Personal Dosimetry of RF Radiation

Laboratory and Volunteer Trials of an RF Personal Exposure Meter

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ABSTRACT

This report describes laboratory testing and volunteer trials that were carried out to evaluate a personal exposure meter (PEM) that has been developed to measure exposure of the general public to radiofrequency (RF) radiation, as from telecommunications base stations, broadcast transmitters, and from personal use of mobile phones. The PEM is designed to measure the electric field strengths of radio signals in several different frequency bands where there are known to be transmitters that contribute significantly to public exposure.

The laboratory tests showed the PEM had performance broadly in line with that required for its intended purpose, however there were several issues requiring further attention. These include that the PEM does not sum together properly the fields of multiple signals in the same band and that there appears to be a battery charging reliability problem.

The PEM has a 50 mV m⁻¹ detection threshold in its bands and data from the volunteer trials suggest that this may limit the ability to construct an exposure gradient over the range of likely public exposures within a study. Nevertheless, the PEM does seem able to discriminate the relatively high exposures of people who live near to mobile phone base station and television broadcast transmitters from those of people living elsewhere.

Currently, it cannot measure signals from TETRA base stations, wireless computer networks (WLANs) and digital cordless phones (DECT), but these capabilities could be added.

Recommendations have been made that should improve the usefulness of the PEM for validating exposure modelling techniques and as a monitor to assess RF exposure.

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1 INTRODUCTION

1.1 Background

There are considerable challenges in assessing the exposure of individuals in the general population to radiofrequency signals. These include the number and range of sources involved, not least the personal use of mobile phones, and the effect of the environment on ambient signal strengths as people move around.

Some people believe that mobile phone base stations, or other radio transmitters near to them, have affected their health due to the radio waves that are emitted. It is important to respond to such concerns scientifically, but little information is available on personal exposures to radio waves and how they might vary with factors such as distance of residence from a base station.

Exposure data for radio waves are generally reported in the form of spot measurements, i.e. measurements made (effectively) at a point in time and space when/where a person may be present. The measurements are generally of the electric field strengths and plane-wave equivalent power densities (Mann et al, 2000; Cooper et al, 2004). Sometimes the data are processed to develop exposure quotients in relation to guidelines, such as those from the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998).

Many of the available spot measurement data have concentrated on signals from base stations but have not included contributions to exposure from sources operating in other parts of the spectrum (e.g. Bergqvist et al, 2001; Ofcom, 2005). There are some published wide-spectrum data and these suggest that exposure can be constructed by concentrating on parts of the spectrum where there are certain sources that are either powerful, widespread or used near to the body (Mann et al, 2000).

If a personal exposure meter (PEM) could be developed and used to reliably characterise RF exposures of people, this might offer a way forward for scientifically robust research into the health of people living near to base stations. Such an instrument could be used to assess directly the exposure of subjects in a study or as a tool for the validation of modelling approaches.

1.2 Aims and objectives

This project aims to evaluate a newly developed and commercially available personal exposure meter, the Antennessa DSP090 (Antennessa, 2005), that is designed to be carried by people, sometimes mounted on their body, and to record their exposures to radiofrequency signals over time. The project comprises laboratory investigations and a volunteer trial to assess

- a the technical performance of the instrument, and
- b the practical aspects of its use in studies.

The project is supported by the UK's Mobile Telecommunications and Health Research Programme (MTHR, 2005) and its results should assist the appropriate use of the PEM by researchers and the future development of the PEM by its manufacturer.

1.3 Report structure

Section 2 of this report describes the study protocol, the instrumentation, and the analysis techniques that were used in this project. Detailed results from the laboratory investigations of the PEM performance are described in Section 3. Section 4 describes spot measurements made with a precision measurement system at locations where the volunteers spent a significant proportion of their time with the PEM. The logged data obtained from the volunteer trial are analysed in Section 5, and feedback from the volunteers on their experiences and perceptions of the PEM are summarised in Section 6. The overall results from the project are discussed and conclusions are drawn in Section 7.

2 MATERIALS AND METHODS

This section first describes the protocols used to gather and process data in this study. The project used a newly developed RF personal exposure meter (PEM), whose operation is detailed. The PEM records the electric field strength present in several different frequency bands at regular intervals so it can be downloaded at a later time. Spot measurements of electric field strength were made with an antenna on a tripod connected to a spectrum analyser at positions where the PEM was used and this system is described. Finally, a questionnaire that was used to gather feedback from the volunteers who used the PEM in the trials is outlined.

2.1 Overall study protocol

The study comprised an initial series of laboratory investigations to characterise the functionality and electrical properties of the PEM, followed by a volunteer trial to investigate the practical aspects of its use. As the volunteer trial progressed, further laboratory investigations were carried out to examine matters that arose.

2.1.1 Laboratory testing

Eight PEMs were supplied to the study and the initial laboratory testing of these instruments was carried out in the final quarter of 2004. Functionality tests examined the performance of the PEM software as well as the hardware, and suggestions for improvement were made to the manufacturer, leading to revised issues of the software during the course of this project.

Tests of electrical performance examined parameters such as filter selectivity, response to modulated and unmodulated signals, linearity and isotropy. Tests were also carried out to examine the instrument performance in multi-signal RF environments and to determine immunity from commonly encountered electromagnetic fields in other bands, including 50 Hz electric and magnetic fields, and domestic TV and PC monitor fields. The details of the laboratory testing and its results are presented in Section 3.

2.1.2 Volunteer trial

Ten volunteers took part in the trial and each carried a PEM with them for a period of one week. The first volunteer acted as a pilot for the procedures and received a PEM in December 2004. The main trial involving the remainder of the volunteers then took place in the latter half of January and early February 2005. The protocol used for the volunteer trial is given in Appendix A and the results are presented in sections 4 to 5.

2.1.2.1 Personal measurements

The personal measurements and results obtained from the volunteers using the PEMs are described in Section 5. A recording interval of 2 minutes was used, as this could be sustained for a week on a single full charge of the PEM batteries. The volunteers kept a diary while they used the PEMs and this indicated where they were at a given time. The diary was used to aid interpretation of the logged electric field strengths.

2.1.2.2 Narrowband spot measurements

In advance of receiving the PEM, the volunteers were asked to list locations where they expected to spend most of their time over the trial week. Typically, these locations included their office at work, and their kitchen, bedroom and living room at home. Spot measurements were made at these locations on the day of deployment and on the day of collection of the PEM. The measurements and results are described in Section 4.

The spot measurements were of signal electric field strengths over the RF spectrum from 80 MHz to 2.5 GHz and they were processed to derive the total field in each of the frequency bands of the PEM (see Table 1). The equipment used for the narrowband spot measurements is described in Section 2.4.

The data on deployment and collection of the PEM were compared to determine the repeatability of the narrowband spot measurement procedure (as in Appendix D) and to identify any significant changes in the RF exposure environment. The data on deployment were also analysed to determine whether the signals present in the PEM frequency bands were of sufficient strength to be logged and whether there were any signals present in bands not covered by the PEM.

2.1.2.3 PEM spot measurements

The narrowband spot measurements, both on deployment and collection of each PEM, were compared with the readings from a second PEM placed at the same position. This was to determine the degree of correlation between the PEM readings and precision measurements under realistic exposure conditions, rather than in a laboratory.

2.1.2.4 Spot measurements and personal exposures

The narrowband spot measurements made on deployment were compared with the PEM personal exposure readings when the diary showed the volunteer to be at the location in question. This showed how well the spot measurements could be used to approximate personal exposures at the same location.

2.1.2.5 Feedback questionnaire

The volunteers completed a questionnaire reporting on their experiences and perceptions of the PEM at the end of their week-long trial. The questionnaire was divided into four sections, the first of which considered how much of the time the PEM had been worn and where it had been placed when it was not worn. The second section asked for views on the design aspects of the instrument and the practicality of wearing it in various situations. The volunteers were asked to suggest any improvements for the design of the PEM and whether they felt using it had modified their behaviour in any way. The third section asked about experiences, such as whether the volunteers had felt self-conscious with the instrument or whether it had attracted any attentions/comment from others. Finally, the volunteers were asked how long they would be prepared to use the instrument if asked to do so again, both with and without keeping a diary. Similarly, they were asked how long they felt it would be reasonable to ask a member of the public to use the PEM. The questionnaire is in Appendix G and the information gathered using it is summarised in Section 5.

2.2 Personal exposure meter

2.2.1 Physical characteristics

The external appearance of the PEM is as shown in Figure 1. It has the approximate dimensions of $19.5 \times 9.5 \times 7.5$ cm and weighs 0.45 kg. The belt clip can be seen on the rear, and generally the instrument would be worn hanging from the belt.



Figure 1 Front and rear views of the Antennessa DSP090 personal exposure meter

During the volunteer trials, the instrument was worn and carried on the person in various ways, or placed in their vicinity, and this is discussed in Section 5.

2.2.2 Frequency bands

The PEM is designed to measure the electric field strength in nine different frequency bands, as shown in Table 1, and it has three orthogonal sensors in order to provide an isotropic response.

Band name	Active sources in the UK	Range MHz
FM	VHF broadcast radio	88–108
TV3	Digital audio broadcasting	174–223
TV4&5	UHF broadcast television	470–830
GSMtx	GSM mobile phones (900 MHz)	890–915
GSMrx	GSM base stations (900 MHz)	935–960
DCStx	GSM mobile phones (1800MHz)	1710–1785
DCSrx	GSM base stations (1800 MHz)	1805–1880
UMTStx	3G mobile phones	1920–1980
UMTSrx	3G base stations	2110–2170

Table 1 Specified PEM measurement frequency bands

Note, tx and rx are abbreviations for the transmitted and received radio signals from the point of view of a mobile phone

The first three bands cover the frequencies used for broadcast radio and television in France, however the TV3 band is not used for television in the UK. The TV3 band is used for a variety of other applications in the UK including digital audio broadcasting (DAB) in the range 217–230 MHz. The FM and TV4&5 bands have the same applications in the UK as France, although the UK TV band extends somewhat higher in frequency, to 854 MHz. The other bands seem broadly as expected, although the GSM bands do not include the E-GSM portions, as used in the UK, which extend down to 880 and 925 MHz for the GSMtx and GSMrx bands respectively.

Other frequencies not covered by the PEM include those used by cordless phones, wireless networks for home/work computers and Terrestrial Trunked Radio (TETRA). Early analogue cordless phones, which are still widely used in the UK operate around 30–50 MHz and tend to transmit only when a call is made. More recent digital cordless phones are based on DECT (Digital Enhanced Cordless Telephony) and the base stations transmit in the 1880–1900 MHz band even when calls are not being made. Similarly, the transmitters in wireless-equipped computers tend to transmit even when no data are being transferred. The frequencies used are in the 2400–2500 MHz band with most wireless computer communication systems presently in use. TETRA is a cellular radio system used by the emergency services in the UK and its base stations use the 390–395 MHz band.

2.2.3 Format of logged data

The user can program the PEM to make measurements at set recording intervals and for a set total duration, within the constraints of its battery life and available memory. In addition to the field strengths in the nine bands, each record contains a measurement of the battery voltage and the temperature so that the data appear as in Figure 2, when exported to Microsoft Excel.

Sample	Date	Time	Battery (mV)	Temperature °C	FM	TV3	TV4&5	GSMtx	GSMrx	DCStx	DCSRx	UMTStx	UMTSrx
1	10/12/2004	13:02:46	4017	23.9	0,05	0,05	0,05	0,05	0,19	0,05	0,07	0,05	0,05
2	10/12/2004	13:04:46	3989	23.7	0,05	0,05	0,05	0,05	0,21	0,05	0,10	0,05	0,05
3	10/12/2004	13:06:46	4030	23.5	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
4	10/12/2004	13:08:46	4062	23.3	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
5	10/12/2004	13:10:46	4010	23.2	0,05	0,05	0,05	0,05	0,08	0,05	0,09	0,05	0,05
6	10/12/2004	13:12:46	3986	22.9	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05
7	10/12/2004	13:14:46	3999	23.0	0,05	0,05	0,05	0,19	0,06	0,05	0,05	0,05	0,05
8	10/12/2004	13:16:46	4008	23.0	0,05	0,05	0,05	0,05	0,06	0,05	0,05	0,05	0,05
9	10/12/2004	13:18:46	3992	22.9	0,05	0,05	0,05	0,05	0,07	0,05	0,05	0,05	0,05
10	10/12/2004	13.20.46	4014	22.0	0.05	0.05	0.05	0.05	0.08	0.05	0.05	0.05	0.05

Figure 2 Example of logged data from the PEM

2.2.4 Recorded field strengths

The exact physical meaning of the field strengths recorded by the PEM depends on its detailed internal design. The manufacturer supplied a diagram showing the internal functional arrangement and this is shown as Figure 3. This shows that the PEM contains filters, switches and amplifiers, which separate the signals from its sensing antennas into the different bands and then pass them to detectors.



Figure 3 Arrangement of the RF functions within the PEM

The PEM has to measure from the three sensing antennas and in the nine bands, so a total of 27 measurements must be performed during each recording interval. The order in which these measurements are performed is shown in Table 2. In order to conserve the batteries, each amplifier is only switched on for the part of the recording interval when it is needed to make a measurement.

During the periods when the amplifiers are switched on, samples are taken from the detectors every 330 μ s, so individual GSM bursts of 577 μ s duration are not missed. The maximum values from sequences of 70 samples are recorded for the GSMtx and DCStx bands and the minimum values from sequences of 20 samples are recorded for the remaining bands, other than UMTStx. For UMTStx, the average value from a sequence of 20 samples is recorded, as shown in Table 2. Hence, in addition to bandpass filtering, the PEM uses special techniques to differentiate between TDMA (pulsed) signals, as from GSM mobile phones, and continuous signals, as from GSM base stations, in order to improve its band selectivity.

	U					
Order	Frequency band	Antenna number	Processing	Number of samples	Modulation	
1	FM	3	Min	20		
2	TV3	3	Min	20		
3	TV4&5	3	Min	20		
4	FM	2	Min	20		
5	TV3	2	Min	20		
6	TV4&5	2	Min	20		
7	FM	1	Min	20		
8	TV3	1	Min	20		
9	TV4&5	1	Min	20		
10	GSMtx	3	Max	70	TDMA	
11	GSMrx	3	Min	20		
12	GSMtx	2	Max	70	TDMA	
13	GSMrx	2	Min	20		
14	GSMtx	1	Max	70	TDMA	
15	GSMrx	1	Min	20		
16	DCStx	3	Max	70	TDMA	
17	DCStx	2	Max	70	TDMA	
18	DCStx	1	Max	70	TDMA	
19	DCSrx	3	Min	20		
20	DCSrx	2	Min	20		
21	DCSrx	1	Min	20		
22	UMTStx	3	Average	20		
23	UMTSrx	3	Min	20		
24	UMTStx	2	Average	20		
25	UMTSrx	2	Min	20		
26	UMTStx	1	Average	20		
27	UMTSrx	1	Min	20		

Table 2 Order and configuration of the measurements made by the PEM

2.3 Imputation of missing data

In many cases where the PEM was used to log electric field strength over a period of time, the resulting data sets showed the field strength was below the detection threshold of 50 mV m^{-1} for an appreciable proportion of the time. In such cases it is possible to develop numerical approaches to impute the most likely value of the mean field strength and to develop an associated uncertainty estimate.

The approach applied in this project was the same as that of Cooper et al (2004) with occupationally acquired personal exposure records. The Uncensor 4 program, as available on the Internet from the Virginia Institute of Marine Science, was used to implement Helsel's Robust Method. This program fits a lognormal distribution to those data values that are above a detection threshold and then generates data values at random according to the fitted distribution to replace the "censored" values below the detection threshold. Once all of the censored values have been replaced, the arithmetic mean of all the data is evaluated.

Uncensor 4 can process a maximum of 1000 data values. Consequently, data sets from the PEM of greater than this size were sampled randomly to produce sets with exactly 1000 entries. Also, the floating point format of Uncensor 4 was fixed in the program and so the field values (in V m⁻¹) were converted to mV m⁻¹ in order to improve the precision of the program output.

2.4 Narrowband spot measurements

The equipment used to make precision spot measurements comprised an ARCS Siebersdorf Miniature Biconical dipole antenna mounted on a wooden tripod and connected to an Agilent E4407 spectrum analyser. The protocol under which this equipment was used is in Appendix D and the results are in Section 4.

The antenna was inclined at an angle of 35.3° to the horizontal plane and its base plate allowed it to be rotated in steps of 120°. Thus three orthogonal polarisations could be measured in turn by rotating the antenna. These measurements were summed to obtain the resultant field strength.

The measurements were also made at three heights (1.1, 1.5 and 1.7 m) above floor level over which the field strength was averaged to reduce the effect of spatial fading. The use of appropriate dwell times and an average detector mode on the spectrum analyser helped to reduce the effects of temporal aspects of fading.

3 LABORATORY TESTING

This section describes the laboratory testing that was carried out to determine the electrical performance of the PEM as a stand-alone instrument for the measurement of RMS electric field strength in the frequency ranges of its various bands (see Table 1).

3.1 Introduction

3.1.1 Co-ordinate system

First, it is necessary to define a co-ordinate system to describe the orientation of the instrument relative to the test field. The x, y and z-axes of the instrument are shown in Figure 4 and also correspond to the orientations of the 3 antennas within the instrument.



Figure 4 Definition of the x, y and z axes of the PEM

The corresponding X, Y and Z orientations of the PEM, (defined as where the corresponding axis of the instrument is vertical) are shown in Figure 5 as seen through

the open door of the GTEM test cell. The origin of the co-ordinate system was taken as the centre of the 3-axis sensor.



Figure 5 Orientations of the PEM inside the GTEM cell

3.1.2 Test methods

The majority of the tests were carried out in a large GTEM Cell (EMCO model 5311), as shown in Figure 6. Specially shaped foam blocks of a low dielectric constant material (Eccostock SH 2, Emerson & Cuming) were manufactured to hold the instrument so that when it was placed in the cell in either the X, Y or Z orientations, the origin of the x, y and z axes was always in the same position. This position was at a height of 30 cm above the chamber floor and 70 cm below the septum.

The GTEM exposure system allowed known fields of up to about 5 V m⁻¹ to be established at the instrument test position, at any frequency between 30 and 4200 MHz. An Agilent E4483C Vector signal generator formed the primary signal source, the output of which was amplified using a Mini-Circuits ZHL42-W wide-band amplifier. Appropriate directional couplers and a power meter or RF millivoltmeter allowed monitoring of the drive level applied to the cell. An RF change-over relay, operated via the GTEM door interlock system, effectively allowed exposures to be started or stopped by closing or opening the chamber access door.

For the majority of tests, the instrumentation was controlled by a general purpose PC running specially written control software to allow automatic input power level (and hence exposure field) control. Where more than one signal was required, Marconi 2031 and Hewlett-Packard HP4831B signal sources were also used, the outputs from the sources being combined using appropriate hybrid combiners before being fed to the amplifier. A spectrum analyser (Agilent E4407B) was used to confirm the spectral purity and composition of the signal being fed to the GTEM cell. Where modulated signals were required, the majority of these could be provided by the E4483C vector signal source, with the exception of broadcast television (both analogue and digital) and digital audio broadcasting (DAB) signals. Analogue TV signals at a low level were obtained from a commercial TV test source including the sound and colour sub-carriers. For Digital TV and Radio modulation, an effective equivalent was obtained by using 100%



amplitude modulation with random noise, and simultaneous frequency modulation, using a triangle waveform.

Figure 6 EMCO Model 5311 GTEM test cell, as used to generate known exposure fields for testing the PEM

To establish the field within the GTEM Cell at the test position, a Holaday HI-6005 3-axis electric field probe was used, with a fibre-optic output. This had a calibration traceable to national standards, with a typical uncertainty of ± 1 dB.

In general, each particular field condition — for one orientation, frequency and or field level — lasted for 1 minute, the opening and closing of the chamber door being used to control the period. By adhering to a strict time format, and using periods of no-field before and after each exposure, a series of tests could be conducted in one session. After downloading the session results, each individual exposure could then be clearly and unambiguously identified. For the majority of tests, the instrument was configured for a 5 s measurement cycle and a maximum data collection time of 120 minutes.

To gain some idea of variability between instruments, the unmodulated field tests, as described later, were conducted on each of the 8 instruments supplied; but the other tests were generally conducted on one or two instruments.

3.2 Acceptance tests

Before the main laboratory investigations started, all instruments were subjected to an acceptance test, to confirm the completeness and functioning of the supplied components. This comprised an initial visual inspection, electrical safety testing of the supplied battery charger, checking and installation of the supplied software CD and initial battery charging before a functional test. Each instrument was then configured for a 5 s measurement period, with a data collection period of 100 minutes and the internal clock was set to the current time (UTC). An initial file download operation was necessary as the instruments contained data when they were supplied. Each instrument was placed in the GTEM cell, started, and left for 5 minutes with no field applied to establish the no field response. The acquired data were then downloaded from the instrument and the results recorded. The minimum displayed field is 0.05 rather than 0.00 V m⁻¹ and was, in this test only, recorded as such. Finally, a response test was made to confirm the operation of each measurement axis. An 895.5 MHz (the centre of the GSMtx band) CW field of $2.5 \pm 0.2 \text{ V m}^{-1}$ was established in the cell at the reference position, and the instrument placed on the foam block support for a 1-minute period in the X, Y and Z orientations. The instrument data was then downloaded and the mean recorded field for each band was noted.

With the exception of one unreadable set-up file on one instrument's CD, all instruments passed their acceptance tests. However, it should be noted that the battery chargers supplied have continental style mains connectors, and an appropriate continental to UK 13A adapter will have to be provided by the user. The certificates of calibration, supplied with each instrument, appear identical to each other, with the exception of the serial number of the PEM. In particular, the performance data seem identical for each one, being merely described as typical characteristics. The equipment used for the calibration, although mentioned, is not given any calibration accreditation nor is there any mention of uncertainty.

3.3 Response to unmodulated signals

The instrument has nine response bands, as detailed in Table 1. In addition to the inband performance, it was necessary to evaluate the out-of-band performance. Consequently, a large number of test frequencies were used. In addition to three frequencies per response band (lower, mid and upper) a number of out-of-band frequencies were also selected. The test frequencies are all shown in Table 3. For operational reasons, the set of frequencies were divided into Low Band (below 1300 MHz) and High Band (1300 MHz and above).

	-	
Frequency MHz	PEM band	UK application
49		Licence free devices
75		Runway ILS
90	FM	FM Radio Broadcasting
98	FM	FM Radio Broadcasting
106	FM	FM Radio Broadcasting
125		Aircraft communication
145		Amateur radio, Paging
176	TV3	PMR
198	TV3	PMR
222	TV3	DAB radio
380		TETRA
430		Amateur Radio, Licence free devices
475	TV4&5	UHF TV Broadcasting
590	TV4&5	ATC radar
650	TV4&5	UHF TV Broadcasting
820	TV4&5	UHF TV Broadcasting
880	GSMtx	GSM900 Handset
895.5	GSMtx	GSM900 Handset
912	GSMtx	GSM900 Handset
940	GSMrx	GSM900 Base Station
947.5	GSMrx	GSM900 Base Station
955	GSMrx	GSM900 Base Station
1300		ATC Radar
1715	DCStx	GSM1800 Handset
1747.5	DCStx	GSM1800 Handset
1780	DCStx	GSM1800 Handset
1810	DCSrx	GSM1800 Base Station
1840	DCSrx	GSM1800 Base Station
1875	DCSrx	GSM1800 Base Station
1900		
1925	UMTStx	3G Handset
1950	UMTStx	3G Handset
1975	UMTStx	3G Handset
2115	UMTSrx	3G Base Station
2140	UMTSrx	3G Base Station
2165	UMTSrx	3G Base Station

Table 3 Test frequencies

The GTEM cell system was used, according to the test methods in Section 3.1.2. A field of 2.5 V m⁻¹ was established in the GTEM cell using the Holaday HI-6005 probe as a reference. This was then removed and the instrument was exposed to the field for

1 minute in each orientation. The instrument was then removed from the chamber whilst the next frequency in the series was set up. On completion of the series, the instrument was connected to a PC and the data downloaded using the supplied software. For each frequency and orientation, the mean value for each individual band, as shown by the analysis software, was recorded. Values of 0.05 V m^{-1} were taken as zero field. A typical set of response data for one axis of one instrument is shown in graphical form as Figure 7 and an example data set can be found in Appendix C.



Figure 7 X-axis response of one PEM with CW signals

3.3.1 In-band response summary

The results of pooling the data from the in-band tests of all 8 instruments are shown in Table 4. The mean recorded field is shown with the standard error (n=72) and is also expressed as the difference from the actual field value in dB. The uncertainty in the table is the sum of both the uncertainty in the exposure field and the manufacturer's figure for isotropicity.

All of the responses, except for that with the FM band, are within the expected uncertainty. These results are for continuous (unmodulated) signals and the responses with modulated signals are discussed in Section 3.4.

Band	Mean recorded field V m ⁻¹	dB rel. 2.5 V m ⁻¹	Uncertainty dB
FM	1.94 ±0.05	-2.20	1.50
TV3	2.43 ±0.08	-0.24	2.00
TV4&5	2.56 ±0.09	+0.19	2.60
GSMtx	2.90 ±0.12	+1.29	3.10
GSMrx	3.33 ±0.07	+2.49	3.10
DCStx	2.66 ±0.06	+0.53	3.70
DCSrx	2.55 ±0.03	+0.17	3.70
UMTStx	2.55 ±0.08	+0.18	3.70
UMTSrx	2.10 ±0.04	-1.51	3.70

Table 4 In-band responses

3.3.2 Out-of-band responses

A number of out-of-band responses were identified as a result of the CW testing. An arbitrary response level of 10% or more of the exposing field — in other words 0.25 V m⁻¹ or more — was set as a significant out-of-band (OOB) response level. There were several sets of conditions that generated OOB responses. These were

- a FM band responses to frequencies below (49, 75 MHz) and above (125, 145 MHz) the FM band.
- b A TV4&5 response to 430 MHz, a frequency below the band edge.
- c TV4&5 responses to GSMtx frequencies (880, 895.5 and 912 MHz)
- d A DCStx response to a frequency in the DCSrx band (1780 MHz)
- e A DCSrx response to a frequency in the DCStx band (1810 MHz)
- f DCSrx and UMTStx responses to an OOB frequency (1900 MHz)

These responses reflect the difficulty of making perfect band-pass filters. In some cases, these OOB responses are of little consequence. For example the FM band responses render the instrument sensitive to pager, PMR and other signals, which whilst outside the specified band, nevertheless represent actual exposure of the subject. The same cannot be said of the TV4&5 response to GSM frequencies (c) or the DCS responses (d and e) since recording a single frequency exposure in both bands at once will increase the recorded exposure. However, the response for modulated signals addresses these problems, as will be described later (see Section 3.4).

3.3.3 Linearity

In-band linearity tests were performed on two instruments. For each of the nine response bands, a field of 2.5 V m⁻¹ was established in the test position in the GTEM cell using the appropriate mid-band test frequency. The cell line voltage was then reduced by a factor of two to generate a field of 1.25 V m⁻¹ and this process repeated a further three times, resulting in a final field of about 0.156 V m⁻¹. No significant non-linearity was seen.

A more detailed investigation of the linearity at low fields in the FM and TV4&5 bands was carried out using one instrument. This used a similar method to the earlier linearity

tests, but used fields of 2.5, 0.25, 0.125, 0.10, 0.08, 0.06 and 0.05 V m⁻¹. There were difficulties in carrying out this measurement using fields close to the instrument's lower response limit. Taking account of this, no significant non-linearity was found.

3.4 Response to modulated signals

An extensive series of tests was conducted to determine the response of the instrument to modulated signals. In general, these were conducted with one or two instruments at field strengths of 1.0 and 2.5 V m⁻¹, using both modulated and unmodulated signals for each of the X, Y and Z orientations. Confirmation of the consistency of field between modulated and unmodulated states was obtained by the use of a thermal power meter (Rohde & Schwarz model NRS).

3.4.1 FM broadcast

This was conducted at a frequency of 98 MHz, using a frequency modulated signal with 150 kHz deviation at a rate of 400 Hz. Responses were essentially identical with or without modulation at field strengths of 1.0 and 2.5 V m^{-1} .

3.4.2 Narrowband FM

This is meant to be representative of communications systems such as PMR (mobile radio services such as taxis), found within the FM and TV3 response bands of the instrument. A frequency of 198 MHz was used, with a single tone modulating frequency of 400 Hz at 3 kHz deviation. Again, responses with or without modulation were essentially identical at field strengths of 1.0 and 2.5 V m⁻¹.

3.4.3 Digital audio broadcasting (DAB Radio)

In the UK this broadcast service occupies frequencies around 220 MHz, which falls within the TV3 response band of the instrument. As it was not possible to generate a true DAB signal, a signal with a similar RF spectrum was generated by a combination of 100% amplitude modulation using random noise and simultaneous 3.0 MHz FM modulation using a 1 kHz triangle wave. A 2.5 V m⁻¹ field gave a mean response of 2.31 V m⁻¹.

3.4.4 Analogue TV broadcast

UK TV broadcasting is allocated 8 MHz spaced channels (numbered 21 to 68) in the frequency range 470 to 854 MHz. A single transmission was simulated by using the output from a commercial TV test signal source, which provided both modulated video and sound carriers at frequencies of 591.25 and 597.25 MHz respectively (CH36). Measurements using a field of about 0.38 V m⁻¹, resulted in mean recorded fields of 0.71 V m⁻¹ with little difference between results using modulated or unmodulated signals. This error of about +5.4 dB is not inconsistent with the CW data, since it was made with a single instrument at a single frequency where there is a pronounced peak in the instrument's response. The CW data is a mean for measurements made with all 8 PEMS and for the three frequencies used for the CW tests.

3.4.5 Digital TV broadcast

A similar approach to the DAB test was used, as a DTV signal source was not available. A 602 MHz carrier 100% amplitude modulated with white noise and simultaneously frequency modulated by a triangle wave with a deviation of 6.5 MHz was used to give a spectral occupancy similar to that of a DTV broadcast multiplex. Fields of 2.5 and 1.0 V m⁻¹ resulted in recorded mean fields of 2.79 and 1.14 V m⁻¹ respectively, differences of 1.0 and 1.4 dB.

3.4.6 GSM 900 handset

This was simulated using the Agilent E4438C signal source set to GSM uplink mode with 1/8 active slots. A modulated field of 2.49 V m⁻¹ (during transmitted bursts) resulted in a recorded mean field of 2.80 V m⁻¹; without modulation, the recorded field was 3.28 V m^{-1} (GSMtx band) with an additional response in the TV4&5 band of 3.54 V m^{-1} . This additional response, which was evident from the CW response data, was *not* present when the modulated signal was used. Similarly with a field of 1.01 V m^{-1} , the modulated signal gave a mean in-band response of 1.20 V m^{-1} and the unmodulated signal an GSMtx band response of 1.30 V m^{-1} and an out-of-band TV4&5 response of 1.47 V m^{-1} .

3.4.7 GSM 900 base station

This was simulated using the Agilent E4438C signal source set to GSM uplink mode with between 1 and 8 active slots at a frequency of 950 MHz. A second signal source generating a CW signal of 947.5 MHz was used to simulate the Broadcast Control Channel (BCCH), which is transmitted continuously. If this BCCH surrogate was omitted, transmissions with up to 7 active slots were not recorded. The mean field strength recorded with the BCCH surrogate carrier alone was very slightly higher than that recorded when both signals were present, irrespective of the number of active slots. This implied that the instrument response for multiple signals may be in error and it was investigated subsequently (see Section 3.5.2).

3.4.8 GSM 1800 handset

This was simulated using the Agilent E4438C signal source set to GSM uplink mode with 1/8 active slots. The results were similar to those for the GSM 900 handset tests.

3.4.9 GSM 1800 base station

In a similar way to the GSM 900 base station signal test described above, the GSM framed transmissions were generated on a frequency of 1840 MHz, with the surrogate BCCH carrier being on 1842.5 MHz. Identical behaviour was seen, the field strength recorded when just the BCCH carrier was present being very slightly higher than that when both signals were present.

3.4.10 DECT 1800

DECT (Digital Enhanced Cordless Telecommunications) devices in the UK are allocated 10 frequencies in the range 1880 – 1900 MHz. Most modern cordless telephones use DECT transmissions. Although not specifically mentioned in the instrument specifications, DECT was included in the tests as use of such phones could contribute significantly to personal exposure. The Agilent signal source was set to generate a DECT modulated signal at 1890 MHz with 1 of the 12 possible timeslots active. No response to fields of either 2.5 or 1.0 Vm^{-1} was seen.

3.4.11 UMTS (3G) handset

The WCDMA (3GPP) uplink modulation option of the Agilent 4438C signal source was used for this test, with an RF frequency of 1950 MHz. Exposing fields of 2.5 and 1.0 V m^{-1} resulted in recorded mean fields of 2.51 and 0.95 V m⁻¹ respectively.

3.4.12 UMTS (3G) base station

The WCDMA (3GPP) downlink modulation option of the Agilent 4438C signal source was used for this test, using a frequency of 2140 MHz. Exposing fields of 2.5 and 1.0 V m^{-1} resulted in recorded mean fields of 1.26 and 0.63 V m⁻¹, implying the recorded field was in error by about -50% or -6 dB.

3.4.13 Radar

Some Air Traffic Control (ATC) radar frequencies fall within the possible response range of the instrument. The response to simulated radar signals at a frequency of 1300 MHz, using several pulse widths and repetition rates (4 μ s and 660 Hz; 34 μ s and 825 Hz; 66 μ s and 430 Hz) was investigated using a peak field strength of 2.5 V m⁻¹. No responses were seen.

3.4.14 Summary of modulated signal responses

The results for the signals in the bands to which the PEM is designed to respond are shown below in Table 5, expressed as a relative response (the mean of the X, Y and Z orientation responses at all field strengths tested). The Analogue TV response was significantly higher than expected, and both the DCSrx and UMTSrx responses were significantly lower.

		U	•
Band	Response dB \pm SE		Signal Frequency and Modulation
FM	−1.8 ± 0.5		98 MHz WBFM ±75kHz deviation
TV3	-0.4 ± 0.5		220 MHz pseudo Digital Audio Broadcasting
TV4&5	+5.4 ± 0.4		591.25 MHz Analogue PAL TV
TV4&5	+1.2 ± 0.5		602 MHz pseudo Digital TV
GSMtx	+1.0 ± 1.0		895.5 MHz GSM uplink 1/8 slots active
GSMrx	-0.7 ± 0.4		947.5 MHz BCCH, 950 MHz 8/8 slots active
DCStx	+0.2 ± 0.6		1747.5 MHz GSM uplink 1/8 slots active
DCSrx	-3.0 ± 0.2		1842.5 MHz BCCH, 1840 MHz 8/8 slots active
UMTStx	+0.4 ± 0.1		1950 MHz 3G RT TDMA uplink
UMTSrx	−5.7 ± 0.9		2140 MHz 3G RT TDMA downlink

3.5 Response to multiple signals

A number of tests were conducted to investigate the response of the instrument to multiple signals occurring both in the same or in different bands. Outputs from the signal sources were combined using an appropriate power combiner and the resultant signal fed to the amplifier. The fields of each individual component and of the combined signal

were checked with the HI-6005 probe. In each case, the RMS sum of the individual components corresponded closely with the field of the combined signal. Finally, a spectrum analyser, coupled to the system, was used to confirm that no unwanted spurious mixing products were present.

3.5.1 Signals in different bands

These are summarised in Table 6. All signals were modulated appropriately, except where indicated. GSMrx signals were unmodulated (CW), simulating the BCCH channel.

Table 0	Table 6 PEM behaviour with two signals in uniferent bands									
Signals	applied se	parately		Signals	applied too	gether	Change > 10%?			
Signal 1	l	Signal 2	2	Signal	1	Signal 2				
Band	E, V m ⁻¹	Band	E, V m ^{−1}	Band	E, V m ⁻¹	Band	E, V m ^{−1}			
FM	1.76	TV3	1.00	FM	1.70	TV3	0.97	No		
FM	1.09	GSMrx	1.65	FM	1.10	GSMrx	1.66	No		
FM	1.13	TV4&5	1.04	FM	1.11	TV4&5	1.02	No		
TV4&5	1.52	GSMtx	1.43	TV4&5	1.47	GSMtx	1.41	No		
TV4&5*	0.97	GSMrx	1.56	TV4&5	0.64	GSMrx	1.55	Yes, TV4&5: -34%		
TV4&5†	1.43	GSMrx	1.59	TV4&5	0.96	GSMrx	1.57	Yes, TV4&5: -33%		
GSMrx	1.59	DCSrx	1.28	GSMrx	1.62	DCSrx	1.28	No		
* modula	ited ATV † u	nmodulat	ed ATV							

Table 6 PEM behaviour with two signals in different bands

The majority of combinations of signals in different bands showed no significant change between single-signal and simultaneous signal results. However, there was one important exception. Recorded field strength of signals in the TV4&5 band were significantly reduced, by about one third, in the presence of a GSM 900 (Base station, CW equivalent to the BCCH transmission) signal.

3.5.2 Signals in the same band

These were carried out in several bands, and are summarised in Table 7. Two or three signal sources were combined using an appropriate power combiner and the resultant signal was fed to the amplifier. The fields of each individual component and the combined signal were checked with the HI-6005 probe. In each case, the RMS sum of the individual components corresponded closely with field resulting from the combined signal.

PEM band	Individual	signal E-field	ds, V m ^{−1}	E-field of signals together, V m ⁻¹			
	Signal 1	Signal 2 Signal 3		Recorded	Predicted	Error %	
FM	1.66	1.98		1.77	2.65	-34%	
FM	0.71	0.66		0.65	0.97	-33%	
FM	0.71	0.86	0.91	1.03	1.44	-31%	
FM	1.66	0.66		1.59	1.78	-11%	
GSMrx	1.92	1.83		1.75	2.65	-34%	
DCSrx	1.47	1.34		1.31	1.99	-45%	
UMTSrx	1.63	1.65		1.73	2.32	-34%	

Table 7	PEM	behaviour	with	multiple	signals	in the	e same ban	d
		Sonarioui		manupio	orginalo			-

The results are shown as mean field (the mean of the recorded field in the X, Y and Z orientations) for each signal and for the recorded and predicted results. It can be seen that the instrument does not respond correctly to multiple in-band signals, the response being significantly less than the RMS sum. Thus the instrument will under-read in situations where there is more than one simultaneous transmitter in a band. This is a situation that will occur in practice, particularly with broadcast (FM, TV4&5) signals, and with multi-operator cellular sites.

3.6 Electromagnetic immunity

3.6.1 Power frequency electric fields

A parallel plate system with a large uniform field volume was used to establish a 50 Hz electric field strength of 5 kV m⁻¹. The instrument was placed in the field such that its x, y and z-axes were aligned in turn with the field for 1 minute each, and then the logged data were downloaded. No responses were seen.

3.6.2 Power frequency magnetic fields

A 0.6 m diameter Helmholtz coil system was used to establish a 50 Hz field of 100 μ T. The instrument was placed in each of the X, Y and Z orientations in turn in the field for 1 minute and then the data were downloaded. No responses were seen.

3.6.3 TV receiver and PC monitor fields

In order to evaluate the possibility of interference from these sources, instruments were placed close to a number of PC monitors and domestic TV receivers. No responses were seen.

3.6.4 HF fields

The instrument response to frequencies of 1.8 and 27.12 MHz was examined by exposing the instrument in a TEM cell exposure system. The method was similar to that employed for the CW tests in the GTEM cell system and a field of 5.0 V m^{-1} was used. Whilst there was no response to the 1.8 MHz field, for the 27.12 MHz exposures the mean field was recorded as being 0.59 V m⁻¹ in the FM band.

3.7 Isotropy of response

In order to investigate the response of the instrument in differing orientations, a jig was prepared (Figure 8) which allowed rotation in different planes. This was used in the GTEM cell (where the field was substantially in the z direction).



Figure 8 Rotational jig and rotations used to examine isotropy of the PEM when inside the GTEM cell.

The experimental method was similar to that for other tests, using a nominal 2.5 V m^{-1} field. Rotational increments of 10° were used with a recording duration of 1 minute for each position. Due to time constraints only a limited number of bands could be used; the middle frequency for the FM, GSMtx and UMTStx bands was chosen, and the response examined for rotation in the X-Y, X-Z and Y-Z planes, and about the X-axis, as shown in Figure 8. A summary of results is shown in Table 8, and a representative polar response is shown in Figure 9.

Table 8 Isotropic and rotational tests							
Band	Specification	X-Z	X-Y	Y-Z	X axis		
FM	±0.5 dB	−0.2, −13.8 dB	+0.2, -2.3 dB	+1.4, −9.9 dB	−1.3, −2.8 dB		
GSMtx	±2.0 dB	+5.3, −3.6 dB	+4.4, +1.5 dB	+4.4, −3.8 dB	+5.1, +2.0 dB		
UMTSrx	±2.5 dB	−0.2, −7.8 dB	+3.4, -0.2 dB	+0.3, -11.0 dB	+2.9, −8.7 dB		



Y-Z plane polar response 2140 MHz

Figure 9 Representative polar response

3.8 Capacity and integrity of data storage

Tests were undertaken to establish the practical battery life and data retention time using data acquisition parameters likely to be used in the volunteer study.

3.8.1 Battery life

For the first test, seven instruments were used, all with a recording interval of 120 s and data collection periods of between 5 and 7 days. As the test was conducted in a "quiet" RF environment, the number of events logged was taken as a measure of the intrinsic noise level of the instruments. The results are summarised in Table 9.

Serial no.	1	2	3	4	5	6	7
Data collection days	5	5	6	6	7	7	7
Download after day	5	7	6	7	7	8	10
Final battery voltage	3.82	3.88	3.87	3.83	3.81	3.84	??
Data retained	Yes	Yes	Yes	Yes	Yes	Yes	No
No. of events	1	7	None	~200	6	None	??
Event bands	TV4&5	TV4&5		TV4&5, UMTSrx	TV4&5		??

Table 9 Battery duration and data retention

3.8.2 Storage integrity

It is clear that a 7-day data collection period is practical as long as the instrument is downloaded promptly. The 10-day download failed, as shown in the final column of Table 9, the software showing no data present. Further investigation showed that, if the battery becomes discharged, the logged data become irrecoverable. This is a serious shortcoming in a device designed for use away from the controlled environment of the laboratory. It is also surprising since a flash memory device (which is inherently non-volatile) is used for logged data storage. The manufacturer has explained that some data needed to access the logged results are not stored in a non-volatile form.

3.8.3 Spurious recording events

One unit (number 4) recorded a large number of events, defined in this context as isolated records above the 0.05 V m^{-1} threshold. Unit numbers 1, 2 and 5 also recorded a small number of isolated events.

3.8.4 Charging reliability

Following some problems during the field trials, all eight instruments were again set up in the laboratory for a run of 7 days and with a 120 s recording interval. Each instrument was charged immediately before the run with the supplied charger, until the charger showed that the fast charging was complete. All were periodically inspected during the working day to confirm they were still operating, as shown by the flash of the logging LED every 2 minutes. Any instrument that stopped logging was immediately downloaded, recharged and returned to the trial. Six instruments ran satisfactorily throughout the trial. One, (number 4) stopped after about 6 h, and was recharged and restarted. It then ran for 2.9 days before again stopping. The second (number 7) ran for 4.8 days before stopping. In all cases logging was stopped because of low battery voltage.

In the light of the above, there would therefore appear to be some question about reliability of the battery and charging arrangements. It was noted that, although the instruments use Nickel Metal Hydride (NiMH) batteries, the supplied chargers are labelled as suitable only for Nickel Cadmium types.

3.8.5 Temperature recording

During these investigations, it was noted that, although the instruments were operated in a temperature-controlled environment $(21\pm1 \ ^{\circ}C)$, the maximum and minimum temperatures recorded varied quite widely outside these limits. Since the maximum temperatures could reflect elevated temperatures following battery charging, these were ignored, however 2 out of 7 instruments that completed the 7 day duration test had both mid run (record 2500) and end of run recorded temperatures that were up to 5 $^{\circ}C$ lower than the laboratory temperature.

3.9 Low temperature tolerance

Following the volunteer trials, it became apparent that there were intermittent problems with data loss or instrument malfunction. Inspection of the records suggested that there might be a problem when the instrument temperature dropped below 10 °C. Two instruments were used to investigate this possibility. They were set to a 30 s recording rate, fully charged, then left in the laboratory for 2 h to reach thermal equilibrium after charging. They were then started and placed in a laboratory refrigerator at 4 °C overnight for 19 h. They were taken out, and left for 2 h in the laboratory at 21 °C before downloading was attempted.

The LED was still indicating correct operation when the instruments were removed from the refrigerator, and before downloading. Even so, both had corrupted data, it being clear from the battery/temperature trace that once the instrument temperature approached 10°C malfunctioning occurred. The recorded duration was incorrect and the battery voltage and temperature graphs showed that zero values were often logged. Inspection of the data as linked to an Excel spreadsheet showed frequent patterns of alternating extra records, these having an invalid date (such as 1/8/1900), no time, and zero values for the battery voltage and temperature. However it was possible to use the volunteer data by removing these null records. The manufacturer has since provided a revised software release, which corrects this problem.

3.10 Summary of laboratory measurements

In summary, the laboratory investigations have shown that the PEM has

- Broadly correct field strength recording for single signals.
- An incorrect response to multiple in-band signals.
- Errors in recording TV4&5 fields when a GSM 900 base station signal is present.
- An inaccurate calibration for UMTS base station signals.
- Greater than specified departures from isotropy.

In addition, for use within the UK, some further issues need to be addressed, including the lack of provision for the UK TETRA band. In any country, the instrument's lack of response to DECT cordless phone signals is likely to be a problem.

The specification for the PEM was taken to be the Technical Data table on page 4 of the supplied user manual, most of which is repeated in the Certificate of Calibration included with each of the instrument. This is also the same as in the separate DSP090 data sheet available from the manufacturer.

The isolation referred to in the calibration certificate is for modulated signals within the designated response bands; it does not refer to out-of-band signals. The PEM has responses outside the designated bands as described in Section 3.3.2, however these do not necessarily have serious consequences.

The manufacturer's axial isotropy specification would seem to refer to measurements made with rotation around only one axis (Z, which is vertical) in a vertical or horizontal field. The measurements in Section 3.7 were made using rotation in three different planes and about one axis to get a clearer picture of overall isotropy, which is considerably poorer than the axial isotropy given in the specification.

One important shortcoming in the instrument's performance was the apparent inability to deal correctly with multiple in-band signals, as shown in 3.5.2. This is a serious shortcoming in view of the co-siting of TV and FM broadcast transmitters in the UK, where for example, five TV signals of similar field strength would be found in most locations. Co-sited mobile phone base transmitters could also be problematical.

The use of a signal discrimination technique to assign signals in adjacent bands to the appropriate logging band (for example TV4&5 and GSMtx) to overcome the shortcomings of the RF band filtering is an innovative technique. It can, however, mean that the lack of a correct response to multiple in-band signals also applies when signals are in adjacent bands, since from the point of view of the PEM they may considered as occurring in the same band.

4 SPOT MEASUREMENT EVALUATIONS

Each of the ten volunteers was asked to identify locations where they expected to spend an appreciable proportion of the time over the week in which they would use a personal exposure meter (PEM). Spot measurements were made at four of these locations on the days of deployment and collection of the PEM.

The aims of making the spot measurements were as follows.

- To identify the dominant signals contributing to exposure at each location, and to identify whether the PEM could be expected to measure these signals based on its specified sensitivity and filter bandwidths.
- To compare spot measurements made at the beginning and end of the week in order to examine repeatability of the measurement procedure and to assess whether the RF spectrum had changed significantly over the week.
- To compare spot measurements made with a precision narrowband system with those made with a PEM at the same fixed position in order to examine their degree of correlation in a real exposure situation.
- To provide spot measurement data at the locations that could be compared with personal exposure data gathered when the volunteer diaries showed that they were using the PEM at the same location.

The results from analyses of the spot measurement data are presented in this section.

4.1 Narrowband spectral measurements

Spot measurements of signal strengths over the RF spectrum from 80 MHz to 2.5 GHz were made at the identified locations according to the protocol in Appendix D.

4.1.1 Data acquisition

The measurements were made with an ARCS miniature biconical antenna mounted on a wooden tripod and connected via a coaxial cable to an Agilent E4407B spectrum analyser. The spectrum analyser was controlled from a laptop computer so that all of its settings were applied automatically and the only manual involvement during the measurement was to change the antenna height and polarisation when requested by the software.

The measurement was made in 13 sub-bands each configured with appropriate bandwidths, frequency resolutions and dwell times in order to measure the RMS voltage corresponding to any signals present. Given the bandwidths used, this required measurements at 14788 spot frequencies in order to avoid any gaps in the spectrum.

The measurements were made in three orthogonal polarisations and at heights of 1.1, 1.5 and 1.7 m above floor level, leading to nine sets of measured voltages stored in a table on the computer. This data acquisition took around an hour to perform.

4.1.2 Post-processing

Post-processing of the data was carried out in order to derive the voltage corresponding to the resultant field strength at each of the three heights and then a spatially averaged value over the three heights was calculated on an RSS^{*} basis. Finally, a peak search algorithm was used to form tables of signal frequencies and field strengths, and apply correction factors to account for power loss due to the restricted spectrum analyser bandwidths.

The individual signal frequencies and RMS electric field strengths were summed to evaluate the total RMS electric field strength present in each of the PEM's specified frequency bands (see Table 1). The RMS field strength was also evaluated in the TETRA base stations band (390–395 MHz), the 2.4–2.5 GHz band used by wireless local area networks (WLANs), and the DECT cordless phones band (1880–1900 MHz). Finally, the RMS field strengths of signals that did not fall in any of these 12 bands were accumulated as "other".

The resulting narrowband spot measurement data taken on the day the PEM was given to each volunteer are shown in Table 10. Field strengths shown in blue should be measurable by the PEM as they are in its specified bands and above the 50 mV m⁻¹ detection threshold. Fields shown in red and black should not be measurable by the PEM, the former because they of insufficient strength and the latter because they describe signals of frequencies outside the specified bands. The total column includes the nine PEM bands and the four other bands in the table.

4.1.3 Field strengths in the PEM bands

Table 10 shows that signals were not always detected in the PEM bands, even with the sensitive narrowband system. Signals were detected at 12 out of the 40 spot measurement locations in the FM band, and at 2 locations in the TV3 band. The field strengths in these bands never exceeded the 50 mV m⁻¹ PEM detection threshold.

Signals detectable with the narrowband system were found in the TV4&5 band in all but three of the volunteer's houses, but the field strengths were only above the PEM detection threshold in the house of one volunteer.

Signals in the GSMtx and DCStx bands were rarely detected with the narrowband system, and the field strength was always below the PEM detection threshold, suggesting that the signals were from distant phones. No signals were detected in the UMTStx band.

Signals were detected with the narrowband system at 34 and 24 out of 40 locations in the GSMrx and DCSrx bands respectively. However, the fields were only above the PEM detection threshold at three locations, all in the house of Volunteer 1. Signals were detected with the narrowband system in the UMTSrx band at three locations, all in the house of Volunteer 1, and the signal strengths at two of these locations were above the PEM detection threshold.

^{*}Root-sum-squares: Each voltage was squared, then summed together and the square root taken.
Table 10 Spot measurements of signal electric field strengths made with the narrowband measurement system, spatially averaged over heights of 1.1, 1.5 and 1.7 m, and summed across the PEM and other relevant frequency bands. Signals in red are too weak to be measured by the PEM and those in black are outside its specified frequency bands

Spot measurement		Electri	ic field str	ength (RM	1S), mV r	n ⁻¹								
data source	•	PEM f	requency	bands						Other ba	ands			Total
Volunteer	Location	FM	TV3	TV4&5	GSMtx	GSMrx	DCStx	DCSrx	UMTStx UMTSp	TETRA	WLAN	DECT	Other	
1	Home, Living room					86		77	39	113		36		170
1	Home, Dining room					104		119	56	116	72	11		217
1	Home, Bedroom					170		113	55	104		37		238
1	Work, Office					9		18						21
2	Home, Study room					4							5	6
2	Home, Kitchen	4				8							3	9
2	Home, Bedroom	11		11		16							6	23
2	Work, Office			14		18		7		1			26	35
3	Home, Living room			18	9					3		14	5	25
3	Home, Kitchen			16		3				1			7	17
3	Home, Bedroom	5		16	12					3		60	6	64
3	Work, Office					4		7		1				8
4	Home, Living room			8		3		23		1			11	28
4	Home, Kitchen			18		2		11					6	22
4	Home, Bedroom	7		9		11		33		2			14	39
4	Work, Office					18		37		1			16	44
5	Home, Living room	18		69						3		22	8	75
5	Home, Kitchen	16	15	82						2		36	12	93
5	Home, Bedroom	39	11	130	17	6				5		15	26	141
5	Work, Office					7		15						17
6	Home, Living room					11				3			7	13
6	Home, Kitchen					5				2	102	10	4	103
6	Home, Bedroom	7				37		22		7			34	56
6	Work, Office					20		42		1			43	63
7	Home, Living room												3	3
7	Home, Kitchen												3	3
7	Home, Bedroom					5		6		4			11	14
7	Work, Office					5		7		1			10	13
8	Home, Living room			11		8		12		1		14	12	26
8	Home, Kitchen			8		4		23		1		8	11	28
8	Home, Bedroom			30		13		43					22	58
8	Work, Office			23		6							14	27
9	Home, Living room			11		28		16		13			11	38
9	Home, Kitchen	4		31		45		30		12			17	66
9	Home, Bedroom	6		13		25		28		24			9	48
9	Work, Office					4				1				4
10	Home, Living room			4		15		9		37			20	46
10	Home, Kitchen					13		7		24			20	34
10	Home, Bedroom			8		17				27			28	44
10	Work, Office	5				6		7					11	15

4.1.4 Location and source circumstances

It is not the purpose of this project to carry out an exhaustive investigation into the relationship between where a volunteer lives, or the sources present in their home, and their likely exposure level. Nevertheless, certain observations can be made, which help to explain the spot measurement and personal exposure data (see Section 5.2).

All ten volunteers worked in the same building, although in different offices some of which faced in different directions. The office measurements all yielded field strengths below the detection threshold of the PEM in all of its bands. The building was in a rural area and not close to any base stations.

Volunteer 1 lived significantly closer to a mast than any of the other volunteers, at a distance of around 300 m. The mast had antennas for several GSM and 3G operators, as well as TETRA installed. The signals in this volunteer's house were several times stronger than those in the houses of the other volunteers.

Volunteer 5 lived in Southeast London and nearer to VHF/UHF broadcast radio masts than the other volunteers. This is evident in that the field strengths in the FM and TV4&5 bands were greater in the house of this volunteer than the houses of the other volunteers.

Volunteer 7 lived in a stone house in a village far from any masts. The narrowband equipment was only able to measure signals in the second floor bedroom of this house, which was above the stone walls and inside the tiled roof space.

4.1.5 Field strengths outside the PEM bands

Table 10 shows the strengths of TETRA, WLAN, DECT and other signals measured with the narrowband system. These signals will contribute to exposure, but fall outside the PEM's specified bands and are not accounted for.

TETRA signals make a measurable contribution in all but 10 of the 40 locations, and they make a dominant contribution for the three locations in the house of Volunteer 1. DECT signals were measured in the houses of five of the volunteers and gave significant contributions to the total field.

Two of the volunteers (1 & 6) had home computers with 802.11b wireless local area network capability in their houses. The 2.4–2.5 GHz emitted signals were detected when the narrowband measurements were made in the same room as the computers, but not when the measurements were made in other rooms.

Detailed examination of the signals grouped under the "other" category showed that truncation of several of the bands caused signals that should rightly be included in the PEM bands to be neglected. TV signals were missed between 830–854 MHz and E-GSM base station signals were missed in the range 925–935 MHz.

Paging signals in the 153–155 MHz range gave significant contributions with some of the volunteers and a difficult question will be whether this band should be included in the PEM.

4.1.6 Effect of varying the PEM detection threshold

Some indication of the improvement in signal measurability that could be gained from lowering the PEM detection threshold is shown in Table 11. This shows that, even if the detection threshold could be lowered to 10 mV m⁻¹, there would be many locations where the field strength in the PEM bands would still be below the detection threshold.

PEM frequency	Electric fie	eld strength c	letection thresh	hold in mV m ⁻¹						
band	50	40	30	20	10					
FM	0	0	1	1	4					
TV3	0	0	0	0	2					
TV4&5	3	3	4	6	15					
GSMtx	0	0	0	0	2					
GSMrx	3	4	5	7	17					
DCStx	0	0	0	0	0					
DCSrx	4	6	9	15	22					
UMTStx	0	0	0	0	0					
UMTSrx	2	2	3	3	3					

Table 11 Number of the 40 spot measurement locations where signals wou	ld be
measurable for a given PEM detection threshold	

4.2 Repeatability of narrowband measurements

4.2.1 Data acquisition and processing

The spot measurement data in Section 4.1 were taken on deployment of the PEM. The measurements were also repeated a week later, on collection of the PEM, and the two sets of measurements were compared to examine the changes in band field strengths. Since the interest was in relative rather than absolute differences in the field strength levels, the differences between the field data for each PEM band were expressed in decibels (dB) according to the following expression.

Difference =
$$20 \times \log_{10} \left(\frac{E_{\text{collection}}}{E_{\text{deployment}}} \right)$$
 (1)

Data were only processed if both the opening and closing field strengths were above 10 mV m⁻¹ in order to reduce the effect of noise on the results due to signal strengths being near the narrowband measurement detection threshold. The results of this analysis are shown in Table 12. Values differing by more than 3 dB are shown in red.

Table 12 Differences between narrowband spot measurements of electric field strength on deployment and collection of the PEM. Individual signal strengths have been summed over the PEM and other frequency bands for situations where both data sets were above 10 mV m⁻¹ and expressed in dB.

Spot measurement	Ratio of	Ratio of closing to opening RMS electric field strength, dB												
data source		PEM fre	equency ba	ands						Other ba	inds			
Volunteer	Location	FM	TV3	TV4&5	GSMtx	GSMrx	DCStx	DCSrx	UMTStx	UMTSrx	TETRA	WLAN	DECT	Other
1	Home, Living room					1.02		1.08		0.71	-0.70		-2.03	
1	Home, Dining room					-0.96		-0.76			-0.16	-2.31	3.12	
1	Home, Bedroom					0.20		0.44		-3.01	-0.89		-2.71	
1	VVork, Office							1.10						
2	Home, Study room													
2	Home, Kitchen			0.26		_1 00								
2	Mork Office			0.30		-1.02								
2	Homo Living room			-0.56		-1.40							4 40	
3	Home Kitchen			-0.50									4.49	
3	Home Bedroom			2.13									-0.87	
3	Work Office			2.15									0.07	
4	Home Living room							-0.94						0.95
4	Home Kitchen			3 01				-0.01						0.00
4	Home, Bedroom			0.01				-1.60						-0.21
4	Work, Office					0.18		1.20						
5	Home, Living room	0.23		-0.78									-0.92	
5	Home, Kitchen	0.72		-1.39									2.42	7.67
5	Home, Bedroom	1.13	-0.37	0.38										-6.37
5	Work, Office							1.42						
6	Home, Living room					-0.05								
6	Home, Kitchen												3.61	
6	Home, Bedroom					2.02		-1.14						-0.79
6	Work, Office					-2.95		1.68						
7	Home, Living room													
7	Home, Kitchen													
7	Home, Bedroom													
7	Work, Office													
8	Home, Living room			-0.63				2.46					0.73	7.24
8	Home, Kitchen			0.57		0.05		-0.54						0.07
8	Home, Bearoom			0.57		2.85		5.50						3.37
<u>o</u>	Home Living room			-0.32		_4 74		_1 01						1 15
9	Home, Living room			-1 70		-4.74		-1.01			2.02			1.15
9	Home Bedroom			-1.70		-1.06		-2.26			2.02			
9	Work Office					1.50		2.20						
<u> </u>	Home Living room					-2 12					-2.67			-2.68
10	Home Kitchen					0.73					-0.63			-0.57
10	Home Bedroom					-1 17					-4 81			-4 03
10	Work, Office													1.00
Band averages	3	0.69	-0.37	0.32		-1.22		0.12		-1.15	-1.12	-2.31	0.87	0.52
u		0.00	0.01	0.02				\$.1 E		0		2.31	0.01	0.02

4.2.2 Results

Table 12 indicates that the RMS field strengths summed over the PEM bands generally have a remarkable degree of consistency between the measurements made at the beginning and end of the week-long trials. Of the 51 points where comparison could be made, 43 are within 3 dB and 20 are within 1 dB.

It is likely that the few extreme outliers in the distribution, e.g. -9.36, 6.57, -4.74 dB, arose due to changes in the RF spectrum over the week and so they may not have implications for the repeatability of the narrowband spot measurement procedure. Nevertheless, more than 63%, i.e. 33 of the points are within 1.7 dB and so this suggests the spot measurements in the PEM bands are repeatable to within ± 3.4 dB (95% confidence).

Similarly good repeatability is shown in the bands other than those logged by the PEM, except for the one described as "other". This is to be expected because the signals in the parts of the spectrum described by this category may well be intermittent or of variable power, e.g. paging and PMR signals.

4.3 Comparison of narrowband and PEM spot measurements

4.3.1 Data acquisition and processing

As described in Section 4.1, the narrowband spot measurement data were gathered at heights of 1.1, 1.5 and 1.7 m and then processed to derive a spatially averaged resultant RMS electric field strength. For the analysis in this section, the data for 1.5 m height were used alone. The peak search algorithm was used to extract individual signal frequencies and powers, and then the signal field strengths were summed to derive the total RMS electric field strength in each of the PEM frequency bands.

Immediately after each of the above narrowband spot measurements was made, both on deployment and collection of the PEM used by the volunteer, the miniature biconical antenna was removed from the tripod and a second PEM was mounted on a special jig at the 1.5 m height position. In this way, spot measurement data were acquired with the second PEM for comparison with the narrowband measurement data.

The PEM was known not to be as isotropic in its response as the precision narrowband equipment and so it was rotated through 45° steps in azimuth at 1-minute intervals, while recording every 5 seconds. After the measurements, the data acquired over the eight minutes required to give a full 360° rotation were averaged over the rotation. Where some of the data were below the detection threshold of the PEM, numerical methods were used to estimate the mean (see Section 2.3). Hence, some of the PEM spot measurement values are reported as below the 50 mV m⁻¹ detection threshold.

The results were processed to express the ratio of the PEM spot measurements to the narrowband spot measurements (in dB), where both were above 30 mV m⁻¹, and they are shown in Table 13. Given the availability of data on deployment and collection of the PEM at four locations for each of the ten volunteers, this gave 80 sets of data for comparison.

Spot measu	Spot measurement ata source	Ratio,	dB									
data source	e		PEM fr	requency b	ands							Total
Volunteer	Day	Location	FM	TV3	TV4&5	GSMtx	GSMrx	DCStx	DCSrx	UMTStx	UMTSrx	
1	Deployment	Home, Living room					1.32		-3.98			-3.62
1	Deployment	Home, Dining room					1.24		-0.76			-4.30
1	Deployment	Home, Bedroom					-2.89		-4.66		-0.42	-3.59
1	Collection	Home, Living room					0.05		2.45			-1.13
1	Collection	Home, Dining room					-0.61		-0.16			-3.52
1	Collection	Home, Bedroom					-3.14		0.13			-3.52
4	Deployment	Work, Office							0.83 [#]			-0.04
5	Deployment	Home, Kitchen			-6.82							-3.36
5	Deployment	Home, Bedroom			-4.00	1.27						-3.88
5	Collection	Home, Bedroom			-4.49							-4.91
6	Deployment	Work, Office							1.86 [#]			0.92
6	Collection	Home, Bedroom					0.64					0.04
8	Deployment	Home, Bedroom							-1.43			-4.38
8	Collection	Home, Bedroom							-1.12			-2.82
9	Deployment	Home, Kitchen					-0.23					-2.26
Band averag	les				-5.11	1.27	-0.45		-0.50		-0.42	-2.69
#				1								

Table 13 Ratios of PEM spot measurement data at 1.5 m height to corresponding narrowband spot measurements of electric field strength at the same positions where both values were above 30 mV m⁻¹

[#] denotes that numerical techniques were used to impute the PEM spot measurement value.

4.3.2 Results

Table 13 shows that there were only 15 of the 80 situations, 7 of which were with the same volunteer, where the electric field strength in the PEM bands was great enough to allow a comparison between spot measurements made with the PEM and the narrowband equipment. The absence of measurable signals with the PEM in the FM, TV3 and UMTStx bands also meant no comparisons could be made for these bands.

The data for Volunteer 5 suggested the PEM was under-reading significantly in the TV band and so the original signal strength data were examined in the narrowband measurements. These showed that the TV part of the spectrum consisted of many signals, some of which had similar strengths, e.g. (45.7, 44.5, 5.4, 34.2, 32.8, 4.6, 27.5, 31.9, 4.8, 19.1, 20.8) mV m⁻¹ in the case of the kitchen measurements on deployment. Summing these signals together gives an RMS total field strength of 112 mV m⁻¹, whereas the maximum individual signal strength is 45.7 mV m⁻¹, i.e. 7.8 dB lower. In Section 3.5.2, the PEM has been noted to under-read and in such situations give a reading more equivalent to the maximum individual signal strength in the band.

The PEM also seems to under-read in the GSMrx and DCSrx bands, and probably also due to multiple signals in the bands not being accumulated correctly to give the RMS total field strength. The error seems to be less than with the TV signals, probably because there were fewer signals of similar strength present.

4.4 Summary of spot measurements

The spot measurement data indicate that the PEM bands do not capture all of the signals that contribute significantly to exposure at the spot measurement locations. Omission of the DECT, TETRA, E-GSM and WLAN bands, and of the TV band above 830 MHz, would be a problem for use of the dosimeter in the UK.

Other signals frequently detected with the narrowband equipment were those used for wide area paging, around 138 and 153 MHz, and other ones of unknown origin at 469.8 and 961.0 MHz. Signals were occasionally measured at other frequencies, such as 168, 185, 206 and 453 MHz. The maximum field strength of any of these paging and other signals was 12.4 mV m⁻¹ and considerably below the 50 mV m⁻¹ detection threshold of the PEM. This suggests that there would be little merit in adding further bands to the PEM, beyond those listed in the previous paragraph.

Comparison of the spot measurements made on deployment with those made a week later on collection of the PEM showed good repeatability of the spot measurement procedure, with the data overall showing repeatability to within 3.4 dB based on 95% confidence with a normal distribution.

Spot measurements made with the PEM at the same locations as the narrowband equipment supported the observations made during the laboratory testing that the PEM does not sum the strengths of multiple in-band signals correctly.

5 PERSONAL MEASUREMENTS WITH THE PEM

Ten volunteers each carried a personal exposure meter with them for a period of one week, while it logged the electric field strength in its bands (Table 1) once every two minutes. The volunteers kept diaries over the week so that the logged readings could be correlated with their whereabouts and the results are reported in this section. A template diary is shown in Appendix E.

5.1 Analysis of the logged data

The logged data were downloaded from the PEM and exported into an Excel spreadsheet so they appeared as in Figure 2.

5.1.1 Corrupt records

Initially, the ~5000 logged data points were inspected for corrupt records, e.g. where the temperature fell below 10° (see Section 3.9), and such records were edited out. The numbers of correct and corrupt records for each volunteer are shown in Table 14.

Volunteer number	Number of correct records	Number of corrupt records
1	5019	21
2	5040	0
3	5040	0
4	4797	243
5	5040	0
6	5022	18
7	5040	0
8	4524	21
9	4433	607
10	All data lost	

 Table 14 Total numbers of correct and corrupt records in the downloaded personal exposure data from the volunteers

Only an empty file could be downloaded for Volunteer 10, despite the volunteer recalling that the indicator on the instrument had been flashing to denote normal operation over the week. It was suspected that the battery had failed with this instrument due to incomplete charging (see Section 3.9).

5.1.2 Analysis by location

Each record in the personal exposure data was assigned a tag number based on where the diary showed the volunteer was present at that point in time. The first four tag numbers were the spot measurement locations for each volunteer, but a small number of other tag values were assigned as well, e.g. travelling in car, and time spent outdoors. This allowed the recorded data to be partitioned and analysed separately for each location. The PEM records the field strength in V m⁻¹ and to two decimal places. A histogram was formed for each partitioned data set, and also for the entire data set, arising from each volunteer and with each of the 495 levels from 0.05 to 5.00 V m⁻¹ defined as a separate bin. The data were then further processed to form curves, similar to that in Figure 10, in which the *x*-axis was a field strength threshold and the *y*-axis was the percentage of the appropriately tagged values above that threshold.



Figure 10 Example of processed personal exposure record results for the exposure of one volunteer in the GSMrx band

Figure 10 shows that the highest GSMrx exposures for Volunteer 1 occurred in the dining room, where the field strength of 96% of the values (i.e. 96% of the time) was above 50 mV m⁻¹. Very little of the time was the field strength for any of the locations above 250 mV m⁻¹. A set of graphs similar to Figure 10, but covering all volunteer/band/tag combinations is shown in Appendix F.

5.1.3 Sensitivity aspects

The graphs in Appendix F show that the recorded field strength was below the 50 mV m^{-1} PEM detection threshold for much of the time and this was analysed in more detail. Among the 43,934 records taken across all the volunteers, only 8 values were above the detection threshold in each of the FM, TV3 and UMTStx bands. Table 15 shows the number of values above the detection threshold for the remaining PEM frequency bands. The sequence of location numbers in the table reflects the order in which the locations appear in the key to the relevant graph in Appendix F.

Frequency	Location	Volun	iteer nu	Imber							Total for all	
band	number	1	2	3	4	5	6	7	8	9	volunteers	
TV4&5	All 1 2 3 4 5 6 7	66 7 16 27 3 14 2	19 1 0 1 1 13 3	225 0 2 4 2 51 166	84 2 1 3 0 27 28	1809 252 183 1215 1 40 17 11	33 1 1 0 1 10 20	67 12 0 1 39 13 1	104 1 0 15 4 67 17	205 10 4 1 0 45 145	2612	
GSMtx	All 1 2 3 4 5 6 7	96 79 3 3 4 0 7	7 0 0 0 3 4	709 8 2 651 5 4 37	97 14 1 14 14 10 44	161 15 19 11 14 13 48 36	33 1 3 0 3 2 24	79 12 3 1 3 4 20 35	36 0 0 8 27 1	112 10 1 2 4 0 95	1330	
GSMrx	All 1 2 3 4 5 6 7	2825 1389 439 911 0 17 69	8 1 0 0 2 4	48 0 0 0 0 32 16	115 0 0 0 29 86	141 0 1 0 2 96 13 29	28 1 0 1 7 19	76 4 0 0 18 34 3	108 0 1 0 0 107 0	257 0 1 0 0 0 256	3606	
DCStx	All 1 2 3 4 5 6 7	4 3 0 0 0 0 1	4 0 0 0 2 2	36 2 0 9 0 3 22	59 7 0 5 0 5 41	98 2 8 10 5 36 18 19	18 1 3 0 1 2 11	35 0 1 0 1 1 20 12	12 0 1 0 0 11 0	89 0 0 0 0 0 89	355	
DCSrx	All 1 2 3 4 5 6 7	1606 599 395 539 1 11 61	9 1 0 5 2	56 0 2 0 1 45 8	79 0 0 0 18 61	282 0 1 0 74 191 16	41 1 0 4 15 21	58 2 0 0 13 38 4	116 0 1 0 0 115 0	315 1 0 1 1 11 302	2562	
UMTSrx	All 1 2 3 4 5 6 7	2 0 0 0 1 1	1 0 1 0 0 0	19 0 0 0 0 12 7	14 0 0 0 5 9	46 0 1 1 0 36 4 4	4 0 0 0 1 3	25 0 0 0 9 13 2	29 0 0 0 0 29 0	83 0 0 0 0 0 83	223	
Total number of records	All 1 2 3 4 5 6 7	5019 2070 458 1021 1025 194 158	5040 1130 808 1736 874 343 149	5040 1143 462 1902 910 236 384	4797 698 165 1810 651 269 1087	5040 634 421 1510 720 473 1075 84	5022 737 424 1891 946 216 808	5040 943 796 1742 744 263 353 80	4524 793 321 1718 754 734 152	4412 775 107 1095 515 47 1873	43934	

 Table 15 Number of personal measurements above the PEM detection threshold for various volunteer/band/location combinations and the corresponding total number of records

Considering the data in Table 15 and the graphs in Appendix F, a range of exposures was evident in the TV4&5 bands across the volunteers and locations, although 94% of values taken across all volunteers were below the detection threshold. Of the values above the threshold, 69% were acquired from Volunteer 5, who, as noted in analysing the spot measurement data (see Section 4.1.4), lived in Southeast London and nearer to VHF/UHF broadcast radio masts than the other volunteers.

Unlike the other bands, the GSMtx, DCStx and UMTStx bands do not contain signals that are continually present; they contain the generally short duration transmissions from individual mobile phones to base stations while calls are taking place. The phones may be used by the volunteers or by other nearby people. Simple calculations suggest a mobile phone would have to be within around 100 m of a PEM to produce a field above the PEM detection threshold^{*}. It is notable that, when Volunteer 5 travelled into London on a commuter train, the effect of passengers using their mobile phones in the train was pronounced.

A range of exposures is evident among the volunteers in the GSM and DCS mobile phone transmit bands, as Volunteer 2 recorded only 11 values above the detection threshold in these bands over the entire week, whereas Volunteer 3 recorded 745. When Volunteer 3 was in the bedroom, 651 of these values were recorded in the GSMtx band overnight. The values were at a level too low to be associated with a phone in the same house, and given that the house of Volunteer 3 was in a sparsely populated area, this seemed a puzzling result. Discussions with Volunteer 3 revealed that the PEM had been placed next to a DECT base station on a bedside table and so it seems likely that the signals from this have been registered in the GSMtx band.

As noted in Section 4.1.4, Volunteer 1 lived at a distance of around 300 m from a mast and significantly closer to a mast than any of the other volunteers. This is evident in the personal measurements for the GSMrx, DCSrx bands, in that field strengths above the PEM detection threshold are recorded for an appreciable amount of the time, up to 96% in the case of this volunteer's dining room. The readings from the other volunteers exceed the detection threshold for much smaller amounts of time, typically less than 10%, in these bands and the strongest signals seem to be recorded when the volunteers are outdoor or in their cars, rather than in the home. Few signals are recorded above the detection threshold in the UMTSrx band.

5.2 Personal exposure mean estimates

5.2.1 Derivation

Numerical methods, as described in Section 2.3, were used to impute the mean electric field strength in the PEM frequency bands for the different volunteers and locations. The approach was likely to be unreliable for the intermittent nature of the signals in the three mobile phone tx bands and so these bands were excluded. Also, the FM and TV3 bands could not be considered due to lack of data above the detection threshold. The personal exposure mean estimates are shown in Table 16 with the 95% confidence interval, as reported from the numerical algorithm (not a measurement uncertainty).

^{*} Assumptions: 2 W power, as for GSM900 peak, unity gain for the antenna and an inverse square dependence of power density on distance. This gives an electric field strength at 100 m = 77 mV m⁻¹.

Volunteer	unteer Location number			Frequency band								
number			TV4&5		GSMrx	DCSrx	UMTSrx					
1	All 1 2 3 4	Living room Dining room Bedroom Office (Work)	33 (30–35) 41 (38–45) 42 (39–45) 31 (29–34) 6.5 (5.7–7.5)	8 4	73 (64–84) 77 (67–88) 104 (77–144) 115 (100–132)	53 (47–61) 56 (49–64) 68 (59–78) 131 (97–181)						
	5 6	Car	15 (13–17)	9	38 (33–43) 27 (24–31) 9	25 (19–35) 34 (26–48) 6						
2	All		2.7 (2.3–3.1)	5	8.1 (7.1–8.3) 2	2.2 (2.0–2.6) 3						
	1 2 3 4	Dining room Bedroom Office (Work)										
	5	Car	14 (12–16) 17 (13–24)	3	25 (23–27) 2	8.1 (7.5–8.8) 5						
3	All	Outdoor	15 (11–21)	<u> </u>	2.9 (2.2–4.0) 6	15 (11–21)	9.0 (8.3–9.7) 4					
	1 2 3	Living room Kitchen Bedroom	2.7 (2.5–2.9)	2		3.9 (2.9–5.4) 2						
	4 5 6	Office (Work) Car Outdoor	14 (13–16) 53 (39–73) 67 (58–77)	2	39 (29–53) 50 (32–84)	46 (34–64) 18 (13–25) 8	25 (22–29) 12 (10–13) 7					
4	All 1 2 3 4	Living room Kitchen Bedroom Office (Work)	9.0 (6.7–12) 16 (14–17)	2	12 (9.2–17)	9.8 (9.1–11)	4.1 (3.5–4.7) 5					
	5 6 7	Car Outdoor Bathroom (Home)	26 (23–30) 9.1 (8.0–11) 51 (47–55)		29 (21–40) 19 (18–21)	21 (18–24) 16 (15–17)	12 (9.3–17) 5 5.4 (4.8–6.3) 4					
5	All 1	Living room	52 (48–56) 55 (51–59)		11 (7.9–15)	18 (14–25)	8.1 (7.1–9.3)					
	2 3	Kitchen Bedroom	53 (49–57) 68 (63–74)		13 (10–19)	14 (11–20) 8	9.0 (7.8–10) 6					
	4 5 6 7 8	Otfice (Work) Car Outdoor Train Study (Home)	26 (24–31) 29 (27–32) 530 (330–820 98 (85–110)))	1.5 (1.4–1.6) 2 49 (36–68) 26 (24–28) 63 (47–89)	40 (30–56) 54 (40–75) 47 (36–67)	27 (23–31) 33 (25–46) 3 40 (35–45) 4					
6	All 1	Living Room	4.7 (4.4–5.1)	4	5.5 (4.8–6.3) 2	4.2 (3.9–4.5) 8						
	2 3 4 5 6	Bedroom Office (Work) Car	90 (79–100) 25 (24–27) 19 (16–22)	2 10	16 (12–22) 7 7.6 (5.6–10)	15 (14–16) 4 21 (19–22) 10 (7.6–14)						
7	All 1 2	Living Room Kitchen	4.3 (3.8–5.0)	1	6.3 (4.7–8.8) 2.9 (2.7–3.2) 4	2.6 (2.4–2.8) 5 0.4 (0.4–0.5) 2	15 (13–17) 8					
	3 4 5 6 7	Bedroom Office (Work) Car Outdoor Train	39 (34–45) 15 (14–17)		19 (16–21) 30 (22–41) 60 (45–85) 3	19 (17–22) 27 (23–31) 14 (13–15) 4	26 (24–28) 9 25 (22–29) 70 (65–76) 2					
8	All 1 2 3	Living Room Kitchen Bedroom	7.1 (5.2–9.8)		8.8 (7.7–10)	8.1 (6.0–11)	13 (12–14) 3					
	4 5 6 7	Office Car Outdoor Dining Room	5.0 (4.4–5.8) 30 (22–41) 40 (38–44) 16 (14–18)	4	36 (26–49)	36 (27–50)	19 (17–22)					
9	All 1 2 3	Living Room Kitchen Bedroom	13 (9.3–17) 15 (14–16) 31 (23–44) 60 (56–65)	3 3	13 (9.9–18)	17 (13–24)	9.8 (7.3–14)					
	5 6	Music Room Outdoor	100 (95–110) 24 (18–34)		36 (23–60)	56 (51–60) 46 (29–77)						

Table 16 Personal exposure mean electric field strength estimates in mV $\rm m^{-1}$ (95% CI) for various volunteer/band/location combinations

Note, estimates shown in red were derived on the basis of fewer than ten measured data points above the detection threshold. The exact number of such data points is shown to the right of the confidence interval

5.2.2 Resulting mean field values

Where small numbers of values above the detection threshold were used in the analysis, the algorithm seems to sometimes become unreliable. For example, with Location 7 (train) for Volunteer 7, there were 2 values out of 80 above the detection threshold in the UMTSrx band and they were both at a level of 70 mV m⁻¹. In these circumstances, it would not be possible to fit a lognormal distribution through the two data points in a meaningful way and the algorithm gives a doubtful electric field strength of 70 (65–76) mV m⁻¹ for the mean. Where less than ten values have been used to derive the mean estimate, the means are shown in red in Table 16 and the number of values used is shown to the right of the confidence interval.

The data generally show that mean estimates could be constructed much more frequently when volunteers were outdoors, or travelling in cars and trains, than when they were indoors. This is because the fields were above the detection threshold for more of the time at these locations, as can be seen in the figures in Appendix F.

5.2.3 Correlation with spot measurements

The personal exposure mean estimates in the above section were compared with narrowband spot measurements taken at the same locations and the results are shown in Table 17, where values for both sets of data were available.

Circumstar	nces	Electric	field stre	ngth, V r	n ⁻¹			Ratio, dB			
		Persona	al measu	rement	Spot me	easureme	ent				
Volunteer	Location	TV4&5	GSMrx	DCSrx	TV4&5	GSMrx	DCSrx	TV4&5	GSMrx	DCSrx	
1	1	41	77	56		86	77		-1.0	-2.8	
	2	42	104	68		104	119		0.0	-4.9	
	3	31	115	131		170	113		-3.4	1.3	
	4	6.5				9.5	18				
3	2	2.7		3.9	16	2.9		-15			
	4	14				3.6	6.9				
4	1	16			8.5	3.4	23	5.5			
5	1	55			69			-2.0			
	2	53	13	14	82			-3.8			
	3	68			130	5.9		-5.6			
	4		1.5			7.1	15		-13		
6	4	90				20	42				
7	1		2.9	0.4							
8	4	5.0			23	6.1		-13			
9	1	15			11	28	16	2.9			
	2	31			31	45	30	0.0			
	3	60			13	25	28	14			

 Table 17 Difference between personal exposure mean estimates when the diaries showed the volunteers were at the spot measurement locations and narrowband spot measurements

Note, values shown in red were derived on the basis of fewer than ten measured data points in the personal exposure records above the PEM detection threshold.

The values in red were derived from small numbers of values above the detection threshold, and, as mentioned above, were regarded as potentially unreliable.

There were few situations where good data were available from both spot measurements and personal exposure means. These were confined to the TV4&5 band in the house of Volunteers 5 and 9 and the GSMrx and DCSrx bands in the house of Volunteer 1. In this limited set of cases, the data are within 6 dB of each other, suggesting that the spot measurements were representative of personal exposures at the locations.

5.3 Summary of personal measurements

On the whole, the PEMs acquired data in accordance with their specifications, although there were two functional problems encountered. A software problem, which has since been corrected by the manufacturer, caused the corruption of all records where the instrument temperature was below 10°C. Also, one of the PEMs seems to not have been charged fully at the start of the run, despite being charged in accordance with the instructions, and this resulted in total loss of the data from one of the volunteers.

Much of the time, the recorded data were below the 50 mV m⁻¹ detection threshold of the PEM and this lack of sensitivity seems likely to limit its ability to construct an exposure gradient within a study. Nevertheless, the PEM does seem to work well in discriminating the relatively high exposures of people who live near to mobile phone base station and television broadcast transmitters from those of people living elsewhere. The data also generally showed higher exposures in all the bands when the volunteers were outdoors, or travelling in cars and trains, than when they were indoors.

The diaries showed when the volunteers were at particular locations and so the personal exposure records could by analysed to develop mean exposure estimates for locations, even where much of the time the exposure level was below the detection threshold. In a small number of cases, where there were at least ten personal exposure values above the detection threshold and spot measurements were also available, the two sets of data agreed well. This suggests that spot measurements might be a reasonable surrogate for personal exposures occurring at indoor locations.

6 VOLUNTEER EXPERIENCES AND PERCEPTIONS

This section summarises the results from the questionnaires completed by the volunteers following the their week-long trials of the personal exposure meter (PEM). A template questionnaire, as supplied to each volunteer on returning the PEM, is included in Appendix G.

6.1 Strategies for wearing the PEM on the body

The volunteers were not given prescriptive instructions about how and when they were to wear the PEM on their body, but the belt clip and the method of mounting on the waist were drawn to their attention in the guidelines for volunteers document (see Appendix B). The volunteers were encouraged to experiment with wearing the PEM in different ways to find what suited them and their clothing style.

Volunteers 1, 4, 5, 8, and 9 did not use any form of bag/rucksack and reported varying degrees of success in wearing the PEM using its belt clip. It was apparent that, apart from Volunteers 1 and 5, these volunteers had struggled, and had found it preferable to carry the PEM when walking and place it beside them at other times.

Volunteer 2 wore the PEM inside a small rucksack behind the shoulders. This meant that the PEM did not interfere with movement when standing and walking, but the rucksack had to be removed when sitting down. There would be the possibility of the PEM rotating inside the rucksack to face the body, thus shielding its sensors, but this was avoided by hanging the PEM by its belt clip from a loop of tape inside the rucksack. This volunteer also placed the PEM inside a large handbag on occasions.

Volunteers 3 and 7 used the PEM inside a bag strapped around their waist. This had the comfort advantages of using a rucksack and also allowed the bag to be rotated around the waist to a convenient position when sitting, standing, driving etc.

Volunteer 6 used a soft binocular case worn across body to contain the PEM. The loose shoulder strap allowed the PEM to be moved around the body to a convenient position, even when driving. Volunteer 10 used a similar arrangement with a small shoulder bag about the size of a 1 litre bottle.

Particular difficulties reported with wearing the instrument from the waist with its belt clip included

- a The clip pushed off the belt when the volunteer sat down
- b When hung from the waist of loose trousers with an elasticated waist, the PEM developed a pendulum effect while walking
- c The clip did not fit with all types of clothes, e.g. dresses without belts
- d It was not practical to wear the PEM during exercise, e.g. running, cycling, dancing
- e The PEM kept hitting things inside the house as the volunteer turned

6.2 **Practicality of wearing the PEM**

The responses to the question about practicality of wearing the PEM in various situations are summarised in Table 18. Volunteer 10 did not assign any scores.

Situation	Volunteer number and gender										
	1 (M)	2 (F)	3 (F)	4 (F)	5 (F)	6 (M)	7 (F)	8 (F)	9 (F)	10 (M)	
Standing	2	4	1	5	1	1	1	3	1		
Walking	2	4	2	5	1	1	1	3	2		
Sat at table	3	5	3	5	4	4	1	4	4		
Sat on sofa	4	5	4	5	4	5	2	5	5		
Reclining	4	5	5	5	4	4	5	5	5		
Scoring system	1) No p 2) Mino 3) Som 4) Fairly 5) Total	 No problem Minor problems Somewhat problematic, but still practical on balance Fairly impractical Totally impractical 									

Table 1	8 Practicality	of wearing t	he PEM in	various situations,	as reported by the volunteers
<u></u>					

The table shows a wide variation in the reported practicality of wearing the instrument from volunteer to volunteer even within the same situation. The volunteers generally found it practical to wear the PEM from the waist when standing or walking, but not when sitting or reclining. In these situations, where the volunteer is not moving around, it would be usual to take the PEM off and place it nearby.

6.3 Placing the PEM near the body

When the volunteers were not moving around, they generally removed the PEM and placed it nearby. When in their lounges, volunteers were usually sat on a sofa or chair and placed the PEM on the arm of the chair, or on a table next to the chair. The volunteers indicated that it was easy to forget to pick up the PEM when they went to the kitchen or bathroom, and that sometimes when they knew they would only be away for a few minutes, they chose to leave the PEM behind.

When in the kitchen, volunteers (except for numbers 2, 4 and 8, who wore the PEM) tended to put the PEM on a work surface at a variable distance, generally up to 1-2 m, away from them.

When in the bedroom, the volunteers generally placed the PEM near to the bed, but at a variable height due to differing bedroom furniture. Some put the PEM on the floor, others on a table of similar height to the bed and others on taller furniture such as a chest of drawers.

6.4 Design of the PEM

There was a clear consensus among the volunteers that the instrument was larger than ideal and that it should be made smaller if possible. The exact text of the comments on the size of the PEM were as follows:

- Make much smaller
- Far far too big to wear
- Very large and noticeable when worn on body
- It's too big
- Quite big
- OK for a week, but would need to be smaller if worn for a longer period
- It would be easier if smaller
- Too big for constant wearing
- Smaller would obviously be better
- It would be easier if it was smaller

One volunteer observed that a good target size would be similar to a large mobile phone. However, two volunteers pointed out that the large size of the PEM meant that they were more likely to notice it and therefore less likely to forget to pick it up.

Views on the weight of the instrument were split roughly equally, with only two volunteers strongly expressing that the PEM was too heavy when worn on the waist. Carrying the PEM in some form of shoulder bag would probably lessen concerns about its weight.

There were no major problems with the colour and appearance of the PEM. On the whole, the volunteers were happy with its shape, although two observed that it could be worn less obtrusively under clothes if it were thinner. It was observed that the less conspicuous the instrument appears the better. As such, it will be important to avoid bright colours, logos and labels in a study.

There were mixed feelings over the belt clip and it was noted that it was only of use to volunteers who wear trousers. Some volunteers felt it was not strong enough and some experienced the PEM detaching unexpectedly, particularly when they sat down. One asked for a belt clip that could be used at 90° to the current one so the PEM could be clipped to braces.

6.5 Perceptions of the PEM

6.5.1 Effect on behaviour

Using a body worn instrument, such as a personal exposure meter, inevitably causes some changes in the behaviour of the wearer. The important question is whether any of these changes in behaviour affect their exposure. The volunteers were asked whether there were any situations in this trial where they felt using the PEM had appreciably modified their behaviour. The main issues were associated with filling in the diary (which, as one volunteer observed, rapidly became a habit) and keeping the PEM near the volunteer.

One volunteer felt they had moved around less in their house due to the burden of knowing that they would have to complete a diary entry. Another highlighted forgetting to pick up the instrument on leaving a location, because they then had to retrace their movements.

6.5.2 Self consciousness

Volunteers should not feel self-conscious or ill at-ease when using the PEM and so a question was asked about this. Generally the volunteers felt comfortable with the instrument, although it was regarded as better to wear the PEM under clothes or in a bag so it was not on view.

It was noted that the PEM does not really resemble any other device in common use and so it is unlikely to be mistaken for anything else. However, one volunteer thought it might have been mistaken for some form of listening device. Another noted that it gave them a lop-sided appearance when walking with it under clothes and felt that this might have aroused suspicion.

6.5.3 Questions from others

The volunteers were asked whether they had been questioned about the PEM by people other than friends, family and immediate work colleagues. Few situations had arisen and any questions had been simply answered. One person had remarked to a volunteer that the PEM looked like a baby monitor.

6.5.4 Safety aspects

The volunteers were asked to identify any situations where they had felt it unsafe to use the PEM and had chosen not to wear or carry it with then. Driving and sleeping had been highlighted as examples of such situations in the guidelines for volunteers (see Appendix B). Other situations encountered by the volunteers were in an aerobics class and in a nightclub, where it was felt the PEM might get damaged or stolen. One volunteer chose to leave the PEM at home on a day when they spent some time supervising a small child because they wanted to be able to move more freely.

6.6 Use of the PEM in future studies

Questions were asked about how long the volunteers would be prepared to use the PEM in a future trial with and without keeping a written diary and the results are shown in Table 19. Generally, a week was seen as the maximum time while keeping a written diary, with seven of the volunteers indicating this period. Without keeping a written diary, some of the volunteers would be prepared to wear the PEM for longer, so two to four weeks would seem practical. One volunteer was prepared to use the PEM for three months, with or without keeping a diary "if they were not expected to wear it on their body or carry it every time they went out of the room for a few minutes."

The volunteers were then asked to consider how long they felt it would be reasonable to ask a member of the public to use the PEM in a future study and these results are also shown in Table 19. With a diary, most of the volunteers felt a week would be acceptable,

but there were a number of reservations and one volunteer felt it would not be reasonable to expect a member of the public to keep a diary for any length of time. One volunteer felt that much would depend on whether the PEM could be made lighter and smaller. Another suggested that there should be a review at one week, after which the trial could be terminated for any volunteer who wished to leave it. If a member of the public were not expected to keep a diary, again it would seem possible to use the PEM for longer, with 1–2 weeks seeming acceptable to the volunteers.

Maximum period regarded as	User of the PEM								
acceptable	Volunteer in t	his trial	Member of the public						
	With diary	Without diary	With diary	Without diary					
Not at all			1						
3 days	1*	1*							
1 week	7	2	8	4					
2 weeks	1	2		3					
1 month		4		2					
3 months	1	1							

 Table 19 Number of volunteers indicating particular periods of time that they regarded as the maximum for the PEM to be used in future trials

* This volunteer could not find a comfortable way to wear the PEM, but indicated they would be prepared to use it for longer if a way could be found

6.7 Other comments

At the end of the questionnaire the volunteers were asked if they had any final comments and a range of views were expressed.

Keeping a diary was regarded as tedious, and particularly so because it was not easy to sit down to write when wearing the PEM. The diary was given to the volunteers in the form of printed A4 sheets on a clipboard and it was suggested that it would have been more convenient as a smaller spiral-bound book that could fit in a pocket.

One volunteer observed that having to complete the diary was a useful prompt to remember where they had put the PEM when they were not wearing it and that they might have tended to "lose" the PEM more if they had not had to keep a diary.

One volunteer felt the PEM should be supplied with a bag having versatile straps that can be used around the waist or over the shoulder.

It was suggested that it would be helpful to be able to confirm that the PEM was working at any point in time, especially with long recording intervals where the light only illuminates infrequently. Some way of linking the unit's internal clock with events was suggested as possibly useful, either with the unit displaying its own time so that can be used with a written diary, or with the provision of event buttons. The possibility of entering location data on the PEM via a keypad instead of keeping a written diary was also raised. One volunteer developed an interest in the detailed technical aspects of the PEM. It was suggested that the PEM could use a memory card, similar to that in digital cameras, in order to facilitate easy transfer of data and storage in a non-volatile format. The volunteer also suggested that developing a charging cradle on which the PEM could be placed at night next to people's beds would allow trials of longer than a week and with shorter recording intervals.

6.8 Summary of volunteer feedback

The feedback from the questionnaires highlights the importance of ensuring that a comfortable way of wearing the PEM is established for study participants.

There was a strong consensus among the volunteers that the PEM needs to be smaller in order for it to be used as a body-worn instrument. Weight was felt to be less of a problem than size. A better way to use the current version of the PEM seems to be inside some form of shoulder or waist-mounted bag, since this allows it to be moved around the body easily to suit posture and to make it more discreet. People differ in their preferred ways of wearing the PEM and it would be useful to develop a carrying bag that can be worn in several different ways

Completing the diary was regarded as a burden by the volunteers and a number of ways to reduce this burden were suggested. The format of the diary could be improved, since the clip pad with A4 sheets used in this trial was not ideal. A smaller spiral-bound pocket-sized notebook would be better. Alternatively, the PEM could be developed to allow entry of the location identifier via a keypad, thus avoiding the need for a diary.

7 CONCLUSIONS AND RECOMMENDATIONS

This section gives the conclusions from the laboratory testing and volunteer trials of the PEM. Recommendations following from the conclusions are italicised.

7.1 **RF performance aspects of the PEM**

7.1.1 Frequency bands

The personal exposure meters (PEMs) supplied to this project had specified measurement bands appropriate for FM broadcast radio, GSM1800 (DCS) mobile phones and base stations, and UMTS mobile phones and base stations in the UK. The bands specified for UHF television broadcast, and GSM900 mobile phones and base stations, were of insufficient width to capture all such active sources in the UK. The TV3 band supplied to account for VHF broadcast television transmitters in France is unnecessary for the UK, where such sources are not present. Important omissions from the present band coverage of the PEM include TETRA (emergency services radio), DECT (cordless phones) and WLAN (wireless computer networking).

The GSM900 and UHF TV bands on the PEM should be widened to cover sources active in the UK. Additional bands should be provided for TETRA base stations, DECT and WLAN.

7.1.2 Filter selectivity and signal discrimination

The performance of the PEM band filters reflects the difficulties of designing such filters. With continuous signals, not having the TDMA characteristics of real telecommunications signals, there is evidence of significant out of band responses, including measurements of signals with frequencies in some of the PEM bands, by other PEM bands, i.e. they could be measured twice. In particular, there is negligible rejection of continuous signals in the GSM900 mobile phone band by the filters for the broadcast television band.

In practice, the manufacturer has designed the PEM to discriminate between continuous and intermittent (TDMA) signals in order to (effectively) improve the band selectivity. This means that only the bands designed to receive signals from GSM mobile phones should be able to receive such signals. Conversely, only bands except for those for GSM mobile phone signals should be able to measure continuous signals, as for broadcast radio and television.

With GSM base station signals, broadcast carriers (BCCH) are emitted continuously at the maximum power level, whereas other secondary carriers (TCH) are emitted intermittently with variable slot occupancy and power levels. Consequently, the signal discrimination function will prevent the secondary carriers from being measured in the appropriate band, unless they have full slot occupancy. Also, the signal discrimination function will not prevent such carriers from being measured in the mobile phone transmit bands when they have partial slot occupancy.

The performance of the PEM band filters should be improved, if possible, and appropriate measurement of the secondary carriers from GSM base stations should be addressed.

7.1.3 Response to modulated signals

Across all eight PEMs, the responses to appropriately modulated signals were broadly correct (within 3 dB) for individually applied signals. However, when considered individually, one of the PEMs was found to under-respond to UMTS base station signals by about 6 dB.

The calibration certificates supplied with the PEMs appeared to show typical responses for the PEMs, rather than individual calibrations traceable to standards.

The PEMs should be individually calibrated so that their readings are traceable to appropriate standards with defined uncertainties.

7.1.4 Response to multiple signals

The PEMs do not respond correctly to multiple signals present in the same band, and seem to give a reading more equivalent to the field strength of the strongest signal than to the appropriate result, which would be the RMS field strength of all the signals combined. This is a particular problem where multiple signals of similar strength are present, as from broadcast television stations in the UK that may produce up to five signals of similar strength.

The response of the PEM to multiple in-band signals should be examined to see if it can be rectified. If this cannot be done, consideration should be given to the additional uncertainty introduced in any studies carried out.

7.1.5 Isotropicity

The PEM sensing element incorporates three orthogonal electric monopoles mounted on the faces of a cuboid. Such a configuration is potentially able to give a fairly isotropic response; however, the PEM has circuit boards and batteries of appreciable size adjacent to its sensor and these can be expected to degrade its isotropicity.

Measurements confirm that the sensor is significantly less isotropic than the ± 0.5 to ± 2.5 dB (according to band) claimed in its specification. Nulls of at least 13.8 dB depth and peaks of at least 5.3 dB were identified. Given the design difficulties, it is difficult to see how this situation could be greatly improved.

When the PEM is being carried by a moving person, it is likely that the effect of the movement will be to average out the polar response over time so the lack of isotropicity would not be a problem. The lack of an isotropic response would also not be a problem if the PEM were placed in a fixed position in a fading multipath environment because the same averaging of its response over time will take place.

Lack of isotropicity is a potential problem for the stationary PEM if there is a dominant field component in a particular direction. In such situations it may over-read or under-read by the above amounts according to how it is aligned with the field.

The polar response of the PEM should be measured in an appropriate test facility and the specification updated in the light of the results. Any changes to the design that can improve the polar response should be enacted.

7.1.6 Sensitivity

The 50 mV m⁻¹ detection threshold of the PEM in each of its bands reflects the sensitivity that can be expected of an instrument of its size, and it would probably be difficult to lower the threshold significantly without making the PEM larger. Little practical advantage would be gained by improving the sensitivity by a small amount due to the range of exposures present in the population.

Much of the time, the recorded data from the ten volunteers who each used the PEM for a week in this project were below detection threshold, and this lack of sensitivity seems likely to limit its ability to construct an exposure gradient within a population study. Nevertheless, the PEM does seem able to discriminate the relatively high exposures of people who live near to mobile phone base station and television broadcast transmitters from those of people living elsewhere.

7.2 Functional aspects

7.2.1 Software

The PC software had a number of bugs when the PEMs were first supplied to the study and these were communicated to the manufacturer, leading to revised versions of the software. All major issues encountered now seem to have been resolved.

7.2.2 Battery charging

There seems to be a problem with the reliability of the battery charging arrangements for the PEM in that the chargers sometimes indicate charging is complete when it is not. It was noted that, although the PEMs use Nickel Metal Hydride batteries, the supplied chargers are labelled as suitable only for Nickel Cadmium types.

The charging reliability problems should be resolved before the PEM is used in further studies. If studies take place before they are resolved, the battery voltage should be examined each time after charging to ensure the PEM really is fully charged.

7.2.3 Storage integrity

The storage of data in the PEM is (effectively) volatile, in that the data are irretrievably lost if the battery becomes discharged, for example due to the data not being downloaded promptly after a logging run has been completed. This is likely to result in the loss of some data in a practical study, and it should be avoidable through design.

The data storage hardware should be reconsidered to make lost data recoverable after recharging of the batteries. If redesign is not possible, critical care will have to be taken in studies to fully charge PEMs immediately before use and download the data immediately on completion of logging.

7.3 Ergonomic aspects

7.3.1 Wearing

Volunteers generally found the PEM difficult to wear on their waist, and not supplying an alternative method for them to carry the PEM caused them difficulties in this trial. Several of the volunteers devised other ways of carrying the PEM on their person, such as in a small rucksack, in a bag worn on the waist, or in a shoulder bag. On balance, the shoulder bag seemed the most practical since it could be rotated about the body when the volunteers sat down or were driving etc.

The PEM should be supplied with a shoulder bag so it does not have to be worn on the waist. The bag should allow for the PEM to be attached inside so it cannot rotate to face the body.

7.3.2 Size

There was also a strong consensus among the volunteers that the PEM needed to be smaller to be used as a body-worn instrument. Weight was felt to be less of an issue than size. It is likely that concerns over the size of the PEM could be ameliorated by supplying it in some form of shoulder bag, as recommended above.

7.4 Placement when not on body

An important technical question when the PEM is taken off the body and placed nearby is where is the most appropriate position to put it in order for it to give a realistic estimate of personal exposures? It is not easy to answer this question definitively in the absence of detailed experimental testing in houses where the exposure levels are consistently above the PEM detection threshold.

Poor placement of the PEM will give systematically higher or lower exposures and it may be possible to develop guidance in order to avoid poor placement. Positioning the PEM on window sills will lead to over-estimates of exposure and positioning it at floor level will lead to under-estimates.

Since the laboratory testing has shown the PEM is not perfectly isotropic, it is also interesting to ask whether the PEM should face towards or away from a volunteer when placed nearby. One volunteer remarked that they always placed the PEM on its back so it was less likely to be knocked over. Using this orientation would avoid the need to decide whether the PEM should face towards or away from the person being monitored.

Guidance should be developed for users of the PEM in order to avoid inappropriate placement when it is not carried on the body.

7.5 Use in future studies

It is possible to envisage two broad applications for the PEM, and the technical requirements are different for each application. First, the PEM could be used as a validation tool for exposure modelling techniques, in which case it only has to measure

the field of individual signals from known transmitters. Second, the PEM could be used as a tool to measure the total exposure of subjects to all RF signals, in which case it needs to sum the signals in the context of the chosen exposure metric. With due heed given to the recommendations made above, the PEM should be useful for both applications.

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APPENDIX A

Volunteer Trial Protocol

This appendix contains the protocol that was developed for the volunteer trial and which the project workers followed. The guidelines for volunteers and the consent form to which this appendix refer are included in Appendix B. The narrowband spot measurement protocol referred to is in Appendix D.

Volunteer Protocol for MTHR PEM Evaluation Project

This document specifies the procedures for the involvement of volunteers who will use the Personal Exposure Meter (PEM) into the study. It specifies the procedures to be used by the study investigators in managing the volunteer inclusion, informed consent and supporting the acquisition of data.

Initial approach to potential volunteers

An initial informal approach to potential volunteers is to be accompanied by distribution
of the Guidelines for Volunteers document to those who show an interest in the project.
Those who are still interested in taking part will then be given a few days to discuss
taking part with their line management and others who may be affected, such as their
family, after which they will be contacted again.

Inclusion of volunteers

- Those volunteers who are able to take part are to be individually talked through the Guidelines for Volunteers document by the investigator. This is to ensure they fully understand the nature of their involvement and to answer their questions.
- The spot measurement equipment will be shown to the volunteers and they will identify, through discussion with the study investigator, the five locations where they normally spend most of their time and where spot measurements will be made on distribution and collection of the PEM.
- The arrangements for making the spot measurements safely, particularly when in the houses of the volunteers, will be discussed and the importance of removing any clutter and breakables from the locations and access ways will be stressed.
- The volunteers will be shown a PEM and encouraged to consider how they might wear it on their person and where they might place it if they feel the need to remove it. It will be ensured that that they have a suitable belt or other means of attachment.
- The volunteers will be given the Consent Form and encouraged to ask any remaining questions. Once they have signed the form, they will be considered as included in the study.

Confirmation of arrangements

- A seven day interval during which the volunteer is able to use the PEM and during which their activities are expected to be fairly typical will be agreed.
- The order in which the spot measurement locations are to be visited will be confirmed, ideally starting with those in the workplace and then continuing with those in the home.
- The precise dates, times and meeting points for distribution of the PEM and the initial set of spot measurements will be double-confirmed.
- Written confirmation of the arrangements will be sent to the volunteer.

Distribution of PEMs

- The volunteer will be met at the agreed location/time and the spot measurements will be made in the agreed sequence.
- The location occupancy diary will be given to the volunteer and discussed so they are sure how/when to complete it.
- The feedback form will be given to the volunteer and discussed so they are clear what information is being sought.
- The arrangements for collection of the PEM and repeat of the spot measurements a week later will be confirmed.
- The PEM will be programmed to record once every 2 minutes for 10080 minutes, i.e. 7 days, and its clock will be synchronised to that of the survey laptop computer.
- The PEM will be started logging and given to the volunteer.

Collection of PEMs

- The volunteer will be met at the agreed location/time and the spot measurements will be repeated in the agreed sequence.
- The PEM will be collected and the data contained within it downloaded to a computer without delay.
- The completed location occupancy diary will be collected from the volunteer.
- The completed feedback form will be collected from the volunteer.

Note on Spot measurements

Each spot measurement will first be made according to the Spot Measurement Protocol for Environmental RF Exposures (80 MHz - 2.5 GHz) and then with a specially configured PEM (other than the one to be given to the volunteer). This second PEM is mounted on the same tripod as used for the first measurement and at a single height of 1.5 m. Its clock is to be synchronised to that of the survey laptop computer and it is to record once every 5 seconds for the full day (assume 9 hours). The start time of each spot measurement with this PEM is noted from the laptop computer and the PEM is manually rotated in azimuth through 45° every minute. The stop time is them noted when a minute has been spent at each angular position over a full 360° .

APPENDIX B

Guidelines for Volunteers and Consent Form

This appendix contains a document that was drawn to the attention of all 270 staff at the Health Protection Agency's Centre for Radiation Chemical and Environmental Hazards located in Chilton, Oxfordshire, UK, in order to inform them about the study and encourage them to take part in the volunteer trial. The document explains the commitment that would be required and gives sufficient information for the volunteers to provide written informed consent to take part. The consent form is also included in this appendix.
Personal Dosimetry of RF Radiation Guidelines for Volunteers

Background

Some people believe that mobile phone base stations, or other radio transmitters near to them, have affected their health due to the radio waves (radiation) that they emit. However, there are considerable challenges in assessing the exposure of people to radio waves during their everyday lives and little research has been carried out.

This project is being carried out by NRPB under the Mobile Telecommunications and Health Research (MTHR) Programme. It aims to develop new ways to assess the exposure of people to radio waves in order to extend the possibilities for scientific research. We will need the assistance of volunteers and we hope you will consider taking part.

The project will evaluate a newly developed personal exposure meter (PEM) that is able to log people's exposures over time and as they move around. We will need ten volunteers to use the PEMs to gather data and provide feedback on their experiences and perceptions. The PEM can be worn on the body when walking or placed near to the body when stationary.

The project is not a study of people's health and the radio waves involved will only be those to which the volunteers would normally be exposed.



Commitment from Volunteers

Wearing the Instrument

Each volunteer will be given a PEM to carry with them for a period of one week, e.g. Monday-Monday, while it logs their personal exposure from environmental radio transmitters, and also from their personal use of mobile phones[†]. On the days the instrument is handed out and collected, there will be a substantial time-commitment from the volunteers during their normal working hours, hence agreement to take part should be sought from line managers.

Spot Measurements

The volunteers will each be asked to list up to five locations where they generally spend most of their time, when not travelling. Examples might be their office, bedroom, living room and kitchen. On the days the PEM is given to and collected from the volunteers, the research team will visit these locations and make spot measurements of the ambient RF field levels with the survey equipment shown overleaf.

[†] Only the time of mobile phone use and the exposure level are collected. No information is collected on the call content or destination.

Each of the spot measurement locations will take around an hour to survey and the equipment used is quite bulky. We would therefore ask that sufficient space is cleared for us to make the measurements and carry the equipment through your house in safety. In particular, we would ask that any breakables are cleared away.



Volunteer Location Diary

The volunteers will be given a diary to complete, in which they will identify the periods of time during which they have been present at each location.

Feedback on the Instrument

On final collection of their PEM and on repeat of the spot measurements, the volunteers will be asked to complete a questionnaire on their perceptions of the instrument, such as how easy it was to wear and whether it modified their behaviour in any way.

How to wear the Instrument

The PEM is supplied with a belt clip so it can be worn to the rear of the waist and so that the arms do not swing in front of its sensing antennas. The photograph to the right illustrates the position, although the research team will be happy to provide further guidance.

If you find the PEM inconvenient to wear on occasions, please take it off and place it near to you. There will be occasions when it would not be safe to wear the instrument, for example, when driving or in bed. It is also not waterproof. Please remember when you take the instrument off and where you place it so we can gain feedback on these aspects.



Volunteer Consent Form MTHR PEM Evaluation Project

Having read the Guidelines for Volunteers document, I would like to take part in the above project being carried out by the EMF Dosimetry Group at NRPB. I understand that my involvement in the project will require me to

- Carry a personal exposure meter (PEM) with me for a period of one week, sometimes mounted on my body, while it logs my personal exposure to RF radiation.
- Identify up to five locations in my home and workplace where I spend most of my time and arrange access so that spot measurements of RF signal strengths can be made on the days I receive and return the PEM.
- Complete a location occupancy diary for the week showing when I have been present at the spot measurement locations and where I have been at other times
- Complete a questionnaire on my perceptions of the PEM and how using/wearing it affected me.

I consent that the data arising from the above activities may be used by NRPB for the scientific purposes of the current study.

I may receive a copy of the data and any publications arising from the project if I wish.

I understand that NRPB will not publish personal information, such as my name and address.

I have seen the spot measurement equipment and will make sure that the locations where it will be used in my home are tidy and safely accessible to NRPB staff.

I understand that NRPB staff will take reasonable care of my home and possessions when the spot measurements are made.

I will move any possessions that could easily be damaged when making the spot measurements and carrying the equipment through my home.

I will inform the study team if there are any special hazards in my home that they should be aware of. Examples of such hazards would be low ceilings, dogs locked in particular rooms or missing floorboards.

I understand that I can revoke this consent at any time during my involvement in the project.

Signature

Date

Print Name

APPENDIX C

Laboratory Test Results

This appendix contains a typical dataset showing the response of a PEM to CW (continuous and unmodulated) signals of various frequencies. Spurious (out of band) responses are shown in red.

% Response in GTEM cell to CW field strength of 2.5 V/m, X orientation, PEM s/n 001									
Frequency	PEM frequency band								
MHz	FM	TV3	TV4&5	GSMTx	GSMRx	DCSTx	DCSRx	UMTSTx	UMTSRx
49	29.9								
75	80.6								
90	83.4								
98	107.3								
106	85.4								
125	51.9								
145	9.0	6.3							
176		68.5							
198		86.5							
222		78.4							
380		5.0	12.7						
430			57.2						
475			71.3		2.3				
590			152.0						
650			123.5						
820			160.4						
880			166.8	87.7					
895.5			182.8	189.7					
912			150.4	131.1					
940			16.2	-	127.2				
947.5			-		164.3				
955					122.9				
1300									
1715						124.0			
1747.5						112.2	7.9		
1780						129.7	44.5		
1810				4.4		33.7	100.7		3.0
1840				7.9	4.7	8.3	93.9		2.9
1875				4.0	6.9	2.6	93.2	13.2	
1900				3.0	6.0		49.0	73.0	
1925				2.6	3.3		9.6	155.7	
1950								94.2	
1975					2.1			80.1	
2115									69.7
2140									71.0
2165									66.3
2450									

APPENDIX D

Narrowband Spot Measurement Protocol

This appendix contains the protocol that was used to carry out narrowband spot measurements with a small biconical dipole antenna connected to a spectrum analyser. The procedure involves the use of carefully chosen settings for the spectrum analyser to reduce the effects of temporal fading, and averaging of measurements over three heights in order to reduce the effects of spatial fading.

Spot Measurement Protocol for Environmental RF Exposures 80 MHz – 2.5 GHz

Equipment List

- 1) **Spectrum Analyser**. Agilent model E4407B equipped with RMS averaging detector option. Calibration by EMF laboratory is required to derive correction factors for specific modulated signal classes with respect to a power meter.
- Receiving Antenna and Connecting Cable. ARCS miniature biconical antenna calibrated with its cable to give antenna factors. Supporting base plate allows rotation of the antenna through increments of 120° in order to cover three orthogonal polarisations.
- 3) **Antenna Tripod**. To be made of wood/plastic and with index marks to allow the antenna to be mounted quickly and repeatably at heights of 1.1, 1.5 and 1.7 m.
- 4) **Control Computer and GPIB Interface**. Equipped with software to completely control the spectrum analyser settings and indicate when the operator is to change the antenna height or polarisation.
- 5) **Notebook**. To write down accurate descriptions of each measurement position including its juxtaposition with respect to the base station of interest.



Location Characteristics

The antenna shall be mounted on the tripod and such that it is at least 1 m from any conducting or dielectric objects (other than the ceiling), which might disturb its calibration.

The cable to the antenna shall be routed such that it is kept as far away from the antenna cones as possible. If necessary, it is to be realigned after each rotation.

Band Settings

The spectrum analyser shall sweep according to the sequence of band settings in the table below, which have been chosen on the following basis:

- 1) The resolution bandwidths are as wide as possible, while still being narrow enough to reliably resolve individual signals.
- 2) The number of points is chosen to give a spectral resolution significantly finer than the resolution bandwidth
- 3) The sweep time is chosen to give a dwell time for each measurement point that is long enough to give a stable reading with the relevant signal modulations.

Band	Frequency	, MHz	Number of	Resolution	Sweep time,	Frequency	Notes
	Start	Stop	points	bandwidth	seconds	Step	
1	80	154.95	1500	30 kHz	4.5	50 kHz	Includes FM Radio
2	155	389.9	2350	100 kHz	12	100 kHz	
3	390	394.998	1667	10 kHz	15	3 kHz	TETRA base stations
4	395	469.9	750	100 kHz	7.5	100 kHz	
5	470	854	1537	1 MHz	40	250 kHz	UHF Television
6	855	923.5	138	1 MHz	4.1	500 kHz	
7	924	961	1481	100 kHz	45	25 kHz	GSM base stations
8	961.5	1803.5	843	3 MHz	25	1 MHz	
9	1804	1880	3041	100 kHz	90	25 kHz	GSM base stations
10	1880.25	1901	416	100 kHz	13	50 kHz	DECT
11	1901.5	2108.5	208	3 MHz	6.2	1 MHz	
12	2110	2170	201	3 MHz	6	300 kHz	UMTS base stations
13	2172.5	2500	656	3 MHz	20	500 kHz	Includes WLAN

The video bandwidth shall be set to automatic and the detector to RMS mode. The amplitude scale shall be in logarithmic voltage with 10 dB per division and a reference level of -5 dBm (125.7 mV). The input attenuator shall be set to 5 dB.

Survey protocol

The measurement equipment shall be set up at the survey location with all cables connected. The height of the antenna is to be 1.1 m and it is to be in *x*-polarisation.

The spectrum analyser is to be switched on and the control software is to be set running on the computer. The instructions given by the software, including specifying a filename in which the data are to be saved, are to be followed.

The software will execute the sequence of sweeps listed in the above table and then ask the operator to move the antenna to the next polarisation (y then z) and height (1.5 then 1.7 m). When all nine sets of data have been acquired and saved, the measurement is complete.

The computer and spectrum analyser are to be switched off, and the equipment dismantled.

The total time to execute the above is 63 minutes.

Post-processing

The output from the procedure, as saved in the specified file, is a table in an Excel spreadsheet containing ten columns of data and 14788 rows below the headings. The first column is frequency and the remaining columns are the measurements for each of the nine polarisation/height combinations.

The post-processing proceeds as follows and is achieved by a second computer programme.

- 1) The three voltage measurements for each polarisation measured at a given height are reduced to total voltage values, corresponding to the underlying total field. This is done on a root sum squares basis, i.e. $V_{tot} = (V_x^2 + V_y^2 + V_z^2)^{\frac{1}{2}}$.
- 2) The total voltage values for the three heights are summed on a root sum squares basis and then divided by the square root of three. This is because the intent is to spatially average the power density, i.e. $V_{avg} = [(V_{tot1}^2 + V_{tot2}^2 + V_{tot3}^2)/3]^{\frac{1}{2}}$.
- 3) A peak search algorithm is used to extract the voltages and frequencies of individual signals from the table of spatially averaged voltages.
- 4) The signal voltages are converted to power densities taking account of the cable losses, the antenna calibrations,
- 5) Modulation-specific correction factors are applied for each band to account for the restricted spectrum analyser bandwidths. Within each UHF TV channel, a test is carried out to identify whether a digital or analogue signal is present before selecting the appropriate correction factor.

Spectrum graphs and pie charts can then be produced by the user for incorporation into reports.

Uncertainty Budget

The spectrum analyser is calibrated through substitution for a power meter when connected to a source producing a particular modulated signal of constant power. Uncertainties arising in measurements when using this calibration are associated with linearity and drift of the spectrum analyser, the correction factor itself and the calibration of the power meter. Since the antenna factor is derived including the cable, its uncertainties include those in the cable loss. A small amount of extra uncertainty is added to account for any coupling between the antenna and its surroundings.

Quantity	Value (dB)	Probability distribution	Divisor	Sensitivity coefficient	Standard uncertainty (dB)
Linearity	0.5	Normal	2	1	0.25
Drift	0.2	Normal	2	1	0.1
Correction factor	0.2	Normal	2	1	0.1
Power meter	0.1	Normal	2	1	0.05
Antenna factor	1.0	Normal	2	1	0.5
Coupling	1.0	Normal	2	1	0.5
Combined standard uncertainty					0.6
Expanded uncertainty (k=2)					1.2

APPENDIX E

Volunteer Location Diary

This appendix contains a template diary that was used by the volunteers to indicate their whereabouts at a given time so the measurements with their PEM at that time could be interpreted. The diary was supplied to the volunteers with their name and spot measurement locations already inserted. It was in the form of printed A4 sheets attached to a clipboard.

Personal Dosimetry of RF Radiation Volunteer Location Diary

Name	
Location 1	
Location 2	
Location 3	
Location 4	
Location 5	

Date	Time i	nterval	Location Number
	Start	Stop	Please specify if elsewhere

APPENDIX F

Processed Personal Exposure Records

This appendix contains graphs summarising the personal exposure data acquired for each volunteer over their week-long trial of the PEM. The data are presented with nine graphs covering a single frequency band on each page so they can be visually compared.







F2 PERSONAL EXPOSURE RECORDS: TV3







F4 PERSONAL EXPOSURE RECORDS: GSMTX







F6 PERSONAL EXPOSURE RECORDS: DCSTX



Electric field strength, V m

F7 PERSONAL EXPOSURE RECORDS: DCSRX



F8 PERSONAL EXPOSURE RECORDS: UMTSTX



Electric field strength, V m

F9 PERSONAL EXPOSURE RECORDS: UMTSRX

APPENDIX G

Volunteer Questionnaire

This appendix contains a copy of the questionnaire that was e-mailed to each volunteer after completing their week-long trial of the PEM in order to obtain feedback.

Personal Dosimetry of RF Radiation Volunteer Feedback Form

You have used the Personal Exposure Meter (PEM) for one week and we would now like you to answer some questions on your perceptions of the instrument, noting that it is intended to be worn by members of the public involved in scientific studies.

Please complete the form electronically and e-mail it to Simon Mann.

Volunteer name:				
	Date	Time		
Meter received:				
Meter returned:				
Spot measurement Loca	ations:			
Location 1:				
Location 2:				
Location 3:				
Location 4:				
Location 5:				

Please read all of the questions before deciding how to answer each of them.

A) Your use of the PEM

1) Estimate the percentage of the time that you wore the instrument on your body when at each of the spot measurement locations and indicate where you placed it when not on your body				
Location	% time	Position and distance from body when not worn		
1				
2				
3				
4				
5				

B) Your Perceptions of the PEM

2. How pract situations?	2. How practical did you feel it was to wear the instrument in the following situations?			
Situation	Score	Comments		
Standing				
Walking				
Sat at table				
Sat on sofa				
Reclining				
Scoring System:		 No problem Minor problems Somewhat problematic, but still practical on balance Fairly impractical Totally impractical 		

3. How did you feel about the design aspects of the instrument and what would you recommend for its future development?				
Aspect	Comment			
Size				
Shape				
Colour				
Weight				
Appearance				
Belt clip				
Other				

4. Were there any situations where you felt using the instrument appreciably modified your behaviour and, if so, in what way?			
Situation	Comment		

C) Your experiences with the PEM

5. Were there any situations where you felt self-conscious when wearing the instrument?				
Situation	Comment			

6. Were there any situations where persons other than friends and family and immediate work colleagues asked you to explain what the instrument was?			
Situation	Comment		

7. Were there any situations where you felt it was unsafe to use the instrument and chose not to either wear or carry it with you?			
Situation	Comment		

D) Future use of the PEM

7. What would be the longest period that you would be prepared to use PEM in any future study (delete all but your response from the list)?				
While keeping a diary	Without keeping a diary			
Not at all, one day, three days, one week, two weeks, one month, three months	Not at all, one day, three days, one week, two weeks, one month, three months			

8. What would be the longest period that you would feel it reasonable to ask a member of the public to use the PEM if they were involved in a future study (delete all but your response)?

While keeping a diary	Without keeping a diary
Not at all, one day, three days, one week, two weeks, one month, three months	Not at all, one day, three days, one week, two weeks, one month, three months

9. Do you have any final comments				

Let us know if you would like a copy of the data from your use of the PEM, or to be talked through it. We can also send you a copy of the final report if you wish. Thank you for helping us with this project.

Simon Mann, NRPB 17 December 2004