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Radiation hazards to personnel from non-ionizing fields of broadband HF systems onboard a vessel: Measurement and simulation

L.F. Sánchez[a,*], F.J. Calviño[a], S. Garcia[a], J.Mª. Núñez-Ortuño[b], J.M. Taboada[c], M.G. Araujo[d], J.L. Rodríguez[d], I. García-Tuñón[d], F. Obelleiro[d]

[a] Electromagnetics Measurements Center of Spanish Navy (CEMEDEM), Escuela Naval Militar, 36920 Marín, Spain
[b] Centro Universitario de la Defensa, Escuela Naval Militar (Defense University Centre, Spanish Naval Academy), Pza. de España s/n, 36920 Marín, Spain
[c] Department of Tecnologías de los computadores y de las comunicaciones, Escuela Politécnica, Universidad de Extremadura, 10003 Cáceres, Spain
[d] Department of Teoría do Sinal e Comunicacións, E.E. Telecomunicación, Universidade de Vigo, 36310 Vigo, Spain

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ABSTRACT

Modern warships have to accommodate onboard a great number and variety of electronic systems in order to be able to accomplish their missions. People standing on the metal deck of a warship near antennas are constantly exposed to intense electromagnetic fields, so the hazards of non-ionizing electromagnetic radiation to personnel (HERP) must be studied. HERP are mainly caused by transmitter antennas, which are confined to a limited space onboard a vessel. Particularly, high frequency (HF) band antennas are indispensable in shipboard communication systems and usually represent one of the main sources of HERP. This paper describes a measurement procedure for the non-ionizing electromagnetic field due to the HF broadband systems on a modern warship. This procedure is validated and complemented with the simulations performed with an accurate full-wave electromagnetic solver (M3/HEMCUVE).

1. Introduction

Today, modern warships employ many radiating systems integrated onboard within a very limited space. The great number of radio frequency (RF) antennas sharing such reduced space is responsible for a very complex electromagnetic environment. These transmitter systems are designed to operate at frequencies from HF to Ka-band and perform their functions: communications, radars, electronic warfare (EW), etc. Such transmitters are the source of the electromagnetic radiation (EMR) that produces radiation hazards (RADHAZ). Ionizing radiation and non-ionizing radiation are a possible classification for EMR. Ionizing radiation is caused when the EMR is capable of ionizing atoms, breaking chemical bonds. Sources of ionizing radiation are: nuclear fusions reactions, nuclear weapons, ultraviolet and X-ray, for example [1]. On the other hand, non-ionizing radiation is a form of radiation that does not have sufficient energy to produce ionization of atoms or molecules. Electromagnetic emissions from laser, radar, communication and microwave sources are examples of non-ionizing radiation [2], which is the sort of radiation present on a vessel and the concern of our study.

RADHAZ is categorized according to the hazard of the EMR to ensure safety for: personnel (Hazards of Electromagnetic Radiation to Personal, HERP), fuels and flammables of aircrafts and ships (Hazards of Electromagnetic Radiation to Fuel, HERF), munitions and weapon systems embodying electro-explosive devices (EEDs), ordnance (Hazards of Electromagnetic Radiation to Ordnance, HERO) and safety critical electronic systems (SCES) [2,3]. The measurement procedure and comparisons with simulations included in this work are focused on the evaluation of HERP. Radar and communication systems onboard use high-power RF transmitters, which represents a biological hazard to personnel near these systems [4]. The potential RF radiation hazards on people can be defined in terms of [5,6]:

(a) Direct effects:
- Thermal effects on the human body due to the absorption of the RF energy that is converted to heat. If it cannot be dissipated it will result in biological damage.
- Non-thermal effects: these effects are dependent on peak power. For example: change in orientation and polarization of protein molecules, mutation, etc.
- Shocks and burns as the result of ungrounded conductors located

* Corresponding author.
E-mail addresses: lsanalv@fn.mde.es (L.F. Sánchez), fcaldop@fn.mde.es (F.J. Calviño), sgarcia@fn.mde.es (S. Garcia), jnunez@cud.uvigo.es (J.M. Núñez-Ortuño), tabo.unex@gmail.com (J.M. Taboada), martaga@com.uvigo.es (M.G. Araujo), banner@com.uvigo.es (J.L. Rodríguez), inesgt@com.uvigo.es (I. García-Tuñón), obi@com.uvigo.es (F. Obelleiro).

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(b) Indirect effects:
- A thermal effects like: fatigue, anxiety, loss of memory, and nausea.
- Interference with devices like heart pacemakers and passive metal plates.
- Effects on HERF and HERO.

Vessels represent an environment where personnel are aware of the potential danger of RF exposure, especially on ship topsides due to the high power emitted by communication and radar systems. There are several standards that provide recommendations to protect personnel against adverse health effects associated with exposure to electric (E) and magnetic (H) fields over the frequency range from 0 Hz to 300 GHz. All of these standards are expressed as dosimetric reference limits (DRLs) and exposure reference levels (ERLs), which incorporate safety factors to establish a margin of security [7]. The DRLs are expressed in terms of specific absorption rate (SAR). Sometimes, depending on the standard, ERLs are defined as permissible exposure limits (PELs) [1] or exposure limit values (ELVs) [8], all of which are expressed in terms of environmental exposure fields (E and H) and power density (S), being magnitudes easily measurable with commercially available instruments.

Communications in the HF band are one of the primary concerns in modern vessels. Although with the advent of satellite communications (SATCOMs), providing enhanced data rates and usability, the use of HF was expected to decay, at present it is still of great relevance. Mainly, HF systems are long-range and very robust communication systems independent of any relay mechanism (such as a satellite), which is of strategic importance in the naval environment. However, unlike in SATCOMs, personnel onboard are required to know the potential hazards of exposure to the high-power RF sources required for HF communications.

The goal of the paper is to present a measurement procedure to certify the fulfillment of the Radiation Hazards (RADHAZ) requirements onboard a war ship. The procedure has been adopted by the Spanish Navy in all the measurement campaigns developed onboard its vessels. This procedure will be validated and complemented with the simulations performed with an accurate full-wave solver (M^3/HEMCUVE) [9]. As far as we know, it is the first publication addressing such kind of RADHAZ study both with simulation and measurements onboard a real war ship.

2. Safety regulations for HERP: civil and military

Several governments as well as professional bodies have determined a large number of safety regulations and standards regarding the exposure to electromagnetic fields. Among all of them, only European civil regulations and North Atlantic Treaty Organization (NATO) military regulations are considered in this paper. With regard to civil regulations, they usually have two different recommendations, namely one for the general public and the other for the protection of workers.

In Europe, the legislation protecting general public comes from "*Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to* electromagnetic fields (0 Hz to 300 GHz) (1999/519/EC)" [10], while the legislation for the protection of workers comes from "*Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields)*" [8]. In 1999/519/EC, we can find defined:

(a) Basic restrictions: magnetic flux density (B), current density (J), and specific energy absorption rate (SAR).

(b) Reference levels: These levels are provided for practical exposure-assessment purposes to determine whether the basic restrictions are likely to be exceeded. The quantities are electric field strength (E), magnetic field strength (H), magnetic flux density (B) and power density (S).

Directive 2013/35/EU includes ELVs (SAR) and action levels (ALs). ALs correspond to calculated or measured field values at the workplace in absence of workers. ALs (E) and ALs (B) are derived from the SAR or power density ELVs based on the thresholds related to internal thermal effects caused by exposure to (external) electric and magnetic fields. Both, the Directive and the Recommendation, are based on the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP). It's mandatory by Spanish and E.U. laws that any non-ionizing RADHAZ measurements must be carried out using calibrated equipment. Any report including RADHAZ measurements must include the calibration certificate of any equipment used during the measuring process. The equipment calibration certificate is valid only during a period of 1 year, after which the equipment must be sent for a new calibration.

The Directive says that for the armed forces the Member States should be able to implement equivalent or more specific protection systems, such as internationally agreed standards, for example NATO standards. This is the case of the Standardization Agreement (STANAG) 2345 (Edition 4):"*Military workplaces-force health protection regarding personnel exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz"*[11] of the NATO Standardization Agency (NSA) that includes the standard *IEEE Std C95.1-2345™-2014* [7]. This standard is divided into two exposure environments (restricted and unrestricted) and three zones (Zone 0 applies to unrestricted environments; Zone 1 and Zone 2 apply to restricted environments). Military workplaces open to all personnel are considered as Zone 0. There are DLRs and ERLs defined in this standard, the reference levels of fields being comparable to those for general public in recommendation 1999/519/EC. Only informed personnel are allowed to enter areas where exposure levels may exceed the Zone 0 ERLs but not the Zone 1 ERLs. As workers are informed personnel, the Zone 1 ERLs are like ELVs and ALs included in Directive 2013/35/EU. In order to be able to compare the levels of the previous standards, all the levels for the HF band are summarized in Table 1.

It is necessary to be able to determine the areas aboard a vessel where the electromagnetic levels exceed the safety levels of the standards abovementioned, so that those areas could be delimited and marked. For this purpose, a measurement procedure for

Table 1
HERP values (E and H) for the HF frequency band.

Frequency (f) (MHz)	Recommendation 1999/519/EC (Reference levels) General public (averaging time 6 min)		Directive 2013/35/EU (ALs) Workers (averaging time 6 min)		STANAG 2345 Ed. 4 (IEEE Std C95.1-2345 TM-2014) (ERLs) Zone 0 (f < 3 MHz averaging time f^2/0.3 min, f > 3 MHz, averaging time 30 min)		Zone 1 (averaging time 6 min)	
	E (V/m)	H (A/m)	E (V/m)	H (A/m)	E (V/m)	H (A/m)	E (V/m)	H (A/m)
1–10	$87/f^{0.5}$	0.73/f	610/f	2/f	823.8/f	16.3/f	1842/f	16.3/f
10–30	28	0.073	61	0.2	823.8/f	16.3/f	1842/f	16.3/f

Note: All values for E and H are root mean square (rms) values.