (15mm–3mm)

Technical details of the ATCA mm systems are presented in MMICS for the AT mm-wave receiver system (<http://www.narrabri.atnf.csiro.au/observing/EuMW2004Gough.pdf>) by Gough et al. (Proc. 12th European Gallium Arsenide and other Compound Semiconductors Application Symposium, 2004, pp.359-362) and Cryogenically Cooled mm-wave Front Ends for the Australia Telescope (<http://www.narrabri.atnf.csiro.au/observing/EuMC2008Moorey.pdf>) by Moorey et al. (Proc. European Microwave Conference, 2008, pp.155-158). This section builds on many of the concepts described in the previous section on centimetre wavelength observations, which should be read before reading this section.

### 1.4.1 15mm Observations

All six antennas of the Compact Array are equipped with 15mm receivers covering the frequency range 16–25 GHz. The 15mm system shares a common dewar with the 7mm and 3mm receivers, and the separate feed horns at the top of the dewar are moved to the Cassegrain focus of the Compact Array antennas using the rotator positioning system. Because the 15, 7 and 3 mm receivers have separate feed horns, observations cannot be simultaneous between the 15, 7 and 3 mm bands.

## 1.4.2 7mm Observations

The ATCA can observe within the frequency range 30–50GHz. Feeds and receivers were installed into the existing mm-wave receiver packages on all 6 antennas in 2007, with the 7mm upgrade jointly funded by the ATNF and NASA’s Deep Space Network to enable the ATCA to participate in occasional spacecraft tracking.

The wide 7mm band presents difficulties in signal down-conversion, as the aliased signal from the first down conversion stage can also be within the 7mm band. Although image rejection filters are used, variations in receiver gain across the band, combined with the frequency-dependent performance of the filters themselves, can result in appreciable signal levels being added to the observing band. Generally, this aliased signal does not cross-correlate and is present as a contribution to the noise level. However, in some circumstances, notably as the delay rate drops to zero (e.g., around source transit on north-south baselines), the aliased component can cross-correlate and be visible as “beating” on some baselines. This data must be flagged during the data processing.

A swap-program may, if possible, be scheduled for 7mm projects — see the following section for details.

## 1.4.3 3mm Observations

The inner five ATCA telescopes (i.e., excluding CA06) are outfitted with a 3mm receiver and can observe in the range 83 to 105 GHz. A noise diode has been added to the 3mm system on CA02 (only) to aid with 3mm polarisation calibration. Aliasing effects similar to those described at 7mm can also arise in the 3mm band.

A limited form of flexible scheduling is operational for observations at millimetre wavelengths. Consult the document *Flexible Scheduling at ATCA* (<http://www.narrabri.atnf.csiro.au/observing/flexsched.html>) for details.

A quickstart guide for 3mm observing is available at <http://www.atnf.csiro.au/observers/docs/3mm/quickstart.html>.

## 1.4.4 Procedure for mm observations

Observations in the mm band are run from a schedule file in the same way as cm-band observations. However, due to the effects of atmosphere stability, mm observations require bandpass and phase-calibration checks at a much more frequent rate.

Note that as ATCA does not Doppler track, it is important to have a good estimation of the magnitude of the Doppler shift for the line of interest. This is particularly so for the higher frequencies available to the 3mm system. The sky frequency can be calculated using an online calculator at

<http://www.narrabri.atnf.csiro.au/observing/obstools/velo.html>.

A simple phase reference observation takes about an hour to run, including calibration. The following procedure is typical:

Pointing calibration → Paddle calibration → Bandpass/Phase calibrator → Target source → Paddle calibration → Bandpass/Phase calibration → Target observation.

The CABB web scheduler at

<http://www.narrabri.atnf.csiro.au/observing/sched/cabb/>.

can be used to construct the observing schedule.

### 1.4.4.1 Warnings for mm observations

Elevation angles close to the array horizon should be avoided because of the increased opacity and poorer atmospheric stability. Therefore, observations of objects with a declination further north of  $-50^\circ$  are best made using hybrid configurations, or one using the N-S spur in order to achieve sufficient  $(u, v)$ -coverage.

Observations using very compact telescope configurations should be made with caution, as telescope shadowing can be a significant problem, especially for sources at declinations which do not achieve elevations high above the horizon. See section [Shadowing Diagrams \(page 108\)](#) for details.

## 1.4.5 Calibration

For observations using a narrow bandwidth, a delay calibration is best made using a coarser channel resolution. Note that using a different correlator configuration will not affect your delay calibration as long as the frequencies and bandwidths match those of your target observations.

### 1.4.5.1 Flux calibration

At wavelengths shorter than a few centimetres, extra-galactic sources generally prove to be too variable to be useful as flux density calibrators. So at these wavelengths, the blackbody emission from the planets are often used as flux standards. The two most commonly used planets for the ATCA at 3mm are Mars and Uranus. Note Jupiter is too large for use as an ATCA flux density calibrator. Neptune would also be a possible flux density calibrator. However Neptune is quite close to and half the strength of Uranus, and so does not offer anything over Uranus.

Uranus is the preferred flux density calibrator for the ATCA. Mars is less suitable for a number of reasons: some models of Mars' average brightness temperature suggest variations in the temperature of up to 10% as a result of Mars' diurnal rotation, its distance from the Sun and the viewing geometry of Earth-based observers. Definitive measurements and confirmation of these models are poorly studied in the literature. Depending on its distance and the array configuration, structure on Mars is also readily detected with the ATCA: Mars has hot equatorial and cold polar regions.

Details of planet rise and set times can be determined at <http://www.parkes.atnf.csiro.au/cgi-bin/utilities/planets.cgi>.

### 1.4.5.2 Bandpass calibration

Bright extragalactic continuum sources (such as 0537-441, 1253-055, or 1921-293) are useful for bandpass and delay calibration as well as pointing. A 15 minute integration will usually provide an adequate bandpass, except at the narrowest bandwidths where extra time should be allowed. Refer to the [ATNF calibrator catalogue](http://www.narrabri.atnf.csiro.au/calibrators) (<http://www.narrabri.atnf.csiro.au/calibrators>) and use the form to select bright sources (by specifying a lower limit to the flux density) near your target source – but be sure to avoid CenA, i.e., 1322-427 at cm wavelengths and other sources with large “defects” (see catalogue webpages for details) at your frequency in your array, and resolved planets.

### 1.4.5.3 Gain calibration

To find the nearest gain calibrator to your source, use the position and flux-limited calibrator online search engine from the [ATNF calibrator catalogue](http://www.narrabri.atnf.csiro.au/calibrators) (<http://www.narrabri.atnf.csiro.au/calibrators>). The list of calibrators interrogated by this engine includes OVRO and BIMA sources, which will be useful for observations of sources north of  $-30^\circ$ .

The spatial and time separation of source and phase calibrator measurements has a strong dependence on telescope configuration and the atmospheric conditions. The [ATNF online calibrator cycle calculator](http://www.narrabri.atnf.csiro.au/calibrators/calcycle.html) (<http://www.narrabri.atnf.csiro.au/calibrators/calcycle.html>) can be used to estimate of the rate of gain calibrator measurements for a number of different phase decorrelation percentages.

Daytime observations, or observations with long baselines should require much more frequent gain calibration measurements than those made during nighttime observations and with compact configurations.

A technique that can be applied at frequencies and array configurations where decorrelation is severe, is to observe a relatively weak (0.5 Jy) ‘test’ quasar, near the target source, in addition to your gain calibrator.

The test quasar should show up if the gain calibration is adequate and it is possible to determine whether a non-detection is due to a weak source or just bad phases. Another reason to observe a second (not necessarily weak) quasar is to check the reliability of phase referencing. The observation would consist of a mosaic of source, gain-cal, and test quasar that is repeated every 5 minutes.

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#### 1.4.5.4 Pointing calibration

Regular pointing checks (every hour or so) are essential because of the small size of the ATCA primary beam at mm wavelengths. Pointing corrections are valid within an area with a diameter of around 15-20 degrees, centred on the azimuth/elevation of the pointing scan.

To refine your pointing during your observation, it is best to choose a pointing calibrator near your target source (within  $10^\circ$  if possible), not only because the pointing changes with position, but also because you will want to observe it throughout your run. Generally, any quasar with a flux density of 100 mJy or more will suffice.

#### 1.4.5.5 Paddle (vane) calibration

At millimetre wavelengths, the atmosphere can no longer be approximated as perfectly transparent. It degrades overall sensitivity in two ways: the atmosphere emits radiation, and so raises the system temperature, and the atmosphere attenuates the astronomical signal. For ATCA at 3mm wavelength, the effect of the atmospheric opacity is corrected for via a measurement of the effective system temperature - the so-called "above atmosphere" system temperature. More details are available in the MIRIAD User Guide.

The ATCA uses the chopper wheel method (also call paddle or vane calibration) in its 3mm system to determine an above atmosphere system temperature. This involves placing an ambient load (paddle) in front of the receiver horn. This is a standard procedure at 3mm wavelengths for placing the amplitudes on a brightness temperature scale. You will need to include periodic paddle measurements in your schedule file — about every 10–20 minutes. The entire paddle scan takes about 2 minutes.

### 1.5.1 Available Frequency Range

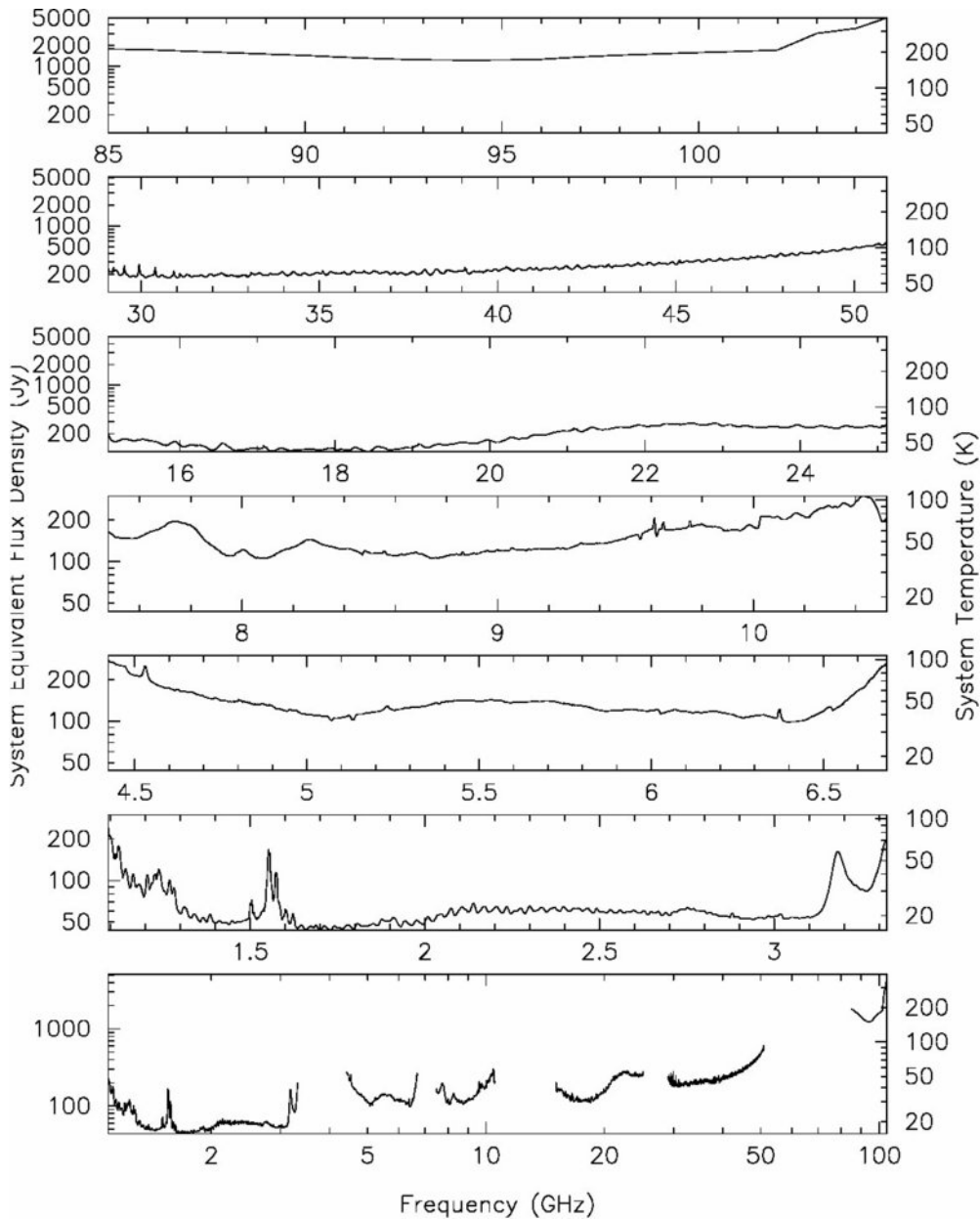


Figure 1.3: Average Compact Array system temperatures and system equivalent flux densities (SEFDs) for each observing band at high elevation under reasonable observing conditions. These are based on hot-cold load measurements, and include the atmosphere at the time of observation, thus representing the total system temperature. These measurements were made by J. Stevens in July/August 2010 with the CABB system, except for the 3mm measurements which were made by T. Wong in September 2004. The 6cm and 3cm receivers share a common feed-horn and it is possible to observe simultaneously at any two wavelengths within these bands. You can also switch automatically to other wavelengths within tens of seconds (with the exception of the 7mm band as described previously). Similarly the 16cm receiver has a single feedhorn and observations with this package will cover the entire 1.1 - 3.1 GHz range simultaneously. Observations at two simultaneous frequencies are possible in the 15mm band or the 7mm, or the 3mm bands. With CABB frequencies currently need to lie within 6 GHz of each other (and tighter constraints possibly resulting from the exact frequencies chosen). Typical observing frequencies for continuum observations

using the 128 MHz bandwidth available with the original ATCA correlator were 1384, 2368, 4800, 8640, 18496/19520, 34496/34524, 44096/44224, and 93504/95552 MHz. These frequency designations follow the ATCA custom of stating the central frequency of the chosen observing frequency range. For CABB, the nominal standard frequencies are 2100, 5500, 9000, 17000/19000, 33000/35000, 43000/45000, and 93000/95000 MHz.

Switching between the 15/3mm bands, the 6/3cm bands, and the 16cm band involves a change in feed horns by means of a turret rotation. This is done automatically under computer control and takes about 20 seconds. Turret rotation should be limited to once every 15 minutes unless a compelling scientific case is made for more frequent rotations. The additional overhead in changing to or from 7mm has been described earlier in this document.

Observing frequencies may be set to the nearest half-MHz only and no on-line Doppler tracking is done.

Observations of weak H90 $\alpha$  recombination lines *may be* affected by a trapped mode in the 6/3cm horn at  $8857 \pm 18$  MHz. There are also notches reported in the passband due to trapped modes in the receiver waveguides at  $1326 \pm 10$ ,  $5328 \pm 10$  and  $8780 \pm 10$  MHz which may need to be flagged during data reduction.

### 1.5.2 Interference

In the lower frequency bands radio frequency interference (RFI) may be a problem. The interference is worse at lower frequencies with the main offenders being microwave links, microwave TV, microwave ovens, navigation satellites and self-generated interference. There has also been significant interference at 1381 MHz from the GPS L3 beacon on occasions. These channels may have to be removed from the data. It is wise to watch for interference by continually displaying the spectrum of the signal received on the shortest baseline. You can then note any channels with narrowband interference for subsequent elimination. The frequency range of 2300 to 2400 MHz, formerly occupied by microwave TV services, is presently clear again.

Recently, a very strong new source of RFI has been noted, with primary peaks of 1265 and 1310 MHz. When this RFI is present (usually during daylight hours and on weekdays, leading it to be called "midweek RFI"), large portions of the 16cm band become unusable due to harmonics of these two frequencies.

To avoid solar interference, a rule-of-thumb is to observe at a time of year when your source is further than about 40° from the Sun, where possible. It is recommended to specify in your proposal dates that are not suitable for observations if the sun angle is too small. Low-frequency observations, particularly in spectral-line mode, should be made at greater distances. You are advised to observe at night in cases where good quality 21cm HI data is essential on the shortest (30m) baseline. For spectral-line observations, software exists in MIRIAD to model and subtract out solar interference. Some information about solar activity can be obtained from the [Ionospheric Prediction Service \(http://www.ips.gov.au/\)](http://www.ips.gov.au/).

There appears to be no significant interference within the mm bands.

## 1.6 Choosing Angular and Frequency Resolution

### 1.6.1 Image Complexity, Angular Resolution and Observing Time

A synthesis imaging telescope such as the Compact Array provides a great deal of flexibility when deciding how to image an object. In addition to the well-known trade-off between observing time and sensitivity, we have trade-offs with maximum resolution and with the sampling interval in the visibility plane.

The choice of angular resolution is fairly straightforward. Increased angular resolution (resulting from longer baselines) leaves the point-source sensitivity constant, but decreases brightness sensitivity in proportion to the beam area (see Table 1.2).

The choice of  $(u, v)$ -plane coverage is more difficult. The amount of independent information needed to specify the image should not exceed the number of independent  $(u, v)$ -plane samples. But unfortunately neither of these 'independents' is easily defined. At one extreme, consider making a high resolution image of a complex source filling the entire primary beam. In this case full  $(u, v)$ -coverage is obtained by using all

baselines between 30m and 6000m in increments of 15m. Although this was theoretically possible (it takes 25 separate array configurations), it was never attempted and, since the decommissioning of the second 6km station, is no longer actually possible!

If on the other hand the image is smaller than the primary beam then the Nyquist sampling interval is larger and the number of  $(u, v)$ -samples required is reduced. The observing time can then be reduced either by decreasing the number of configurations or the amount of hour angle coverage, depending on the array configuration. For east-west arrays, reducing the total number of configurations is the more practical option. If the source is large but partly empty it can be considered to have a size corresponding to its area. For ordinary observations gives the maximum sizes of structures that can be reliably imaged for typical sets of observing configurations. This is only a rough guide since the actual coverage needed depends on details of the 2-dimensional brightness distribution, on the actual distribution of baselines, and on the type of deconvolution. Additionally, other techniques such as [Mosaicing \(page 22\)](#) and [Multi-frequency Synthesis \(page 23\)](#), can be extremely effective at improving  $(u, v)$ -coverage.

A further consideration is the minimum spacing available. This is never less than 30 m and for a given configuration can be much larger. This acts as a high-pass filter removing all Fourier components less than the minimum spacing. If this is a serious problem, short baseline information (e.g., from a single dish) can be added separately during processing.

### 1.6.2 Array Configurations and Baselines

Antenna 6 sits permanently on station W392. Maximum baselines to this antenna (the last 5 columns) are shown for all configurations in section [Array Configurations \(page 105\)](#), but form part of a designed array only for configurations 6.0A to 6.0D.

The antennas can be moved to, and set up on, a limited number of fixed stations. Because of this and other physical restraints, the shortest spacing available is 30 m, the longest is 6 km, and the minimum grating increment is 15 m. Predetermined east-west configurations are offered, each with approximately uniform spacings, and thus with good single-day  $(u, v)$ -coverage. From 2006 October, the standard set of configurations has been:

- 1 hybrid configuration with a nominal maximum baseline of 75 m (H75)
- 1 hybrid configuration with a nominal maximum baseline of 168 m (H168)
- 1 hybrid configuration with a nominal maximum baseline of 214 m (H214)
- 2 east-west configurations with a maximum baseline of about 375 m
- 4 east-west configurations with a maximum baseline of about 750 m
- 4 east-west configurations with a maximum baseline of about 1500 m
- 4 east-west configurations with a maximum baseline of about 6000 m.

Snapshot observations using the Northern spur in hybrid configurations will generate a two-dimensional sampling of the  $(u, v)$ -plane. The Northern spur was installed so that good coverage of the  $(u, v)$ -plane was achievable for observations which are limited to hour-angles near transit. Observations at mm wavelengths should be limited to higher elevations to avoid large atmospheric opacities. Hybrid arrays are also useful for observations of northern sources which are similarly restricted in hour-angle range.

The 6 km antenna may also be added to any of the shorter configurations, but in these cases the distribution of array spacings is bi-modal.

The predetermined set of configurations offered for forthcoming observing terms will assist in planning multi-configuration proposals. See <http://www.narrabri.atnf.csiro.au/observing/configs.html> for details of previous configurations and those being offered in coming semesters, or see [Table 1.3](#).

Note that proposals requiring two or more configurations will usually be allotted two or more widely separated times; therefore, expect to make two or more observing visits, or conduct the second observation using remote observing. If you are not allotted all the configurations requested, you should re-apply in the next term, as the proposal will not be automatically reconsidered.

The overall philosophy is that, in each semester, there will be a 6km, 1.5km, and 750m configuration, and for these baselines, the full set of 4 configurations will generally be covered in three semesters. Each semester will also contain at least one 375m configuration. Analysis of user preferences for the past few years show some configurations to be more generally useful (e.g., providing better single-configuration  $(u, v)$ -coverage), and it is desirable to offer these more frequently. Millimetre observing conditions are optimal in the (southern hemisphere) winter, so arrays of 214m or smaller will be offered mainly in the April semester.

Semester	2010APRS	2010OCTS	2011APRS	2011OCTS	2012APRS
Array					
6A	•	•	•	•	•
6B			•		
6C	•			•	
6D		•			•
1.5A		•		•	
1.5B		•			•
1.5C			•		
1.5D	•			•	
750A		•			•
750B			•		
750C	•			•	
750D		•		•	
EW367		•		•	
EW352	•	•	•	•	•
H214	•	•	•		•
H168	•		•	•	•
H75	•		•		•

Table 1.3: Array configurations that will be offered in future semesters.

Besides the predetermined configurations, you can request any standard or non-standard configuration in any term. When writing your application, your scientific justification should include a very convincing argument of why you need to use a special array configuration, rather than one of those offered for the term. If you realise the need for such a 'wildcard' request for a significant amount of observing time (e.g., more than  $5 \times 12\text{h}$ ), you can enhance the probability of it being scheduled if you contact ATNF well in advance of the deadline (preferably even before the call for proposals announcement). The wildcard can then be advertised as a potential additional configuration for the term, which may then lead to other proposers requesting it, and making its scheduling viable.

For those who wish to improve their  $(u, v)$ -coverage by re-observing on different days with different antenna configurations, specific sets of configurations combines well, e.g., 6A, 6C, 1.5B and 1.5D — for more details see

[http://www.narrabri.atnf.csiro.au/observing/users\\_guide/html/ATCA\\_Array\\_Configurations.html](http://www.narrabri.atnf.csiro.au/observing/users_guide/html/ATCA_Array_Configurations.html).

An interactive tool, the *Virtual Radio Interferometer* (VRI), is available to assist users in exploring the  $(u, v)$ -coverage of standard (and non-standard) configurations; it can be found at

<http://www.narrabri.atnf.csiro.au/astronomy/vri.html>.

It is strongly recommended that the proposer gives a clear indication of the maximum extent of their sources. You should also specify the maximum and minimum baselines, and the number of configurations (days) needed.

### 1.6.3 Bandwidths and correlator

The CABB now provides a variety of frequency resolutions. The available resolution options are more commonly denoted by the CABB configuration that is used to provide them. When development of CABB is complete, four correlator configurations will be offered:

#### Currently available modes

- **CFB 1M-0.5k**: 2048 channels per 2048 MHz continuum IF (1 MHz coarse resolution), and 2048 channels per 1 MHz zoom band (0.5 kHz fine resolution).
- **CFB 64M-32k**: 32 channels per 2048 MHz continuum IF (64 MHz coarse resolution), and 2048 channels per 64 MHz zoom band (32 kHz fine resolution). This mode is not yet fully developed. Currently, the continuum bands contain all thirty-two 64 MHz channels, but only one of these channels can be selected by the user for a zoom band in each IF.

There is also a rudimentary “hybrid” mode available which provides one continuum 2048×1 MHz IF, and one 64 MHz zoom band in the other IF, sacrificing 2 GHz of bandwidth.

#### Modes available in the future

- **CFB 4M-2k**: 512 channels per 2048 MHz continuum IF (4 MHz coarse resolution), and 2048 channels per 4 MHz zoom band (2 kHz fine resolution).
- **CFB 16M-8k**: 128 channels per 2048 MHz continuum IF (16 MHz coarse resolution), and 2048 channels per 16 MHz zoom band (8 kHz fine resolution).

It should be noted that the correlator routinely computes double the number of channels as is recorded. This second set of channels is offset from the available set by half the channel width, and are there to provide flexibility in choosing the zoom band frequency, as well as to ensure that it will always be possible to avoid observing a spectral line at the edge of a channel. It is also possible to combine a number of overlapping zoom bands that are separated by half a continuum channel into a seamless single zoom band.

## 1.7 Additional Observing Notes and Techniques

### 1.7.1 Short Observations

You may not wish to make detailed high resolution images but instead, for example, survey a large number of compact or simple sources. Under these circumstances, if the sources are strong enough, short observations will suffice (Table 1.4). In scheduling these, slew time becomes an important consideration; these may be calculated see [Mosaicing \(page 22\)](#), or more easily, by running `ATCASCHED`. A single short observation in an E-W array will give a 1-dimensional strip distribution; two or more short observations will give some 2-dimensional information. In such short observations consequent higher sidelobe levels will exacerbate problems caused by confusing sources in the primary beam. Because the Compact Array has poor  $(u, v)$ -coverage, in contrast to its good sensitivity, this confusion makes it difficult to reach the receiver noise limit when observing weak sources or searching for detections, particularly at lower frequencies. Current experience suggests that at 6cm at least 8 short observations well distributed in hour angle are needed to reduce confusion to the noise level. At 16cm, short observations are unlikely to ever reach the noise limit.

Observing Time	6 or 3km	1.5km	0.75km
25 days	6'[a]	-	-
12 days	4.5'	6'	-
4 days	160"	4'	8'
2 days	115"	160"	5'
1 day	80"	115"	230"
6x 1-10 min[b]	30"	50"	100"
1-10 min[c]	20"	40"	80"

[a] For other wavelengths, scale sizes by  $\lambda/6\text{cm}$

[b] Well distributed in hour angle

[c] One-dimensional information only

Table 1.4: Largest well-imaged structure at 6cm wavelength.

### 1.7.2 Polarimetry

Two orthogonal linear polarisations are measured simultaneously. The position angle of the polarisation splitter is stationary with respect to the alt-az-mounted antennas and so rotates on the sky. A suite of tasks in MIRIAD is available for polarimetric calibration of Compact Array data. No specific calibrators, other than the usual flux and gain calibrators, are needed for polarisation calibration. An observation of B1934-638 is essential when only making short observations. Small drifts with time can be corrected for using the on-line measurements of the  $XY$  phase differences to an accuracy of 0.5 degrees at all bands. Best polarimetric calibration results when the gain calibrator is observed at a good sampling of different parallactic angles.

MIRIAD is routinely used to calibrate data in all bands, with consistent results being achieved over several months in the cm bands. The on-axis instrumental polarisation is typically below 2-3%. After calibrating for instrumental polarisation, we are currently able to reduce on-axis instrumental effects to 0.1%, and better with some care. Procedures for 3mm polarisation observations are still being established.

The off-axis polarisation increases roughly as the square of the distance from the pointing centre at least up to the half-power point. At 16, 6 and 3cm, the instrumental polarisation is about 1.6%, 9%, 1.6% and 3% of the *apparent* total intensity at the half power point, respectively. At 16 and 6cm this error is almost purely linearly polarised (there is no circularly polarised component), whereas at 3cm the circularly polarised component is somewhat less than 1% at the half-power point.

Because the ATCA antennas have an alt-az mount, the off-axis response varies with parallactic angle, and will be smeared out by a factor of a few by a long synthesis. This smearing is a function of declination. The MIRIAD task OFFPOL can be used to simulate off-axis polarimetric response of a long synthesis observation. Mosaicing smears out the off-axis response still further, by as much as an order of magnitude.

At 16cm, instrumental polarisation has significant frequency dependence, showing variations of several percent at 1327 and  $1444 \pm 5$  MHz. Leakages of more than 10% occur at  $4550 \pm 10$ ,  $5328 \pm 10$  MHz and  $8780 \pm 10$  MHz. Data near these frequencies may need to be flagged.

### 1.7.3 Mosaicing

Objects which are of similar size or larger than the primary beam will need to be *mosaiced*. In such cases, the recommended spacing of pointing centres is half of the primary beamwidth. The Compact Array antennas and control system allow for rapid switching between pointing centres — as frequently as once per integration cycle. This enables a source to be rapidly mosaiced without necessarily losing  $(u, v)$ -coverage. In mosaicing mode, data is not recorded when antennas are driving between fields. The antenna acceleration limit is 800 deg/min/min, and the slew limit is 38 deg/min in azimuth and 19 deg/min

in elevation. Mosaicing mode may also be useful for observing large numbers of nearby sources, as the observing overheads are reduced.

There is also a facility for “on-the-fly” mosaicing, whereby the antennas are continuously driven. This type of mosaicing may be especially useful for large-area mosaics at low frequencies, where the drive times between mosaic pointings are significant.

Section [How to Prepare a Mosaic File \(page 41\)](#) explains how to set up mosaic files. The [Miriad User Guide \(<http://www.atnf.csiro.au/computing/software/miriad/userguide/userhtml.html>\)](#) describes how to reduce a mosaic data set.

### 1.7.4 Multi-frequency Synthesis

As  $(u, v)$ -distance is proportional to frequency as well as baseline length, different  $(u, v)$ -spacings can be obtained not only by varying the antenna configuration, but also by varying the frequency.

Additional  $(u, v)$ -coverage can be obtained in the mm bands by observing at multiple frequencies. Observing at two frequencies has the added advantage of increasing sensitivity, as they can be observed simultaneously. Observing more than two frequencies requires time sharing. While this will not improve the sensitivity further, it can significantly improve the  $(u, v)$ -coverage. However, there is a trade off between gaps in the tangential and radial directions in the  $(u, v)$ -plane. Typically two or three pairs of frequencies, observing each setting for 10 minutes, is a good compromise.

When you use both bandwidth synthesis and two or three configurations, and require  $(u, v)$ -coverage to 6km, the best choice of configurations is not two or three 6km arrays, but a combination of 6km with 1.5km and 750m arrays (all arrays using the 6km antenna).

The flux density of most sources will often vary significantly between different frequencies and, furthermore, this variation itself (i.e., the spectral index) will vary across the source. This complicates the task of combining data from the different frequencies when you want high-dynamic-range images. However software is available in MIRIAD to account for the spectral variations in the imaging, deconvolution and self-calibration steps. These algorithms solve for, or use, both a basic flux-density image and a spectral-index image. For typical spectral indices, they are appropriate for frequency ratios less than about 1.25.

### 1.7.5 Reference Pointing

After each antenna reconfiguration a pointing solution is determined. Generally, rms errors of around 5 arcsec are achieved at this time. These solutions degrade with thermal (and other) effects. By the time observations are undertaken, rms errors of about 10 arcsec (or more) are likely. There is a significant offset (of up to 30 arcsecs) between the mm and the cm receivers.

A reference pointing mode is available which is recommended for mm observations. In this mode, a 1 Jy calibrator, about  $5^\circ$  to  $10^\circ$  away from the target will hold the pointing to 10 arcsec rms. A bright (say 5 Jy) calibrator at  $2^\circ$  to  $3^\circ$  from the target will reduce the errors to about 5 arcsec rms. A reference pointing scan generally takes 3-4 minutes to complete. See the [Reference Pointing Guide \(<http://www.narrabri.atnf.csiro.au/observing/pointing>\)](#) for details.

## 1.8 High Time Resolution, Pulsars, Planets and VLBI

### 1.8.1 High Time Resolution and Pulsar Observing

CABB now offers a pulsar binning mode, and will soon offer a high time resolution mode.

In pulsar binning mode, the correlator cycle time (normally 10 seconds) is divided into an integer number of pulsar periods. Each pulsar period is further divided into  $N$  equal time intervals called bins. The integration in the correlator is done separately for each bin, such that at the end of the cycle,  $N$  quantities are produced, each of which represents the integrated value at a particular pulsar phase.

The pulsar binning mode is still in development, and the number of bins, and the pulsar period needs to be set in the correlator configuration. To do this, it is necessary to discuss your project requirements with observatory staff, particularly Warwick Wilson, before your observations.

The correlator will also record both the full 2 GHz continuum bands in addition to the pulsar binning data, analogous to how the zoom modes are recorded.

Time binning mode should be available very soon, and will likely offer 10-20 ms time resolution.

### 1.8.2 Solar System Objects

The Compact Array can track sources with non-sidereal rates, such as planets or comets. In this case delay tracking is adjusted continuously to account for source proper motion. However the pointing tracks a fixed celestial position during a scan. Thus scans must be short enough that there is not significant proper motion across the primary beam in the course of a scan. This is rarely a problem.

JPL ephemerides of the planets are built into the observing program, and a simple mechanism exists to import current JPL ephemerides of other solar system objects (e.g. new comets).

### 1.8.3 Tied Array Mode

A tied array capability is available. It provides tying of the array at one or two frequencies and, for CABB, initially at a bandwidth of 64 MHz.

The tied array adder is controlled via a process called `catie` which runs within `CACOR`. This allows the choice of which antennas are included and whether the adder produces linear or circular polarisation outputs. The array is phased up in the usual way, and an option to allow the insertion of a 90° phase offset between the A and B linear polarisations at each antenna – thereby forming circular polarisation at the tied-array output – is available.

The tied-array adder can be fed into the LBA (*Long Baseline Array*) DAS which provides outputs for the VLBI disk-based recorders at bandwidths between 62.5 kHz and 64 MHz. Simultaneous Compact Array and tied array operation is possible, although currently this is limited to 64 MHz in both IFs, or 64 MHz in one IF and the full 2 GHz (which is not formed into a tied array) in the other.

## 1.9 Other Things to Consider

### 1.9.1 Confusion

The presence of field sources in the primary antenna beam can limit continuum image quality. These sources produce unwanted sidelobes in the images and can lead to dynamic range and aliasing problems. The brightest source expected on average in the half-power primary antenna beam (away from the Galactic plane) is listed in Table 1.1. Note that confusion becomes much worse as you go to lower frequencies, and that this can be particularly serious for snapshot observations (See [Short Observations \(page 21\)](#)). The [SUMSS catalog and database \(http://www.astrop.physics.usyd.edu.au/sumsscat\)](http://www.astrop.physics.usyd.edu.au/sumsscat), and the [Molonglo Galactic Plane Survey \(MGPS-2\) catalogue and database \(http://www.physics.usyd.edu.au/sifa/Main/MGPS2\)](http://www.physics.usyd.edu.au/sifa/Main/MGPS2) are useful references to search for potential confusing sources in the 16cm band, where the effects of confusion are greatest.

### 1.9.2 Weather

At short wavelengths and/or long baselines, atmospheric refraction can cause serious phase errors. The problem becomes progressively less serious at longer wavelengths and shorter baselines. Atmospheric conditions are most favourable during winter and at night. A seeing monitor at Narrabri continuously monitors the phase stability at a frequency of 21 GHz and over a baseline of 200 m. See [The ATCA Seeing Monitor \(http://www.atnf.csiro.au/observers/docs/7mm/seeing.pdf\)](http://www.atnf.csiro.au/observers/docs/7mm/seeing.pdf) for details<sup>1</sup>.

### 1.9.3 Artefacts

As with other synthesis instruments, system errors such as DC offsets and sampler harmonics can lead to artefacts at the centre of the field. These artefacts have not yet been observed to affect the data from

<sup>1</sup> This paper describes the initial system. In 2008 a new satellite beacon was adopted, resulting in a change in the frequency from 30GHz to 21GHz.

the CABB correlator, but if such an error would severely degrade your science goals (eg. in a detection experiment), it is preferable to displace the source positions a few (synthesized) beamwidths from the field centre.

## 1.10 Submitting a proposal

The Compact Array usually operates under a semester system with two application deadlines each year: June 15 for observations from October 1 to March 31; and December 15 for observations from April 1 to September 30. During each semester array maintenance, upgrades and array reconfigurations (moving the antennas to different stations) are scheduled in addition to astronomical observations.

Target of Opportunity (ToO) requests for observations of extremely important transient or non-predicted events can be made at any time, see [http://www.atnf.csiro.au/observers/apply/too\\_apply.html](http://www.atnf.csiro.au/observers/apply/too_apply.html) for details.

Based on previous experience, observing at 3mm usually ends by October 15, restarting in late April. Detection experiments at 7mm and 15mm usually end by October 31, restarting in early March. Observations of bright compact sources, for which self-calibration is possible, may be made throughout the year. Observations at times other than those indicated above require an explicit justification in the proposal.

For information about the current status of the ATNF facilities see:

<http://www.atnf.csiro.au/observers/apply/avail.html>.

Before submitting proposals to observe particular objects, you should check that the observation you are proposing has not already been made. Previous Compact Array proposals and observations can be found in the ATOA (Australia Telescope Online Archive) (<http://atoa.atnf.csiro.au/>). After the proprietary period has expired, the data files from previous observations may be downloaded from ATOA. An archive of older proposals (submitted between 1990 Quarter2 and the 2005 OCTS observing semester) is held in the [Projects Database](http://www.atnf.csiro.au/observers/search_proj.html) ([http://www.atnf.csiro.au/observers/search\\_proj.html](http://www.atnf.csiro.au/observers/search_proj.html)).

All ATNF Telescope Applications must be submitted using OPAL (<http://opal.atnf.csiro.au/>).

### 1.10.1 A 'Friend'

First-time observers may wish to request a 'friend' who can help them write the schedule file in Sydney prior to coming to the observatory. To request a friend, check the box in your proposal for observing time; or if you decide later to request a friend, email [atnf-enquiries@atnf.csiro.au](mailto:atnf-enquiries@atnf.csiro.au) as soon as possible after observing schedules have been published.

Your 'friend' will be an ATNF astronomer in Sydney, who will help you create schedule files and get you started with the data analysis after the observations. The 'friend' does not go to the observatory with you.

A duty astronomer (or DA, [http://www.narrabri.atnf.csiro.au/observing/support/da\\_support.html](http://www.narrabri.atnf.csiro.au/observing/support/da_support.html)) is provided at Narrabri who will help in the initial setting up of the telescope and with any problems which arise in the course of the observations. In addition, they may also help with schedule preparation and initial data analysis, although requesting a 'friend' is a better option for observers that require this help, as they will be involved much earlier than the DA. The duty astronomer however has no obligation to participate in the observing.

## 1.11 Successful Proposals

If your proposal is successful and is assigned observing time, you should be notified shortly after the Time Allocation Committee meeting.

Generally, at least one member of the observing team must be present at the observatory for the observations. ATNF staff will be available to help and instruct observers. The visiting observer should be well-versed with needs of their observing program before arriving, particularly if they did not write the observing proposal or schedule files. Remote Observing is only available for experienced observers.

Occupational Health and Safety regulations require that observers are not to observe for more than 16 hours, so **for long observations you will need more than one observer**.

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Plan your trip to the Compact Array with the help of the ATNF [Visitor's Information](http://www.atnf.csiro.au/observers/visit) (<http://www.atnf.csiro.au/observers/visit>). You will need to book transport, accommodation and computer resources in Sydney and at the observatory before arrival.

Note that multi-configuration observations are likely to occur weeks or even months apart, so you may need to plan either one long visit or several short trips.

New observers should plan on spending at least one day (during normal business hours) at the observatory to prepare for their observations. A few days spent at the ATNF Sydney headquarters is also recommended but not necessary. Overseas observers will require a valid visa and passport for entry into Australia.

The Compact Array is controlled from user generated schedule files. We recommend you prepare your schedule files before arrival at Sydney or Narrabri.

Schedule files are prepared with the CABB web scheduler at:

<http://www.narrabri.atnf.csiro.au/observing/sched>.

Schedules contain source names, positions, frequencies, bandwidths, and any other information that CAOBS needs for observations.

COORD is a useful program that tells you the altitude, azimuth, and rising and setting times of astronomical objects, which may help with preparation of your schedule files. Currently, this is most easily accessed via the [Parkes website](http://www.parkes.atnf.csiro.au/cgi-bin/utilities/coord.cgi) (<http://www.parkes.atnf.csiro.au/cgi-bin/utilities/coord.cgi>). When using this tool be sure to change the site to Australia Telescope Compact Array, and change the elevation limit to 12 degrees for cm observing at the ATCA.

### 1.11.1 The Duty Astronomer

A Duty Astronomer will be present at the observatory to get your observations started and help with any problems that arise during the observations. The list of duty astronomers can be found at <http://www.narrabri.atnf.csiro.au/observing/support>. The Duty Astronomer has **no obligation** to participate in the observing.