Observations on the relationship between magnetic field characteristics and exposure conditions

Elizabeth A. Ainsbury and Denis L. Henshaw

H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

Tel: +44 (0) 117 926 0353; Fax: +44 (0) 117 925 1723; E-mail: Liz.Ainsbury@bristol.ac.uk

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Abstract
The authors have been investigating metrics of extremely low frequency magnetic field exposure in different circumstances. In this paper, we describe the properties of magnetic fields in homes, in the vicinity of powerlines, on trains and from a library security system. We conclude that there are key differences between each of these fields. This suggests that there may be a characterisable pattern for magnetic fields in different situations.

1. Introduction

The prevalence of electrical systems in today's society means that, at extremely low (ELF) frequencies, magnetic fields are extremely complex. In general, magnetic fields are not easily attenuated, and field characteristics are dependent on the interaction of fields from all the sources in the vicinity. The complex nature of the interaction of factors affecting magnetic fields means that it is not always easy to accurately predict field characteristics. In homes, sources of magnetic fields may include overhead powerlines, indoor and outdoor wiring and appliances (Preece *et al.* 1997). Fields also depend heavily on power usage, which varies with time of day and time of year (Reitan *et al.* 1996). In the vicinity of powerlines it is well documented that the lines themselves make the dominant contribution to the levels of magnetic field strength (e.g. Levallois 1999, Forssen *et al.* 2002). However, metrics such as field polarisation and rate of change are respectively dependent on the phases of fields from all other nearby sources and the occurrence of transients.

Many different metrics have been proposed for magnetic field characterisation. Investigations normally include spot measurements (e.g. Feychting and Ahlbom 1993) and calculations of time weighted average (TWA) magnetic field strength (e.g. Foliart *et al.* 2001). Despite the large body of research to date, conclusions regarding the relationship between magnetic fields and health effects remain conflicting. It is therefore desirable to investigate metrics other than those that are normally considered in the literature. Recently, metrics such as rate of change (RCM) and total harmonic distortion (THD) of the field have become more popular (e.g. Yost 1999). In epidemiological studies, metrics are discussed in the context of their relation to health effects. In two recent studies by Li *et al.* (2002) and Lee *et al.* (2002), the authors explored the association between 24-hour magnetic field exposure and spontaneous abortion. Li *et al.* detected no associated miscarriage risk with wire-code, but increased risk was seen with maximum magnetic field levels above 1.60 μT (odds ratio = 1.8; 95% CI = 1.2 - 2.7). Lee *et al.* found an association only when considering a maximum field above 3.5 μT or with the RCM. RCM is defined as the root mean square value of the change in magnetic field between successive sequential samples, and is used to explore the variation in the magnetic field with measurement timescale. The standardised RCM (Yost 1999) is a measure of the temporal stability of the field. As with all metrics, its usefulness depends heavily on the circumstances of exposure: RCM is directly related to the length of time between successive measurements. Wilson *et al.* (1996), for example, found that the RCM was much more effective in characterising magnetic fields from electric blankets and waterbed heaters than TWA. The results of these studies suggest that metrics other than the commonly used time-weighted average may be of biological importance. There is evidence to suggest that combinations of magnetic fields at different frequencies could also be biologically relevant (Ishido *et al.* 2001). Villeuneuve *et al.* (1998) suggested that variability in the field intensity between successive measurements may be related to health effects. The THD is a measure of the harmonic content of the field. In this study we have calculated THD by taking the ratio of the field strength at the fundamental frequency (e.g. 50 Hz for powerlines) to the sum of the fundamental plus harmonic field strengths, to give the percentage field at the fundamental frequency. Field polarisation is the ratio of the minor to major axes of the ellipse traced out by processional orientation of the field vector. A ratio of 0 indicates a linearly polarised field and 1 indicates a circularly polarised field. In this study we represent the ratio values in terms of a percentage: 0% is a linearly polarised field and 100% is a circularly polarised field.

Much work has been carried out exploring the appropriate metrics for magnetic field classification (e.g. Bowman and Methner 2000). However, little has been done to characterise the properties of magnetic fields in different exposure situations. The authors have compared the properties of magnetic fields found in six areas where members of the public may be exposed to extremely low frequency magnetic fields.

2. Methods

The dc and ac field strength and broadband frequency (0 - 3000 Hz) of the magnetic fields were measured using the Multiwave® System II and software (ERM 1997). The Multiwave II was calibrated by the manufacturers on the 17/10/05, and the ability of the Multiwave II to resolve magnetic flux densities of up to 5 nT (ERM 1997) across the range of operating frequencies was confirmed. The configuration of the Multiwave II limited the sampling rate to one measurement per second and this configuration was used to collect all of the data presented in this study, unless otherwise stated. The EMDEX II, and EMCALC™ 95 software (ENERTECH Consultants 1997) was used to measure the x, y and z components and the resultants of the harmonic (100 - 800 Hz) and broadband (40 - 800 Hz) magnetic fields. The EMDEX II display limits the resolution of the measurements to 0.01 µT. A sampling rate of 1.5 seconds was used to collect all of the data presented in this study.

The homes and powerlines summaries are based on previously published data (Ainsbury 2005, Ainsbury 2006). The substations summary is based on numerous repeated observations at two locations in the Bristol area over the period October 2003 to June 2005. The trains summary is based on data collected on fourteen journeys in the South West, London and Birmingham areas, in November 2004 and March 2006. Fifteen measurements were carried out on electrified lines (25 kV ac) and third-rail electrified (750 V dc) lines; seven measurements were carried out on non-electrified lines. In all cases the meters were positioned on a seat as close as possible to the centre of the carriage, on scheduled passenger services.

Electronic article surveillance (EAS) systems are normally comprised of two pedestals placed at the exit of a shop or library. Audio frequency magnetic ('EM') systems are usually at frequencies between 218 Hz and 530 Hz: Tags of magnetic material are placed in the merchandise or books. Passage of the tag through the electromagnetic field between the pedestals results in magnetic saturation of the tag. The security system summary is based on observations carried out in five libraries in the Bristol area, between October 2003 and July 2006. For each of the measurements, the TWA magnetic field strength; percentage field vector polarisation; total harmonic distortion and rate of change of field strength were calculated. For the library security systems as the levels of field strength encountered were considerable greater than the maximum measurable field of the Multiwave II of 70 µT. The EMDEX II was used for these measurements, and therefore no values of field polarisation are presented.

3. Results

Table 1 summarises the results of the magnetic field measurements in six common exposure situations, with four common metrics of field classification: TWA, vector polarisation, THD, and RCM. Figures 1 to 4 show examples of the magnetic field strength and/or polarisation for each type of exposure.

Figures 1 (a) and (b) illustrate the overnight 50 Hz magnetic field strength and polarisation in the bedroom of a one-bedroom flat, 'Residence A'. Both the field strength and polarisation data are reasonably variable, with values of 0.02 ± 0.01 μT and 44 ± 28% respectively, and in both cases, there are peaks greater than two standard deviations in the mean.

Table 1. Magnetic field characteristics in several situations of human exposure.

MF location	Description	Distinguishing characteristics			
		Field strength	**Polarisation**	**Harmonic distortion, THD**	**Rate of change, RCM**
Background field in homes	Constant and steady in the centre of the room, variations dependent on the wiring of the home and other outside interactions, generally 50 Hz	Typically 0.01 - 0.02 µT at room centre	~ 50%, extremely variable due to interactions of fields from all sources in the room	Low, field at 50 Hz 90 – 100% of the time	Medium to low (if no appliances in use), ≤ 0.005.
Close to appliances	Dependent on appliance usage and configuration, generally 50 Hz	≤ several hundred µT adjacent to appliance, decreasing by ~ $1/r^2$ to ~ nT at 1 m from appliance	Typically <10% adjacent to appliance, increasing to background level at 1 m from appliance	Generally low (in most cases the majority of the field contribution is from the appliance)	Generally low, consistency depends on type of appliances and sampling time scale
High voltage powerlines	Complex and turbulent, vary with line configuration and individual line load, dependent on many factors including time of day, time of year, weather, generally 50 Hz	Max dependence line height, ~1 – 10 µT under centre line, background levels ~100 m from the line	0 – 100%, dependent on interaction of fields from line conductors, peaks directly under the line or to either side of the line	Low, dependent on line configuration, field at 50 Hz 80 – 90% of the time.	Extremely low (< 0.001) over short measurement periods, variable over longer periods

Table 1 continued.

MF location	Description	Distinguishing characteristics			
		Field strength	**Polarisation**	**Harmonic distortion, THD**	**Rate of change, RCM**
Substations	As high voltage lines	≤ tens μT depending on distance	0 - 100%, depending on substation configuration and measurement location	Low, fields at 50 Hz 90 – 100% of the time	Medium (0.01 – 0.1), due to interactions of fields from all the constituent lines
Trains	Complex and varying	Non electrified: up to ~5 μT, 50 Hz Electrified: ~ tens μT dc and ac broadband	Non electrified: 0 - 50% Electrified: 50 – 100%	High for electrified lines, low for non-electrified and dc lines	High: ~ 0.5 for non electrified and dc, ~ 1 for electrified lines
EM Library security systems	Centred on the security system scanner	Dependent on type of system: ≥ 600 μT for constant field EM systems	No data available	Medium (80 – 90% field at operating frequency), system interacts with other fields in the scanner vicinity	Medium - high, extremely dependent on system type

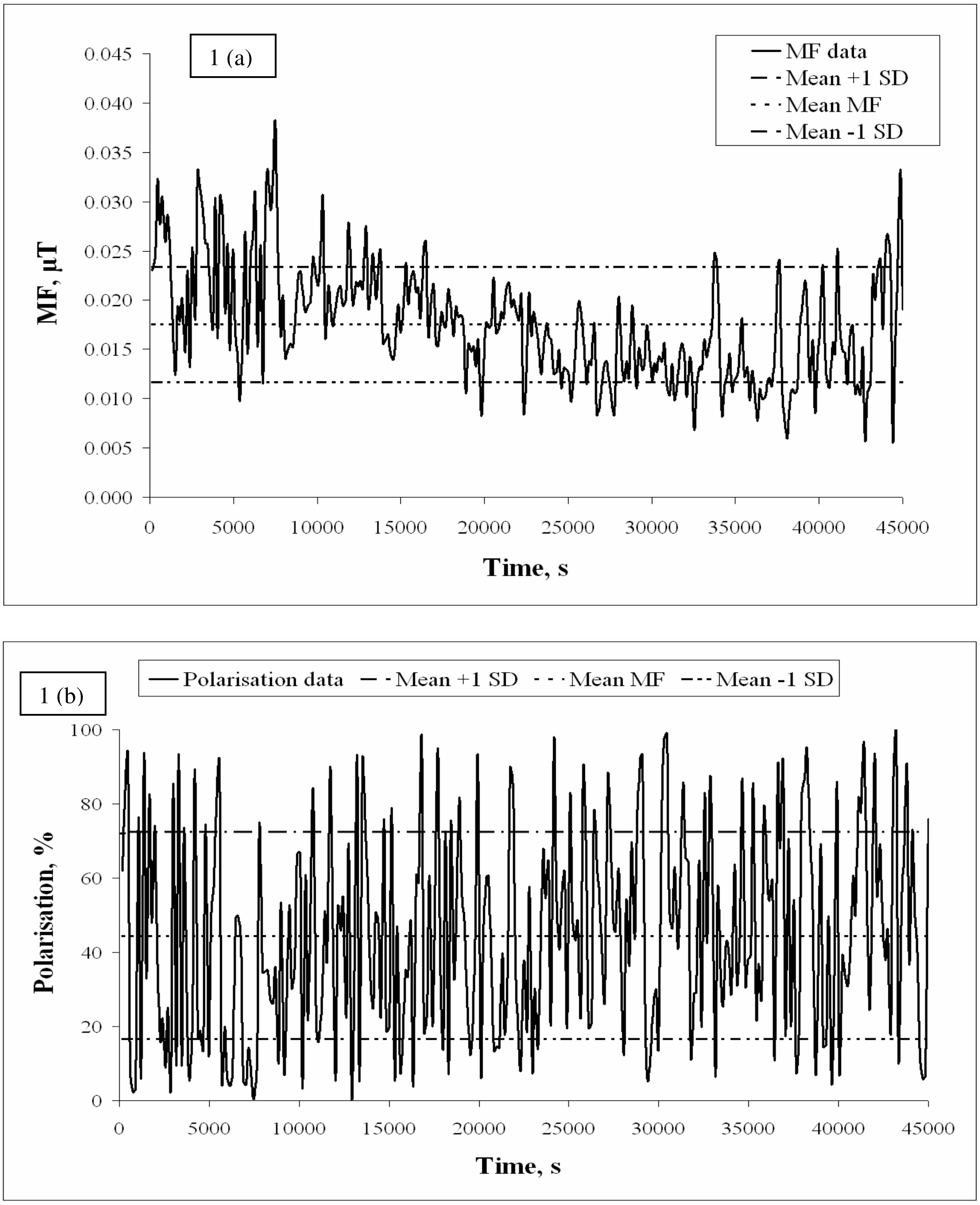

Figure 1. (a) 50 Hz magnetic field strength and (b) magnetic field polarisation overnight in Residence A, from 20:00 on the 2nd July to 08:30 on the 3rd July 2004.

Figure 2 illustrates the vector polarisation of the magnetic field under 'F' line, a Western Power 132 kV powerline, at Yatton, South Bristol, between winter 2004 and summer 2005. The arithmetic mean (AM) magnetic field strength was highest in summer in the morning and lowest in summer in the afternoon; the mean AM over all measurements was 5.30 ± 2.41 µT. The field polarisation under the centre of the line was consistently greater than 20%, and was between 40 and 50% up to 30 m either side of the line. The THD was low; the field was at 50 Hz for 92 ± 8% of the time. The RCM of the field at each measurement position was extremely low, with a mean value of 8 x 10^{-4} µT s^{-1} under the centre of the line, and 5 x 10^{-5} µT s^{-1} at distances greater than 40 m from the line.

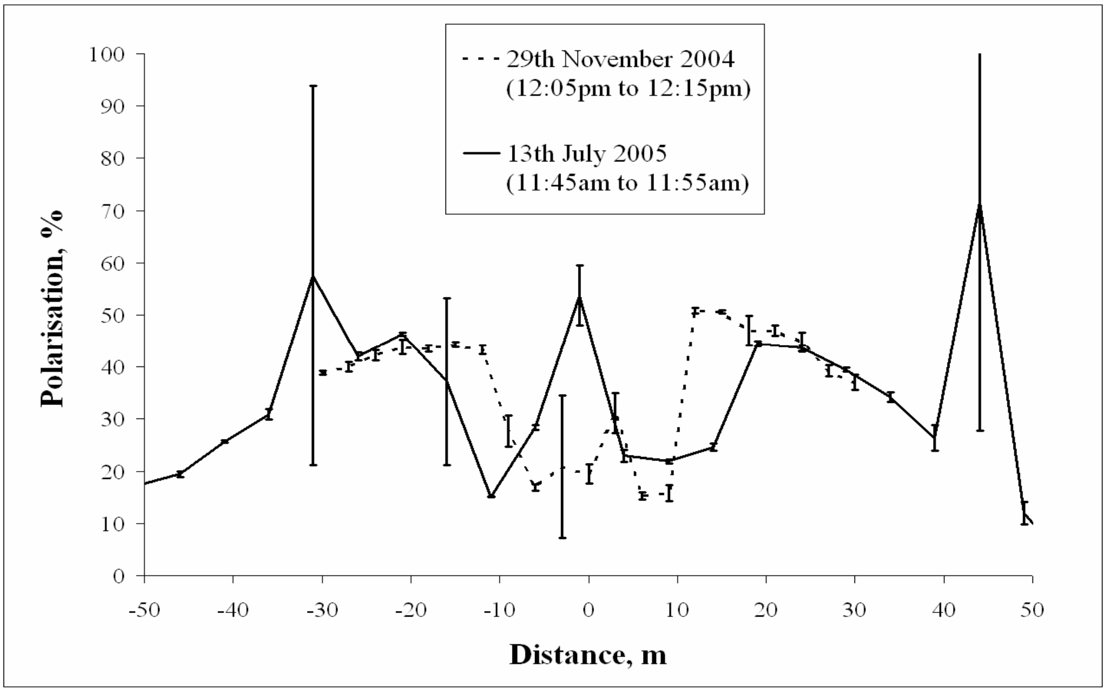

Figure 2. 50 Hz magnetic field polarisation measured underneath and close to Western Power's 'F' 132 kV high voltage powerline, Yatton (South Bristol), winter 2004 and summer 2005.

Figure 3 illustrates the magnetic field strength measured every 12 seconds, on the Euston to Birmingham line, on the 11th November 2004. The line is electrified with a voltage of 25 kV. The field was at 50 Hz for 93 ± 10% of the time; for the non-electrified line (not shown) the THD was extremely high, with the field at 50 Hz only 13 ± 7% of the time. RCM was high in both cases, with values of 0.94 μT s^{-1} for the electrified line and 0.38 μT s^{-1} for the non-electrified line.

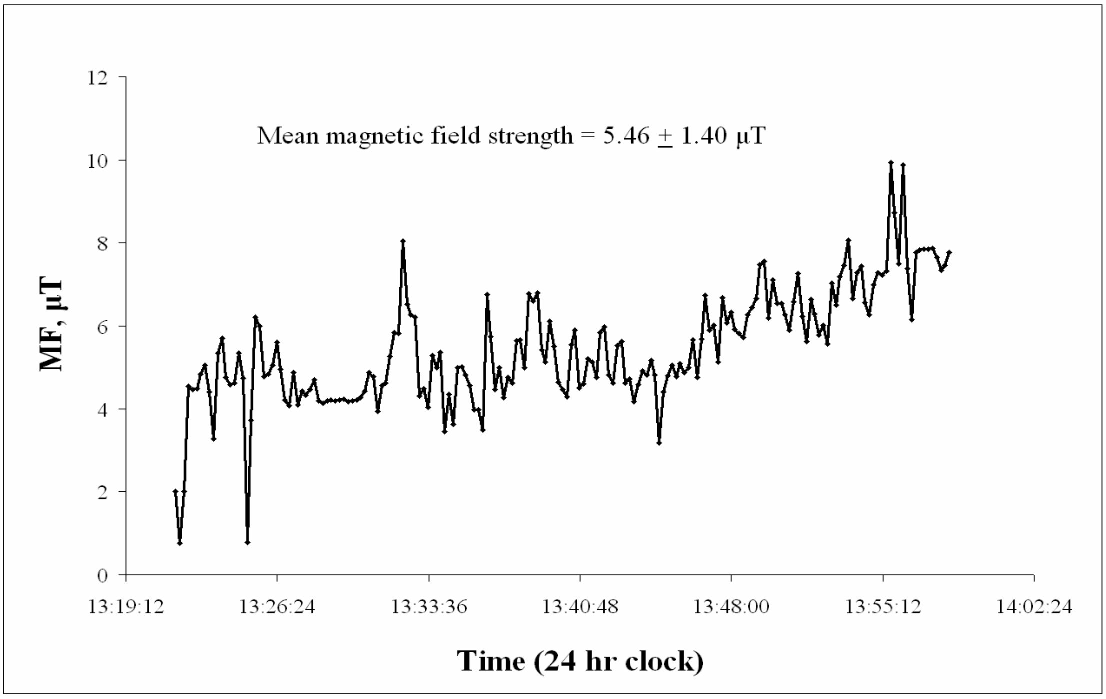

Figure 3. AC broadband (1-3000) Hz magnetic field strength on the Euston - Birmingham (electrified, 25 kV) train line on the 11th November 2004.

Figure 4 illustrates the magnetic field strength measured in between the pedestals of the library A security device, over a 1 ½ hour period on the 26th July 2006. The magnetic field strength is highest at the pedestals, and peaks at 566.1 μT. The THD was 96 ± 11%; the RCM had a value of 0.84 $\mu T\ s^{-1}$.

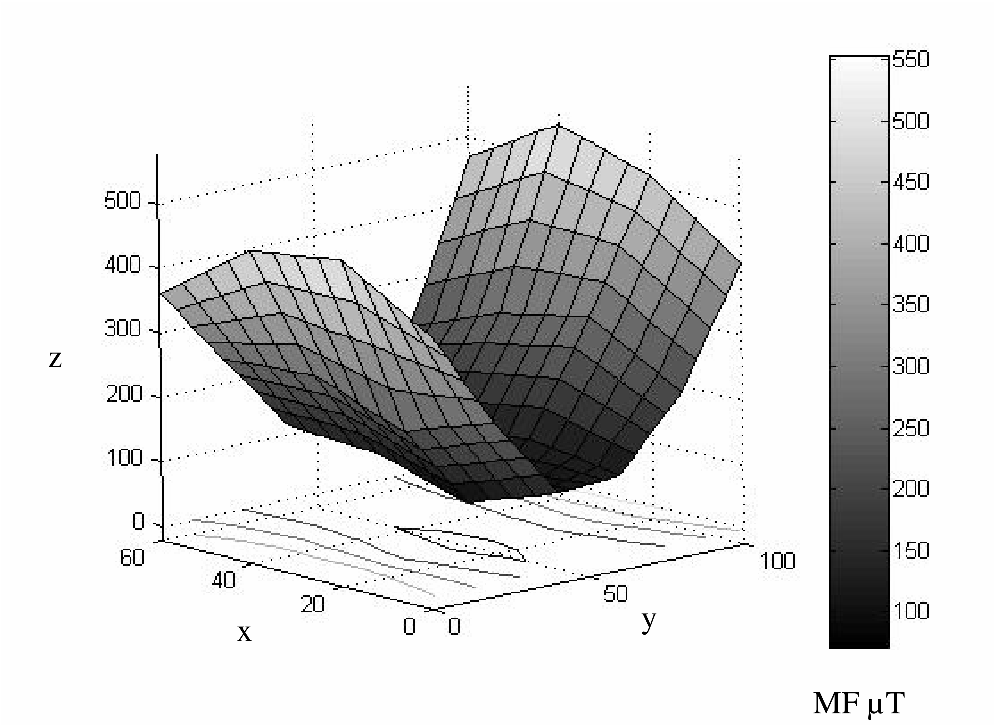

Figure 4. 218 Hz magnetic field strength between the pedestals at library A.

4. Discussion

Figure 1 (a) shows peaks in the night-time magnetic field strength of Residence A, at approximately 22:00 (just before 'bed-time') and at 08:00 (breakfast time), when the electricity usage in the home is greatest. As suggested by table 1, the background magnetic field in the home was low, 0.02 ± 0.01 μT. Field polarisation was extremely variable, in this home the measured value was 42 ± 28%. Standard error calculations have confirmed that the polarisation calculated using the Multiwave II software are accurate to for field levels ≥ 5 nT. As this level is approached in this case it is possible that the large variations may be due to errors in the calculations. However in the fifteen other homes summarised for this study, the polarisation showed the same degree of variability for higher mean field strengths. It is assumed from this that the variation is real, and was probably due to the interaction of magnetic fields from all the sources in the room. The THD and RCM were also generally low, although the THD from appliances such as televisions and microwaves can be much higher as a result of the way in which they operate. RCM also varied between rooms due to the different appliances present, and can be much higher as a result of the large transient fields induced by switching of appliances. Measurements taken close to appliances showed a reduction in magnetic field strength, and an increase in field polarisation, with distance from the appliance. This was as expected, as the contribution of the appliance magnetic field to the overall field strength diminishes with distance from the appliance, while the field polarisation increases due to the increasing contributions to the field from all other magnetic field-sources in the room.

Figure 2 illustrates the polarisation of the magnetic field in the vicinity of Western Power's 'F' powerline, at Yatton, in winter of 2004 and summer of 2005. The dip in magnetic field polarisation at the very centre of the line is due to the interaction of fields from the two sides of the line. The large increase in polarisation to 40% at approximately 12 m either side of the line indicates that there was an imbalance in the currents on the line. The high values of polarisation at large distances from the line are due to the increasing importance of background magnetic field contributions with distance from the line. The THD was low: the field was at 50 Hz for 92 ± 8% of the time, indicating that the powerline was the major source of the magnetic field in the area. The RCM at each measurement position was extremely low, as the measurements were taken over a short time period (≤ 60 seconds). The RCM would be much greater over longer measurement periods, as the field varies with power usage.

Magnetic field strength and polarisation varied along the boundary of the substations measured, with varying distance from the powerlines and main transformer. The THD was low, as the 50 Hz powerlines and transformers are the dominant sources of magnetic fields close to substations. The RCM varied between 0.003 μT s^{-1} and 0.039 μT s^{-1} with position around the substation boundary.

An example of the magnetic field strength measured on an electrified train line (Euston - Birmingham, 25 kV) train line on the 11th November 2004, is illustrated in figure 3. Magnetic fields on trains are generally complex. In addition to the magnetic field produced by the 25 kV ac and 750 V dc lines on the electrified services, operating equipment such as the traction motors give rise to large fields at 50 Hz and harmonic frequencies (Chadwick and Lowes 1998). In this study, meters were positioned on a seat as close as possible to the centre of the train carriages. However, Chadwick and Lowes (1998) found that peak magnetic field exposures were recorded at the ends of carriages and close to the floor. More work is required here to more fully characterise exposures from all sources of magnetic fields on trains. Passengers are also exposed to magnetic fields from external sources and fields induced by moving through the Earth's field, though it is estimated that this contribution would be small in comparison to the fields from other sources. The mean field strength was much lower on the non-electrified lines, (e.g. Bristol – Salisbury line: 0.27 ± 0.34 μT) than the electrified lines, such as the Euston – Birmingham line shown (5.6 ± 1.4 μT). The source of the apparent increase in field strength through the course of the measurement is assumed to be due to the increase in external sources of magnetic field exposure. This increase was confirmed by two meter readings independent to the illustrated data. In all cases the polarisation was variable, due to the changing field contributions throughout the journey. Polarisation was much higher for the electrified lines: 76 ± 16% compared to 22 ± 26% on the non-electrified lines, due to the interaction of the magnetic fields from the several sources on electric trains with the overhead line. The THD on the electrified lines was low, with the field at 50 Hz for 93 ± 10% of the time; for the non-electrified lines the THD was extremely high: 13 ± 7% of the field was at 50 Hz. The RCM in most cases was high, as the magnetic field at each location was dependent on the (changing) position of the train with regard to the various sources of magnetic fields along the line. There was no significant difference between the ac (25 kV) and dc (750 V) electrified lines for any of the measured metrics.

Measured values of field strength of the library security systems were variable, depending on the design and operating frequency of the individual system. As with as with all the situations, magnetic fields measured in the vicinity of library security systems are subject to contributions from field from other sources. At library A, as in all the libraries, the field strength was highest adjacent to the system pedestals. The maximum value of magnetic field strength was 556.1 μT, adjacent to the centre of the right-hand pedestal. This value is much greater than the ICNIRP recommended limit of 100 μT for public exposure at 50 Hz (ICNIRP

1998). It should be noted here that much of the research into the effects of EAS systems has focussed on the currents that are induced in the body by these magnetic fields (e.g. Harris *et al.* 2000). EAS systems often operate at frequencies much higher than 50 Hz, and the magnitude of currents induced by magnetic fields increases with f. The THD at library A was variable, with 96 ± 11% of the field at 50 Hz, and this is also dependent on the operating frequency of the system. The RCM of the library security system magnetic field was 0.84 μT s^{-1}, again indicating there is some interaction of the field with other sources within the vicinity.

The results of this study suggest that, for the exposure situations investigated in this study, the characteristics of the magnetic fields in may be summarised by field strength, polarisation, RCM and THD, as in table 1. For the homes background, appliance, powerline and substation magnetic fields, the summaries in table 1 are based on large amounts of data from repeated measurements at several locations, and hence it is valid to summarise the data in this manner. For homes, other authors have found similar values of field strength from appliances and background field strength. In a sample of 50 homes, Preece *et al.* (1996) found that the mean background field level was 0.044 ± 0.06 μT. This value is slightly higher than the value presented in table 1, and more work is required to investigate this. For powerlines and substations, the values of field strength summarised in table 1 are similar to those measured in other studies (Grainger and Preece 2000, Swanson 1995). The summary of the trains' magnetic field characteristics is based on fourteen sets of data, collected on several journeys. Chadwick and Lowes (2000) found field strengths of approximately 5 μT at a seating position with the field varying between 0.1 and 100 μT, this corresponds well to the results of this study. It is well documented that magnitude of magnetic field strength in the vicinity of powerlines varies diurnally and annually, and this may also be true of train magnetic fields, so the summary of train magnetic fields presented in table 1 may be incomplete. However, it is expected that this would only affect the magnetic field strength, and not the field polarisation, THD or RCM characteristics, as these metrics continually change throughout the journey, with the changing location of the train.

The summary of the library security systems' data is based on repeated observations of magnetic fields from 'EM' security systems. The values of field strength measured correspond well to data collected in other studies (e.g. Harris *et al.* 2000). However, data were only collected for five library security systems, which may not display magnetic field characteristics typical to all systems. More work is needed here to fully characterise magnetic fields from the many types of individual low frequency security systems.

5. Conclusions

This work confirms the complex nature of magnetic fields at power frequencies. Figures 1 to 4 and the summaries given in table 1 highlight the marked differences between magnetic field characteristics in the different situations. Magnetic fields are generally difficult to predict, however, the findings indicate that metrics such as magnetic field strength, vector polarisation, THD and RCM may be used to estimate the field's origin. In conclusion, we find that the circumstances of magnetic field exposure depend heavily on the field characteristics and exposure situations. This suggests that magnetic fields may display a type of 'genetic fingerprint.' Much more work is needed to fully characterise each type of magnetic field, and future work should also focus on identifying the metrics appropriate to each specific type of magnetic field.

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