Sharing Between UWB and Radioastronomy Service

Final Report

Ofcom

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ÆGIS spectrum engineering

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1 INTRODUCTION

This document reports the results of a study aimed at evaluating the impact of emissions from Ultra-Wideband (UWB) devices on the Radio Astronomy service (RAS) in the UK. The study examined the implications for the regulation of UWB, the consequences for Radio Astronomy, and the potential for implementing mitigation effects.

The Report is structured as follows:

The first section (2) gives a brief overview of the problem and a summary of previous work on the topic.

Sections 3 and 4 describe the characteristics of the Radio Astronomy service in the UK, and the proposed characteristics of UWB devices, respectively. In each case, representative characteristics for use in sharing studies are defined.

Section 5 establishes a ‘baseline’ sharing scenario, using the results of simple, single-entry, interference calculations, as well as Monte Carlo simulations. The results are expressed in terms of the separation distances required between UWB devices and RAS receivers and also in terms of the implied emission limits for UWB devices at realistic separation distances.

Section 6 examines site-specific and operational characteristics of both the RAS and UWB devices that might ease the sharing situation.

Section 7 extends the study to the RAS bands lying outside the nominal bandwidth of the UWB emissions.

Section 8 summarises the findings of the study, and makes recommendations for regulation and further work.

2 OVERVIEW OF UWB / RAS SPECTRUM SHARING

The UWB devices currently being proposed will operate in the band 3.1–10.6 GHz and will radiate a noise-like signal with a very low power spectral density. The actual power levels and the spectrum mask for UWB operation in CEPT countries have yet to be determined.

The FCC, however, permit operation of these devices with a mean power spectral density of –41.3 dBm/MHz, with a roll-off of the spectrum mask as indicated in Figure 2.1. The peak power is required not to exceed 0 dBm when measured in a bandwidth of 50 MHz for 1 ms integration time.

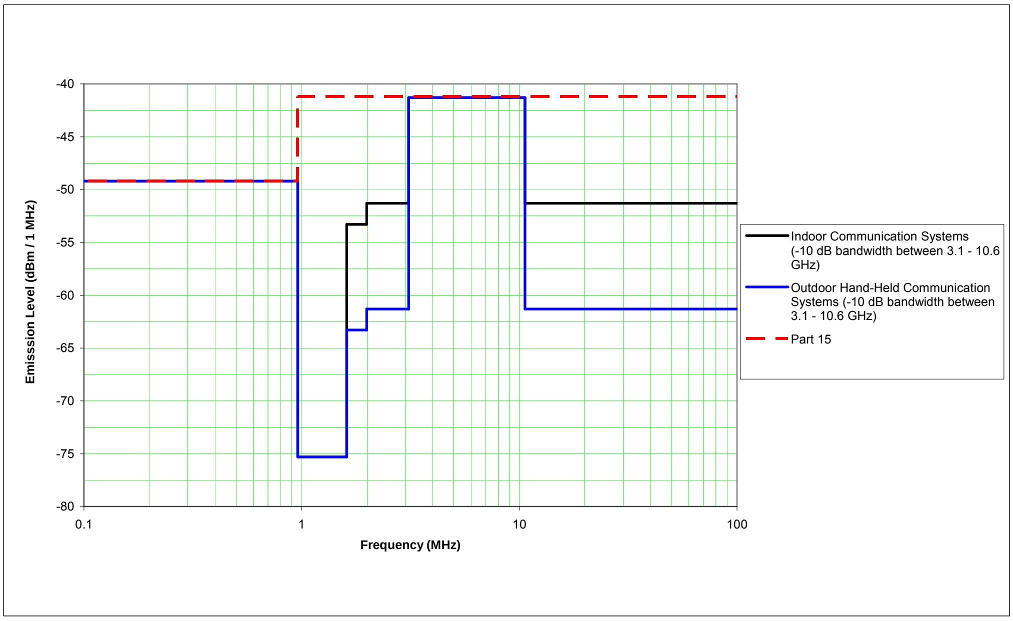

Figure 2.1: FCC mask for UWB devices

The Radio Astronomy Service routinely makes use of several bands that fall within, or close to, the proposed emission bandwidth. It is important to recognise that RAS observations are made both within bands formally allocated (with a variety of protection levels) to the RAS, and within bands chosen for scientific reasons and, opportunistically, for a lack of interference.

This study is concerned with the UK situation, and the various frequencies used for Radio Astronomy are described in more detail in Section [3]. In summary, however, this study is mostly concerned with determining interference in the 6 cm band at 4990–5000 MHz, as this is the only primary allocation to the RAS that actually falls within the bandwidth of the proposed UWB devices. The worst-case sharing situation will therefore be likely to occur in this band.

Other important RAS allocations exist above and below the nominal 3.1–10.6 GHz UWB bandwidth, and these may also be affected by UWB operation. The sharing situation in these bands will be considered explicitly, to inform decisions on the required roll-off of the UWB spectral emission mask.

2.1 Previous studies in the USA

The current FCC emission limits for UWB devices were informed by the need to protect radio astronomical use. The situation in the US is, however, somewhat less constrained than that in Europe, as RAS sites generally have larger areas, and associated quiet zones, within which deployment of active radio devices is restricted.

At a meeting of the Committee on Radio Frequencies (CORF) in 2003, Andrew Clegg of the National Science Foundation (NSF) assessed [5] the risk from UWB to RAS observation as ‘low to moderate’. The main threat was felt to be from vehicular and systems. It was noted that control of vehicles was already necessary, to restrain emissions from ignition and RF systems in cars. It was assumed that any handheld devices close enough to cause interference would be associated with observatory staff.

2.2 Previous studies in Europe

In March 2004, The European Commission issued a mandate to CEPT requesting an identification of harmonised conditions for the use of radio spectrum by UWB devices in the European Union. In response, ECC TG 3 has produced *ECC Report 64*, which has been approved at the ECC meeting in March 2005. The report includes 16 annexes and is over 300 pages long. It presents the findings of sharing studies between UWB devices and other radio systems operating below 10.6 GHz. It concludes that the UWB emission mask of –41.3 dBm/MHz (which has been adopted by the US administration) does not provide adequate protection for other radio services operating in the 3.1–10 GHz band. Further studies are being conducted with an emission mask of –55 dBm/MHz. On the approval of the EC Report 64, the ECC agreed that further work is needed in order to develop regulations for UWB deployment in the EU and new terms of reference have been produced with a view to completing the studies by October 2005.

In ECC Report 64, Annex 4 addresses UWB – RAS sharing. The analysis presented in the annex is based on the following method and assumptions.

- The model is based on a distribution of UWB devices in concentric rings around a victim radio telescope. The UWB devices are evenly spaced on each ring and the spacing between rings is constant. The effect of these spacing rules is that transmitters are approximately evenly spaced over the entire area enclosed between innermost and outermost rings. The idea of using this simplified ring concept is to reduce the number of path loss calculations necessary to determine the aggregate power level.

- In the calculations, the average power from each UWB transmitter is linearly summed to arrive at an aggregate total interference power at a victim receiver. It is assumed that all transmitters radiate the same EIRP towards the victim receiver for 100% of the time (i.e. 100% activity factor has been assumed for UWB devices). The clear-air propagation models defined in Rec.452 are used to model the propagation effects—in practice, this means that free-space loss is assumed to the radio horizon.

- Using the interference threshold levels given in Rec.769 together with a maximum acceptable percentage time for data loss of 2% (defined in Rec.1513), the maximum tolerable UWB EIRP levels are calculated for different density figures for RAS bands below 10.6 GHz. The calculations assume that the first ring is located at 30 m from the radio telescope and the last ring is 500 km from the first ring with a ring width of 10 m.

- Further assumptions include 50 m height and 0 degree elevation for the radio telescope and 0.5 m height for the UWB transmitters. Initial results are based on all UWB transmitters operating outdoors while the second set of results consider 20% outdoor + 80% indoor operation with an assumed building attenuation in the range 5–17 dB.
- The results indicate that the maximum tolerable UWB EIRP is in the range of –80 dBm/MHz to –145 dBm/MHz, which is well below the proposed emission limit of –41.3 dBm/MHz. It is therefore concluded that the co-existence between UWB and RAS is not possible.

The modelling method used in Annex 4 is based on a very early US NTIA study on the assessment of compatibility between UWB devices and selected federal systems (January 2001). As can be seen, a number of significant assumptions have been made regarding the activity factors, indoor/outdoor operation, interference thresholds, antenna heights and transmitter distributions. The use of P.452 as a propagation model is also open to question, as this is intended for application to isolated interferers located at clear sites, rather than dense distributions of cluttered interferers. This study examined the implications of these assumptions in detail.

The Ofcom consultation document on UWB devices (January 2005) invited comments on the protection of UK RAS sites from UWB interference. The consultation document notes that the sharing situation could potentially be improved by:

- tightening the UWB emission mask
- controlling the UWB energy radiated per information bit
- limiting emissions in certain RAS bands using OFDM UWB approach
- using perimeter fencing physically to exclude devices
- conducting RAS measurements at night when UWB activity is expected to be lower
- siting RAS receivers well away from populated areas.

In commenting on the Annex 4 of ECC Report 64, the consultation document notes that RAS observations employ significant integration times to reduce the impact of measurement noise. Therefore, these measurements should be assessed in terms of energy received rather than instantaneous power. In this context, the assumption of continuous emission from a UWB interferer is considered to be unreasonable. It is argued that a limited activity factor will reduce the energy potentially received by a radio telescope, which may largely mitigate the incompatibility. Furthermore, it is recommended that the current noise levels associated with emissions from consumer electronics and spurious emissions from existing communications systems should also be considered as these emissions are comparable to UWB transmissions.

Responses to the Ofcom's UWB consultation document state that:

- The use of low RAS receive antenna sidelobes and physical structures such as fences around RAS sites can provide sufficient protection for radio telescopes. The analysis of EC Report 64 is unreasonable and exaggerated.
  The black-body radiation from people, cars and buildings will result in higher interference values than those calculated in the report if the same method is to be used. The assumption of the nearest ring being 30 m from the receiver antenna implies that UWB transmitters are within the RAS antenna as these antennas 30 m diameter or more (***Freescale Semiconductors***).

- The RAS receivers already employ a number of mitigation techniques to reduce the impact of interference from existing systems. These together with the fact that most UWB devices will be indoors should significantly reduce the risk to RAS sites (***Intel***).

- The geographical condition of the RAS antenna location (i.e. rural area) and the surrounding exclusion area will keep interference from UWB devices within tolerable levels (***Texas Instruments***).

- Radiations from existing radio devices are at far higher levels than those permitted for UWB devices. Therefore, the operation of RAS receivers must already be impossible given that their protection requirements are so demanding. This indicates that the level of RAS protection requirements is not realistic. The existing noise levels at RAS sites should be observed and used as a basis for policy-making. In addition, the EC Report 64 analysis should take account of an average RAS receive gain pattern (which is more appropriate for aggregate interference analysis) rather than the Rec.509 pattern which is based on the envelope of the peaks (***Thales***).

- There are several ETSI standards defined for licence-exempt bands (2.4 GHz and 5 GHz) where emission limits are even more relaxed than the FCC limits (***Philips***).

- The suggestion of relocation of RAS facilities is not realistic as the cost will be in excess of £100M. The suggestion of perimeter fences is also not realistic given that there are 6 sites to be protected to distances of the order of 10 km. The suggestion of restricting observations to periods of low activity will devalue the scientific programmes, which are undertaken 24 hr per day and 7 days a week. There is no understanding of the diversity of radioastronomy techniques, not all of which involve time averaging over long periods (***The UK Radioastronomy Community and Royal Astronomical Society***).

As can be seen from the responses, the proponents of UWB argue that the RAS protection requirements are not realistic and emissions from existing radio systems should already be causing problems at RAS sites. The Radioastronomy community, on the other hand, argues that interference from uncontrolled UWB deployment may have a significant impact on observations and proposed mitigation techniques are not realistic.

It should be noted that the ITU-R TG 1/8 has also been addressing sharing issues between UWB and other radio services. Many contributions presented to the EC TG 3 are also put forward to TG 1/8 meetings for consideration.

3 RADIO ASTRONOMY IN THE UK

The UK has held a leading position in Radio Astronomy since the end of the Second World War. The centres of activity at Jodrell bank and Cambridge were established in 1945 – that at Jodrell being chosen specifically to avoid EMI problems in central Manchester. Much of the initial work was undertaken by engineers and physicists, but by the mid-1950's Radio Astronomy had been assimilated into the mainstream of astronomy, offering one of an increasing number of windows on the cosmos.

From an early date, distinct forms of observations emerged—the 'continuum' radiation from sources was measured using single dish instruments or interferometer arrays, and from the discovery of the 1420 MHz hydrogen line in 1951, the study of spectral lines has been important. Aperture synthesis has extended the interferometer principle, in conjunction with computer processing, to allow high-resolution images to be produced.

In 1967, the first pulsar was discovered at Cambridge, and the detection and study of these intermittent sources requires further specialised techniques.

The characteristics of these observations are described briefly below, paying particular attention to their vulnerability to interference.

3.1 Types of observation

3.1.1 Continuum

The most straightforward type of observation is that of the continuum radiation from cosmic sources. It was initially assumed that such radiation might be thermal in origin, but observation at multiple frequencies soon showed that most sources did not follow the expected black-body' curve.

The study of these emissions, and their spectral characteristics, is an important way of understanding high-energy mechanisms (such as synchrotron radiation) that often cannot be replicated on Earth. To characterise the emission spectra, however, it is necessary to be able to make observations at many wavelengths. For this reason, radio astronomers have sought to protect 'windows' across the spectrum at approximately octave spacing.

Within one of these 'windows', the variation of power flux from a source is not significant – the only requirement is to determine the power flux as accurately as possible, using a radiometer. The sampling error of a mean value decreases as the square root of the number of observations. For a radiometer, this implies that the measurement precision will scale with the square root of both radiometer bandwidth, and the integration time of the measurement. This principle allows variations in received power to be detected that are orders of magnitude below the noise floor of the receiver.

The sensitivity of a radiometer (often expressed as a minimum detectable temperature) is given by the expression:

$$\Delta t = \frac{K_{sys} \cdot T_{sys}}{\sqrt{B \cdot \tau}}$$

Where B is the receiver bandwidth (Hz), τ is receiver integration time (s), T_{sys} the receiver system temperature (K) and K_{sys} a dimensionless constant, dependant on the type of receiver (unity for a simple, total-power radiometer).

For typical values, at 6 cm, of T_{sys} = 22 K, B = 10 X 10^6 Hz and $\tau = 2000$ s, the sensitivity will therefore be 1.6 x 10^{-4} K (0.16 mK, or some 52 dB below the radiometer noise floor).

3.1.1.1 *Sensitivity to interference*

These sensitivity calculations are the basis for the protection limits given in ITU-R RA.769-2. 0.16 mK corresponds to an input power of –197 dBW / 10 MHz (–177 dBm/MHz). It is assumed that the 'harmful interference' level is that that introduces a 10% uncertainty into the radiometer measurement, i.e. –207 dBW / 10 MHz (–187 dBm/MHz).

To give a quick feel for the implication of this assumption, the free space distance required from a single UWB device can be calculated. If the device radiates with an EIRP of –41.3 dBm/MHz, and the radio telescope antenna has a gain of –10 dBi in the direction of the UWB, a path loss of 135.7 dB is implied. At 5 GHz, this corresponds to a separation distance of 30 km. If a telescope gain of 0 dBi is assumed, the separation distance increases to 95 km.

The validity of these limits has been questioned by some UWB proponents. In particular, it has been noted that the achievement of such sensitivity levels assumes that the receiver system noise temperature does not change significantly over the course of the observation, and it has been questioned whether this can be the case.

Ignoring sky temperature, the antenna noise temperature will be determined by the half-hemisphere of ground visible to the antenna. If this ground is assumed to be at 300 K, and the antenna has an average –10 dBi response over this half-hemisphere, the antenna noise temperature will be 30 K. If the telescope sensitivity is 0.3 mK, this would imply that the surface temperature should be stable to 0.001% over the time of the observation. It has been asserted that this is unlikely to be the case, and that, as the RAS antenna changes pointing during an observation, the terrestrial thermal noise entering the sidelobes will change significantly. Astronomers make allowance for such variation in single-dish observation through the use of repeated scans or multibeam receivers.

However, these arguments are not generally relevant in the case of UK radio telescopes. Such continuum measurements are, apparently, never made using single-dish instruments in the UK, except on an occasional basis for system calibration purposes, when shorter integration times are likely to be used. For continuum studies, a multi-element telescope configuration will always be used, and such systems are able to reject interference to a much greater degree (see Section 3.22 below).

3.1.2 Spectral line

In contrast to the continuum case, substantial use is made of single telescopes, particularly the 76 m Lovell telescope at Jodrell Bank, for spectral line work. For these observations, it is generally the information contained in the spectrum (particularly the Doppler structure) that is of interest, rather than precise resolution of the angular detail of the source.

The most important spectral line is that of hydrogen, at 1420 MHz, and for this reason an international passive allocation has been made at 1400–1427 MHz. The analysis of the Doppler characteristics of galactic spectra allows the dynamic behaviour of galaxies to be examined. As the universe is expanding, the overall Doppler shift associated with objects also allows distances to be determined.

Unfortunately, there is increasing interest in more distant sources, which are consequently highly red-shifted, causing them to fall outside the passive allocation. Severe problems have been encountered at Jodrell Bank, trying to investigate the spectra of far red-shifted objects, due to the presence of interference from low-power, licence-exempt, video senders operating at 1389–1399 MHz.

3.1.2.1 Sensitivity to interference

By definition, spectral line observations are limited in the bandwidth over which integration may be carried out. Where a continuum observation may only be limited by the need to exclude interference, and employ a bandwidth of tens of MHz, line studies will need to resolve spectral detail, and will be limited to bandwidths of tens of kHz. This will reduce the observational sensitivity, and hence susceptibility to interference, by a factor of around $\sqrt{1000}$ or some 15 dB.

For the specific case of observations near 5 GHz, RA.769-2 gives a representative observational bandwidth of 10 MHz for continuum observation (at 4995 MHz) and 50 kHz for spectral line observation (at 4830 MHz). Both assume an integration time of 2000 s. The line observation therefore has a sensitivity and interference limit 11.5 dB less than that for the continuum case.

The Lovell telescope spends a substantial portion of observing time engaged on spectral line work. As noted above, the single most important band for such studies is at 1400 MHz, but other bands are also significant, in particular:

- Hydroxyl at 1.61, 1.66 and 1.72 GHz
- Formaldehyde at 4.8 GHz
- Methanol at 6.6 GHz

Of these bands, only that at 1.66 GHz is afforded full protection (see Section 3.3, below), and no protection at all is afforded at 6.6 GHz. Despite this, a new 6.0–6.7 GHz ‘multibeam’ receiver is being constructed at Jodrell, for use in the study of Methanol masers, as well as continuum and pulsar work.

Given the importance, currently and in the future, of such spectral line work, the relevant interference limit will be assumed in evaluating interference to single-dish telescopes. In practice, it is the Lovell telescope at Jodrell Bank that will primarily be concerned with such observations.

The single-dish, spectral line interference limit (from Table 2 of RA.769-2) is –218 dBW/50 kHz at the receiver input, corresponding to –175 dBm/MHz. Expressed as a power spectral flux density, this is **–230 dBWm^{-2}.Hz^{-1}**. Performing the same simple 'required path loss' calculation as in 3.1.1.1 above gives[1] a required separation distance of 8 km for a telescope gain of –10 dBi, and 25 km for 0 dBi.

3.1.3 Pulsars

Since their discovery at Cambridge in 1967, pulsars have been a major area of study for UK researchers. In particular, a very significant portion of telescope time at Jodrell bank is devoted to the study of these objects.

A pulsar is a collapsed star, of very great density. These stars are typically only 20 km across, and rotate very rapidly. Their strong magnetic field gives rise to 'lighthouse' type beams of radio energy, giving rise to pulses of received energy with a distinctive repetition rate, as shown in Figure 3.1 [from 2].

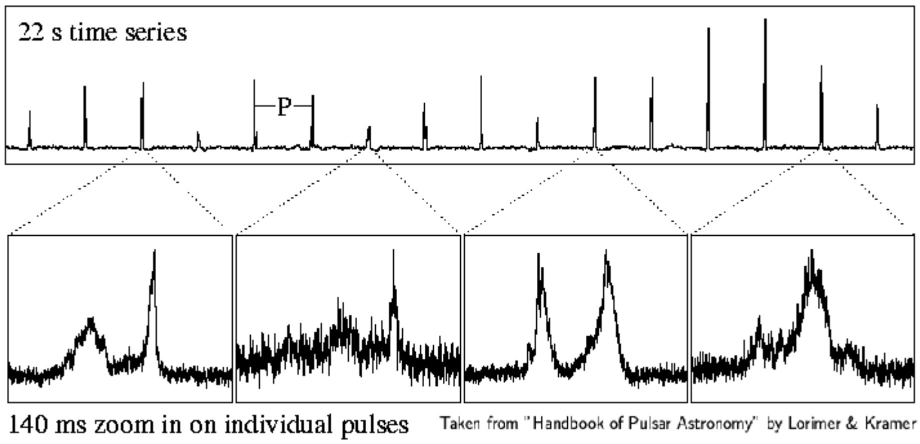

Figure 3.1: Pulse series from typical pulsar (Arecibo telescope)

The period of pulsars is extremely stable, and varies between a few seconds to around one millisecond. Most pulsars are weak radio sources, and can only be examined by the coherent addition of a large number of pulses. This process, known as *folding* gives an integrated pulse profile that is characteristic of the source. Examples are shown in Figure 3.2.

[1] Path loss required = 123.7dB at 4.8 GHz, assuming -10dBi towards UWB device.

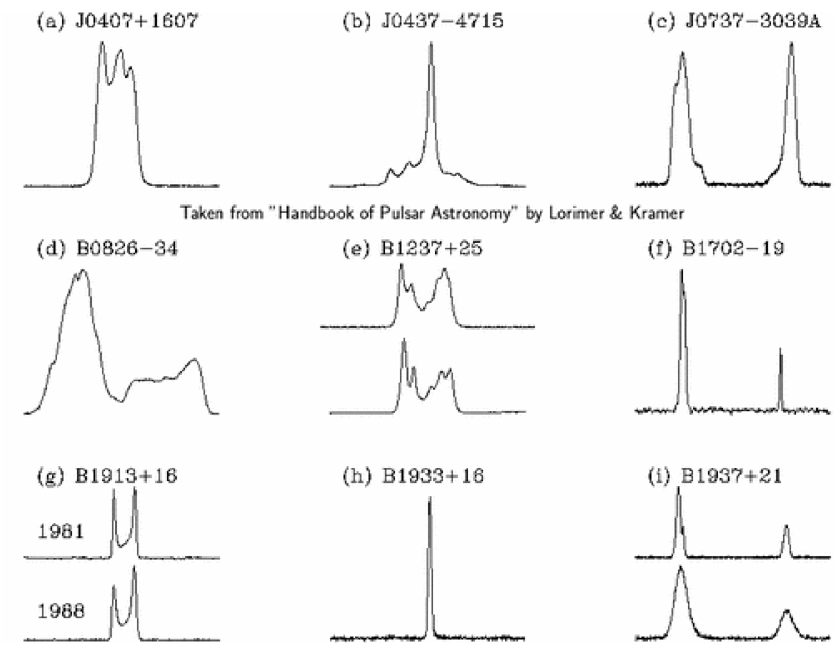

Figure 3.2: Showing the variety of pulse profiles

A characteristic of pulsars is that the received signal displays a characteristic pulse dispersion, with pulses at lower frequencies being delayed with respect to those at higher frequencies.

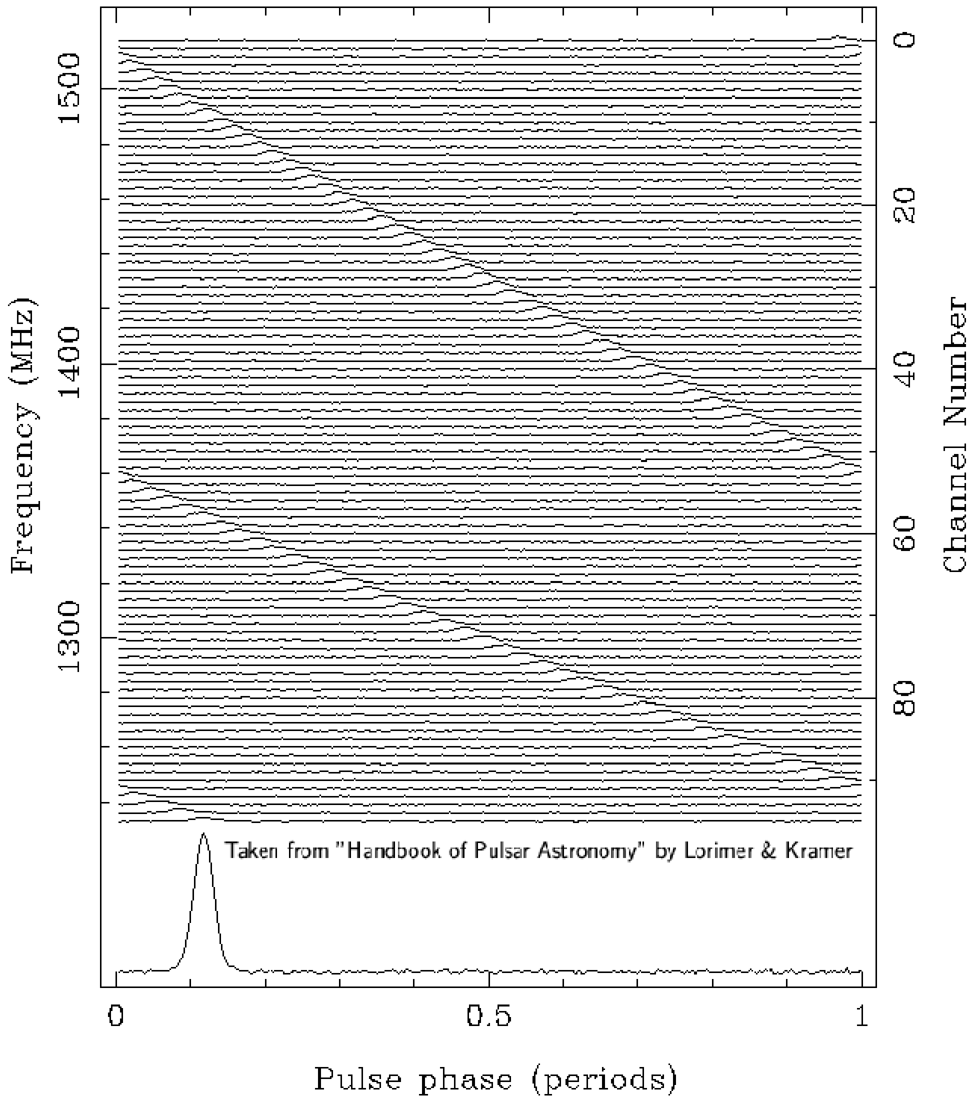

Figure 3.3: showing pulse dispersion

This dispersion is due to the ionised interstellar medium (ISM) and is illustrated in Figure 3.3.

Pulsars are scientifically very valuable. Not only are the objects themselves inherently interesting, but the stable timing of the pulses finds applications in celestial mapping, and the dispersion of pulses with frequency gives information on the interstellar medium.

3.1.3.1 Sensitivity to Interference

It is clear that the coherent addition of pulse profiles will strongly reject non-coherent interference. The real impact of interference will be on the search process.

The most common search procedure is to Fourier transform a time series, so that it can be searched in the frequency domain, allowing the identification of periodic signals. This process is complicated by the ISM dispersion illustrated above – if this is not corrected, the pulse in a wideband observation will be ‘smeared’ out, reducing the signal-to-noise ratio. The tactic is to analyse the data for a range of assumed dispersion values. The power series for each assumed dispersion value (DM, or Dispersion Measure) will then contain a number of candidates for further analysis. Some of these will appear for several dispersion values with different signal-to-noise ratios, and the time series can then be folded at the appropriate period, to allow further examination. It is also possible to examine time series directly for pulses that exceed a set signal-noise level while varying the assumed dispersion.

It is very likely that some forms of terrestrial interference will have a periodicity that might be confused with that of a pulsar. Few such sources, however, will appear dispersed, and this will allow interference to be identified and ignored.

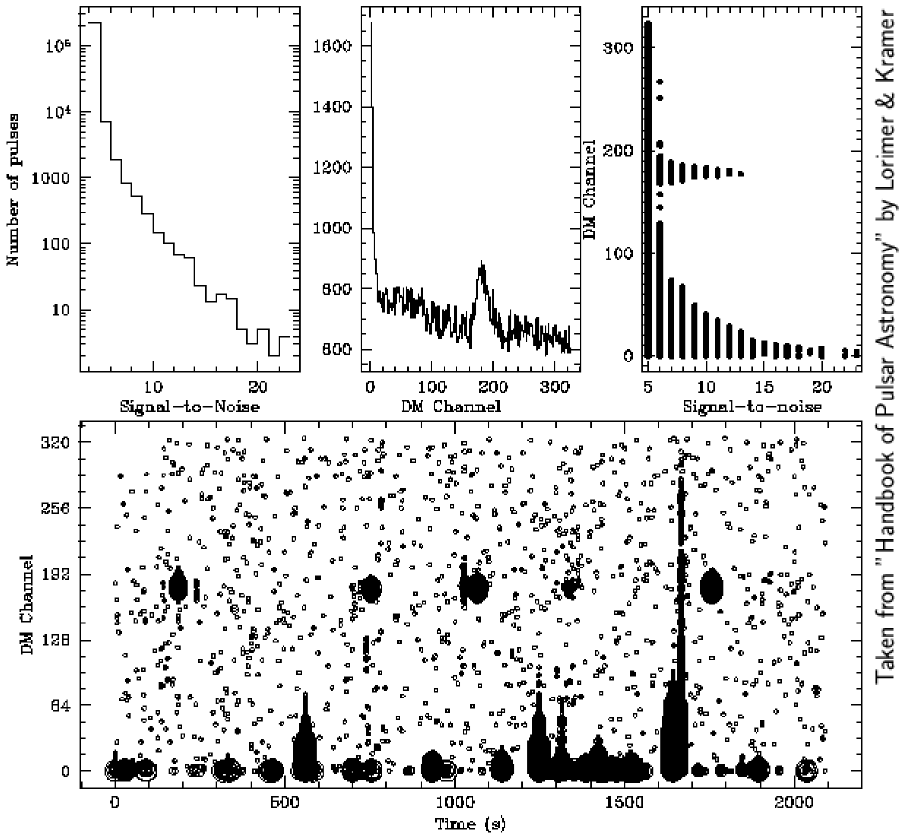

Figure 3.4: Showing pulsar, with zero-dispersion interference

An example is shown in Figure 3.4, where, in addition to a dispersed pulsar, periodic interference is evident at zero dispersion.

The main impact of interference is to clutter the search algorithm with false candidates, which will reduce the possibility of detecting weak, genuine sources. Likely interference cases can be masked from the record either by removing samples with unexpectedly large amplitudes (most pulsars are weak) or by keeping track of the frequencies on which zero-dispersion interference is seen to occur. Unfortunately, neither of these tactics is likely to be useful in the face of UWB interference, which will be both weak and broadband.

Further work is required to quantify the impact of UWB interference on pulsar searching. It seems likely that a large population of emitters will have a minimal effect – however, attention should be paid to the time domain behaviour of UWB devices, as a single, nearby UWB piconet might operate with a data burst structure that would appear similar to a pulsar signal (i.e. with a repetition rate in the range ~0.1 Hz to 1 kHz).

3.2 Methods of observation

3.2.1 Single dish

Single dish observations have been described above, and are typically employed for the study of emissions from a specific object in the frequency domain (e.g. to investigate the rotation curves of galaxies, as betrayed by Doppler shift of the hydrogen line) or in the time domain (e.g. pulsar studies).

Single-dish observation is the most sensitive to interference, and will be judged in the modelling below according to the spectral line criterion given in RA.769-2.

3.2.2 Aperture synthesis

Astronomy is generally associated, by the layman, with the imaging of celestial objects. This initially posed great problems for radio astronomers, as the resolution available with practical apertures at these frequencies is very limited.

To increase resolution, interferometers were rapidly adopted, and these allowed the determination of the angular dimensions of simple, discrete sources. It was not until the digital computer became readily available that it became possible to synthesise a large effective aperture from a number of small telescopes.

In aperture synthesis, the principle is to make simultaneous observations in a given direction using a number of telescopes, and to allow the rotation of the earth to scan these across the sky. In this way, a sparse scan can be made of what is referred to as the *u,v* plane, perpendicular to the source direction, which may then be Fourier transformed to reconstruct the brightness distribution of the source. As the synthesised aperture is so sparsely filled, the initially-transformed image will be dominated by artefacts. However, given a known feature in the field of view, and knowing the geometry of the sparse scan, the majority of these artefacts can be removed.

In the UK, aperture synthesis is performed on a small scale with the Ryle telescope at Cambridge (15 GHz) and the Cambridge Low-Frequency Synthesis Telescope (151 MHz). On a larger scale, and covering the frequency bands of interest to the current study, is the MERLIN network.

This network of telescopes stretches from Jodrell Bank to Defford (Worcestershire) to the south and Cambridge to the East. The locations are indicated below.

Figure 3.5: The MERLIN network

3.2.2.1 Sensitivity to Interference

It is intuitively reasonable to suppose that an interferometer, or array of telescopes, will show some immunity to interference, as such interference will be decorrelated between the elements.

The question was studied quantitatively by Thomson [3, 4], and this work was ultimately incorporated in ITU-R P.769. It is, however, conceded by Thompson in [4] that the adopted limit is somewhat arbitrary.

In an interferometer network, such as MERLIN, the measurement is of the degree of correlation between sources as seen from different positions on the earth. In effect, the relative phase of the interferometer elements is equalised in the direction of the target source.

Correlated interference from other direction will therefore give rise to characteristic fringes, which may be rejected in signal processing. In the case of UWB, the situation is simplified, as there is no practical possibility of correlated interference from a UWB device being seen at two elements of a large interferometer network, such as MERLIN.

The effect of such interference is simply to degrade the sensitivity of the victim element. Consequently, an interference limit corresponding to 1% of the RA receiver noise floor has been applied (the same limit would be generally applicable to Very Long Baseline Observations (VLBI)).

3.3 RAS frequency allocations

The table below summarises the international and UK allocations to the Radio Astronomy service.

Frequency band	Substance	Status (ITU R1)	Status (UK)	Notes (UK)
1400–1427 MHz	Hydrogen (H)	**Primary** (passive band)	**(A) Primary** (passive band)	
1610.6–1613.8	Hydroxyl Radical (OH)	**Primary** (shared band)	**(B) Primary** (shared band)	MSS uplinks
1660–1670	Hydroxyl Radical (OH)	**Primary** (shared band)	**(A) Primary** (shared band)	Bottom 0.5 MHz shared with LMSS (B) Top 2 MHz shared with FS (D, and C for Jodrell)
1718.8–1722.2	Hydroxyl Radical (OH)	FS, MS	(C) secondary by 5.385.	Shared with GSM. MERLIN and single-dish
2290–2300	Continuum		**(D) footnote for Jodrell**	VLBI & Pulsars at Jodrell
2655–2670	Continuum		**(D) footnote for Jodrell**	VLBI & Pulsars at Jodrell
2670–2690	Continuum		**(D) footnote for Jodrell**	5.149 Mapping, pulsars (& MERLIN?)
2690–2700	Continuum	**Primary** (passive band)	**Primary** (passive band)	
3.3 GHz	Methyladine (CH)	RADIOLOCATI ON	RADIOLOCATI ON	No use? UK11
4600–4950	Formaldehyde (H_2CO) (4825–4835)	FS, MS	FS, MS	(C) at Jodrell for H_2CO at 4825–4835
4950–4990	Continuum		FS, MS	(C) for MERLIN

Frequency band	Substance	Status (ITU R1)	Status (UK)	Notes (UK)
4990–5000	Continuum	**Primary** (shared band)	**Primary** (shared band)	MoD tactical links
6650–6675.2	Methanol (CH_3OH)	FS, FSS(↕), MS	FS, FSS(↑), MS	(D) CH_3OH & MERLIN Used for MASER observation 5.458A
8400–8500	Continuum			(D) Cambridge & Jodrell, VLBI
8665	Helium ($^3HE^+$)	RADIOLOCATION	RADIOLOCATION	No use?
10.6–10.7 GHz	Continuum	**Primary** (shared band, top 20 MHz passive)	**Primary** (shared band, top 20 MHz passive)	UK126 Co-ordinated with FS links

3.4 Assumed RAS characteristics

3.4.1 Antenna characteristics

Much debate concerning sharing issues with the RAS has centred on the assumptions made regarding telescope antenna performance.

Astronomers maintain that the pattern given in SA.509 for large earth station antennas is a realistic representation of the performance of a typical RAS instrument. It is unfortunate (and surprising) that there are very few published patterns for the overall response of such antennas, though the main beam performance is, typically, very well characterised.

SA.509 does include, in the annex, a comparison of the antenna model with the measured performance of the Lovell telescope (prior to the current refurbishment) at L-band. The measured pattern is extremely sparse, but appears to show that, for off-axis angles beyond 20° the mean sidelobe level lies between –10 and –20 dBi. There are, however, excursions towards 0 dBi at around 20° and 90°.

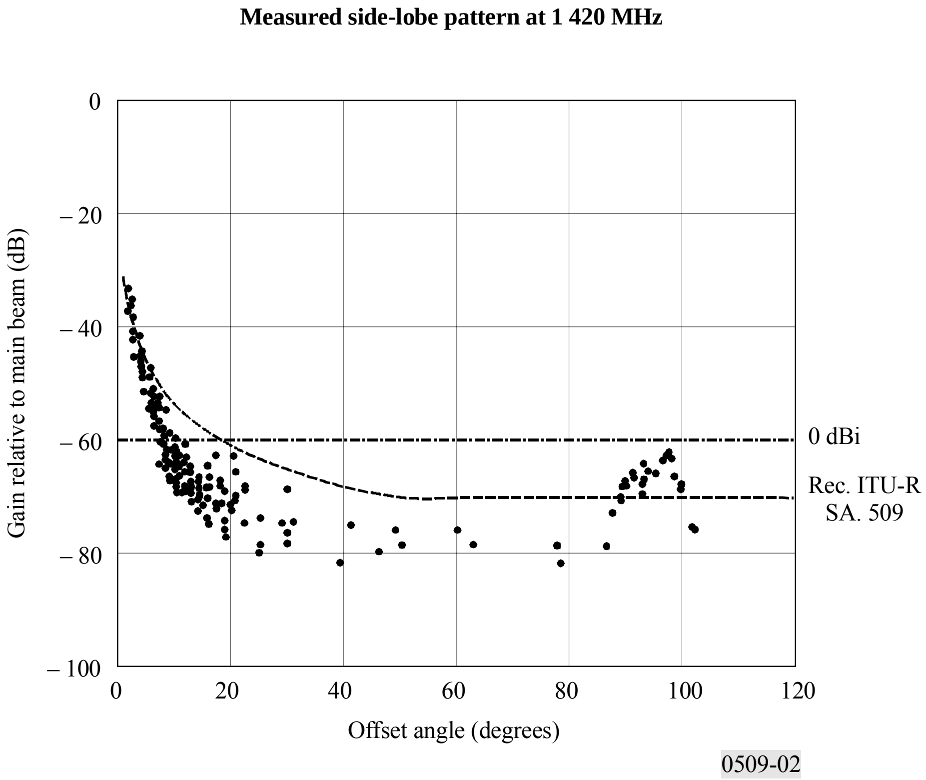

Figure 3.6: Lovell telescope sidelobe measurements

If the SA.509 pattern is adopted, and interference protection arranged assuming a 0 dBi gain, this would allow observation to within 19° of the horizon. If –10 dB were adopted, this would reduce the usable area of the sky, to elevation angles greater than 48°.

In this report, on the basis of the limited data available, the –10 dBi assumption is adopted for aggregate interference prediction purposes. As this will not capture the worst-case excursions of the sidelobes, single-entry models additionally assume a 0 dBi gain.

There appears to be a requirement to gather more data on the actual far-sidelobe performance of radio astronomy antennas, as this will allow more reliable estimates of interference probability to be made.

3.4.2 Interference levels

To re-iterate the assumptions stated above, the following RAS protection limits will be assumed.

For the single dish case, the 'spectral line' values from RA.769-2 will be adopted. Thus at 4830 MHz, a value of –218 dBW/50 kHz with 0 dBi and –10 dBi gain will be used. This corresponds to –230 dBW/Hz.m^2 and –220 dBW/Hz.m^2 (–24.3 dBµV/m and –14.3 dBµV/m. This value applies to the Formaldehyde line, which is only secondary, but the protection value is also appropriate for continuum measurements with short integration times.

For MERLIN observations, the VLBI values from 769-2 will be adopted, due to lack of correlation of UWB devices. Thus, at 4.995 GHz, a value of –200 dBW/Hz.m^2 will be used, with a gain of 0 dBi (5.8 dBμV/m).

4 UWB: SYSTEMS AND PROPOSALS

In April 2002, the FCC released *FCC 02-48* to allow low-power UWB emissions in the band 3.1–10.6 GHz for indoor communications devices. UWB emissions are limited to –41.3 dBm average power in 1 MHz bandwidth and 0 dBm peak power in 50 MHz bandwidth where average power is measured over a 1 ms integration time.

Early UWB designs were based on the transmission of very narrow, low-power, baseband pulses (typically in the order of nanoseconds). In order to approximate the UWB signal to a noise-like signal, these devices randomise the pulse position (commonly referred to as pulse dithering) by using a channel code that is a pseudo-random noise (PN) sequence. The process of shifting each pulse's time position according to a PN sequence is also referred as 'time-hopping'. UWB technology using this scheme is, therefore, called 'time-hopping UWB (TH-UWB)'.

More recently, the focus of UWB developments has moved from simple pulse-based, or carrier-less, technology towards more sophisticated pseudo-carrier-based technologies where pulse-shaping techniques are employed. There are two main proposals to provide high data rate communication services to Wireless Personal Area Networks (WPANs) in 3.1–10.6 GHz: the Direct Sequence Ultra Wide Band (DS-UWB) led by Motorola and the Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) led by Intel.

Proponents of DS-UWB and MB-OFDM have submitted their proposals for standardisation in IEEE 802.15 Working Group 3a. This working group addresses high rate (>20 Mbps) wireless personal area networks (WPAN). These networks are intended for short distance (<10 m) wireless networking of portable and mobile computing devices (e.g. PCs, PDAs, digital cameras, mobile phones and other consumer electronics). The standardisation process has reached a stalemate in that neither proposal has obtained a 75% voting approval. The primary concerns are related to the interference potential into other radio systems.

According to the initial FCC rules, UWB devices were required to be tested for compliance with average and peak power limits as an always-on-system under full power even if they intend to operate with frequency hopping and/or gating. In August 2004, MB-OFDM proponents requested a waiver of this rule. They argued that UWB test procedures were developed specifically for pulse-based systems, putting their system (which is based on frequency hopping between 528 MHz bands) at an unfair disadvantage. On the other hand, DS-UWB proponents argued that should the FCC grant a waiver to MB-OFDM systems it must do so in a technology-neutral manner allowing any UWB device to be measured under normal operating conditions.

In March 2005, the FCC granted the waiver (FCC 05-58) stating that frequency hopped, frequency stepped, band sequenced and gated emissions all appear similar to receiver and should be treated equally under the conditions of the waiver. With the new ruling, the previous power penalties associated with frequency hopping MB-OFDM and gated DS-UWB technologies are removed and compliance tests will be based on average power measurements under normal operating conditions. In practice, the new ruling means that UWB devices can be configured to operate as frequency hopped and/or gated systems where they can transmit higher power levels and then sit quiet as long as they meet the same limits for average power density during certification testing.

4.1 DS-UWB

The DS-UWB proposal is based on the use of two frequency bands: the lower band (3.1–4.85 GHz) and the upper band (6.2–9.7 GHz). In each band, user data is scrambled, encoded (FEC), interleaved and spread before being transmitted using shaped wavelets.

Data rates of 28, 55, 110, 220, 500, 660, 1000 and 1320 Mbps are supported. In a DS-UWB transmitter, a scrambler is employed to ensure that there are an adequate number of bit transitions to support clock recovery. Convolutional coding is used with coding rates of ½ and ¾ for most data rates supported. Coded bits are interleaved to disperse potential burst errors. For data rates of 660 and 1320 Mbps, an un-coded operation over a very short range (< 3 m) has been proposed.

The use of different code sequence lengths for different data rates is proposed for spreading. Sequence lengths range from 1 to 24 chips. Two modes of operation are defined: mandatory and optional modes. In the mandatory mode of operation, each data bit is used to determine whether the spreading code with the desired length is transmitted with a polarity of either (+1) or (–1). In the DS-UWB specifications, this process is referred as “BPSK modulation”. In the optional mode of operation, data bits are divided into two-bit blocks. Each two-bit block is then used to select one of two possible spreading codes for the desired data rate and the polarity of either (+1) or (–1). In DS-UWB specifications, this process is referred as “Quaternary Bi-Orthogonal Keying (4-BOK) modulation”.

UWB communication devices form piconets. For example, a piconet may represent a wireless printer used by a group of users in an office or simply two laptops exchanging files. The DS-UWB proposal supports a total of 12 piconet channels (6 in each band). For each piconet channel, the chip-rate and centre frequency are defined together with a set of spreading codes for use with BPSK and 4-BOK, as shown in the following table.

Piconet Channel	Chip Rate (MHz)	Centre Frequency (MHz)	Spreading Code Set
1	1313	3939	1
2	1326	3978	2
3	1339	4017	3
4	1352	4056	4
5	1300	3900	5
6	1365	4094	6
7	2626	7878	1
8	2652	7956	2
9	2678	8034	3
10	2704	8112	4
11	2600	7800	5
12	2730	8190	6

Table 4.1: DS-UWB Channels

All DS-UWB devices are required to support piconet channels 1 – 4 (mandatory mode) while the support for piconet channels 5 – 12 is optional. In each channel, the centre frequency is equal to (3 x chip-rate). It is stated that this relationship allows relatively simple frequency synthesis, pulse generation and demodulation of the DS-UWB waveforms.

Bursts of high chip rate impulsive wavelets are used to transmit data. The wavelets are always 3-cycles of RF per chip (and spaced 3-cycles apart) which makes the centre frequency 3 x chip rate. The system bandwidth is defined by the bandwidth of the basic wavelet and is proportional to the inverse of the length of the wavelet. The bandwidth increases with the centre frequency. The following figure illustrates an example wavelet and its spectrum.

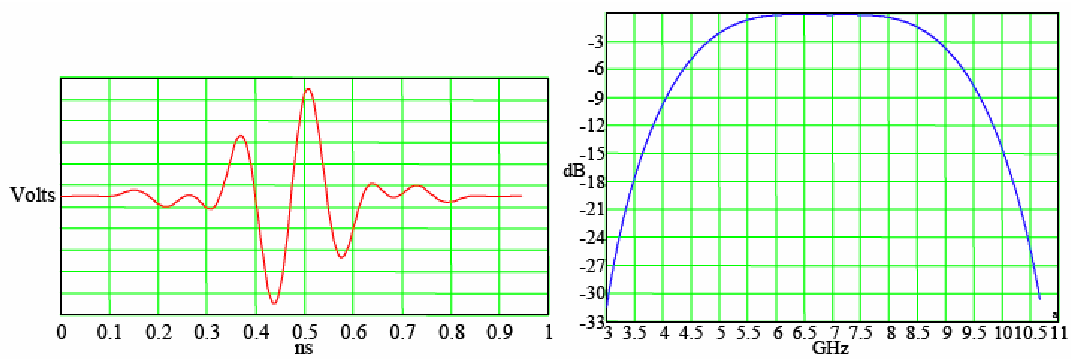

Figure 4.1 : Example Wavelet and Its Spectrum
(Taken from a document provided by Freescale Semiconductor titled 'Key Attributes of DS-UWB & Answers to Frequently Asked Questions', 31.May.2005)

The following figure shows an example code sequence in the time and frequency domain where it is stated that the total power is 1.5 dB lower than would be the case for a perfectly 'white' code.

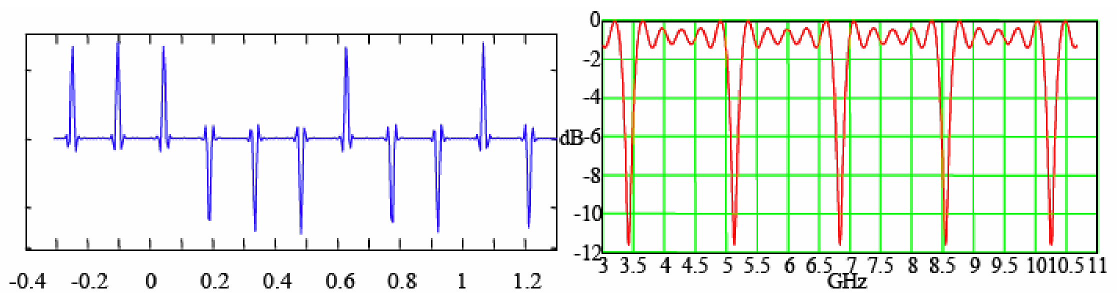

Figure 4.2 : Example Code Sequence in Time and Frequency Domain (Taken from a document provided by Freescale Semiconductor titled 'Key Attributes of DS-UWB & Answers to Frequently Asked Questions', 31.May.2005)

In the time domain, convolving the wavelet, code and data results in the transmitted signal. The data is processed to guarantee that it is white and zero-mean which, in turn, means that the spectrum of the transmitted signal is effectively that of the pulse and code. The following figure illustrates the DS-UWB signal in the time and frequency domain.

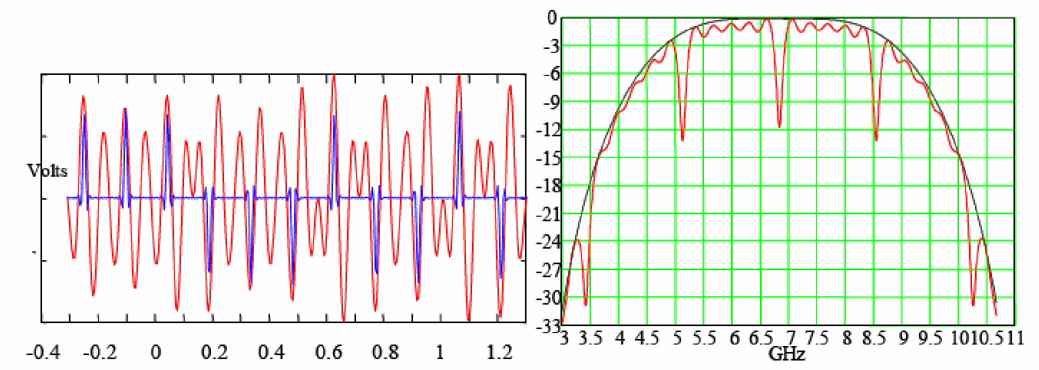

Figure 4.3 : Example DS-UWB signal in Time and Frequency Domain (Taken from a document provided by Freescale Semiconductor titled 'Key Attributes of DS-UWB & Answers to Frequently Asked Questions', 31.May.2005)

If the code were perfectly white then the transmitted spectrum would be simply that of the pulse.

The maximum transmit power is specified as –2.5 dBm within a signal bandwidth. Transmitters are capable of reducing their power in 3–5 dB steps to a minimum level of –10 dBm. Receiver performance requirements are defined for a packet error rate of 8% and a packet length of 1024 bytes. The minimum signal levels are in the range –85.5 to –68.4 dBm for data rates 28–1000 Mbps.

In DS-UWB applications, the centralised piconet controller allows the scheduler in the Medium Access Control to distribute data packets over time and make transmit power adjustments according to the code used, the packet size used (emission duration), how close together packets are sent over a link (duty cycle) and effective antenna gain to comply with peak and RMS limits. For example, it is stated that a link using 10 ms packets would operate below the peak limit and would be limited by the –41.3 dBm/MHz RMS over 1 ms specification while a link using very short 25 μs packets spaced over 1 ms apart would operate below the RMS limit and would be limited by the 0 dBm/MHz peak in a 50 MHz reference bandwidth specification. When transmitting, the DS-UWB transmitter sends data continuously and then turns-off (i.e. goes to sleeping mode). By allowing a link to transmit short bursts, potentially up to the peak limit, and sending data at the fastest rate over the distance required by the link, sleep-time is maximised, hence the time for other users is maximised.

In the US, Institute for Telecommunications Sciences (ITS) of the National Telecommunications and Information Administration (NTIA) has been studying the interference potential of UWB signals under a cooperative research agreement with Motorola/Freescale Inc. It is noted that the study has produced two reports in 2005 and further reports will follow. These documents can be found at http://www.its.bldrdoc.gov/home/programs/uwb_interference/.

The following figures are based on the NTIA study and illustrate an example DS-UWB signal's measured amplitude probability distribution (APD), spectrum plot and time domain representation.

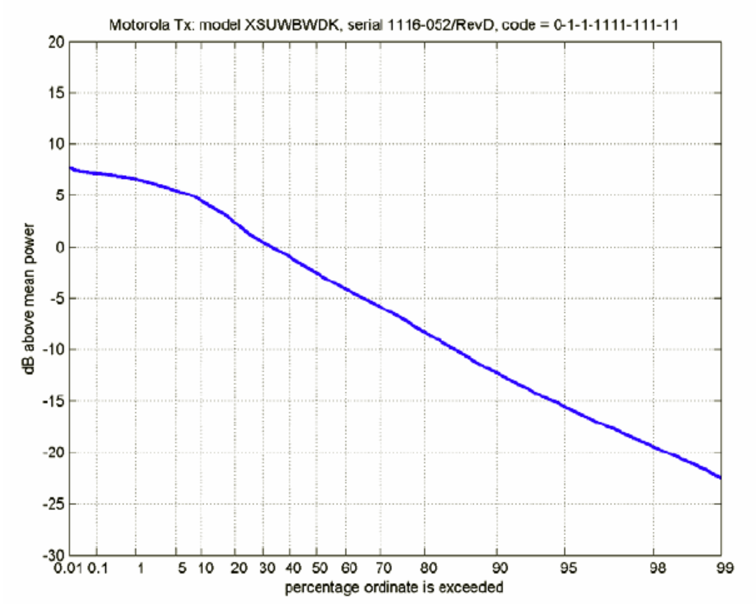

Figure 4.4 : APD in 36 MHz Bandwidth of DS-UWB Emission (TX Designed to Operate In The Lower Band (3.1–4.85 GHz) with BPSK Modulation and Code Length 12) (Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

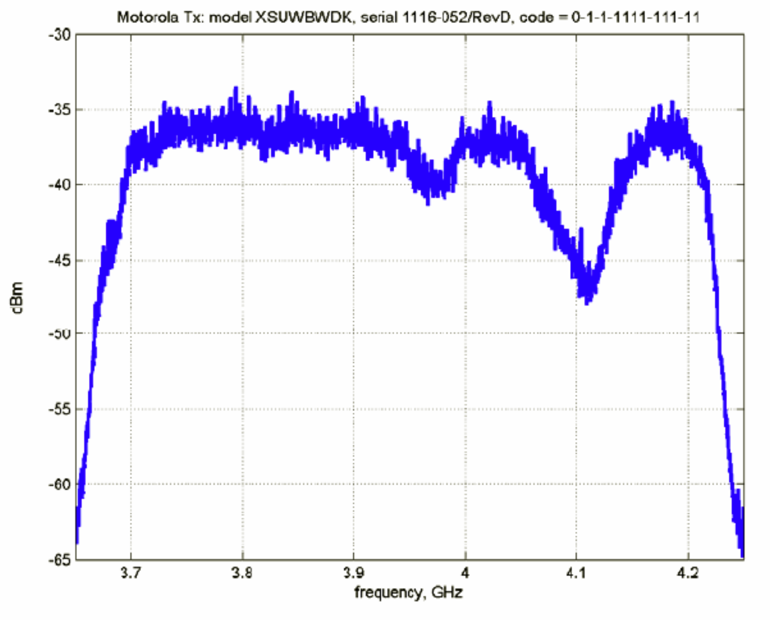

Figure 4.5 : Spectrum Plot of DS-UWB Emission
(Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

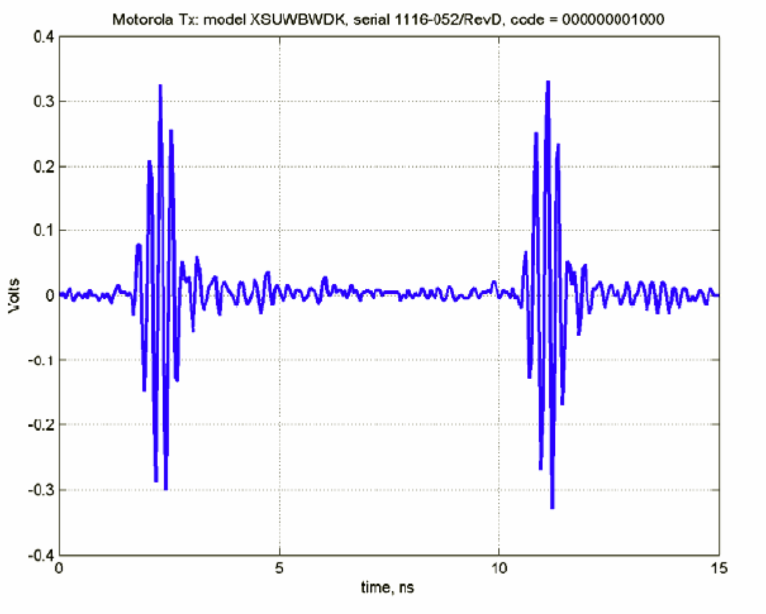

Figure 4.6 : DS-UWB Emission in the Time Domain
(Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

For the purposes of comparison, further plots are re-produced below representing Gaussian noise signal.

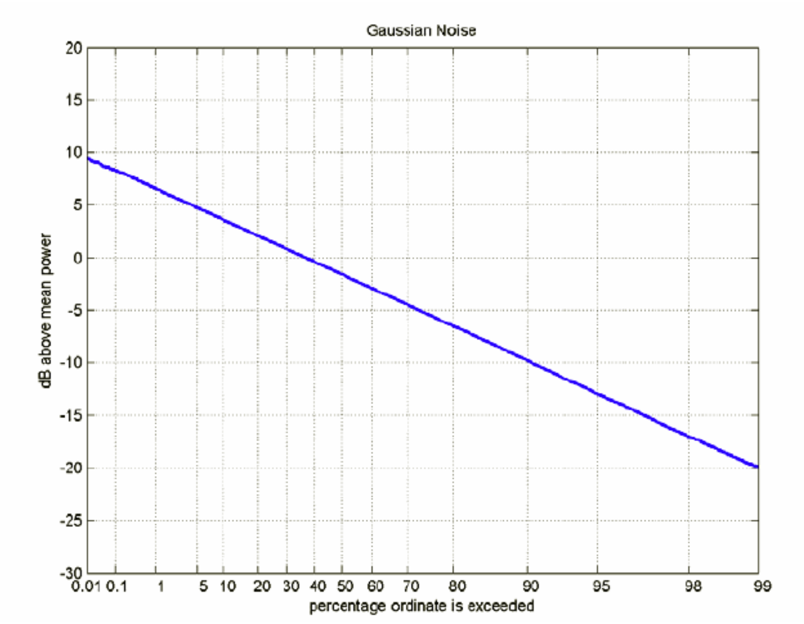

Figure 4.7 : APD in 36 MHz Bandwidth of Gaussian Noise (Generated by a Noise Diode) (Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

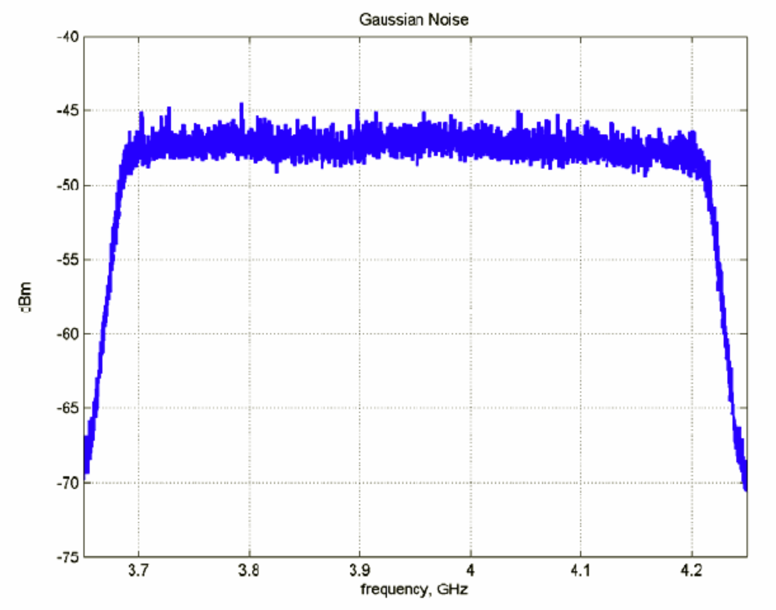

Figure 4.8 : Spectrum Plot of Gaussian Noise (Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

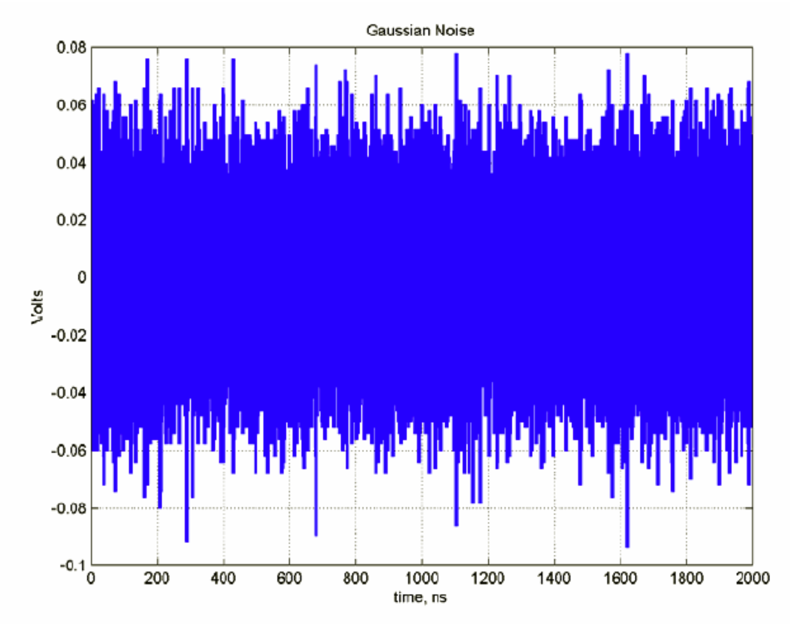

Figure 4.9 : Gaussian Noise Emission in the Time Domain (Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

4.2 MB-OFDM

The basic idea of the MB-OFDM proposal is to divide the 3.1–10.6 GHz spectrum into 14 contiguous 528 MHz bands. The following figure illustrates the band plan.

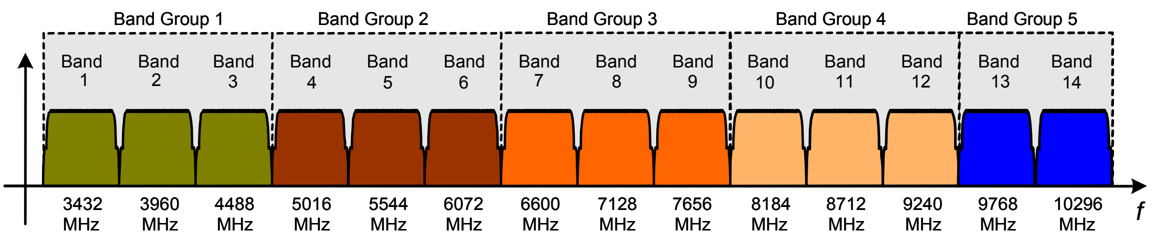

Figure 4.10: MB-OFDM Bands

All devices using this technology are required to be able to tune to the bands within the first band group (i.e. bands 1–3). The ability to use other bands is optional. User data is coded, interleaved and transmitted using an OFDM ensemble of orthogonal carriers in each band. Frequency hopping between the bands is employed over a link to exploit frequency diversity, which mitigates multipath and interference.

A total of 128 orthogonal carriers (tones) are employed in each band. 100 tones carry user data and each tone is modulated using QPSK. Each data tone is 4.125 MHz. 12 tones are dedicated to pilot signals to achieve robust coherent detection against frequency offsets and phase noise. 10 tones are used to provide a guard band while the remaining 6 tones are set to zero and classified as null tones.

The guard band tones carry no useful information and the main purpose of these tones is to ensure that the spectrum is greater than 500 MHz (so that the signal can be classified as UWB). Concerns have been expressed over the use of guard bands just to increase the signal bandwidth to meet the minimum bandwidth requirement. The recent update of MB-OFDM specification proposes that the data tones towards the edge of an ensemble can also be mapped onto the guard tones to improve the robustness at the band edges.

Devices using MB-OFDM are required to support data rates of 55, 110 and 200 Mbps while 80, 160, 320 and 480 Mbps data rates are optional. The channel bit rate is specified to be 640 Mbps for all data rates. Convolutional encoders with coding rates 11/32, 1/2, 5/8 and 3/4 are used.

Channelisation is achieved by utilising different preambles and time-frequency codes for different piconets. Time-frequency codes define frequency-hopping patterns. 4 codes are defined for the band groups 1–4 and 2 codes are defined for the band group 5. This enables a total of 18 piconets simultaneously to operate.

For data rates of 55, 80, 110, 160 & 200 Mbps, a time-domain spreading is performed. The same information is transmitted over two OFDM symbols in different bands. For example, for a time-frequency code of [1 2 3 1 2 3], the information in the first OFDM symbol is sent in bands 1 & 2, the information in the second OFDM symbol is transmitted in bands 3 & 1 and the information in the third OFDM symbol is repeated in bands 2 & 3.

In order to facilitate co-existence with other radio systems, it is proposed that transmissions in bands and tones (i.e. OFDM carriers) can be turned on/off dynamically.

Example link budgets indicate that average transmit power levels are –10.3 dBm for the mandatory mode (i.e. the operation in the first band group) and –6.6 dBm for the optional mode. The transmit and receive antenna gains are 0 dBi and the receive noise figure is 6.6 dB for a device operating in the mandatory mode and 8.6 dB for a device operating in optional mode. Required E_b/N_o ratios are 4, 4.7 & 4.9 dB for data rates 110, 200 and 480 Mbps, respectively. The receiver sensitivity levels are in the range –83.5 to –70.7 dBm (depending on the data rate and mode of operation) for a maximum packet error rate of 8% with a packet size of 1024 bytes.

The proposed transmit power spectral density mask remains flat over 260 MHz on either side of the centre frequency. It then falls off by 12 dB at 285 MHz and by 20 dB at 330 MHz, as shown in the following figure.

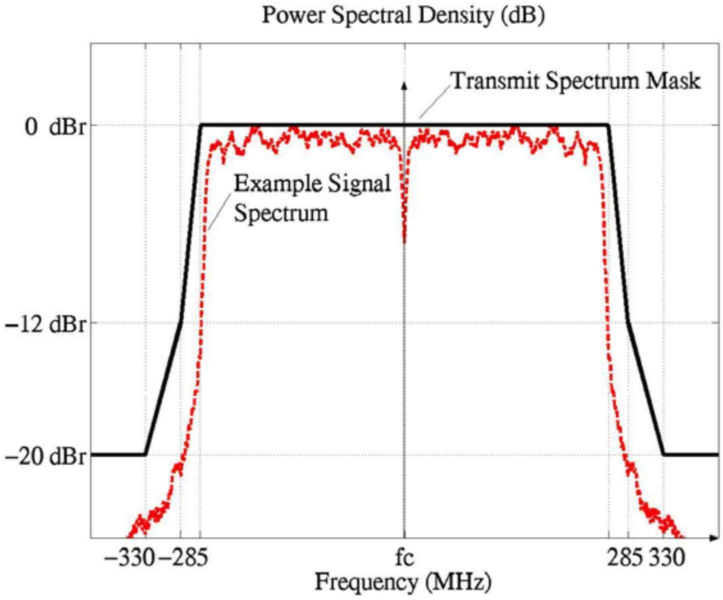

Figure 4.11: MB-OFDM Transmit Power Spectral Mask

MB-OFDM signals use at least three channels. The transmission on a single channel lasts for 242.4 ns followed by an off period of 695.1 ns. A complete transmission cycle is therefore 937.5 ns.

As mentioned in the preceding subsection, the current NTIA study has measured amplitude probability distributions, spectrum plot and time domain representation of various UWB signals. The following figures illustrate an example MB-OFDM signal's APD, frequency and time domain plots. It is stated that the transmitted signal was offset by 264 MHz from the frequency specifications of MB-OFDM physical layer proposal. Therefore, the centre of the second band was measured at 4224 MHz rather than 3960 MHz.

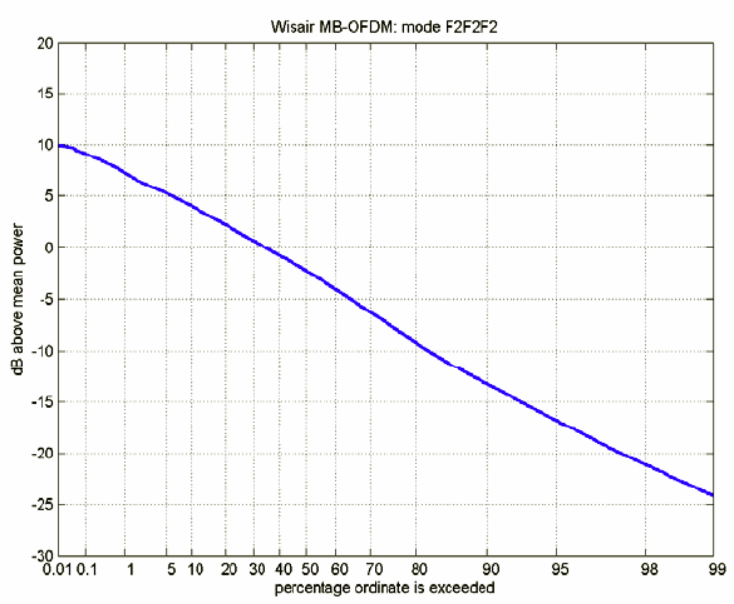

Figure 4.12 : APD in 36 MHz Bandwidth of MB-OFDM Emission in A Non-Hopping Mode (TX Designed to Hop In The First Band Group)
(Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

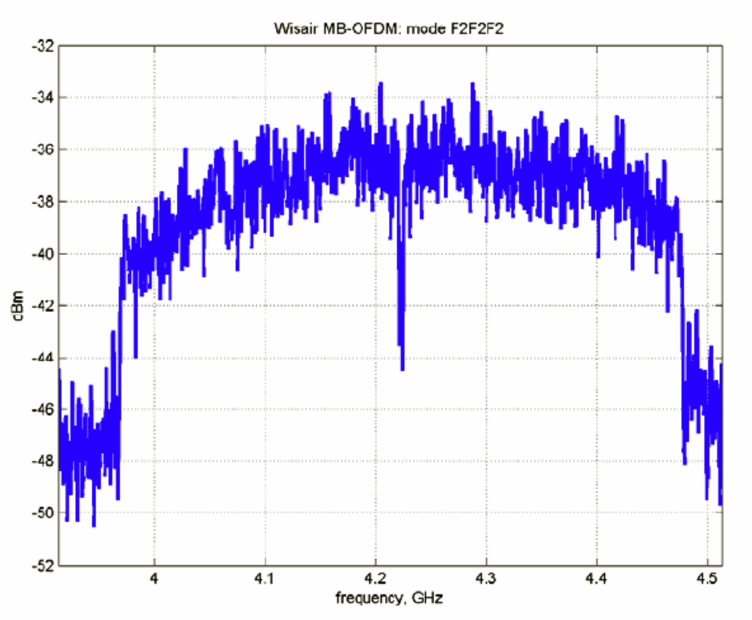

Figure 4.13 : Spectrum Plot of MB-OFDM Emission in A Non-Hopping Mode
(Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

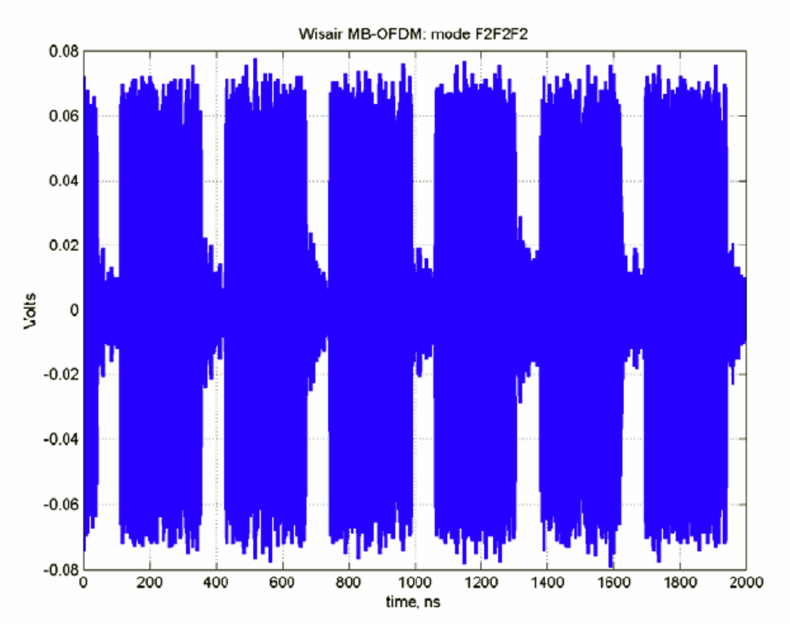

Figure 4.14 : MB-OFDM Emission in A Non-Hopping Mode in the Time Domain (Taken from an ITS NTIA document titled 'Task 1 Report of A Study to Define Metrics that Determine the Interference Potential of Various UWB Waveforms')

5 MODELLING

5.1 Introduction

Models have been developed to examine the impact of single-entry and aggregate UWB interference into RAS receivers. The simulator developed for the Ofcom by Aegis during the earlier study examining sharing between UWB and FS / FSS receivers has been used for the aggregate interference baseline modelling.

5.2 Single-entry Interference Analysis

The single-entry analysis model is used to calculate the separation distance between an RAS receiver and a UWB transmitter required to satisfy the RAS receiver interference criterion. Input parameters for the model include antenna heights, receive antenna pattern and diameter, UWB EIRP, receiver interference threshold (expressed in terms of maximum allowed interference PFD), receiver/transmitter bandwidths, receiver elevation angle.

Required separation distances are calculated using a flat-Earth model. From an interference point of view, this represents the worst-case situation. In the calculation process, the minimum distance between the UWB transmitter and the RAS receiver is assumed to be 1 m and the distance is increased in 1 m steps until the receiver interference criterion is satisfied.

Simultaneous variations in the path loss and the receive antenna gain (as a function distance) can be taken into consideration in the calculation process; however, in the results reported here, the RAS antenna gain was assumed fixed at either –10 dBi or 0 dBi towards the UWB device. The separation distance is the distance beyond which interference remains below the receiver interference criterion. The following figure illustrates the interference geometry of UWB single-entry interference into a RAS receiver.

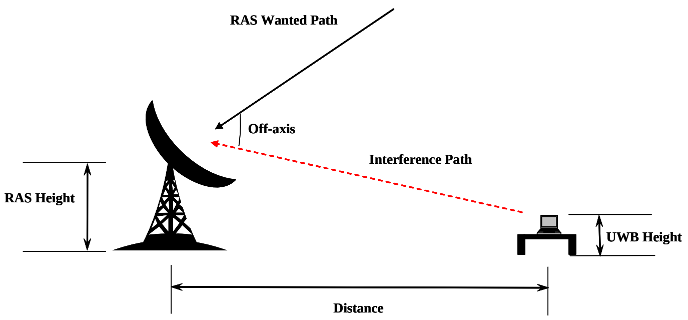

Figure 5.1: Single-entry UWB-RAS Interference

5.2.1 Modelling Parameters

The following table shows assumed parameter values for the baseline single-entry model. The RAS receive bandwidth and interference criteria values are based on ITU-R Rec.769-2.

	Single-dish	***Single-dish (–10 dBi)***	***Merlin***
RAS RX Operating Frequency	4.830 GHz	4.830 GHz	4.995 GHz
RAS RX Bandwidth	50 kHz	50 kHz	10 MHz
Interference Criterion (PFD)	–230 dBW/m^2 Hz	–220 dBW/m^2 Hz	–200 dBW/m^2 Hz
RAS RX Antenna horizon gain	0 dBi	–10 dBi	0 dBi
Propagation	Free Space		
UWB EIRP	–41.3 dBm/MHz		

Table 5.1: Baseline Single-entry Model Parameters

5.2.2 Results

Using the modelling parameters, the following minimum required separation distances are calculated.

Single Dish	25 km
Single Dish –10 dBi	7.9 km
Merlin	770 m

Table 5.2: Single-entry Separation Distances

Further analysis has been implemented to calculate a maximum tolerable UWB EIRP level for a given separation distance. The following table illustrates the results.

Distance (m)	***Max. Tolerable UWB EIRP (dBm/MHz)***		
	Single Dish (0 dBi)	***Single Dish (–10 dBi)***	***Merlin (0 dBi)***
50	–95.0	–85.0	–65.0
500	–75.0	–65.0	–45.0
1000	–69.0	–59.0	–39.0

Table 5.3: Max. UWB EIRP vs Distance

Results indicate that, to achieve protection at 500 m distance, a reduction of ~34 dB in the FCC UWB EIRP level of –41.3 dBm/MHz is required to protect the RAS single dish receivers, falling to ~25 dB if a –10 dBi antenna gain can be assumed. In the case of Merlin, a reduction of only ~4 dB is needed.

It should be noted that the above calculations are based on the assumption of free-space propagation. It is expected that most UWB devices will be indoor. In addition, the interference path may be subject to a clutter loss. For example, a representative total building penetration and clutter loss of 20 dB reduces the minimum required separation distance from 25 km to 2.5 km for the single dish (0 dBi) observation and from 770 m to <77 m for the Merlin observation.

However, these are single-entry calculations, and it does not seem unreasonable to suppose that a radio telescope might ‘see’ at least one UWB device on an unobstructed path.

5.3 Aggregate Interference Analysis

The analysis has been carried out by aggregating interference from urban centres located near RAS sites.

5.3.1 Modelling Parameters

Aggregate interference levels from a moderate size town and a city have been estimated. The moderate size town is assumed to be representative of Knutsford while the city is modelled on Greater Manchester. Both areas are near Jodrell Bank. The following table summarises the modelling assumptions.

	Town	***City***
Area	3.5 x 3.5 km^2	21.3 x 21.3 km^2
Distance from town centre to RAS site	8 km	25 km
Population	13,000	2.5 million
No of houses	6,000	1 million
No of UWB devices per house	2	2
UWB density	1,000 / km^2	4,400 / km^2

Table 5.4: Baseline Aggregate Interference Modelling Assumptions

The RAS receive system parameters are the same as those used in the single entry interference analysis.

The following multi-slope model is used for modelling propagation effects.

- Path Loss = 20 log (4 π d / λ) for d ≤ 100 m
- Path Loss = (Loss at 100 m) + 30 log (d / 100) for 100 m < d ≤ 2000 m
- Path Loss = (Loss at 2000 m) + 40 log (d / 2000) for d > 2000 m

It is assumed that all UWB transmitters are indoors. The building penetration loss is represented by a log-normal distribution with a mean of 10 dB and a standard deviation of 5 dB.

5.3.2 Results

In the first analysis, UWB transmitters (with a density of 1,000 per km^2) are randomly distributed over a town with an area of 3.5 x 3.5 km^2. The centre of the town is located at 8 km distance from the RAS site.

For each interference path, propagation loss is calculated using the multi-slope model. In addition, each interference path is subject to an additional loss due to building penetration modelled by sampling a log-normal distribution.

Interference from a population of UWB transmitters is aggregated for 1,000 Monte Carlo trials. The following example figure compares interference spectral PFD statistics against the single dish (0 dBi) criterion for 1% and 17% UWB activity figures. If a –10 dBi gain can be assumed, no harmful interference is caused.

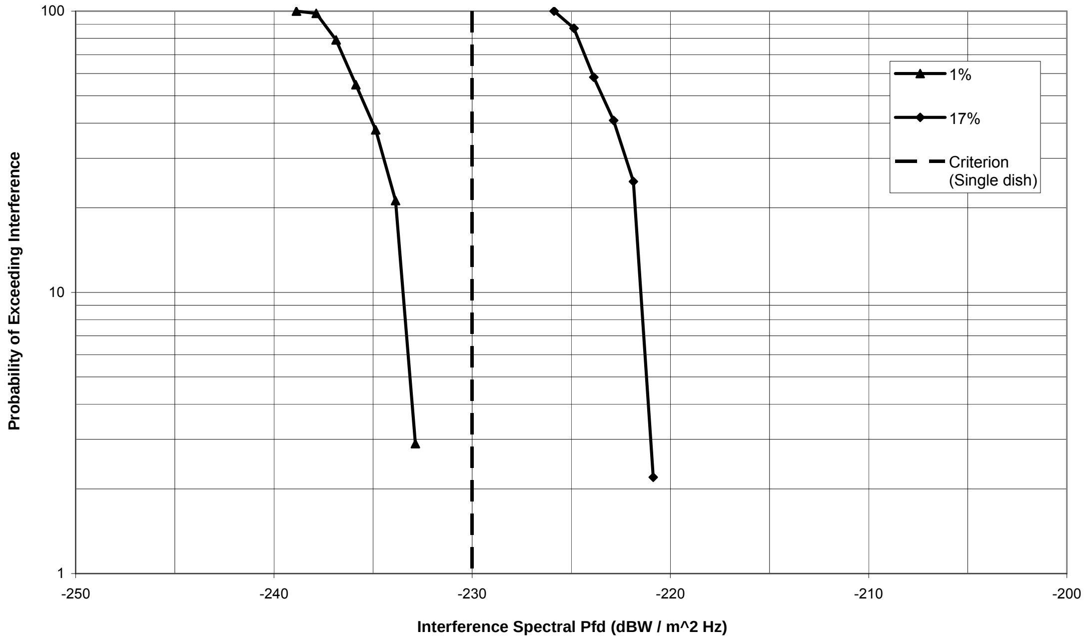

Figure 5.2: Interference Statistics (Single-dish)

The results indicate that interference spectral PFD varies up to 6 dB over 1,000 Monte Carlo trials due to the variations in active transmitter positions and building penetration losses. In the remainder of this report, mean aggregate interference spectral PFD levels (dBW/m^2 Hz) corresponding to an exceedence probability of 50% are used to derive maximum allowed UWB EIRP levels.

The following table shows mean aggregate PFD levels for a number of UWB activity factors. It is assumed that the UWB EIRP is –41.3 dBm/MHz.

UWB Activity	No Of Active TXs	Interference Spectral PFD (dBW/m^2 Hz)		
1%	122	–236		
5%	612	–229		
10%	1,225	–226		
17%	2,082	–224		
Interference Criterion (dBW / m^2 Hz)		**Single dish 0 dBi**	**Single dish –10 dBi**	**Merlin 0 dBi**
		–230	–220	–200

Table 5.5: Baseline Aggregate Interference Modelling Results (Town)

Based on the results, the maximum allowed UWB EIRP levels are calculated and shown in the following table.

UWB Activity	Max. Tolerable UWB EIRP (dBm/MHz)		
	Single dish	Single dish –10 dBi	Merlin
1%	–35.3	–25.3	–5.3
5%	–42.3	–32.3	–12.3
10%	–45.3	–35.3	–15.3
17%	–47.3	–37.3	–17.3

Table 5.6: Max. Allowed UWB EIRP (Town)

In the second analysis, UWB devices are assumed to be operating in a city of area 21.3 x 21.3 km^2. The centre of the area is located at 25 km distance from the RAS site. The transmitters are randomly positioned with a density of 4,400 / km^2. The same propagation and building penetration loss models are used and the UWB EIRP is assumed to be –41.3 dBm/MHz.

Mean aggregate interference spectral PFD levels (dBW/m^2 Hz) corresponding to an interference aggregation over 500 Monte Carlo trials are shown in table below for different UWB activity factors.

UWB Activity	No Of Active TXs	Interference Spectral PFD (dBW/m^2 Hz)		
1%	20,416	–230		
5%	102,080	–223		
10%	204,160	–219		
17%	347,072	–217		
Interference Criterion (dBW / m^2 Hz)		**Single dish**	**Single dish –10 dBi**	**Merlin**
		–230	–220	–200

Table 5.7: Baseline Aggregate Interference Modelling Results (City)

Based on the results, the maximum allowed UWB EIRP levels are calculated and shown in the following table.

UWB Activity	Max. Tolerable UWB EIRP (dBm/MHz)		
	Single dish	Single dish –10 dBi	Merlin
1%	–41.3	–31.3	–11.3
5%	–48.3	–38.3	–18.3
10%	–52.3	–42.3	–22.3
17%	–54.3	–44.3	–24.3

Table 5.8: Max. Allowed UWB EIRP (City)

5.3.3 UWB Population Sensitivity Analysis

The implications of UWB transmitter population have been examined by comparing the following scenarios:

1) ***Town***: The same model is used where indoor UWB transmitters (with a density of 1,000 per km^2) are randomly distributed over an urban area of 3.5 x 3.5 km^2 and the centre of the urban area is located at 8 km distance from the RAS site.

2) ***Town and Rural Area with 10 Buildings per km²***: The moderate size urban area model is populated with additional indoor UWB transmitters assumed to represent rural usage around RAS sites. It is assumed that additional indoor UWB transmitters operate within an annular area of 500 m inner radius and 7,500 m width. It is further assumed that there are 10 two-storey buildings (10 m x 10 m x 6 m) per square kilometre and 2 devices operate in each building.

3) ***Town and Rural Area with 20 Buildings per km²***: The same as the second scenario except 50 buildings per square kilometre.

In all scenarios, it is assumed the UWB activity figure is 17% and interference is aggregated for 1,000 Monte Carlo trials. The following figure compares the results against the single dish criterion.

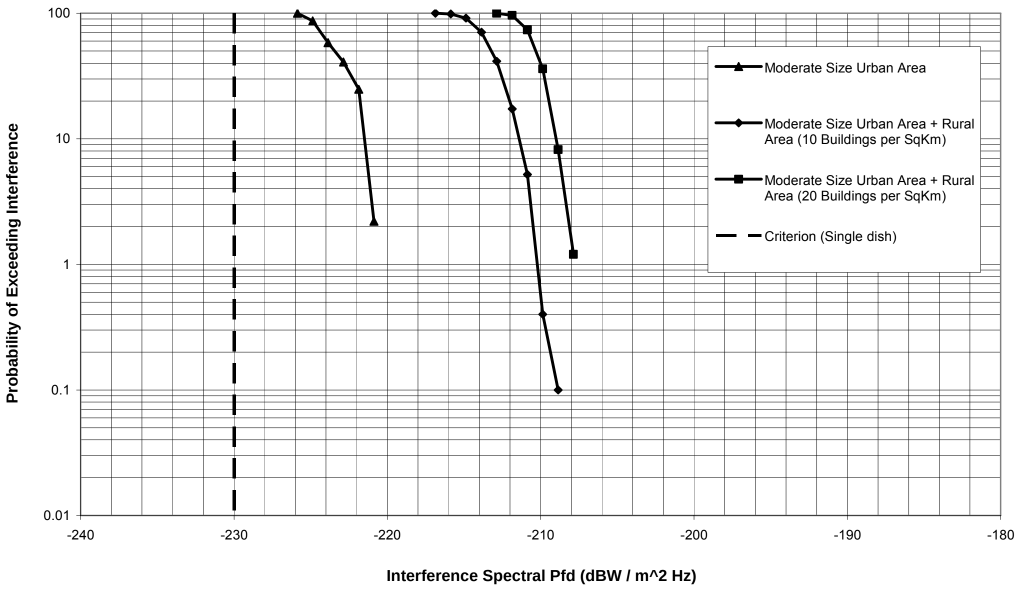

Figure 5.3: UWB Population Sensitivity (Single-dish)

The maximum interference PFDs corresponding to the urban + rural scenarios are 12–13 dB higher than that of urban scenario which indicates that interference contribution from nearby transmitters is significant as, in urban + rural scenarios, indoor UWB transmitters could be located at 500 m from the RAS site.

These results, and those of the single-entry case above, suggest that the most significant interference problems will arise due to a few local interferers. This situation is examined, in a site-specific manner, in the next section.

6 SITE-SPECIFIC MODELLING

It has been suggested that greater compatibility between the RAS and UWB may be demonstrated if site-specific factors, such as local terrain and vegetation are accounted for.

Local terrain features are significant in two respects. Firstly, intervening terrain will introduce additional diffraction loss in the interference path and, secondly, surrounding features may constrain the minimum elevation of the telescope, limiting the sidelobe gain towards the horizon.

The telescopes of the Merlin network are at the locations given in the table below.

Site	Area	NGR	Assumed height Metres (agl)	T_{sys} K (5 GHz)	Notes
Jodrell Bank	Cheshire	SJ 797 714	40 m	37	Lovell or Mark II
Defford	Worcs.	SO 903 447	15 m	55	25 m
Knockin	Shropshire	SJ 329 219	15 m	33	25 m E-systems
Pickmere (Tabley)	Cheshire	SJ 704 769	15 m	33	25 m E-systems
Darnhall	Cheshire	SJ 645 613	15 m	33	25 m E-systems
Cambridge	Cambs.	TL 395 545	20 m	32	32 m (1991)

Table 6.1: Merlin Telescopes

6.1 Horizon elevation angles

Horizon profiles have been determined for these locations, using the Ordnance Survey UK 50 m terrain database. The results are shown in the figures below.

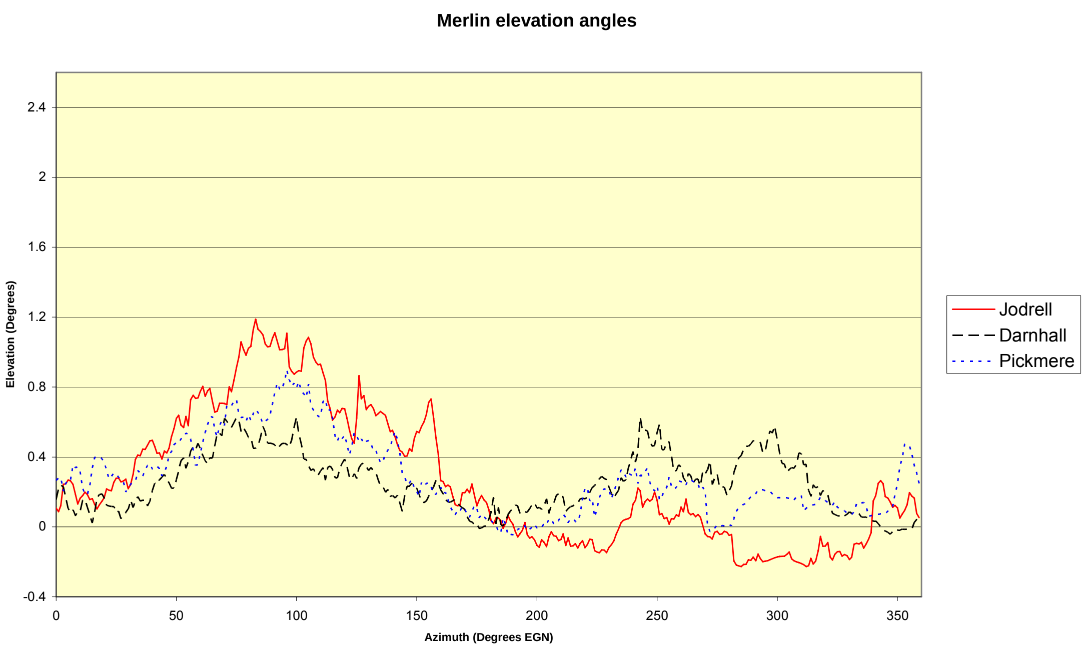

Figure 6.1a: Horizon elevation for Cheshire telescopes

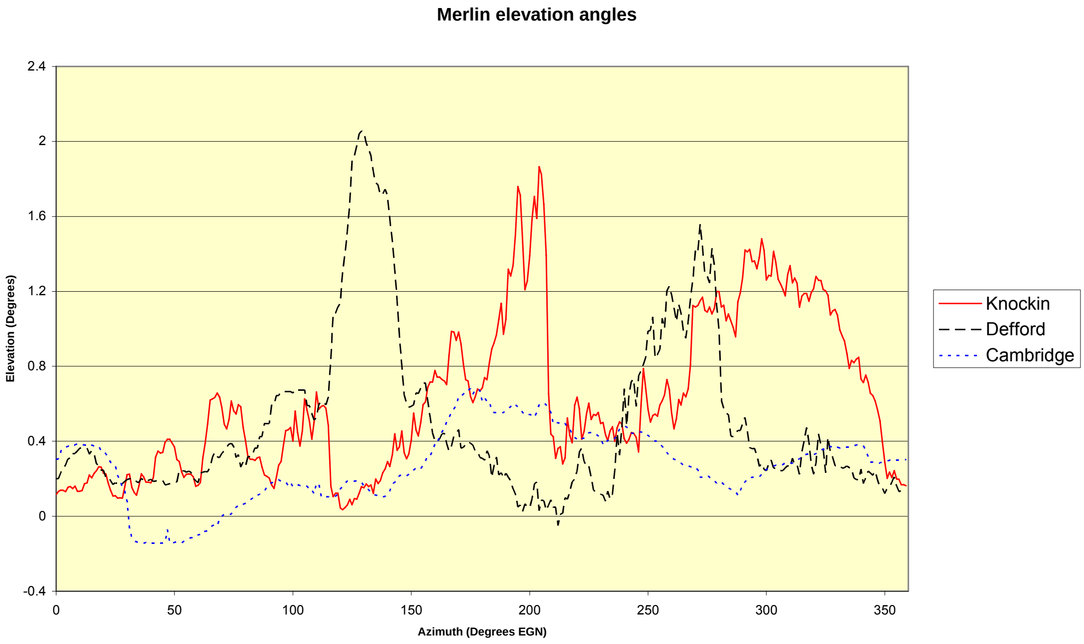

Figure 6.1b: Horizon elevation for other MERLIN telescopes

It can be seen that horizon elevation angles are typically around 0.5 degrees, rising to 1.2 degrees (Jodrell Bank towards the Peak District) or 2 degrees (Defford towards Bredon Hill and the Malvern Hills and Knockin towards Long Mountain).

In terms of limiting interference entries, these elevation angles are not likely to be significant. In particular, the directions of high elevation tend to correspond to areas of low population density.

6.2 Exclusion area plots

The interference protection levels defined in Section 3.4.2 can be used to plot ‘required single-entry exclusion areas’, for a given assumed UWB EIRP.

In the plots given below, these areas have been calculated based on the FCC limit of –41.3 dBm/MHz, and the RAS interference criteria tabulated below.

Observation	Assumed telescope horizon gain	SPFD (dBW/Hz.m^2)	Equivalent FS (dBµV/m.MHz)	Contour
Spectral Line	0 dBi	–230	–24.3	Red
Spectral Line	–10 dBi	–240	–14.3	Blue
Merlin	0 dBi	–200	5.8	Green

Table 6.2: Modelling parameters

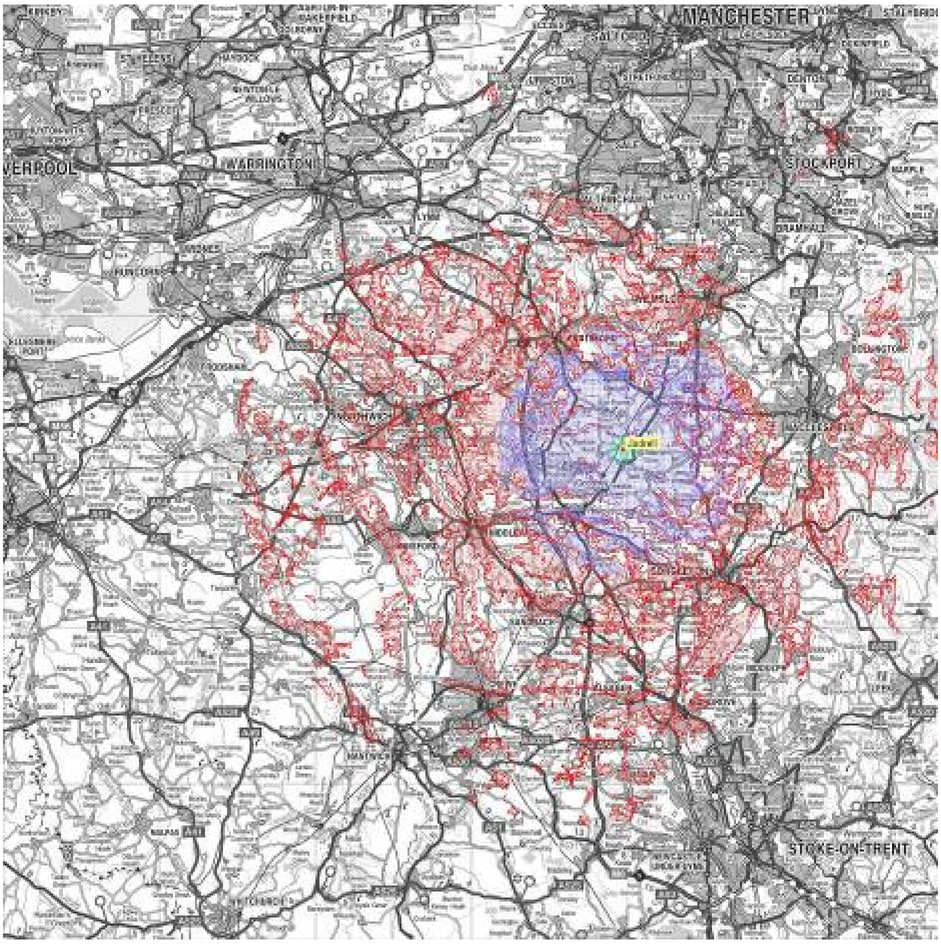

Figure 6.2a: Jodrell Bank

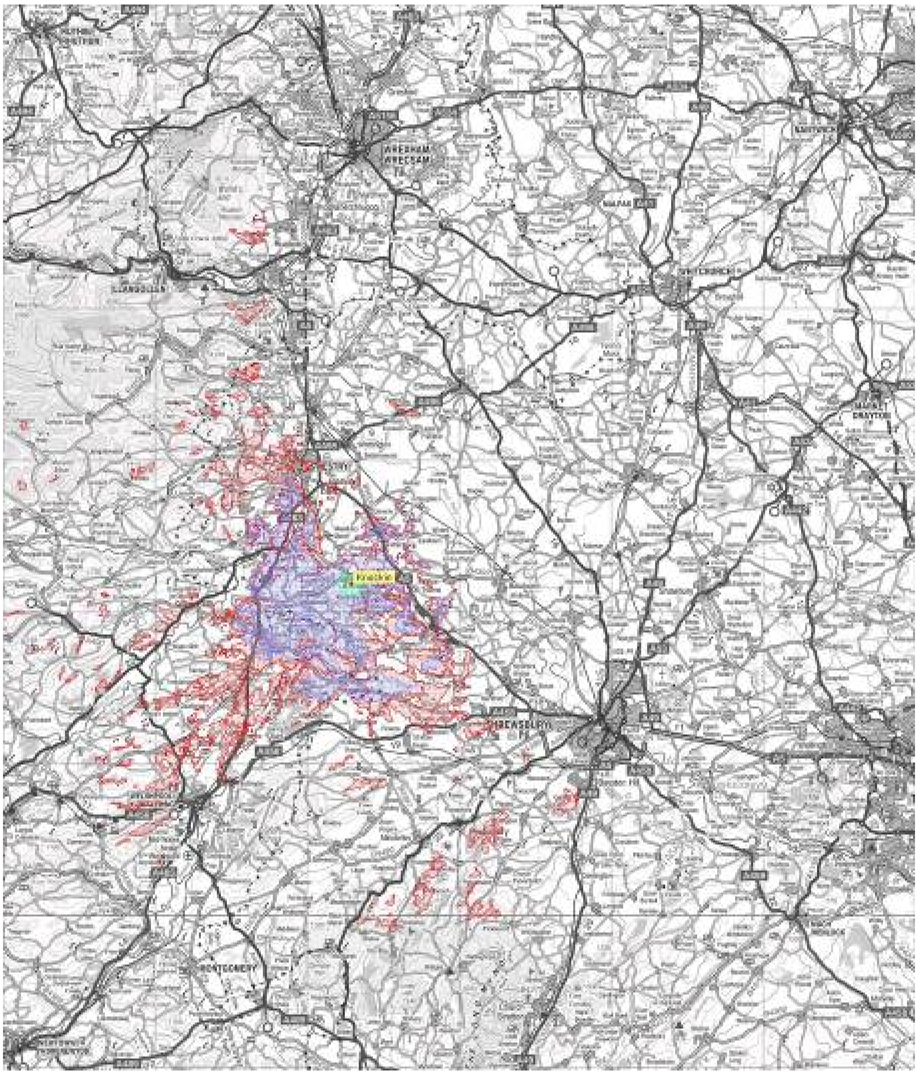

Figure 6.2b: Knockin

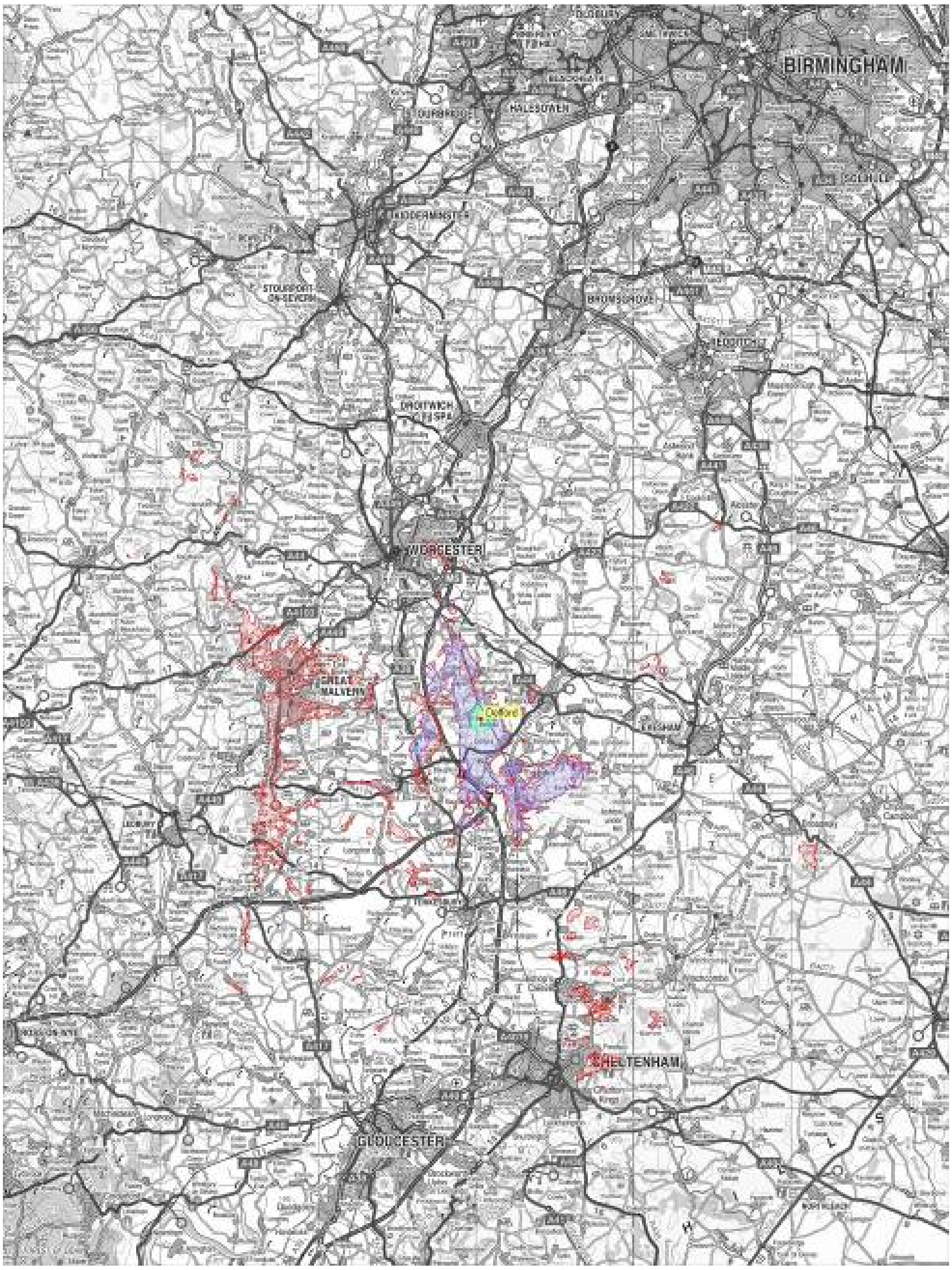

Figure 6.2c: Defford

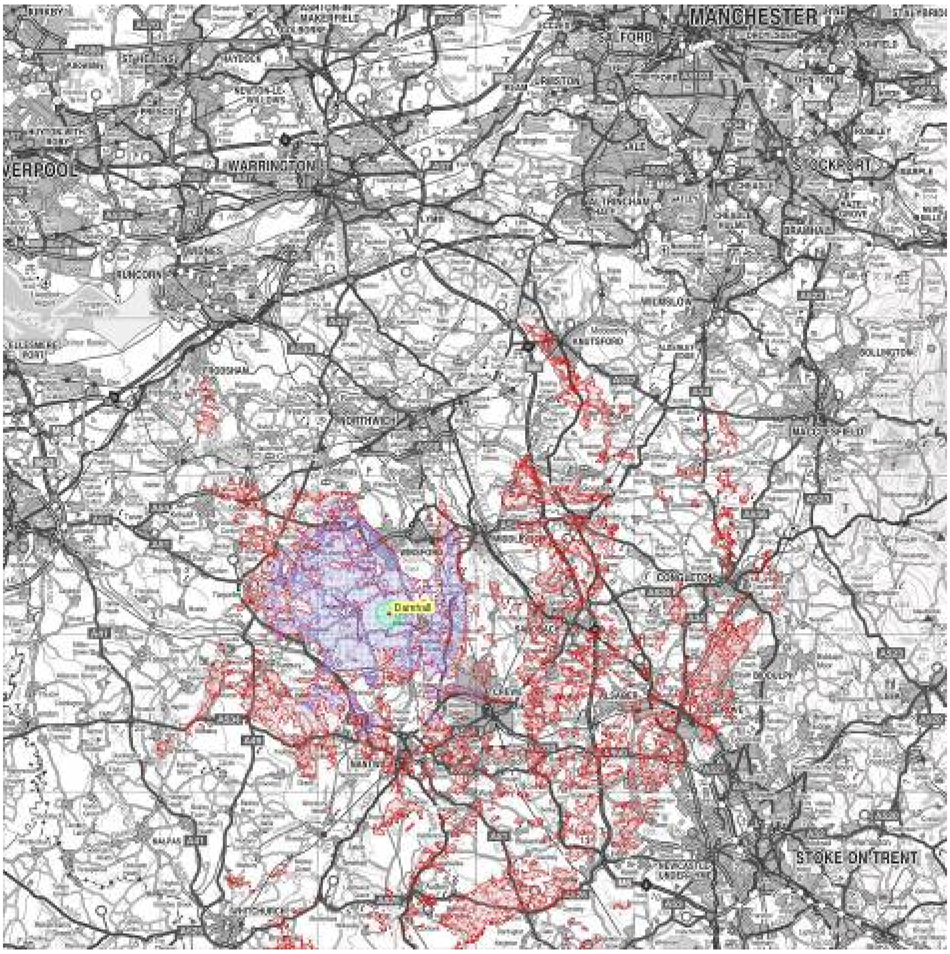

Figure 6.2d: Darnhall

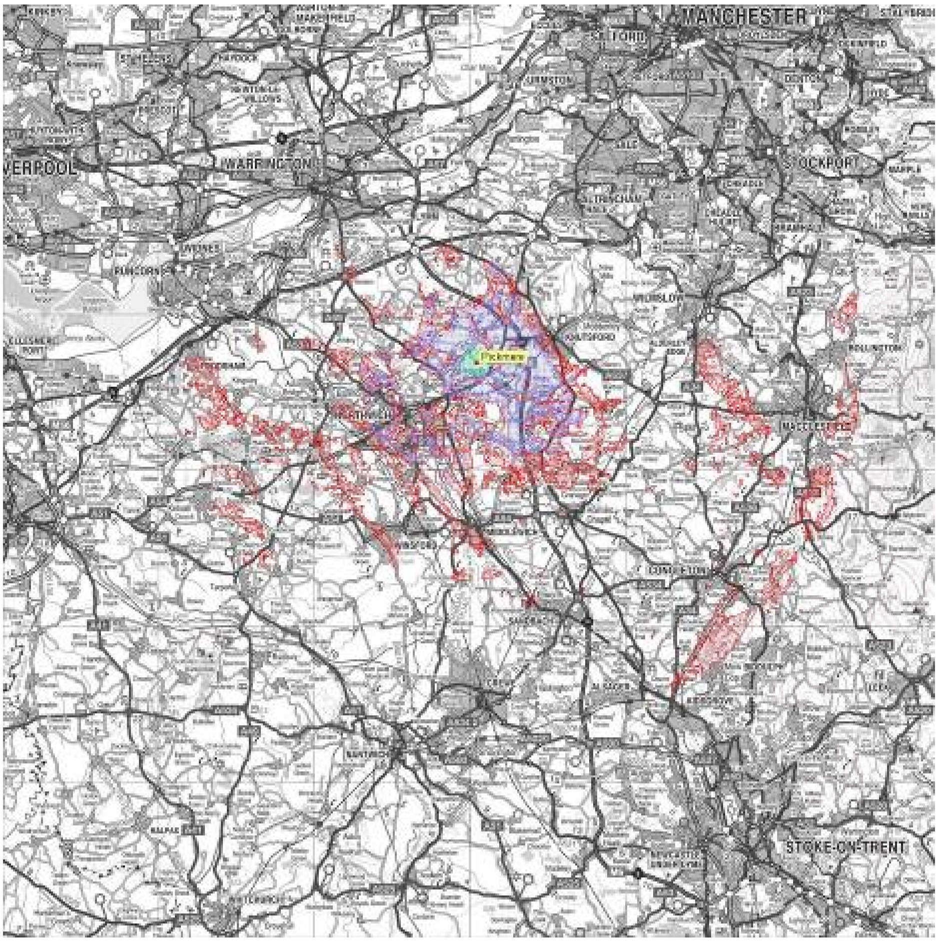

Figure 6.2e: Pickmere

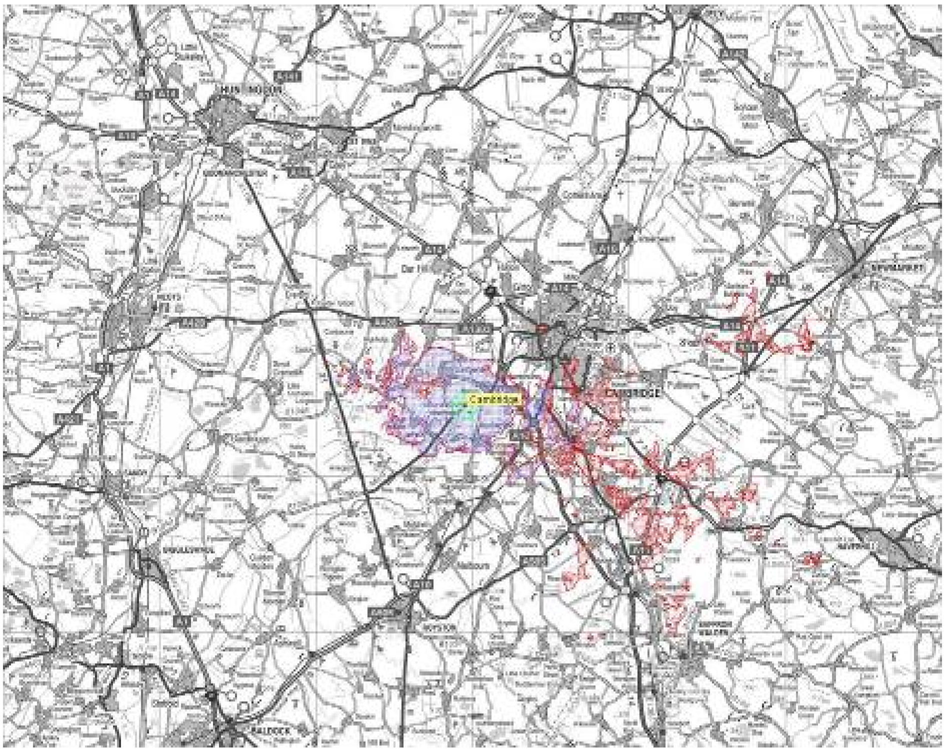

Figure 6.2f: Cambridge

The impact of the terrain is clear in the plots of Figure 6.2. In particular, it is clear that the height of the Lovell telescope gives rise to the possibility of line-of-sight interference from some distance. For the Cheshire telescopes, the surrounding countryside includes a number of significant terrain features at distances of up to 20 km that allow long line-of-sight paths. By contrasts, the telescope at Cambridge, although higher than most others, is surrounded by flat terrain, and such distant paths do not generally occur.

It is worth noting, however, that most of the distant features that might give rise to interference paths are sparsely populated.

Towns that might be significant sources of aggregate interference are Northwich (Pickmere), Winsford (Darnhall), Knutsford (Jodrell) and Holmes Chapel (Jodrell).

6.3 Other mitigation factors

6.3.1 Shielding due to clutter & vegetation

There has been considerable discussion regarding the most suitable form of propagation model for studies such as this. In particular, UWB proponents have questioned the use of a free-space model. For the case of single-entry interference, however, it is quite reasonable, for interferers within the horizon, to assume that a line-of-sight path might arise.

For aggregate interferers, on the other hand such an assumption is clearly unreasonable. In almost any conceivable scenario, the majority of individual paths will be significantly faded due to terrain and local clutter. Sophisticated path loss models are available that take terrain and building diffraction into account on a site-specific basis. Such models are, however, computationally demanding, and are not justified where large populations of interferers are concerned. In such cases it is necessary only that the aggregate path loss is adequately captured.

A wide variety of models are suitable for such modelling, and often reduce to the use of a power law that changes with path length. For the Monte Carlo modelling described above, we have used such a multislope model with break-points at 100 m and 2 km, but many other similar models might also be applied. One suggestion has been to employ the model described in ITU-R M.1225. The relationship between path loss and range is plotted for this model, and compared with the model used in our Monte Carlo trials, in Figure 6.3, below.

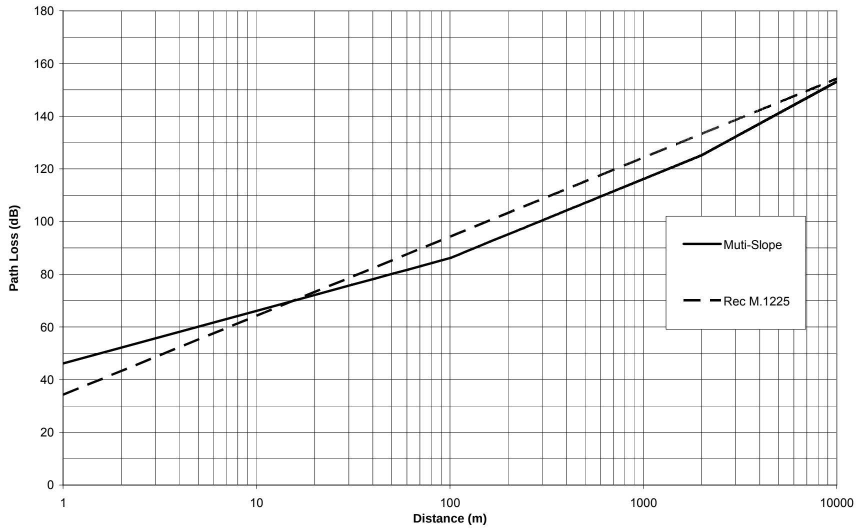

Figure 6.3: Comparison of propagation models

To put the discussion regarding appropriate propagation models in context, it is useful to see representative telescopes in relation to the surrounding terrain. Figure 6.4 shows the Lovell telescope at Jodrell Bank from a point some 2 km to the South.

Figure 6.4: Jodrell Bank

The telescope at Pickmere is shown in Figure 6.5 below.

Figure 6.5: Pickmere telescope

It can be seen that, in both cases, the telescopes are a dominant feature in the landscape. It is clear that the likelihood exists for line-of-sight paths from interfering devices at a significant distance. The areas with such views of the telescopes are limited, but there are many scattered dwellings where it is quite plausible that UWB-enabled devices might be used outdoors or near windows.

6.3.2 Boundary Fences

Detailed site plans have been obtained for the telescopes in the Merlin network. It is clear that, in most cases, the sites are only barely large enough to contain the telescope antenna. Most sites, however, are located some way from the nearest building, and it would seem that a pragmatic 'exclusion' distance of 500 m may be assumed.

Maps are given in Appendix B of the area immediately surrounding each site. The telescopes at Cambridge and Defford are located well away from any domestic or industrial buildings, while at Darnhall and Pickmere only a few farms are within a kilometre of the site. At Jodrell and Knockin there is a higher density of domestic and other building, and in all cases, there is a significant village or town[2] within 2 km of the telescope.

6.3.3 Observational measures

One 'interference avoidance' technique that has been suggested is for astronomers to make observations only in the night-time, when UWB activity levels might be expected to be minimal.

[2] Goostrey (Jodrell), Defford, Knockin, Higher Wincham (Pickmere), Winsford (Darnhall) and Comberton (Cambridge).

Such an approach would have the obvious disadvantage that the valuable capital resource of the telescopes would be dramatically under-utilised. It the available telescope time were limited, it might be necessary to compress observations into a shorter time-frame. This would imply reduced integration times, and hence lower sensitivity, ultimately negating the benefit of interference-free observations.

A more subtle problem relates to the use of aperture synthesis by the Merlin network. As noted above, the Fourier components of the brightness information are derived by sampling the scanning the *u,v* plane. The degree of coverage achieved in the plane will determine the quality of the results, and a 12 hour observing time is normally chosen to maximise this. The observing schedule has, of course, to be tied to the time that the field of interest becomes visible.

Other time constraints for astronomers would relate to measurements being scheduled simultaneously in different countries or continents for VLBI, or for the observation of irregular events.

Clearly, it is possible to co-ordinate observation with predicted sources of interference to some degree. For example, the 4.9 GHz band is used by the military for tactical radio links. Such use is, however, very sporadic, and we understand that Jodrell Bank are given advance warning, so that observations may be appropriately scheduled. On a different timescale, a system was agreed with the Iridium satellite system, whereby pulse-blankers would be installed at radio telescopes, synchronously to disable telescope receivers during TDD transmission bursts from the satellite constellation.

6.3.4 Antenna improvements

Astronomers already have a great incentive to minimise the sidelobe response of their systems, as this will tend to determine the antenna temperature of the system. While minor improvements may be possible, physical law probably limits much further improvement.

6.3.5 Screening fences

Screening fences are routinely used for observation at higher (millimetric) frequencies. One example is shown in Figure 6.6, for a telescope (the Very Small Array) intended to observe the Cosmic Microwave Background (CMB) at 31 GHz.

Figure 6.6: VSA showing ground shield

The practicality of erecting a similar screen at Jodrell Bank may be judged from Figure 6.3, above.

6.3.6 Terrain screening

Some observatories have been deliberately located in natural bowls, and in areas of very low population density (e.g. Green Bank in the USA). This is not generally the case for the UK telescopes. While Jodrell Bank was originally chosen as a site to escape from the interference environment in Manchester, few locations in England enjoy the isolation of the Green Bank site. This area (13,000 square miles in West Virginia) was set aside as a 'radio quiet' zone by the FCC in 1958.

The UK equivalent might be to re-locate observatories to remote areas of Scotland. Estimating the cost of such an exercise might be relevant if a formal cost-benefit analysis were to be conducted.

7 OTHER FREQUENCY BANDS

Based on the baseline modelling approach presented in Section 5, the implications of single-entry and aggregate UWB interference have been examined for other RAS frequency bands.

7.1 Single-entry Interference Analysis

7.1.1 Single-dish, spectral-line (0 dBi)

The following table shows assumed parameter values for the single dish interference analysis. The RAS receive bandwidth, operating frequency and interference criteria values are based on ITU-R Rec.769. For the 10.65 GHz band, parameters given for 14.488 GHz are used and a correction factor is applied to the criterion to account for the frequency difference.

Frequency (GHz)	1.420	1.612	1.665	10.65
RAS RX Bandwidth (kHz)	20	20	20	150
Interference Criterion (PFD) (dBW / m^2 Hz)	–239	–238	–237	–224
RAS RX Antenna horizon gain	0 dBi			
Propagation	Free Space			

Table 7.1: Assumed Parameters for Single-dish Single-entry Analysis

On the basis of the above parameters, maximum tolerable UWB EIRP levels for separation distances of 50 and 500 m are determined. The following table shows the results.

Distance (m)	***Max. Tolerable UWB EIRP (dBm/MHz)***			
	1.420 GHz	***1.612 GHz***	***1.665 GHz***	***10.65 GHz***
50	–104.0	–103.0	–102.0	–89.0
500	–84.0	–83.0	–82.0	–69.0

Table 7.2: Max. UWB EIRP in Different Bands (Single-dish)

7.1.2 Single-dish (–10 dBi)

The following table shows assumed parameter values for the single dish interference analysis. The RAS receive bandwidth, operating frequency and interference criteria values are based on ITU-R Rec.769. For the 10.65 GHz band, parameters given for 14.488 GHz are used and a correction factor is applied to the criterion to account for the frequency difference.

Frequency (GHz)	1.420	1.612	1.665	10.65
RAS RX Bandwidth (kHz)	20	20	20	150
Interference Criterion (PFD) (dBW / m^2 Hz)	–239	–238	–237	–224
RAS RX Antenna horizon gain	–10 dBi			
Propagation	Free Space			

Table 7.3: Assumed Parameters for Single-dish Single-entry Analysis

On the basis of above parameters, maximum tolerable UWB EIRP levels for separation distances of 50 and 500 m are determined. The following table shows the results.

Distance (m)	**Max. Tolerable UWB EIRP (dBm/MHz)**			
	1.420 GHz	**1.612 GHz**	**1.665 GHz**	**10.65 GHz**
50	–94.0	–93.0	–92.0	–79.0
500	–74.0	–73.0	–72.0	–59.0

Table 7.4: Max. UWB EIRP in Different Bands (Single-dish, –10 dBi)

7.1.3 Merlin

Using the same approach, the impact of single entry interference is examined for a number of Merlin bands. Parameter values and calculated separation distances are shown in the following tables.

Frequency (GHz)	0.611	1.413	1.665	2.695	10.65
RAS RX Bandwidth (MHz)	6	27	10	10	100
Interference Criterion (PFD) (dBW / m^2 Hz)	–212	–211	–209	–205	–193
RAS Antenna horizon gain	0 dBi				
Propagation	Free Space				

Table 7.5: Assumed Parameters for Merlin Single-entry Analysis

Distance (m)	**Max. Tolerable UWB EIRP (dBm/MHz)**				
	0.611 GHz	**1.413 GHz**	**1.665 GHz**	**2.695 GHz**	**10.65 GHz**
50	–77.0	–76.0	–74.0	–70.0	–58.0
500	–57.0	–56.0	–54.0	–50.0	–38.0

Table 7.6: Max. UWB EIRP in Different Bands (Merlin)

7.2 Aggregate Interference Analysis

Using the aggregate interference levels from the moderate size town and metropolitan urban area scenarios (described in Section 5 of this report), the maximum tolerable UWB EIRP levels are calculated for the same frequency bands used in the single-entry analysis.

7.2.1 Single-dish (0 dBi)

The following table shows the maximum tolerable UWB EIRP values corresponding to the moderate size town scenario.

UWB Activity	Interference Spectral PFD (dBW/m^2 Hz)			
1%	–236			
5%	–229			
10%	–226			
17%	–224			
	Max. Tolerable UWB EIRP (dBm/MHz)			
Frequency	***1.420 GHz***	***1.612 GHz***	***1.665 GHz***	***10.65 GHz***
Interference Criterion (dBW / m^2 Hz)	***–239***	***–238***	***–237***	***–224***
1%	–44.3	–43.3	–42.3	–29.3
5%	–51.3	–50.3	–49.3	–36.3
10%	–54.3	–53.3	–52.3	–39.3
17%	–56.3	–55.3	–54.3	–41.3

Table 7.7: Max. UWB EIRP (Moderate Size Urban Area) (Single-dish)

The same exercise is repeated with the metropolitan urban area. The results are presented in the following table.

UWB Activity	Interference Spectral PFD (dBW/m^2 Hz)			
1%	–230			
5%	–223			
10%	–219			
17%	–217			
	Max. Tolerable UWB EIRP (dBm/MHz)			
Frequency	***1.420 GHz***	***1.612 GHz***	***1.665 GHz***	***10.65 GHz***
Interference Criterion (dBW / m^2 Hz)	***–239***	***–238***	***–237***	***–224***
1%	–50.3	–49.3	–48.3	–35.3
5%	–57.3	–56.3	–55.3	–42.3
10%	–61.3	–60.3	–59.3	–46.3
17%	–63.3	–62.3	–61.3	–48.3

Table 7.8: Max. UWB EIRP (Metropolitan Urban Area) (Single-dish)

7.2.2 Single-dish (–10 dBi)

The following table shows the maximum tolerable UWB EIRP values corresponding to the moderate size town scenario.

UWB Activity	**Interference Spectral PFD (dBW/m^2 Hz)**			
1%	–236			
5%	–229			
10%	–226			
17%	–224			
	Max. Tolerable UWB EIRP (dBm/MHz)			
Frequency	***1.420 GHz***	***1.612 GHz***	***1.665 GHz***	***10.65 GHz***
Interference Criterion (dBW / m^2 Hz)	***–239***	***–238***	***–237***	***–224***
1%	–34.3	–33.3	–32.3	–19.3
5%	–41.3	–40.3	–39.3	–26.3
10%	–44.3	–43.3	–42.3	–29.3
17%	–46.3	–45.3	–44.3	–31.3

Table 7.9: Max. UWB EIRP (Moderate Size Urban Area) (Single-dish)

The same exercise is repeated with the metropolitan urban area. The results are presented in the following table.

UWB Activity	**Interference Spectral PFD (dBW/m^2 Hz)**			
1%	–230			
5%	–223			
10%	–219			
17%	–217			
	Max. Tolerable UWB EIRP (dBm/MHz)			
Frequency	***1.420 GHz***	***1.612 GHz***	***1.665 GHz***	***10.65 GHz***
Interference Criterion (dBW / m^2 Hz)	***–239***	***–238***	***–237***	***–224***
1%	–40.3	–39.3	–38.3	–25.3
5%	–47.3	–46.3	–45.3	–32.3
10%	–51.3	–50.3	–49.3	–36.3
17%	–53.3	–52.3	–51.3	–38.3

Table 7.10: Max. UWB EIRP (Metropolitan Urban Area) (Single-dish)

7.2.3 Merlin

The following table shows the maximum tolerable UWB EIRP values corresponding to the moderate size town scenario.

UWB Activity	Interference Spectral PFD (dBW/m² Hz)				
1%	–236				
5%	–229				
10%	–226				
17%	–224				
	Max. Tolerable UWB EIRP (dBm/MHz)				
Frequency	***0.611 GHz***	***1.413 GHz***	***1.665 GHz***	***2.695 GHz***	***10.65 GHz***
Interference Criterion (dBW / m² Hz)	***–212***	***–211***	***–209***	***–205***	***–193***
1%	–17.3	–16.3	–14.3	–10.3	1.7
5%	–24.3	–23.3	–21.3	–17.3	–5.3
10%	–27.3	–26.3	–24.3	–20.3	–8.3
17%	–29.3	–28.3	–26.3	–22.3	–10.3

Table 7.11: Max. UWB EIRP (Moderate Size Urban Area) (Merlin)

The maximum tolerable UWB EIRP values corresponding to the metropolitan urban area scenario are calculated in the following table.

UWB Activity	Interference Spectral PFD (dBW/m² Hz)				
1%	–230				
5%	–223				
10%	–219				
17%	–217				
	Max. Tolerable UWB EIRP (dBm/MHz)				
Frequency	***0.611 GHz***	***1.413 GHz***	***1.665 GHz***	***2.695 GHz***	***10.65 GHz***
Interference Criterion (dBW / m² Hz)	***–212***	***–211***	***–209***	***–205***	***–193***
1%	–23.3	–22.3	–20.3	–16.3	–4.3
5%	–30.3	–29.3	–27.3	–23.3	–11.3
10%	–34.3	–33.3	–31.3	–27.3	–15.3
17%	–36.3	–35.3	–33.3	–29.3	–17.3

Table 7.12: Max. UWB EIRP (Metropolitan Urban Area) (Merlin)

8 CONCLUSIONS

Sharing between the Radio Astronomy Service and UWB devices will, potentially be problematic, particularly for the case of single-dish observations.

While it appears that ECC Report 64 overestimates the likely severity of interference to the RAS from UWB devices, it will be necessary to set EIRP limits lower than those of the FCC to protect European radio astronomy operation.

Analysis has suggested that interference to RAS observation is likely to be dominated by a small number of local interferers.

To afford protection from a single UWB device located, beyond the control of an observatory, at 500 m range, would require an EIRP limit of –65 dBm/MHz at around 5 GHz. This limit assumes that protection is required for spectral line observations.

In the UK, however, only one primary RAS allocation (4990–5000 MHz) falls within the nominal bandwidth of proposed UWB devices, and this is used only for continuum observations which (in the UK, at any rate) will generally be made with an interferometer network.

If it is assumed that the victim telescope is part of such a network, the EIRP limit increases to –45 dBm/MHz. An EIRP limit of –85 dBm/MHz will offer protection to the RAS bands below 3 GHz and above 10.7 GHz.

In contrast to the case in the US, there is little scope for limiting interference by geographical exclusion. No ‘radio quiet’ zones exist around UK sites, and perimeter fences are drawn tightly around the telescopes. A study of site plans and maps, and a number of site visits, suggests that a value of 500 m is a representative value for the radius over which it may be assumed that interferers can be excluded.

For the frequency bands of interest in this study, the use of RAS site shielding will be precluded by the size of the structures required.

The following recommendations for further work are made:

- An appropriate protection criterion for pulsar observation should be developed;
- Data should be gathered on the sidelobe performance of existing RAS telescope antennas, as the information in SA.509 is insufficient to allow realistic aggregate interference models to be constructed;

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