**NRPB-R321**

# Exposure to Radio Waves near Mobile Phone Base Stations

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## Abstract

Measurements of power density have been made at 17 sites where people were concerned about their exposure to radio waves from mobile phone base stations and where technical data, including the frequencies and radiated powers, have been obtained from the operators. Based on the technical data, the radiated power from antennas used with macrocellular base stations in the UK appears to range from a few watts to a few tens of watts, with typical maximum powers around 80 W. Calculations based on this power indicate that compliance distances would be expected to be no more than 3.1 m for the NRPB guidelines and no more than 8.4 m for the ICNIRP public guidelines. Microcellular base stations appear to use powers no more than a few watts and would not be expected to require compliance distances in excess of a few tens of centimetres.

Power density from the base stations of interest was measured at 118 locations at the 17 sites and these data were compared with calculations assuming an inverse square law dependence of power density upon distance from the antennas. It was found that the calculations overestimated the measured power density by up to four orders of magnitude at locations that were either not exposed to the main beam from antennas, or shielded by building fabric. For all locations and for distances up to 250 m from the base stations, power density at the measurement positions did not show any trend to decrease with increasing distance. The signals from other sources were frequently found to be of similar strength to the signals from the base stations of interest.

Spectral measurements were obtained over the 30 MHz to 2.9 GHz range at 73 of the locations so that total exposure to radio signals could be assessed. The geometric mean total exposure arising from all radio signals at the locations considered was 2 millionths of the NRPB investigation level, or 18 millionths of the lower ICNIRP public reference level; however, the data varied over several decades. The maximum exposure at any location was 230 millionths (0.023%) of the NRPB investigation level, or 1800 millionths (0.18%) of the ICNIRP reference level. The exposures are therefore well within guidelines and not considered hazardous.

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# 1 Introduction

## 1.1 Background

Liberalisation of the UK telecommunications market, combined with the development of digital radio technology in the 1980s, stimulated the development of mobile phones resulting in the proliferation of new radio antenna sites throughout the 1990s. Many of these new antenna sites are close to people's homes and workplaces and this, combined with their rapid deployment, has led to concern that the radio waves transmitted could be harmful to health.

NRPB has carried out many surveys in response to requests for measurements of radio wave signal strength at and around specific new radio antenna sites; the data from 17 different site visits have been drawn together to form this report. Eight of the sites were schools with base station antennas mounted on their roofs and the majority of the remaining sites were residential tower blocks. The first site was visited in Spring 1998 and measurements have been performed at a number of locations at each site.

The selection of sites is inherently biased because the sites were chosen on the basis of specific requests. Furthermore, the locations where measurements were made were chosen to be where the highest power densities would be expected to occur. In view of this bias, care should be taken not to over-interpret the data or extend its results to the UK population as a whole. A much larger study with more carefully selected locations would be necessary to produce results of validity to the population as a whole.

## 1.2 Objectives

The objectives of this report are:

(a) to provide factual information about exposures,

(b) to clarify further the basis for the NRPB scientific position.

# 2 Base station characteristics

The first generation of mobile phone base stations was deployed in the UK in the early 1980s and used the analogue Total Access Communication System (TACS). At this time, there were only two operators (Vodafone and Cellnet) and the number of mobile phone users was considerably less than that today. For these reasons fewer base stations were required to fulfil operational considerations with consequential lesser impact on the environment. TACS systems are still in existence; however, the number of users is dwindling and the radio spectrum used by these systems is progressively being reallocated. The networks are scheduled to be shut down before the year 2005.

The arrival of second generation systems based on the digital Global System for Mobile Telecommunications (GSM) initially required more sets of antennas to be installed at existing radio sites; however, increasing usage of mobile phones quickly led to new sites being required. It was with the licensing of two more network operators (Orange and One 2 One), and the need to install two completely new networks in the early 1990s, that the number of base station sites began to increase rapidly. It is estimated that there are around 20,000 base stations in the UK today.

Third generation networks using the Universal Mobile Telephone System (UMTS) are now being planned and the Government is to issue five licenses as a result of the recent spectrum auction. Whilst some reuse of existing base station sites is anticipated, it is only when there is no further increase in the use of mobile phones that the number of base stations will stabilise.

This report includes a total of 17 sites visited by NRPB where one or more base stations have been installed. In addition to performing measurements, the operators of the base stations have been approached in order to obtain details of radiated powers, antenna characteristics etc. This section begins with a general description of the operation of cellular radio networks for mobile telecommunications and then summarises the specific information that has been obtained for the sites visited.

### 2.1 Principles of cellular radio networks

Most people are familiar with the use of radio to permit wireless communication of signals between transmitting and receiving antennas. Perhaps the most familiar example is the network of very tall towers (eg Crystal Palace, Sutton Coldfield and Emley Moor) that are used to broadcast television signals to the antennas (aerials) that most houses have mounted above their roofs. Mobile phones communicate by radio signals passing to and from an antenna mounted on the phone and antennas connected to the base station. The radio link from the phone to the base station is known as the *uplink* and carries the speech from the mobile phone user. A separate radio link from the base station to the phone is known as the *downlink* and this carries the speech from the person to whom the phone user is listening. This principle is illustrated in Figure 1.

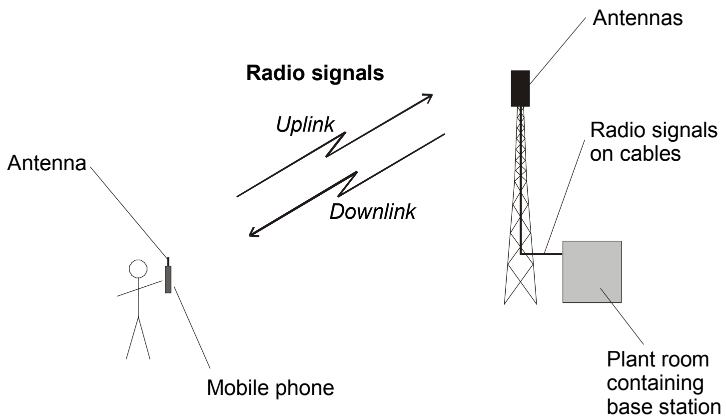


**FIGURE 1 Radio signals used for communication between mobile phones and base stations**

The antennas connected to the base station tend to be mounted high above ground level because the radio signals would be blocked by buildings etc if the antennas were nearer the ground. Antennas used with *macrocellular* base stations are generally placed between 15 and 50 m above ground level because they are designed to provide communications over distances of several kilometres. However, *microcellular* base stations have their antennas mounted nearer ground level as communications are only carried out over distances of a few hundred metres. Antennas tend to be mounted directly on existing structures, such as buildings, when this is convenient, but ground-based lattice towers, shorter masts mounted on roofs, and lamp-post type systems are also used.

#### 2.1.1 Providing coverage

Transmitted signal strength falls off rapidly with distance from base stations and mobile phones, but a certain minimum signal strength is required for adequate reception. The current generation of GSM base stations cannot communicate over distances greater than 35 km because the delay in receiving radio signals becomes too great. However, the decline of signal strength with distance places a practical limit on coverage of around 10 km. This means that a large number of base stations is needed to provide coverage of the whole of the UK by all four current networks.

The use of a number of base stations to provide complete coverage of an area of land is illustrated by Figure 2. The figure shows how the area covered by each base station can be regarded as a hexagon if there is a fixed distance between neighbouring base stations. In practice, the location of base stations is influenced by many factors so cells vary in shape and size.

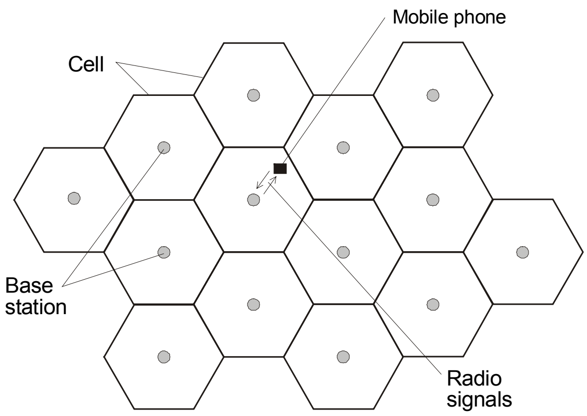


**FIGURE 2 Radio signals travelling via the uplink from a mobile phone to a base station and via the downlink in the reverse direction**

### 2.1.2 Power control and network capacity

An important design consideration that tends to limit the radiated powers of base stations is the desire of operators to use the available radio spectrum as efficiently as possible. Network operators have a certain number of radio channels assigned to them and they aim to use these for the maximum number of mobile phone users. This is achieved by reusing any given radio channel many times in a network and carefully controlling base station powers so that signals arising in different parts of the network do not interfere. Figure 3 shows how four different radio channels can be shared between the cells in a network with no adjacent cells having to use the same channel.

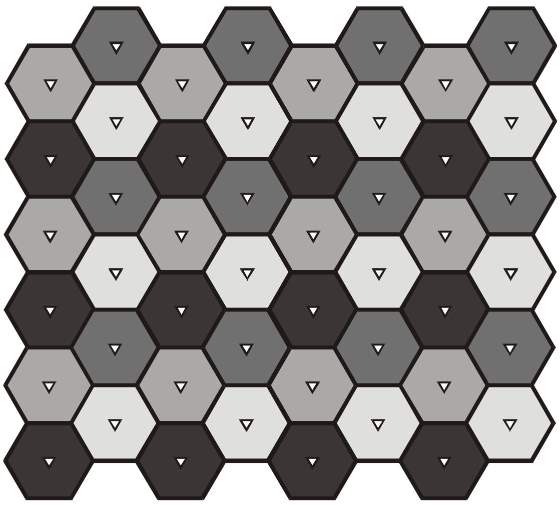

**FIGURE 3 Frequency reuse in a cellular network. Cells that have the same shading use the same radio channels as each other**

The power radiated by base stations has to be carefully controlled in any frequency reuse scheme to limit the distance travelled by signals. If a base station were to transmit with too much power, its signals might be strong enough to interfere with signals in other cells using the same radio channel. An example of frequency reuse in another area of technology is in the choice of channels for broadcast radio in the FM band; a radio station in one town can use the same frequency as another provided powers are limited so that the effective range does not give rise to interference.

### 2.1.3 Cell sectors

Operators tend to divide the area about a base station into three *sectors* and then mount three different sets of antennas on a mast such that each set provides coverage of a 120º arc about the mast. Most base station antennas are oriented such that Sector 1 is directed towards grid north, Sector 2 is directed 120º east of grid north (EGN) and Sector 3 is directed 240º EGN. This gives rise to the familiar triangular configuration that is seen at the head of many of the older base station masts, as depicted in Figure 4. In some cases omni-directional antennas are used to provide full 360º coverage.

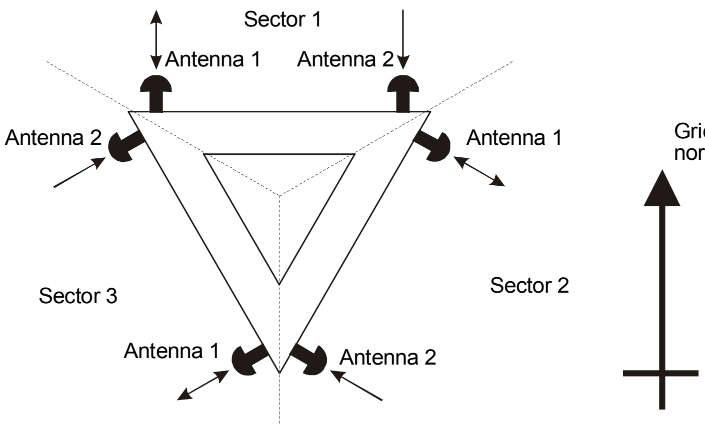


**FIGURE 4 Six antennas are arranged on some masts in order to provide coverage of a cell divided into three sectors. Arrows indicate the directions of signals to and from the antennas**

Figure 4 shows how a single antenna can be used to transmit signals, whereas two antennas are used to receive signals from a sector. This arrangement of *diversity reception* allows continuous operation even if one of the antennas experiences a reduced or *faded* signal. Some of the more modern antennas effectively contain two sets of receiving elements that are arranged perpendicularly to each other inside a single case. These *dual polar* antennas give rise to much more compact mast heads since only three are used to cover a cell.

## 2.2 General technical aspects

When discussing base stations, it is important to be clear that, in strictly engineering terms, it is the electronic equipment contained in the plant room shown in Figure 1 that is the base station. Nevertheless, it has become common practice to describe the complete installation, including antennas and mast, as the base station. The features of a typical base station installation are shown in Figure 5.

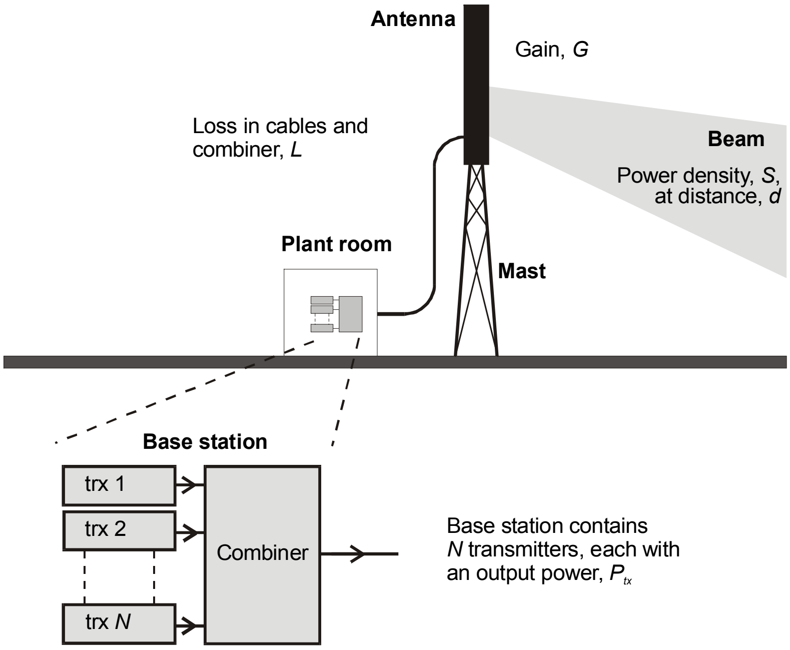


**FIGURE 5 A base station contains a number of radio transmitters (trx) whose outputs are combined before being fed to an antenna and transmitted as radio waves**

### 2.2.1 Electrical characteristics

Base stations contain a number of radio transmitters and each of these has the same maximum output power, $P_{tx}$. The outputs from the individual transmitters are then combined and fed via cables to the base station antenna, which is mounted at the top of a mast (or other suitable structure). It therefore follows that the total power fed into the base station antenna, $P_{ant}$, is given by

$$P_{ant} = NP_{tx}10^{-L/10} \tag{1}$$

where $N$ is the number of transmitters and $L$ is the loss (in decibels) in signal strength that occurs in the combiner and connecting cables.

The power that is fed into the base station antenna is launched into a radio wave travelling away from the tower and the strength of this radio wave decays with distance from the antenna according to the inverse square law. The power density, $S$, in the beam thus varies with distance, $d$, according to the following expression

$$S = \frac{NP_{tx}}{4\pi d^2}10^{(G-L)/10} \tag{2}$$

The antenna gain, $G$ (in decibels), is discussed further in Section 2.2.5 and is a measure of how much the antenna is able to focus the radiated power in the direction of its beam. It should also be noted that equation 2 is strictly only valid at distances greater than around 10 m from a typical sector antenna and will overestimate the power density at lesser distances (see Section 5.2).

### 2.2.2 Frequency allocations

The frequency bands used by current and future mobile phone networks in the UK are as shown in Table 1. Each frequency band contains a large number of channels and these are shared between the operators according to licenses issued by the Radiocommunications Agency. The analogue TACS systems operate close to 900 MHz, as do some of the GSM systems, which will be denoted as GSM900 in this report. Other GSM systems operate close to 1800 MHz and these will be referred to as GSM1800 in this report. UMTS systems will operate close to 2000 MHz, although the structure of uplink and downlink bands is more complicated than with the GSM systems.

**TABLE 1 Frequency bands currently allocated to mobile phone networks in the UK. Base stations transmit on the downlink frequencies and mobile phones transmit on the uplink frequencies**

| System | Frequency band (MHz) Uplink | Downlink | Channel spacing (kHz) | Number of channels |
|---|---|---|---|---|
| TACS | 872–888 | 917–933 | 25 | 640 |
| GSM900 | 890–915 | 935–960 | 200 | 174 |
| GSM1800 | 1710–1785 | 1805–1880 | 200 | 374 |
| UMTS | Various between 1900 and 2200 | | 5000 | – |

Vodafone and Cellnet use predominantly GSM900 for their networks, although they do have some channels allocated in the GSM1800 band that may be used at some future date. Orange and One 2 One operate purely in the GSM1800 band.

Each GSM radio channel consists of paired uplink and downlink frequencies that are exactly 45 MHz apart for GSM900 and 95 MHz apart for GSM1800. This principle of paired frequency bands is illustrated in Figure 6.

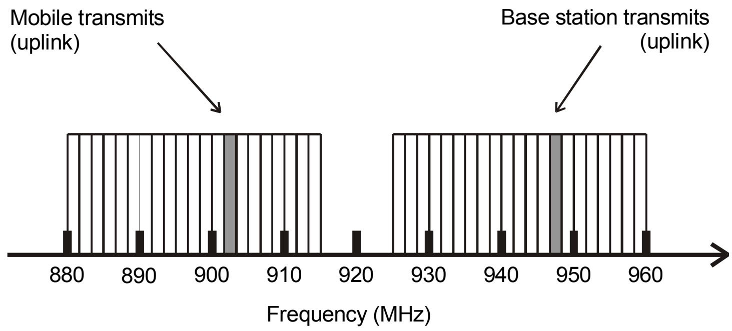


**FIGURE 6 Structure of paired frequency bands showing how transmit and receive frequencies are separated by 45 MHz with GSM900**

### 2.2.3 GSM signal waveforms

GSM base station antennas all transmit at least one radio signal quasi-continuously and this is known as the Broadcast Control Channel (BCCH) carrier because it carries important signalling information that is used to set up calls. The BCCH carrier can also handle up to seven mobile phone calls simultaneously, so it may give sufficient capacity for base stations in lightly loaded areas. Where there is a potential need for more than seven phone calls at the same time, a base station can be configured to transmit extra carriers (non-BCCH carriers), each allowing the base station to provide a further eight mobile phone calls. For example, a GSM base station equipped to transmit four radio carriers could control up to thirty-one mobile phone calls simultaneously.

GSM base stations use Time Division Multiple Access (TDMA) within each radio carrier so a base station communicates with any given mobile phone by sending out 217 frames of information every second. Each frame is divided into eight timeslots, as illustrated in Figure 7, and each timeslot is used for a particular phone call (or for setting up calls in the case of timeslot zero in the BCCH carrier).

The BCCH carrier is transmitted at full power in all eight timeslots, even when no calls are being handled, whereas the non-BCCH carriers (if available) are only transmitted when calls are present. The BCCH carrier is described as quasi-continuous because, although the waveform is transmitted at full power during each timeslot, the power envelope shows transient dips between timeslots.

The information carried by the radio waves from base stations is encoded as small changes in the frequency of the underlying sinusoidal radio carrier, hence the signals are described as *frequency modulated*.

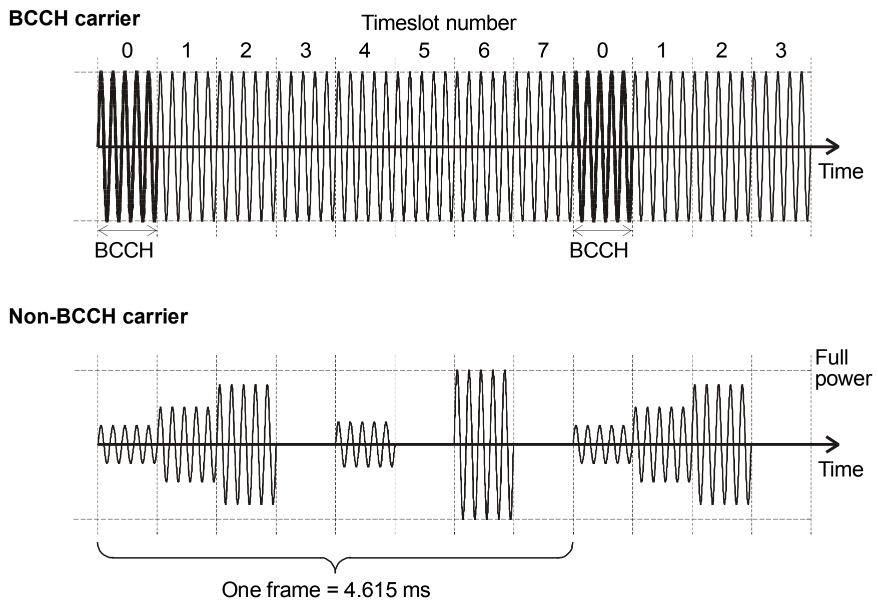


**FIGURE 7 Waveforms of the signals produced by GSM base stations showing how the BCCH carrier is a continuous sinusoid at full power, whereas non-BCCH carriers can have partial occupancy and also use power control**

### 2.2.4 Antenna beam shapes

The radio signals developed by base stations are fed to antennas, which produce beams that are radiated into the cell around the base station. The profile of the beams is carefully chosen by the network planners in order to produce optimal coverage of the cell, but the general principle of beam formation is illustrated in Figure 8.

The beams formed by antennas used with macrocellular base stations are narrow in the plane of elevation with typical widths between 5º and 10º. The beams are also tilted slightly downwards so the top edge of the main beam is approximately horizontal whereas the lower edge is directed up to 10º below horizontal. When considering the heights at which antennas tend to be mounted, this implies that the main beam from base station antennas would be expected to reach ground level typically between 50 and 300 m from the foot of a mast. The antennas used with microcellular base stations have much broader beams in the plane of elevation because they are intended to communicate over much shorter distances.

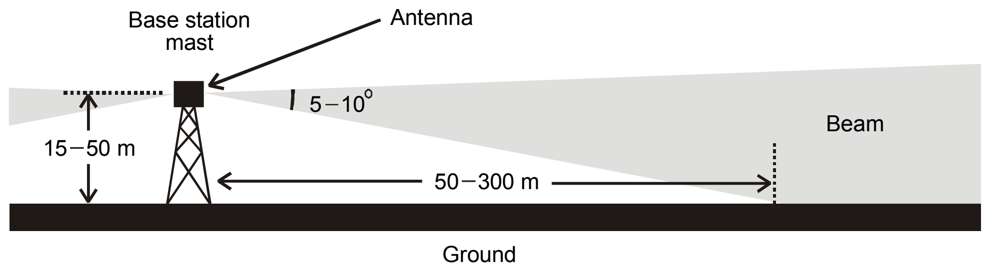


**FIGURE 8 Elevation showing the shape of the beam formed by a typical antenna used with a macrocellular base station**

Figure 8 shows a simplified version of the directional properties of an antenna illustrating why much lower radio wave strengths are found at the foot of a mast than at distances of around 100 m from the mast (see Section 5.3). The beams from real antennas do not have sharply defined lower edges and some power will be directed at all angles below horizontal. Typically the power in the downwards direction is at least a hundred times weaker than in the main beam at the same distance from antennas.

### 2.2.5 Antenna gain

When considering the directional properties of antennas, it is useful to refer to the antenna gain. This is a measure of how effective an antenna is at radiating power in the direction of its main beam. An isotropic antenna is an antenna that radiates equally in all directions, and if a spherical surface enclosing such an antenna is considered, the power density, $S$, at a radial distance, $d$, would be given by

$$S = \frac{P_{rad}}{4\pi d^2} \tag{3}$$

where $P_{rad}$ is the total radiated power.

Any real antenna will employ some means to remove power from undesired radiating directions and channel it into the intended direction of the beam. This means that the power density at a distance, $d$, will be greater than that given by equation 3 by a factor equal to the antenna gain. Gain is normally quoted in decibels relative to an isotropic radiator in the unit dBi.

The beams from antennas used with base stations are narrow in the plane of elevation (see Figure 8), and this is achieved by mounting a stack of radiating elements vertically above each other inside the antenna cases. The taller the stack is in relation to the wavelength, the narrower the beamwidth that is achieved. Mounting reflectors around the radiating elements inside the antenna case can be used to narrow beam widths in the azimuth plane, to between 60º and 120º in order to produce sector antennas. Both of these design techniques cause antennas to radiate preferentially in a certain direction, and hence form a main beam.

Typical gains for the sector antennas used with macrocellular base stations in the UK are in the range 15–17 dBi for GSM900 systems and 16–18 dBi for GSM1800 systems. Omni-directional antennas for macrocellular base stations are much less common than sector antennas, but generally have gains in the range 8–10 dB.

Microcellular base station antennas are not intended to communicate over such large distances as macrocellular base stations so their beams tend to be wider and their gains tend to be lower.

The specific data on antenna gains for the sites considered in this report are given in Appendix A.

## 2.3 Specific data on radiated powers

The power assigned to a given base station is determined from its coverage and capacity requirements; however, the operator's desire to use the licensed spectrum as efficiently as possible will tend to minimise powers used in every cell (see Section 2.1.2). NRPB asked the operators to supply the powers of the base station sites that were visited and this section reviews these data in the context of the licensed powers and technical standards.

### 2.3.1 Data from standards

Published standards for base station transmitters provide specifications for the manufacturers. A variety of different power classes are defined in the GSM standard[1] and these are as shown in Table 2. It should be noted that these are the powers at the output of each transmitter and should not be confused with the power radiated by the antenna (see Figure 5). Power radiated by the antenna will be considered in Section 2.3.2.

**TABLE 2 Output powers from GSM900 and GSM1800 base station transmitters, as defined in the GSM Phase 2+ technical standard**

| GSM900 | | | GSM1800 | | |
|---|---|---|---|---|---|
| Cell type | Power class | Power (W) | Cell type | Power class | Power (W) |
| Macro | 1 | 320 – (<640) | Macro | 1 | 20 – (<40) |
| | 2 | 160 – (<320) | | 2 | 10 – (<20) |
| | 3 | 80 – (<160) | | 3 | 5 – (<10) |
| | 4 | 40 – (<80) | | 4 | 2.5 – (<5) |
| | 5 | 20 – (<40) | | | |
| | 6 | 10 – (<20) | | | |
| | 7 | 5 – (<10) | | | |
| | 8 | 2.5 – (<5) | | | |
| Micro | M1 | (>0.08) – 0.25 | Micro | M1 | (>0.5) – 1.6 |
| | M2 | (>0.025) – 0.08 | | M2 | (>0.16) – 0.5 |
| | M3 | (>0.008) – 0.025 | | M3 | (>0.05) – 0.16 |
| Pico | P1 | (>0.02) – 0.1 | Pico | P1 | (>0.04) – 0.2 |

Table 2 is a classification system but does not imply that base stations exist with every power level. For example, it is highly unlikely that there would ever be a need for the power of a Class 1 or 2 GSM900 base station, given the communication distances involved. It is understood that 20 W and 40 W are the normal maximum powers for individual transmitters used with GSM900 macrocellular base stations used in the UK.

### 2.3.2 Total radiated power

As described in Section 2.1.2 and illustrated in Figure 5, base stations often contain more than one transmitter and the outputs of each transmitter are combined before being fed via cables to the radiating antennas. When the signals are combined, the radiated power would ideally be equal to the sum of the output powers from the transmitters, but some loss occurs in the combiner and connecting cables. This *combiner loss* (normally taken to include the cable loss) is generally between 4 and 6 dB so the power radiated by the antennas will be less than half of that produced by the transmitters.

The technical data from the sites visited by NRPB (see Appendix A) suggest that each transmitter gives rise to a maximum radiated power in the region of 10 W at the antenna. Most of the base stations encountered during the surveys had either one or two transmitters, but two had four and one had five. Site A was quoted as having eight transmitters, but the data given for this site were believed to be generic and not particular to the actual site, as no more than two signals were measured. It will be assumed that the maximum power radiated from a base station antenna is 80 W in this report. This could be taken as equivalent to eight transmitters each producing 10 W at an antenna.

Only the mobile phone industry can give a definitive statement as to the maximum power radiated by base station antennas, as the technology is rapidly developing and power levels may change. Personal communications between the authors and professionals working in the industry indicate that maximum powers radiated from macrocellular antennas in the UK are currently in the region of 25 to 70 W. Microcellular antennas would be expected to radiate no more than a few watts given the short distances over which they are designed to communicate. In a safety guide issued by one operator, it is stated that its smaller base stations radiate no more than 2 W.

#### 2.3.3 Effective isotropic radiated power

The power density formed in the beam from a base station depends upon the radiated power and on the gain of the antenna. The product of the power radiated and the antenna gain is known as the effective isotropic radiated power (EIRP) and is usually quoted in decibels relative to a milliwatt (dBm). By convention, the EIRP is quoted in terms of the power radiated by a single transmitter and this should be taken into account when calculating total radiated power.

The licenses allocated to the operators by the Radiocommunications Agency stipulate that no more than 62 dBm EIRP may be radiated (per transmitter). This arises from considerations associated with the possibility of interference with other electrical equipment in the environment, and is not related to electromagnetic field safety. Ensuring compliance with protection guidelines is a matter for the operators through their general safety obligations.

The EIRPs supplied by the operators for the sites visited during this work (see Appendix A) ranged from 44 to 56.7 dBm. Based on this information, the typical powers of transmitters and the range of antenna gains, it is probable that very few base stations in the UK produce appreciably more than 56 dBm EIRP.

### 2.4 Microwave links

Base stations must be able to communicate with other neighbouring base stations in order to relay calls between mobile phone users in two different cells and connect calls into other networks. In some cases this is achieved using cables but it is more usual for base stations to communicate via *microwave links*. Microwave links employ dish antennas that permit point-to-point communications, as shown in Figure 9.

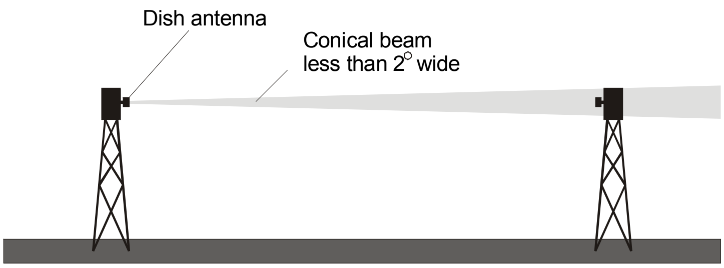


**FIGURE 9 Pair of dish antennas used as terminals for a point-to-point microwave link**

Technical information on the powers used with microwave dishes at the sites visited during this work is given in Appendix A. The frequencies used are mostly in bands spread about 13, 23 and 38 GHz and propagation at these high frequencies is such that a line of sight path must exist between the dishes.

Dish antennas produce narrow conical beams that are 1–2º wide. Typical powers are no more than a few tens of milliwatts because the power is channelled so selectively towards the receiver. The powers used by dish antennas are very much lower than those used by base station antennas so the exposures produced by signals from dish antennas will be negligible in comparison.

# 3 National and international exposure guidelines

A number of different national and international organisations have published guidelines for the protection of people from exposure to electromagnetic fields and radiation. It is a matter for policy makers to determine which set of guidelines should be adopted; however, this section reviews the two sets of guidelines of most importance from a UK perspective.

## 3.1 Basis for guidelines

There is a consensus amongst organisations responsible for providing advice on exposure to electromagnetic fields and radiation. The consensus is as follows.

(a) Heating can occur as a consequence of exposure to electromagnetic fields at telecommunications frequencies.

(b) The established adverse effects on people's health occur at exposure levels where heating would be expected to occur.

(c) Exposures should be restricted to avoid the established effects of exposure to electromagnetic fields.

(d) There is no convincing evidence that adverse effects can occur as a result of exposure within the current protection guidelines.

The views of the National Radiological Protection Board (NRPB) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) form part of this consensus.

## 3.2 NRPB guidelines

The advice relevant to radiofrequency radiation provided by NRPB is contained in published guidelines[2] on restricting human exposure to time-varying electromagnetic fields and radiation with frequencies up to 300 GHz. The guidelines have been developed following comprehensive reviews of scientific data and on the advice of the NRPB Advisory Group on Non-ionising Radiation (AGNIR).

There is no specific legislation in the UK that relates to protection from electromagnetic fields. Nonetheless, there is enabling legislation in the general area of health and safety that places a 'duty of care' on the operators of equipment generating electromagnetic fields. UK Government Departments and Agencies, including the Health and Safety Executive, have looked to compliance with the NRPB guidelines in order to fulfil this responsibility. Notwithstanding, the status of the ICNIRP guidelines has recently been clarified with respect to limiting the exposure of members of the public within the member states of the European Union (see Section 3.3).

### 3.2.1 Basic restrictions

The survey work described in this report was concerned only with exposure to electromagnetic fields with frequencies greater than 10 MHz. The established biological effects of exposure to such fields occur at levels whereby exposure results in significant heating of part or all of the body. The guidelines advise *basic restrictions* on the rate of energy absorption per unit mass of body tissue, or *specific energy absorption rate* (SAR), to ensure that harmful temperature rises do not occur in the body. SAR is quantified in the unit watt per kilogram ($W\ kg^{-1}$). Compliance with NRPB guidelines is demonstrated by showing that none of the basic restrictions is exceeded.

The four basic restrictions on SAR that apply for exposure to electromagnetic fields with frequencies between 10 MHz and 10 GHz are listed in Table 3. The restrictions permit short-term time-averaging so transient exposures may be averaged over specified periods before comparison with the restrictions. The restrictions on localised SAR vary over different regions of the body and apply to contiguous tissue within the region specified.

**TABLE 3 NRPB basic restrictions on exposure to electric and magnetic fields in the frequency range 10 MHz to 10 GHz**

| | |
|---|---|
| SAR averaged over the body and over any 15 minute period | 0.4 $W\ kg^{-1}$ |
| SAR averaged over any 10 g in the head or fetus and over any 6 minute period | 10 $W\ kg^{-1}$ |
| SAR averaged over any 100 g in the neck and trunk and over any 6 minute period | 10 $W\ kg^{-1}$ |
| SAR averaged over any 100 g in the limbs and over any 6 minute period | 20 $W\ kg^{-1}$ |

At higher frequencies, energy absorption becomes increasingly confined to the surface layers of the skin and the heating effect is directly related to the power density of the incident radiation. Consequently, for frequencies between 10 and 300 GHz there is a single basic restriction of 100 $W\ m^{-2}$ that applies to any part of the body. This restriction may be averaged over a period equal to $68/f^{1.05}$ minutes, where $f$ is the frequency in gigahertz.

### 3.2.2 Investigation levels

SARs are not easily measurable in living people, therefore NRPB has introduced *investigation levels* of external electric and magnetic field strength and power density that may be compared directly with measured or calculated exposure levels. Compliance with the appropriate investigation levels in a given exposure situation ensures compliance with the basic restrictions; however, the investigation levels are not limits and exceeding them does not necessarily mean that basic restrictions are exceeded. The investigation levels are frequency dependent and are shown in Table 4 for frequencies greater than 12 MHz. All investigation levels are specified as root mean square (rms) values.

**TABLE 4 NRPB investigation levels for exposure to electric and magnetic fields in the frequency range 12 MHz to 300 GHz**

| Frequency range | Electric field strength ($V\ m^{-1}$) | Magnetic field strength ($A\ m^{-1}$) | Power density ($W\ m^{-2}$) |
|---|---|---|---|
| 12–200 MHz | 50 | 0.13 | 6.6 |
| 200–400 MHz | $250f$ | $0.66f$ | $165f^2$ |
| 400–800 MHz | 100 | 0.26 | 26 |
| 0.8–1.55 GHz | $125f$ | $0.33f$ | $41f^2$ |
| 1.55–300 GHz | 194 | 0.52 | 100 |

$f$ is the frequency in GHz.

The three parameters used for investigating compliance with NRPB guidelines are related to each other and in certain instances it is only necessary to measure one of them. During the survey work in this report, electric field strength was measured and the results were subsequently converted to power density as this quantity can be most readily used to normalise exposure to the transmitter power.

The investigation levels have been derived from the basic restrictions using dosimetric models assuming conservative but nevertheless realistic assumptions of exposure. The assumptions that have been used are as follows.

(a) The exposed person is stood vertically in contact with the ground.
(b) The ground beneath the person is a good conductor.
(c) The electric field is vertically directed.
(d) The electric field is uniform over the space occupied by the person.

In practice it is unlikely that all four conditions would be simultaneously fulfilled, therefore the investigation levels will be conservative indicators of the fields required to produce SARs equal to the basic restrictions.

## 3.3 ICNIRP guidelines

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is an independent scientific organisation responsible for providing guidance and advice on the health hazards of non-ionising radiation exposure. ICNIRP develops international guidelines on limits of exposure to non-ionising radiations and the most recent guidelines on limiting exposure to electromagnetic fields were published in April 1998[3,4].

The profile of the ICNIRP guidelines has recently been raised within Europe because the European Council has published a Recommendation[5] on the limitation of exposure of the general public to electromagnetic fields. The basic restrictions and the reference levels in the document are identical to those advised by ICNIRP; however, implementation and policy matters are also addressed in the European Council Recommendation.

NRPB recently issued advice on the 1998 ICNIRP guidelines[6]. For occupational exposure the ICNIRP guidelines do not differ in any significant way from those previously recommended by NRPB. For members of the public, ICNIRP has generally included a reduction factor of up to five in setting basic restrictions. It is the view of NRPB that the existing UK guidelines on limiting exposure for the general public provide adequate protection and the health benefits to be obtained from further reductions in exposure have not been demonstrated.

While recognising that there was no scientific basis for exposure limits to avoid potential harm from athermal* effects of exposure to microwaves, a House of Commons Select Committee on Science and Technology concluded in a recent report[7] that the Government should adopt the ICNIRP recommended guidelines for microwave exposure 'as a precautionary measure'.

### 3.3.1 Basic restrictions

The ICNIRP guidelines specify basic restrictions on SAR which are analogous to the NRPB basic restrictions and state that 'protection against adverse health effects requires that these basic restrictions are not exceeded'. The basic restrictions on SAR that apply to frequencies within the range 10 MHz to 10 GHz for occupational and public exposure are given in Table 5. All

* Biological effects that have been claimed to arise at exposure levels where heating could not play a role are often referred to as *athermal.*

restrictions are to be time-averaged over a six minute period. The restrictions on localised SAR permit averaging over a 10 g mass of contiguous tissue.

For exposures to radio waves with frequencies between 10 and 300 GHz, the ICNIRP guidelines stipulate basic restrictions on power density alone. The basic restrictions are 50 W $m^{-2}$ for occupational exposure and 10 W $m^{-2}$ for exposure of the general public. Provision is also made for averaging power density over specified areas of the body surface in this frequency range so the ICNIRP guidelines are complied with if the following two conditions are satisfied.

(a) The power density averaged over 20 $cm^2$ is less than the basic restriction.

(b) The power density averaged over 1 $cm^2$ is less than 20 times the basic restriction.

**TABLE 5 ICNIRP basic restrictions on exposure to electric and magnetic fields in the frequency range 10 MHz to 10 GHz for occupational and general public exposure**

| Exposure quantity | Occupational | General public |
|---|---|---|
| SAR averaged over the body and over any 6 minute period | 0.4 W $kg^{-1}$ | 0.08 W $kg^{-1}$ |
| SAR averaged over any 10 g in the head and trunk and over any 6 minute period | 10 W $kg^{-1}$ | 2 W $kg^{-1}$ |
| SAR averaged over any 10 g in the limbs and over any 6 minute period | 20 W $kg^{-1}$ | 4 W $kg^{-1}$ |

### 3.3.2 Reference levels

A system of reference levels, similar to the NRPB investigation levels, is given by ICNIRP and the levels reflect the factor of five difference between the public and occupational basic restrictions. Compliance with the reference levels ensures compliance with the ICNIRP basic restrictions. The reference levels for occupational exposure to electromagnetic fields in the frequency range 10 MHz to 300 GHz are given in Table 6. Reference levels for exposure of the general public are given in Table 7.

**TABLE 6 ICNIRP reference levels for occupational exposure to electromagnetic fields in the frequency range 10 MHz to 300 GHz**

| Frequency range | Electric field strength (V $m^{-1}$) | Magnetic field strength (A $m^{-1}$) | Power density (W $m^{-2}$) |
|---|---|---|---|
| 10–400 MHz | 61 | 0.16 | 10 |
| 400–2000 MHz | $3f^{½}$ | $0.008f^{½}$ | $f$/40 |
| 2–300 GHz | 137 | 0.36 | 50 |

$f$ is the frequency in MHz.

**TABLE 7 ICNIRP reference levels for general public exposure to electromagnetic fields in the frequency range 10 MHz to 300 GHz**

| Frequency range | Electric field strength (V $m^{-1}$) | Magnetic field strength (A $m^{-1}$) | Power density (W $m^{-2}$) |
|---|---|---|---|
| 10–400 MHz | 28 | 0.073 | 2 |
| 400–2000 MHz | $1.375f^{½}$ | $0.0037f^{½}$ | $f$/200 |
| 2–300 GHz | 61 | 0.16 | 10 |

$f$ is the frequency in MHz.

### 3.4 Summary of guidelines

The NRPB investigation level and the ICNIRP reference levels both vary according to the frequency of the radio waves that produce a given exposure. Figure 10 shows this frequency dependence and compares the levels.

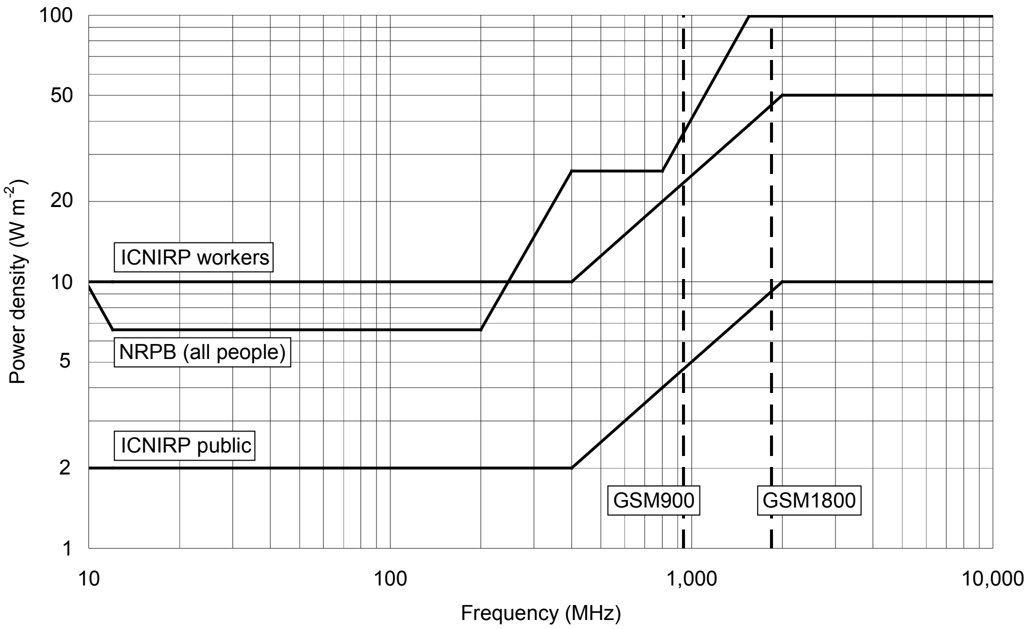


**FIGURE 10 Comparison of the NRPB investigation level and the ICNIRP reference levels for occupational and public exposure**

The investigation/reference levels tend to be most restrictive over the 10–200 MHz frequency range because electromagnetic energy couples most efficiently into the body over this range. The NRPB investigation level is around 15 times lower over this frequency range than at frequencies of several gigahertz. The ICNIRP reference level for occupational exposure is higher, ie less restrictive than the NRPB investigation level at lower frequencies; however, this situation is reversed at higher frequencies. The ICNIRP public reference level for power density is between a factor of 3 and 13 lower than the NRPB investigation level and this reflects the reduction factor of 5 in the underpinning basic restriction.

Figure 10 shows the two main frequency bands at which mobile phone base stations used in the UK transmit, ie close to 940 MHz and close to 1840 MHz (see Section 2). The lowest values of the investigation/reference levels over these bands are summarised in Table 8.

**TABLE 8 NRPB investigation level and the ICNIRP reference levels for public and occupational exposures at the transmit frequencies of UK base stations**

| | Power density (W m$^{-2}$) | |
|---|---|---|
| Guidelines | TACS/GSM900 | GSM1800 |
| NRPB (all people) | 35 | 100 |
| ICNIRP workers | 23 | 45 |
| ICNIRP public | 4.6 | 9 |

### 3.5 Exposure assessment

For exposure to radio waves emitted at a single frequency, a dimensionless quantity known as the *exposure quotient* may be calculated. This exposure quotient is expressed in terms of the measured power density $S^{\text{meas}}$ and the power density investigation level $S^{\text{inv}}$ using the relation

$$\text{exposure quotient} = \frac{S^{\text{meas}}}{S^{\text{inv}}} \tag{4}$$

Compliance with NRPB guidelines is demonstrated if the exposure quotient is less than unity (compliance with ICNIRP guidelines can also be shown using the appropriate ICNIRP reference level in place of the NRPB investigation level).

This report is concerned with simultaneous exposure to many different radio signals, each with a different frequency. All of the individual signals will contribute to a person's exposure and the total exposure quotient will be equal to the sum of the quotients for each signal, as expressed by

$$\text{total exposure quotient} = \sum_{i=1}^{N} \frac{S_i^{\text{meas}}}{S_i^{\text{inv}}} = \frac{S_1^{\text{meas}}}{S_1^{\text{inv}}} + \frac{S_2^{\text{meas}}}{S_2^{\text{inv}}} + \frac{S_3^{\text{meas}}}{S_3^{\text{inv}}} + \ldots + \frac{S_N^{\text{meas}}}{S_N^{\text{inv}}} \tag{5}$$

where $N$ is the total number of signals. Again, a total exposure quotient not exceeding unity indicates compliance with the guidelines.

Exposure quotients offer a convenient form of expressing the exposure due to multiple radio signals present at any given location. For example, it might be stated that the power density measured at the specified location is equivalent to $10^{-3}$ or 1/1000 of the NRPB investigation level. Many of the exposures in the later sections of this report will be expressed in terms of how many millionths of the investigation/reference level they represent.

Exposure quotients may also be used to investigate the contributions of various individual signals (or categories of signals) to the total.

## 4 Measurement equipment and surveying procedures

This section describes the equipment used to measure the electric field strength of radio-frequency signals, the calculation techniques that are used to derive equivalent power densities, and the assessment of exposures at measurement locations. The limitations of the surveying techniques are discussed, as are the uncertainties in the resulting data.

### 4.1 Instrumentation

Hand-held hazard assessment probes can be obtained for measuring electric and magnetic field strengths at levels comparable with the investigation/reference levels given in protection guidelines. The advantages of this type of equipment are that it is portable and may be suitable for use by non-specialists. The disadvantages are that the equipment lacks sensitivity and will tend to read zero at locations that are not in the immediate vicinity and directly in the beam of base station antennas.

The equipment used for the measurements in this report consisted of a spectrum analyser connected to one of a choice of antennas via a coaxial cable, as shown in Figure 11. This set-up allowed measurements to be made over a sweep of frequencies using a narrow measurement bandwidth, permitting the detection of power densities considerably below 1 $\mu\text{W m}^{-2}$. The data collected by the spectrum analyser were transferred to a laptop computer and stored for subsequent analysis in a spreadsheet program.

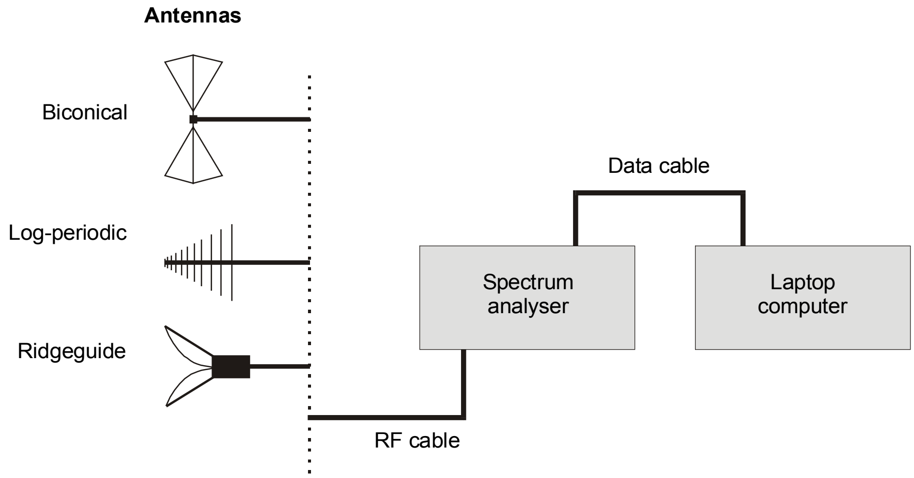


**FIGURE 11 Equipment used for measuring electric field strength of environmental radiofrequency signals**

### 4.1.1 Measurement antennas

Three different broadband antennas were employed in conjunction with the spectrum analyser for measuring electric field strength over different frequency ranges. The antennas were mounted on lightweight tripods providing stable support but permitting their orientation to be varied by hand. The types of antennas that are currently used are listed in Table 9 together with the range of frequencies specified for each model.

**TABLE 9 Antennas used for the measurements in this report**

| Type | Frequency range |
|---|---|
| Biconical | 30–300 MHz |
| Log-periodic | 300–1000 MHz |
| Ridgeguide | 1–18 GHz |

The *antenna factor* of an antenna describes its sensitivity to an electromagnetic field and, in the case of the above antennas, it is defined as follows.

$$\text{antenna factor} = \frac{\text{electric field strength at antenna}}{\text{voltage produced at antenna connector}} \qquad (6)$$

Calibration data supplied with each antenna gave the antenna factors at discrete frequencies. Interpolations were then performed to obtain the antenna factors at the precise frequencies of interest.

The loss (dB) in the cable connecting the antennas to the spectrum analyser was measured by substitution between a signal generator and a power meter at a range of frequencies. Interpolation was used to derive the cable loss at the frequencies of the measured signals.

### 4.1.2 Spectrum analyser

The spectrum analyser was used to measure the strength and frequency of each radio signal over a set frequency range. Many other parameters have to be set on the spectrum analyser in order to measure radio signals with a given waveform correctly. Practically, this means that the radio spectrum has to be scanned in several different parts and then these parts have to be assembled to produce a table covering the complete frequency range. The complete frequency range covered during the measurements in this report was from 30 MHz to 2.9 GHz.

The frequency resolution of the spectrum analyser was determined by the width of the frequency span used during a given sweep. Wider sweeps gave rise to poorer frequency resolution and some imprecision in the measured frequency of individual signals. This imprecision had negligible effect on exposure calculations; however, care had to be taken to resolve signals with frequencies that were close together.

The amplitude displayed by the spectrum analyser indicated the rms voltage at its input connector during the strongest part of each measured signal, ie when the transmission was at its maximum power. This has implications for signals with power modulation, eg video signals for television, that are discussed further in Section 4.3.2.

#### 4.1.3 Data acquisition

A rugged laptop computer with a metal case and a daylight-readable screen was used to collect the data from the spectrum analyser. This computer was used with a PCMCIA card enabling it to communicate directly with the computer inside the spectrum analyser and accept the measured data directly into a spreadsheet on command. The format of the downloaded data was a table of the measured peaks on the spectrum analyser trace, each of which represented an individual radio signal. The first column in the table contained the signal frequencies in megahertz and the second column contained the signal strengths in millivolts.

### 4.2 Data processing

#### 4.2.1 Calculation of power density

The spectrum analyser produced a list containing the frequencies in megahertz (MHz) and amplitudes in millivolts (mV) of each signal detected with the antennas. The following equation was then used to convert the received voltages, $V_{rx}$, into electric field strengths, $E$, corresponding to each signal.

$$E = V_{rx}\, F\, 10^{L/20} \tag{7}$$

where $F$ is the antenna factor ($m^{-1}$) and $L$ is the loss in the cable (dB).

The intrinsic impedance of free space, $\eta$, was then assumed to be equal to 377 Ω so the following equation could be used to calculate the power density, $S$, of each signal.

$$S = \frac{E^2}{\eta} \tag{8}$$

#### 4.2.2 Spreadsheet calculations

Typically there may be a hundred or more radio signals measured at any given location and NRPB uses a spreadsheet template on a laptop computer:

(a) to calculate the measured power densities (see equations 7 and 8),
(b) to calculate the exposure quotients (equation 4),
(c) to sum the exposure quotients to get the total exposure quotient (equation 5),
(d) to assess the proportion of the total exposure arising from different signals.

### 4.2.3 Example results

In order to present measured data in reports, a table in the format shown in Table 10 is used. Where there is a specific interest in a given base station (or other source), its signals can be highlighted provided their frequencies are known in advance.

**TABLE 10 Contributions to total exposure of the ten strongest radio signals measured at an example location. *Note* BS is short for base station**

| Source | Frequency (MHz) | Power density ($\mu$W m$^{-2}$) | Investigation level (W m$^{-2}$) | NRPB exposure quotient ($\times 10^{-6}$) | Percentage of total exposure |
|---|---|---|---|---|---|
| Paging | 153.1 | 0.4 | 6.6 | 0.05 | 1 |
| Mobile radio | 463.5 | 7.8 | 26.0 | 0.30 | 4 |
| GSM900 BS | 939.2 | 3.8 | 36.2 | 0.11 | 1 |
| GSM900 BS | 954.6 | 5.0 | 37.4 | 0.13 | 2 |
| GSM1800 BS | 1835.8 | 4.4 | 100.0 | 0.04 | 1 |
| **GSM1800 BS** | **1848.2** | **85** | **100.0** | **0.85** | **10** |
| **GSM1800 BS** | **1860.6** | **13** | **100.0** | **0.13** | **2** |
| **GSM1800 BS** | **1866.8** | **20** | **100.0** | **0.20** | **2** |
| **GSM1800 BS** | **1868.4** | **36** | **100.0** | **0.36** | **4** |
| **GSM1800 BS** | **1871.8** | **590** | **100.0** | **5.9** | **69** |

It is normally only necessary to tabulate the ten signals that produce the greatest exposure quotients in order to account for almost all of the total exposure. At the location described in Table 10, the total exposure was 8.6 $10^{-6}$, or 8.6 millionths, of the NRPB investigation level and the ten listed signals account for 94% of this. The five signals from the base station of interest (in bold) contribute 77% of the total exposure at this location.

The source categories that were most frequently identified in the tables were broadcast radio (88–108 MHz), paging (138 and 153 MHz), broadcast television (470–860 MHz) and various mobile (including cellular) communications transmitters.

## 4.3 Surveying technique

### 4.3.1 General method

The complex propagation conditions giving rise to measured signals at environmental locations include shielding and shadowing by buildings, multiple reflections from walls and re-radiation from conducting structures that are excited by the radio waves. These effects can cause electric field strength to be non-uniform over small regions of space about the measurement locations. The direction of incidence and polarisation of the radio waves can also be unpredictable and similarly variable.

One aim was to record the maximum field strength from every signal over a volume of space in order to calculate a worst-case exposure quotient in the immediate vicinity of the measurement location. This was achieved by using the spectrum analyser to make a continuous log of the maximum value of the measured signal strengths over a period during which the antenna was carefully manipulated over the region of space of interest.

### 4.3.2 Limitations

For signals from sources that transmit intermittently, such as VHF mobile radio, the maximum instantaneous power density will have been recorded. Exposure assessments based on protection guidelines require averaging of signal strength over either 6 or 15 minutes, consequently the exposure component arising from intermittent signals will have been overestimated. This would be appropriate for a hazard assessment because worst-case conditions are represented; however, further work would be necessary to determine the extent of any effect on the exposure proportions calculated in Section 5.

The amplitude displayed by the spectrum analyser indicated the rms voltage at its input connector during the strongest part of each measured signal, ie when the transmission was at its maximum power. Some signals from base stations are pulsed, so the measurements in this report will represent the peak power during a pulse for such signals. The average power of a pulsed signal is the appropriate quantity for exposure assessment, so the spectrum analyser results would generally overestimate exposures. Again, this conservatism is appropriate for hazard assessment, but may indicate an enhanced contribution to total exposure from pulsed signals.

### 4.4 Measurement uncertainty

There are several sources of uncertainty associated with the method used to measure electric field strength. The uncertainties include:

(a) electrical factors associated with the calibration of the spectrum analyser and antennas,

(b) factors arising from surveying practices, eg positioning and handling of the antennas.

Uncertainties belonging to category (a) are readily obtained from the relevant calibration certificates. The uncertainty in the calibrations of all three antennas was 0.8 dB and the uncertainty intrinsic to the calibration of the spectrum analyser was pessimistically estimated at 2 dB. The uncertainties associated with measuring the loss of the connecting cable would be negligible in comparison with these other electrical factors.

Uncertainties belonging to category (b) are more difficult to quantify. The most significant source of imprecision was likely to arise from disturbance of the antenna factor during measurements. The antenna factor quantitatively describes the coupling between an antenna and a uniform field. It is determined for the idealised situation of the antenna being a long distance from conducting and dielectric objects such that mutual coupling is negligible. During the survey the antennas were mounted on tripods and manipulated by hand causing potentially significant coupling of the antenna with the operator’s body and with other nearby structures such as building fabrics. Typical values for disturbances to antenna factors were estimated to be 6, 4 and 2 dB for the biconical, log-periodic and ridgeguide antennas, respectively.

The uncertainties described above were combined in quadrature to give the overall uncertainty in power density associated with the use of each antenna as summarised in Table 11. It follows that actual power densities may have differed from reported values by factors which are bounded to a 95% degree of confidence by the limits tabulated in the two right-hand columns of the table. Consequently, in measurements made with the log-periodic antenna, for example, there is a 95% certainty that the true maximum power density was not greater than 2.8 times the reported value.

**TABLE 11 Overall uncertainties affecting power density measurements**

| | | Power density multiplier | |
|---|---|---|---|
| Frequency range | Uncertainty (dB) | Minimum | Maximum |
| 30–300 MHz | ±6.4 | 0.23 | 4.3 |
| 300–1000 MHz | ±4.5 | 0.35 | 2.8 |
| 1–2.9 GHz | ±2.9 | 0.51 | 2.0 |

# 5 Results of exposure assessments

In addition to performing measurements of power density from the base station of concern, signals were measured from other environmental radio sources. Technical data were also secured from the operators that allowed calculations of power density to be performed for comparison with measurement. This section begins by presenting calculations based on the technical data supplied by the operators indicating the extent of the maximum distances from base station antennas at which the NRPB and ICNIRP exposure guidelines are likely to be exceeded. Measured data, given in full in Appendix B, are then summarised and compared with theoretical predictions of power density from base stations. Finally, the relative contributions of different sources to the assessed exposures are compared in order to determine whether base stations are a material source of exposure at the locations visited.

## 5.1 Calculation of exposures

Several different approaches to calculating the exposure of a person in the vicinity of a transmitting antenna are possible. In general, the simpler the calculation approach used, the more conservative will be the outcome and the greater the compliance distance that will result (see Section 5.2). Three different calculation approaches will be mentioned here and results will be presented based on the first two.

### 5.1.1 Far-field power density calculation

If the total power fed into an antenna is known as well as the antenna gain, it is possible to calculate the power density in the main beam by assuming an inverse square law dependence upon distance at all distances from the antenna. The following equation is analogous to equation 2 in Section 2.2.1 and may be used to calculate power density, $S$, in this way.

$$S = \frac{P_{rad}\, G}{4\pi\, d^2} \quad (9)$$

where $d$ is the distance from the antenna, $P_{rad}$ is the total radiated power and $G$ is the antenna gain (in linear units).

Reflections may increase or decrease the power density from that calculated by equation 9 if the path length travelled by a reflected wave is comparable with the direct distance to an antenna. The most likely situation where this could occur would be where a wave was reflected from the ground, as indicated in Figure 12. Reflections would be expected to increase the electric field strength by a factor of up to two, thus the total power density would be increased by a factor of up to four.

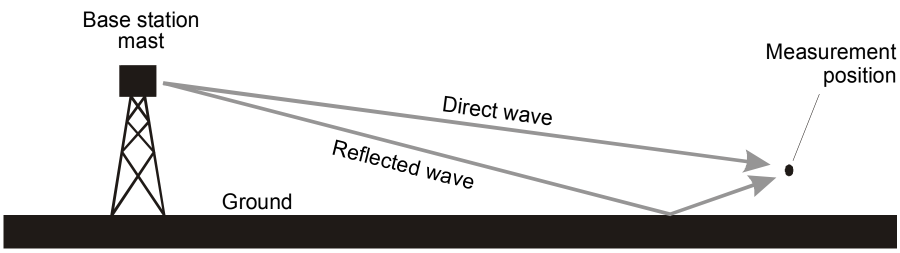


**FIGURE 12 Direct and reflected waves arriving together to increase the power density at a measurement position**

The use of equation 9 will overestimate power density in directions other than the main beam, because the antenna gain is effectively less in these directions. It will also overestimate power density at short distances, generally within 10 m of antennas.

#### 5.1.2 Near-field power density evaluation

If the detailed electrical structure inside an antenna is known, it becomes possible to perform a more rigorous calculation of power density than is represented by equation 9. Such a *near-field* calculation is able to evaluate the precise variation of power density (or field strength) at all distances and in all directions from an antenna. Near-field results are presented later in this section that have been calculated using a physical optics approach.

If field strength is measured close to an antenna, calculations accounting for the near-field character of the antenna should be in good agreement.

#### 5.1.3 Direct SAR evaluation

The most rigorous approach to calculating the variation of the exposure produced by an antenna as a function of distance is to account fully for the electromagnetic coupling between the antenna and an exposed person. This approach should be accurate for exposure at all distances and will generally give the shortest compliance distances. The approach is similar to that used for assessing the exposures produced by mobile phone handsets and can be used for microcellular base stations which radiate similar power levels.

A computer model of an antenna and of the human body can be used for analysis of energy deposition in the body using a computer code implementing Maxwell's equations. Anatomically realistic models of the human body developed from magnetic resonance imaging form the current state of the art and the finite-difference time-domain method (FDTD) is often used to carry out the exposure calculation.

An alternative approach is to carry out SAR evaluation through measurement by producing a physical model of the human body and placing this in the field of the real antenna. Small field probes can be implanted inside the physical model and, if sufficiently sensitive for the powers transmitted, these can be used to measure the SAR that is produced.

### 5.2 Predicted compliance distances

The general approach to evaluating compliance distances is to calculate the variation in some measure of exposure (field strength, power density or SAR) in the space around an antenna. The distance is then ascertained at which the appropriate guideline value is met.

Network operators usually calculate compliance distances in a generic rather than a site-specific way for classes of antennas used in their networks. The calculations are performed using the maximum power that will be radiated by any antenna in that class so that worst-case conditions are represented. As a result, the calculations do not have to be repeated if another transmitter is added or the radiated power is increased. An effective closed surface, often a cuboid, is then defined around sector antennas so that exposure will not exceed guidelines provided people are excluded from this region. Cylindrical exclusion zones are normally defined around omni-directional antennas.

The results in this section serve as example calculations, based on realistic technical data that are expected to reproduce typical worst-case conditions. The results are not intended to supersede or replace the exclusion zones defined by network operators. Results are only given for the direction of the main beam. Compliance distances would be less in other directions.

### 5.2.1 GSM900 base station antennas

A model of the electrical characteristics of a typical 900 MHz sector antenna has been formed by producing a vertical stack of 12 half-wavelength dipole elements with appropriate separation. Each element was then excited to give an omni-directional antenna with a total radiated power of 80 W and a gain of 13 dB. The radiated power of the omni-directional antenna was then increased by a factor of about three to represent a 120º sector antenna and this effectively increased the gain to 17 dB. The model antenna was then used to produce results that could be used to indicate typical maximum power densities produced by GSM900 sector antennas. The predictions from the model are shown in Figure 13, together with predictions from a simpler inverse square law calculation.

Figure 13 shows how power density reduces with distance from the antenna and indicates compliance distances for the NRPB investigation level and the ICNIRP reference level. Assuming an inverse square law would give a compliance distance of 3.1 m for the 35 W $m^{-2}$ NRPB investigation level, whereas the more accurate near-field model indicates a lesser compliance distance of 46 cm. Similarly, the inverse square law would imply a compliance distance of 8.4 m for the 4.6 W $m^{-2}$ ICNIRP reference level for the general public, whereas the near-field calculation would indicate 2.4 m.

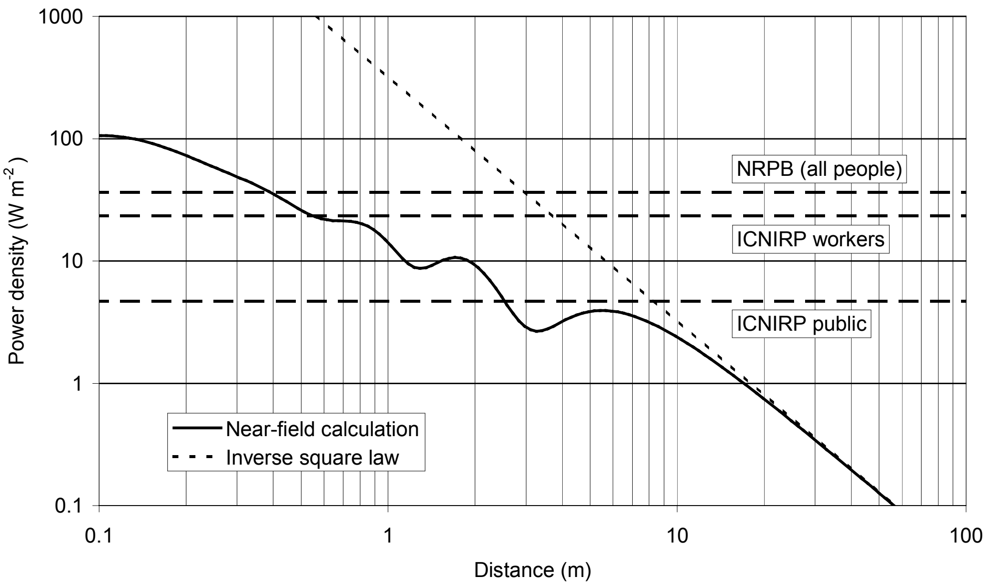


**FIGURE 13 Power density in the beam from a typical GSM900 sector antenna showing the results from calculations assuming an inverse square law and a more detailed near-field model of the antenna. The total radiated power is 80 W and the antenna consists of 12 radiating elements giving a gain of 17 dB**

### 5.2.2 GSM1800 base station antennas

A similar approach to that described for the 900 MHz antenna, but scaled for 1800 MHz, was used to calculate maximum power densities produced by GSM1800 sector antennas. Again, a radiated power of 80 W was chosen, but a slightly higher gain of 18 dB was used. The predictions from the model are shown in Figure 14, together with predictions from a simpler inverse square law calculation.

Figure 14 shows how power density reduces with distance from the antenna and indicates compliance distances for the NRPB investigation level and the ICNIRP reference level. Assuming an inverse square law would give a compliance distance of 2.1 m for the 100 W $m^{-2}$ NRPB investigation level, whereas the more accurate near-field model indicates a lesser compliance distance of 31 cm. Similarly, the inverse square law would imply a compliance distance of 6.7 m for the 9 W $m^{-2}$ ICNIRP reference level for the general public, whereas the near-field calculation would indicate 5.9 m.

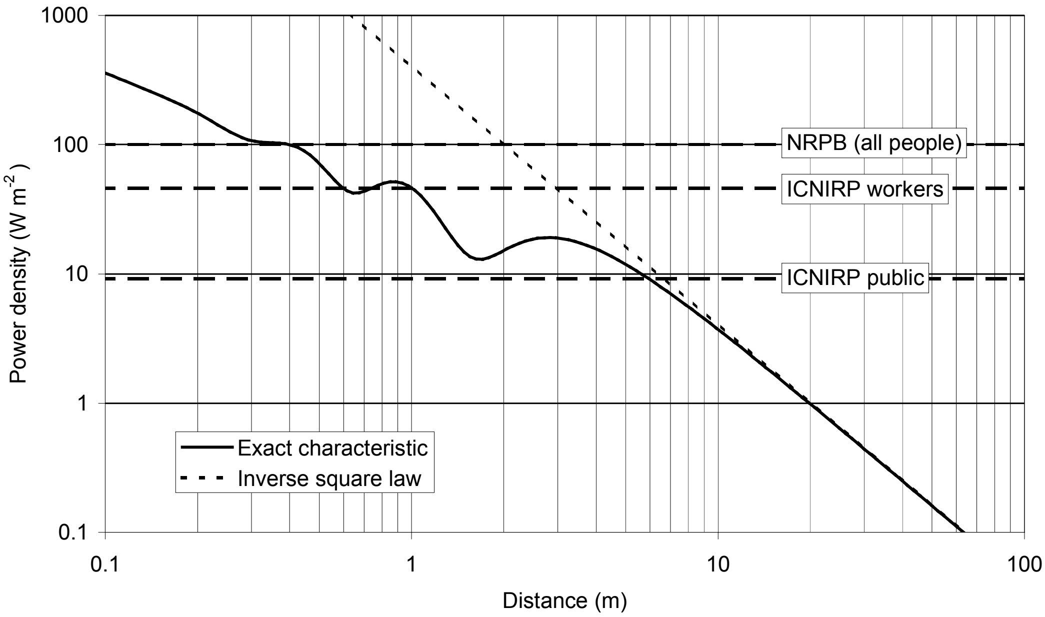


**FIGURE 14 Power density in the beam from a typical GSM1800 sector antenna showing the results from calculations assuming an inverse square law and a more detailed near-field model of the antenna. The total radiated power is 80 W and the antenna contains 12 radiating elements giving a gain of 18 dB**

## 5.3 Power density at ground level

The model GSM900 sector antenna of Section 5.2.1 was adapted to calculate the variation in power density at ground level with increasing distance from a typical mast. The beamwidth produced by the antenna was 6º in the plane of elevation; however, a phase shift was applied to the element excitations in order to tilt this beam downward by 2º. The radiated power was set to give an EIRP of 5000 W, which would correspond to a total radiated power of 80 W from a sector antenna with 18 dB of gain.

The calculation geometry is shown in Figure 12 and the base of the antenna was set at a typical minimum height of 13.7 m above ground level, giving 15 m to the centre of the antenna. Power density was calculated at distances ranging from 1 m to 10 km from the foot of the mast and the direct wave power density was multiplied by a factor of four in order to account for the presence of a reflected wave component. The results are shown in Figure 15.

Figure 15 shows how the power density at the foot of the mast is very much lower than at distances in the range from tens to hundreds of metres. At these distances, *sidelobes* in the antenna's directional pattern give rise to a series of peaks in power density. The lower edge of the main beam begins to become incident at ground level from distances of 100 m; however, the peak power density of 35 mW $m^{-2}$ is not achieved until a distance of 180 m from the mast. Power density then falls off according to the inverse square law at greater distances.

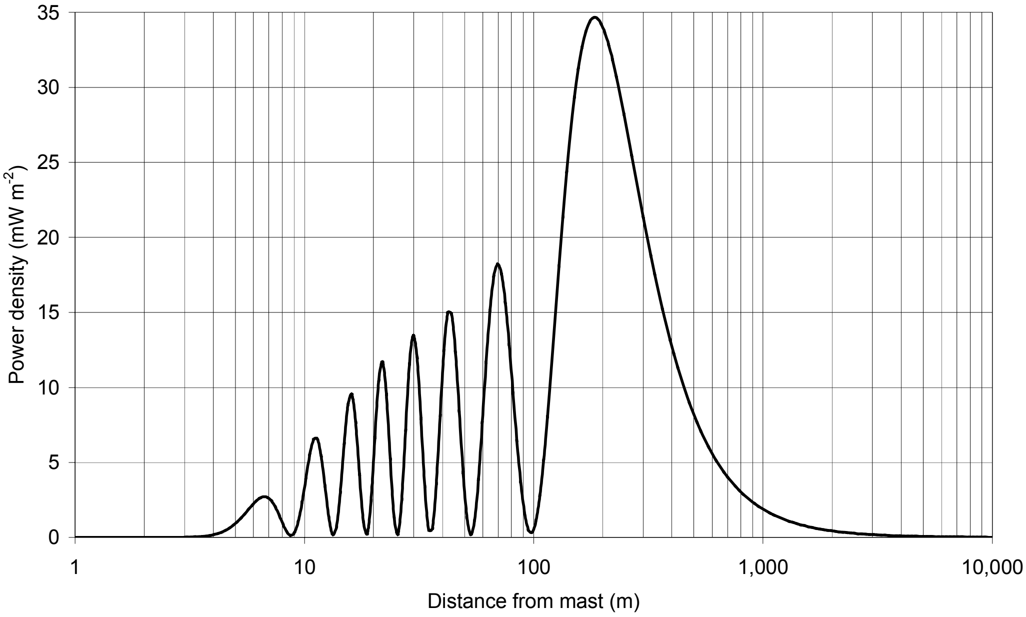


**FIGURE 15 Calculated power density as a function of distance at ground level from a typical 15 m mast with GSM900 antennas producing an EIRP of 5000 W**

## 5.4 Measured power densities

Appendix B presents graphs showing all of the radio signals quantified during this work and this section will summarise the power density aspects of the measurements. Following consideration of the base station of interest, the analysis will be expanded to consider the total power density from all mobile phone base stations and the total power density from all environmental signals.

Measurements were made of signals from the base station of interest at 118 publicly accessible locations at the 17 sites; however, complete spectra were only measured at 73 of these locations. The data are presented as functions of the radial distance directly to the base station antennas irrespective of whether the path was obstructed by walls, roofs etc. Data obtained from indoor and outdoor locations have been reported as separate categories.

### 5.4.1 Base stations of interest

The frequencies of the signals from the base stations of primary interest were known in advance. These signals could therefore be picked out from the measured spectra and their power densities could be summed independently of the rest of the data. This was done for all 118 measurement locations at the 17 sites visited and the results are shown in Figure 16.

Figure 16 shows that there is great variation in the strength of measured signals, even at similar distances from the antennas. The greatest variations occur in measurements at shorter distances from the antennas and this is probably because the indoor measurements were often shielded by building fabric, eg roofs. At greater distances, the measurements tended to be made near windows or outdoors with a line of sight path to the base station antennas.

There does not appear to be any obvious trend for the strength of signals to increase at distances closer to the antennas as the measurement locations would have been outside the main beam. The tendency of power density to fall off with increasing distance due to the inverse square law would have been offset by a tendency progressively to enter the main beam as distance increased.

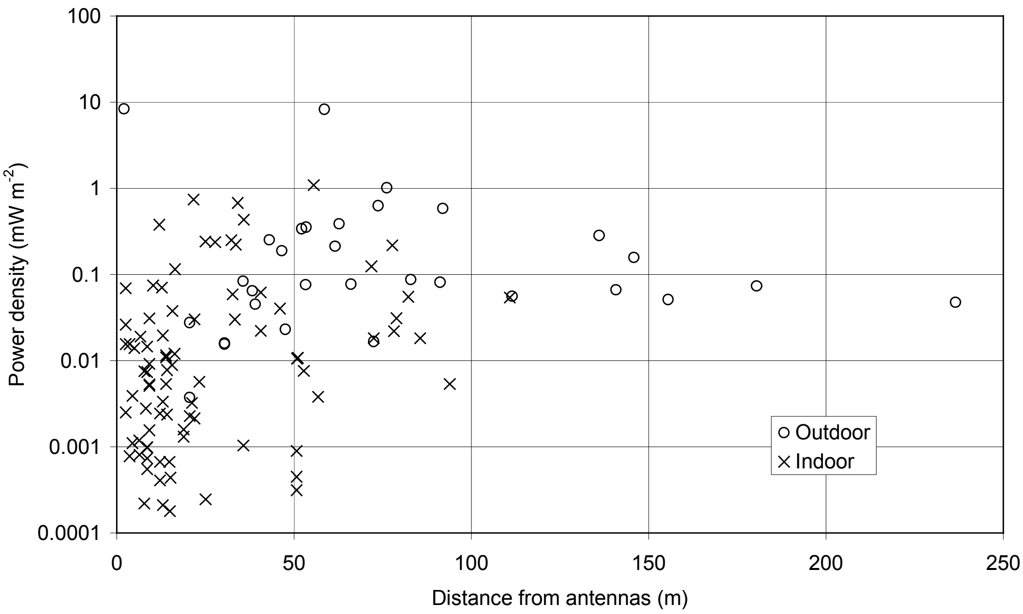


**FIGURE 16 Total power densities measured at 118 locations due to signals arising from the base stations of interest**

The maximum power density measured was 8.3 mW $m^{-2}$ and this was found on a playing field 60 m from a school building with antennas on its roof (E2 in Appendix B). The location had an unobstructed line of sight path to the antennas and may have been sufficiently far away to be fully exposed to the main beam.

Power density was in the range 10 μW $m^{-2}$ to 1 mW $m^{-2}$ at all but 4 of the 31 outdoor locations. Power density at the indoor locations was generally lower, but varied over an even greater range, typically from 0.1 μW $m^{-2}$ to 1 mW $m^{-2}$.

### 5.4.2 Comparison with theory

The measurements of power densities from the base stations of interest were compared with predictions assuming an inverse square law dependence of power density with distance from the base station antennas. For comparison purposes, the measured data were normalised using the quoted radiated powers so that each base station effectively had an EIRP of 5000 W. This would correspond to a typical maximum radiated power scenario with 80 W fed into an antenna with 18 dB of gain. The inverse square law calculations followed the approach of Section 5.1.1, also with an EIRP of 5000 W, but with the result of equation 9 multiplied by four in order to account for reflections.

The normalised measured data are shown in Figure 17 together with the calculated data. It should be noted that 122 data points were obtained from the 118 measurement locations because 4 of the locations were at sites with 2 base stations.

Figure 17 shows that only one of the power density measurements was more than 25% of what would be expected based on calculations. The location where this measurement was performed (E2 in Appendix B) was at a distance of 60 m from a mast above a school and may have been sufficiently far away to be exposed to the main beam. The most likely explanation for the unexpectedly high measurement would have been if the quoted EIRP of 44 dBm was too low. Contractors were carrying out work on the base station at the time of this measurement and the EIRP may have been raised to nearer 52 dBm.

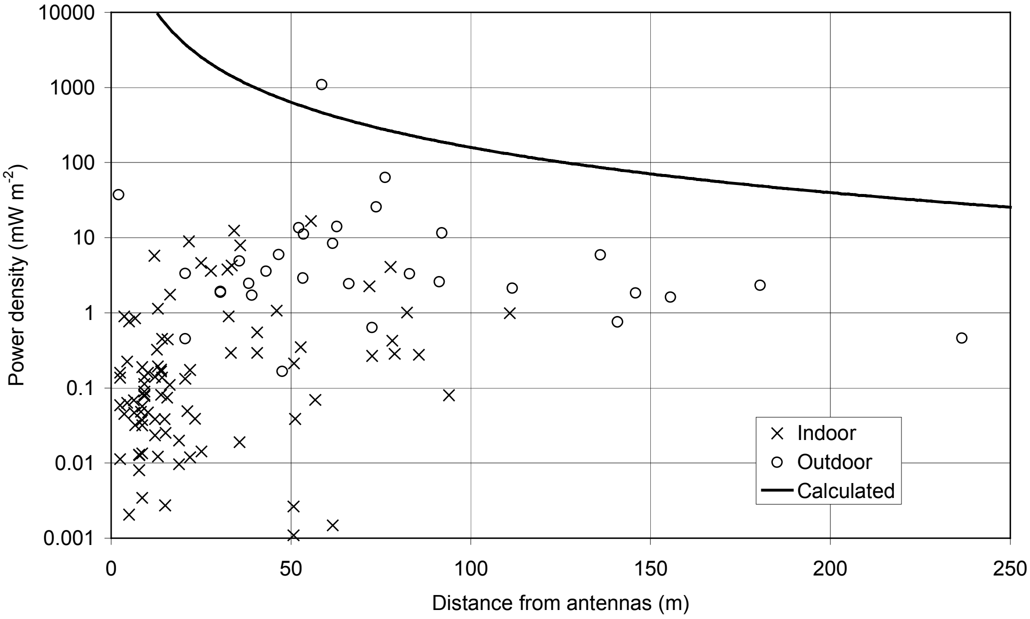


**FIGURE 17 Measured power density data normalised to a total EIRP of 5000 W from each antenna, together with an equivalent inverse square law curve incorporating a direct and a reflected wave component**

A further comparison between measurement and prediction was made at Site D. A turntable ladder was used to position the measurement equipment directly in the beam 20 ± 2 m in front of a sector antenna. This location was remote from any reflecting objects, consequently the measurement of power density was made under close to ideal propagation conditions. The quoted EIRP of 51.2 dBm for the antennas would imply that the power density should have been 27 ± 5 mW m$^{-2}$ and this is in close agreement with the measurement of 20 mW m$^{-2}$ (10–40 mW m$^{-2}$ taking into account measurement uncertainty).

### 5.4.3 All environmental signals

The data from the 73 locations where complete spectra were measured, were analysed to calculate the total power density arising from all radio signals, including the base station of interest. The results are shown in Figure 18 with outdoor and indoor measurements indicated by different symbols.

Figure 18 shows data with a very similar spread to those shown in Figure 16 in that most of the data points are between 10 μW m$^{-2}$ and 1 mW m$^{-2}$. It can be seen that the indoor measurements with the lowest power densities in Figure 16 have been materially increased by the addition of power density from other environmental signals so there are fewer data below 1 μW m$^{-2}$. However, for locations where power density exceeded 1 mW m$^{-2}$, the local base stations dominated the signal strength and other environmental signals had little additional effect.

### 5.4.4 Statistical analysis

The power density from the base stations of interest and also the total power density from all sources combined have been discussed qualitatively above; however, it also instructive to carry out statistical analysis in order to determine the average power density and the general spread of the distributions. The graphs in this section have been presented with logarithmically scaled *y*-axes because the data are spread over several decades and appear more evenly distributed on such a scale.

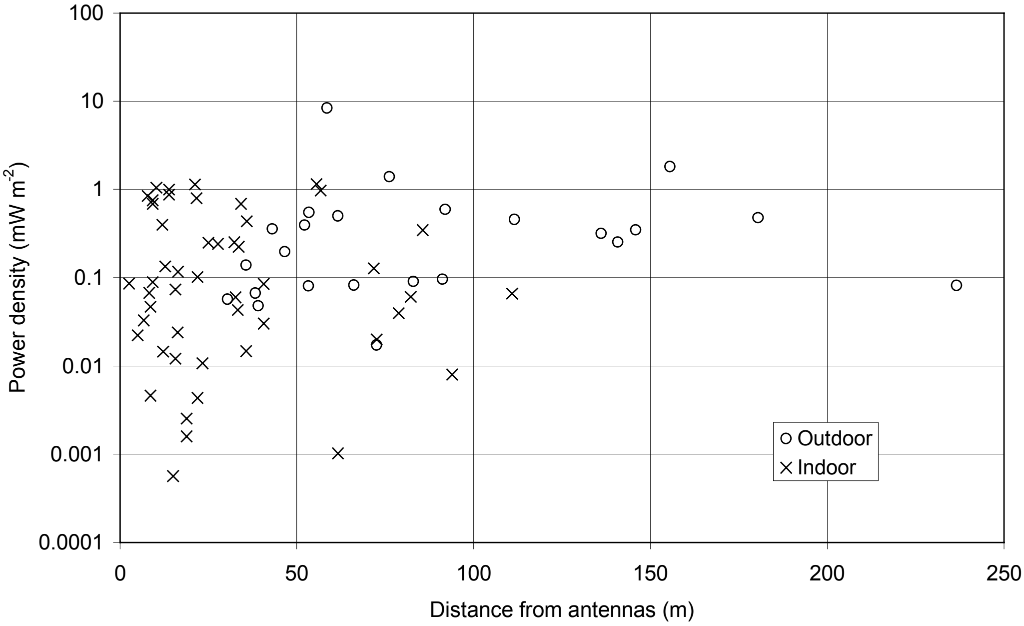


**FIGURE 18 Total power densities due to all environmental radio signals measured at the 73 locations where complete spectra were obtained**

For this reason geometric rather than arithmetic statistics were used to analyse the data. The geometric mean was used to represent the average of the data and the range was taken to be between the 5th and 95th percentiles. Only data from the 73 locations where complete spectra were obtained, were analysed.

Analysis was carried out for the complete set of power density data and various data subsets were also defined. One subset was defined for the total power density neglecting signals from all base stations (TACS, GSM900 and GSM1800), since this might be representative of the situation before the advent of mobile telephony. Another subset was defined for total power density neglecting signals from the base stations of interest since this would represent the situation if the base stations of interest were not present. The results are shown in Table 12 and Figure 19 gives a graphical comparison.

The geometric mean power densities of different data subsets are different and, as would be expected, they have been increased by the presence of signals both from the base station of interest and from other base stations. When the underlying variability of the data is considered, it is clear that the range spanning the 5th to 95th percentiles in each data set far exceeds any difference between the geometric mean of that data set and any other data set. This implies that neither of the following could be stated with any confidence:

(a) that any particular location near to a base station would be exposed to a higher power density than a different location not near to a base station,

(b) that any particular location exposed to base station signals would be exposed to a higher power density than a different location not exposed to base station signals.

The total power density due to signals from the base stations of interest was 33 (0.91–700) $\mu W\ m^{-2}$ and this is comparable with the power density from all other sources combined, ie 21 (0.84–970) $\mu W\ m^{-2}$.

**TABLE 12 Average power densities calculated for all and various subsets of the radio signals measured at the locations in this report using geometric statistics**

| | Geometric mean and range (5th–95th percentiles) of power density (μW $m^{-2}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Base stations of interest | | Total of all signals | | Total neglecting base stations of interest | | Total neglecting all base stations | |
| Indoor | 17 | (0.32–570) | 75 | (1.9–1000) | 16 | (0.76–970) | 5.0 | (0.23–420) |
| Outdoor | 130 | (19–930) | 240 | (49–1700) | 37 | (0.5–360) | 12 | (0.5–360) |
| All locations | 33 | (0.91–700) | 110 | (3.5–1100) | 21 | (0.84–970) | 6.6 | (0.23–380) |

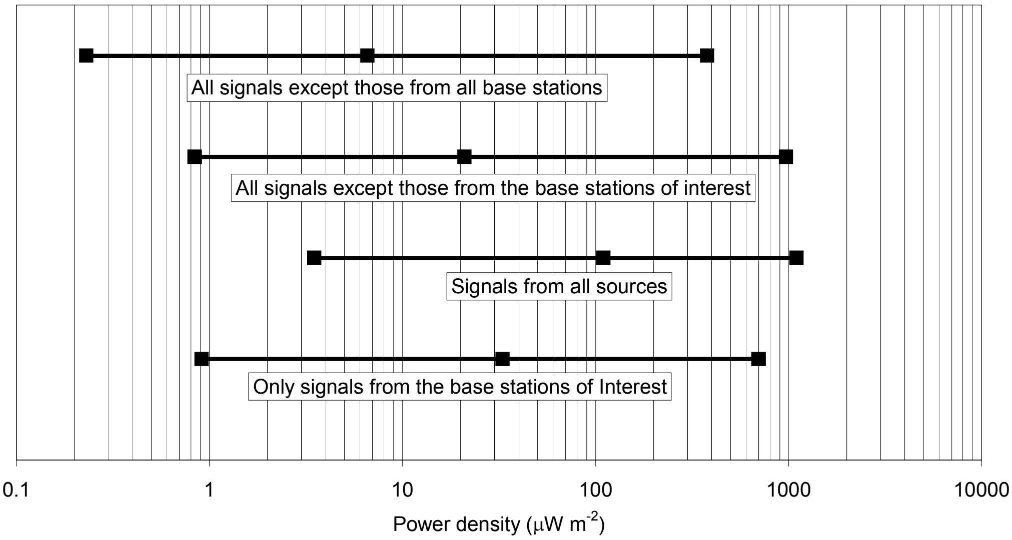


**FIGURE 19 Range and mean strength of power density for the entire data set and various subsets of the measured spectra taken from both indoor and outdoor locations combined**

## 5.5 Exposures produced by base station and other signals

This section considers the measured power densities in comparison with the NRPB investigation level and the ICNIRP public reference level. Comparison will not be made with the ICNIRP reference level for workers because this is broadly in line with the NRPB investigation level and exactly five times higher than the public reference level.

The results in this section will compare the total exposure produced by all radio signals with the investigation/reference levels following the approach of Section 3.5.

### 5.5.1 Exposure due to signals from all sources

Equation 5 was evaluated using both the NRPB investigation level and the ICNIRP public reference level. The results are shown in Figures 20 and 21 for each of the 73 locations where complete spectra were obtained. The figures show that the maximum exposure measured at any location was 1/4400 of the NRPB investigation level, or 1/560 of the ICNIRP public reference level. Typical exposures were highly variable, but generally ranged between 10,000 and 10,000,000 times below the NRPB investigation level, or between 1,000 and 1,000,000 times below the ICNIRP public reference level.

Geometric statistics were used to analyse the data and determine the mean and range of the exposures in terms of 5th and 95th percentiles. The results are shown in Tables 13 and 14 in terms of the total exposure present at the locations and two subsets of the data intended to reveal the influence of signals from base stations on the total exposure. The first subset shows the exposure that would occur if the base stations of primary interest to the survey were not present and the second subset shows what exposure would be if there were no signals from any base stations.

As with the power density statistics in Table 12, there are differences between the geometric means of different data sets, but the ranges of the data in each subset are much greater than these differences. This implies that overall exposure at the locations considered was generally increased due to signals from the local base station. Nevertheless, it would not be possible to state with confidence that exposure at a particular location close to a base station would be any higher than at a similar (indoor/outdoor) location remote from that, or any other, base station.

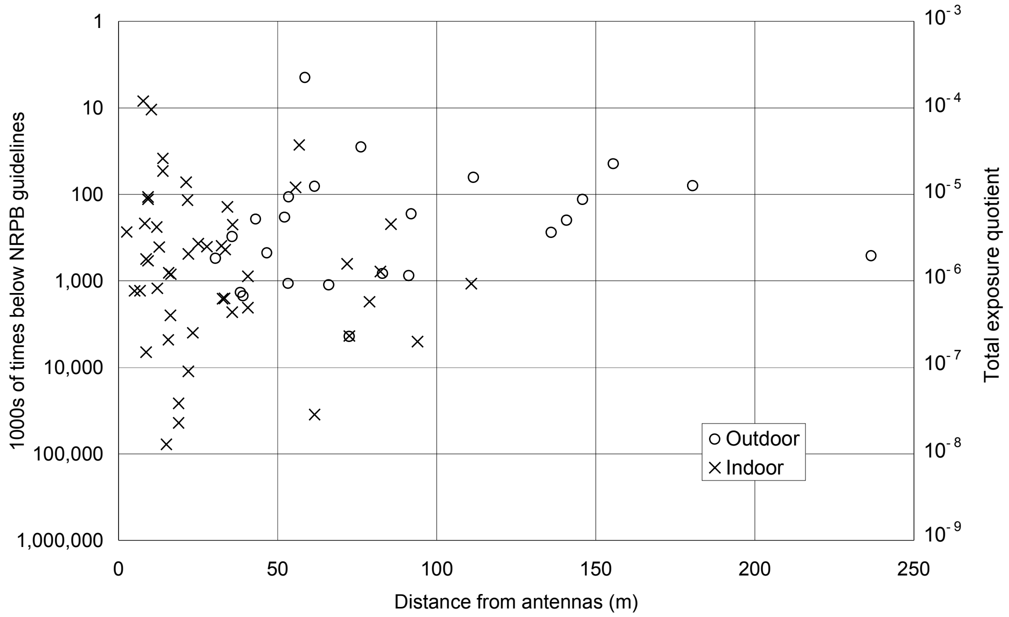


**FIGURE 20 Total exposure in comparison with the NRPB investigation level at each of the 73 locations where complete spectra were recorded**

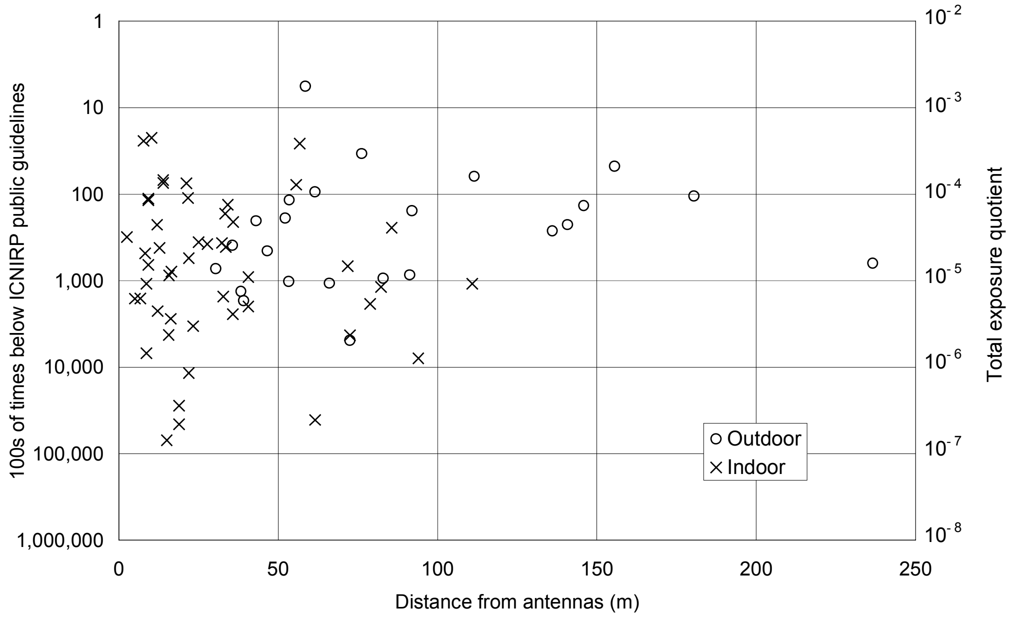


**FIGURE 21 Total exposure in comparison with the ICNIRP public reference level at each of the 73 locations where complete spectra were recorded**

**TABLE 13 Exposures produced by all radio signals and various subsets of radio signals based on the NRPB investigation level**

| Category of location | Geometric mean exposure quotient and range (5th–95th percentiles) in millionths of the NRPB investigation level | | | | | |
|---|---|---|---|---|---|---|
| | Total exposure from all sources | | Exposure neglecting base stations of interest | | Exposure neglecting all base stations | |
| Indoor | 1.4 | (0.032–32) | 0.56 | (0.025–32) | 0.31 | (0.011–28) |
| Outdoor | 4.0 | (0.68–33) | 1.2 | (0.087–15) | 0.68 | (0.041–11) |
| All locations | 2.0 | (0.064–36) | 0.72 | (0.030–24) | 0.40 | (0.011–16) |

**TABLE 14 Exposures produced by all radio signals and various subsets of radio signals based on the ICNIRP reference level for the general public**

| Category of location | Geometric mean exposure quotient and range (5th– 95th percentiles) in millionths of the ICNIRP public reference level | | | | | |
|---|---|---|---|---|---|---|
| | Total exposure from all sources | | Exposure neglecting base stations of interest | | Exposure neglecting all base stations | |
| Indoor | 13 | (0.29–260) | 4.2 | (0.18–260) | 2.1 | (0.10–190) |
| Outdoor | 37 | (6.1–280) | 9.2 | (0.56–140) | 4.5 | (0.23–84) |
| All locations | 18 | (0.61–330) | 5.4 | (0.22–170) | 2.7 | (0.10–110) |

### 5.5.2 Exposure due to the base station of interest

Further analysis of the exposure data was carried out in order to investigate whether signals from the base stations of interest were the strongest contributors to total exposure at the measurement locations. Results are only presented for exposure in the context of the NRPB guidelines, as results with the ICNIRP guidelines were very similar.

The approach taken was to calculate two sums using equation 5, one for the signals from the base station of interest and the other for all the remaining signals. The ratio of these two quantities was then plotted for each of the 73 locations with complete spectra and the results are shown in Figure 22.

Figure 22 shows the data spread about a line of unity, which corresponds to 50% of the total exposure arising from the base station of interest. All locations above this line received more than 50% of their total exposure from the base station of interest and other sources gave more than 50% of the total exposure at locations in the bottom half of the graphs.

The figure shows that the base station contributes over half of the exposure at 32 out of 73 locations; however, the data are so variable that there is no visually obvious trend for it to dominate exposure at either greater or lesser distances from the base station. The geometric mean and range from the 5th to 95th percentile was 0.52 (0.0022–32) indicating that the base stations of concern generally contributed less than half of the total exposure at the measurement locations.

When the data were split into indoor and outdoor categories, the mean and ranges became 0.34 (0.0018–31) and 1.2 (0.040–50), respectively, showing that the indoor locations received a lower proportion of their total exposure from the base station of concern than the outdoor locations. This would be expected because many of the indoor locations were in buildings with antennas above their roofs. As many of the measurement locations were above ground-floor level, the signals from distant sources would enter the building more readily through the windows than would the local signals through the roof.

### 5.5.3 Exposure from all base stations

A similar graph to Figure 22 was plotted including all base stations in the vicinity that contributed to exposure. The resulting data are shown in Figure 23.

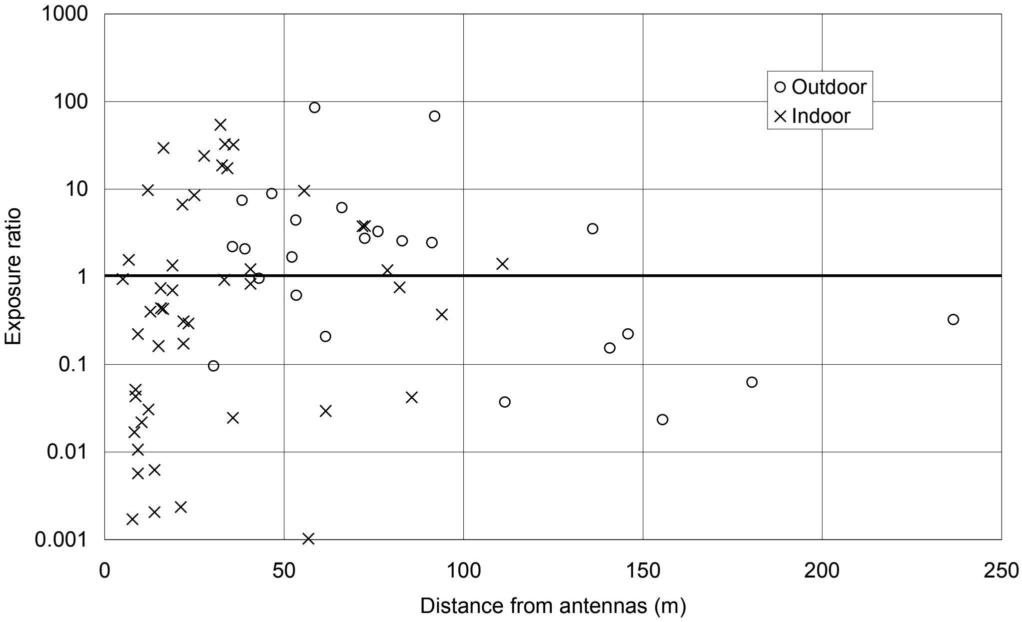


**FIGURE 22 Exposure due to signals from the base stations of interest divided by the exposure from all other signals. Exposures defined in the context of the NRPB investigation level**

The data in Figure 23 are highly variable with 49 out of 73 locations having over half of their total exposure arising from base station signals. Analysis using geometric statistics shows that the average exposure ratio is 2.3 and this suggests that base station signals do generally account for the majority of total exposure at the measurement locations. However, the range between the 5th and 95th percentiles of exposure ratio (0.051–54) is much larger than the enhancement.

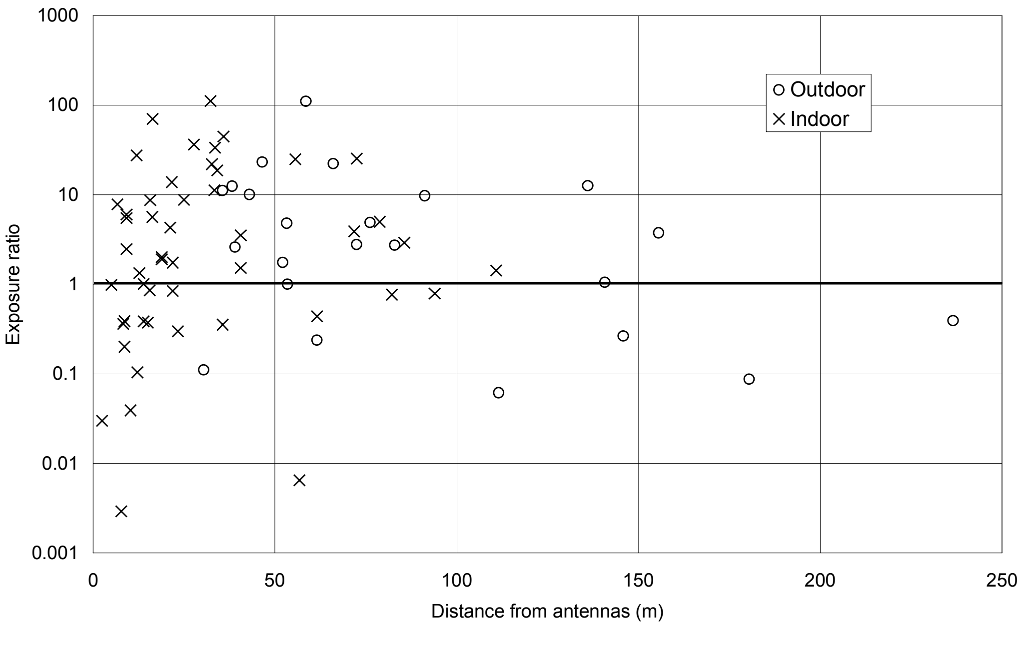


**FIGURE 23 Exposure due to signals from all base stations divided by the exposure from all other signals. Exposures defined in the context of the NRPB investigation level**

## 6 Conclusions

The typical maximum powers radiated by antennas used with macrocellular base stations in the UK appear to be in the region of 80 W and exposures in the beam in the immediate vicinity of the antennas can exceed guidelines. The beams from the antennas are essentially directed towards the horizon and compliance distances in this direction based on the NRPB investigation level should not exceed 3.1 m in the case of GSM900 systems, or 2.1 m in the case of GSM1800 systems. Based on the ICNIRP reference level for the general public, compliance distances would be no more than 8.4 m in the case of GSM900 systems or 6.7 m in the case of GSM1800 systems. Compliance distances in other directions, such as above and below the antennas, would be smaller.

Power density from particular base stations was measured at 118 locations at 17 sites where people were concerned about their exposure to radio waves. Typical power densities were in the range 0.01–1 mW $m^{-2}$ and the maximum power density measured at any location was 8.3 mW $m^{-2}$. For distances up to 250 m from the base stations of concern, there did not appear to be any clear trend for power density to reduce with increasing distance. Calculations using the quoted EIRP of a base station and assuming an inverse square law relationship between power density and distance were found to give conservative predictions.

When measurements are made of radio wave signal strengths at locations of public access near base stations, it is also possible to detect the signals from a variety of other sources. The influence of other radio signals on the total power density was determined by measuring all signals in the frequency range 30 MHz to 2.9 GHz at 73 of the 118 locations. The measured data varied over several orders of magnitude; consequently the mean values and ranges between the 5th and 95th percentiles were calculated using geometric statistics. The total power density due to signals from the base stations of interest was 33 (0.91–700) μW $m^{-2}$ and therefore of the same order as the total power density from all other sources combined, 21 (0.84–970) μW $m^{-2}$.

When considering the exposure produced by radio signals, it is important to account for the frequency dependence of radiofrequency energy absorption, as reflected in the NRPB investigation levels and the ICNIRP reference levels. The maximum exposure at any location was 230 millionths (0.023%) of the NRPB investigation level, or 1800 millionths (0.18%) of the ICNIRP public reference level. The geometric mean exposure and the range between the 5th and 95th percentiles was 2.0 (0.064–36) millionths of the NRPB investigation level, or 18 (0.61–330) millionths of the slightly lower ICNIRP public reference level.

Exposure in the absence of signals from the base stations of interest would have been generally lower and equal to 0.72 (0.030–24) millionths of the NRPB investigation level, or 5.4 (0.22–170) millionths of the ICNIRP public reference level. Exposure in the absence of signals from any base stations would have been lower still at 0.4 (0.011–16) millionths of the NRPB investigation level, or 2.7 (0.10–110) millionths of the ICNIRP public reference level.

The exposures encountered at the survey locations were extremely variable, with the ranges between the 5th and 95th percentiles for total exposure for any given subset of the data overlapping with the ranges for other subsets. For this reason it would appear to be very difficult to discriminate between exposed and unexposed groups in any form of population-based epidemiological study.

When considering the implications of these results, it is important to appreciate that the sites were visited by invitation and were therefore not necessarily a representative sample of base stations in the country. Considerably more data from a selection of sites chosen in a more representative way would be necessary before conclusions could be drawn about the population in general.

## 7 Acknowledgements

NRPB would like to thank the customers who commissioned the surveys that led to this work and for agreement to publish the data anonymously.

Much of the technical information presented in this report has been obtained through written and oral communications between the report authors and professional engineers and scientists working in the mobile communications industry. The authors acknowledge the provision of these technical data, which enables NRPB to provide advice on current practices in such a rapidly developing industry.

## 8 References

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# APPENDIX A

# Technical Data from Operators

Technical data have been provided by the operators of 20 macrocellular base stations at 18 sites (2 of the sites are shared by two operators and 1 site was not visited). This appendix presents data of radiated powers and beam characteristics of the sector antennas and powers radiated by dish antennas.

## A1 Powers from sector and omni-directional antennas

The meaning of the various column headings in Table A1 is explained in Section 2 of the main report.

**TABLE A1 Transmitter details and powers radiated from the sector and omni-directional antennas at the sites considered in this report**

| Site reference | System | Sector number | EIRP* (dBm) | Gain (dB) | Number of transmitters | Total power (W) |
|---|---|---|---|---|---|---|
| A | GSM1800 | 1 | 56† | 18† | 8† | 50.5† |
| | | 3 | 56† | 18† | 8† | 50.5† |
| B | GSM1800 | 1 | 46.2 | 16.5 | 1 | 0.93 |
| | | 2 | 46.2 | 16.5 | 1 | 0.93 |
| | | 3 | 46.2 | 16.5 | 1 | 0.93 |
| C | GSM1800 | 1 | 55 | 18 | 1 | 5.01 |
| | | 2 | 55 | 18 | 1 | 5.01 |
| | | 3 | 55 | 18 | 1 | 5.01 |
| D | GSM1800 | 1 | 51.2 | 16.1 | 1 | 3.24 |
| | | 2 | 51.2 | 16.1 | 1 | 3.24 |
| | | 3 | 51.2 | 16.1 | 1 | 3.24 |
| E | GSM900 | 1 | 44 | 17 | 2 | 1.00 |
| | | 2 | 49 | 17 | 1 | 1.58 |
| | | 3 | 49 | 17 | 2 | 3.17 |
| F | GSM900 | 1 | 45 | 15 | 4 | 4.00 |
| | | 2 | 45 | 15 | 4 | 4.00 |
| | | 3 | 45 | 15 | 4 | 4.00 |
| G | GSM900 | Omni | 43 | 7.5 | 3 | 10.6 |
| | GSM1800 | 1 | 51.2 | 16 | 2 | 6.62 |
| | | 2 | 51.2 | 16 | 2 | 6.62 |
| | | 3 | 51.2 | 16 | 2 | 6.62 |
| H | GSM1800 | 1 | 51.2 | 18 | 1 | 2.09 |
| | | 2 | 51.2 | 18 | 1 | 2.09 |
| I | GSM1800 | 1 | 56 | 18 | 2 | 12.6 |
| | | 2 | 56 | 18 | 2 | 12.6 |
| | | 3 | 56 | 18 | 2 | 12.6 |
| J | GSM1800 | 1 | 52 | 16.1 | 1 | 3.89 |
| | | 2 | 52 | 16.1 | 1 | 3.89 |
| | | 3 | 52 | 16.1 | 1 | 3.89 |
| K | GSM1800 | 1 | 54.9 | 16.5 | 2 | 13.8 |
| | | 2 | 54.9 | 16.5 | 3 | 20.8 |
| | | 3 | 54.9 | 16.5 | 3 | 20.8 |

| Site reference | System | Sector number | EIRP* (dBm) | Gain (dB) | Number of transmitters | Total power (W) |
|---|---|---|---|---|---|---|
| L | GSM900 | 1 | 51.25 | 14.5 | 4 | 18.9 |
| | | 2 | 51.25 | 14.5 | 4 | 18.9 |
| | | 3 | 51.25 | 14.5 | 4 | 18.9 |
| | GSM1800 | 1 | 56.7 | 15.7 | 5 | 63.0 |
| | | 2 | 56.7 | 15.7 | 5 | 63.0 |
| | | 3 | 56.7 | 15.7 | 5 | 63.0 |
| M | GSM1800 | 1 | 55 | 18 | 2 | 10.0 |
| | | 2 | 55 | 18 | 2 | 10.0 |
| | | 3 | 55 | 18 | 2 | 10.0 |
| N | GSM1800 | 1 | 52 | 17.3 | 2 | 5.90 |
| | | 2 | 52 | 17.3 | 2 | 5.90 |
| | | 3 | 52 | 17.3 | 2 | 5.90 |
| O | GSM1800 | 1 | 52 | 16.1 | 2 | 7.78 |
| | | 2 | 52 | 16.1 | 1 | 3.89 |
| | | 3 | 52 | 16.1 | 1 | 3.89 |
| P | GSM1800 | 1 | 52 | 17.3 | 1 | 2.95 |
| | | 2 | 52 | 17.3 | 1 | 2.95 |
| | | 3 | 52 | 17.3 | 1 | 2.95 |
| Q | GSM1800 | 1 | 51.2 | 17 | 2 | 5.26 |
| | | 2 | 51.2 | 17 | 2 | 5.26 |
| | | 3 | 51.2 | 17 | 2 | 5.26 |
| R | GSM1800 | 1 | 51 | 17 | 1 | 2.51 |
| | | 2 | 51 | 17 | 1 | 2.51 |
| | | 3 | 51 | 17 | 1 | 2.51 |

*EIRP is given for a single transmitted signal.

†Believed to be generic rather than specific data.

## A2 Beam characteristics of sector and omni-directional antennas

Data giving the beam widths and elevational downward tilt below horizontal were made available for some of the sites. The available data are given in Table A2.

**TABLE A2 Beam characteristics of the sector and omni-directional antennas at the sites considered in this report**

| Site reference | System | Sector number | Azimuthal beamwidth (°) | Elevational beamwidth (°) | Downwards beam tilt (°) |
|---|---|---|---|---|---|
| A | GSM1800 | 1 | 65 | 5 | – |
| | | 3 | 65 | 5 | – |
| B | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |
| C | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |
| D | GSM1800 | 1 | 115 | 5 | 2 |
| | | 2 | 115 | 5 | 2 |
| | | 3 | 115 | 5 | 2 |
| E | GSM900 | 1 | 60 | – | – |
| | | 2 | 60 | – | – |
| | | 3 | 60 | – | – |
| F | GSM900 | 1 | – | 10 | – |
| | | 2 | – | 10 | – |
| | | 3 | – | 10 | – |
| G | GSM900 | Omni | 360 | 10 | 6 |
| | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |
| H | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| I | GSM1800 | 1 | 87 | 5.5 | 2 |
| | | 2 | 87 | 5.5 | 2 |
| | | 3 | 87 | 5.5 | 2 |
| J | GSM1800 | 1 | 115 | 5 | |
| | | 2 | 115 | 5 | |
| | | 3 | 115 | 5 | |
| K | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |

| Site reference | System | Sector number | Azimuthal beamwidth (º) | Elevational beamwidth (º) | Downwards beam tilt (º) |
|---|---|---|---|---|---|
| L | GSM900 | 1 | 60 | 10 | 4 |
| | | 2 | 60 | 10 | 0 |
| | | 3 | 60 | 10 | 4 |
| | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |
| M | GSM1800 | 1 | – | – | – |
| | | 2 | – | – | – |
| | | 3 | – | – | – |
| N | GSM1800 | 1 | 85 | 5 | 2 |
| | | 2 | 85 | 5 | 2 |
| | | 3 | 85 | 5 | 2 |
| O | GSM1800 | 1 | 115 | 5 | 2 |
| | | 2 | 115 | 5 | 2 |
| | | 3 | 115 | 5 | 2 |
| P | GSM1800 | 1 | 85 | 5 | 2 |
| | | 2 | 85 | 5 | 2 |
| | | 3 | 85 | 5 | 2 |
| Q | GSM1800 | 1 | 85 | 5 | 2 |
| | | 2 | 85 | 5 | 2 |
| | | 3 | 85 | 5 | 2 |
| R | GSM1800 | 1 | 85 | 5 | 2.5 |
| | | 2 | 85 | 5 | 2.5 |
| | | 3 | 85 | 5 | 2.5 |

## A3 Powers from dish antennas

Table A3 summarises the power and gain data that were obtained for dish antennas at the various sites visited. The final column gives a calculated value for the maximum power density that could occur at any location in front of the dishes. The location where this would occur would be within a first few metres in the direction of the main beam and would not normally be accessible to the public.

**TABLE A3 Powers radiated from dish antennas at the sites considered in this report**

| Dish size (m) | Frequency (GHz) | EIRP (dBm) | Gain (dB) | Total power (mW) | $S_{max}$ (W m$^{-2}$) |
|---|---|---|---|---|---|
| – | 37.7 | – | – | 3 | – |
| – | 13.1 | 45.9 | 35.7 | 10.5 | 0.27 |
| – | 38.3 | 58.6 | 43 | 36.3 | 1.49 |
| – | 23.4 | 54.7 | 40 | 29.5 | 0.9 |
| – | 37.7 | 35.7 | 37.5 | 0.66 | 0.09 |
| 0.25 | 38 | 34.6 | 38 | 0.45 | 0.06 |
| 0.5 | 38 | 48.4 | 44 | 2.73 | 0.09 |
| 0.6 | 38 | 59 | 44 | 31.6 | 1.02 |
| 0.3 | 38 | 45 | 38 | 5.01 | 0.64 |
| 0.3 | 38 | 35.2 | 38 | 0.52 | 0.07 |
| 0.3 | 38 | 45 | 38 | 5.01 | 0.64 |
| 0.6 | 38 | 49.4 | 44 | 3.47 | 0.11 |
| – | 37.7 | 31.2 | 38 | 0.21 | 0.03 |
| – | 37.6 | 35.8 | 37.5 | 0.67 | 0.09 |
| – | 37.7 | 55.5 | 37.5 | 63.1 | 8.93 |
| – | 37.5 | 46.1 | 37.5 | 7.26 | 1.02 |
| 0.6 | 38.8 | 53.5 | 43 | 11.2 | 0.47 |
| 0.6 | 14.3 | 54.5 | 35.6 | 77.6 | 2.45 |
| 0.3 | 38.9 | 53.3 | 38 | 33.9 | 4.53 |
| 0.6 | 22.3 | 45.6 | 39.8 | 3.8 | 0.11 |
| 0.6 | 13.0 | 55.5 | 34.7 | 120 | 3.88 |
| 0.6 | 22.3 | 40.6 | 39.8 | 1.2 | 0.04 |
| 0.3 | 39.0 | 45.1 | 38 | 5.13 | 0.69 |
| 0.6 | 38.8 | 51.7 | 43 | 7.41 | 0.31 |
| 0.6 | 22.3 | 54.7 | 39.8 | 30.9 | 0.90 |
| 0.6 | 13.1 | 46.8 | 35 | 15.1 | 0.46 |
| 0.6 | 22.4 | 45.4 | 34.3 | 12.9 | 1.34 |
| 1.2 | 13.0 | 52.5 | 41.4 | 12.9 | 0.09 |
| 0.6 | 22.4 | 50.3 | 39.6 | 11.8 | 0.36 |
| – | 38.2 | 53 | 38 | 31.6 | 4.09 |
| 0.3 | 38 | 56 | 44 | 15.9 | 0.51 |
| 0.3 | 38 | 53 | 38 | 31.6 | 4.05 |
| 0.6 | 22.1 | 57 | 40 | 50.1 | 1.37 |
| 0.3 | 22.3 | 51 | 34 | 50.1 | 5.56 |
| 0.3 | 22.3 | 51 | 34 | 50.1 | 5.57 |
| 0.3 | 37.0 | 54 | 37 | 50.1 | 7.68 |
| 0.3 | 37.7 | 21.1 | 37.5 | 0.02 | 0.003 |
| 0.3 | 37.7 | 39.8 | 37.5 | 1.69 | 0.24 |
| 0.3 | 37.7 | 24.0 | 37.5 | 0.04 | 0.006 |
| 0.3 | 39.0 | 21.1 | 37.5 | 0.02 | 0.003 |
| 0.3 | 39.0 | 27 | 38 | 0.08 | 0.011 |
| 0.6 | 22.3 | 39.3 | 40 | 0.85 | 0.024 |

# APPENDIX B

## Measured Power Density Spectra

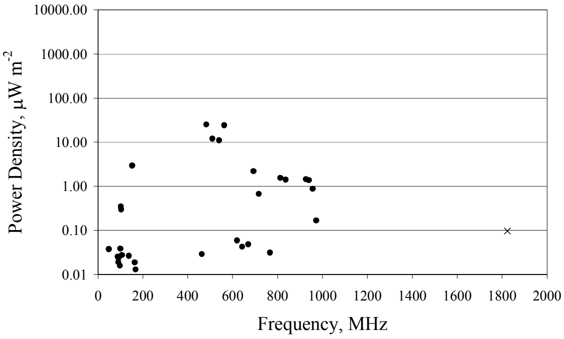
Surveys of environmental radio wave strengths have been undertaken at 17 sites in the UK and, at most of these, measurements have been made at a number of different locations. This appendix graphically presents all 73 complete spectra that were measured at publicly accessible locations. The indexing system used for the figures reflects that of the original (restricted – commercial) contract reports.

The sites were selected on the basis of interest in one or more particular base stations in their immediate vicinity. The transmit frequencies of these were provided by the operators so they could be identified and are denoted by '×' in the graphs. Signals from other sources are denoted by '•'.

The distances quoted to the antennas are direct projected distances ignoring the presence of any intervening structures, eg walls.

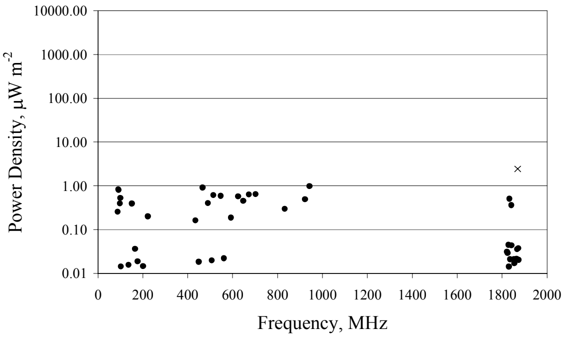
Signal strength is indicated in terms of the power density, quantified in the unit microwatt per square metre ($\mu W\ m^{-2}$). When considering the graphs it should be borne in mind that the ICNIRP reference level for exposure of the general public is never less than $2\ W\ m^{-2}$ over the entire frequency range considered in the graphs.

**Site A Multistorey block of flats with four GSM1800 sector antennas (one sector absent) mounted around the edges of the roof, 50 m above ground level**

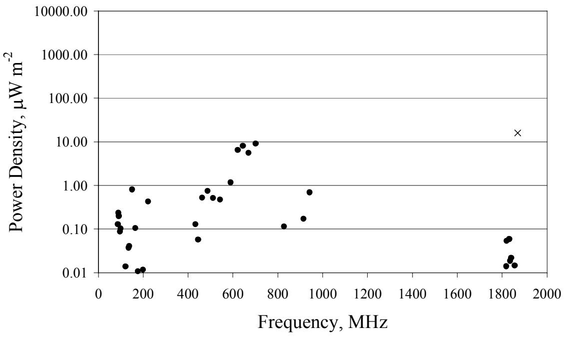



**A6A(2) Top floor flat near windows directly beneath the antennas**

**Site B Two storey school building with six GSM1800 sector antennas mounted on the corners of the structure at a height of 9 m above the ground and just above the windows of rooms on the top floor**

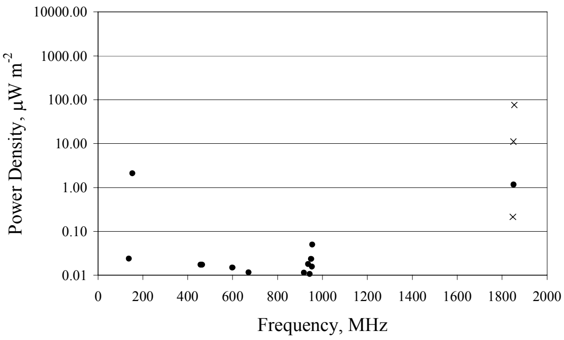



**B5 Centre of first floor classroom beneath an antenna mounted at roof level immediately above the windows**

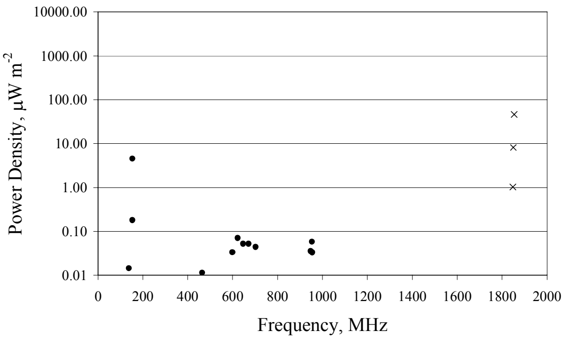



**B7 Playground 30 m from school building beneath antennas mounted at roof level**

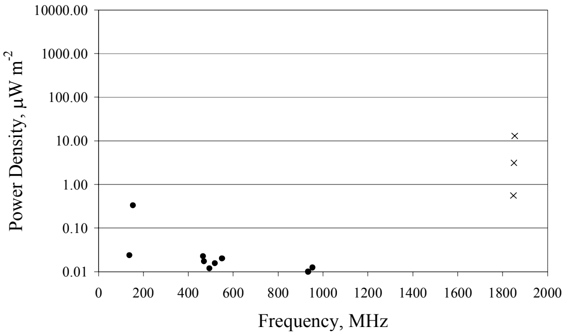
**Site D Residential area around a square-section brick-built tower of 4 m diameter and 18 m height supporting a stub mast on its roof with six GSM1800 sector antennas at a height of 22 m**



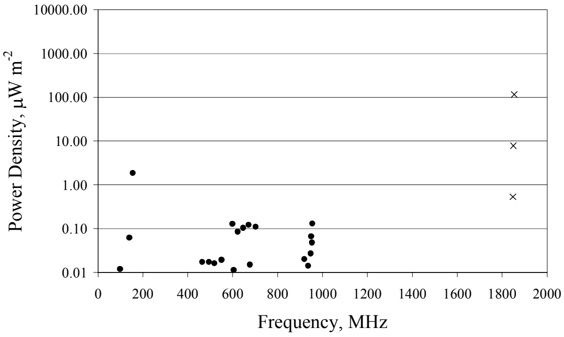

**D5 Garden 80 m from tower a clear view of the antennas**



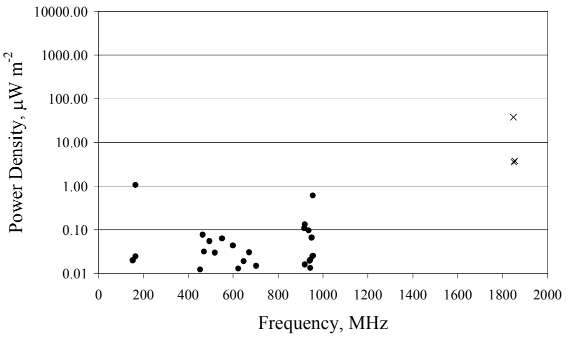

**D6 Near windows of first floor bedroom facing tower at a distance of 80 m**



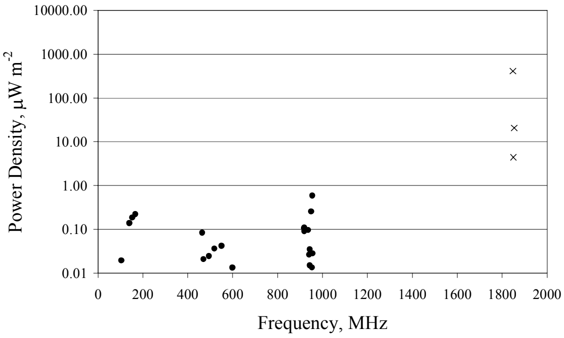

**D7 Sunken garden at a distance of 70 m from tower with a clear view of the antennas**



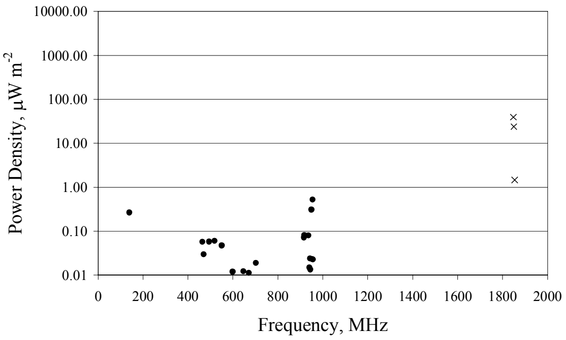

**D8 Near windows of first floor bedroom facing tower at a distance of 70 m**



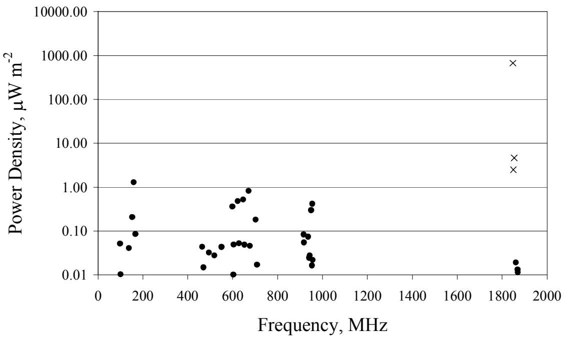

**D9 Patio at a distance of 33 m from tower with a clear view of the antennas**




**D10 Near windows of first floor bedroom facing tower at a distance of 33 m**

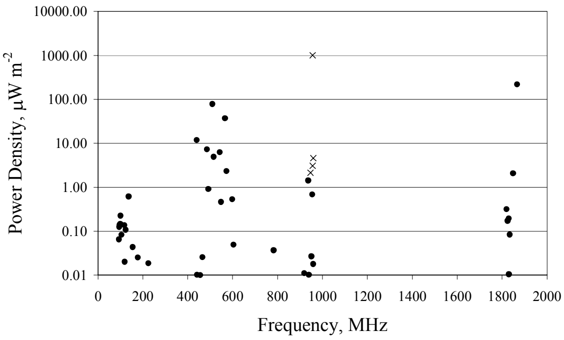



**D11 Garden at a distance of 32 m from tower with a clear view of the antennas**

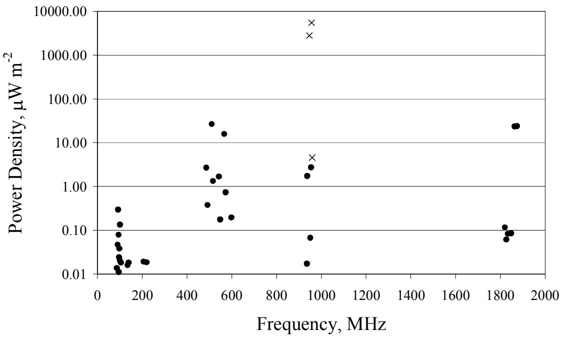



**D12 Near skylight in loft facing tower at a distance of 32 m**

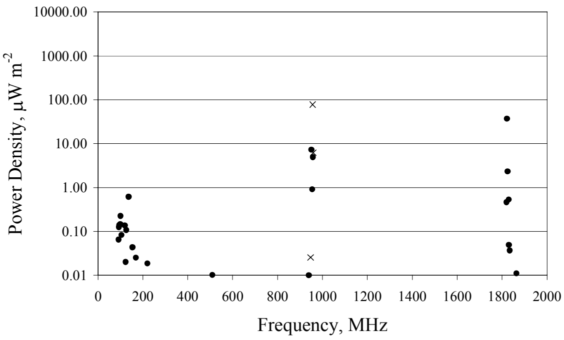
**Site E Two storey school building with three GSM 900 dual-polar antennas mounted 15 m above the ground at the top of a stub mast on the roof of the main building**




**E1 Playground 80 m from and with a clear view of the antennas**

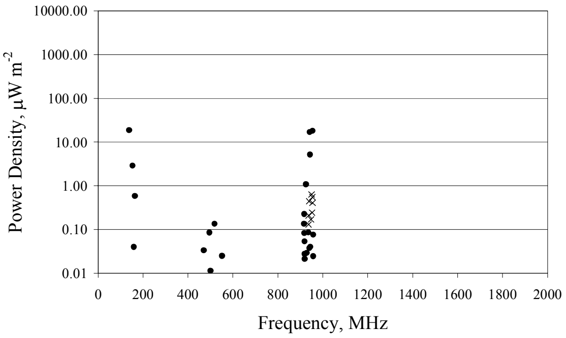



**E2 Playing field 60 m from and with a clear view of the antennas**



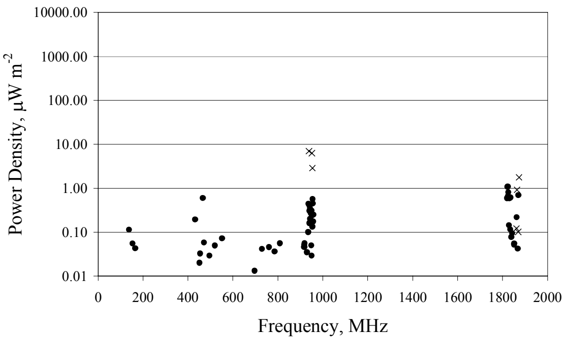

**E3 Playing field 40 m from and with a clear view of the antennas**

**Site F Multistorey block of flats with twelve GSM900 sector antennas mounted above the roof of the building at the top of a 5 m stub mast, 35 m above ground level**

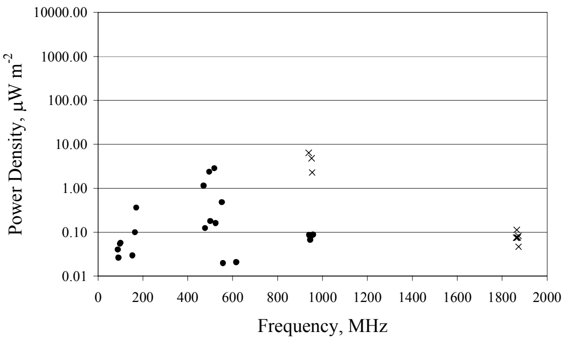



**F4 Top storey landing directly beneath the stub mast**

**Site G Eighteen storey block of flats with a GSM900 omni-directional antenna and six GSM1800 sector antennas mounted 55 m above ground level around the edges of the plant room on the roof of the building**

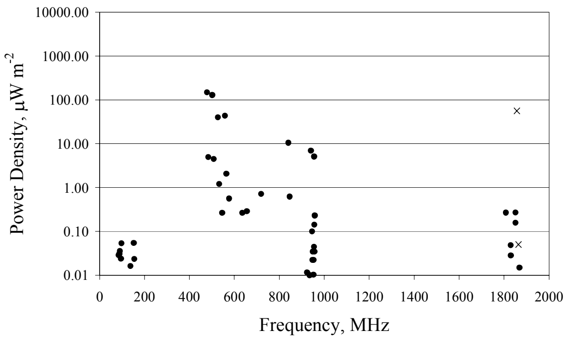



**G3 Top storey corridor directly beneath the plant room**

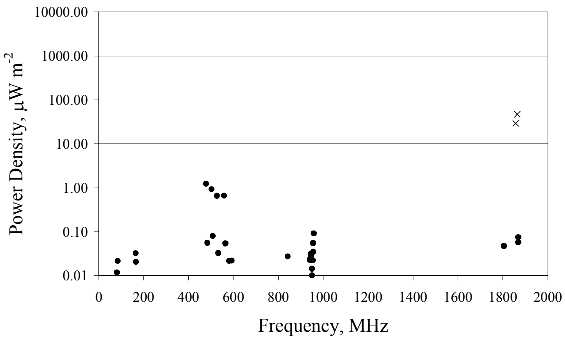



**G4 Top storey landing directly beneath the plant room**

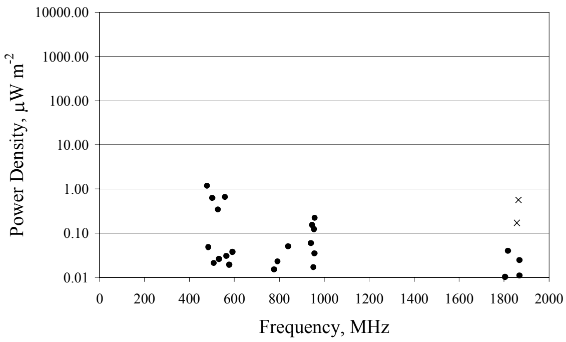
**Site H Four storey school building with four GSM1800 sector antennas (one sector not covered) mounted 20 m above ground level at the top of a stub mast on the roof**



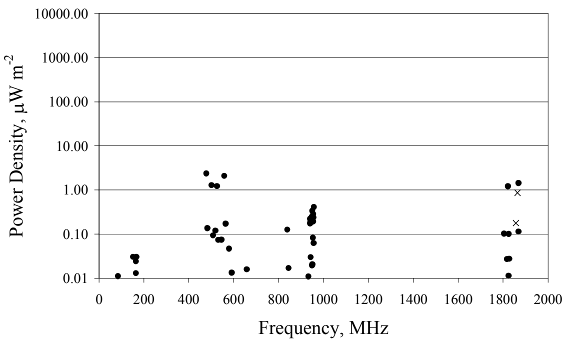

**H1 Footpath 110 m from the stub mast with a clear view of the antennas**



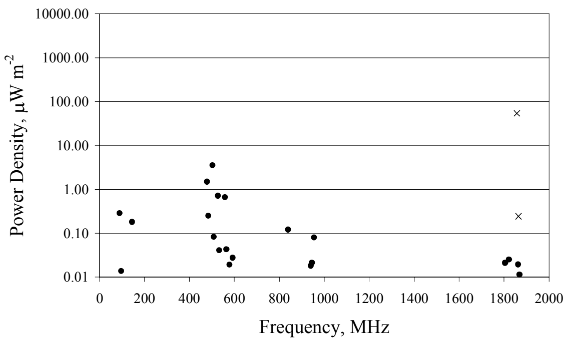

**H2 Playground 55 m from the stub tower with a clear view of the antennas**



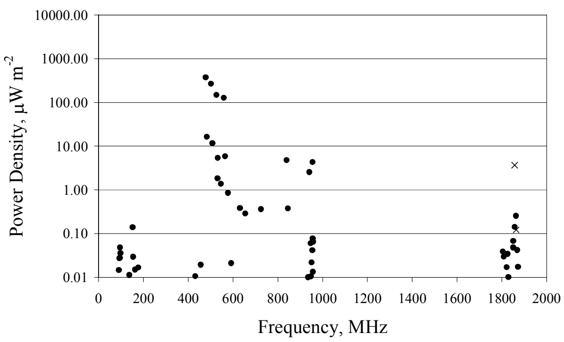

**H3 Top storey classroom directly beneath (7 m below) the stub mast**



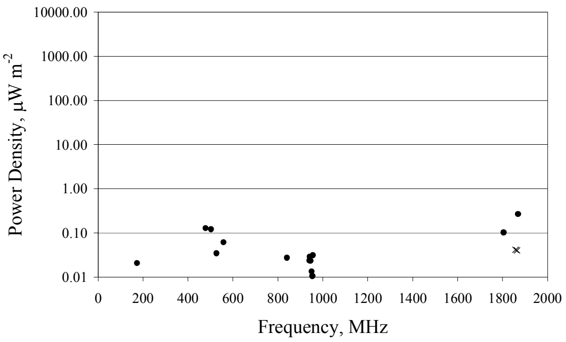

**H4 Top storey classroom in the building beneath the stub mast, 7 m below and 35 m horizontally offset from the antennas**




**H5 First floor classroom in another building 110 m from the antennas and with a clear view of the antennas through its windows**

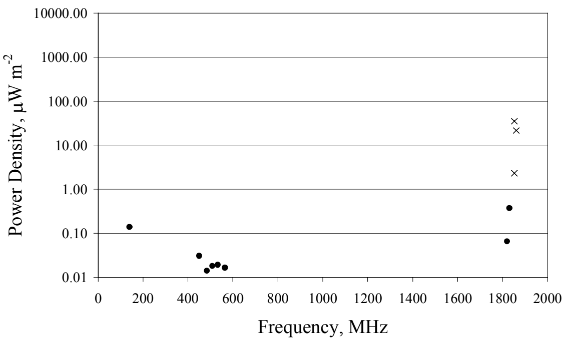



**H6 First floor classroom in the building on which the antennas were mounted, 55 m from the antennas**

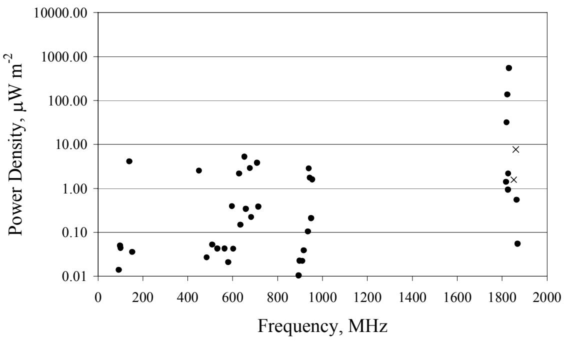



**H7 First floor classroom in the building on which the antennas were mounted, 60 m from the antennas**

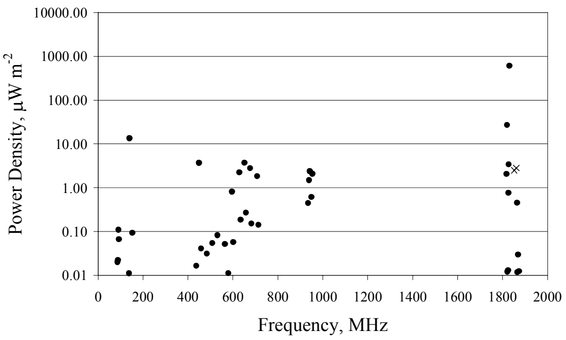
**Site J Four storey school building with six GSM1800 sector antennas mounted 15 m above the ground at the top of a 5 m stub mast on the roof of the building**



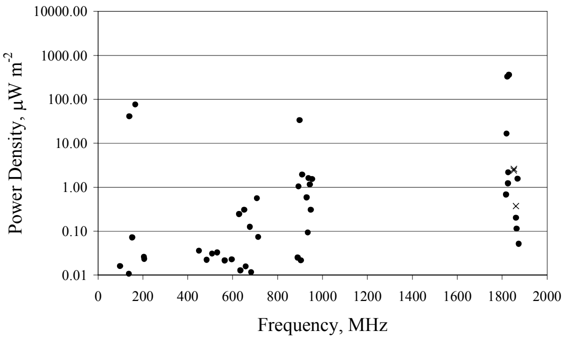

**J1 Ground floor foyer 30 m from the antennas**



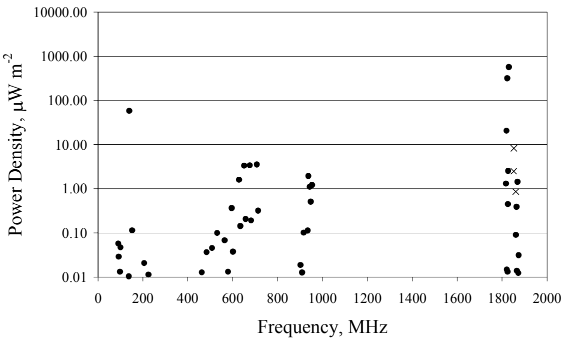

**J2A At the centre of a top storey classroom 9 m from the antennas**



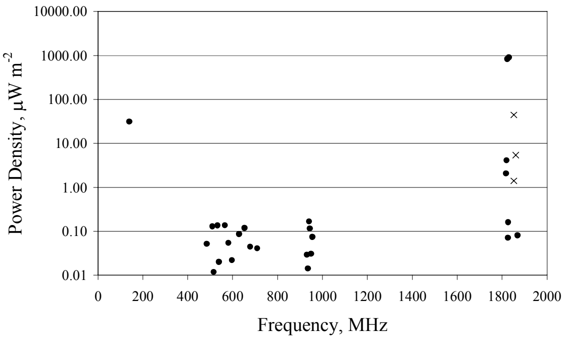

**J2B Near the windows in the same top storey classroom as J2A, 9 m from the antennas**



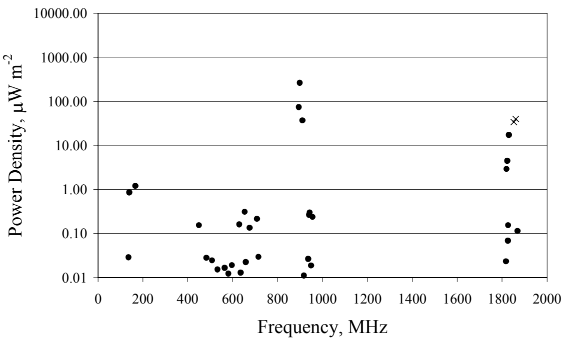

**J4A At the centre of a top storey classroom 14 m from the antennas**



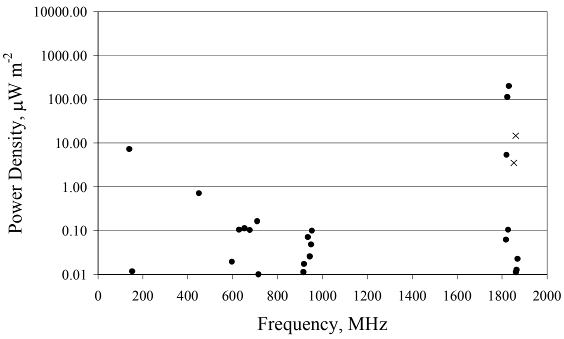

**J4B Near the windows of the same top storey classroom as J4A, 14 m from the antennas**



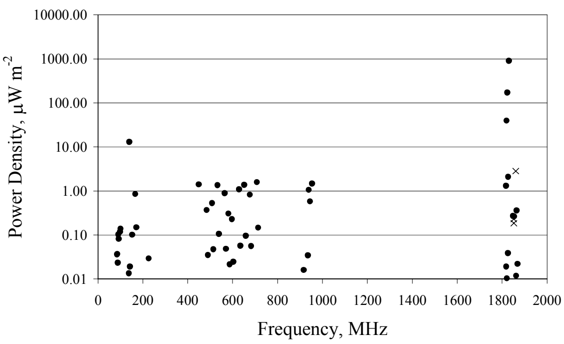

**J5 Playing field with a clear view of the antennas at a distance of 160 m**




**J6 Playing field in a different sector to J5 at a distance of 180 m with a clear view of the antennas**

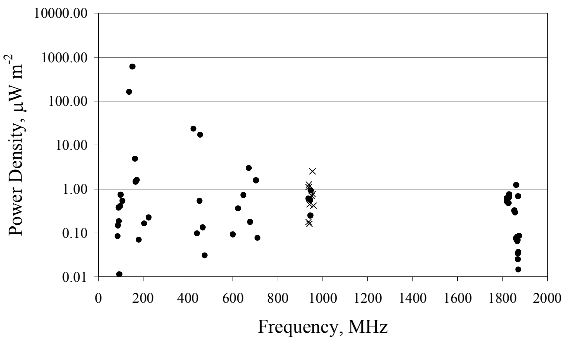



**J7 First floor common room with a clear view through its windows of the antennas at a distance of 90 m**

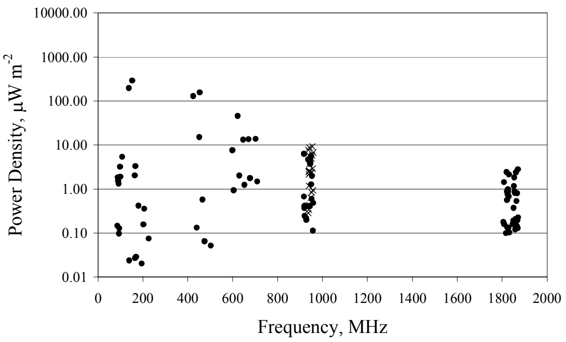



**J8 Near the windows in a top storey classroom 20 m from the antennas on the stub mast**

**Site L Eight storey building with multiple TACS, GSM900 and GSM1800 antennas mounted several metres above the roof and approximately 35 m above ground level. The frequencies of the TACS and GSM1800 carriers were not known at this site**

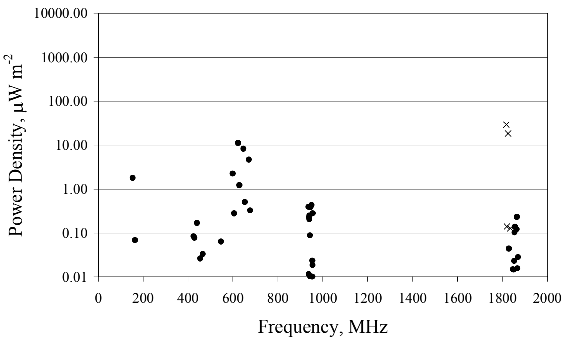



**L2 Corridor on the top storey of the building approximately 8 m from the antennas**



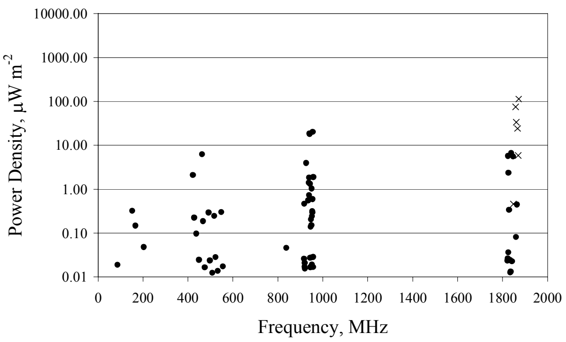

**L3 Room on the top storey of the building approximately 10 m from the antennas**

**Site M Concrete tower of height of 30 m with six GSM1800 sector antennas mounted at the top of a 5 m stub mast above its roof**

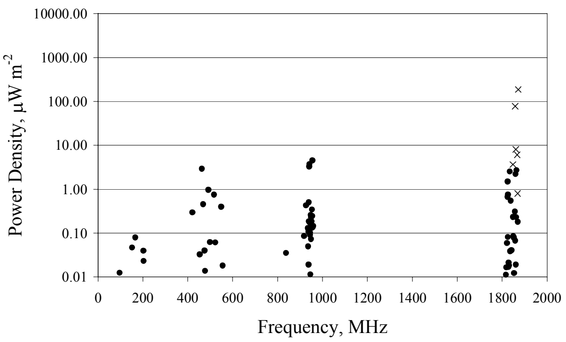



**M4 Ground level at a distance of 230 m and with a clear view of the antennas**

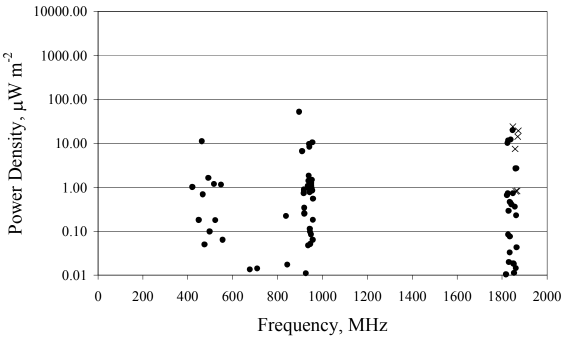
**Site N Three storey school building with three GSM1800 dual polar sector antennas mounted 17 m above the ground at the top of a 6 m stub mast on the school roof**



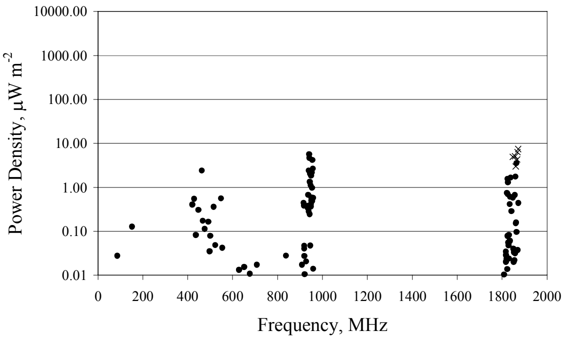

**N1 Car park at a distance of 40 m from the antennas**



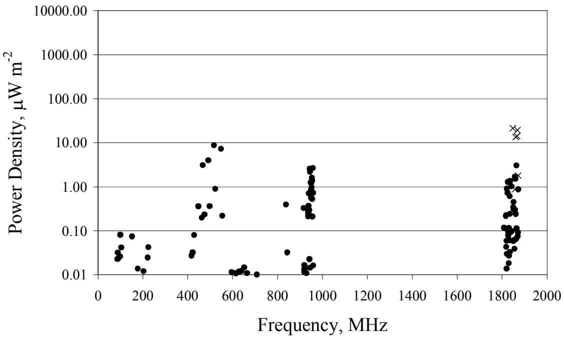

**N2 Playing field at a distance of 140 m and with a clear view of the antennas**



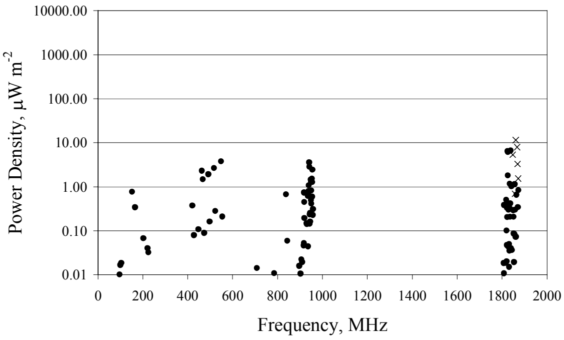

**N3 Playing field in a different sector to N2 at a distance of 140 m with a clear view of the antennas**



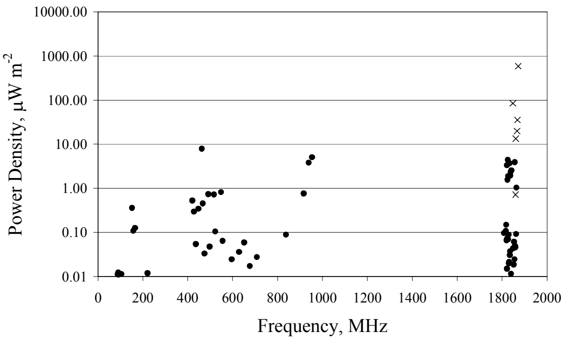

**N5 Top storey classroom directly beneath the stub mast**




**N6 Top storey classroom approximately 13 m from the antennas**

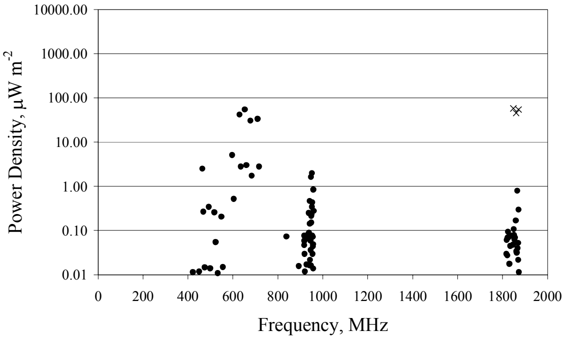



**N7 Top storey classroom 20 m from the antennas**

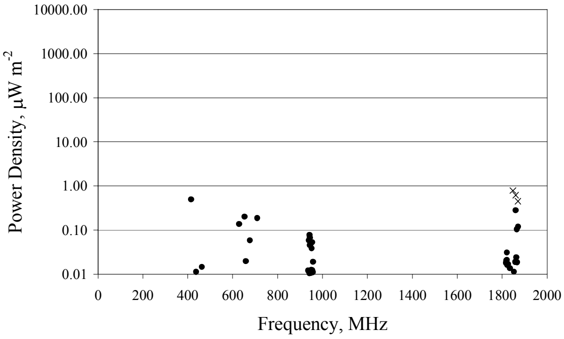



**N8 Classroom with a clear view through its windows of the antennas on the stub mast at a distance of 20 m**

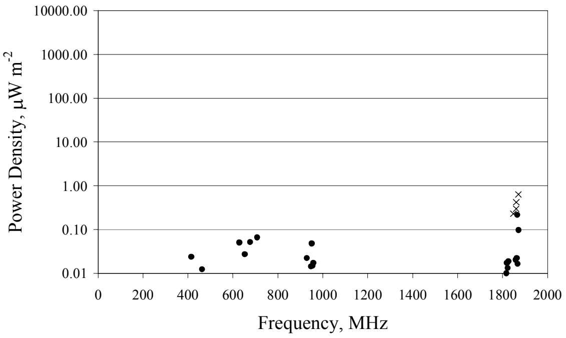
**Site O Two storey school building with six GSM1800 sector antennas mounted 17 m above ground level and 3 m above the roof**



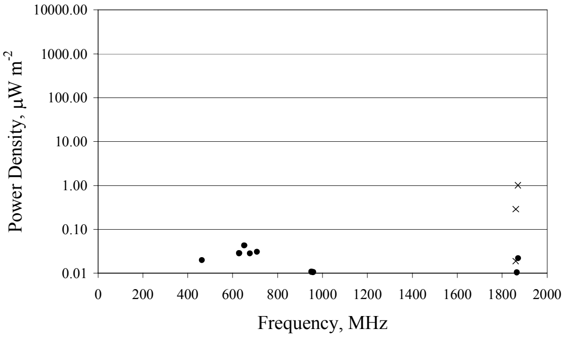

**O1 Playing field with a clear view of the antennas at a distance of 150 m**



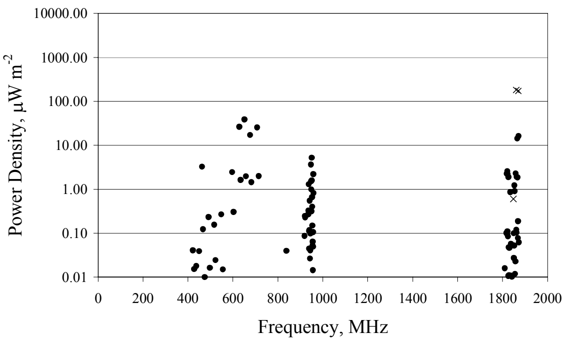

**O2 Ground floor room in the building on which the antennas are mounted at a distance of 20 m**



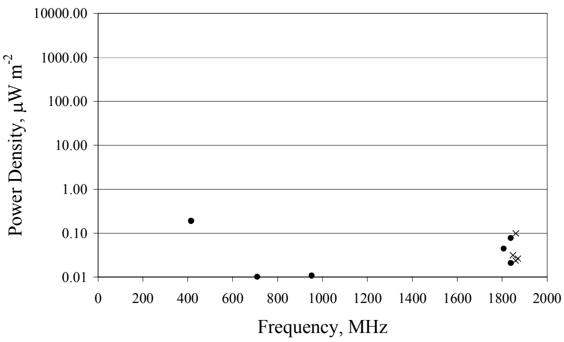

**O3 Ground floor room in the building on which the antennas are mounted at a distance of 20 m**



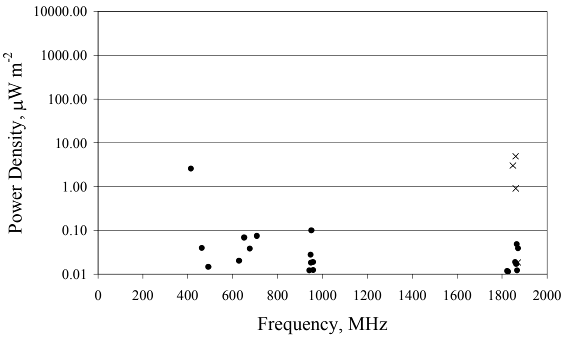

**O4 Ground floor room in an adjoining building at a distance of 20 m**



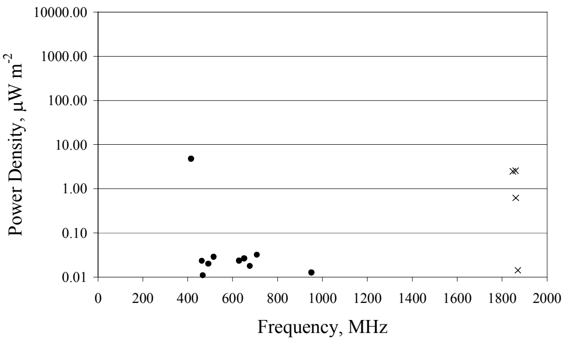

**O5 Car park at a distance of 50 m from the antennas**



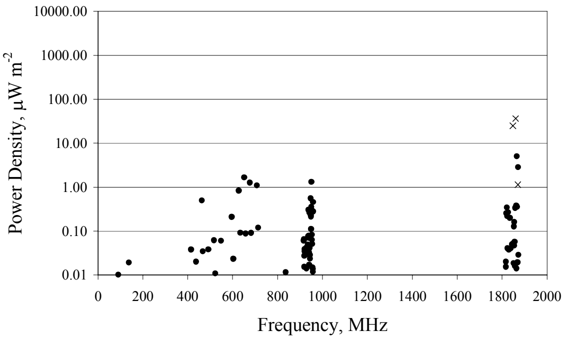

**O6 First floor room in an adjoining building at a distance of 15 m from the antennas**



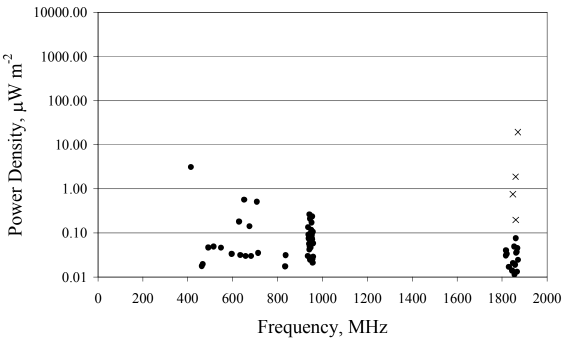

**O7 First floor room in an adjoining building 16 m from the antennas**




**O8 First floor room in an adjoining building 20 m from the antennas**

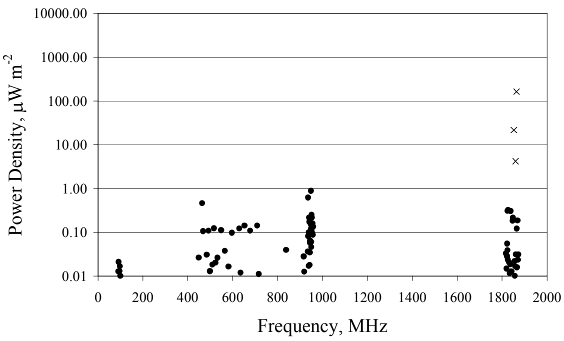



**O9 Second floor classroom in a neighbouring building with a clear view of the antennas at a distance of 40 m through the windows**

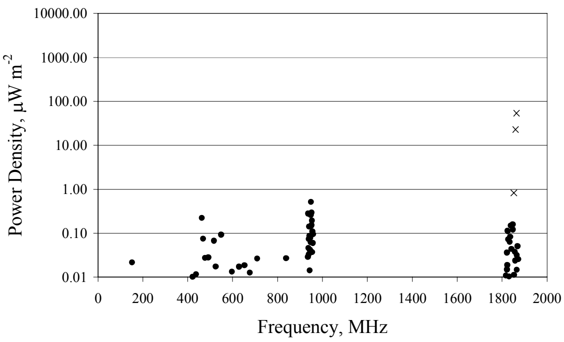



**O10 Second floor classroom in a different neighbouring building to O9, also with a clear view through its windows of the antennas at a distance of 40 m**

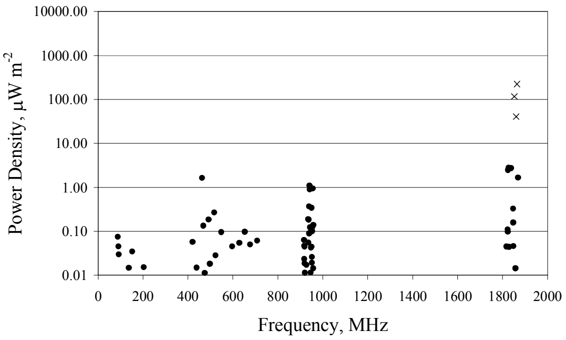
## Site P School with three dual polar GSM1800 sector antennas mounted 13 m above ground level at the top of a 6 m stub mast on the roof of the school hall



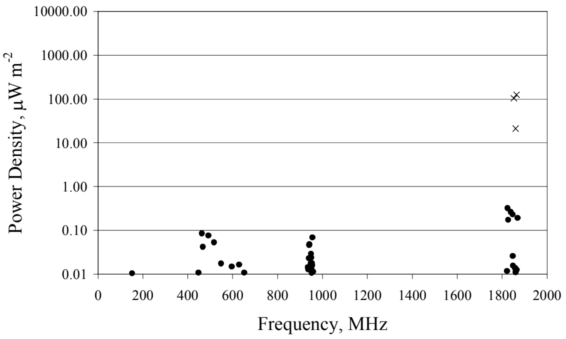

**P1 Playground at a distance of 50 m from the antennas**



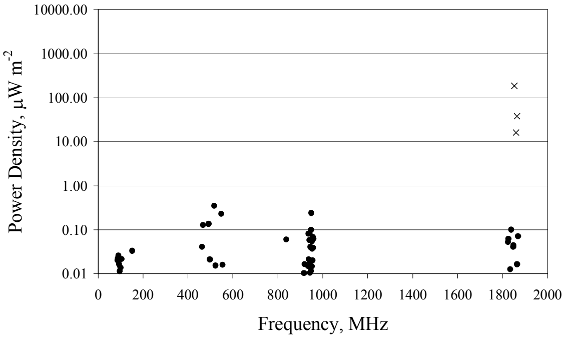

**P2 Playing field at a distance of 70 m from the antennas**



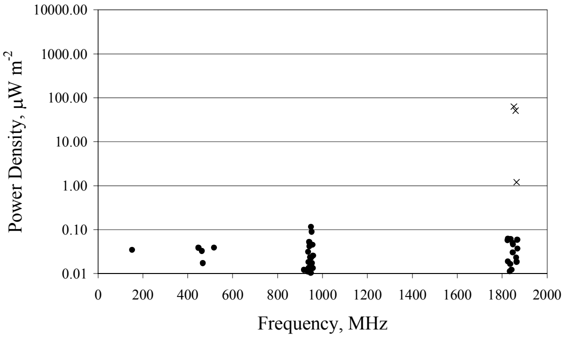

**P3 School hall directly beneath the stub mast**



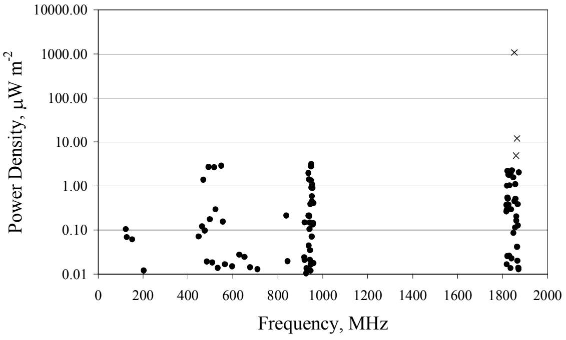

**P4 Ground floor classroom with a clear view of the antennas at a distance of 30 m through its windows**



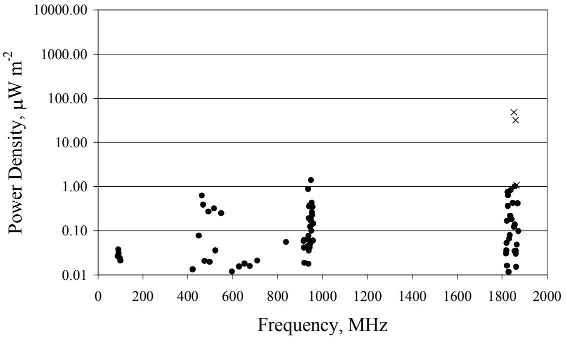

**P5 Ground floor corridor with a clear view of the antennas at a distance of 30 m through its windows**




**P6 Ground floor classroom approximately 16 m from the antennas**

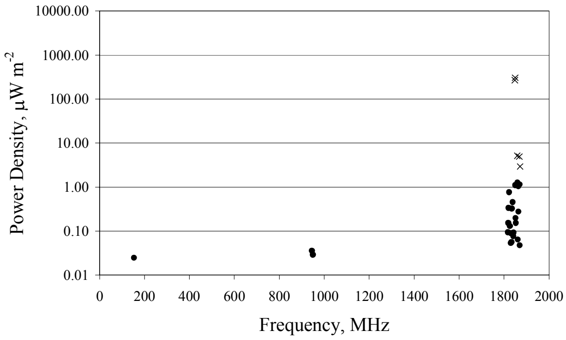



**P7 First floor corridor with a clear view of the antennas at a distance of 60 m through its windows**

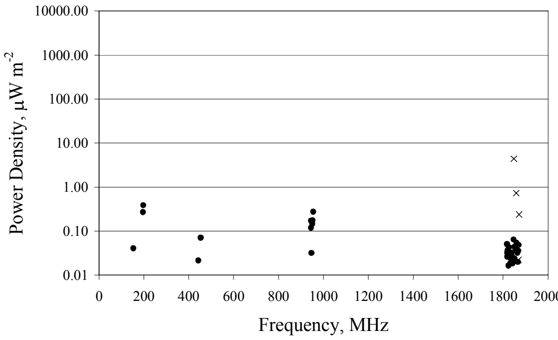



**P8 Playground at a distance of 90 m from the antennas**

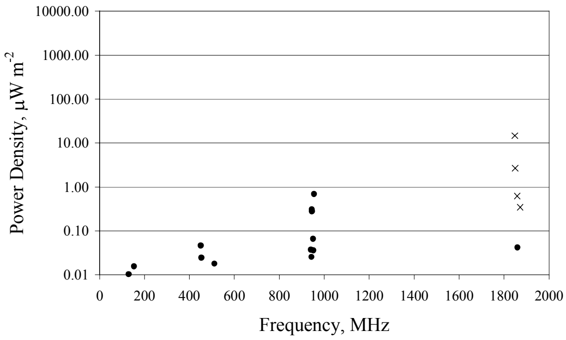
**Site Q Four storey residential block with three dual polar GSM1800 sector antennas mounted 18 m above ground level at the top of a 4 m stub mast on the roof**



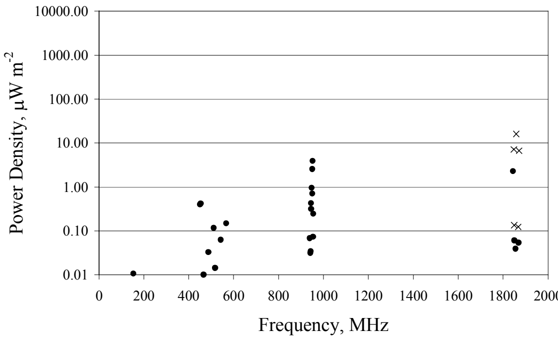

**Q4 Outside a residence at ground level with a clear view of the antennas at a distance of 90 m**



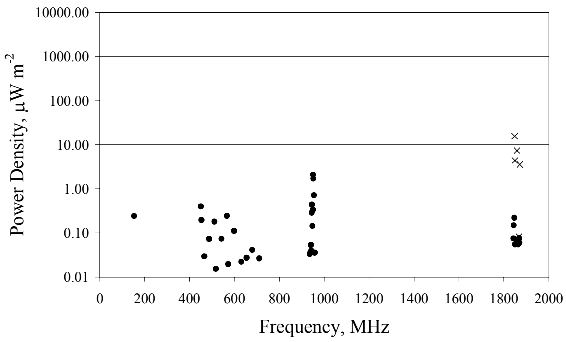

**Q5 Ground floor residence at a distance of 90 m from the antennas**



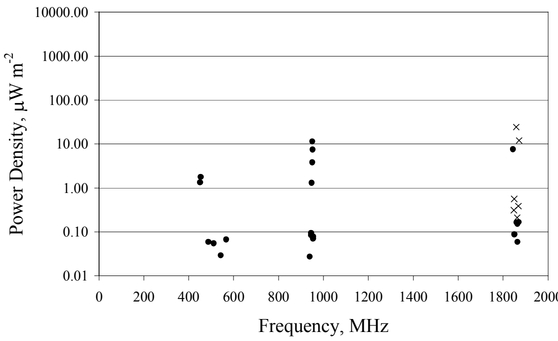

**Q6 Ground floor residence at a distance of 70 m from the antennas**



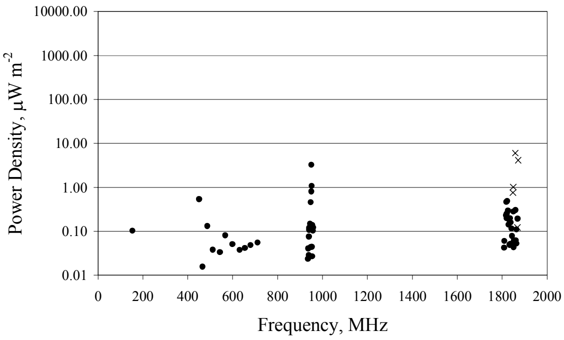

**Q7 First floor residence at a distance of 30 m from the antennas**



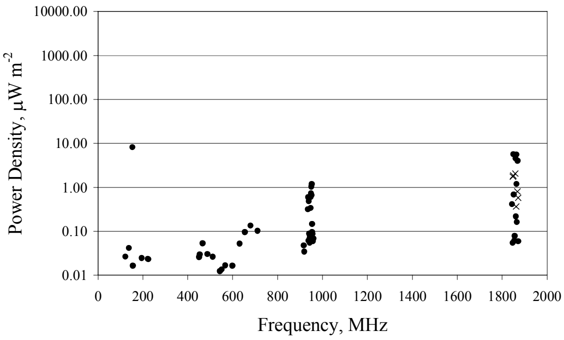

**Q8 Second floor residence at a distance of 80 m from the antennas**




**Q9 First floor residence approximately 16 m from the antennas**

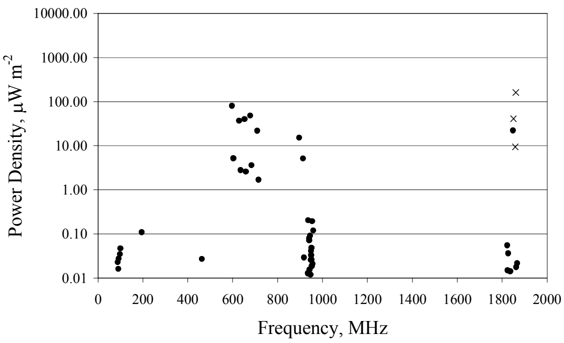



**Q10 Second floor residence approximately 16 m from the antennas on the stub mast**

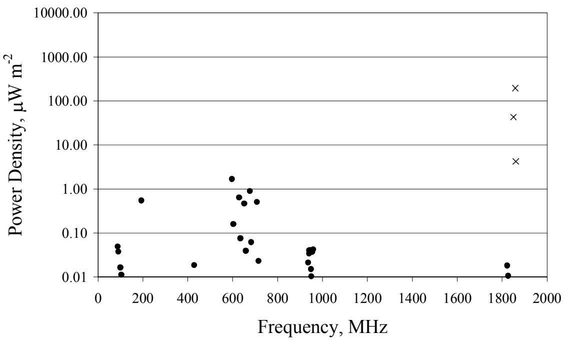



**Q11 Third floor residence approximately 9 m from the antennas on the stub mast**

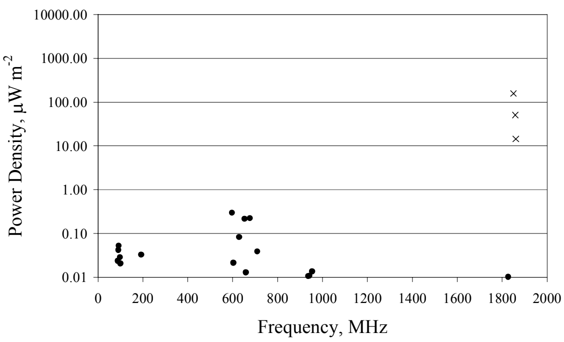
## Site R School building near three dual polar GSM1800 sector antennas mounted on a 15 m free-standing mast



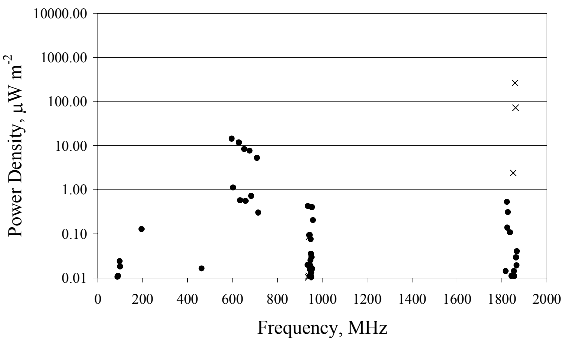

**R1 Playground with a clear view of the antennas at a distance of 60 m**




**R2 Playing field with a clear view of the antennas at a distance of 50 m**




**R3 School hall at a distance of 30 m from the antennas**




**R4 Classroom with a clear view of the antennas at a distance of 30 m through its windows**