Development of an Ultra-Wideband (UWL) Receiver System at Parkes

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Summary

- Installation of a wideband "UWL" receiver covering the band 0.7 GHz to 4.0 GHz on the Parkes 64-m telescope, together with the 20cm Multibeam receiver, would allow more than 90% of current Parkes observations to be made with no receiver changes, greatly improving the efficiency of Parkes operations.
- The digital receiver system could be configured for all types of pulsar observation (except multibeam searches) as well as spectral-line, background and source polarisation observations and VLBI.
- The UWL receiver covers the entire ASKAP band and hence can provide vital short-spacing data for ASKAP as well as make possible a highly sensitive real-time interferometer for ASKAP follow-up studies.
- The UWL receiver would significantly improve the sensitivity of all pulsar timing observations, including those for the Parkes Pulsar Timing Array, and make possible unique studies of frequency-dependent phenomena such as interstellar dispersion, scattering and Faraday rotation as well as studies of pulsar emission mechanisms.
- Development of the state-of-the-art UWL receiver and signal processing system will allow Parkes to maintain its role in producing high-impact science and the CASS engineering groups to maintain their world-leading expertise into the SKA era.
- Coping with the inevitable RFI across the very wide band of the UWL receiver is obviously of paramount importance. With careful attention to receiver linearity and the use of adaptive RFI filtering, at least 90% of the band should be available for astronomy 95% of the time.
- The receiver could be built in two years or less, allowing Parkes to remain competitive for at least the next 8 – 10 years.
- National and international collaborations will allow cost sharing and there are possibilities for external funding that can be explored.

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1. Introduction

This document makes a case for the development of an ultra-wideband receiver covering the band 0.7 GHz to 4.0 GHz and the associated signal-processing system for use on the 64-m Parkes radio telescope. The receiver is named the Ultra-Wideband Low-frequency (UWL) receiver to distinguish it from another proposed ultra-wideband system covering the 5 GHz to 25 GHz band (which could be labelled the "UWH" receiver). The proposed system is similar to a receiver constructed by the Max-Planck-Institut für Radioastronomie for the Effelsberg 100-m radio telescope but has some important differences. The MPIfR receiver covers the band 0.6 GHz to 3 GHz and uses a JPL feed design, whereas the proposed Parkes receiver is at a somewhat higher frequency to avoid the Mt Canobolas digital TV (DTV) transmissions and has an improved feed designed at CASS by Alex Dunning.

A principal motivation for the construction of the UWL receiver is to improve the efficiency of Parkes operations by reducing the number of receiver changes required for normally scheduled observations. This aspect of the case is presented in §2 below. Following its 2012 meeting, the Australia Telescope Users Committee (ATUC) supported the development of new receivers for Parkes with the goal of improving the performance and operational efficiency of the telescope.

The UWL receiver will also greatly improve the efficiency of observations for the Parkes Pulsar Timing Array (PPTA) project, largely since the currently required doubling-up of observations to cover the 10cm, 20cm and 50cm bands will not be needed. Furthermore, the simultaneous frequency coverage over the UWL band will greatly improve correction for dispersion-measure (DM) variations — currently a limiting factor for most PPTA studies — as well enhance science outcomes for a range of projects including pulsar scintillation studies, Faraday rotation measurements including rotation-measure synthesis, studies of the Galactic background polarisation, spectral-line observations and VLBI. In addition, it is ideally suited to provide short-spacing data for ASKAP. These arguments are presented in §3.

The proposed UWL receiver system is at the cutting edge of current receiver and signal-processing technology. As such it will help the CASS engineering staff maintain their current high international reputation as receiver designers and constructors; this is discussed in §4.

With the very wide band and relatively low frequency of the UWL receiver, satisfactory management of the Parkes radio-frequency interference (RFI) environment is very important. Issues related to RFI are discussed in §5.

2. Parkes Operations

Because of budgetary pressures within CASS, there is currently a strong push to improve the efficiency of Parkes operations. With its wide bandwidth and expected low system noise, the UWL receiver would make a major contribution to improved operational efficiency at Parkes by reducing the frequency of receiver changes. Essentially all non-multibeam pulsar observations, which currently occupy close to 40% of scheduled Parkes observing time, could use the UWL receiver. In addition, non-pulsar observations which currently require the "H–OH" receiver, ASKAP tests and some VLBI observations (those at frequencies < 4 GHz), occupy a further 25% of scheduled time. All of these could be made with the UWL receiver. Of the remaining 35%, 20cm Multibeam observations occupy more than 25%. Most of the remaining 10% is for observations at frequencies between 4 GHz and 25 GHz.

Consequently, with a UWH receiver covering 4 GHz – 25 GHz and sharing one side of the translator with the UWL receiver, and the 20cm Multibeam receiver or a future PAF system on the other side of the translator, almost all current Parkes operations could proceed with *NO* receiver changes. Even without the UWH receiver, about 90% of current operations could proceed with no receiver changes. The only significant project incompatible with the 20cmMB/UWL/UWH configuration is "S-X" VLBI, primarily used for geodetic measurements. Both internationally and within Australia, these measurements are increasingly being made with dedicated small-antenna arrays with rapid slew speeds; consequently the demand for the "S-X" system at Parkes will probably decrease as these arrays become more established.

Similar considerations apply to the signal-processing ("back-end") system – an integral part of the UWL development. It is planned that the entire RF band will be directly digitised in the focus cabin with no analogue down-conversion. The digitised baseband signals will be transmitted over optical fibre to the control room for processing by a GPU-based processor. This processor will have great flexibility and will be programmable for observations of pulsars, both "fold" and "search" modes, spectral-line observations, continuum observations and VLBI observations. Maintenance and installation of separate back-end systems for these different observing modes will therefore be avoided, improving operational efficiency.

The fully digital receiver system (after the RF amplifiers) also means that remote operation will be readily achievable, with all control and monitoring via web interfaces.

3. The Science Case

Parkes produces high-impact science! Of the 20 most highly cited papers based on observations using CASS facilities since 2000, 18 were based on Parkes observations and, of these, 12 were based on pulsar observations. The most highly cited paper is the Parkes discovery of the Double Pulsar (Lyne et al., Science, 2004) with 341 citations. It is vital for the continued high profile of CASS within CSIRO, within the Australian and international astronomy communities and with the general public, that high-impact science continues to be produced by CASS facilities – pulsar research at Parkes is at the forefront of this!

In this section we summarise the main science projects that would benefit from having the UWL receiver at Parkes.

3.1. The Parkes Pulsar Timing Array

The Parkes Pulsar Timing Array (PPTA) project (Manchester et al. 2013) has three major goals: 1) to make the first direct detection of gravitational waves (GW), 2) to develop a pulsar-based time standard and 3) to improve knowledge of our Solar System. We have made significant progress towards each of these goals. Hobbs et al. (2012) used the PPTA data sets along with earlier Parkes observations to develop the first pulsar-based time standard that has a precision comparable to the world-best atomic time standards. Champion et al. (2010) used a subset of the PPTA data along with observations from observatories in Europe and the USA to derive the most precise published estimate of the mass of the Jovian system. While we have not yet detected GW, we have recently submitted a paper to Science (Shannon et al. 2013) that uses the PPTA data to obtain the most constraining upper bound on the existence of a background of GW at nanohertz frequencies. As Figure 1 shows, the PPTA data set is by far the best data set of its type available and now seriously limits currently preferred models for black-hole formation and merger in distant galaxies. It hardly needs stating that a direct detection of GW would be of huge significance, especially given the enormous efforts going into development of laser-interferometer GW detection systems world-wide.

While the PPTA data set is the most precise and extensive of any such data set world-wide, we still need to improve it to optimise our sensitivity to GW detection and other PPTA goals. Replacing our existing receiver suite with the UWL receiver would

- Improve the signal-to-noise of the pulse profile for a given observation and hence improve the precision with which we can measure the pulse arrival times. Many of the PPTA pulsars scintillate strongly and hence vary in strength according to the distribution of scintles in the observed band. The UWL receiver would average over many scintles and remove this source of variation.
- We are currently limited by our ability to correct for dispersion measure variations. Errors in these corrections introduces both red and white noise into the residuals. The wide instantaneous frequency coverage of the UWL receiver will significantly reduce the uncertainty in these corrections and hence the amount of added or residual noise.
- Avoid the need to observe separately with two receivers (multibeam and 10/50cm), thereby doubling the number of observations in each band in a given observing time. Also, since few or no receiver changes will be needed, more time will be available for productive observing.

The UWL receiver would therefore substantially increase the PPTA sensitivity for all our major project goals. We have developed a suite of simulation software that can be used to quantify the improvement. This software produces simulated pulse arrival times for each of the PPTA pulsars including realistic session durations and intervals, realistic system temperatures for the different bands, actual pulse widths and flux densities as a function of frequency and realistic dispersion and

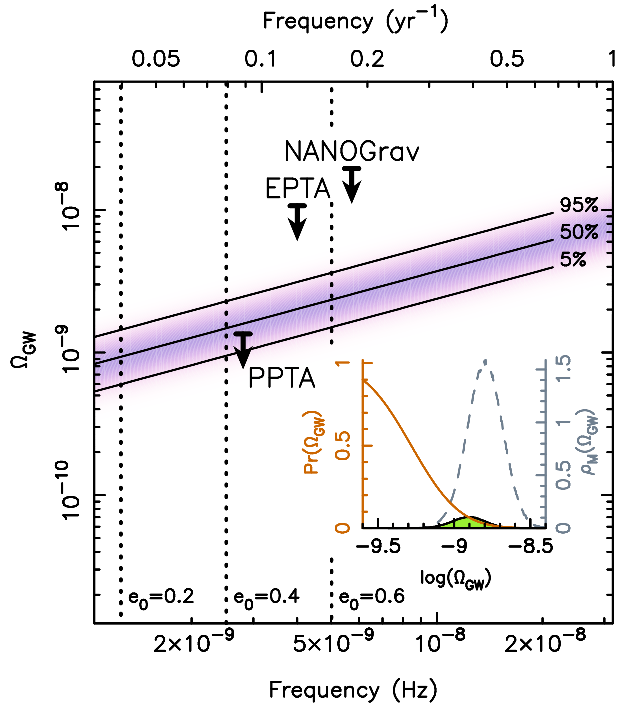

Fig. 1.— Energy density of a GW background in the Galaxy, expressed as a fraction of the closure density of the Universe, as a function of GW frequency. The limit from PPTA obervations is substantially better than similar limits from the other main international PPTA projects. The sloping percentile line give the range of predictions of the background based on the Millenium dark-matter simulation and a widely accepted model for black-hole formation and growth in galaxies. The PPTA result rules out these predictions with 95% confidence, suggesting that black-hole formation in early galaxies is not as ubiquitous as current models predict. (Shannon et al. 2013)

scintillation variations as a function of frequency. Up to now, we have not been limited by intrinsic red period noise, so this is not included in the simulation. For the UWL receiver, assumed to be available in 2015, we assumed a system temperature of 21K plus sky background and rejected 10% of the band as unusable because of RFI. As discussed in §5 below, some or most of the RFI may be removable using real-time adaptive filters. The simulated pulse arrival times can be generated with arbitrarily extended data spans and then be processed in the same manner as the actual data to search for the GW background.

Our current upper bound on the amplitude of the GW background (Figure 1) corresponds to an amplitude for the stochastic GW background $h_c = 2.5 \times 10^{-15}$, but is unlikely that the gravitational wave amplitude is at this level. For the simulation we have assumed an amplitude of 1.0×10^{-15}, at the low end of current predictions. Figure 2 compares the expected detection significance with our existing receiver suite and if the UWL receiver became available in 2015. Although a detection

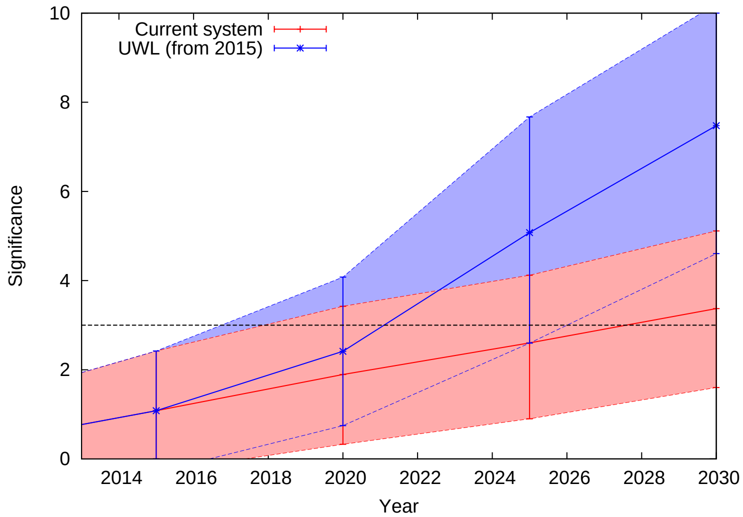

Fig. 2.— Significance of detecting a GW background with an amplitude $h_c = 1.0 \times 10^{-15}$ for data spans extending out to 2030. The red band assumes continuation of the present receiver suite and the blue band assumes that the UWL receiver becomes available in 2015. The significances have a range of values for any given data span primarily because of the stochastic nature of the GW background.

could be claimed with a significance of three, detailed investigation of the properties of the GW signal require higher significance. Figure 2 shows that a significance of five is attained about a decade earlier with the new receiver. Furthermore, the rate at which the significance grows is much greater. This is largely because the greater sensitivity and efficiency of the UWL receiver allows us to substantially increase the sample of pulsars that contribute to the detection. We estimate that it will be possible to add 14 additional pulsars to the PPTA as soon as the new receiver is available with no increase in total observing time and the simulations assume this.

We note that these simulations are conservative in the sense that they assume continuation our current observing and analysis practices (apart from the extra pulsars). We can expect improvements in sensitivity from changes in both these areas. On the other hand, intrinsic pulsar period noise may become an issue with longer data spans. Also, we are collaborating with the EPTA and NANOGrav to produce combined "International Pulsar Timing Array" (IPTA) data sets and ultimately to optimise observing schedules at the different observatories. Because of the diverse nature of the data sets, it is difficult to predict how much more sensitive the IPTA will be, but there is no doubt that the time to a significant detection will be reduced.

These simulations assume that the actual GW signal passing over the pulsars and the Earth is an isotropic, stochastic background. It is possible that the first detection will be of an individual GW source. Various authors (e.g., Sesana et al. 2009; Ravi et al. 2012) predict that a few massive, nearby binaries will be individually detectable by PTAs. The detection of gravitational waves from such systems would make possible the first direct observational tests of the astrophysics of massive black hole coalescence in galaxy mergers. Massive black hole binaries may have large orbital eccentricities. In this case most of the GW emission is concentrated near "periastron" resulting in GW bursts lasting of order months. GW bursts have also been predicted from oscillations of cosmic strings and cosmic superstrings (e.g., Damour & Vilenkin 2005). The parameters of these bursts are extremely uncertain but they are predicted to have a similar timescale. Regardless of their origin, in order to detect GW bursts we require wide-band observations with a cadence such that many observations are obtained across the burst. The UWL receiver helps with this since more frequent observations are possible and sensitivity is higher for a given observation time.

3.2. Other Science Applications

The UWL receiver would bring major benefits to a wide range of science projects in addition to the PPTA. These are discussed in the following sub-sections.

3.2.1. Other pulsar projects

All pulsar timing projects would benefit from the high sensitivity and wide bandwidth of the UWL system in just the same way as the PPTA. There are many such projects, e.g., follow-up timing of survey discoveries, pulsar timing observations in support of the *Fermi* Gamma-ray Observatory, long-term timing of binary pulsars, including the Double Pulsar, etc. Studies of transient sources of known position, e.g., RRATs, intermittent pulsars and magnetars would also benefit from the high sensitivity and wide bandwidth of the UWL receiver.

The wide frequency coverage of the UWL receiver would also greatly enhance studies of interstellar scintillation and Faraday rotation with pulsars. Multiple scintillation bands could be observed simultaneously and, given the $\sim \nu^4$ frequency dependence for scintillation bandwidths and timescales, their properties would change enormously over the nearly 6:1 frequency coverage of the receiver, allowing many studies not previously possible. Similarly, rotation measures (RMs) could be obtained for many more pulsars, allowing improved tomographic studies of the Galactic magnetic field. For stronger pulsars, precise measurements of dispersion and rotation measures would reveal their time variations, allowing studies of electron densities and magnetic fields in the Solar wind and parsec-scale structure in the ISM.

Pulsar emission properties are also frequency dependent with different pulse components commonly having different spectral dependencies. The concept of "radius-to-frequency" mapping depends on measurements of pulse widths as a function of frequency. Component spectra, intrinsic pulse modulations and polarisation properties are also a function of frequency. Investigations of all of these properties will benefit from the wide instantaneous frequency coverage of the UWL receiver.

3.2.2. Long-term Future for Pulsar Observations at Parkes

The Parkes 64-m radio telescope is the only large-aperture fully steerable paraboloid in the Southern hemisphere devoted to radio astronomy. Partly because of its southern location, it has played a dominant role in the discovery and timing of pulsars for the past two decades. Many important pulsars are still difficult to observe from anywhere but Parkes, or can only receive limited time when observed from heavily-oversubscribed Northern Hemisphere facilities. Nevertheless, the 100-m Green Bank Telescope (GBT) has had an impact on Parkes competitiveness for some important targets north of -40°, for example, the Double Pulsar and the globular cluster Terzan 5. This is largely the result of the development of wideband receivers and signal-processing systems at the GBT. To maintain Parkes's competitive position for the next 6 or 8 years, development of similar systems is necessary here.

In the more distant future, the main developments of relevance to pulsar astronomy will be the Chinese FAST 500m telescope, the MeerKAT array and SKA-I. FAST will have great sensitivity for observations of sources north of about -10° initially and ultimately north of -30°, with Aeff/Tsys $\sim$ 2000 m^2K^{-1} (compared to $\sim$ 100 m^2K^{-1} for Parkes). The timeline for FAST is somewhat uncertain, but could be operational in 2017 with a limited receiver complement. Currently, no wideband receiver similar to the UWL receiver is planned. The South African MeerKAT array will initially operate in a single band 0.9 – 1.7 GHz and will have full access to the southern sky. With its single-pixel system, achieving the high sampling rates required for pulsar observations should be quite feasible. With recently upgraded receiver technology Meerkat should achieve Aeff/Tsys $\sim$ 300 m^2K^{-1}. Meerkat should be operational by 2017 and will be a powerful pulsar machine. However, for precision timing, the upper-frequency limitation to 1.7 GHz means that ISM effects will be a limiting factor for the stronger pulsars. SKA-I will have comparable sensitivity to FAST but will be able to see the whole southern sky. It is scheduled for completion in 2020, but it is unlikely to be competitive for precision pulsar timing for several years after that. The nature of pulsar timing is such that it often takes two years or more before timing becomes competitive with existing programmes even if the system is nominally superior. Parkes therefore has a window of opportunity until at least 2019 and will remain competitive in certain areas for several years after that.

3.2.3. Spectral-line observations

The band of the UWL receiver covers the rest frequency of several important spectral lines including HI (1.42 GHz), the four ground-state transitions of OH (1.61 – 1.72 GHz) and the three ground-state transitions of CH near 3.3 GHz. Importantly, the wide bandwidth of the receiver allows detection of highly redshifted lines, in particular, HI to $z \sim 1$ and ground-state OH masers to $z \sim 1.3$. Studies of magnetic fields in distant galaxies will be possible through observations of Zeeman splitting of HI and maser lines. There are also a large number of recombination lines of hydrogen, helium, carbon and possibly other elements which may be studied in ultra-compact HII regions and other sources. The GPU-based signal processing system will readily allow a wide range of bandwidths and resolutions for these studies.

3.2.4. Continuum polarisation and RM synthesis

Even though it has been known since the 1960's that the Galaxy possesses an ordered magnetic field, details of its structure and origin remain largely unknown. Studies of the polarisation of the Galactic diffuse emission are key to solving this mystery. For example, the discovery of the giant magnetised lobes near the Galactic Centre, made using the Parkes S-PASS background polarisation survey (Carretti et al. 2013), dramatically changes our ideas about the structure and evolution of the Galactic magnetic field. Observations over a wide frequency range are necessary to investigate different layers of the Galactic medium because the lower frequencies are depolarised relatively nearby, especially in the Galactic disk, while the higher frequencies penetrate further. Galactic magnetic fields can also be studied using large-scale measurements of RMs of discrete background sources (e.g., Van Eck et al. 2011) as well as RMs of pulsars as mentioned in §3.2.1. The UWL receiver will facilitate all of these studies.

In particular, RM-synthesis requires broad frequency coverage to be effective. Observations in the frequency range 0.3 – 4.0 GHz give an RM resolution of 3.5 rad/m^2 and a maximum RM scale of 400 rad/m^2, an ideal range for study most Galactic environments from the halo (low RMs) to the disk (high RMs). Observations of the diffuse polarised emission at Parkes have already been made by the GMIMS (0.3 – 0.5 GHz), STAPS (1.3 – 1.8 GHz) and S-PASS (2.2 – 2.4 GHz) projects, but much remains to be done. The UWL receiver will enable simultaneous measurements of all bands above 0.7 GHz and in particular, the currently unobserved band from 2.4 GHz to 4.0 GHz, which is vital for probing deep into the Galactic disk.

3.2.5. VLBI

The UWL receiver covers the "L-band" (20cm and 18cm) and "S-band" (13cm) bands often used for VLBI. Given on-going developments in VLBI systems, the UWL receiver and signal processing system will allow flexible operation over wider bands than are currently used. For example, this could permit high-resolution studies of magnetic fields in distant galaxies through Zeeman-splitting observations. The signal processing system can easily be configured to directly output data in a VLBI-compatible format, including circular polarisation if required. As discussed above (§2), simultaneous "S–X" (13cm – 3cm) operation, used mainly for geodesy, will require a receiver change once a UWH receiver is installed, but demand for this mode of operation is expected to decline as this work is being taken over by dedicated arrays of smaller antennas.

3.2.6. Low spatial-frequency data for ASKAP

The UWL band covers the ASKAP band of 0.7 – 1.8 GHz. For projects such as GASKAP (Galactic HI), WALLABY (all-sky HI), EMU (all-sky radio continuum) and POSSUM (all-sky background polarisation) where quantifying the large-scale structure is important, it will be either essential or highly desirable to provide the lowest spatial-frequency data. The shortest baselines for the ASKAP array are about 30m, so the Parkes 64-m antenna with the UWL receiver system is ideally suited to providing these data. Already the SPLASH project is using the H-OH receiver on Parkes to provide short-baseline data for GASKAP – this project could be subsumed into a more general one using the UWL receiver, thereby saving valuable observing time. The UWL signal-processing system will be able to provide data in formats compatible with the ASKAP data products.

3.2.7. A real-time interferometer between Parkes and ASKAP – the PAI

A formidable challenge for ASKAP-EMU is to distinguish star-formation galaxies from AGN. VLBI has been used very successfully for this since many AGN cores have a brightness temperature detectable with VLBI while star forming galaxies do not. A single-baseline interferometer is an efficient way of detecting these high-brightness cores. This approach was used very successfully in the Parkes-Tidbinbilla Interferometer (PTI)Norris & Kesteven (2013). The PTI took advantage of an existing real-time radio-link connecting the Parkes and Tidbinbilla antennas to form the world's longest real-time interferometer. Despite being a very low-cost development, it was very successful, generating some 24 journal papers including 3 Nature papers over 10 years, as well as facilitating the early development of the Australia Telescope Compact Array.

The UWL receiver together with wide-bandwidth fibre links to a tied ASKAP array, would enable a next-generation successor to the PTI, the Parkes-ASKAP Interferometer (PAI), having more than an order of magnitude increase in sensitivity over the PTI, mainly from the wider bandwidth (0.7-1.8 GHz). We would propose to select a representative sample of 50,000 sources from EMU with S ¿ 1mJy, and observe each for 10 mins with the PAI, requiring a total of 1 year of observing time, spread over several years. The result would be by far the largest VLBI survey ever attempted, establishing what fraction of radio sources are AGNs, as a function of flux density, which in turn would enable us to interpret the EMU data to sequence galaxy evolution over cosmic time.

4. Engineering Benefits

CASS currently has world-leading engineering teams for the design and construction of analogue receiver systems and digital signal processing systems. In order to maintain and develop these strengths, the groups need challenging projects which are at the cutting edge of technological development. With the ATCA upgrade essentially complete and ASKAP development (at least for the feed and front-end systems) tapering off, the UWL receiver system will provide such challenges. Broad-band systems with high dynamic range and digital receivers are the way of the future for essentially all radio astronomy applications, including SKA development projects. These include design and construction of broad-band feeds and preamplifiers, high-speed digitisers and FPGA signal conditioners, high data-rate optical fibre systems, high-speed digital switches and GPU-based signal-processing systems.

There is considerable scope for national and international cooperation in these engineering developments. The Swinburne University group would be heavily involved in the design and construction of the GPU signal processing system; they already have considerable experience in this area. As mentioned, the MPIfR group are building a similar system for the Effelsberg telescope and NRAO is considering construction of a similar system for the GBT. There is scope for construction contracts with other observatories, for example, the National Astronomical Observatories of China for the FAST 500-m telescope and with Xinjiang Astronomical Observatory for the proposed 110-m QiTai Telescope (QTT). Collaboration is possible with all of these groups to the mutual benefit of both sides.

Considerable progress has already been made by Alex Dunning on a broad-band feed design that overcomes many of the problems experienced by the MPIfR group with the JPL feed design. Figure 3 shows the theoretical power and cross-polar patterns of the new feed at the bottom, middle and top of the UWL band. The performance is excellent with the power patterns closely matching the ideal and the cross-polar response down more than 25 dB relative to the peak gain over most of the pattern and over the entire UWL band. Still to be investigated are cooling the feed and ortho-mode transducer to reduce the effect of losses, and injection of a calibration signal.

5. Radio-frequency Interference Issues

An obvious issue with the UWL receiver is the degree to which the science data are affected by radio-frequency interference (RFI). RFI comes in two main classes: a) relatively narrow-band quasi-steady transmissions and b) broad-band transient signals. Very strong narrow-band signals can result in non-linear responses which dramatically spread the signal in frequency. Transient emissions are a particular problem for pulsar observations since observing systems have high time resolution.

Here we discuss strategies for estimating the current level of RFI at Parkes within and around the band of the UWL receiver (0.7 – 4.0 GHz), estimating likely future developments, and strategies for mitigating the effect of RFI signals.

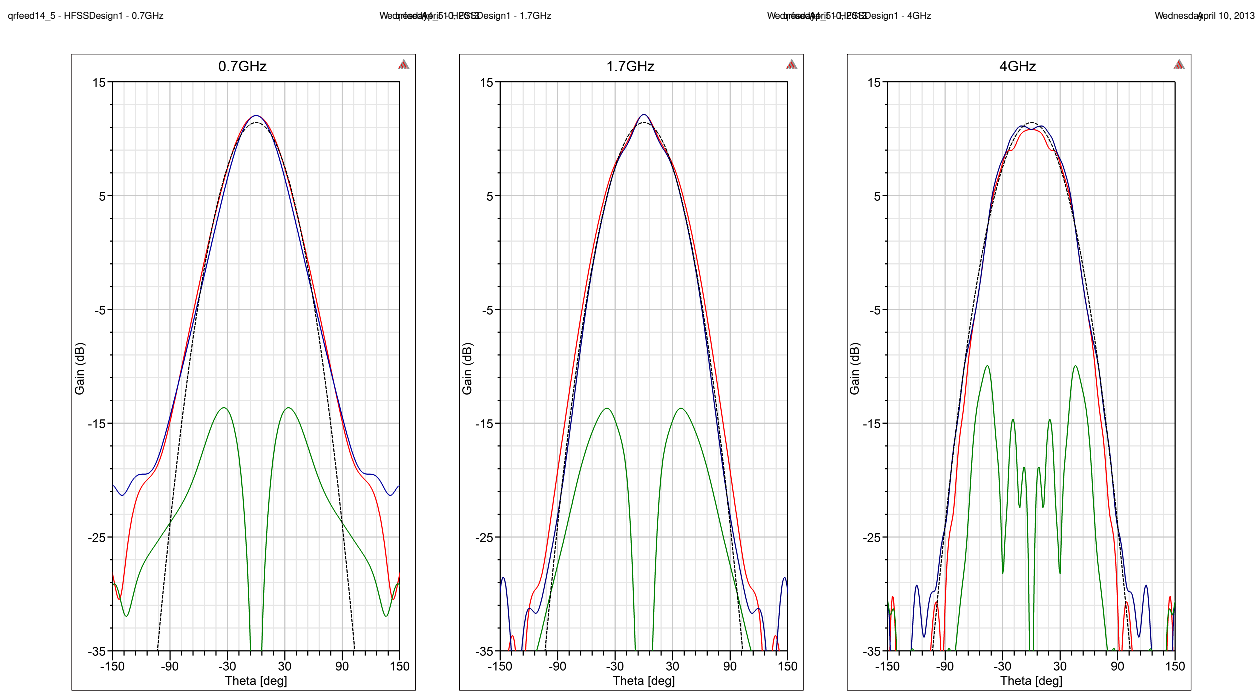

Fig. 3.— Power and cross-polar patterns of a feed design for the UWL receiver by Alex Dunning at three frequencies: left to right, 0.7 GHz, 1.7 GHz and 4.0 GHz. In each case the blue line is the power pattern at 0°, the red line the power pattern at 90° and the green line, the cross-polar pattern at 45°. The dashed line is an ideal power pattern for the Parkes telescope. (Credit: Alex Dunning)

5.1. The current Parkes RFI environment

We have a good knowledge of the Parkes RFI environment in the bands currently used for pulsar astronomy. Although the widths of the observed bands greatly exceed the widths of bands where radio astronomy has some regulatory protection, RFI within them is generally manageable and data quality is not seriously compromised. Outside of the observed bands we have limited knowledge of the radio spectrum and transient interference.

To address this problem, specifically over the band of the UWL receiver, an RFI measuring system covering the band 50 MHz to 6 GHz has been constructed and is being installed at Parkes this week. We will use this to make a high-sensitivity survey of the RFI spectrum and transient activity at Parkes. We aim to repeat the survey at approximately six-monthly intervals to monitor long-term trends in the RFI environment.

Known strong RFI bands affecting the Parkes environmnent are listed in Table 1. Column 3 gives the flux density at the telescope of the in-band signal in dB(W m^{-2} Hz^{-1}). Note that these estimates do not include terrain loss (usually at least a few dB) and so are conservative. For satellite and other transmitters where these parameters are not easy to estimate, observed signal levels from RFI monitoring are taken; this is indicated by "obs" in the Comments column. The next column gives the RFI power received at the preamplifier input in dBm assuming an average sidelobe level of −50 dB relative to the main beam; the effective antenna gain in the far sidelobes (relative to an isotropic antenna) is about +5 dBi. Given the uncertainties in this number, we assume the same effective far sidelobe gain for all frequencies. The amplifier input power levels may be compared with the receiver noise-floor power which is about −89 dBm for $T_{\rm sys} = 25$ K and a 4 GHz bandwidth.

Signals can propagate over the edge of the dish directly into the feed. Given a normal primary beam taper, the feed gain at the edge of the dish is about +3 dBi. Therefore, these "spill-over" signals have very similar levels to those coming in through far sidelobes of the main beam and the levels given in Table 1 are relevant.

Table 1: Known strong RFI bands affecting the Parkes environment

Source	Frequency Range/Bandwidth (MHz)	Flux Density (dB(W m^{-2} Hz^{-1}))	Amp-in Power (dBm)	Comments
Mt Coonambro ATV	412–419	−122	−50	9 × 0.01 MHz
Mt Canobolas DTV	582–637	−116	−23	5 × 7 MHz
Mt Ulandra DTV	652–693	−165	−72	obs, 5 × 7 MHz
GSM Mobile phone	880–915	−131	−56	0.1W @ 1 km, 5 × 0.2 MHz
GSM Mobile base	925–960	−133	−62.5	5W @ 20 km, 2 × 0.2 MHz
Parkes Airport DME	1018/0.1	−180	−116	
ADS-B air navigation	1090/1.2	−134	−57	10km range
GPS L2,L1	1227/2,1575/2	−190	−116	obs
Airborne Defence radar	1260–1335	−90	−20	obs, intermittent
DRCS links	1438/2,1499/2	−175	−98	obs
Thuraya-3	1534–1559	−170	−100	obs, modulated 0.5 MHz bands
Iridium/Globalstar	1610–1626	−180	−107	obs
3G Mobile phone	1920–1980	−145	−63	0.1W @ 1 km, 5 × 5 MHz
3G Mobile base	2110–2170	−147	−69	5W @ 20 km, 2 × 5 MHz

Within the UWL band, the strongest signals are likely to be the airborne Defence radar systems and the ADS-B air-navigation system at 1090 MHz. The former is very strong but only occasionally present. The latter is strong when equipped planes are in Parkes airspace. From 2014 its use will be mandatory on all new aircraft and so it can be expected to be present much of the time. A high-temperature superconducting (HTS) filter between the feed and the preamplifier may be required. Aside from these transmissions, mobile phones used by visitors near the Observatory are likely to be the most problematic. Mobile base stations are not as strong, but are always present. Satellite transmissions are ubiquitous but are usually relatively narrow-band and do not result in non-linear response. Consequently they are relatively easy to filter out in the signal processing system.

Digital television (DTV) signals are broadband (7 MHz/channel) and are the strongest continuous signals in the Parkes environment. Existing transmissions are just below the band proposed for the UWL receiver but may not be significantly attenuated by the feed response. An HTS filter between the feed and the preamplifier may be required.

5.2. Future developments

While we can access some information through the Australian Communications and Media Authority (ACMA) and other relevant agencies, it is very difficult to predict all future developments. For example, satellites can be launched by administrations where we have no control and little access to information. Under the Governments “Digital Dividend”, spectrum in the bands 694–820 MHz and 2500–2690 MHz has been sold to Next-G/4G mobile phone companies. We do not yet know what effect will have on Parkes operations or the timescale on which this may happen. Maintaining close contact with relevant people in ACMA and in the wider communications industry on such issues is essential; such contacts have already been successful in influencing the placement and radiated power of transmission towers in the Parkes area.

Table 2 gives estimated specifications as in Table 1 for known future transmissions affecting Parkes operation. Galileo and BeiDou are the European and Chinese GPS systems respectively. Each has plans for 30 satellites in mid-altitude orbits and each currently has three launched and operating. Both occupy the same spectral bands. The levels for the NBN base station transmissions are estimates based on currently available broadband wireless technologies. Uplink signals from NBN wireless users in the vicinity of the telescope are comparable but likely to be a little stronger.

Table 2: Future RFI bands

Source	Frequency Range/Bandwidth (MHz)	Flux Density (dB(W m^{-2} Hz^{-1}))	Amp-in Power (dBm)	Comments
Galileo/BeiDou	1164–1214, 1260–1300, 1563–1591	−190	−107	15 × 1 MHz
NBN remote	2302–2382	−155	−73	1W @ 5 km, 2 × 20 MHz
NBN base	2302–2382	−160	−78	2 × 20 MHz

5.3. Mitigation strategies

Signals which are strong enough to result in a non-linear response at any point in the receiver chain are mixed with all other signals in the band. If the strong signal is modulated, this modulation is seen in all the mixed products.

Front-end preamplifiers can be designed to avoid significant non-linearity for signals which increase the system noise by 20 dB (100-fold increase) or even more. Strong signals which would saturate the preamplifiers must be avoided by reduced feed gain or by using high-temperature superconducting filters ahead of the preamplifiers. Weaker signals for which the system is linear can be filtered out post-digitisation either by excision or by adaptive filtering if a suitable reference signal is available.

The digitiser itself is a source of non-linearity because of the signal quantisation to a limited number of bits. While 8-bit digitisation is adequate for most purposes, the very high level of some signals in the UWL band may require even more bits. Since very fast (e.g., 8 Gsamp/s) multi-bit digitisers are expensive, it may be worth considering splitting the band into two parts. This would allow use of say 12-bit digitisers and could be designed to avoid a very bad RFI band. For example, the lower band could cover 700 – 1900 MHz and the upper band 2400 – 4000 MHz with two pairs of 4 Gsamp/s digitisers, thereby avoiding the 3G and NBN bands.

Narrow-band signals which do not saturate the amplifier chain, e.g., those from the DRCS links, may be simply excised from the processed spectrum with no significant sensitivity loss. Other signals which cover a wide bandwidth and/or are time variable, e.g., mobile phone transmissions, may potentially be removed by adaptively filtering the digitised signal (Kesteven et al. 2010). This method, which requires an input reference signal containing the RFI, has been successfully applied to remove the Mt Ulandra DTV signals from the original 50cm band. After filtering, the RFI signal in the astronomy channel is reduced to approximately $1/S_r$ of its original strength, where S_r is the signal/noise ratio of the RFI signal in the reference channel. The underlying astronomy signal is unaffected. The filtering can be applied to both polarisations of the astronomy signal using the same reference signal.

For satellite and mobile phone signals, a near-isotropic reference antenna would have to be used. This would have a gain comparable to that of the far sidelobes, so any signal that has an input power of about -70 dBm or more and does not saturate the amplifier chain can effectively be removed from the data.

Impulsive RFI is by its nature broad-band and cannot be removed by spectral filtering. However, since such RFI normally has a very low duty cycle, it can be detected after digitisation and excised from the data stream without significant loss of sensitivity. A system that detects kurtosis in the distribution of digitised baseband voltages has been successfully implemented in the CASPSR recording system at Parkes.

In summary, because of the very broad band and high sensitivity of the proposed UWL receiver, RFI poses a significant challenge to its successful operation. Currently known and expected RFI signals will require a range of mitigation strategies to obtain high-quality astronomy data over the UWL band, but such strategies appear feasible with current technology and it should be possible to obtain good data over 90% of the UWL band more than 95% of the time. A more complete discussion of the RFI issues for the UWL receiver may be found in a report "Parkes RFI and Mitigation", R. N. Manchester (2013).

6. Costs and Timescales

Cost and timescale estimates are still under review, but it is hoped that the receiver and signal processing system can be constructed within two years with a total budget including all capital items, labour and overhead costs of about $900K. George Hobbs' Future Fellowship application included the following statement "CSIRO will fund a design study for the feed design of a 0.7 - 4 GHz receiver package for the Parkes radio telescope, vital for the success of this proposal, and will seek funding to contract the new receiver." (Craig Roy, Deputy Chief Executive, CSIRO, 18 Nov.

2011). Approximately 50% of the feed design work is already completed.

The cost to CASS may be reduced in several ways. First, overheads from CASS labour flow back into the CASS system. These may be as large as \$200K. Second, as discussed in §4, there is considerable scope for cooperative development of this system. For example, Swinburne University would likely fund the development of the GPU cluster. Collaboration with MPIfR on some aspects of the system is also possible. These collaborations could contribute up to \$200K to the project. Thirdly, there is a strong likelihood of contracts for construction of essentially identical systems for other observatories, e.g., the FAST and QTT telescopes in China. It is possible that MPIfR would purchase a system (at least the feed/front-end components) if (as we hope) the performance of the Parkes system is substantially better than they have been able to achieve.

Possible avenues for external contributions to the project that could be explored are:

- Astronomy Australia Limited (AAL) is committed to development of existing astronomical infrastructure and has supported the development of the 4cm upgrade for the ATCA. A case could be made for AAL support for this significant upgrade to Parkes operations.
- ARC LIEF grants have been obtained to support development of astronomical facilities, for example, the Parkes 20cm multibeam system. However, strong support from several universities would be required for this to have any chance of success.

We note that it has been nearly five years since a new receiver was commissioned at Parkes – the last was the 13mm receiver, commissioned in August, 2008. The approximate cost for this receiver system was (in 2007) \$1200K of which \$1000K was labour plus overheads. From design to commissioning took less than two years.

Since then the ATCA has been upgraded with wideband systems for the 16cm (1.1 – 3.1 GHz) band, commissioned in 2011, the 4cm (3.9 – 11.0 GHz) band, commissioned in 2013, and with the CABB signal processing system, commissioned in 2012, although with some developments on-going. These wideband systems have excellent performance, demonstrating the feasibility of such systems and the capability of the CASS engineering teams. For example, Tsys values are 21K and 18K for the 16cm and 4cm systems respectively. These values are better than the Tsys values assumed in the simulations discussed in §3.1, suggesting that the assumed values are conservative. In terms of costs, the ATCA receiver upgrade has cost about \$4000K of which about \$1500K was contributed by AAL. Of the total, component costs are about \$600K and labour and overhead costs are \$3400K. CABB is more complex than the signal processing system required for the UWL receiver, and so a cost comparison of the two systems is not very meaningful. However, it is clear that CABB has been enormously more expensive than the proposed UWL signal-processing system. The bottom line is that compared to the ATCA upgrade, even subtracting the AAL contribution, the UWL receiver and signal processing system is relatively inexpensive.

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