Radiation Hazard Aspect of Shipboard Radiocommunication Equipment

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Abstract: **The paper analyzes the electromagnetic (EM) radiofrequency (RF) radiation hazards onboard a ship arising from shipboard radiocommunication and navigation equipment. EM field effect on personnel and equipment can be harmful if field levels exceed the threshold values. These fields need to be controlled for proper protection. Ships are equipped with lots of EM RF radiation sources with different frequencies and output power levels. Typical shipboard EM RF radiation sources include: terrestrial radiocommunication transmitters, navigational radars and satellite ship earth stations (SES). Examples of these sources are analyzed in the paper. EM field estimation using simple worst-case calculation is given for a typical HF transmitter, X-band navigational radar and the Inmarsat SES A, B, C, F and M. The estimation problems are discussed. The calculation results are compared with international civil and military standards. The results show that potential hazards exist and that a reasonable amount of caution is needed.**

Index terms: **radiocommunications, shipboard radiation hazard, navigation**

I. INTRODUCTION

Electromagnetic (EM) field effect on personnel and equipment can be harmful if field level exceeds the detrimental effect threshold value. Exposure limits are prescribed in relevant documents [1-3] and are acknowledged internationally. Limits are frequency-dependant, expressed separately in terms of electric field strength, magnetic field strength and power density. Above 10 MHz, the quantities can be used interchangeably, i.e. the EM field can be defined with only one quantity. Thus the power density is mainly used for describing limits in radiofrequency (RF) range which is of interest for shipboard communication and navigation equipment. Ships are equipped with lots of EM radiation sources with different frequencies and output power levels. The crew and equipment are exposed to EM radiation and this exposure needs to be controlled for protection.

The confined space of a ship makes the problem even bigger. The crew is bound to occupy spaces in the vicinity of EM sources. Also, the number of sources is large. Modern maritime transport safety is based on radiocommunications, both for communication itself and also for navigation, therefore there is a variety of RF equipment installed onboard.

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The subject of human EM field exposure and protection is becoming more and more regulated. However, maritime applications of RF equipment are still not fully and thoroughly covered regarding this subject. For example, one of the basic standards on maritime navigation and radiocommunication equipment and systems [4], issued by IEC TC 80 [7-8], [12], includes a provision that:

- EM RF radiating equipment above 30 MHz shall be subjected to measurements to determine the level of such radiated energy;
- resulting from such measurements, the maximum distance from the equipment at which the power density level of 100 W/m^2 and 10 W/m^2 has been measured shall be included in the equipment manual.

The principle of this clause does not fully comply with widely accepted documents [1] and [2], regarding its limited frequency scope and limit that is not frequency-dependant. Therefore there is a need to analyze some typical shipboard exposure situations according to [1] and [2].

This paper analyzes some specific but typical EM field sources widely used aboard ships: terrestrial communication transmitter, satellite communication transmitter and navigational radar. Relevant shipboard EM field levels were estimated. The levels were compared to the standards that define maximum permitted exposure limits (PEL) of electric (E) and magnetic (H) field at the specific frequency, considering all exposure conditions.

II. TYPICAL SHIPBOARD EM FIELD SOURCES

A. Terrestrial communication transmitter

Modern ships are commonly equipped with various transmitters for terrestrial communications. Depending on the navigation area, different frequency ranges are used: MF, HF or VHF. For coastal navigation, VHF transmitters are the most common ones. However, their output power is much lower than the power of MF and HF transmitters, and as such is less interesting for this analysis. MF transmitters are used rarely aboard ships in the coastal navigation. Thus, in this paper, an HF transmitter is analyzed. It is in fact an AM SSB radio that operates in the HF band (3 – 30 MHz).

The shipboard EM field levels originating from this source were estimated assuming it is placed onboard a 50 m steel ship. The levels were compared to the standards that define permissible exposure limits (PELs) of electric and magnetic field at the specific frequency, considering all exposure conditions.

B. Navigational radar

The navigational radar is an important EM field source since it is a standard piece of equipment which uses a high output power. Navigational radars operate either in the S band (around 3 GHz) or in the X band (around 9.4 GHz). In this paper, an X-band radar is analyzed. The shipboard EM field levels originating from this source were estimated assuming it is placed onboard a 50 m steel ship. The levels were compared to the standards that define permissible exposure limits (PELs) of electric and magnetic field at the specific frequency, considering all exposure conditions.

Besides these exposure conditions, the radiation hazard aspect of an X-band radar aboard a small ship (e.g. recreational boat) was specifically analyzed. On small ships, the close proximity of the radar antenna to the crew, and also the small or no elevation at all from the antenna to the crew, make this situation a possible threat. The analytic calculation of the electromagnetic power density should enable the comparison of the exposure situation to the relevant human exposure protection guidelines.

C. Satellite communication transmitter

Besides previously mentioned shipboard radiation hazards, there is a need to analyze potential radiation hazards arising from ship earth stations (SES) for satellite communications. Satellite communications usage grows along with the need for new and more advanced services besides analog voice communications and facsimile. Digital data communications are essential for modern fleet management. Internet access is now common also on leisure vessels. All this leads to wider use of SES equipment, even on small boats with space constraints regarding equipment installation. The shipboard satellite communications mostly rely on the Inmarsat system, thus, in this paper, the Inmarsat SES is analyzed. Common shipboard satellite communication installations and their ability to irradiate the crew are reviewed. The shipboard EM field levels originating from several kinds of Inmarsat SES were estimated.

III. Source Characteristics

A. HF transmitter

The HF electromagnetic radiation source is in fact a single side band (SSB) amplitude-modulated (AM) radio transmitter, located onboard a medium size steel-built ship. It works in the HF frequency band, with the peak envelope power (PEP) of 100 W. This analysis and measurements were done at the frequency of 10 MHz.

It uses the four-segmented 6m long whip antenna located on the ship topside as seen on Fig.1. The antenna is electrically short, automatically tuned to the transmitter at the appropriate frequency by a matching network. When tuned, it radiates 100 W of PEP in the AM SSB mode. Its radiation pattern is almost isotropic in the horizontal plane and half-of-eight figured in the vertical plane. Both radiation patterns can be deformed by ship superstructure, but this effect will not be considered here. Mainlobe direction is horizontal. Antenna gain is about 0.75. The source is turned on occasionally for short emissions and then operates with full power, if properly matched.

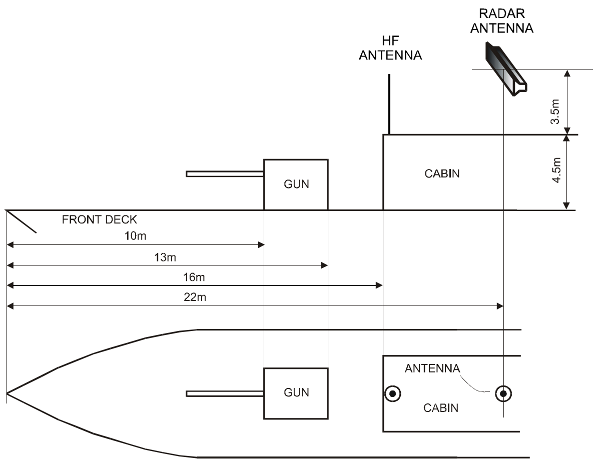

Fig. 1. Topside geometry of a medium size (50 m) ship

B. X-band navigational radar

The radar antenna dimensions typically range from 0.5m to 4m, depending on the size of the ship and output power (which also affects the range). The S-band antennas are larger, because the wanted antenna characteristics must be obtained on the longer wavelength.

Antenna rotates, with typically about 25 rounds per minute, to scan the entire horizon for targets and obstacles. The wanted antenna characteristics are the following:

- about 1º horizontal beamwidth, needed to obtain high azimuthal resolution;
- about 25º vertical beamwidth, needed to ensure that the mainbeam points to horizon even on rough sea, when ship rolls.

Typical antenna gain is around 30 dB.

The navigational radar radiation is pulse modulated. The order of magnitude of the peak output power (during a pulse) is 10 kW. Values range from 2 kW to 50 kW, with typical values of 20 kW for larger ships and 5 kW for small ships.

The first navigational radar considered was a specific radar located onboard the same medium size steel-built ship as the previously mentioned HF transmitter. It uses the Kelvin-Hughes slot array antenna located on the ship topside as seen in Fig.1. The radar works in the X band at 9.4 GHz in pulse mode. Peak output power (in the duration of a pulse) is 20 kW, which is common output power of shipboard radars. The average power depends on the duty cycle, which in turn depends on the radar distance range. The radar uses the maximum power when working in the short distance range, with the pulse duration of T_p = 0.25 μs and repetition frequency f_r = 1700 Hz. The antenna mainlobe characteristics are 1.2º horizontal beamwidth and 20º vertical beamwidth. The antenna is 1.2 m wide, located about half-way from bow to stern, 8 m high above the deck, as shown in Fig.1. and it rotates with 32 rpm.

The radar is turned on continuously when ship is out of the port.

The second case considered is a non-specific typical navigational radar on a recreational boat. A motor boat with the manufacturer specifications and dimensions was randomly chosen. The sideview is given in Fig.2. The antenna position is also suggested by manufacturer. The picture also shows the mainlobe of the radar radiation.

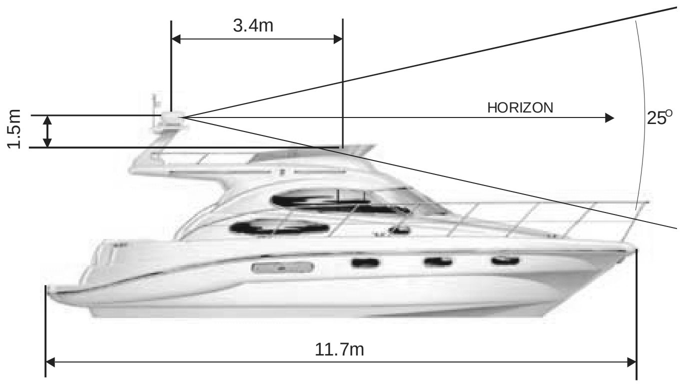

Fig. 2. Geometry of the exposure situation

Fig. 3. Radar mounted on a recreational motor boat

One can see that the people on the top deck (fly bridge) in Fig.3. are most certainly exposed to the main beam of radiation. The distance from the antenna on the smaller ships can be as short as 1 m.

C. Inmarsat SES

Most Inmarsat SES use a surface antenna pointed to the satellite. The tracking mechanism ensures the right direction to the satellite, even in conditions of ship rolling sideways ±25º. The surface antenna (parabolic reflector or planar array) is moving inside a stationary radome that provides an environmental enclosure (see figures). Inmarsat C usually uses stationary lower gain antenna that is hemispherically omnidirectional and cover the whole elevation span at once. In this paper, the emphasis is on the analysis of the high gain aperture antennas.

The antenna is usually mounted on the highest place above deck to avoid obstructions of line-of-sight direction, as in Fig.4. A casual thought of the antenna in the highest place, pointed skywards, would lead to the false conclusion that there is no possibility of radiation hazard to the crew.

Fig. 4. Inmarsat antenna installed on the highest topside construction

Fig. 5. Inmarsat antenna installed on the deck

However, there are situations in which the antenna is mounted right on the deck (sail boats and other small boats), as in Fig.5 and Fig.6. Cases are even reported where antenna is mounted below deck, provided that the deck is non-conductive. Also, the antenna is not always pointed skywards with high elevation. The needed elevation is the result of the SES position relative to the Inmarsat satellite. This relative position depends on the SES latitude and longitude, and at some geographical locations the antenna elevation can be very low. Due to this fact and also due to ship rolling (see Fig.6), the Inmarsat antenna specifications demand that the antenna elevation inside the radome can be anything from -5º to 90º. It is now obvious that there are situations when the crew can be unawarely exposed to the main beam of the Inmarsat SES.

Fig. 6. Inmarsat antenna installed on the deck, ship rolling sideways by ca. 25º

IV. RADIATION HAZARD REGULATIONS

The objective of this analysis is to determine the maximum distance beyond which there is no danger of EM field over-exposure. Two types of hazards can be distinguished: biological hazards and fire/explosion hazards. The biological hazards are sometimes referred to as Hazards of Electromagnetic Radiation to Personnel (HERP), especially in military terminology. Fire and explosion hazards are referred to as Hazards of Electromagnetic Radiation to Ordnance (HERO) and Fuel (HERF). Standard [1] is used for HERP PELs. US Navy Instruction [3] is used for HERO and HERF PELs.

A. Biological Hazards (HERP)

While there is a lack of information on biological effects of EM fields, still there is enough of it to produce regulations, so many countries already issued their standards. They depend on research conducted in the specific country, and that is the reason for differences between them. Considering that the effects are equal anywhere in the world, there is a need to integrate standards into one.

EMF exposure is primarily classified to professional exposure in the workplace and uncontrolled exposure of people not aware of the danger. The US standard [2] uses the terms "controlled environment exposure" and "uncontrolled environment exposure" while ICNIRP [1] uses the terms "occupational exposure" and "public exposure". "Controlled environment" refers to the areas with personnel accepting the exposure as a part of their workplace, aware of the potential danger and constantly (or periodically) subjected to health examinations, as well as protection measures. "Uncontrolled environment" refers to all other exposure conditions and groups of people. Therefore, it is necessary to define more restrictive standards for this type of exposure. PEL (Permissible Exposure Limit) is **time-averaged** exposure value obtained by **spatial averaging** over an area equivalent to the vertical cross-section (projected area) of the human body. In nonuniform fields, peak values could exceed the PELs even though the averaged value does not exceed the PEL.
However, peak field strength is also limited. The peak permissible limit in terms of power density is given as 1000 larger value than the PEL itself at the specific frequency, for frequencies exceeding 10 MHz.

B. Fire & Explosion Hazards (HERF and HERO)

According to [3], there are three HERO categories regarding EM radiation sensitivity. The HERO limit 2 refers to unreliable devices with exposed wires arranged in most susceptible receiving orientation, mostly during assembly/disassembly of ordnance, but also applies to untested ordnance until proven safe. HERO limit 1 applies to the less sensitive ordnance. There is also the third class of ordnance which is totally insensitive to EMF and there are no exposure limits for this class. It is necessary to classify the ordnance into one of these categories which is already done in the US Army. US Navy instruction [3] specifies HERO RADHAZ levels at frequencies below 1 GHz in terms of peak value of electric field strength, while levels above 200 MHz are specified in average power density. The potential danger to ordnance is obvious so these limits are generally lower than personnel limits.

These are some general guidelines to avoid HERF [3]:

- Do not energize a transmitter (radar/comm) on an aircraft or motor vehicle being fueled or on an adjacent aircraft or vehicle.
- Do not make or break any electrical or ground wire, or tie down connector while fueling.
- Radars capable of illuminating fueling areas with peak power density of 5 W/cm^2 should be shut off.
- For shore stations, antennas radiating 250 W or less should be installed at least 15 m (50 ft) from fueling areas.
- For antennas which radiate more than 250 W, the power density at 15 m (50 ft) from the fueling operation should not be greater than the equivalent power density of a 250 W transmitter located at 15 m (50 ft) distance.

V. RADIATION HAZARD ESTIMATION

A. HF transmitter

For the mainlobe direction and the far-field region, power density S is calculated by:

$$S = \frac{P \cdot G}{4R^2\pi} \quad (1)$$

where P is the mean output power, G is gain, R is distance from antenna. For linear antenna, this relation can be used also in the near-field region, yielding the worst-case overestimation.

EMF estimation problem exists because antennas are primarily used to radiate in the far field (Fraunhofer region), and exposure usually takes place in the near field. Thus, manufacturer antenna specifications refer to the far field and are not applicable to the specific exposure situation. Fraunhofer approximation simplifies field calculations assuming the source is far enough to be treated as a point source. R_{99} is the distance from antenna where the actual field equals 99% of the field calculated with the Fraunhofer approximation. That distance is considered the near-field to far-field boundary and is calculated by well known equation:

$$R_{99} = \frac{2D^2}{\lambda} \quad (2)$$

where D is the largest antenna dimension and λ is wavelength. Below the R_{99} boundary the field strength oscillates with the distance. The radiation pattern in the near field is generally different from that of the far field and phase oscillations in the near field decrease the antenna gain in the main lobe direction.

The near-field diagram for linear antenna according to [16] is shown in Fig.7. Power density is normalized to unity (0dB) at R_{99}, which is the point with power density marked as S_{99}. The Y axis values are not marked because they differ from one antenna to another, depending on the current distribution.

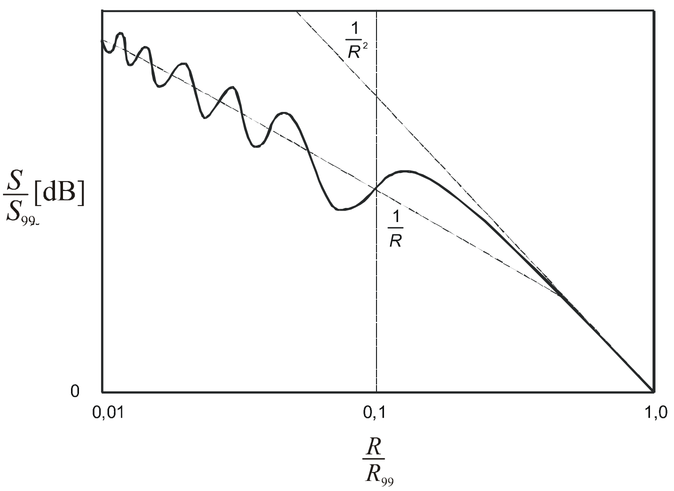

Fig. 7. Power density in the mainlobe direction for linear antenna

Thus, PEL accomplishing distance (designated with R_{PEL}) can be calculated by:

$$R_{PEL} = \sqrt{\frac{P \cdot G}{4\pi S_{PEL}}} \quad (3)$$

where S_{PEL} is PEL in terms of equivalent plane wave current density.

However, in the reflective environment such as ship deck, reflections and diffraction additionally complicate the field estimation and can cause unexpected field levels. There are many metal parts onboard a ship in the radiation region. They cause reflections (object dimensions greater than λ) or scattering (object dimensions less than λ). For these reasons, field strength can be increased by superposition. Superposition, i.e. constructive interference can double the field strength, although [5] suggests more realistic increase factor of 1.6 for the field strength or $1.6^2 = 2.56$ for the power density. Equation (1) then changes to:

$$S = \frac{2.56 \cdot P \cdot G}{4R^2\pi} = \frac{0.64 \cdot P \cdot G}{R^2\pi} \quad . \quad (4)$$

Thus, PEL accomplishing distance (designated with R_{PEL}) could be calculated by:

$$R_{PEL} = \sqrt{\frac{0.64 \cdot P \cdot G}{\pi S_{PEL}}} \quad . \quad (5)$$

Since P is the mean transmitted power, it must be related to the specified peak envelope power (PEP) of the transmitter. For audio signals, PEP is related to the mean power as:

$$P = \frac{\mathrm{PEP}}{10} \quad (6)$$

and the following equation is obtained:

$$R_{PEL} = \sqrt{\frac{0.64 \cdot \mathrm{PEP} \cdot G}{10\pi\ S_{PEL}}} \quad . \quad (7)$$

When radiation hazard estimation is based on peak limit $S_{PELpeak}$, the peak PEL accomplishing distance $R_{PELpeak}$ will be calculated using peak power (PEP) by:

$$R_{PELpeak} = \sqrt{\frac{0{,}64 \cdot \mathrm{PEP} \cdot G}{\pi S_{PELpeak}}} \quad . \quad (8)$$

B. X-band navigational radar on a large ship

For the mainlobe direction and the far field region, equations (1) and (2) apply as given for the HF transmitter. Correction due to reflections must be carefully observed here. Human radiation hazard is estimated in two separate ways: using the field averaged over a human body dimensions, and using the peak field strength. Considering the wavelength, the body dimensions would average the constructive and destructive interferences, so the correction is not needed for average field. However, if the peak field strength value or the value in only one point is needed (e.g. for HERO), possible constructive interference should be taken into account as in (3) and (4).

Power density averaging due to pulse mode decreases the radiated power by duty cycle (pulse period/repetition period ratio) $T_{\mathrm{P}}/T_{\mathrm{R}}$. The antenna rotation causes further decrease by exposure time/rotating time ratio T_E/T_{ROT}. Relations (2) and (4) transform to relations (7) and (8):

$$R_{PEL} = \sqrt{\frac{P \cdot G}{4\pi S_{PEL}} \cdot \frac{T_P}{T_R} \cdot \frac{T_E}{T_{ROT}}} \tag{9}$$

$$R_{PEL} = \sqrt{\frac{0.64 \cdot P \cdot G}{\pi S_{PEL}} \cdot \frac{T_P}{T_R} \cdot \frac{T_E}{T_{ROT}}} \quad . \tag{10}$$

In the shortest distance range operating mode, duty cycle T_P/T_R equals $425 \cdot 10^{-6}$. Because of the sidelobe suppression, in this consideration it can be assumed that the whole energy is concentrated in the mainlobe, and there is no radiation during the rest of the rotation period, so T_E/T_{ROT} equals 1.2/360. The observed antenna numerical gain is 1718.

The question is what the real R_{PEL} is for the particular exposure situation because relation (1) applies only to radiating field and the mainlobe direction. Thus, this equation is valid only in the far-field region or for worst-case analysis, so the far-field condition must be checked according to (2). Calculated distance R_{99} is about 90 m for the antenna dimension of 1.2 m. This means that the ship deck is exposed in the near-field region, and equation (1) can serve only as the worst-case analysis. More accurate analysis cannot be done this simply.

In the near-field region, field can never reach the level greater than calculated here, even in the mainlobe direction, and, because of the antenna height, there is usually no personnel in the mainlobe direction. R_{PEL} calculated by relations (7) and (8) can be assumed to present the safe limit beyond which field greater than PEL cannot occur, for the observed single source.

The near-field diagram for surface antenna according to [16] is shown in Fig.8. Power density is normalized to unity (0dB) at R_{99}, which is the point with power density marked as S_{99}. The Y axis values are not marked because they differ from one antenna to another, depending on the current distribution. The power density oscillates with the distance, but in different way than for linear antennas (Fig.7).

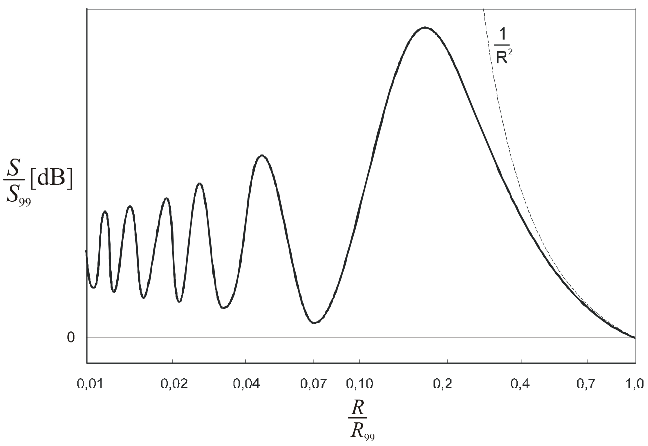

Fig. 8. Power density in the mainlobe direction for surface antenna

When HERP estimation is based on peak limit $S_{PELpeak}$, the peak PEL accomplishing distance $R_{PELpeak}$ will be calculated without time averaging, using the following equation:

$$R_{PELpeak} = \sqrt{\frac{0.64 \cdot P \cdot G}{\pi S_{PELpeak}}} \quad . \tag{11}$$

HERO estimation is based on average field strength at one point in space, so equation (10) is used.

C. X-band navigational radar on a small ship

The electromagnetic power density will again be calculated using analytical equation (1). Since these kinds of ships are made mainly of fiberglass, it can be assumed that there are no reflections that could further increase the power density.

The question of concern is to find if the top deck (fly bridge) is inside the area exposed to power density above PEL. The distance R_{PEL} will be calculated using (9) with all the typical values for small ship radars mentioned earlier, with T_P/T_R ratio of 1/1000. Calculated distance R_{99} is about 20 m for the antenna dimension of 0.6 m.

When radiation hazard estimation is based on peak limit $S_{PELpeak}$, the peak PEL accomplishing distance $R_{PELpeak}$ will be calculated without time averaging, using $R_{PELpeak}$ and $S_{PELpeak}$ in equation (3).

HERO will not be estimated for a small ship (recreational boat).

D. Inmarsat SES

The radiation hazard will be estimated by comparing the calculated power density around the antenna to the permissible exposure limit (PEL) for general public, as given in [1].

This paper gives the analysis of high gain antennas with suppressed sidelobes (by ca. 25dB). The mainlobe is a pencil beam directed to the satellite. Accordingly, only the power density inside the mainlobe will be calculated since the exposure to the main beam is the worst case that can happen in this analysis. The constructive interference from reflections cannot occur.

For the worst case analysis, following assumptions are made:

- continuous maximum transmitted power as defined in specifications for every Inmarsat service analyzed (Table I);
- continuous exposure that takes place inside the mainlobe.

TABLE I

MAXIMUM PERMITTED EIRP AND TYPICAL ANTENNA DIAMETERS FOR VARIOUS INMARSAT SES

Inmarsat...	A	B	C	M	F
Max. EIRP, dBW	36	33	16	27	32
D, m	1.2	0.9	-	0.5	0.8

The power density calculated using the far-field equation (1) presents the top limit of possible power density around the antenna. Using this equation in the near field leads to overestimation of the exposure.

Using the following equations based on empirical model for circular surface antennas [5], the near-field region and transition region power density values can be observed quite accurately.

The reactive near-field and far-field boundaries for such antenna are given by:

$$R_{\mathrm{nf}} = \frac{D^2}{4\lambda}, \qquad R_{\mathrm{ff}} = 0.6\frac{D^2}{\lambda} \quad . \tag{12}$$

where R_{nf} is the reactive near-field boundary, R_{ff} is the far-field boundary, λ is the wavelength (ca. 0.18 m for Inmarsat uplink frequency) and D is the antenna diameter. Typical antennas diameters are given in Table I. The maximum power density at the antenna surface S_{surf} can be approximated by:

$$S_{\mathrm{surf}} = \frac{4P}{A} \tag{13}$$

where P is the TX power and A is the physical area of the aperture antenna. The maximum power density in the reactive near-field or Fresnel region S_{nf} can be calculated by:

$$S_{\mathrm{nf}} = \frac{16\eta P}{\pi D^2} \tag{14}$$

where η is the aperture efficiency. The aperture efficiency is typically 0.5 – 0.75 for circular surface antennas [5]. A value of $\eta = 0.65$ is assumed here.

The maximum power density in the radiating near-field or transition region (the space between the reactive near-field and far-field boundaries) S_{trans} can be calculated by:

$$S_{\mathrm{trans}} = \frac{S_{\mathrm{nf}} R_{\mathrm{nf}}}{R} \tag{15}$$

where R is the distance to the area of interest. At the distance greater than R_{ff}, i.e. in the far-field region, the power density can be calculated by:

$$S = \frac{\mathrm{EIRP}}{4R^2\pi} \tag{16}$$

where

$$\mathrm{EIRP} = P \cdot G \quad . \tag{17}$$

At the distance $R = R_{\mathrm{ff}}$, equations (15) and (16) should give almost the same result marked as S_{ff}. The PEL accomplishing distance R_{PEL} can be calculated from equation (16) if PEL [1] in terms of power density, S_{PEL}, is used.

Doing this analysis using just general Inmarsat and SES manufacturer specifications, two parameters usually lack: the antenna power gain G and the TX power P. The gain can be calculated by equation (6) using the assumed efficiency of $\eta = 0.65$, and the TX power can be calculated from gain and specified EIRP:

$$G = \frac{4\pi\eta A}{\lambda^2}, \qquad P = \frac{\mathrm{EIRP}}{G} \tag{18}$$

Specifically for Inmarsat C, antenna can be any type of stationary antenna (printed antenna, helicoidal antenna etc.) so equations (1) to (6) do not completely apply, and only the far-field values using equation (5) will be calculated. Also, the far-field boundary, R_{ff} is given by more general equation (2) where R_{ff} equals R_{99}.

VI. Hazard estimation

A. HF transmitter

PELs and PEL accomplishing limits are given in following Tables.

TABLE II
PELs FOR HF TRANSMITTER

Frequency: 10 MHz		
HERP S_{PEL}	unctrld.	2 W/m^2
	ctrld.	10 W/m^2
HERP $S_{PELpeak}$	unctrld.	$2\cdot10^3$ W/m^2
	ctrld.	$10\cdot10^3$ W/m^2
HERO $S_{PELpeak}$	Limit 1	0.02 W/m^2
	Limit 2	10^{-4} W/m^2

For frequencies exceeding 10 MHz, HERP peak limit [1] is given as:

$$S_{PELpeak} = S_{PEL} \cdot 1000 \quad . \tag{19}$$

TABLE III
PEL ACCOMPL. DISTANCES FOR HF TRANSMITTER

HF SSB transmitter, PEP = 100 W		
HERP r_{PEL}	unctrld.	0,9 m
	ctrld.	0,4 m
HERP $r_{PELpeak}$	unctrld.	0,1 m
	ctrld.	0,0 m
HERO $r_{PELpeak}$	Limit 1	27,6 m
	Limit 2	390,9 m

B. Navigational radar

PELs and PEL accomplishing distances are given in following Tables. Equation (19) applies.

TABLE IV
PELS FOR NAVIGATIONAL RADAR

Frequency: 9.4 GHz		
HERP S_{PEL}	unctrld.	10 W/m^2
	ctrld.	50 W/m^2
HERP $S_{PELpeak}$	unctrld.	10·10^3 W/m^2
	ctrld.	50·10^3 W/m^2
HERO S_{PEL}	Limit 1	40 W/m^2
	Limit 2	20 W/m^2

Table IV shows that the HERP and HERO limits given in term of average power strength are very similar, being of the same order of magnitude. However, the peak limit is three orders of magnitude higher. This could indicate that this limit is less stringent. On the contrary, PEL accomplishing distance is much larger for peak PEL, as can be seen in Tables V and VI. This means that greater area is endangered with peak PEL than with average PEL. The reason is obviously in time averaging scheme described in equations (9), (10) and (11). The time averaged power density originating from radar decreases 5 to 6 orders of magnitude, while the peak limit is only 3 orders of magnitude higher.

TABLE V
PEL ACCOMPL. DISTANCES FOR
NAVIGATIONAL RADAR ON A LARGE SHIP

Nav. radar on large ship, P = 20 kW		
HERP r_{PEL}	unctrld.	0,6 m
	ctrld.	0,3 m
HERP $r_{PELpeak}$	unctrld.	26,5 m
	ctrld.	11,8 m
HERO r_{PEL}	Limit 1	0,5 m
	Limit 2	0,7 m

TABLE VI
PEL ACCOMPL. DISTANCES FOR
NAVIGATIONAL RADAR ON A SMALL SHIP

Nav. radar on small ship, P = 5 kW		
HERP r_{PEL}	unctrld.	0,3 m
	ctrld.	0,1 m
HERP $r_{PELpeak}$	unctrld.	6,3 m
	ctrld.	2,8 m

C. Inmarsat SES

PELs and PEL accomplishing limits are given in following Tables. Equation (19) applies, but since the continuous radiation is assumed, $r_{PELpeak}$ need not be checked.

TABLE VII
PELS FOR INMARSAT SES

Frequency: 1.6 GHz		
HERP S_{PEL}	unctrld.	8 W/m^2
	ctrld.	40 W/m^2
HERP $S_{PELpeak}$	unctrld.	8·10^3 W/m^2
	ctrld.	40·10^3 W/m^2
HERO $S_{PELpeak}$	Limit 1	2 W/m^2
	Limit 2	1 W/m^2

HERP PEL is given in terms of power density spatially averaged over the entire body and time averaged over any 6 minutes of exposure [1]. If the exposure is only partial (limbs, other body parts), values greater than PEL are permitted by [1], but not for eyes and testes [2]. This deserves further comment.

Since aperture antennas tend to produce pencil beam of radiation, the formed mainlobe is narrow and it cannot irradiate the whole human body, so exposure to the formed beam in the vicinity of the antenna is almost certainly partial.

Non-continuous exposures, shorter than 6 minutes, especially of limbs, would not be so harmful even at the shorter distances to the antenna.

On the other hand, the harmful exposure takes place in the near-field (transition region) where the narrow beam has not yet been formed, so the exposed area of the body is not so small. Considering also the protection of eyes and testes, the use of the whole body PEL is justified for the worst case analysis.

TABLE VIII
NEAR-FIELD POWER DENSITY OF INMARSAT SES

Inmarsat...	A	B	C	M	F
R_{nf}, m	2.0	1.1	-	0.3	0.9
R_{ff}, m	4.8	2.7	0.4	0.8	2.1
S_{surf}, W/m^2	49	78	-	207	100
S_{nf}, W/m^2	32	51	-	134	65
S_{ff}, W/m^2	14	22	20	57	28
R_{PEL}, m	6.3	4.4	0.6	2.2	3.9

Calculation results in Table VIII show that the exposure is mostly above PEL throughout the near-field region.

The power density at the antenna surface (at the radome) and in the transition region is much higher than PEL. Although human exposure in the reactive near-field cannot be well analyzed by analytical equations, it is almost certain that this exposure is harmful.

TABLE IX
PEL ACCOMPL. DISTANCES FOR INMARSAT SES

Inmarsat A SES		
HERP r_{PEL}	unctrld.	5,6 m
	ctrld.	2,5 m
HERO r_{PEL}	Limit 1	2,8 m
	Limit 2	4,0 m
Inmarsat B SES		
HERP r_{PEL}	unctrld.	4,0 m
	ctrld.	1,8 m
HERO r_{PEL}	Limit 1	2,0 m
	Limit 2	2,8 m
Inmarsat C SES		
HERP r_{PEL}	unctrld.	0,6 m
	ctrld.	0,3 m
HERO r_{PEL}	Limit 1	0,3 m
	Limit 2	0,4 m
Inmarsat M SES		
HERP r_{PEL}	unctrld.	2,0 m
	ctrld.	0,9 m
HERO r_{PEL}	Limit 1	1,0 m
	Limit 2	1,4 m
Inmarsat F SES		
HERP r_{PEL}	unctrld.	3,6 m
	ctrld.	1,6 m
HERO r_{PEL}	Limit 1	1,8 m
	Limit 2	2,5 m

VII. CONCLUSIONS

The conclusions are presented separately for each type of analyzed sources.

1. The analysis of the **HF transmitter** field levels shows that fields on the deck are under HERP PELs. The potential danger is still lowered because radio is used mainly for short duration transmissions, while HERP PEL refers to the 6 min average level, as defined by [1]. Nevertheless, these fields cannot be disregarded in the immediate vicinity of the antenna. Also, HERO and HERF unsafe distances may encompass fueling areas and ordnance assembly/disassembly areas. Hazards are real and should be avoided by protective measures.

2. The **navigational radar** electric field on the deck of a **large ship** was well under HERP and HERO PELs. Although the safe distance for HERP peak PEL is much larger than for averaged PEL, the deck can be considered safe since the antenna is positioned quite high on the ship superstructure and the main beam overshoots the deck. This kind of installation can be considered hazard-free according to the present HERP and HERO recommendations. HERF recommendations [3] show that the radiation of navigational radar may encompass fueling areas, potentially causing fuel ignition. Hazards are real and should be avoided by protective measures, especially by emission control.

3. The results of the analysis of a **navigational radar on a small ship** show that the analyzed situation does not completely comply with the relevant human protection guidelines, regarding the top deck (fly bridge) exposure to peak field values above the limit for peak HERP PEL. There is certainly a need for caution in approach to the navigational radar antenna installation. Considering the limited dimensions of a small ship, extending the antenna distance from the crew is not possible. Nevertheless, raising the height of the antenna should solve this problem without the need for further adjustments.

4. The analysis of the radiation hazard of **shipboard Inmarsat SES** refers to the worst case: whole body or sensitive body parts exposure, exposure to the main beam of radiation, exposure longer than 6 minutes. The analysis shows that the exposure to typical Inmarsat SES could be harmful in the main beam, at the distances within few meters from the transmitting antenna. Since the direction of the main beam is not observable to the crew, approach to the immediate vicinity of the antenna should be restricted at the calculated distances.

The conclusions of the analysis presented in this paper encourage further research of different exposure configurations.

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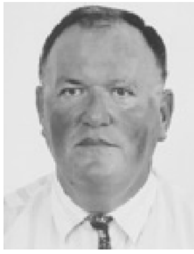

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