Exposure to EMFs from Lightweight Aviation Transponders

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ABSTRACT

An investigation has been carried out to determine exposure to electromagnetic fields from proposed lightweight aviation transponders operating in Mode S and used near the body. The assessment has been made for peak radiated powers of 30 W and 80 W with a duty factor of 0.55%, in accordance with advice from the Civil Aviation Authority. This implies the time-averaged powers, as relevant for comparison with exposure guidelines, are 0.165 W and 0.44 W respectively.

Numerical models of a generic transponder have been developed with typical antennas and simulations have been carried out to investigate the electric and magnetic fields. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) public exposure reference levels were exceeded within 3.6 cm and 5.4 cm for 30 W and 80 W transponders respectively. For occupational exposure, the corresponding distances were 3.0 and 3.9 cm respectively.

A scientific literature review was performed and indicated that localised SAR in the head and body should be within the 2 W kg^{-1} public exposure basic restrictions for 30 W transponders with similar size and shape to mobile phones. There is a possibility that the basic restriction might be exceeded by 80 W transponders. Whether this would occur in practice would further depend whether transponders are located in close proximity to the body for long periods of time and the duty factor in practice, which might be considerably less than 0.55%. The 10 W kg^{-1} occupational exposure basic restriction seems unlikely to be exceeded by transponders.

Lightweight transponders will have similar output powers to other devices used near the body for which testing is carried out by manufacturers against the ICNIRP guideline values. The technical standards which are evolving to support this testing may contain procedures suitable for testing aviation transponders, and such testing by manufacturers would seem appropriate, particularly for 80 W transponders.

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1 INTRODUCTION

Lightweight transponders are self-contained low powered radio devices designed for use on small aircraft, including gliders, balloons and microlights. They could also be used on unmanned aerial vehicles and for test flight monitoring and analysis. The devices are expected to be of a similar size to early mobile phones and to be mounted at a minimum distance of approximately 0.3 m from the pilot typically; however, in some circumstances they may be mounted closer to or on the pilot's body. Hence human exposure levels to the electromagnetic field emissions are of interest.

The Civil Aviation Authority (CAA) has previously commissioned work from the National Radiological Protection Board (now the Radiation Protection Division of HPA) in order to evaluate exposure to the electromagnetic fields from a lightweight aviation transponder made by Racal and to comment on compliance with advised restrictions on such exposure (Cooper and Mann, 1998). The work previously carried out comprised of three elements. Firstly, a review of published scientific papers describing the results of experimental and theoretical evaluations of the specific energy absorption rate (SAR) due to body mounted radio transmitters, such as mobile phones, in order to assess the likely SAR produced by a transmitter of a given output power. Secondly a computer model of a Racal lightweight transponder was developed and analysis was carried out to determine the electric and magnetic field strengths close to the transponder. Thirdly, the prevailing advice on exposure restrictions for electromagnetic fields was summarised and the results from the first two elements were compared with the advised restrictions in order to comment on the compliance of exposures.

Since 1998, more scientific papers containing SAR data have been published and the policy position with regard to restricting exposures has evolved. Technical developments have also occurred with the transponder specification, including the deployment of another mode of transmission, known as "S-mode", which implies a different time-averaged output power. This report was prepared in response to a request from CAA to update the previous report taking account of the above technical and advisory developments, and also to allow for the assessment of transponders in general, rather than a particular product.

Section 2 of the report summarises the emission characteristics of aviation transponders focusing on the information relevant to assessing exposures in the various transmitting modes. Next, Section 3 provides a summary of the guidelines on limiting exposures to radiofrequency (RF) electromagnetic fields from the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and their practical implementation through policy measures and technical standards. Field strengths are calculated as a function of distance from some model RF transmitters considered likely to be representative of lightweight transponders in Section 4 and maximum distances at which the ICNIRP reference levels can be exceeded are derived. An updated review of the scientific literature covering SAR produced by similar transmitting devices, typically mobile phones, used close to the body is provided in Section 5 and used to determine the likelihood of the ICNIRP basic restrictions being exceeded by transponders. Finally, in Section 6 the results are discussed and overall conclusions provided.

2 AVIATION RADAR AND TRANSPONDERS

2.1 Introduction

Primary radar systems typically involve fixed ground-based antennas emitting pulsed radio signals into narrow beams and rotating in azimuth. The pulsed signals are reflected back towards the radar antennas by targets, such as flying aircraft, and the radar is able to deduce the distance of the target from the time delay. These systems require high power transmitted pulses because little power is reflected by targets, but they cannot easily provide accurate altitude information for the targets.

Secondary surveillance radar (SSR) does not require as much power as primary radar because it equips target aircraft with transponders that transmit radio replies in response to incoming radar signals. A variety of information, including altitude, can be encoded onto the transmitted replies. SSR Mode A transponders transmit a “squawk” code set by the pilot and Mode C additionally provides for altitude information in responses. Mode S provides much more detailed information about the aircraft in the responses and allows for selective interrogation through coded requests.

Large aircraft such as military jets and commercial passenger aircraft have for many years had SSR transponders on board. Light aircraft have also carried transponders in many circumstances. However, the increasing number of aircraft in the skies is now driving the development of lightweight transponders for use on small aircraft, including gliders, balloons and microlights.

An initial Racal device was built as part of a Civil Aviation Authority (Safety Regulation Group) research study to develop a specification for lightweight transponders operating in SSR Modes A and C. The National Radiological Protection Board (NRPB), now the Radiation Protection Division of the Health Protection Agency (HPA), carried out an assessment of exposure to the electromagnetic fields transmitted from this transponder (Cooper and Mann, 1998), including describing its emissions. A newer low power version of a Mode S transponder, the Lightweight Aviation SSR Transponder (LAST), is now being developed and is described in this section.

2.2 Technical Aspects

The European Organisation for Civil Aviation Equipment (EUROCAE) provides the minimum operational performance specification (MOPS) for radar transponders. This was originally published in EUROCAE document, ED-73A, which was superseded by ED-73B in January 2003 (EUROCAE, 2003).

The Lightweight Aviation SSR Transponder (LAST) is conceptualised as supporting modes A/C and S, and operates in accordance with technical standard ED-115 (EUROCAE, 2002). This standard essentially refers to ED-73A in describing the communications protocol and emission characteristics.

2.2.1 Frequency bands

The signals transmitted from the ground are at a frequency of 1030 MHz and those from transponders are at a frequency of 1090 MHz.

2.2.2 Peak output powers

The standards referred to above specify minimum and maximum equivalent isotropically radiated powers (EIRPs) for Class 1 and Class 2 transponders, as shown in Table 1. The power levels of lightweight transponders during transmission are not yet standardised, but two levels have been proposed and they are lower than those of conventional transponders, as shown in the table.

Table 1 Standardised power classes for aviation transponders

Standard	Class	Minimum Output Power (EIRP)		Maximum Output Power (EIRP)	
		dBW	watts	dBW	watts
ED-73B	1	21	125	27	500
	2	18.5	70	27	500
N/A	LPST 1	18.5	70	19	80
	LPST 2	14.5	25	15	30

CAA envisages lightweight transponders operating only to the lowest power class in Table 1, with a minimum output power of 25 W and it has asked for this work to proceed on the basis of an assumed maximum power of 30 W and 80 W for LPSTs, as shown in the table.

2.2.3 Physical characteristics

No prototype is yet available and the exact physical characteristics of LPSTs are unknown. CAA indicated that the developed devices would be the size of an old analogue mobile phone, typically with an antenna mounted on the top of the body shell and with some form of display panel and keying buttons on the front.

For numerical modelling and calculations in this report (see Section 4), it will be assumed that a typical transponder unit is 198 mm long and 93 mm wide with a depth of 45 mm for the lower section increasing to 54 mm for the upper section. These are the dimensions of the specific Racal transponder that formed the subject of the previous report for CAA (Cooper and Mann, 1998).

The technical information in ED-73A/B suggests that that the antenna should have an essentially isotropic radiation pattern in the horizontal plane and emit predominantly vertically polarised radiation. Example transponders with monopole, helical and patch antennas are considered in Section 4 of this report.

2.3 Communications Protocol

Mode S transponders are also required to be able to operate in modes A and C, and ground-based radar stations are required to support A, C and S modes. The ground stations transmit radar pulses in such a format that all types of transponders in the area can determine if a given interrogation is relevant to their mode of operation.

The ground station radar antenna transmits using a 1030 MHz carrier frequency with Differential Phase Shift Keying (DPSK) modulation to encode the transmitted information, including interrogation signals for transponders. Transponders use Pulse Position Modulation (PPM), in which data are transmitted on a carrier frequency of 1090 MHz by varying the position of the pulses within a time-domain frame while the amplitude and width of individual pulses remains constant. Thus, in PPM the transmitter power remains constant since the pulses are of constant amplitude and duration. The transmissions are repeated periodically, many times a second, while the transponder is being interrogated.

The sections below describe in more detail the broadcast communication between ground station antennas (rotating radar and omni-directional antennas) and the structure of the responses from transponders. The “squitter” signal, which is emitted from Mode S transponders, even in the absence of interrogations, in order to provide identification information to other aircraft is also described.

2.3.1 Ground station transmissions

The radar signal is transmitted through a rotating directional antenna and, ideally, the beam produced would be narrow and only transmitted in the direction in which the antenna is pointing. However, real antennas produce subsidiary beams at angles away from their main beams, known as sidelobes. Although sidelobes are considerably weaker than main beams, there would be a possibility that transponders might mistakenly respond to a sidelobe sweeping past them and thereby cause radio interference. In order to avoid this, the interrogation signal consists of two pulses sent by two different types of antennas. The first pulse (P1) is sent through the directional antenna and then a second pulse (P2) is sent shortly after through an omni-directional antenna. Transponders compare the strengths of the two pulses received to make a judgement as to whether the main beam or a sidelobe is sweeping past them.

The transmissions from ground stations include interrogation signals aimed at all the transponders in the air-space and mode A/C signals are as shown in Figure 1.

All these interrogation signals use the same frequency (1030 MHz) and the time between the first and third pulses, P1 and P3, defines the type of mode. In Mode A interrogation, the time between the start of P1 and P3 is 8 μs, whereas the this time is 21 μs in the case of Mode C. In Mode S, this format has an additional pulse added that is used to recognise the signal as a Mode S interrogation, and indicate the need to respond with a Mode S reply. The duration of these interrogation pulses is 0.8 μs.

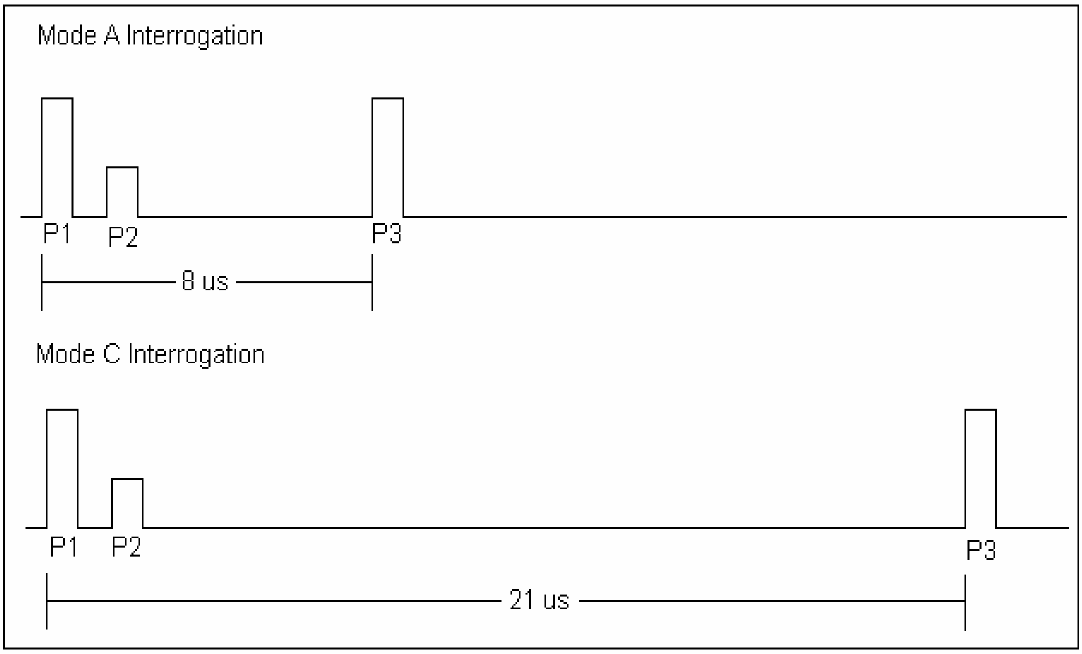

Figure 1 Mode A/C Interrogation pulses transmitted from an SSR ground station

2.3.2 Transponder replies in Mode A/C

In Modes A and C, there is no difference in terms of the reply format, and the reply consists of two framing pulses, each of 0.45 µs, which start 20.3 µs apart. Between these framing pulses are data pulses at 1.45 µs increments from the start of the previous pulse; however, the pulse at 10.15 µs is absent. Modes A/C, therefore, contain 12 data pulses between two framing pulses as shown in the Figure 2. There may be an additional pulse at 24.65 µs which stays on for maximum of up to 18 seconds when the pilot is requested to press a button for additional information.

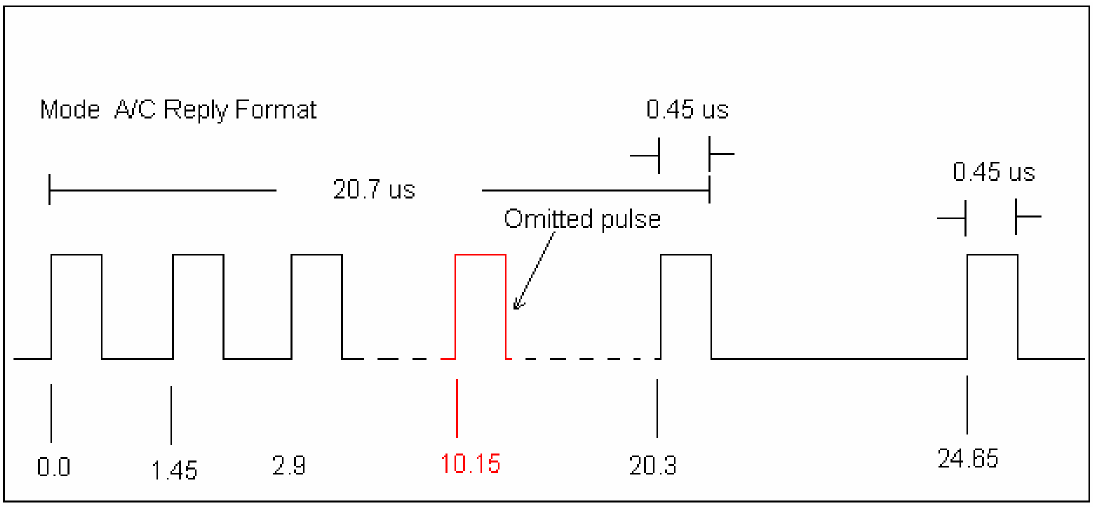

Figure 2 Mode A/C reply format

2.3.3 Transponder replies in Mode S

The signal format in Mode S replies has a four pulse preamble and a data set of either 56 or 112 bits of information. The four preamble pulses identify a Mode S reply and are shown in Figure 3.

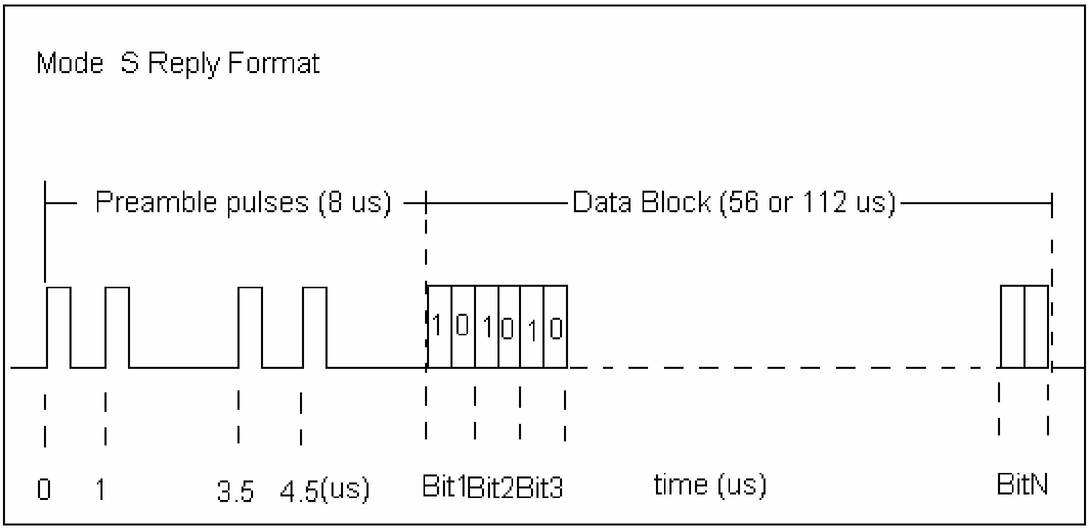

Figure 3 Mode S reply format

These preamble pulses of 0.5 µs are spaced at 1, 3.5 and 4.5 µs from the start of the first pulse and are followed by a data block of 56 or 112 pulses, depending upon the length of the message, as shown in the Figure 3. Reply data pulses start at 8 µs from the start of first preamble pulse. Two possible 0.5 µs wide pulse positions are used with each bit, with the position chosen depending on the bit value (0 or 1). If two adjacent pulses are transmitted then these are merged into a single wider pulse. Replies with 56-bit and 112-bit data blocks are known as short replies and long replies respectively.

2.3.4 Unsolicited transponder emissions

Mode S transponders are required to transmit “squitters” or unsolicited transmissions to provide information such as their altitude and 24-bit address code to other aircraft flying nearby. These transmissions occur under all circumstances, independently of any interrogations, and the pulses are scheduled not interfere with Mode A/C or S replies. The acquisition squitter, which contains the aircraft address and its communications capability, is transmitted once per second as a short reply. Extended squitters are also produced as long replies and can contain various other types of information including airborne position and speed. CAA advised HPA to assume that *extended airborne velocity* and *event driven* squitters would not be produced by lightweight transponders but that *airborne position* and *speed* would. This would mean than extended squitters would be produced at an average rate of 2.2 per second.

2.4 Duty Factors and Time-averaged Powers

The format of the different types of replies from transponders operating in modes A/C and S has been described above. The technical standards ED-73A/B specify minimum reply rates of which transponders should be capable, however they do not give maximum rates. These data are summarised below, together with information passed to HPA by CAA regarding reply rates expected under pessimistic operational scenarios. This information is used to derive the likely maximum time-averaged radiated powers from lightweight transponders.

2.4.1 Mode S transponder under specification conditions

Earlier transponders operating in Mode A and C transmitted 15 pulses of 0.45 μs at a minimum repetition rate of 1000 per second, implying a duty factor of 0.675%. Mode S transponders are also capable of replying in Mode A/C and Mode S at the same time. However the maximum specified replies sent in Mode A/C from a Mode S transponder, are reduced to an average of 500 replies per second. Thus, the total reply rate of a Mode S transponder is the sum of the Mode A/C reply rate and the Mode S reply rate.

The technical standard ED-73A/B defines the minimum Mode S reply rates as follows:

Short Reply Rates:

A transponder equipped for only short Mode S Downlink Formats (DF), shall have the following minimum reply rate capabilities.

- *50 Mode S replies in any one-second interval*
- *18 Mode S replies in a 100-millisecond interval*
- *8 Mode S replies in a 25-millisecond interval*
- *4 Mode S replies in a 1.6-millisecond interval*

Long Reply Rates:

A transponder equipped for long Mode S reply formats shall be able to transmit at least

- *16 of the 50 Mode S replies in any one-second interval*
- *6 of the 18 Mode S replies in a 100-millisecond interval*
- *4 of the 8 Mode S replies in a 25-millisecond interval*
- *2 of the 4 Mode S replies in a 1.6-millisecond interval.*

CAA has indicated that the lightweight transponder will fall into the latter category and will be able to transmit both short and long Mode S replies.

Replies would only be produced when a transponder is being addressed, e.g. when a given ground-based radar station is directed towards it. There may be several ground-based stations able to address an aircraft transponder at a given time, but any given radar station will only be directed towards a transponder for a small fraction of the time. For example, a radar antenna with a typical value of 2 degree beamwidth (a typical value) would only address a given aircraft for 2/360, i.e. 0.56% of the time.

CAA has indicated that the realistic maximum reply rate in Mode S is 50 replies per second in which 16 are long replies and 34 short replies along with 1 short reply and 2.2

long replies as squitters. On this basis, and taking into account the Mode A/C replies, the maximum cumulative transmission times are as shown in Table 7.

Table 2 Maximum cumulative transmission times per second from Mode S transponders

Transmission	Number of replies	Number of pulses	Pulse duration, μs	Cumulative duration, μs
Mode A/C replies	500	15	0.45	3375
Short Mode S replies	34	4+56	0.5	1020
Long mode S replies	16	4+112	0.5	928
Short squitters	1	4+56	0.5	30
Long Squitters	2.2	4+112	0.5	127.6
Total cumulative transmit duration				5480.6

The above cumulative transmission time of 5480.6 μs in every second corresponds to a duty factor of 0.55%. Thus, for peak radiated powers of 30 W and 80 W, the equivalent time averaged powers are 0.165 W and 0.44 W respectively.

2.4.2 Mode S transponder under expected worst case conditions

CAA provided a report containing information on worst case reply rates in busy airspace expected in the year 2020 (QinetiQ, 2007). QinetiQ carried out a modelling exercise based on a scenario that represented high density future airspace traffic. In the report a snapshot of the airspace environment in June 2006 was extrapolated to predict a worst case reply rate expected in year 2020, given expected air-traffic growth.

The QinetiQ report considered reply rates from transponders on civil and military aircraft, which differ in their receiver sensitivities. The civil transponder was the most sensitive, having a threshold received signal strength level of −74 dBm for replies to be produced, while the military transponder had a sensitivity of −72 dBm. The more sensitive a transponder, the greater the reply rate it can be expected to produce, because it will respond to interrogations from ground stations that are further away.

CAA advised that HPA should consider the data in the QinetiQ report for the Military transponder, as a pessimistic scenario for the lightweight transponder. QinetiQ determined that in the year 2020, a Mode S transponder would have 475.3 replies in Mode A/C and 3.6 long, 27 short in Mode S, leading to transmit times shown in Table 3.

Table 3 Maximum cumulative transmission times per second from Mode S transponders according to scenario modelling for the year 2020.

Transmission	Number of replies	Number of pulses	Pulse duration, μs	Cumulative duration, μs
Mode A/C replies	475.3	15	0.45	3208.3
Short Mode S replies	27	4+56	0.5	810
Long mode S replies	3.6	4+112	0.5	208.8
Short squitters	1	4+56	0.5	30
Long Squitters	2.2	4+112	0.5	127.6
Total cumulative transmit duration				4384.7

The above cumulative transmission time of 4384.7 μs in every second corresponds to a duty factor of 0.44%. Therefore, for peak powers of 30 W and 80W, the equivalent time averaged powers would be 0.132 W and 0.352 W respectively and thus slightly lower than determined in Section 2.4.1.

2.5 Summary

Lightweight transponders will transmit at a frequency of 1090 MHz and may be placed in close proximity to people on light aircraft. They are expected to be of similar size to early mobile phone handsets and have similar configurations, with keyboards, displays and projecting antennas.

The radio emissions are in the form of replies to interrogations from radar signals, and each reply will consist of a number of short pulses. The replies are repeated continuously while a given transponder is being interrogated. The peak power during the replies will be a minimum of 25 W or 75 W, depending on the class of transponder, and CAA advised that HPA should consider corresponding maximum peak powers of 30 W and 80 W for the assessment in this report.

The time-averaged power is a more relevant quantity than peak power for safety considerations (see Section 2) and depends on how often a transponder is interrogated and the types of replies it gives. CAA gave HPA information on the realistic maximum reply rate that could be expected from transponders and this implied maximum time-averaged powers of 0.165 W and 0.44 W for the two power classes. CAA also passed a report prepared by QinetiQ in which modelling results were given for a transponder in busy airspace, as expected in the year 2020. This indicated lower time-averaged powers of 0.132 and 0.352 W for the two power classes.

3 EXPOSURE GUIDELINES AND STANDARDS

3.1 Introduction

The previous report for CAA was published in 1998, the same year as the present guidelines on exposure to radiofrequency electromagnetic fields were issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998). The ICNIRP guidelines were summarised in the report, however, at that time, the UK had its own guidelines, which had been published by NRPB in 1993 and were being used by regulatory bodies such as the Health and Safety Executive (HSE).

A significant development in the advisory position was the advice from NRPB in March 2004 that the UK should adopt the guidelines on limiting exposures from ICNIRP (NRPB, 2004a). Subsequently, NRPB merged into the Health Protection Agency in April 2005, where it became the Agency's Radiation Protection Division (RPD).

The major difference between the 1998 ICNIRP guidelines and the 1993 NRPB guidelines concerns general public exposures. For occupational exposure, the basic restrictions are broadly the same in both sets of guidelines and so there should not have been any major change in the position as regards occupational use of transponders. The ICNIRP public exposure basic restrictions are around five times more restrictive than those specified in the 1993 NRPB guidelines (for all people). Hence, for aviation transponders used by the general public there has been a five-fold tightening of the restrictions.

3.2 UK Advisory Position

In the UK, the HPA has the responsibility for providing advice on exposure guidelines for non-ionising radiations, a function formally carried out by NRPB. As part of a policy of ongoing evaluation of scientific evidence and health risk assessment, advice on limiting exposure to electromagnetic fields was reviewed in 2003 and at the request of the Department of Health, the issues of uncertainty in the science and aspects of precaution were particularly addressed.

As a result of this review, it was recommended (NRPB, 2004a) that the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for limiting exposure to electromagnetic fields between 0 and 300 GHz should be adopted in the UK. ICNIRP is an independent scientific organisation responsible for providing guidance and advice on the health hazards of non-ionising radiation exposure. Its guidelines were recommended by NRPB for adoption following a thorough review of current knowledge on the effects of electromagnetic fields (NRPB, 2004b) and an extensive consultation exercise.

The guidelines published by ICNIRP represent scientific advice. However it is for policy makers to make decisions on the implementation of guidelines. The remainder of this section explains the framework of the guidelines and summarises the current UK position on adoption.

3.3 Public and Occupational Exposure Situations

The ICNIRP guidelines distinguish between occupational and general public exposures. In justifying this approach, ICNIRP noted that *"the occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of the potential risk and to take appropriate precautions."* By contrast ICNIRP indicated that *"the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their exposure to EMF. Moreover, individual members of the public cannot reasonably be expected to take precautions to minimise or avoid exposure."* It is these considerations that underlie the adoption of more stringent exposure restrictions for the public than for the occupationally exposed population and has led to ICNIRP generally including a reduction factor of up to five in setting basic restrictions for members of the public.

NRPB noted in its 2004 advice that *"occupational situations will generally be to healthy adults working under controlled conditions and that these conditions include the opportunity to apply engineering and administrative measures and, where necessary and practical, provide personal protection".* NRPB also noted that *"the general public includes people of all ages and widely varying health status and that exposure is likely to occur under uncontrolled conditions"* (NRPB, 2004a).

In the scientific review accompanying its advice to adopt the ICNIRP guidelines (NRPB, 2004b), NRPB considered the existence of groups of people within the general population who may be more susceptible to heat-related disorders and who might benefit from the more stringent ICNIRP general public exposure restrictions. Such groups were felt to include older people, infants, children, pregnant women, other adults taking certain medications and people undertaking cognitively demanding tasks.

3.4 ICNIRP Guidelines

3.4.1 Scientific basis

The main objective of the ICNIRP guidelines is to provide protection against known adverse health effects, i.e. effects that cause detectable impairment of the exposed individual or of their offspring. The guidelines advise basic restrictions that are based directly on adverse health effects and it is stated that protection against adverse health effects requires that these basic restrictions are not exceeded.

When a radio transmitter is used near the body, radio waves are incident on the body and penetrate into the body tissues. Absorption of the energy in the radio waves occurs and this absorption can lead to heating. The guidelines aim to place restrictions on the rate at with energy is absorbed in order to limit heating of the whole body or any part of it.

The ICNIRP guidelines apply to exposure of people and do not mention how such exposure arises, or the sources that may be involved. The restrictions applicable to exposure at a frequency of 1090 MHz, as from aviation transponders, are presented below.

3.4.2 Basic restrictions

The guidelines contain basic restrictions on the specific energy absorption rate (SAR) of energy to ensure that harmful temperature rises do not occur in the body. Basic restrictions are placed on whole-body SAR in order to prevent harmful rises in core temperature and on localised SAR in order to prevent harmful rises in localised tissue temperature. The restriction values are given in Table 4.

Table 4 ICNIRP basic restriction quantities and values between 10 MHz and 10 GHz

Quantity	Basic restriction value, W kg^{-1}	
	Occupational	General public
Whole-body averaged SAR	0.4	0.08
Localised SAR in the head and trunk	10	2
Localised SAR in the limbs	20	4

Averaging masses of 10 g are specified for the localised SARs and these are specified as contiguous masses, i.e. they are of arbitrary shape and in a single tissue type. Averaging times of 6 minutes are specified to be used with all of the basic restrictions. These imply that higher SAR values may be permitted for shorter periods of exposure than 6 minutes; for example, workers could be exposed to whole body SARs of 1.2 W kg^{-1} for 2 minutes, if no exposure occurred in the 4 minutes leading up to and the 4 minutes after the exposure period.

3.4.3 Reference levels

SAR is not easily measurable in people, and ICNIRP therefore specifies reference levels of external electric and magnetic field strength, and power density. The reference levels have been derived from the basic restrictions on SAR using dosimetric models that assume maximal coupling of the electromagnetic field to the body, such as the electric field strength being uniform over the space occupied by an exposed person.

Comparison of measured or calculated exposure values with the reference levels can be used to assess whether compliance with the basic restrictions has been achieved. However, reference levels are not limits and if they are exceeded it does not necessarily follow that the basic restrictions are exceeded.

The ICNIRP reference levels are frequency-dependent and the levels for power density, over the frequency range 10 MHz to 10 GHz, are shown in Figure 4. The reference levels are most restrictive over the frequency range 10–400 MHz where electromagnetic energy couples most efficiently into the body. The ICNIRP power density reference level for general public exposure is five times below the occupational reference level, reflecting the difference between the underpinning basic restrictions. All of the reference levels are specified as root mean square (RMS) values.

Aviation transponders operate at a frequency of 1090 MHz where the occupational reference levels have the values shown in Table 5. The ratio of the electric field strength reference level to the magnetic field strength reference level, i.e. the wave impedance, is 377 Ω at this frequency. Therefore, in situations where the wave impedance of the exposure is close to 377 Ω, compliance with one of the reference level quantity will ensure compliance with the others. For situations where the wave impedance departs appreciably from 377 Ω, e.g. where exposure is in the reactive near field region of a source, typically within around a quarter of a wavelength, both electric and magnetic field strength reference levels must be complied with.

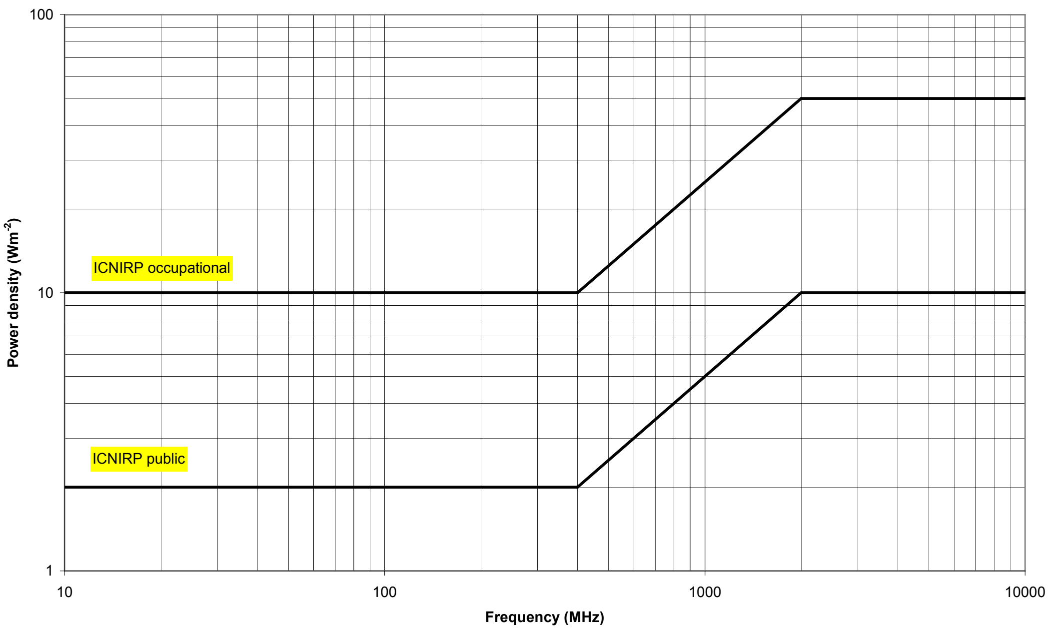

Figure 4 ICNIRP reference levels for power density at frequencies between 10 MHz and 10 GHz

Table 5 ICNIRP reference level values at a frequency of 1090 MHz

Quantity	Exposure Circumstance	
	Occupational	General public
Electric Field Strength, V m^{-1}	99	45.4
Magnetic Field Strength, A m^{-1}	0.264	0.122
Power Density, W m^{-2}	27.3	5.45

3.4.4 Microwave auditory effect

The above reference levels are specified for continuous signals and, reflecting the 6-minute averaging period inherent in the SAR restrictions, people can be exposed to higher power densities for periods shorter than 6 minutes. However, there is a limit to the extent to which short duration pulses can have ever increasing powers because of the onset of the microwave auditory effect (see the ICNIRP guidelines). ICNIRP guards against this by additionally specifying reference levels for peak power density (RMS power density while a pulse is transmitted) and these are set at a value 1000 times higher than the continuous values in Figure 4. Therefore it can be important to additionally consider the peak power of pulsed emissions from radio transmitters, where the duty factor is less than 0.1%. As indicated in Section 2.4, aviation transponders are expected to have a greater duty factor than this and so the microwave auditory effect does not have to be considered further. Note, the factor of 1000 in terms of power density becomes $1000^{1/2}$, i.e. 32, for the electric and magnetic field strength quantities.

3.5 Status of Exposure Guidance

There is currently no specific legislation in the UK relating to protection from electromagnetic fields, although this situation is expected to change shortly with respect to occupational exposure. The prevailing political situation in respect of exposure guidelines is summarised below.

3.5.1 Public exposure

In relation to exposure of the general public to electromagnetic fields, European Member States have formally adopted a European Union Recommendation (CEU, 1999) as a framework for limiting exposure. This document incorporates the ICNIRP public exposure guideline values. The Council Recommendation states that it applies *“applies, in particular, to relevant areas where members of the public spend significant time in relation to the effects covered by this recommendation”*. Clearly, the political interpretation of the phrase “significant time” will be important in the decision to apply the Council Recommendation values to a particular situation.

The UK government responded to the 2004 advice from NRPB to adopt the ICNIRP guidelines (DH, 2004) that *“the guidelines incorporate a significant cautionary element but specifically do not take into account social or economic factors or the risks or disbenefits that may occur from action to limit exposure”*. It referred to its agreement of the EU Recommendation on public exposure in 1999 and wrote that this *“advocated the use of ICNIRP levels but accepts the need for consideration of risks and benefits when implementing the guidelines”*.

The Government recalled that following publication of the Stewart Report on Mobile Phones and Health (IEGMP, 2000), the mobile phone industry had voluntarily adopted ICNIRP guidelines for public exposure to radio frequency fields. For all other sources, the Government indicated that it *“expects the NRPB guidelines to be implemented in line with the terms of the EU Recommendation, that is, taking account of the risks and benefits of action”*.

3.5.2 Occupational exposure

Every employer has a duty under the Management of Health and Safety at Work Regulations 1999 to assess the risks arising from its activities, and the Health and Safety Executive currently accept compliance with HPA guidance as evidence that the risks from exposure have been adequately controlled.

The Health and Safety Executive has indicated that it expects the new European Physical Agents Directive (EU, 2004), which requires compliance with the ICNIRP guidelines in relation to workers, to be transposed into UK Regulations in 2008. It has recommended that employers start preparing as soon as possible to comply with this new law.

3.6 Technical Standards

The European Union has mandated the European Committee for Electrotechnical Standardization (CENELEC) to develop assessment standards for electromagnetic fields for two different purposes.

Firstly, product emission standards are being developed to ensure radio-emitting products placed on the market and put into service in Europe do not cause public exposures to exceed the levels in the 1999 EU Council Recommendation (see section 3.5.1). These standards are being listed as harmonised standards under the Radio and Telecommunications Terminal Equipment (RTTE) Directive (EU, 1999) whose essential requirements include “protection of the health and the safety of the user and any other person” (article 3.1a).

Secondly, occupational exposure assessment standards are being prepared in support of the coming EMF Physical Agents Directive (see section 3.5.2). In carrying out these tasks, CENELEC is working closely with the International Electrotechnical Commission (IEC) to ensure standards are developed globally, wherever possible.

To the author’s knowledge, no standards have been published or are in the process of being prepared that are specifically applicable to lightweight transponders, although several standards addressing the assessment of localised SAR from radio transmitters used near the body might be possible to apply.

Mobile phones have time-averaged output powers of up to 250 mW and are tested according to the product standard EN50360 (CENELEC, 2001a), which calls-up EN50361 (CENELEC, 2001b), a basic standard containing the assessment procedures, and provides a link to the restriction values in the EU Council Recommendation. EN50360 is presently being replaced by an IEC standard, IEC62209-1, but EN 50360 will continue to provide the link to the Council Recommendation.

The mobile phone testing standards mentioned above are only applicable to mobile phones that are held to the side of the head. Phones placed against other parts of the body or held in front of the head do not yet have a standardised assessment procedure, but this is shortly to change. Another IEC standard, IEC62209-2, is at a late stage of preparation and aims to provide an SAR measurement procedure that can be used for devices placed near any part of the body. It defines a flat-bottomed tank filled with tissue equivalent liquid against the bottom of which, a radio device under test is mounted. A robot manipulates a small electric field probe inside the tank which samples the SAR distribution created. Software then calculates the maximum SAR averaged over 10 g.

The procedures in IEC62209-2 should be suitable for testing lightweight aviation transponders, although a control system will be necessary to make them transmit with their maximum time-averaged power during the test. Commercial test houses will probably invest in the necessary equipment and become accredited for this test procedure, as many already are for EN50360/1.

3.7 Summary

For general public exposure, the exposure guidelines at the transponder frequencies prevailing in the UK recommend that SAR should not exceed

- 0.08 W kg^{-1} when averaged over the entire mass of the body, or
- 2 W kg^{-1} in any 10 g mass of contiguous tissue in the head and trunk, or
- 4 W kg^{-1} in any 10 g mass of contiguous tissue in the limbs,

when averaged over any six-minute period. These basic restrictions can be complied with by ensuring the RMS power density (based on electric field and magnetic field measurements or calculations) incident on the body does not exceed 5 W m^{-2} when averaged over any six-minute period. Guideline values for occupational exposure are five times higher. The assessment in Section 4 of this report considers electric and magnetic fields strengths in terms of the ICNIRP reference levels to determine the possible exposures from transponders.

The decision whether transponders should comply with public or occupational guidelines is not clear-cut and would depend on who is using them and in what circumstances. Complying with the public exposure values will ensure compliance with the occupational values and so it is simplest for lightweight aviation transponders to comply with these values and this will be the basis on which the assessment in the remainder of this report is conducted.

The whole-body SAR restriction of 0.08 W kg^{-1} could only be exceeded if the entire output power of a transponder under practical usage conditions (0.44 W, see Section 2) were to be absorbed in a person of mass less than 5.5 kg. This would seem unlikely to occur in practice and so it is the localised SAR basic restriction 2 W kg^{-1} in any 10 g mass of contiguous tissue in the head and trunk that is the limiting condition for transponders. The assessment in Section 5 of this report considers possible exposures from transponders in the context of this basic restriction.

A number of products having similar time-averaged radiated powers to transponders, such as mobile phones, already have product standards in place requiring testing to ensure compliance with ICNIRP public exposure guideline values. It might be possible to use some of these procedures to evaluate exposures from transponders used next to the body.

4 ELECTROMAGNETIC FIELD CALCULATIONS

The previous project (Cooper and Mann, 1998) developed a detailed wire-grid model of a Racal lightweight transponder and carried out analyses to determine the electric and magnetic field strengths as a function of distance from it using Numerical Electromagnetics Code (NEC). The field strengths were normalised in order to represent the modes of operation envisaged at the time, i.e. A and C, and so Mode-S transmissions were not considered.

This report considers a general transponder for which, as noted in Section 2.2.3, there is no specific physical definition. Hence, in this section various NEC models of hypothetical Mode S transponders having linear monopole, helical monopole and patch antennas have been considered. NEC simulations were carried out to understand the characteristics of electromagnetic fields in the vicinity of these transmitters to gain an understanding of the fields likely to be produced by real lightweight transponders.

The field strengths from the models are investigated, taking into consideration the duty factor arising from various transmission characteristics (see Section 2.4) and the maximum peak powers envisaged (30 W or 80 W). The models are approached from all possible sides to calculate the power density and compliance distances in terms of the ICNIRP reference levels (see Section 3.4.3).

4.1 Generic Transponder Model

Numerical Electromagnetic Code (NEC-Win Pro, 1997) is a computer program able to calculate electric and magnetic fields around wire antennas and conducting structures. It uses the method of moments to solve electric field and magnetic field integral equations, taking account of sources exciting radiating structures or external fields to which structures are exposed.

The basic NEC model of a Mode S transponder is comprised of cylindrical wire segments connected together at their ends and each with a given radius. The locations of the wire segments and their lengths have been carefully selected so that the length of each segment is small in relation to the wavelength at the operating frequency of the transponder (1090 MHz). Additionally, the diameter of segments is made small in relation to their length in order to ensure longitudinal currents on the segments dominate any circumferential currents.

Where grids of wires are used to represent the conducting surfaces of the transponder, the wire segment radius is set equal to the segment length divided by 2π. A basic grid spacing of around 10 mm has been used in the model but this is reduced to 5 mm in the box around the antenna. These grid spacings are at least 27 times less than the wavelength (275 mm) at the carrier frequency of the transponder and so the structures should behave as surfaces from an electromagnetic perspective. The dimensions of the modelled transponder are in Section 2.2.3 and the NEC model is shown in Figure 5.

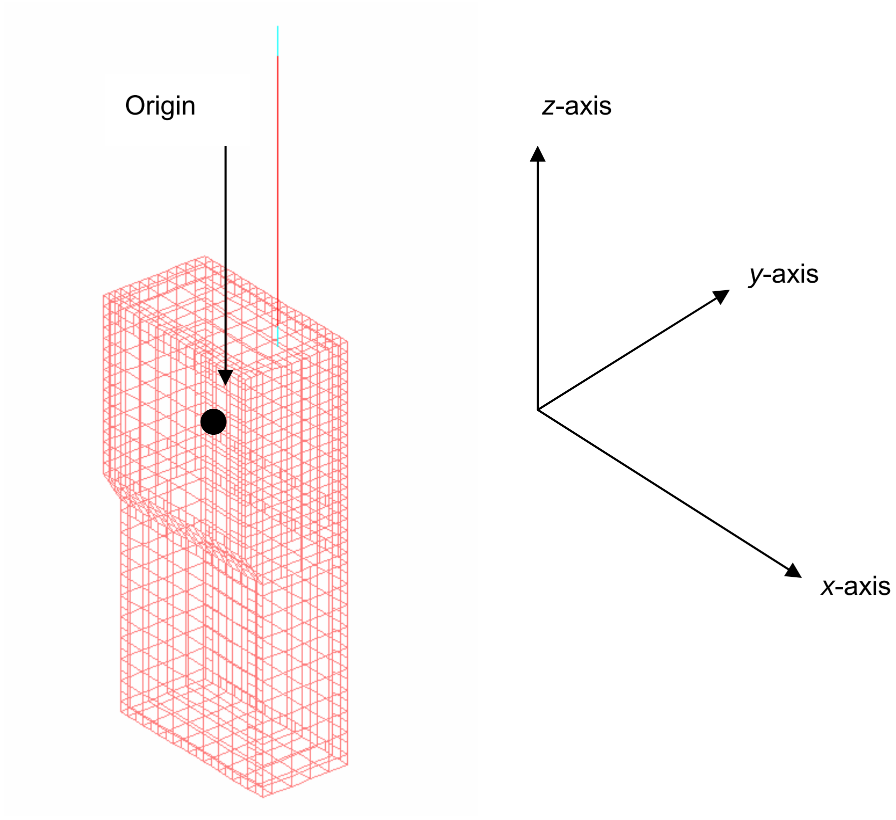

Figure 5 NEC model of the Mode S transponder with a monopole antenna

The origin of the coordinates system is in the middle of the upper section of the unit mid-way between the display screen and back, as shown in Figure 5. The antenna is attached at the coordinate position x = 3 cm, y = 0 cm and z = 4.55 cm and the front face of the transponder faces in the negative y-direction.

The NEC model of the transponder body-shell was investigated with a half-wavelength monopole antenna of 150 mm, to represent a relatively large antenna, and a normal mode helical antenna of approximately 40 mm length, to represent a relatively short antenna. The first 10 mm length of each antenna was a straight wire excited with a voltage source set to give the required time-averaged radiated power. The precise dimensions of the helical antenna were: a diameter of 8.4 mm, space between the turns of 6.5 mm and a total of five turns. In considering the length of the monopole antenna, it is of note that the antenna of the specific Racal transponder considered in the previous report (Cooper and Mann, 1998) was of length 148 mm.

Three different types of antennas (patch, helical and monopole) were considered in NEC simulations in order to investigate the field strength as a function of distance.

4.2 Fields near the Generic Transponder

The coordinate system used to investigate the electromagnetic fields in the vicinity of the NEC model was orientated with its origin in the centre of the upper half of the transponder unit. The monopole or helical antenna was mounted on the top face towards the right side of the unit parallel to the *z*-direction, as shown in Figure 5.

The radiated power was set to 0.165 W, as appropriate for the maximum time-averaged power from a transponder having a peak power of 30 W (See Section 2.4).

Electric and magnetic fields were examined over various planes, each normal to a particular coordinate axis, and the distance of the planes from the six faces of the transponder was varied in order to understand the maximum field strength at any given distance on the various sides of the generic transponder.

A large number of graphs were generated during this part of the work and, while these are referenced in the text, most have been included in Appendix A.

4.2.1 Monopole antenna

4.2.1.1 Electric fields

The electric field components E_x, E_y and E_z over the planes were evaluated with the monopole antenna and the results are described here.

The electric field components in front of the transponder (negative *y*-values) were first calculated in the *xz*-plane at various displacements along the *y*-direction and the resultant field values were also calculated. The maximum value of the resultant field was found to be at x = 3 cm and z = 9 cm, and Figure A1 shows the variations in the components and the resultant as a function of *y*, subject to these *x*- and *z*-values. Similarly, Figure A2 shows the variations in the maximum electric fields as a function of distance away from the back of the transponder. For distances up to 12 cm from the transponder, the *y*-directed component of the electric field dominated, whereas for greater distances, the *z*-directed component dominated.

On the left and right sides, the maximum value of the resultant electric field in *yz*-plane occurred for y = 0 cm and z = 5 cm, and the *z*-directed component of electric field dominated for distances greater than around 2 cm from the transponder, as shown in figures A3 and A4. The fields are much greater on the right hand side because the antenna is much nearer. Nevertheless, the reduction with distance is very rapid (Figure A4).

When approaching the transponder from the top, the maximum value of electric field strength in the *xy*-plane was found for x = 3 cm and y = 0 cm, i.e. at the surface of the antenna and on a line extending beyond its tip. These fields are likely to be strongly affected by numerical artefacts in the NEC model and the way it applies boundary conditions at the surface of the antenna, however the results are shown in Figure A5. Three peaks are shown along the antenna surface and then a rapid reduction in field strength occurs beyond the antenna tip. Below the base of the unit, the *z*-component dominated the resultant electric field, as shown in Figure A6. With increasing distance, all the components of the electric field decreased rapidly.

The electric field components over the *xz*-plane at 7 cm from the front surface of the generic transponder are of particular interest since this is the approximate distance at which the resultant field falls within the 45.4 V m^{-1} ICNIRP general public reference level (see Figure A1 and Section 3.4.3). Compliance with the reference level will be considered in more detail later in Section 4.3. Figures A7 to A9 show the field components and Figure A10 shows the resultant field.

4.2.1.2 Magnetic fields

The magnetic field strengths were examined with increasing distance from the surfaces of the transponder. The magnetic field components H_x, H_y and H_z over the planes were evaluated in the same way as described in the Section 4.2.1.1 and the results are described here.

The magnetic field components in front of the transponder (negative *y*-values) in the *xz*-plane showed that maximum value of the resultant magnetic field was at x = 3 cm and z = 9 cm, and Figure A11 shows the variations in the components and the resultant as a function of *y*, subject to these *x*- and *z*-values. Similar variations in magnetic field strengths were also observed as a function of distance away from the back surface of the transponder as shown in Figure A12. On the front and rear side with increasing distance away from the surface of the transponder, the *x*-directed component dominated the *y*- and *z*-directed magnetic field components.

On the left and right sides, the resultant magnetic field in the *yz*-plane, was found to be maximum at y = 0 cm and z = 5 cm, and the *y*-directed component of magnetic field dominated, as shown in figures A13 and A14. The magnetic fields are much greater on the right hand as compared with left side because the antenna is much nearer to the right side of the transponder. Even so, the reduction in magnetic field strength with distance is very rapid (Figure A14).

The magnetic field strength, when the transponder was approached towards its top face in the *xy*-plane, was found to be maximum at x = 3 cm and y = 0 cm, i.e. along the antenna axis. There were three peaks along the antenna surface followed by a rapid reduction in field strength with distance beyond the antenna tip, as shown in Figure A15. The *x*- and *y*-directed components were greater than *z*-directed magnetic field along the antenna surface, but the fields at the antenna surface are likely to be strongly affected by numerical artefacts in the NEC model and its application of boundary conditions. Below the base of the unit, the *y*-component dominated the resultant magnetic field and all the individual components decreased rapidly with increasing distance away from the transponder, as shown in Figure A16.

The resultant magnetic field was also noted to be well within (around 50% of) the 0.122 A m^{-1} ICNIRP reference level at approximately 7 cm in the *xy*-plane, indicating that electric field strength was the more restrictive quantity in terms of compliance. The magnetic field distributions for the components are shown in figures A17 to A19 and Figure A20 shows the resultant magnetic field distribution.

4.2.2 Helical antenna

The normal mode helical antenna is smaller than the monopole antenna, with an overall length of 40 mm instead of 150 mm. The field strength predicted by NEC was found to be extremely sensitive to the design parameters of the antenna. In order to evaluate the electromagnetic field strength due to the change of antenna type (from monopole to helix), the basic generic transponder body-shell shown in Figure 5 was modelled with a normal mode helical antenna in place of the monopole antenna, having the dimensions indicated in Section 4.1. As with the monopole, the electric and magnetic field components were investigated in the vicinity of the transponder.

4.2.2.1 Electric fields

The electric field strengths were examined with increasing distance from the front surface of the transponder. The electric field components E_x, E_y and E_z were evaluated over a plane in the same way as described in Section 4.2.1.1 for the monopole antenna and then along a line moving away perpendicular to the front face passing through the maximum field strength found in the plane. The resultant electric field strength as a function of distance from the front surface of the transponder is shown in Figure A21.

The investigations showed that the same components of the field dominated the distribution as with the monopole antenna, but the field at the smallest distances was slightly less than with the monopole antenna (see Figure A1). Very close to the helical antenna, the electric field components were found to fall off slightly more rapidly than with the monopole antenna, but the fields converged to similar values at large distances.

The value of the resultant electric field exceeded the ICNIRP reference level for distances up to 6 cm; however, a detailed compliance analysis with the reference level will be considered later in Section 4.3.

4.2.2.2 Magnetic fields

The magnetic field strengths in front of the transponder were investigated in the same way as the electric field strengths and the results are described here. The resultant magnetic field strength with the displacement of distance away from the antenna is shown in the Figure A22.

The data analysis showed that the same components of the field dominated the distribution as with the monopole antenna. Close to the helical antenna, the magnetic fields were stronger than those with the monopole antenna, in contrast to the situation with the electric fields.

The resultant magnetic field strength exceeded the ICNIRP reference level for distances up to 5 cm from the front surface of the transponder.

4.2.3 Patch antenna

Some simple modelling was carried out to investigate resonant patch antennas with transponders and a patch antenna of 140 × 140 mm (λ/2) was designed in NEC. It would have been difficult to mount the patch antenna on the basic transponder body-shell used for the monopole and helical antennas (Figure 5) because of its size and so the patch antenna was simulated at 10 mm height over a perfectly conducting ground plane.

Patch antennas have directional characteristics that are different from helical and monopole antennas and the results suggested it would probably be a difficult task to build a transponder with a sufficiently isotropic radiation pattern in the horizontal plane using patch antennas. It is also more likely that a patch antenna could become covered over, thereby leading to shielding and performance problems with a transponder. For these reasons, modelling using helical antennas was not pursued any further.

4.3 Field Compliance Distances

The electric and magnetic fields derived in Section 4.2 were further processed in order to determine the maximum distance at which the general public and occupational reference levels were exceeded. The data are for the monopole antenna because this was found to produce stronger electric and magnetic fields at distances where the field strengths were comparable to the reference levels. The electric field data are from figures A1 to A6 and the magnetic field data are from figures A11 to A16 for a 30 W transponder with the maximum reply rate (time-averaged power of 0.165 W). These data are shown in Figure 6 and Figure 7, together with the ICNIRP general public and occupational reference levels. The distances have been adjusted to be to the surface of the transponder rather than to the origin of the coordinate system, except in the case of the distance to the "top" which is to the antenna tip.

The ICNIRP reference levels were exceeded within various distances from the different surfaces of the 30 W unit, except for the left side and base, as shown in Table 6. The antenna was mounted on the top right hand side of the unit and, as would be expected, the field strengths were greater for a given distance when approaching the transponder from this side. The strongest electric fields were above the transponder and near the antenna tip, but the magnetic fields were low here because of the current null.

For general public exposure, the greatest compliance distances were in respect of the electric field strength and the maximum was 3.6 cm. For occupational exposure, the distances were shorter due to the higher reference level and the magnetic field gave the larger distance of 3.0 cm.

Similar calculations were performed for an 80 W transponder (time-averaged power of 0.44 W) for those surfaces that produced the strongest fields and these results are also shown in Table 6. The distances under the conditions of the QinetiQ evaluation (see Section 2.4.2) are also shown in the table as "Expected in 2020". For this scenario, the time-averaged powers of 30 W and 80 W transponders were 0.132 W and 0.352 W respectively.

Table 6 ICNIRP reference levels and the distances under which the exposures are exceeded for Mode S aviation transponders

Transponder power and repetition cycle		Compliance Distance from the transponder, cm			
		Electric field strength		Magnetic field strength	
Power (W)	Reply rate	Public	Occupational	Public	Occupational
30	Maximum	3.6	2.0	2	3
	Expected in 2020	3.3	1.8	2	2.9
80	Maximum	5.4	2.6	2.6	3.9
	Expected in 2020	5.0	2.4	2.5	3.7

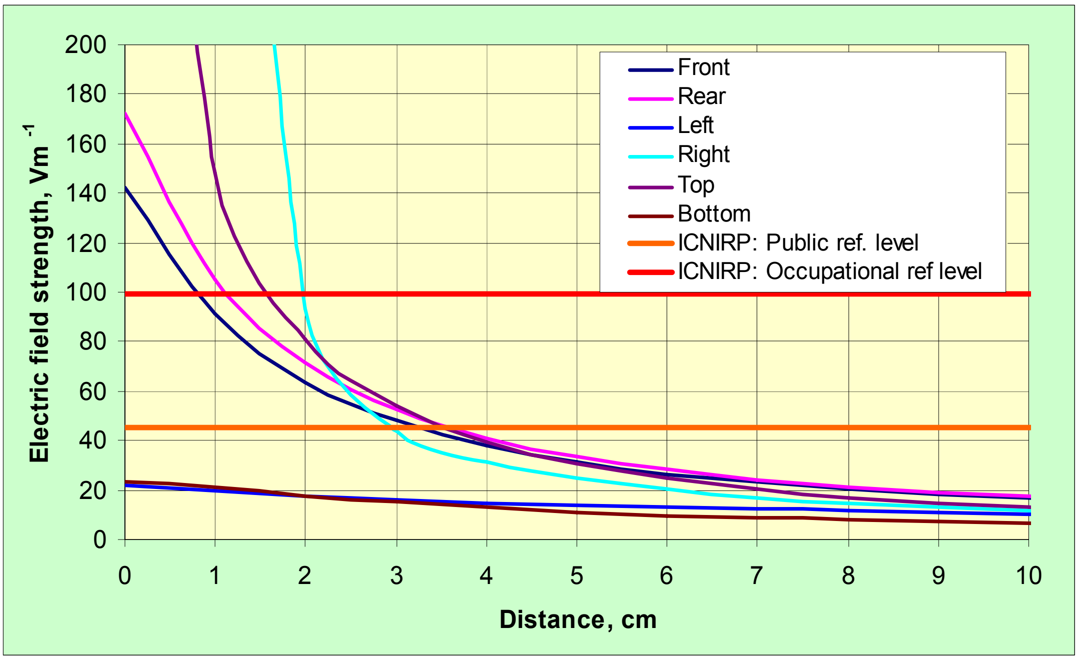

Figure 6 Electric field strength as a function of distance from various sides of the transponder in relation to the ICNIRP reference levels

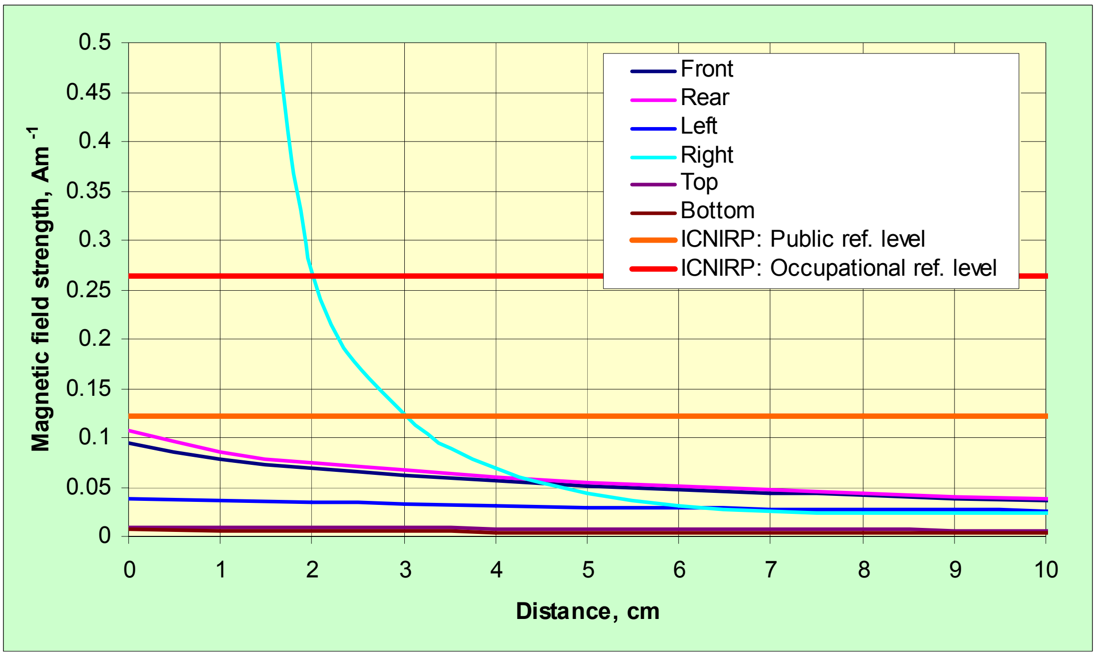

Figure 7 Magnetic field strength as a function of distance from various sides of the transponder in relation to the ICNIRP reference levels

4.4 Summary and Discussion

The field strengths near both the 30 W and 80 W peak power transponder models operating under maximum expected duty factor conditions, implying 0.165 and 0.44 W time-averaged powers respectively, exceeded the ICNIRP reference levels within a few centimetres. For the generic transponders modelled in this section, the maximum distance for public exposure was 3.6 cm for the 30 W transponder and 5.4 cm for the 80 W transponder. Shorter distances apply in the context of the occupational reference level.

The precise compliance distances with real transponders would depend on the type of antenna used, the size and shape of the transponder body shell and where the antenna is mounted. A pessimistic figure for the distance that is likely to be applicable in the case of public exposure from all transponders with low gain antennas, such as helices and dipoles, would likely be around 5 cm for 30 W and 10 cm for 80 W peak powers. This distance would be to the nearest point of the antenna or the body-shell.

In considering the reference levels and the above compliance distances, it is important to note that, as explained in Section 3.4.3, the reference levels are derived assuming the field strength is uniform over the entire body. With a transponder placed a few centimetres from the body, the field strength would only be comparable to the reference level over a small region of the body. The rapid reduction of field strength with distance would mean that most of the body would be exposed to levels much lower than the reference level. Under such conditions, the coupling of the field to the body would be weaker than assumed in deriving the reference levels and a more sophisticated analysis against the basic restrictions might show that the ICNIRP guidelines are not exceeded. Such an analysis follows in the next section.

5 REVIEW OF LITERATURE ON LOCALISED SAR

Lightweight aviation transponders are expected to be carried on small aircraft and may be in close proximity to the pilot and other people onboard for extended periods. As explained in Section 3.4, when a radio transmitter is used near a person, some of the energy in the emitted radio waves is deposited in the body tissues and there are accepted guidelines on limiting such exposure (ICNIRP, 1998).

Research has been carried out to measure or calculate the distribution of absorbed power in the body from various different types of radio transmitters over the years. Early studies tended to be experimental in design, but computational capabilities have now advanced to the point where calculations can be carried out with greater anatomical realism and finer resolution than is possible with experimental methods. Most recent research has addressed mobile phone handsets, particularly when they are held next to the head in the normal usage position within 1-2 cm.

GSM900 mobile phones operate in the 890–915 MHz frequency band and some phones in North America and other parts of the world use a frequency band from 824–849 MHz. Transponders operate at 1090 MHz, which in relation to interaction with the body, is very similar to these frequencies, and exposure of the body to these frequencies would elicit very similar responses in body tissues.

In addition, the likely design of transponders, i.e. a box with a monopole antenna on the top surface, is similar to the mobile phone models for which assessments have been reported, justifying a study of mobile telephone-related research in the literature.

The previous report for CAA (Cooper and Mann, 1998) included a review of mobile phone-related studies in the 800/900 MHz frequency range. This chapter considers more recent developments on the topic and estimates the SAR values likely to be created by aviation transponders used near to the body.

5.1 Evaluation of Specific Absorption Rate

5.1.1 Definition

Specific energy absorption rate (SAR) is quantified in the unit watt per kilogram (W kg^{-1}) and it is a measure of the rate at which energy is absorbed per unit mass of tissue when the body is exposed to radio waves. SAR can be defined at a point inside the body or averaged over a given mass of tissue.

In both experimental and theoretical methods, SAR can be determined from the electric field strength measured or calculated at any point in the body through the following expression

$$SAR = \frac{\sigma |E|^2}{\rho}$$

where E is the RMS electric field strength in the biological tissue, σ is the conductivity and ρ is the mass density of the tissue.

Scientific papers in the literature report SAR values for devices with a variety of different radiated power levels. However, SAR is proportional to radiated power, so the values reported here have been normalised to the radiated power to aid comparisons. Thus, SAR is reported in terms of watts per kilogram per watt (W kg^{-1} / W).

5.1.2 Averaging masses

The localised SAR values reported in the scientific literature and elsewhere are presented in the following three different ways.

- Spatial peak SAR in a region of the body
- Peak SAR averaged over any 1 g mass in a region of the body
- Peak SAR averaged over any 10 g mass in a region of the body

It is therefore important to identify the type of SAR value (exposure metric) being reported in any given study, and only to directly compare values that are for the same exposure metric.

For practical situations with a radio transmitter used near the body, the spatial peak SAR would be higher than the 1 g mass averaged SAR which would, in turn, be higher than the 10 g mass-averaged SAR.

As noted in Section 3.4.2, exposure guidelines require SAR to be averaged over 10 g of contiguous tissue before comparison with the basic restrictions on localised SAR in a given part of the body. Hence, only the third quantity can be compared with the ICNIRP guidelines.

5.1.3 Experimental methods

Experimental methods for SAR determination involve the construction of a physical model, or phantom, of the human head or body using materials with electrical (conductivity and permittivity) properties as close to human tissue as possible. A transmitting device is then placed next to the phantom to produce the desired SAR distribution.

Thermal methods to investigate the SAR distribution were discussed in the previous report for CAA (Cooper and Mann, 1998), but these methods are now largely obsolete, having been overtaken by methods using implantable electric field probes. The major difficulties are that the output power of most real transmitters is too small to deposit sufficient energy into a phantom for a measurable temperature rise to occur, and the need to achieve energy absorption and make measurements quickly before thermal diffusion smears-out any temperature distribution created.

Some of the more sophisticated physical phantoms have had several tissue types incorporated, but it is difficult to measure the internal electric field strength at many positions inside such phantoms as moveable sensors would break-up the internal structure. Thus, most experimental work tends to be carried out with homogeneous phantoms containing liquids through which an electric field probe can easily be moved.

5.1.4 Theoretical methods

A variety of theoretical methods have been used for the calculation of SAR in the body over the years and many of the simplifications used in earlier methods are no longer necessary due to advances in computational power. The modern approach is to develop high-resolution anatomically realistic models of the body from magnetic resonance imaging (MRI) or from images of closely spaced slices successively removed from frozen cadavers.

The models are in the form of 3-dimensional arrays of 1-2 mm diameter cuboidal cells, known as voxels, each of which has a tag defining it as a particular tissue, e.g. muscle, blood, or brain, or the surrounding air. The conductivity and permittivity of each tissue type is parameterised as a function of frequency so all of the information necessary to solve the fundamental electromagnetic “Maxwells” equations is available.

The Finite Difference Time Domain (FDTD) method is usually used to solve Maxwells equations with voxel phantoms at the frequencies used by mobile phones and transponders. Many authors have published their results for SAR produced in the body both from plane waves and from radio transmitters, such as mobile phones, placed near various parts of the body. Early results were given in the previous report for CAA and these are reproduced here, together with more recent results.

5.1.5 Mobile phone compliance testing

As noted in Section 3.6, a standard test procedure became available in 2001 for evaluation of SAR in the head from wireless devices such as mobile phones held to the ear. The method uses a Specific Anthropomorphic Mannequin (SAM) phantom with standardised dimensions, test position for the phone, and tissue-simulating liquid.

The phantom shell is often in a generic twin format, which consists of an open tank formed from the two halves of the head separated and extended so that left and right ears are on the under-side, where a mobile phone can be placed.

A miniature electric field probe is manipulated inside the phantom through its open top surface by a robot arm above. A control system moves the probe over a grid of positions and evaluates the 10 g mass-averaged SAR from interpolations/extrapolations of the sampled data.

5.2 Results with 1 g Averaging Mass

The present ICNIRP guidelines were published in 1998 and the previous ICNIRP guidelines did not contain restrictions on localised SAR. Hence, localised SAR values reported in the literature up to around 1996/7 were obtained mainly with a 1 g averaging mass, as used in IEEE exposure guidelines advised at that time. The 1998 ICNIRP guidelines introduced localised SAR restrictions with 10 g averaging masses and hence publications since 1997 tend to also include data for 10 g averaging masses. Moreover, IEEE updated its guidelines in 2005 and since then there has been an international consensus to use a 10 g averaging mass with localised SAR basic restrictions.

SAR data with a 1 g averaging mass are therefore not comparable with present-day exposure restrictions and so, for simplicity of presentation, they have been separated out from data with a 10 g mass in this report. The continuing value of these data is in terms of the trends they show with respect to transmitter design and placement and in the overall variability in reported values that is evident.

5.2.1 Experimental methods

The most anatomically realistic phantom heads constructed to date for use with implantable E-field probes have been composed of five tissue types simulating muscle, eyes, brain, skin and bone. A study by Anderson and Joyner (1995) of analogue mobile phones operating at 835 MHz found peak SARs of 1.38 W kg^{-1} / W in the brain and 0.35 W kg^{-1} / W in the eye. These values were increased by up to 29% when metal-framed spectacles were placed on the phantoms. The authors estimated that an improved anatomically realistic phantom with more accurate dielectric properties would be likely to yield higher SARs, probably in the range 2.2–2.7 W kg^{-1}/W.

An earlier study conducted by Cleveland and Athey (1989) investigated the SAR from radios with different antennas transmitting at frequencies between 800 MHz and 900 MHz. A peak SAR of 3.5 W kg^{-1}/W was produced in a 4-tissue head phantom by the radio using a sleeve-dipole $\lambda/2$ antenna whereas the radio transmitter with a $\lambda/4$ whip produced a similar peak SAR of 3.2 W kg^{-1}/W.

Balzano *et al* (1995) have investigated SARs induced by two cellular telephones in a fibreglass skull filled with a homogeneous material to simulate the brain. The telephones operated at frequencies within the range 800–900 MHz and were placed 0.4 cm away from the skull. The antenna of the larger phone was situated several cm from the head during normal usage and the maximum SAR induced in the head was found to be 0.7 W kg^{-1}/W. The smaller telephone had a collapsible antenna which was positioned closer to the head. The resulting SAR was found to have a maximum of 1.3 W kg^{-1} / W with the antenna extended and 2.7 W kg^{-1} / W with the antenna collapsed. Other studies carried out by Chou (1996) using relatively simplistic head phantoms have reported peak SARs up to 6.0 W kg^{-1}/W.

An assessment of body-mounted communications transceivers has been made by Chatterjee *et al.* (1985) using a homogeneous whole-body phantom. A peak SAR in the body of 1.3 W kg^{-1}/W was found for an 800 MHz transceiver positioned vertically on the chest. When the transceiver was repositioned vertically in front of the face the peak SAR in the head was established to be 0.8 W kg^{-1}/W.

5.2.2 Theoretical methods

Gandhi *et al* (1996) modelled a mobile phone operating at 835 MHz using FDTD. The authors employed a computer model of the head with 15 different tissues and voxels of $1.875\times1.875\times3$ mm^3. Peak SARs from a $\lambda/4$ monopole antenna held 1.4 cm away from the head ranged from 4.88 W kg^{-1} / W in an adult head to 7.48 W kg^{-1} / W in the head of a five-year-old child. The peak SARs were reduced to 2.67 W kg^{-1} / W and 3.13 W kg^{-1} / W respectively when the antenna was substituted by a $3\lambda/8$ monopole. The results for the $\lambda/4$ antenna could be reduced by changing the orientation of the handset with respect to the head.

A hand-held portable radio transmitting at 900 MHz has been modelled by Watanabe *et al* (1996). The head model consisted of $(2.5\ mm)^3$ voxels, each assigned to one of seven tissue types. With the $\lambda/4$ monopole antenna positioned 2 cm away from the head the peak SAR was calculated to be 3.2 W kg^{-1}/W. A λ/2 dipole antenna produced a lower peak SAR of 1.3 W kg^{-1}/W when averaged over the same mass of tissue. The SARs fell to 1.7 W kg^{-1}/W and 0.9 W kg^{-1}/W for the λ/4 and λ/2 antennas respectively when the head-antenna distance was increased to 3 cm.

Bernardi *et al* (1996) modelled a head with 12 types of tissue using cubic voxels with 5 mm sides. Analysis was made of a cellular phone with a λ/2 sleeve dipole and a 5λ/8 whip antenna successively radiating at 900 MHz. The whip antenna could either be extended or retracted inside the handset. The dipole was modelled 5 cm away from the head and gave rise to a peak SAR of 0.57 W kg^{-1}/W. The whip antenna was placed closer to the head at a distance of 1.5 cm. The highest recorded spatially averaged SAR with from the whip antenna when extended was 2.2 W kg^{-1}/W although this was increased to 5.4 W kg^{-1}/W with the antenna retracted. The authors also investigated the effects of placing conducting surfaces close to the head whilst the phone was transmitting. It was found that an overhead conducting surface caused greater dispersion of power resulting in decreased SAR at 'hot spots' whilst elsewhere SAR was increased. The introduction of a vertical reflecting wall raised SAR in the head universally causing the worst case value to be approximately doubled for the whip antenna. A vertical glass wall was found to have insignificant impact on measured SAR.

5.3 Results with 10 g Averaging Mass

Most recent work (since 1996/7) has used theoretical methods to evaluate localised SAR in anatomically realistic voxel phantoms. Such work has included data for 10 g averaging masses and is reviewed here, including comparative analyses involving transmitters placed near different parts of the body.

Most of the studies listed here are for phones transmitting in the 800/900 MHz bands, but there are also some data for 1700/1800 MHz. These data are useful since they give an idea of how SAR changes with rising frequency, and thus an indication as to how the SAR at 1090 MHz, the frequency of the transponder, may differ from that at 800/900 MHz.

5.3.1 Mobile phones used near the head

A study by Dimbylow and Mann (1994) of a 900 MHz and 1800 MHz mobile communication transceiver situated 2 cm away from the head employed a computer model with voxel size 2 $(mm)^3$. At 900 MHz with a λ/4 monopole antenna the transceiver was found to produce peak 1 g and 10 g mass-averaged SARs of 4.74 and 3.09 W kg^{-1}/W. Replacing the transceiver with an isolated λ/2 dipole antenna increased these SARs to 7.12 and 4.84 W kg^{-1}/W respectively. At 1800 MHz with a λ/4 monopole antenna the peak 1 g and 10 g mass-averaged SARs were 6.75 and 3.84 W kg^{-1}/W respectively. Replacing the transceiver with an isolated λ/2 dipole antenna increased the SARs to 11.9 and 6.19 W kg^{-1}/W.

Okoniewski and Stuchly (1996) have examined a mobile phone handset operating at 915 MHz and held 1.5 cm from the head. The handset was found to induce a spatial peak SAR of 11.2 W kg^{-1}/W in a low-resolution head model employing seven types of tissue with voxels of dimensions 3.9×3.9×5 mm^3. The maximum SAR averaged over a

10 g mass was 4.8 W kg^{-1} / W. However, for a high resolution model comprising 26 tissue types with voxels of 1.1×1.1×1.4 mm^3, the SAR was reduced to a spatial peak value of 3.9 W kg^{-1}/W and a 10 g mass-averaged value of 1.8 W kg^{-1}/W.

Hombach *et al* (1996) modelled a mobile telephone operating at 900 MHz using the Finitie Integration Technique (FIT), a method similar to FDTD. The authors compared one head model having 12 tissue types and voxel dimensions 1.875×1.875×3 mm^3 with two higher-resolution head models having 13 tissue types and cubic voxels with 1 mm sides for the first model and 1.075 mm sides for the second. The high-resolution models yielded maximum SARs averaged over 10 g of tissue of 6.4 W kg^{-1}/W and 6.0 W kg^{-1}/ W for the two heads respectively. The computation for the low-resolution model gave a decreased SAR of 4.2 W kg^{-1}/W, apparently contrary to the findings of Okoniewski and Stuchy (1996), as above. However, the two models of Okoniewski and Stuchly contained disparate numbers of tissue types, unlike those of Hombach *et al*.

The IBREHT study (1997), examined SAR produced in a head model obtained by an MRI scan. The model contained 13 tissue types and the cubic voxels had sides measuring 2.5 mm. The study found considerable variation in SAR depending on the orientation of the handset, the type of antenna and the distance between the handset and the head. The highest SARs were found in eye tissues with the handset placed vertically in front of the face. However, a more realistic orientation of the handset induced a maximum SAR in the skin. It was found that a centre-fed λ/2 monopole induced higher SARs than an end-fed λ/2 monopole. An end-fed λ/4 monopole induced greater SARs still. Not surprisingly it was found that SAR increased with decreasing separation between the handset and the head. In some tissues the maximum average SAR doubled when the separation was reduced from 5 mm to 0 mm. In most tissues there was a further increase when the handset was pressed against the cheek. Worst case SARs were evaluated using a handset pressed against the cheek with a λ/4 monopole antenna transmitting at 900 MHz and 1800 MHz. The peak SAR was found to be 4.2 W kg^{-1}/W using a 1 g averaging mass which was reduced to 2.5 W kg^{-1}/W for a 10 g averaging mass at 900 MHz. The values at 1800 MHz were 8.2 W kg^{-1} / W reducing to 5.9 W kg^{-1}/W.

Wang and Fujiwara (2003) carried out a study based on the FDTD method to calculate the SAR produced in an adult head consisting of 17 different tissue types. With a 0.45λ dipole antenna, the 10 g averaged peak SAR derived from a cube of 2.2×2.2×2.2 cm^3 was reported as 4.6 W kg^{-1}/W.

Kouloudrdis *et al* (2005) simulated a quarter-wavelength monopole antenna mounted on the top corner of an electrically conducting box operating at 1710 MHz next to the head. With 2.5 mm distance between the ear of the head model and the box of the mobile terminal, the peak 10 g averaged SAR was 7.2 W kg^{-1} / W in an adult sized head. When distance was doubled to 5 mm, this reduced to 5.5 W kg^{-1} / W

Hadjem *et al* (2005) developed models of two real mobile phones in the form of rectangular boxes with dual band patch antennas and simulated these next to two different head models, both scaled to represent children and adults. With the “COMOBIO head”, the peak 10 g averaged SAR values in contiguous tissue regions for an adult-sized head were 4.64 and 5.6 W kg^{-1} / W at 900 and 1800 MHz respectively.

The simulations were repeated using a “Visible Human” head and values became 3.64 and 3.52 W kg^{-1} / W respectively.

Bit-Babik (2005) carried out simulations of exposure and SAR calculations at 900 MHz using the Nagoya Institute of Technology (NIT) head model scaled to represent adults, and 7- and 3-year old children. The results for the adult-sized head showed a peak 10 g averaged SAR of 3.0 W kg^{-1} / W. With a different simulation computer program, known as XFDTD, the value was 3.44 W kg^{-1} / W. The paper concluded that the apparent difference may be attributed due to different computing algorithms used in these codes.

5.3.2 Mobile phones used near the body

Kang and Ghandi (2002) calculated the peak 1 g and 10 g cube-averaged SARs for four typical mobile phones with monopole-like antennas, two operating at each frequency of 835 and 1900 MHz, and located as though they are placed in a shirt pocket. An anatomically realistic model of the body at 2 mm resolution was used and truncated above the neck, below the waist and at the elbows. The handsets were located in the pocket positions facing backwards and forwards, the former resulting in an antenna separation distance from the body of as little as 4 mm and the latter in a greater distance by around 12-16 mm. Comparative data for localised SARs from the same handsets near an anatomically realistic head were not provided. The 10 g averaged SARs for the two 835 MHz handsets were around 3.4 and 3.2 W kg^{-1} / W for the forwards position and around 6.4 and 6.0 W kg^{-1} / W for the backwards position. Those for the two 1900 MHz handsets were around 0.8 and 1.6 W kg^{-1} / W for the forwards position and around 3.2 and 3.6 W kg^{-1} / W for the backwards position.

Kang and Ghandi also made measurements of the SARs produced by the four handsets placed beneath a flat bottomed tank containing tissue-simulant material, and compared these results with the SARS produced in a similarly homogeneous phantom head having a 6 mm dielectric spacer for an ear. The tank was made of a dielectric material and had base thicknesses of 2, 4, 6 and 8 mm for the measurements. It was noted that the peak 1 g and 10 g SAR values for the phantom head were very similar to those in the flat phantom with the same base thickness as the dielectric spacer in the ear, i.e. 6 mm.

The peak SAR values in the tank were observed to increase at a compounding rate of 10-15% for every millimetre of closer placement of the radiating handset to the flat phantom. For the flat phantom, increasing the separation distance from 2 to 8 mm reduced both 1 g and 10 g SARs by a factor of 1.5 to 2.1 at 835 MHz and 1.45 to 2.59 at 1900 MHz. It was noted that very similar results had been reported for head models by Dimbylow and Mann (1994) and by Okoniewski and Stuchly (1996) where reduction factors of 1.52 to 1.88 for an additional 6 mm separation and 1.45 to 1.66 for an additional 5 mm separation had been found respectively.

Troulis *et al* (2003) used FDTD modelling to investigate peak SARs from the use of 1800 MHz mobile phones placed near the head and waist. The body model was of a complete 1.7 m tall adult and had a resolution of 5 mm and contained six tissue types. The handset was represented as a perfectly electrically conducting (PEC) box fitted with a monopole antenna on its top surface of the box. The proportion of the output power radiated away from the body (rather than absorbed in it) was 66.4% for operation near the head and 52% for operation near the waist, corresponding to peak 10 g mass averaged SARs of 1.76 and 2.12 W kg^{-1} / W respectively.

Troulis *et al* concluded that a change in handset operating position from head height to waist level produced increases of 28.6% and 20.5% in peak 1 g and 10 g SAR values respectively. These increased values, amongst other reasons, were felt to be due to the increase in tissue volume around the antenna, different tissue properties and tissue distribution characteristics.

5.3.3 Different types of antenna

Alexiou *et al* (2005) modelled a normal mode helical antenna attached on a handset near a phantom head and evaluated the results against a monopole antenna. A homogeneous brain tissue spherical model was used and the head was geometrically modelled with 320 volume entities called bilinear hexahedra. The far-field radiation pattern was examined at 900 MHz in the presence of the phantom and within a RF shielded anechoic chamber. It was demonstrated that, under equivalent conditions, the amount of power absorbed by the head is larger with the helical antenna than with the monopole antenna. It was also found that with both antennas the SAR in the head reduced very rapidly with increasing distance between the handset and the head. When the handset was in contact with the head, the absorbed power with the helical antenna was 85% of the total power delivered and that with the monopole antenna was 62%. The absorbed power was estimated as 60% of the input power when the handset was 1 cm away from the head, while the corresponding theoretical result was about 55%.

5.4 Results of Mobile Phone Compliance Testing

Standardisation and compliance testing used for product assessment have followed the experimental pathway because the actual product, rather than a model of it, can be tested.

Mobile phone manufacturers who are members of the Mobile Manufacturers Forum (MMF) make the SAR values available for their phones on a website (www.mmfai.org.uk). The data available in June 2003 were for 111 GSM phones and showed SAR values in the range 0.2–1.4 W kg^{-1} (AGNIR, 2003), as shown in Figure 8.

GSM phones can operate in bands close to 900 MHz and 1800 MHz, and it is not clear which band would have produced the maximal values. Nevertheless, taking the values in Figure 8 as representative of the 900 MHz band in which phones have a time-averaged radiated power of 0.25 W, implies 10 g averaged SARs of 0.8–5.6 W kg^{-1} / W.

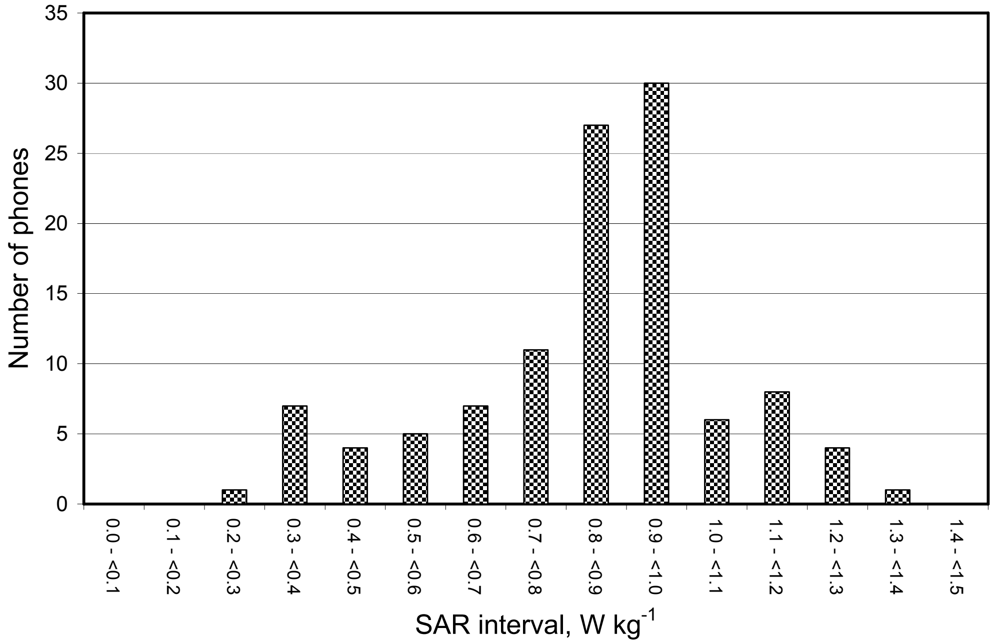

Figure 8 Reported SAR values from compliance testing of 111 mobile phones (AGNIR, 2003)

5.5 Summary and Discussion

The data summarised above in this section illustrate the range of typical SAR values that can be expected with mobile-phone-like transmitters used against the body and transmitting at frequencies similar to 800/900 MHz mobile phones. The values in the scientific literature for head SARs lie in the range 1.8–6.4 W kg^{-1} / W, as shown in Table 7. This seems consistent with the data reported from compliance testing of mobile phones, which lie in the range 0.8–5.6 W kg^{-1} / W.

There are fewer data giving localised SAR values when transmitters are used near parts of the body other than the head, but what data are available suggest higher SARs than when next to the head. This may be because more tissue is able to become in close proximity to the antenna when transmitters are located near the body. For example, the torso is more flat than the surface of the head and curves away less from the transmitter. It is difficult to quantify the increase in SAR based on the papers reviewed the highest quoted SARs with the handset next to the head may be least affected, since these will be where the handset is closest to the head, or has a smaller antenna, which would be less influenced by the head curving away from it.

Studies also indicate there is an increase in SAR values with an increase in frequency. The study by Dimbylow and Mann (1994) and the IBREHT study show 25% and 140 % increased SARs per unit power respectively in changing from 900 to 1800 MHz. Even so, the maximum value of 5.9 W kg^{-1} / W found in the IBREHT study at 1800 MHz is still within the typical range of SAR values found by the studies (1.8–6.4 W kg^{-1} / W).

The SAR values are expected to reduce rapidly with increasing distance and the variability of the SAR values at a particular frequency from one study to another probably reflects variability in position of the handset with respect to the head more than any other factor. It is difficult to define a general trend defining the rate at which SAR reduces with distance based on the data reviewed.

Table 7 Published localised SAR values from mobile phone models placed against the head with averaging over 10 g

Reference	Head model characteristics		Transmitter characteristics		SAR value W kg^{-1} / W	
	Voxel size (mm)^3	Number of tissues	Box dimensions (cm)^3	Antenna type	900 MHz	1800 MHz
Dimbylow and Mann 1994	2 × 2 × 2	10	15 × 6 × 2.4	λ/4 monopole	3.09	3.84
			No box	λ/2 dipole	4.84	6.19
Okoniewski & Stuchly 1996	3.9 × 3.9 × 5	7	15 × 6 × 3	λ/4 monopole	4.8	
	1.1 × 1.1 × 1.4	26	15 × 6 × 3	λ/4 monopole	1.8	
Hombach *et al* 1996	1.87 × 1.87 × 3	12	Mobile phone (no dimensions given)	0.45λ dipole	4.2	
	1 × 1 × 1	13		0.45λ dipole	6.0 (model 1)	
	1 × 1 × 1	13		0.45λ dipole	6.4 (model 2)	
IBREHT Study 1997	2.5 × 2.5 × 2.5	13	11 × 5 × 2	λ/4 monopole	2.5	5.9
Wang and Fujiwara 2003	2.2 × 2.2 × 2.2	17	No Box	0.45λ dipole	4.6	
			11 × 4 × 2	λ/4 monopole	3.0	
Troulis *et al* 2003	5 × 5 × 5	6	3 × 5 × 13	λ/4 monopole		
				Head operated		1.76
				Waist operated		2.12
Hadjem *et al* 2005	1 × 1 × 1	8	4.4 × 1.5 × 10	Internal patch	4.64	5.6
	1 × 1 × 1	21	4.4 × 1.8 × 10.3	Internal patch	3.64	3.52
Bit Babik 2005	1 × 1 × 1	24	15.4 × 2.8 × 5.5	Monopole (NIT)	3.0	
	2.2 × 2.2 × 2.2	17	12 × 4 × 2	Monopole (XFDTD)	3.44	

The data in the table include values for both 900 and 1800 MHz and so do the mobile phone compliance testing data in Section 5.4. Lightweight transponders have a frequency of 1090 MHz, which is intermediate between these frequencies, but closer to 900 MHz. Thus, it seems reasonable to regard the totality of the available data as suggesting that SARs from lightweight aviation transponders with similar physical characteristics to mobile phones and used in a similar position with respect to the head/body might lie in the range 0.8 to 6.4 W kg^{-1} / W. For a 30 W transponder (maximum time averaged power of 0.165 W), these values imply localised SAR values in the range of 0.13 -1.1 W kg^{-1}. For an 80 W transponder (maximum time averaged power of 0.44 W), the SAR values are expected to be in the range 0.35 – 2.8 W kg^{-1}.

The likely localised SAR values from aviation transponders may be compared with the ICNIRP basic restrictions (Section 3.4.2) in order to gain an understanding of whether real transponders are likely to comply with guidelines if used in close proximity to the body. The range of SAR values for 30 W transponders seems within the 2 W kg^{-1} public exposure basic restriction, whereas there seems a possibility that the basic restriction may be exceeded by 80 W transponders. Whether this would occur in practice would depend whether transponders are located in close proximity to the body for periods of time comparable to, or longer, than the 6-minute averaging time in the ICNIRP guidelines, and the duty factor of transponders. The duty factor would depend on the rate at which replies are emitted. The 10 W kg^{-1} occupational exposure basic restriction seems unlikely to be exceeded by transponders.

6 CONCLUSIONS AND RECOMMENDATIONS

The peak power of the 30 W Mode S transponder is 15 times higher than that of a GSM900 mobile phone, but the maximum duty factor of the transponder is only 0.55% as compared to 25% for mobile phones. Therefore, the maximum time-averaged power of a Mode S transponder is 0.165 W and less than the 0.250 W maximum of mobile phones. Conversely, a Mode S transponder with 80 W power has a time-averaged power of 0.44 W, greater than that of a mobile phone.

Predictions of electric and magnetic fields in the vicinity of generic transponder models showed that the ICNIRP reference levels can be exceeded within a few centimetres of transponders. For the 30 W transponders, the maximum public exposure compliance distance was 3.6 cm, and for occupational exposure it was 3.0 cm. For the 80 W transponder, the distances were 5.4 cm for public exposure and 3.9 cm for occupational exposure.

The precise distances for compliance with the reference levels with a real transponder would depend on the type of antenna used, the size and shape of the transponder body shell and where the antenna is mounted. A pessimistic figure for the distance that is likely to be applicable in the case of public exposure from all transponders with low gain antennas, such as helices and monopoles, would likely be around 5 cm for 30 W and 10 cm for 80 W peak powers. Exceeding the reference levels does not automatically indicate that the guidelines are exceeded, but it does indicate the need for a more detailed analysis in the context of the basic restrictions to determine compliance.

An analysis of reported localised SAR values from mobile phone-like transmitters used near the body suggests values in the range of 0.13–1.1 W kg^{-1} with a power of 0.165 W and 0.35 – 2.8 W kg^{-1} with a power of 0.438 W. Given that transponders are expected to be of similar size and shape to mobile phones, this suggests that SARs from 30 W transponders will be within the 2 W kg^{-1} public exposure basic restriction, but there is a possibility that the basic restriction might be exceeded by 80 W transponders. Whether this would occur in practice would depend whether transponders are located in close proximity to the body for periods of time comparable to, or longer, than the 6-minute averaging time in the ICNIRP guidelines, and the duty factor in practice, which might be considerably less than 0.55%. The 10 W kg^{-1} occupational exposure basic restriction seems unlikely to be exceeded by transponders.

It is notable that the maximum time-averaged output powers of transponders are similar to those of other devices that may be used near to the body and for which technical standards have recently been written requiring SAR assessments, e.g. mobile phones. Some of these standards contain procedures that may be suitable for testing aviation transponders and such testing by manufacturers would seem appropriate, particularly for 80 W transponders. A means to control the transponders during the testing to sustain the maximum time-averaged power envisaged would have to be developed.

7 REFERENCES

AGNIR (2003). Heath effects from radiofrequency electromagnetic fields. Report of an Advisory Group on Non-Ionising radiation. Documents of the NRPB, **14**(2), www.hpa.org.uk/radiation/publications/documents_of_nrpb/abstracts/absd14-2.htm

Alexiou A, Kostarakis P and Christofilakis VN (2005). Interaction between GSM handset helical antenna and user's head: Theoretical analysis and experimental results. The Environmentalist-**25**, 215-21.

Anderson V and Joyner KH (1995). Specific absorption rate levels measured in a phantom head exposed to radio frequency transmissions from analog hand-held mobile phones. Bioelectromagnetics, **16**, 60-9.

Balzano Q, Garay O and Manning TJ (1995). Electromagnetic energy exposure of simulated users of portable cellular telephones. IEEE Trans. Veh. Tech., **VT-44**, 390-403.

Bernardi P, Cavagnaro M and Pisa S (1996). Evaluation of the SAR distribution in the human head for cellular phones used in a partially closed environment. IEEE Trans. Electromag. Compat., **EMC-38**, 357-66.

Bit-Babik G, Guy AW, Chou CK, Faraone A *et al* (2005). Simulation of exposure and SAR estimation for adult and child head exposed to radiofrequency energy from portable communication devices. Radiation Research, **163**, 580-90.

CENELEC (2001a). Product standard to demonstrate the compliance of mobile phones with the basic restrictions related to human exposure to electromagnetic fields (300 MHz – 300 GHz). Available from BSI (www.bsi-global.com/) as standard BS EN 50360:2001.

CENELEC (2001b). Basic standard for the measurement of specific absorption rate related to human exposure to electromagnetic fields from mobile phones (300 MHz – 3 GHz). Available from BSI (www.bsi-global.com/) as standard BS EN 50361:2001.

CEU (1999). Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 MHz). 1999/519/EEC. Official Journal of the European Communities, **L199**, 59-70. ec.europa.eu/health/ph_determinants/environment/EMF/emf_en.htm

Chatterjee I, Gu YG and Ghandi OP (1985). Quantification of electromagnetic absorption in humans from body-mounted communication transceivers. IEEE Trans. Veh. Tech., **VT-34**, 55–62.

Chou CK , Bassan H, Osepchuk J, Balzano Q *et al* (1996). Radio Frequency Electromagnetic Exposure: Tutorial Review on Experimental Dosimetry, Bioelectromagnetics, **17**, 195-208

Cleveland R F and Athey T W (1989). Specific absorption rate (SAR) in models of the human head exposed to hand-held UHF portable radios. Bioelectromagnetics, **10**, 173-86.

Cooper TG and Mann SM (1998). Exposure to pulsed UHF radiation transmitted by the racal lightweight transponder. Contract Report NRPB-M954. Restricted – Commercial.

DH (2004). Government response to NRPB's 2004 advice on exposure to electromagnetic fields. www.dh.gov.uk/en/PolicyAndGuidance/HealthAndSocialCareTopics/DH_4089500

Dimbylow PJ and Mann SM (1994). SAR calculations in an anatomically realistic model of the head for mobile communication transceivers at 900 MHz and 1.8 GHz. Phys. Med. Biol-**39**, 1537-53.

EU (1999). Directive 1999/5/EC of the European Parliament and of the Council of 9 March 1999 on radio equipment and telecommunications terminal equipment and the mutual recognition of their conformity.
ec.europa.eu/enterprise/rtte/dir99-5.htm

EU (2004). Corrigendum to Directive 2004/40/EC of the European Parliament and of the Council of 29 April 2004 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (18th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). Official Journal of the European Union, **L184**, 1-9.
eur-lex.europa.eu/JOHtml.do?uri=OJ:L:2004:184:SOM:EN:HTML

EUROCAE (2002). Minimum Operational Performance Specification for Light Aviation Secondary Surveillance Radar transponders. Available from Eurocontrol (www.eurocontrol.int/) as standard ED-115.

EUROCAE (2003). Minimum Operational Performance Specification for Secondary Surveillance Radar Mode S transponders Available from Eurocontrol (www.eurocontrol.int/) as standard ED-73B.

Gandhi OP (1996). Electromagnetic absorption in the human head and neck for mobile telephones at 835 and 1900 MHz. IEEE Trans. Mic. Theory Tech. **MTT-44**, 1884-97.

Hadjem A, Iautru D, Wong MF, Hanna VF and Wiart J (2005). Study of Specific Absorption rate (SAR) Induced in two child head models and an adult heads using mobile phones. IEEE Transactions on microwave theory and techniques, **MTT-53**(1), 4-11.

Hombach V, Meier K, Burkhardt M, Kuhn E and Kuster N (1996). The dependence of EM energy absorption upon human head modeling at 900 MHz. IEEE Trans. Mic. Theory Tech., **MTT-44**, 1865-73.

IBREHT (1997). Interaction of the Body with the Radio Emissions from Hand-held Transceivers – IBREHT Final Report (A McKinlay, A Sharma, T Kenny and G Worsley, editors). Chilton, NRPB, pp 10-122.

ICNIRP (1998). Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Physics, **74**(4), 494–522.
www.icnirp.org

IEGMP (2000). Mobile phones and health. Report of an Independent Expert Group on Mobile Phones, NRPB, Chilton.
www.iegmp.org.uk

Kang G and Ghandi O P (2002). SARs for pocket mounted mobile telephones at 835 and 1900 MHz. Phys. Med. Biol., **47**, 4301-13.

Koulouridis S, Christopoulou M and Nikita KS (2005). Comparative assessment of power absorption in heads of adults and children exposed to the radiation of cellular phones at 1800 MHz. The Environmentalist, **25**, 223-32.

NEC Win Pro (1997). NEC Antenna analysis software, Nittany Scientific, Inc.
www.nittany-scientific.com

NRPB (2004a). Advice on limiting exposure to electromagnetic fields (0–300 kHz). Documents of the NRPB, 15(2).
www.hpa.org.uk/radiation/publications/documents_of_nrpb/abstracts/absd15-2.htm.

NRPB (2204b). Review of the scientific Evidence for Limiting Exposure to Electromagnetic Fields (0-300 GHz) Volume 15(3), 110–112.
www.hpa.org.uk/radiation/publications/documents_of_nrpb/abstracts/absd15-3.htm.

Okoniewski M and Stuchly MA (1996). A study of the handset antenna and human body interaction. IEEE Trans. Mic. Theory Tech., **MTT-44**, 1855-64.

QinetiQ (2007). Calculation of Low Power SSR Transponder Maximum Credible Reply Rates. Civil Aviation Authority (CAA) Contract No. 7D/HC6104/04.

Troulis SE, Scanlon WG, and Evans NE (2003). Effect of hands-free wire on specific absorption rate for a waist-mounted 1.8 GHz cellular telephone handset, Phys. Med. Biol., **48**, 1675-84.

Wang J and Fujiwara O (2003). Comparison and evaluation of electromagnetic absorption characteristics in realistic human head models of adult and children for 900 MHz mobile telephones. IEEE Transactions on microwave theory and techniques, MTT-**51**(3), 966-71

APPENDIX A

Field Strength Graphs in the Vicinity of the Generic Transponder Models

All of the graphs in this section have been plotted for the generic transponder having a mean output power of 0.165 W, as appropriate for a peak power of 30 W duty factor-compensated at 0.55% (see Section 2.4).

The distances referred to in figures A1-A22 are taken from the origin of the coordinate system, as described in Section 4.1 and illustrated in Figure 5. Figures A1 to A20 relate to the transponder with the monopole antenna and figures A21 and A22 relate to it with the helical antenna.

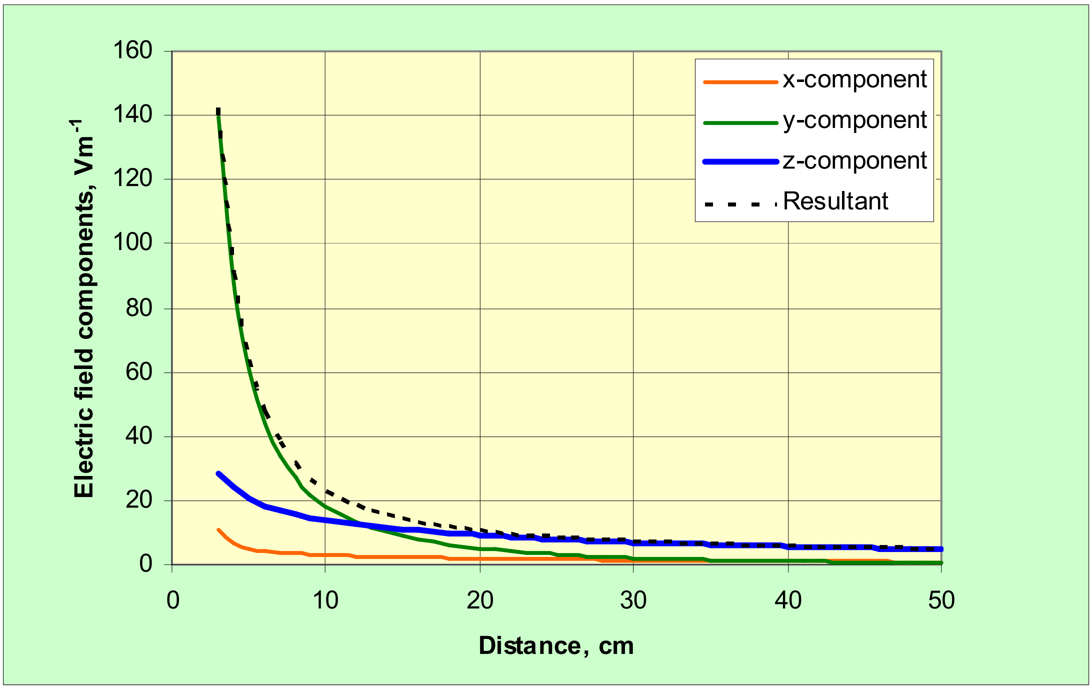

Figure A1 The components of electric field strength and the resultant as a function of distance along the negative *y*-direction at *x* = 3 cm- and *z* = 9cm

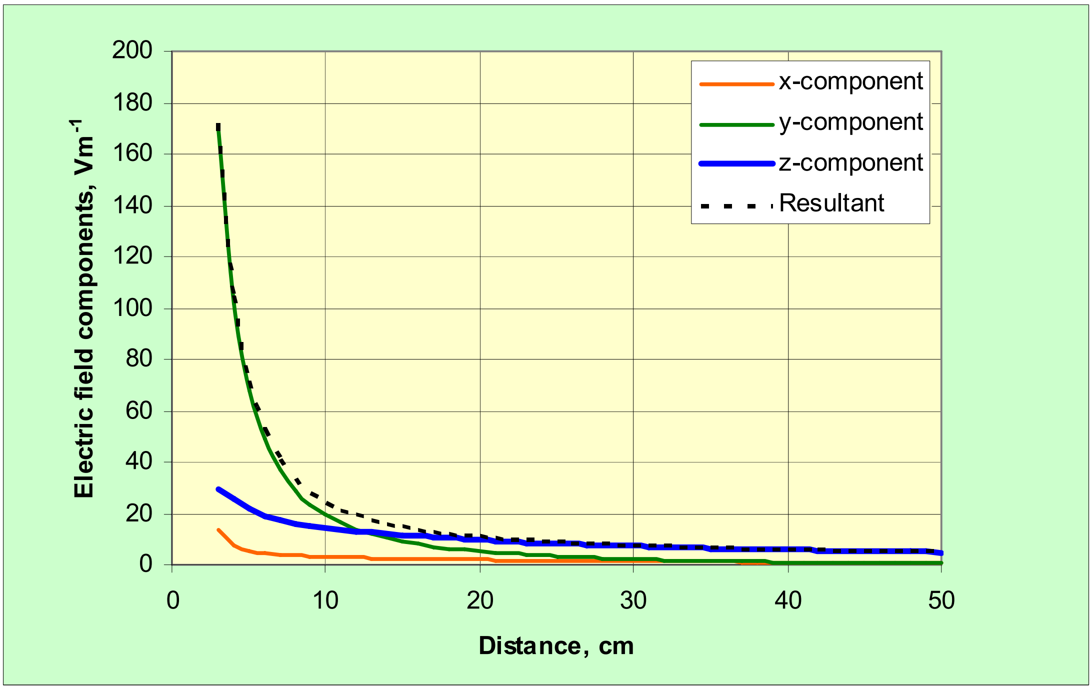

Figure A2 The components of electric field strength and the resultant as a function of distance along the positive y-direction at *x* = 3 cm- and *z* = 9cm

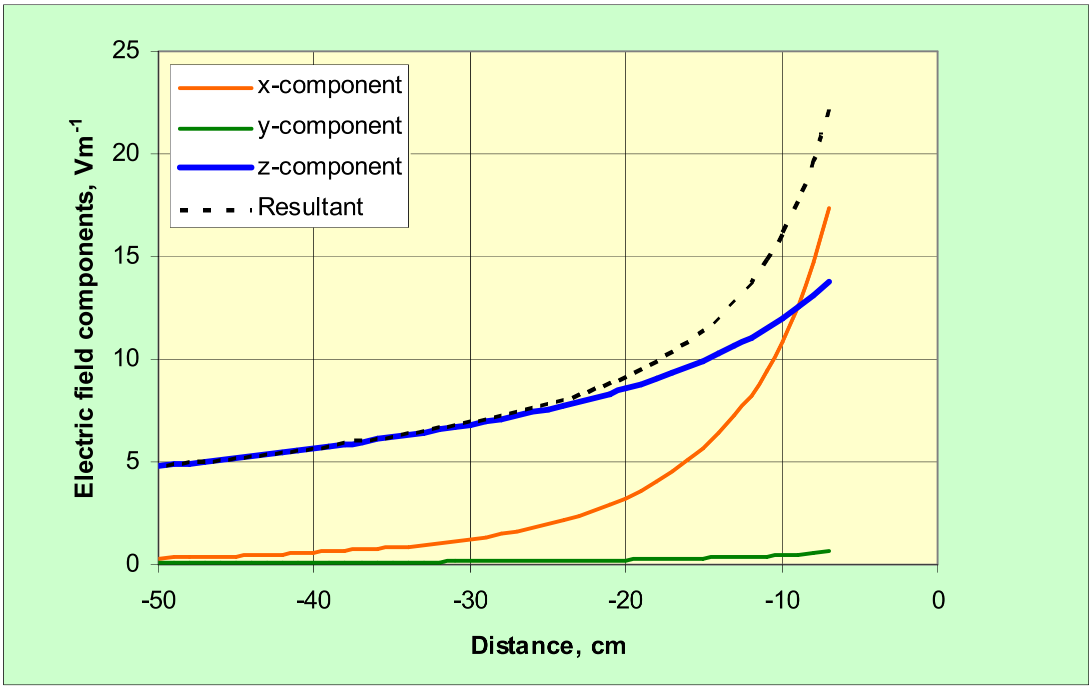

Figure A3 The components of electric field strength and the resultant as a function of distance along the negative *x*-direction at *y* = 0 cm and *z* = 5 cm

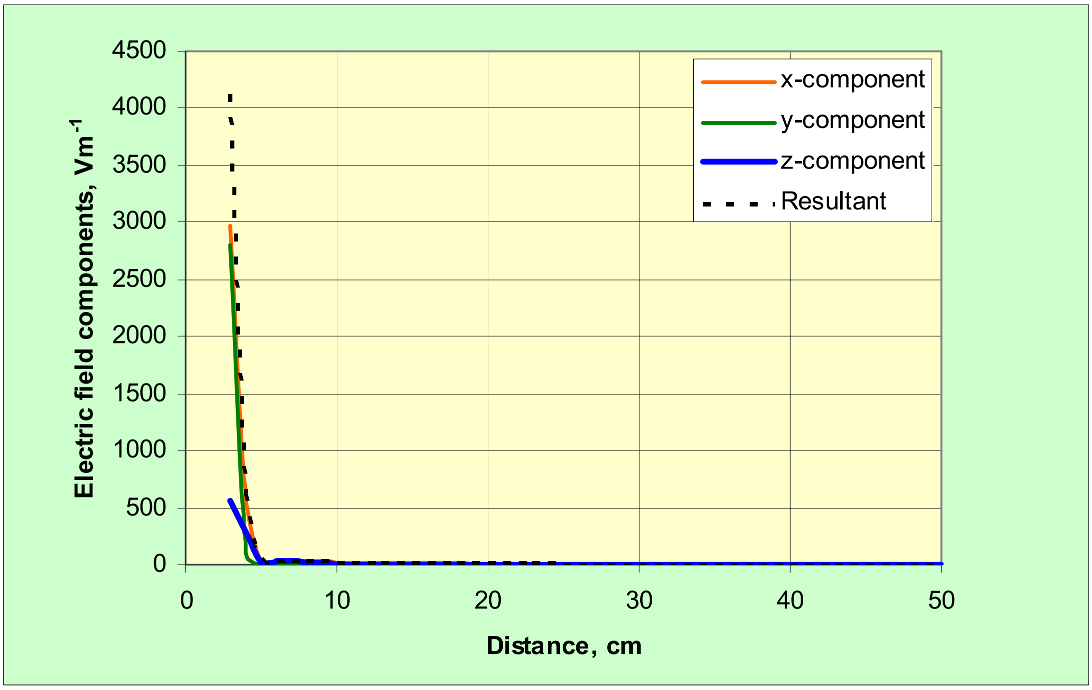

Figure A4 The components of electric field strength and the resultant as a function of distance along the positive *x*-direction at *y* = 0 cm and *z* = 5 cm

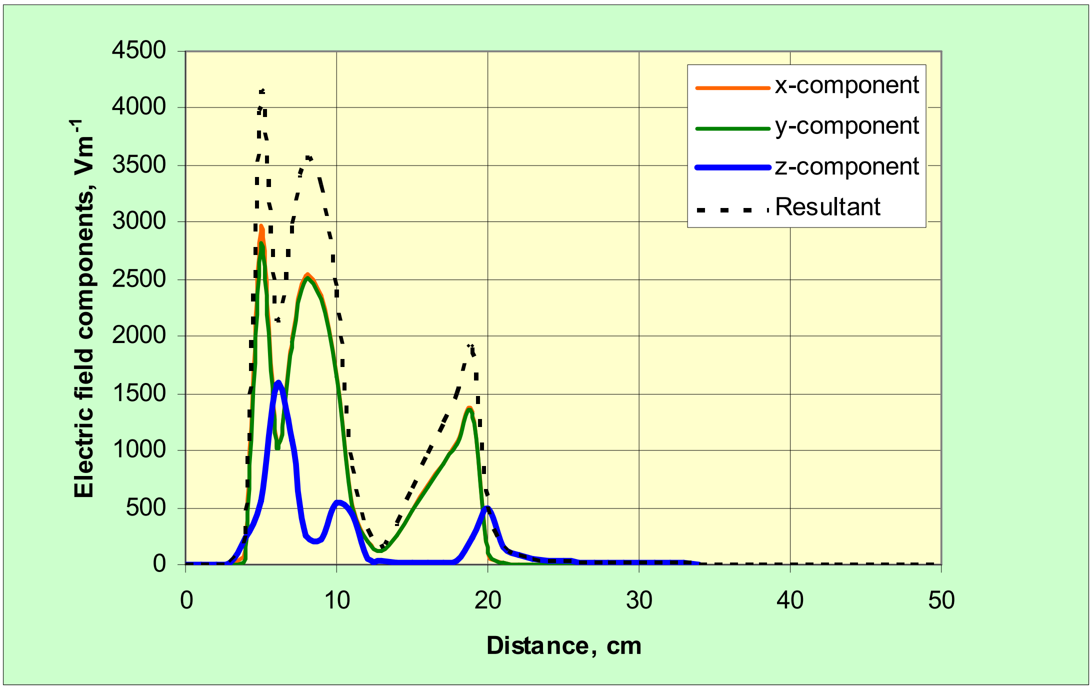

Figure A5 The components of electric field strength and the resultant as a function of distance along the positive *z*-direction at *x* = 3 cm and *y* = 0 cm

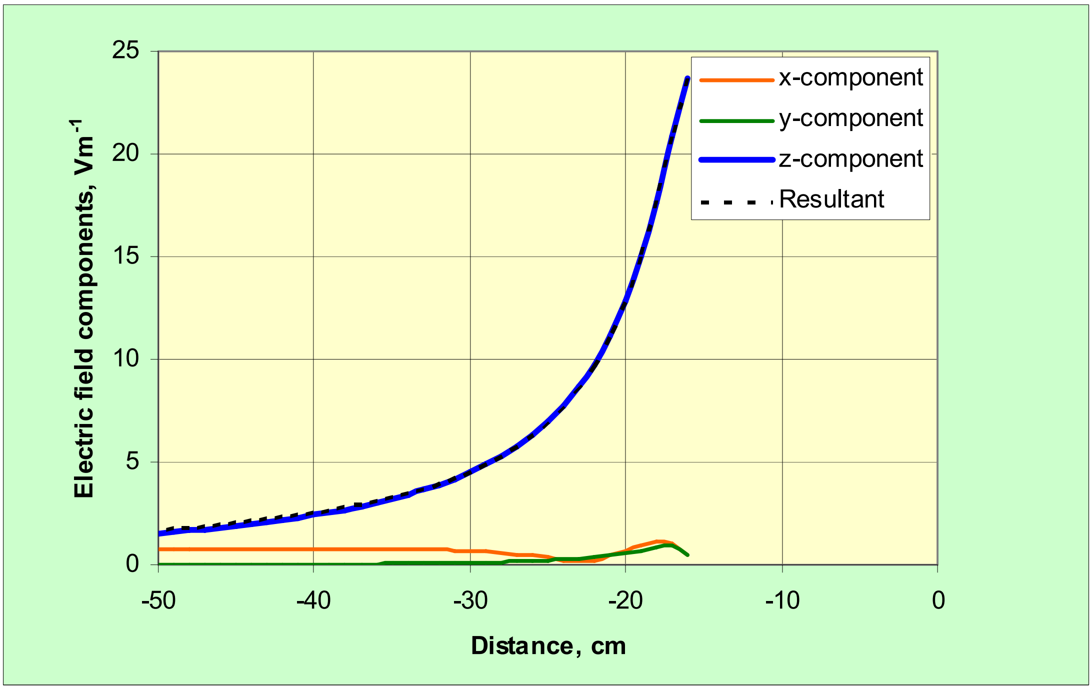

Figure A6 The components of electric field strength and the resultant as a function of distance along the negative *z*-direction at *x* = −2 cm and *y* = 0 cm

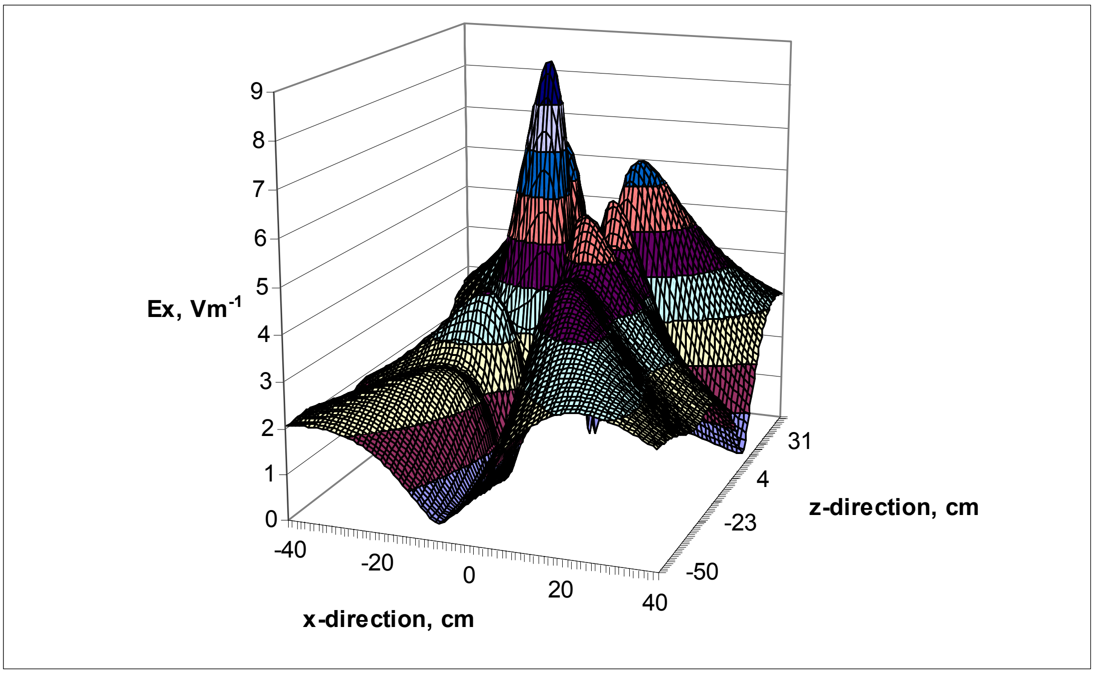

Figure A7 The *x*-component of electric field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

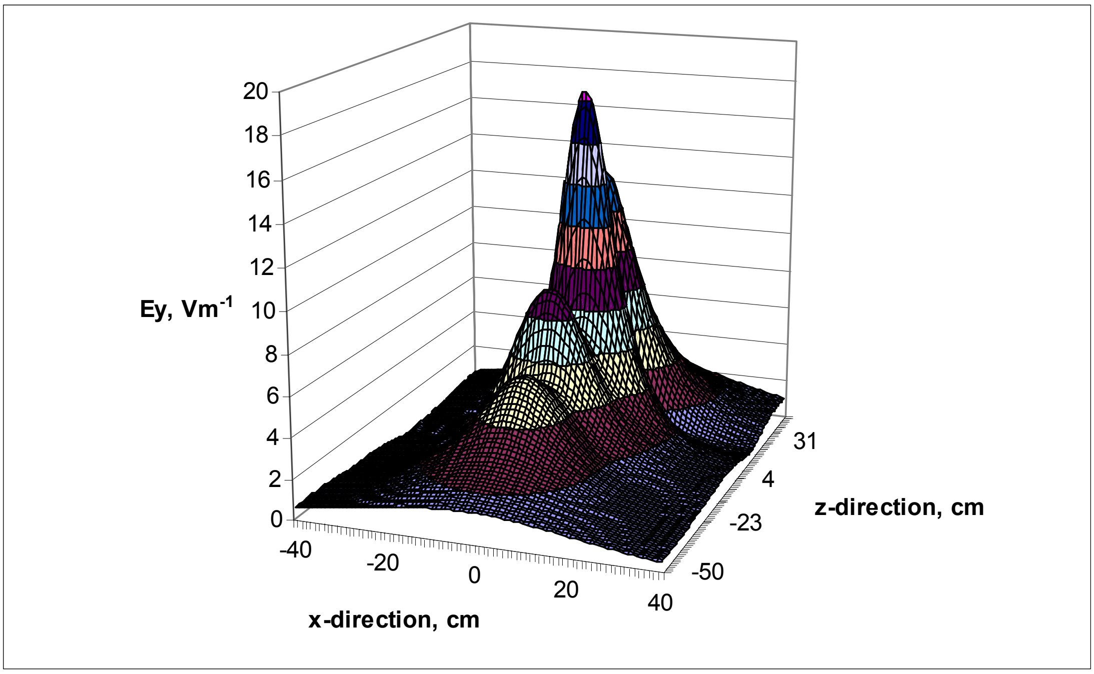

Figure A8 The *y*-component of electric field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

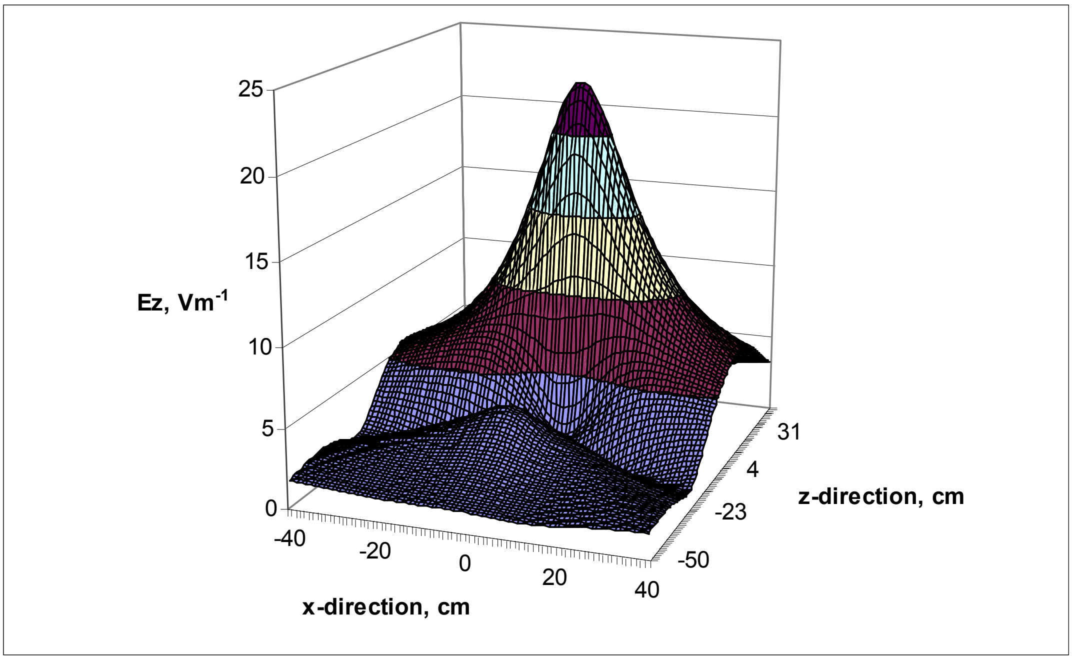

Figure A9 The *z*-component of electric field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

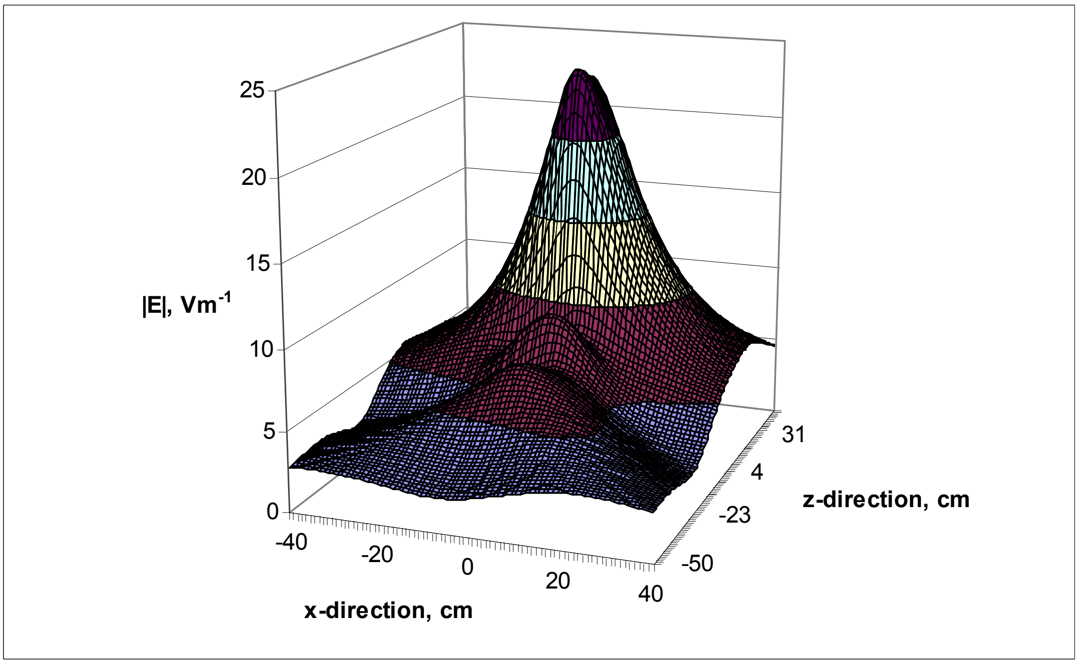

Figure A10 The resultant electric field strength as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

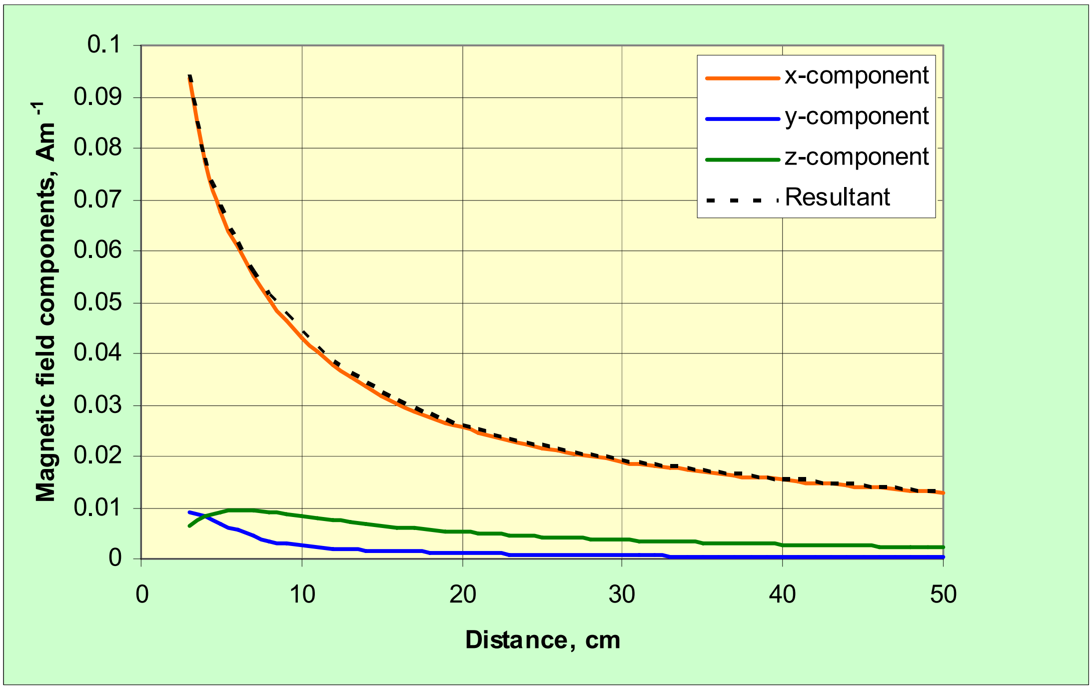

Figure A11 The components of magnetic field strength and the resultant as a function of distance along the negative *y*-direction at *x* = 3 cm and *z* = 9cm

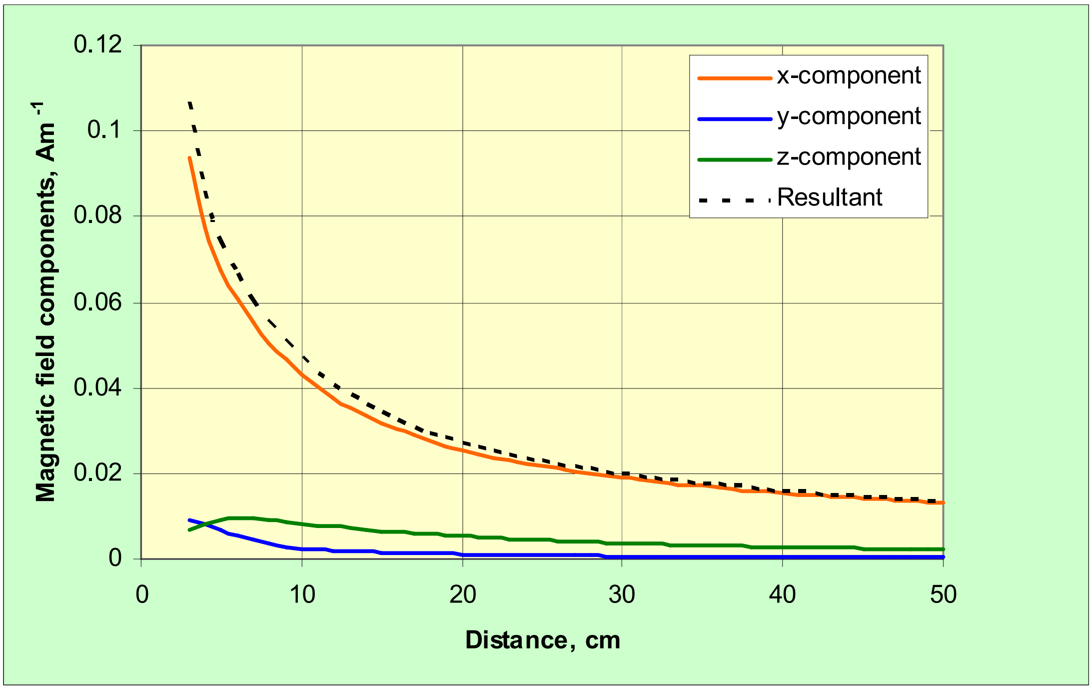

Figure A12 The components of magnetic field strength and the resultant as a function of distance along the positive *y*-direction at *x* = 3 cm and *z* = 9 cm

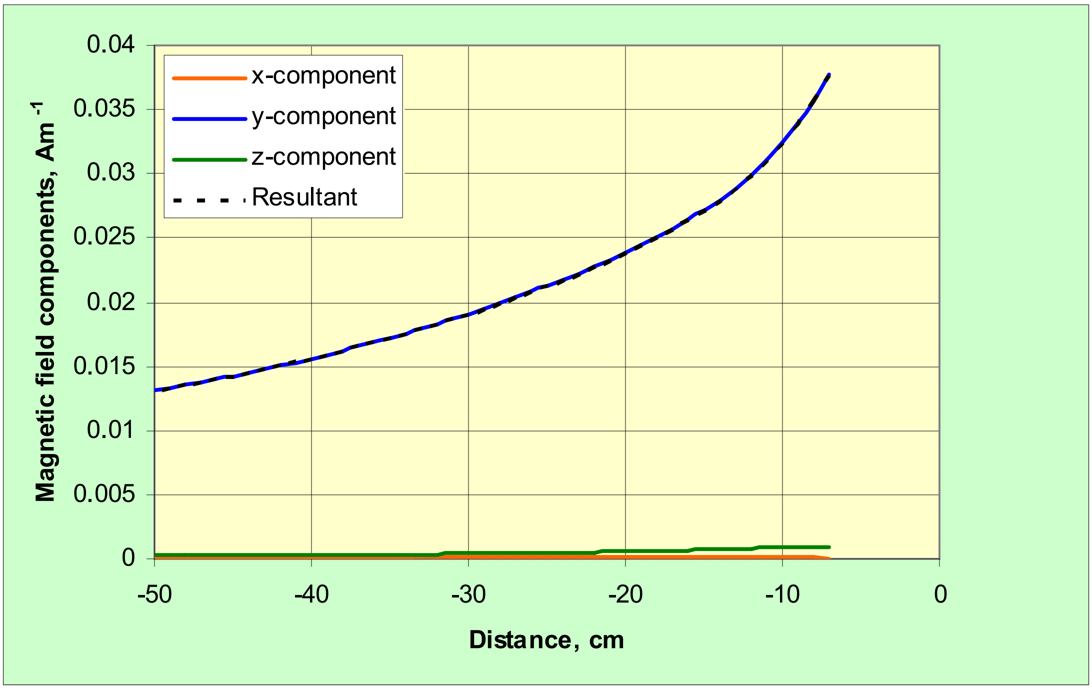

Figure A13 The components of magnetic field strength and the resultant as a function of distance along the negative *x*-direction at *y* = 0 cm and *z* = 5 cm

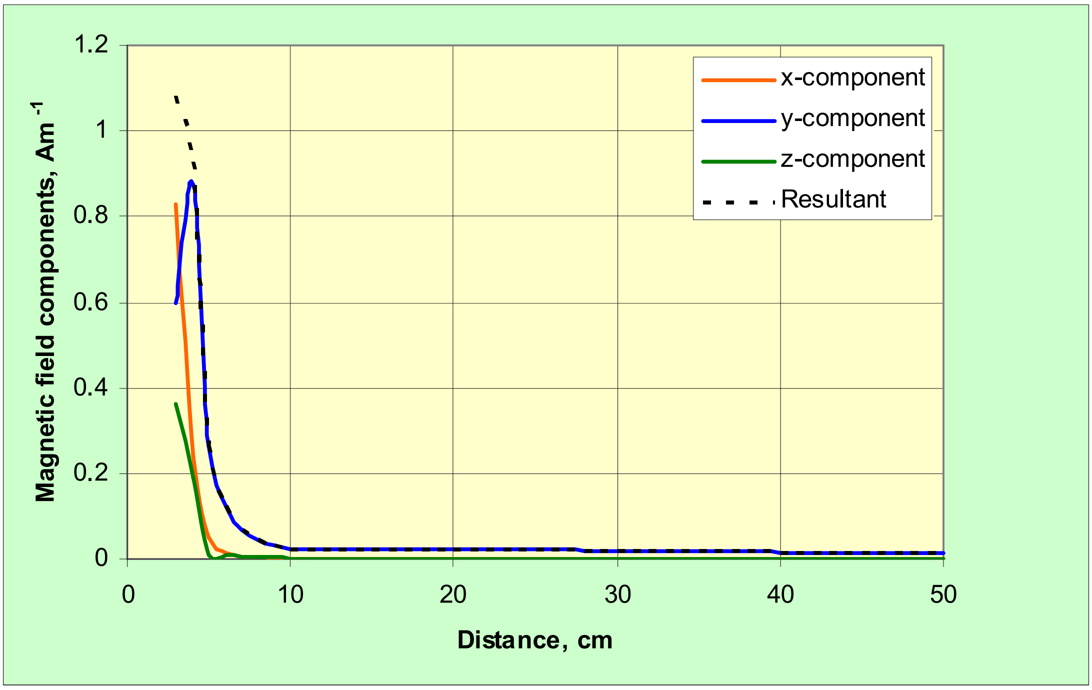

Figure A14 The components of magnetic field strength and the resultant as a function of distance along the positive *x*-direction at *y* = 0 cm and *z* = 9 cm

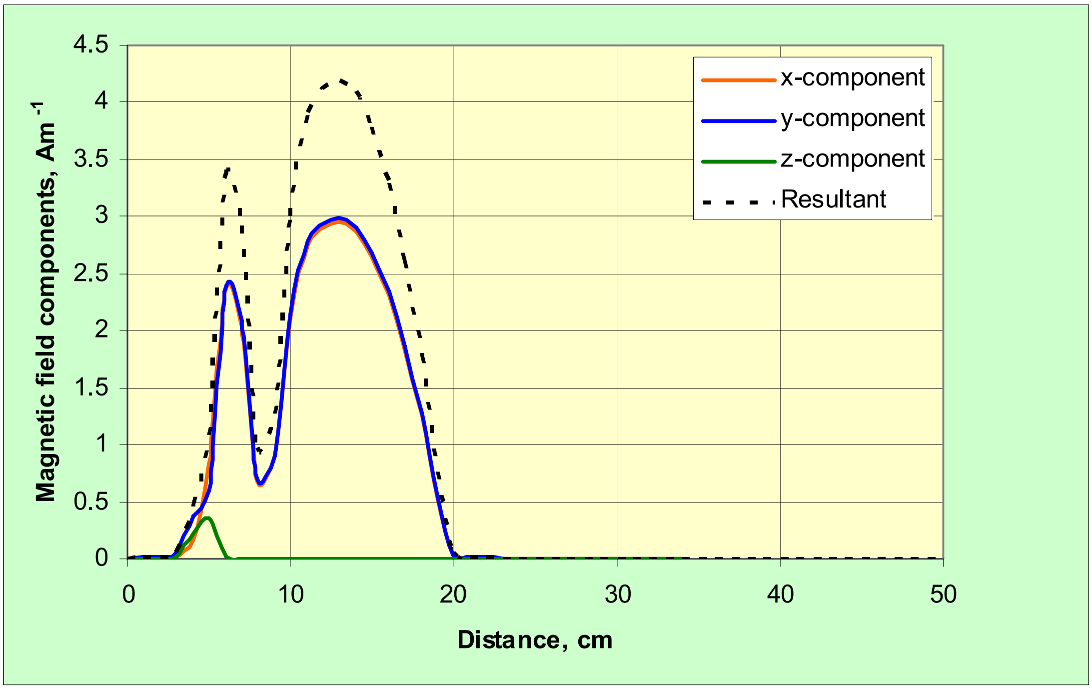

Figure A15 The components of magnetic field strength and the resultant as a function of distance along the positive *z*-direction at *x* = 3 cm and *y* = 0 cm

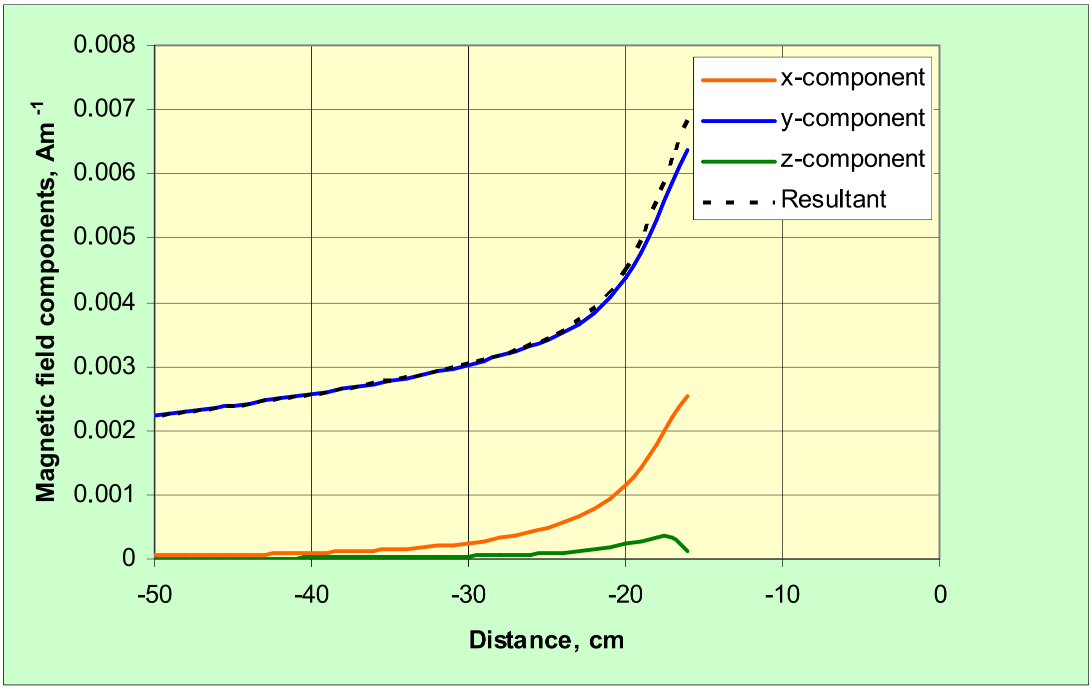

Figure A16 The components of magnetic field strength and the resultant as a function of distance along the negative *z*-direction at *x* = −2 cm and *y* = 0 cm

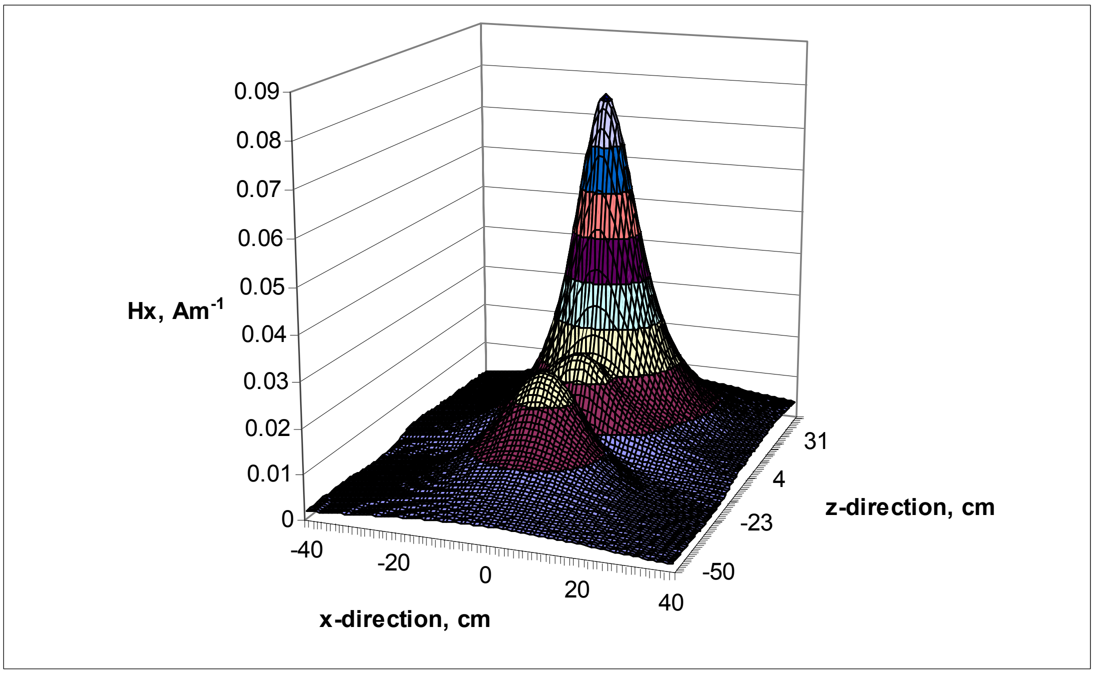

Figure A17 The *x*-component of magnetic field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative y-direction

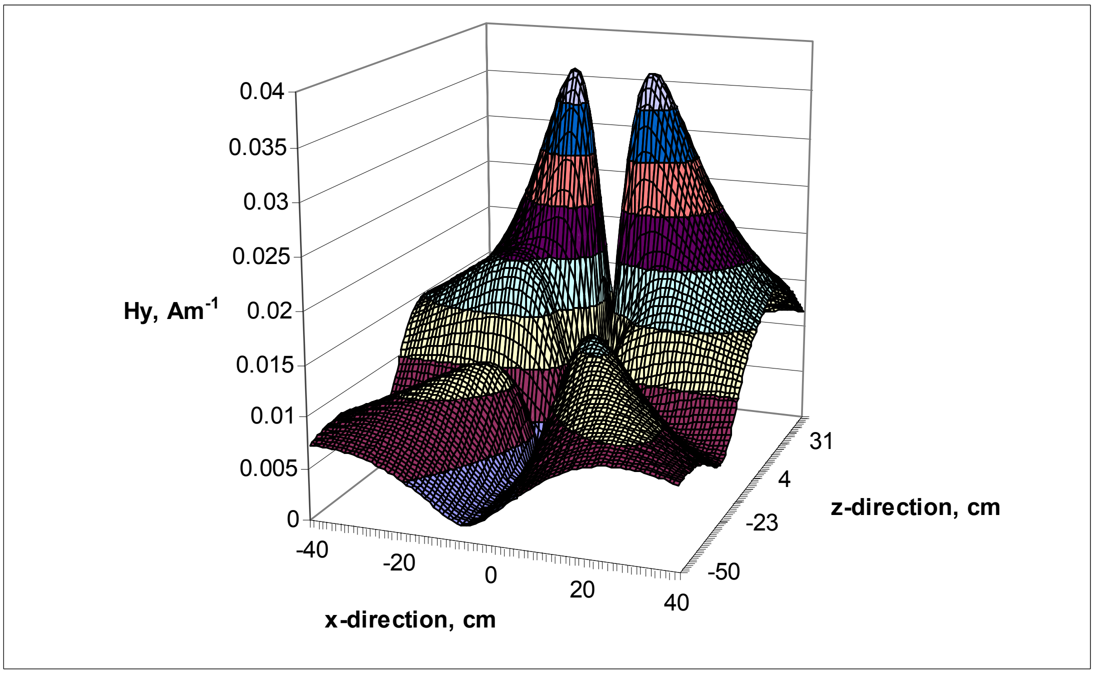

Figure A18 The *y*-component of magnetic field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative y-direction

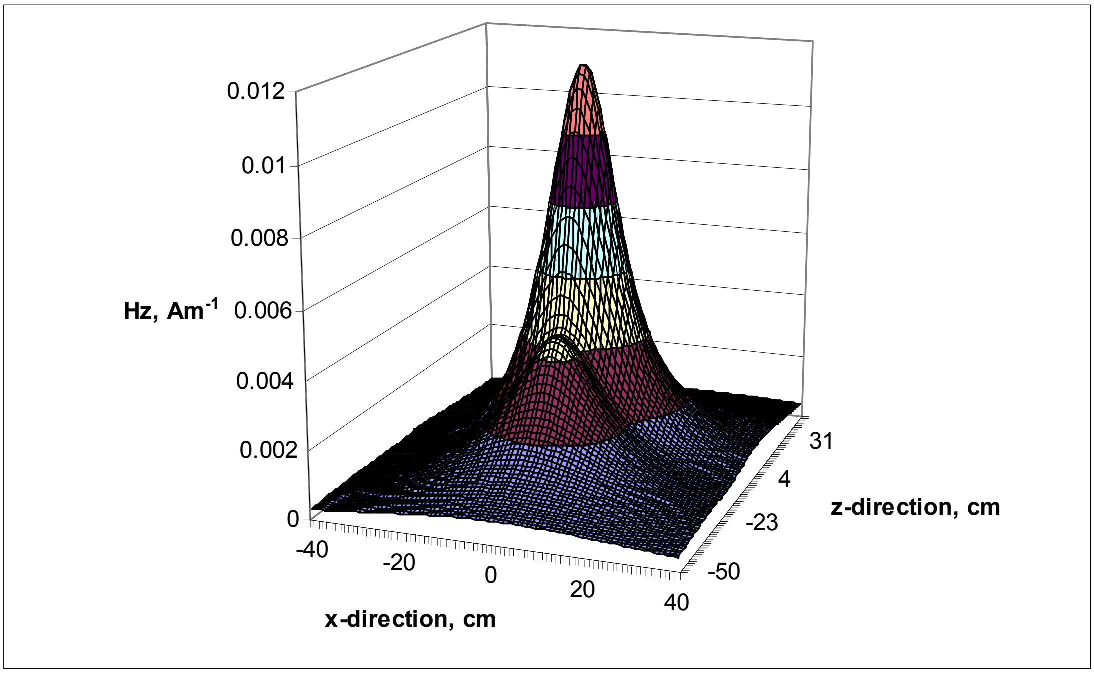

Figure A19 The z-component of magnetic field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

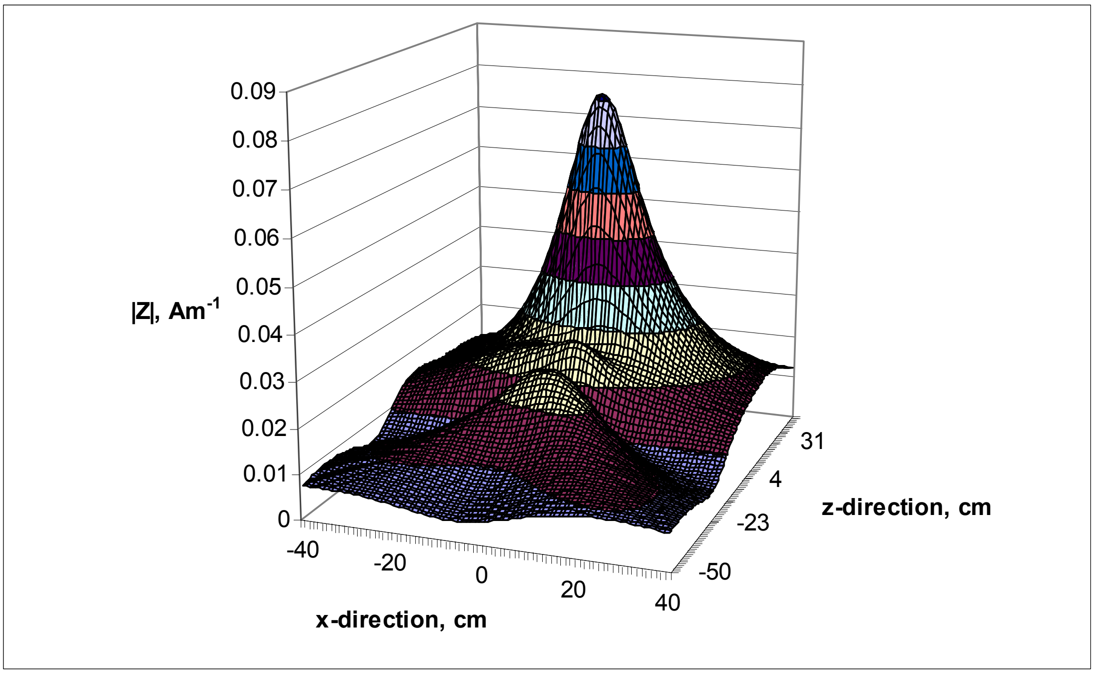

Figure A20 The resultant magnetic field as a function of *x* and *z* at a displacement of 7 cm from the transponder along the negative *y*-direction

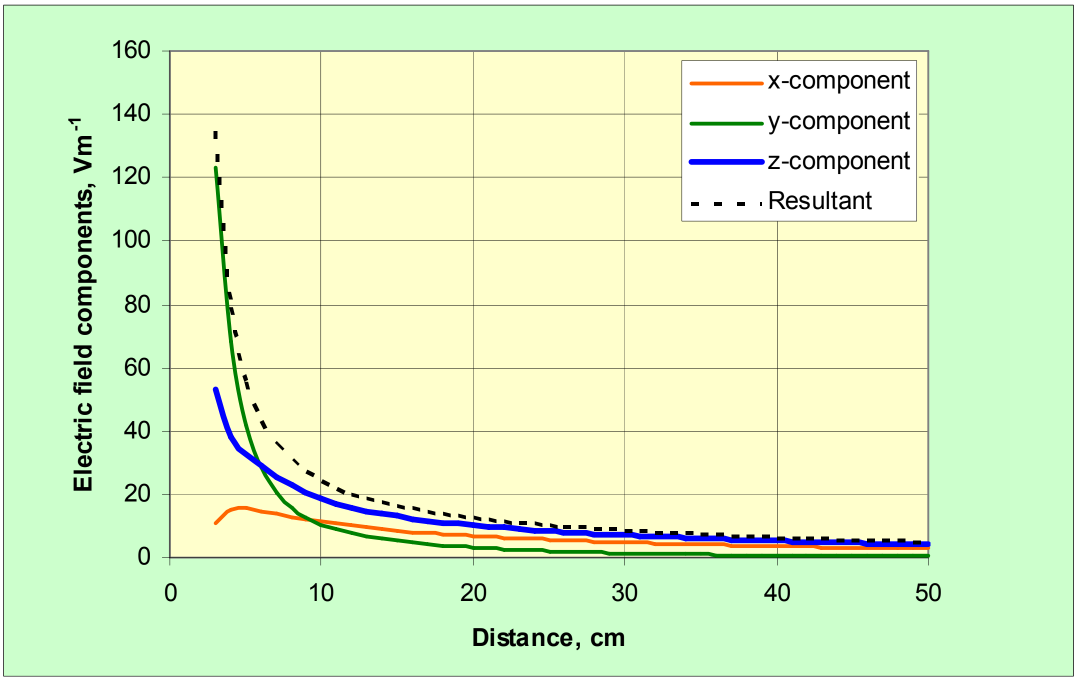

Figure A21 The components of electric field strength and the resultant as a function of distance along the negative *y*-direction at *x* = 3 cm and *z* = 9 cm

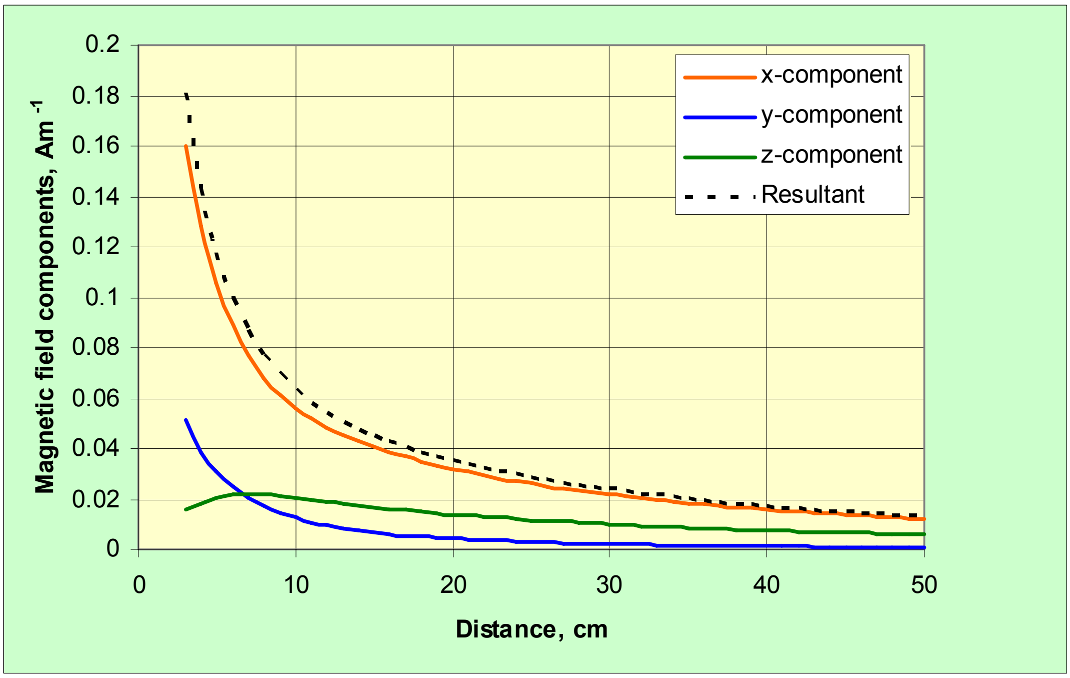

Figure A22 The components of magnetic field strength and the resultant as a function of distance along the negative *y*-direction at *x* = 3 cm and *z* = 9 cm