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

The Parkes Pulsar Timing Array Team
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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 and VLBI observations.

• 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 allowing Parkes to remain competitive for at least the next 8 – 10 years.

• The total cost of the receiver and signal-processing system is about $900K, of which $500K is labour and overheads. National and international collaborations will allow cost sharing and there are possibilities for external funding that could be explored.
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.

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 and studies of the Galactic background polarisation. 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 of paramount importance. 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 all but about 8%.

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, all but a few per cent of 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 geodesy and astrometry. Because of its limited zenith-angle range and relatively slow slew speeds, Parkes is not well suited to geodetic and astrometric VLBI. The demand for the “S-X” system at Parkes will probably decrease as the Global Geodetic Observing System (CGOS) dedicated VLBI array becomes 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.

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 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
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 observations is substantially better than similar limits from the other main international PPTA projects. The sloping percentile line gives 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)

available in 2013, we assumed a system temperature of 25K plus sky background and rejected 65% of the band as unusable because of RFI. As discussed in §5 and §6 below, system temperatures should be lower than assumed and 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 is $2.5 \times 10^{-15}$, but is unlikely that the gravitational wave amplitude is at this level. For the simulation we have assumed an amplitude of $1.0 \times 10^{-15}$. Figure 2 compares the expected detection significance with our existing receiver suite and if the UWL receiver became available in 2013. Of course, this is not possible, but the interval to detection after receiver commissioning remains roughly correct. The simulations indicate that the UWL receiver will give a detection about seven years earlier than continuation.
Fig. 2.— Significance of detecting a GW background with an amplitude of $1.0 \times 10^{-15}$ for data spans extending out to 2030. The green band assumes continuation of the present receiver suite and the red band assumes that the UWL receiver became available in 2013. The significances have a range of values for any given data span primarily because of the stochastic nature of the GW background. A significance level of at least 3.0 is required in order to claim a detection.

with our present system. Note that if we are lucky and the actual GW background is at the upper level of the stochastic variations and construction of the receiver commenced now, we could have a detection by about 2020. If the amplitude is say $2.0 \times 10^{-15}$, we could have a detection in 2016.

We note that these simulations are conservative in the sense that they assume our current observing and analysis practices. 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. It is difficult to predict how much more sensitive the IPTA data sets will be, but there is no doubt that they will reduce the time to a significant detection.

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

In addition to PPTA observations, the UWL receiver would be used for a range of science
projects. 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 in-
terstellar 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 greatly over the nearly 6:1 frequency coverage of
the receiver, allowing many studies not previously possible. Similarly, rotation measures 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 com-
monly having different spectral dependencies. The concept of “radius-to-frequency” mapping de-
pends 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. 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 OH (masers) to $z \sim 1.3$. 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.

3.2.3. Continuum polarisation and RM synthesis

The UWL receiver will facilitate studies of both the polarised Galactic background continuum and the polarisation of discrete continuum sources. While limited by the relatively wide beam of the Parkes telescope (resolution for the background, confusion for discrete sources), the extended frequency coverage will benefit RM-synthesise studies of both types of continuum emission. ***more?

3.2.4. eVLBI

The UWL receiver covers the “L-band” (20cm and 18cm) and “S-band” (13cm) bands often used for VLBI. With developments in eVLBI, the receiver and signal processing system will allow flexible operation over wider bands than are currently used. The signal processing system can easily be configured to directly output data in an eVLBI-compatible format, including circular polarisation if required. As discussed above (§2), simultaneous “S-X” (13cm – 3cm) for geodesy and astrometry will not be possible with the new receiver, but demand for this mode of operation is expected to decline as Parkes is not well suited to it and this work is being taken over by dedicated arrays of smaller antennas.

3.2.5. 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. The UWL signal-processing system will easily be able to
provide data in formats compatible with the ASKAP data products.

3.2.6. Long-term Future for Pulsar Observations at Parkes

The Parkes 64m 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 100m-class Green Bank Telescope (GBT) has had an impact on Parkes competitiveness for some important targets north of $-40^\circ$, 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.

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 $-10^\circ$ initially and ultimately north of $-30^\circ$, with $A_{\text{eff}}/T_{\text{sys}} \sim 2000 \text{ m}^2\text{K}^{-1}$ (compared to $\sim 100 \text{ m}^2\text{K}^{-1}$ 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 a single-pixel system, achieving the high sampling rates required for pulsar observations should be quite feasible. With recently upgraded receiver technology Meerkat should achieve $A_{\text{eff}}/T_{\text{sys}} \sim 300 \text{ m}^2\text{K}^{-1}$. 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.

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 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 cross-polar 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.
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 currently undergoing commissioning tests at Marsfield. 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 environment 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 $T_{sys} = 25$ 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

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

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 Government’s “Digital Dividend”, spectrum in the bands 694–820 MHz and 2500–2690 MHz is scheduled for auction from April 2013. We do not know what effect users of this spectral space 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

<table>
<thead>
<tr>
<th>Source</th>
<th>Frequency Range/Bandwidth (MHz)</th>
<th>Flux Density (dB(W m$^{-5}$ Hz$^{-1}$))</th>
<th>Amp-in Power (dBm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo/BeiDou</td>
<td>1164–1214, 1260–1300, 1563–1591</td>
<td>$-190$</td>
<td>$-107$</td>
<td>$15 \times 1$ MHz</td>
</tr>
<tr>
<td>NBN remote</td>
<td>2302–2382</td>
<td>$-155$</td>
<td>$-73$</td>
<td>$1W @ 5$ km, $2 \times 20$ MHz</td>
</tr>
<tr>
<td>NBN base</td>
<td>2302–2382</td>
<td>$-160$</td>
<td>$-78$</td>
<td>$2 \times 20$ MHz</td>
</tr>
</tbody>
</table>

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. A more complete description of the RFI implications 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 necessarily approximate at this stage. Table 3 gives estimates of the component and labour costs for design and construction of the main components, where labour costs include an 80% overhead component. Approximately 50% of the feed design work is already completed.

The total cost of the system is just under $A900K. The cost to CASS will or may be reduced in several ways. First, overheads from CASS labour flow back into the CASS system. These
Table 3: Cost and labour estimates for the UWL receiver system

<table>
<thead>
<tr>
<th>Item</th>
<th>Component cost ($AK)</th>
<th>Labour time (person-yr)</th>
<th>Labour cost ($AK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed and OMT</td>
<td>50</td>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>Dewar</td>
<td>100</td>
<td>1.5</td>
<td>180</td>
</tr>
<tr>
<td>Receiver</td>
<td>50</td>
<td>1.5</td>
<td>180</td>
</tr>
<tr>
<td>Digitiser/pre-processor</td>
<td>50</td>
<td>0.4</td>
<td>50</td>
</tr>
<tr>
<td>GPU cluster</td>
<td>150</td>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>Totals:</td>
<td>400</td>
<td>4.0</td>
<td>490</td>
</tr>
</tbody>
</table>

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 may 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.

There are several avenues for a possible external contribution to the project which could be explored.

- The Science and Industry Endowment Fund (SIEF) has recently been revitalised by a major injection of funds from the settlement of the CSIRO wifi patent-rights case. The ideas behind the now universally used wifi system developed at CSIRO by John O’Sullivan and his colleagues were initially conceived in the context of a search for radio-astronomical transients, a topic closely related to the applications of the UWL receiver. SIEF has a “Landmark Research Infrastructure” program to support “the creation or development of nationally significant facilities for the conduct of research” including “investment into national scale scientific equipment and special purpose facilities for the conduct of scientific research.” The UWL receiver development clearly fits those guidelines and would be appropriate given the wifi “connection” to radio astronomy.

- 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.

7. Acknowledgements

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