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# Base Band Data for Testing Interference Mitigation Algorithms

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**Abstract:** Digital signal processing is one of many valuable tools for suppressing unwanted signals or interference. Building hardware processing engines seems to be the way to best implement some classes of interference suppression but is, unfortunately, expensive and time-consuming, especially if several mitigation techniques need to be compared. Simulations can be useful, but are not a substitute for real data. CSIRO's Australia Telescope National Facility has recently commenced a 'software radio telescope' project designed to fill the gap between dedicated hardware processors and pure simulation. In this approach, real telescope data are recorded coherently, then processed offline. This paper summarises the current contents of a freely available database of base band recorded data that can be used to experiment with signal processing solutions. It includes data from the following systems: single dish, multi-feed receiver; single dish with reference antenna; and an array of six 22 m antennas with and without a reference antenna. Astronomical sources such as OH masers, pulsars and continuum sources subject to interfering signals were recorded. The interfering signals include signals from the US Global Positioning System (GPS) and its Russian equivalent (GLONASS), television, microwave links, a low-Earth-orbit satellite, various other transmitters, and signals leaking from local telescope systems with fast clocks. The data are available on compact disk, allowing use in general purpose computers or as input to laboratory hardware prototypes.

**Keywords:** instrumentation: detectors — interferometers — techniques: interferometric — methods: data analysis

## 1 Introduction

Radio astronomers make passive use of wide spectral bands (sometimes hundreds of MHz) outside the much smaller bands allocated for passive use. The prime motivation for this is achieving greater sensitivity, since sensitivity improves as the square root of the bandwidth for broadband sources. The wide spectral bands inevitably carry other legally licensed emissions, which are typically much stronger than the desired astronomical signals. Without the means to suppress unwanted signals, the utility of wideband astronomy systems may be limited. Furthermore, astronomical spectral line sources are at very specific frequencies. If interference is also present in these frequency channels, we need a suppression approach that makes these frequency channels usable. We have already reached the point where it can be difficult to obtain good-quality data for particular experiments. In the next 10–20 years, when next-generation radio telescopes such as the Square Kilometre Array (SKA) and Low Frequency Array (LOFAR) are built (Butcher 2000), suppressing interference will be essential. There is no silver bullet for mitigating against interference. A successful mitigation approach is most likely to be hierarchical or progressive through each of the telescope, signal conditioning and signal processing systems (see Ekers & Bell 2000 for a summary). The techniques of blanking time samples or frequency channels that are affected by interference are already used extensively for observations of astronomical sources. In this paper, we focus on digital signal processing solutions for tackling the suppression problem, and present a data base to use in testing techniques.

In many communications systems the modulation or coding of the desired signal is known. As shown in Figure 1a, the modulation or coding signal can be used at the receiver as a reference signal for adaptively selecting the desired signal in preference to the interfering signal. For most radio astronomy this is not possible because there is no coded or modulated signal, just band-limited or frequency-dependent noise. As a result, radio astronomy is forced to try to find a reference signal for the interference (see Figure 1b), use that to adaptively select the interference, then cancel it. There are many well-known adaptive suppression techniques (Haykin 1995; Widrow & Stearns 1985; Ellingson 1999) ready for testing. The key outcomes of those tests are the level of suppression they can achieve (up to 80 dB may be necessary), and how harmful

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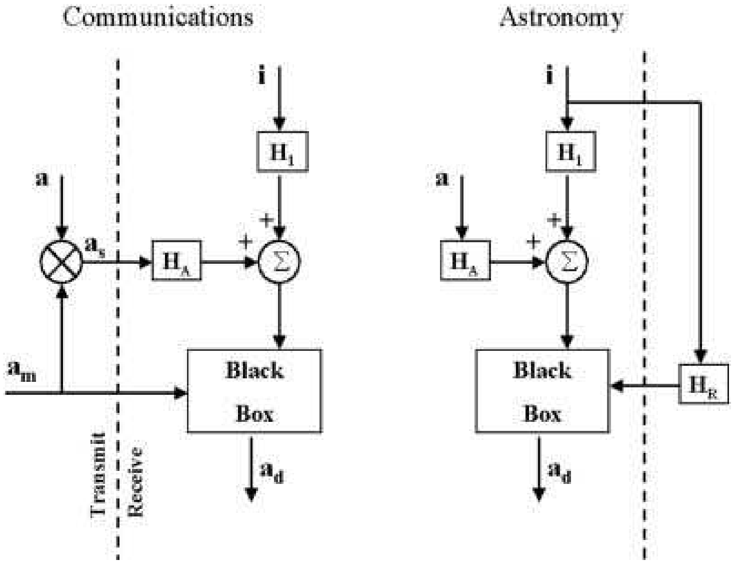

**Figure 1** (a) Left: Typical communications system, where the known modulation or coding $a_m$ (which applied to the data signal $a$ gives the transmitted signal $a_s$) is used in a black box to select the desired signal in preference to the interference, giving the detected data signal $a_d$. $H_A$ and $H_1$ are the unknown transmission functions of the desired and interfering signals respectively. (b) Right: Typical radio astronomy system, in which the properties of the desired signal $a$ are unknown and a reference signal for the interference must be obtained instead via some other receiver (to the right of the dashed line).

or toxic they are to the weak astronomical signals. Some have already been successfully tested with astronomical data (Leshem and van der Veen 2000; Leshem, van der Veen & Boonstra 2000; Barnbaum & Bradley 1998; Ellingson & Hampson 2000; Sault 1997; Kewley, Sault & Ekers 1999; Briggs, Bell & Kesteven 2000; Kesteven et al. 2000; Kewley et al. 2000).

Finding a high-quality reference signal for the interference is of key importance. There are several ways of devising a suitable reference:

1. From a prior knowledge of the modulation or coding properties of the interference. Using the data presented here, Ellingson, Bunton & Bell (2000) have demonstrated a parametric cancelling technique that uses the known coding sequence of signals from GLONASS (the Russian global positioning system) to cancel them.
2. Use of a specially designed, separate reference antenna that optimises the interference-to-noise ratio, and does not detect the astronomical signals. A simple horn was used as a reference antenna to obtain some of the data presented in this paper. These data have already been used to demonstrate effective cancelling of interfering signals from a point-to-point microwave link (Briggs, Bell & Kesteven 2000). Barnbaum & Bradley (1998) also used such an antenna with a real-time, least-mean-square (LMS) based adaptive canceller to remove frequency modulated (FM) transmissions.
3. Use of multi-feed receiver systems, such as the Parkes 21 cm multibeam receiver (Staveley-Smith et al. 1996), allowing a reference signal to be obtained by cross-correlating signals from groups of receivers to form a reference for another (Sault 1997; Kewley, Sault & Ekers 1999). The dataset described in this paper includes data from the multibeam receiver. Tests by Briggs, Bell & Kesteven (2000) and Barnbaum & Bradley (1998) suggest that this is not as effective a reference as a separate antenna.

In this paper we summarise data in which all the above methods for obtaining reference signals are used. The interfering signals and how they affect astronomical observations made at the CSIRO ATNF Parkes and Narrabri observatories are described in Section 2. The properties of the reference antenna are described in Section 3. The available data, including formats and sample spectra, are presented in Section 4. Matlab scripts for reading the data are available at http://www.atnf.csiro.au/SKA/intmit/.

## 2 Properties of Interfering Signals

The kinds of interfering signals we chose included terrestrial communications (television and microwave links), space-based communication and navigation systems (GLONASS, GPS, LEO satellite) and astronomical sources such as the Sun. These were chosen because they either already cause problems or are expected to cause more problems in the future. Details of the transmissions discussed below were obtained from the Australian Communications Authority (ACA) databases (Australian Communications Authority 1998; Sarkissian 1999), except where otherwise noted.

**Sun:** While the sun is an interesting source of radio waves to some, to others it is one of the most dominant sources of interference. Unlike the communications signals discussed below, it is not band-limited in any sense and affects observations at all frequencies. It is particularly troublesome to spectral-line and continuum observations, but pulsar observations have some immunity due to their periodic nature. In principle it can be treated as just another source of interference.

**MW links:** A number of microwave (MW) links were recorded. These are digital, point-to-point or fixed-to-mobile services. They do not necessarily impinge on vital spectral lines, but they are the most numerous of the unwanted signals. As an example, the 1499 MHz NSW government point-to-point MW link is a persistent source of interference due south of the Parkes telescope, causing 3–4% of the data to be discarded from the Parkes multibeam pulsar survey (Manchester et al. 2000). The 1503 MHz MW link from Mt Dowe (east of the CSIRO ATNF Australia Telescope Compact Array at Narrabri, NSW) is another persistent source of interference.

**MDS TV:** The Multipoint Distribution Service (MDS) TV transmitter on Mt Dowe, due east of the ATCA at Narrabri, has strong transmissions around 2350 MHz. While these do not affect known spectral lines, they do disrupt 13 cm continuum observations.

**GLONASS:** Many papers in the astronomical literature cite problems with interference from the Russian *Global'naya Navigatsionnaya Sputnikovaya Sistema* (GLONASS) system of navigational satellites when trying to observe 1612 MHz OH spectral-line emission. GLONASS satellites transmit at frequencies between 1602 and 1616 MHz, and have shared primary user status with radio astronomy for the 1610·6–1613·8 MHz band (Combrinck, West & Gaylard 1994). There are 24 carrier frequencies spread over the 14 MHz band at intervals of 0·5625 MHz. The carrier is modulated by a pair of noise-like, equal-power, pseudo-noise (PN) codes of 0·511 and 5·11 MHz. The unfiltered sinc$^2$ side lobes of these signals have relative power levels as high as $-25$ dB, extending out to 20 MHz on either side of the main carrier in some cases (Galt 1991). GLONASS satellites launched more recently do have some band-limiting filters. Galt (1991) & Combrinck et al. (1994) both present data demonstrating the damaging effect of GLONASS signals on astronomical data. Some reports have stated that up to 50% of observations have had to be discarded (Galt 1991).

**GPS:** GPS is the rather better known US equivalent to GLONASS. GPS also has a constellation of 24 satellites. In this case all the satellites transmit at frequencies of 1575 MHz, 1380 MHz and other military frequencies. Each satellite uses a different pseudo-noise code but they all contain 1023 chips (0° or 180° phase shifts) and run at a chip rate of 1·023 MHz. There is also an equal-power 10 MHz-wide military signal. The signals in the 1380 MHz band cause the most trouble for radio astronomy. This is because redshifted 1420 MHz H I emission or absorption at particular velocities may occur in the 1380 MHz region. In practice, it severely affects about 5% of the data from the Parkes multibeam H I survey (Barnes et al. 2000).

**LEO Satellites:** Low-Earth-orbit and hence fast-moving satellites are likely to present significant challenges in the future. For example, the parametric signal modelling technique used to suppress GLONASS signals (Ellingson, Bunton & Bell 2000) required the carrier phase to be adjusted about once every millisecond. If such a technique was to be applied to signals from a LEO satellite, the update rate would be about 10 times faster. The LEO satellite chosen for one recording session was UO-11, designed for amateur radio experimentation at 2401·5 MHz. UO-11 orbits at a height of 674 km.

## 3 Reference Antenna

Many interference mitigation algorithms are limited by how well the interfering signals can be characterised, and in practice this depends on the interference-to-noise ratio (INR). Mostly the interfering signals are received through the 0 dBi side lobes of parabolic dish radio telescopes, or side lobes of the feed systems. One way to obtain a higher INR is to use a reference antenna with a gain somewhat higher than the 0 dBi dish side lobes. We obtained an old 1400 MHz band horn with a 60° beam width and a gain of 10 dBi that was once used to illuminate the CSIRO ATNF Parkes dish. This was coupled to a transition and some borrowed ambient-temperature RF amplifiers. The system temperature of the completed package, determined from hot and cold load measurements, is 450 K (dominated by the amplifiers). Other details of the system perfomance are given in Table 1. Our packaging of the feed and electronics is somewhat unusual in that the assembly is housed in a plastic bucket, earning the reference front-end the appellation 'bucket receiver' (see Figure 2). The improved INR obtained with the reference receiver is clearly shown in Figure 3. Far from being a state-of-the-art system, the reference receiver is a low-cost, first prototype.

## 4 Description of Available Data

### 4.1 Array Data: ATCA at Narrabri

The first dataset from CSIRO's Australia Telescope Compact Array (ATCA) at Narrabri (designated aieo in Table 2) included an OH source and interfering signals from a LEO

**Table 1. Properties of the reference antenna**

| | |
|---|---|
| Frequency (MHz) | 1400–1600 |
| Gain (dBi) | 10 |
| System temperature (K) | 450 |
| Nominal amplifier noise figure (K) | 360 |
| Beam width (degrees) | 60 |
| Polarisation isolation (dB) | −20 |
| Return loss (dB) | −15 |
| Noise coupling (dB) | −35 |

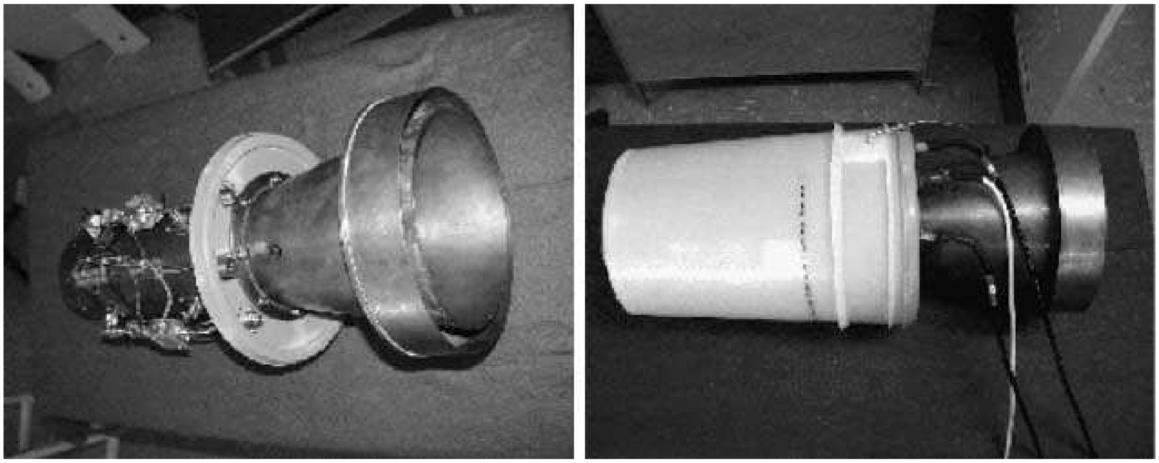

**Figure 2** The reference receiver. (Left) Uncooled front-end amplifier system. (Right) Waterproofed for outside use and ready to go!

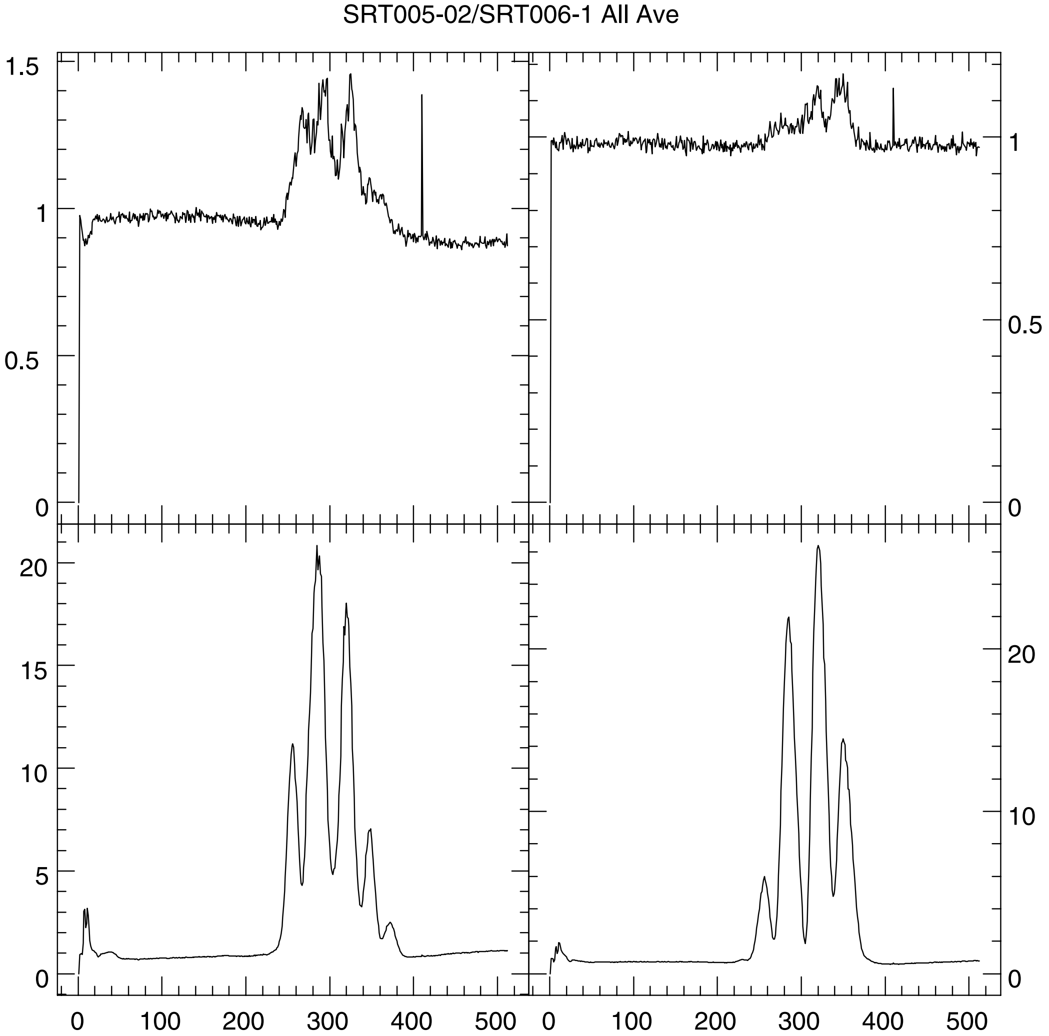

**Figure 3** Averaged autocorrelation spectra from SRT005_02 centred on 1499 MHz with 512 spectral bins across the 5 MHz bandwidth. The top two panels show two linear polarisations from the centre beam of the multibeam. The bottom two panels show two linear polarisations from the reference receiver. In all cases the vertical axes are amplitude and the horizontal axes are spectral bins.

**Table 2. Parameters for data taken 1998 June 04, 1999 Nov 04 and 1999 Nov 05**

The J2000 position of IRAS 1731–33 is 17:35:02·3 –33:33:31, the positions of the other sources are those in standard catalogues. The MDS TV and 1503 MW link transmitters are on nearby Mt Dowe, which is due east of the array. No reference antenna was available for the aieo datasets. For datasets designated srtca16–20 the reference receiver was removed and antenna 1 was connected back into the signal path in the normal way. However, it was moved away from the astronomical source to investigate the use of a slightly mispointed antenna as a reference. # Data are currently available on CD for these datasets; the other datasets can be put onto CD upon request. MW link = microwave link, AGC = automatic gain control.

| Dataset | UT | Astro. Source | Interf. | Freq. | S2 on | S2 off | AGC | Reference antenna |
|---|---|---|---|---|---|---|---|---|
| aieo01# | 17:33 | IRAS 1731–33 | GLONASS | 1610 | — | — | on | none |
| aieo02# | 18:02 | none | LEO, MDSTV | 2402 | — | — | on | none |
| srtca01# | 06:41 | PKS 1934–638 | MW link | 1503 | 00:00 | 00:15 | on | Reference – Mt Dowe |
| srtca02# | 07:00 | none | MW link | 1503 | 00:15 | 00:30 | on | Reference – Mt Dowe |
| srtca03 | 07:30 | PSR B1749–28 | MW link | 1503 | 00:30 | 00:41 | on | Reference – Mt Dowe |
| srtca04 | 07:45 | PKS 1934–638 | MW link | 1503 | 00:41 | 00:51 | off | Reference – Mt Dowe |
| srtca05 | 08:04 | PKS 1934–638 | MW link | 1503 | 00:11 | 01:02 | on | Reference – Mt Dowe |
| srtca06 | 08:23 | PSR B1749–28 | MW link | 1452 | 01:02 | 01:14 | on | Reference – Mt Dowe |
| srtca07 | 08:36 | PSR B1749–28 | MW link | 1452 | 01:14 | 01:22 | off | Reference – Mt Dowe |
| srtca08# | 03:42 | PKS 1934–638 | MW link | 1452 | 01:22 | 01:36 | on | Reference – Mt Dowe |
| srtca09# | 04:31 | PKS 1934–638 | GPS | 1575 | 01:36 | 01:52 | on | Reference – Az330, Z45 |
| srtca10 | 04:47 | PKS 1934–638 | GPS | 1575 | 01:52 | 02:05 | on | Reference – Az330, Z45 |
| srtca11 | 05:00 | PKS 1934–638 | GPS | 1575 | 02:05 | 02:21 | off | Reference – Az330, Z45 |
| srtca12# | 05:47 | PSR B1749–28 | GPS | 1575 | 02:21 | 02:32 | on | Reference – Az330, Z45 |
| srtca13 | 05:58 | PSR B1749–28 | GPS | 1575 | 02:32 | 02:42 | off | Reference – Az330, Z45 |
| srtca14# | 06:45 | IRAS 1731–33 | GLONASS | 1613 | 02:42 | 02:55 | on | Reference – Az330, Z45 |
| srtca15 | 07:03 | IRAS 1731–33 | GLONASS | 1613 | 02:55 | 03:10 | off | Reference – Az330, Z45 |
| srtca16# | 10:13 | PKS 1934–638 | MW link | 1503 | 03:10 | 03:20 | on | CA01 2° off |
| srtca17 | 10:32 | PKS 1934–638 | MW link | 1503 | 03:20 | 03:31 | on | CA01 2° off |
| srtca18# | 10:51 | PKS 1934–638 | GPS | 1575 | 03:31 | 03:40 | on | CA01 2° off |
| srtca19 | 11:17 | PSR J0437–4715 | GPS | 1575 | 03:40 | 03:50 | on | CA01 2° off |
| srtca20 | 11:30 | PSR J0437–4715 | MW link | 1503 | 03:50 | 04:01 | on | CA01 2° off |

satellite, MDS TV and GLONASS (Smegal & Wilson 1999). The data contain single-polarisation 8 MHz bandwidths, sampled using 4 bits for each of six antennas. A second Narrabri experiment (designated srtca in Table 2) collected more such data, but this time with dual polarisation, more carefully controlled sampler levels and a separate reference antenna. In this case 4 MHz of bandwidth was recorded with 4-bit dynamic range. Recordings included interfering signals from GLONASS, GPS and microwave links, together with astronomical signals from an OH maser, a pulsar and a continuum source. The reference receiver was bolted onto the backing structure of the easternmost antenna (antenna 1) (that is, the unshadowed antenna closest to the transmitters on nearby Mt Dowe, east of the ATCA). The main reason for doing this was (a) to simplify the cabling required to connect the signals into the standard conversion system, and (b) to make use of the antenna drive systems in pointing the reference receiver. While the reference receiver was in use, no astronomical signals were recorded from antenna 1. The outputs of the reference receiver were fed via heliax cable and plugged directly into the input of the 1400 MHz-band RF module of the ATCA receiver conversion system (Gough & Graves 1999). The locations of the antennas and other system parameters for the datasets are summarised in Table 3. In both cases, the data were recorded using three S2 recorders (Cannon et al. 1997), allowing a total recording rate of 384 Mb s$^{-1}$. The data were extracted from the S2 tapes using the s2tci system (Wietfeldt et al. 1998), demultiplexed and stored on DLT and CD media. Table 2 summarises the data collected. Sample spectra for a range of the datasets are shown in Figure 4a–f. These spectra were obtained by integrating several seconds of data in most cases. The mapping of the 4-bit levels is as follows:

| Bits | Levels | Bits | Levels |
|---|---|---|---|
| 1000 | −7·5 | 0000 | +0·5 |
| 1001 | −6·5 | 0001 | +1·5 |
| 1010 | −5·5 | 0010 | +2·5 |
| 1011 | −4·5 | 0011 | +3·5 |
| 1100 | −3·5 | 0100 | +4·5 |
| 1101 | −2·5 | 0101 | +5·5 |
| 1110 | −1·5 | 0110 | +6·5 |
| 1111 | −0·5 | 0111 | +7·5 |

In the aieo dataset, there is one polarisation and one antenna per file, each of which contains a simple stream of 4-bit numbers. In the srtca dataset, there are two polarisations and two antennas per file. Each file contains four interleaved 4-bit data streams, with each 16-bit

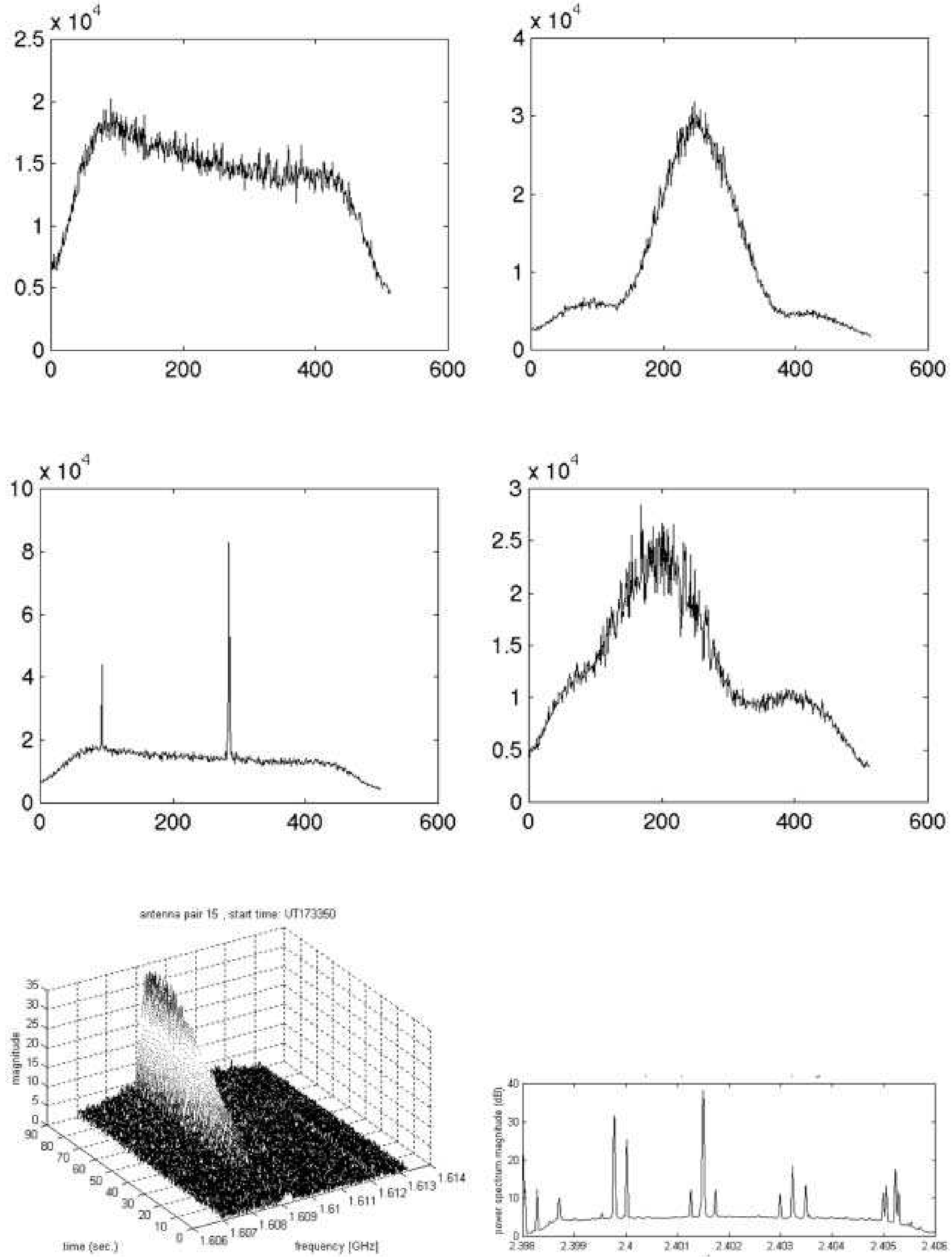

**Figure 4** Example spectra from the Narrabri datasets. The scales for the top four plots contain 512 spectral channels covering the 4 MHz bandwidth on the *x*-axis and amplitude on the *y*-axis. (a) Top left: srtca_14_01—a clean passband useful for bandpass calibration. (Note: During this scan we were aiming to detect GLONASS, but no GLONASS signal appeared.) (b) Top right: srtca_01_01—MW link at 1503 MHz. (c) Middle left: srtca_08_01—MW link at 1452 MHz. (d) Middle right: srtca_18_01—GPS at 1575 MHz. (e) Bottom left: aieo01—GLONASS at 1609·3 MHz. (f) Bottom right: aieo02—LEO satellite at 2401·5 MHz and intermodulation products (*x*-axis scale is frequency in GHz).

word containing:

| Bits | Antenna | Polarisation |
|---|---|---|
| 0–3 | 1 | 1 |
| 4–7 | 1 | 2 |
| 8–11 | 2 | 1 |
| 12–15 | 2 | 2 |

### *4.2 Parkes 64 m*

At Parkes the DLT-based Caltech–Parkes–Swinburne recorder (CPSR) system was used (van Straten et al. 2000). A range of interferers (including point-to-point MW links and the Sun) and astronomical sources (pulsars) were recorded; details are summarised in Tables 3 and 4. The first dataset obtained contains dual polarisation for two beams from the multibeam system, the idea being to use one as the reference antenna for the other. However, a much higher interference-to-noise ratio was obtained by using the reference receiver. The reference receiver was placed on the landing outside the top floor of the Parkes control room (as indicated schematically in Figure 5a). From there, heliax cables carried the signals directly into the control room and down-conversion equipment. Consequently the cable run is substantially shorter for the reference receiver than for the multibeam, leading to a significant delay mismatch between the two systems.

For both of the datasets collected, the resulting four signals were converted to base band. In the case of the multibeam however, base band 0–320 MHz signals were obtained from the regular multibeam equalisers. These signals were then passed through 5 MHz low-pass filters and fed directly into the CPSR, that is, the normal CPSR

**Table 3. Configuration of the ATCA and Parkes observations**

The six antennas are designated CA01–CA06; distances are in m.

| Dataset | AIEO | SRTCA | SRT |
|---|---|---|---|
| Array configuration | 0·750E | 0·210 | — |
| CA01 position (m) | 2100·0 | 1500·0 | — |
| CA02 position (m) | 2205·0 | 1530·6 | — |
| CA03 position (m) | 2520·0 | 1561·2 | — |
| CA04 position (m) | 2580·0 | 1668·4 | — |
| CA05 position (m) | 2730·0 | 1714·3 | — |
| CA06 position (m) | 6000·0 | 6000·0 | — |
| Bandwidth (MHz) | 8·0 | 4·0 | 5·0 |
| Sampling rate (MHz) | 16·0 | 8·0 | 20·0 |
| Bits per sample | 4 | 4 | 2 |
| Number of data levels | 16 | 16 | 4 |
| Range of data levels | $-7{\cdot}5\ldots+7{\cdot}5$ | $-7{\cdot}5\ldots+7{\cdot}5$ | $-3,-1,1,3$ |
| System temperature (K) | 40 | 40 | 25 |
| Polarisations | 1 linear | 2 linear | 2 linear |
| Polarisation isolation (dB) | — | $\sim$15 dB | $\sim$15 dB |
| UT date | 1998 Jun 04 | 1999 Nov 05 | 1999 Jul 03 & Nov 19 |
| Reference antenna used | no | yes | yes |

**Table 4. Summary of data from Parkes using beams 1 and 13 of the multibeam system (UTdate = 1999 Jul 03) and using beam 1 of the multibeam and the reference antenna (UTdate = 1999 Nov 19)**

All signals were translated to a base band centre frequency of 2·5 MHz. *For this dataset the multibeam receiver was tuned away from the interferer, so an interference-free recording is available for bandpass correction, or comparison of the pulsar signals. The interference in datasets SRT002_03 and SRT002_04 may be from local sources, the VLBI data acquisition system and S2 recorder. # Data are currently available on CD for these datasets; the other datasets can be put onto CD upon request.

| Dataset | UT | Astron. source | Interferer | Frequency | Astron. ant. | Ref. ant. |
|---|---|---|---|---|---|---|
| SRT001_08# | 11:07:00 | PSR J0437–4715 | MW link | 1499 | Mb1 | Mb13 |
| SRT002_01 | 12:06:30 | PSR J0437–4715 | MW link | 1525 | Mb1 | Mb13 |
| SRT002_02# |  | PSR J0437–4715 | MW link | 1440·5 | Mb1 | Mb13 |
| SRT002_03 | 12:47:20 | Vela | unknown | 1422 | Mb1 | Mb13 |
| SRT002_04 | 13:26:30 | Vela | unknown | 1547·5 | Mb1 | Mb13 |
| SRT002_05 | 13:26:30 | Vela | Sun | 1547·5 | Mb1 | Mb13 |
| SRT005_01# | 09:37:00 | none | MW link | 1499 | Mb1 | Reference |
| SRT005_02# | 09:37:00 | none | MW link | 1499 | Mb1 | Reference |
| SRT006_01#* | 10:24:35 | PSR J0437–4715 | MW link | 1509/1499 | Mb1 | Reference |
| SRT006_04# | 10:26:39 | PSR J0437–4715 | MW link | 1499 | Mb1 | Reference |

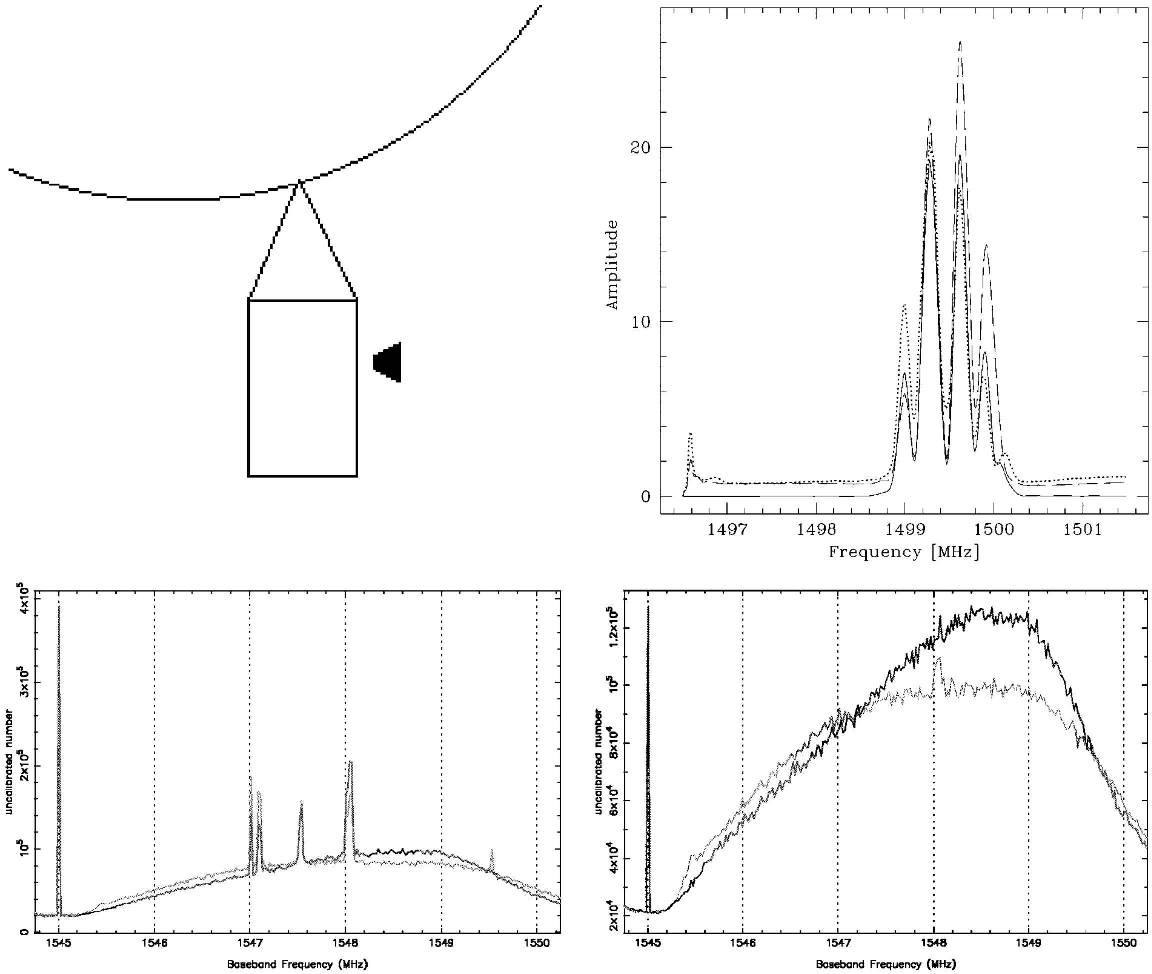

**Figure 5** (a) Top left: Location of reference antenna relative to telescope. At the time of the experiments it was pointing south, towards the town of Parkes. (b) Top right: SRT005_02, interference from a NSW government microwave link. (c) Bottom left: SRT002_04, some narrowband interference of unknown origin. (d) Bottom right: SRT002_05, interference from the Sun.

quadrature sampling down-converter was bypassed. The CPSR recording system was then used to 2-bit sample the data at 20 MHz (50 ns resolution) and write it to DLT tape in 1 GB files. The data are therefore oversampled by a factor of two. Four 2-bit samples (i.e., one for each of the four channels) are packed into each byte in the files on tape and on disk. Unfortunately, it was only possible to record 2-bit data with the CPSR system, as the 4-bit recording mode was not working at the time. Example spectra in Figure 5 show the nature of some of the interfering signals.

## 5 Conclusions

This database has proved very useful, with a number of interference suppression algorithms being successfully tested and improved (Ellingson, Bunton & Bell 2000; Briggs, Bell & Kesteven 2000; Kewley et al. 2000; Kesteven et al. 2000). So far we have really only scratched the surface of the problem, and many more tests, comparing different algorithms and their toxicity, are required. Since we advertised that this dataset is freely available, 50 CDs have been distributed to about 12 different groups who are also experimenting with their favourite algorithms.

## Acknowledgments

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