1 Introduction

1.1 Background

In collaboration with its transmission partner, Babcock International Ltd, the BBC World Service owns and operates a number of high power HF (High Frequency – Short Wave (3MHz-30MHz)) and MF (Medium Frequency – Medium Wave (300 kHz-3MHz)) transmitting stations located in the UK and around the world. Radio wave propagation, at short wave frequencies, occurs via ionospheric refraction from the F^2-layer[1].

Typically an HF station will incorporate between 2 and 10 transmitters and between 6 and 40 high gain directional antennas. Although there are exceptions, each transmitter will generally be connected to only one antenna at any one time. However it is technically possible to connect each transmitter to some or all of the antennas on a given station. While a small number of transmitters have an output power of 100kW the majority are 250kW, 300kW or 500kW. Most of the antennas are high gain arrays of between 2 and 16 co-planar dipoles. The antenna gain can be as high as 20dBi and so the ERP (Effective Radiated Power) from the transmitter antenna combination can be 50MW.

The MF stations for the BBC World Service are simpler and consist of single transmitter permanently connected to a dedicated antenna. Transmitter powers are between 200kW and 800kW. Directional antennas are employed. These antennas consist of between 2 and 6 vertical monopoles standing above a ground plane. One or more (sometimes all) elements are driven with a particular phase relationship while the others act as directors and reflectors.

The first BBC World Service transmission was in December 1932 and the 1940s saw a major expansion of the network. In subsequent years the general trend has been for transmitter powers, used by the BBC and other international broadcasters, to increase.

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[1] The upper region of the earth's atmosphere is an ionized layer, when a radio wave is transmitted into this layer, it would cause refraction or bending of the wave. The E-layer exists from about 62-75 miles, which refract signals up to 20MHz. HF communication uses this ionosphere layer.

The few remaining 100kW transmitters will be replaced with 250kW or 300kW versions at the end of their operational life. Coinciding with this increase in transmitter power there has also been increasing public and administrative interest in the potential health hazards which are posed to the public and those employed at the transmitting stations. The hazard arises from the use of non-ionising radiation at radio frequencies (RF).

Limits for human exposure to non-ionising radiation[2] are recommended by the International Commission on Non-Ionising Radiation Protection (ICNIRP) [1.1]. The fundamental limit is called the ‘Basic Restriction’ [1.2]. This is defined in terms of either Specific Absorption Rate (SAR - of radiated energy) or, at certain lowers frequencies, in terms of currents flowing in different parts of the body [1.1], [1.3]. The limits of ICNIRP are set to a fraction of that which gives any measurable physiological effect on the body. For this reason past attempts to use on human beings have met with little success. The internal E-field and SAR are very difficult to measure directly. In some cases, volunteers or cadavers have been used to evaluate SAR and induced current density inside the human body when exposed to electromagnetic field (EMF) [1.4], [1.5] . Alternatively a phantom, either physical or numerical, can be used as a surrogate for a human body. The study of RF dosimetry from exposure requires the phantom to have electrical properties equivalent to those of a human or human body parts. This allows the SAR and current density to be measured via non-invasive methods. Physical phantoms have used various types of material such as liquid, gel or jelly, along with numerical phantoms which are computer model based on numerical methods. Most human exposure in electromagnetic field (EMF) are from dosimetric analysis, and these studies where first conducted by a numerical methods approach along with validation of phantom measurements [1.6-1.9].

When the human body absorbs radiated energy this manifests itself through the heating of the body [1.2]. The human body however is very good at discarding excess heat, in order to maintain a constant internal temperature. For this reason it is not possible to measure body heating without far exceeding the levels of radiation which are deemed

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[2] Non-ionising radiation is radiation at frequencies below about 300GHz. All these frequencies there is insufficient energy to cause ionization. All terrestrial broadcasting takes place at a lower frequency than this and so all radiation from broadcast transmitters is non-ionising.

(by ICNIRP) to be safe [1.10], [1.11]. A series of research studies have been conducted on animals, such as monkeys [1.12], [1.13] and rats [1.14], as well as human. Those studies are presented in an early report by the World Health Organisation (WHO) [1.15], which has established the health risk associated with a rise in body temperature due to RF exposure. The ICNIRP reviewed and evaluated a series of scientific and experimental research studies in order to devices guidelines for human exposure. It points out that, in general, when a relaxed human exposure for 20-30 min, under conditions in which whole-body averaged SAR (WBSAR) was less than 4W/kg, caused the body core temperature rise just less than 1 ℃ [1.2], [1.15-1.18]. The rise in core body temperature caused by the absorption of energy from external EM fields has a direct effect particularly on some sensitive areas of body. These effects include alterations in neural and neuromuscular functions [1.19-1.21]. The ICNIRP also publish what it calls ‘Reference Levels’ of electromagnetic Field Strength because this is an easier quantity to measure [1.2]. These reference levels are related to the SAR which is the energy absorption per unit mass of biological tissue [1.22]. Generally speaking it can be assumed that if the measured field strength is below the reference level, the basic restriction will not be exceeded [1.2]. However, the reference levels are designed to be universal enough to apply in any situation and the inbuilt safety factors might not be relevant to any particular application. These safety factors can be an order of 10 or 100, and it cannot be assumed that a field strength which is above the reference level will result in a breach of the basic restriction. Furthermore, an additional safety factor of 5 is applied on occupational exposure levels to form limits for general public exposure levels. These are corresponding to general public and occupational exposure in many standards and guidelines. It is therefore possible that a high power broadcast station could exceed the reference level but the resultant SAR will be comfortably below the basic restriction.

1.2 Motivation

The aim of this PhD is to explore the relationship between field strength and the actual levels of SAR encountered in close proximity to high gain, high power broadcast antennas. The underlying methodology is computer simulation using accurate models of humans and a specific broadcast antenna.

In MF antenna studies the Health Protection Agency (UK HPA), Radiation Protection Division (formerly the National Radiation Protection Board – NRPB[3]) investigated SAR levels and the electromagnetic fields in the near-field of MF transmitting antennas. Their research resulted in the production of a new computer model for humans, called Norman (a normalized man) [1.23] and Naomi his female partner [1.24] in the presence of uniform vertical and horizontally polarized electric fields at MF and HF broadcast frequencies.

In MF frequency band broadcasting, radiation from a vertically polarised MF transmitter can approach the ‘plane-wave’ and ‘perfect conducting earth’ idealisation even close to the radiating elements. In reality, the near-field region of the MF transmitter is far from uniform. However, the field variation with height above the ground at MF frequency broadcast band is much smaller than HF[1.25]. Later BBC World Service conducted a field strength and ankle current measurements in one of their UK transmission site, the results showed good correlation with the results from the NEC 2 calculations. It verified the finding of HPA. Considering the near-field region at the frequency range as well as the field level up to about 2 m above the ground, the variation of field in front of the HF frequency band antennas would be much higher. The vertical component of the electric field is by far the most significant of the various E and H orthogonal components on a MF broadcast site, when considering the localised SAR produced in the ankles. Ideally, all E and H components should be measured, but the additional uncertainty of only measuring the vertical electric field, or even the resultant electric field using an isotropic probe, may be quite small in most cases. On a multi-frequency site, it would be necessary to measure the individual field strengths, not just the combined field strength as recorded by a broadband probe. Hence a somewhat specialised instrument ought to be used for assessments based on field strength.

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[3] The Health Protection Agency Act 2004 repealed the Radiological Protection Act. On 1 April 2005, NRPB became the Radiation Protection Division of the Health Protection Agency (HPA). Under the terms of the Health and Social reactive Care Act 2012, the HPA was abolished, and responsibility for radiation protection functions was assigned to appropriate Government authorities in the UK

The results of this work have been published in [1.25] and [1.26]. Informal, unpublished work by the BBC World Service and National Grid Wireless (previously the transmission partner for the BBC transmitter network) showed encouraging similarity between the HPA simulations and field measurements. To date this work has not been formalised.

Of greater importance to the BBC World Service is the situation at the HF transmitting stations. HF curtain antennas are complicated structures. Polarisation is horizontal but it can reasonably be assumed that the near field radiation is anything but ‘plane-wave’, and the field is highly reactive. The HPA work suggested that the human body is considerably less sensitive to horizontally polarised radiation thank to vertically polarization but it was not clear whether the polarisation of the dominant component in the near field of an HF broadcast antenna was horizontal or vertical.

1.3 HF antenna human exposure assessment

Wireless communication technology by means of radio waves has enjoyed explosive growth, especially in last 2 decades. It is rarely possible or, for that matter ethical, to use live human subjects for SAR exposure experiments. Consequently most of the early studies relied heavily on the use of animals, as mentioned earlier. Meanwhile most of the early numerical methods for electromagnetic modelling were based on the Method of Moments [1.27]. In-house codes based on the Finite Differential Time Domain (FDTD) method were also used at this time. The FDTD method is based on Maxwell’s equations in partial differential form [1.23], [1.28], [1.29]. During the early 2000’s commercial numerical computational software (such as XFdtd from REMCOM [1.30], and EMPIRE [1.31], the earliest commercial electromagnetic simulation software) being available and reliable to use. They were tested in earlier energy absorption mechanism in human head [1.32] for mobile phone antenna [1.33]. CST microwave studio [1.34] and SEMCAD [1.35] were used in this project and widely recognised and used in industries as well as by academics worldwide. Meanwhile there were also big leaps in the development of phantoms from the early homogenous phantoms to later anatomical heterogeneous human and animal phantoms [1.23], [1.24], [1.36].

The BBC world Service has commissioned a number of research studies in order to assess the occupational exposure risk associated with a HF transmitter station. Those studies also investigated the public exposure risk. Prior to this project the Norman phantom, which was the product of research by the HPA, was based on computational predictions obtained by assuming the most extreme exposure conditions [1.25], [1.26]. The Finite Difference Time Domain (FDTD) solution of Maxwell’s curl equation was used to compute the whole body Specific Absorption Rate (SAR). In addition, a quasi-static Scalar Potential Finite Difference (SPFD) solution of Laplace’s equation was used to compute limb SAR. Limb SAR was obtained as a function of induced current. This was then linked to the incident field strength taking over the whole body by using the FDTD algorithm [1.37].

This project continues previous work to assess human exposure in the near-field of a high power HF broadcasting antenna against the ICNIRP guidelines. The purpose of this PhD was to access various aspect scenarios and conditions both human and the high power transmitting station. The intention was to develop a methodology for assessing human exposure which could be applied to various high power HF broadcasting transmitter sites. It was hoped that this would lead to an understanding of the key criteria which influence SAR within a human subject exposed to fields from a high power HF array. This should enable us to produce a simplified assessment technique following high resolution EM modelling. Future work will be conducted in order to quantify restricted quantities according to the simple prediction by checking the key criteria of each transmitter site.

1.4 Thesis outline

This thesis is not organised according to the chronological order that the work was conducted in instead follows structure. The remainder of this thesis is structured as follows:

Chapter 2 presents a literature review which covers the numerical methods and other theorems that form the basis for this work. This includes background information on high power HF transmitting stations. The chapter also reviews international RF exposure limits and guidelines. Furthermore, it discusses the research which has been carried out into human exposure to high power RF fields from mobile phone base stations as well as the high power HF broadcasting antennas employed by the BBC World Service. A brief over view of the numerical methods and some basic Electromagnetic theories for modelling and calculating the relevant RF exposure levels are then be presented. The chapter finishes by drawing a comparison between various numerical techniques and software which yields a better understanding on how related the research has been conducted by various attempts.

Chapter 3 focuses on describing the plane-wave irradiation of the human phantom. Two computer simulation packages (namely, SEMCAD and CST microwave studio) are used to compute the RF exposure. The values obtained are compared with the reference levels stated in ICNIRP. Various ‘Virtual Family’ human phantom parameters and modelling techniques are tested in this chapter. Meanwhile part of the model and results are compared with the earlier Norman phantom exposure results obtained by HPA in order to validate the credentials of the ‘Virtual Family’ human phantom, used in this study. Furthermore, the significant ground interference on the WBSAR calculation will be noted and explored fully.

Chapter 4 uses the numerical techniques, mentioned in the Chapter 2, in order to model a HF curtain array antenna driven with a 300kW transmitter. The computer simulations considered varying degrees of infrastructure complexity. This chapter is mainly focused on mapping and analysing the near-field electromagnetic field characteristic of the HF curtain array antenna. The first step was to determine an initial set of computer simulation models which included the antenna array and its supporting masts. Following this field measurements were conducted at a transmitter site to verify the results of the simulation. The first field strength measurements and mapping lead to further improvements the modelling of the ground slope and the metal poles of the ground infrastructure each with its own polarisation. An investigation was also conducted to assess the impact of these poles on the near-field electric field distribution. They significantly changed the field strength values.

Chapter 5 presents an investigation into a novel hybrid approach for improving the efficiency and simplifying the model and assessing its suitability for calculating the WBSAR as the main parameter when evaluating the human exposure in a non-ironing radiation environment.

Chapter 6 describes the design and performance of a Radio over Fibre measurement system. The system was specifically developed for the purpose of this project. It helps to avoid the interference effect of a human being close to the measurement position along with the influence of the metal coaxial cables, which would otherwise be required. The chapter presents several field measurement results including a set of ankle current measurements. The human phantom, validated in the previous chapter, was exposed to RF fields from a curtain array. This was achieved by positioning the phantom in front of a complete model of the curtain array. The array, with its supporting towers and ground infrastructure, was modelled in CST microwave studio for the calculation of the WBSAR.

Finally, chapter 7 summarises the results obtained through the investigations presented in this thesis. It also describes topics for possible future work.

Publications

1. Ying Fu, G. Cook, M. Hate, D. Fisher, J. McCalla, “EMC Compliance Testing of BBC World Service HF Transmitter Sites”, Loughborough Antennas & Propagation Conference LAPC, pp. 613 - 616, Loughborough, Nov. 2009.

2. Y. Fu, M. Hate, R.J. Langley and J.M. Rigelsford “The Effects of Ground Characteristics on Near-field Modelling of HF Transmission Sites for EMC Compliance Testing” Proc. of the 20th International Conference on Applied Electromagnetic and Communications, 2010.

3. Ying Fu, M. Hate, R.J. Langley, J.M.Rigelsford,”The Effects of Ground Characteristics on Near-field Modeling of HF Transmission Sites for EMC Compliance Testing” ICECom, pp. 1-4, Dubrovnik, Sept 2010.

4. Y. Fu, M. Hate, D. Fisher, J. McCalla, G. Cook, R.J. Langley and J.M. Rigelsford “A Human Exposure Modelling Method for HF Transmitter Sites”, Loughborough Antennas & Propagation Conference LAPC, pp. 525 - 528, Loughborough, Nov. 2010.

5. Y. Fu, M. Hate, J. McCalla,R.J. Langley, J.M.Rigelsford “Variations in Calculated Whole Body SAR for Different Ground Coupling Models”, Loughborough Asntennas & Propagation Conference LAPC, Loughborough, Nov. 2011.

6. Ying Fu, M. Hate, R.J. Langley, J.M.Rigelsford,”The Effects of Support Structures on Near-field Exposure Levels for HF Antennas”, Antennas and Propagation (EUCAP), pp. 892-895, Rome, Italy, April 2011.

7. Y. Fu, R. J. Langley, J. M. Rigelsford, M. Hate, and J. McCalla, “The effects of local terrain topology and antenna infrastructure on simulated near-field characteristics for HF broadcast antennas,” in *2012 6th European Conference on Antennas and Propagation (EUCAP)*, 2012, pp. 1218–1221

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