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Mathematical Approach of Electromagnetic Interference Analysis and Safety Radiation Zones Identification

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Abstract

A modeling approach of systems interference analysis and electromagnetic radiation exposure identification is presented. The method is suited particularly when a new system is going to be installed inside military base. Characteristic results of interference are presented both for wanted and unwanted radiation frequencies. In addition, graphically presentation of the personnel safety zones is given. In addition, some preliminary comparisons with experimental measurements are included.

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1 Introduction

A little more than a century ago, the notion of transmitting information in a wireless manner must have seemed like science fiction. Since 1897 when the pioneer of mobile communications Marconi demonstrated the first wireless communication system between a land-based station and a tugboat, important developments in the field have shrunk the world into a communication village ([7]). After many years of reliance on analog-based technology for telecommunications, we now live in a mixed analog and digital world and we are rapidly moving toward digital networks. Modern military equipment not only follows this revolution but most of the time is a frontier in designing new technology. Hellenic Air Force in order to continue playing its crucial role, couldn't do anything else than to be equipped with the state of the art wireless technology such as hand-held mobile radio, ground to air data links, 3rd generation microwave systems and satellite communications.

Despite though the great importance of all these systems on countries security, perception must be given when it comes to personnel safety. Exposure to RF at sufficiently high intensity can lead to effects associated with tissue heating and can induce currents in the human body that can lead to shocks. Permissible Exposure Levels (PELs), have been developed ([6]) in order to prevent such effects. Protection against harm is achieved by identifying areas/sources where potential exposures might exceed the PELs and applying the appropriate administrative or engineering controls.

Furthermore, the continuously raise of the installed systems inside military bases brings into surface the issues of frequency management and electromagnetic interference analysis both prior and post installation of new equipment.

In the current work a modeling approach of systems interference analysis and electromagnetic radiation exposure identification, is presented. After a short description of the adapted methodology followed by a discussion about its limitations, characteristic results of interference are presented both for wanted and unwanted radiation frequencies. In addition, graphically presentation of the personnel safety zones is given. Based on the presented results some preliminary comparison with experimental measurements is included. The analysis is based on two real case scenarios. The first one is the installation of a new RADAR system and the second one the installation of a radio amateur's UHF repeater inside a military base. We use the first one in order to present the interference and the second one for the RF exposure modelling approach because there are more representative results when continuous wave RF emitters are under consideration when it comes to RF exposure analysis. It is noted that both the geographical and technical details have been altered in order this work to be unclassified.

2 Interference Modeling Approach

Interference analysis is divided into two main tasks, the electromagnetic interference analysis and the analysis of shadowing, which are further divided into sub tasks (Figure 1). Of course when a new system is considering for installation inside an area where other systems operate, interference analysis has to be two-way; meaning that both the interference of the new system to others and others to the new system has to be calculated. However in order not to extent the length of the current work in what follows only one-way interference is examined (interference of the system to the others). The other way is similar.

As shown in Figure 1, the first thing under consideration when it comes to electromagnetic interference is the operating frequency examination. Thus the operating frequency of every system inside the considering area is compared with

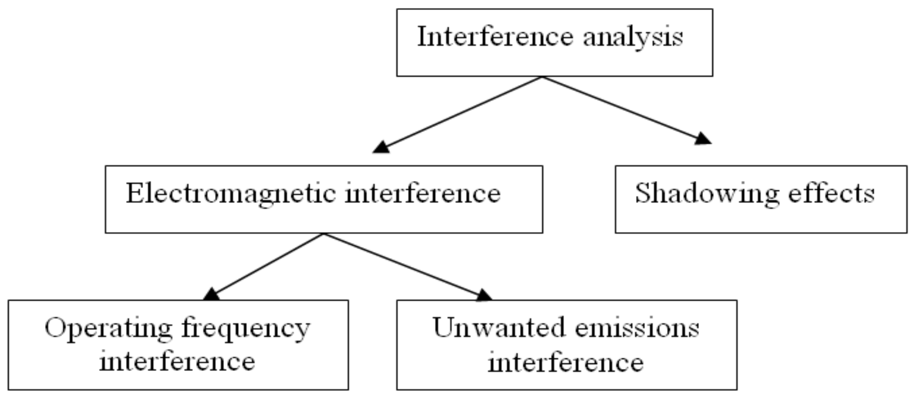

Figure 1: Interference analysis' main tasks

that of the system under evaluation. If any of those coincide, computation of the received power density for every installed system, which seems to be interfered, has to be performed ([5]):

$$P_{Rx} = P_{Tx} \frac{G_{Tx} \cdot G_{Rx} \cdot \lambda^2}{16\pi^2 R}. \qquad (1)$$

$P_{Rx}$is the received power from the transmission of the nearby transmitter (that operates inside the bandwidth of the receiver's frequency), P_{Tx} is the transmitted power of the nearby transmitter, G_{Tx} is the gain of the transmitter's antenna directed to the receiver's antenna, G_{Rx} is the gain of the receiver's antenna directed to the transmitter's antenna, λ is the wavelength and R is the distance between the transmitter and the receiver. In order to make the calculations simpler a different formulation of Equation (1) is used, known as Link Budget ([5]):

$$P_{Rx}(dB) = P_{Tx} - C_{Tx} + G_{Tx} - Pl + G_{Rx} - C_{Rx} \qquad (2)$$

Here C_{Tx} is the power loss of the transmitter's cables, C_{Rx} is the power loss of the receiver's cables, Pl is the attenuation of the signal in free space for LOS connections and is given by:

$$Pl = 32.4 + 20 * log(f) + 20 * log(R) \qquad (3)$$

where f is in MHz and R is in km.

The prerequisite for two systems in order not to interfere is:

$$P_{Rx} < Receiver's\ sensitivity \quad (4)$$

If the above condition is not satisfied, electromagnetic interference between the two systems occurs.

This first step is assumed to me the most important because of the great values of transmitted power in the operating frequency. After this evaluation, however estimation interference caused by unwanted emissions has to be done, considering the harmonic frequencies: $2f_c, 3f_c, 4f_c,$ e.t.c., where f_c is the carrier frequency. Unwanted emissions are probably caused also due to constructional problems of the transmitters.

Furthermore, the transmitters that generate the carrier frequency f_c by multiplying it with a lower value frequency f_x seem to evoke large problems to the receiver with the generating frequencies: $f_c + f_x$ and $f_c - f_x$.

Even if the above do not create problems to the receivers, there the transmitters frequently generate intermodulation products, which should be examined. They are given by:

$$f = \alpha_1 f_1 + \alpha_2 f_2 + \alpha_3 f_3 + \cdots \quad (5)$$

where $\alpha_1, \alpha_2, \alpha_3, \ldots$ are positive, negative and zero integers and $f_1, f_2, f_3, \ldots$ are the frequencies of the various oscillations that exist in a transmission station. The sum: $|\alpha_1| + |\alpha_2| + |\alpha_3| + \cdots$ constitutes the class of a single intermodulation product.

Electromagnetic interference analisis has to be followed by shadowing analysis. Shadowing effects occur when the dimensions of one system are large enough and the system is installed in such a place where it blocks an other system to operate, by simply hidind some areas. Simulating such a problem is not straightforward, because not only demands complicated mathematecal modelling but accurate geographical information too. In order to calculate this kind of interference a software named AREPS (Advanced Refractive Effects Prediction System) is used. The AREPS program computes and displays a number of tactical decision aids to assess the influence of the atmosphere and terrain upon the performance of electromagnetic (EM) radiating systems. It contains the ability to calculate free-space range from radar system parameters such as frequency, pulse length, etc., in addition to ESM free-space intercept and communications intercept ranges ([1]).

The used paths containing land features depend on terrain data obtained from the National Geospatial-Intelligence Agency's (NGA) Digital Terrain Elevation Data (DTED).

3 RF Exposure Modeling Approach

In order to identify the radiation limits in a place where many radio telecommunication systems are located, estimation in all regions should be done. Those regions are the near, the transition and the far field region. The adopted method is that proposed by National Agency of Atomic Energy and are incorporated in ΕΛΟΤ 1422-3 (Greek Version) and is based on power flux density calculation in three different regions: near, transient and far field

The near field is extended from the antenna till:

$$R_{nf} = \frac{D^2}{4\lambda}. \tag{6}$$

The transient field is extended from where the near field ends till:

$$R_{ff} = \frac{2D^2}{\lambda}. \tag{7}$$

The far field is extended from the end of the transient field.

Inside near field, the maximum power flux density (W/m^2) is independent of distance and given by:

$$S_{nf} = \frac{16\, P_{in}}{\pi\, D^2}. \tag{8}$$

where D is the diameter of the antenna and P_{in} is the maximum antenna's input power.

When transition field is considering the power flux density inversely depends on distance and is given by

$$S_t = \frac{S_{nf} R_{nf}}{R},\ R_{nf} \le R \le R_{ff} \quad (9)$$

where S_t is the power density inside the transition region in a point that has distance R from the center of the antenna, S_{nf} is the maximum power density in the near field region, R_{nf} is the distance inside where the near field is extended (m) and R is the distance from the center of the antenna to the calculation point.

Lastly when far field is considered the power flux density inversely depends on the square of distance and is given by:

$$S_{ff} = \frac{P_{in} G}{4\pi R^2}\ u^2 \quad (10)$$

where P_{in} is the antenna's maximum input power density, G is the gain of the antenna toward the destination of interest (dbi) and is given by:

$$G = 10^{dBi/10},$$

R is the distance from the centre of the antenna to the point of calculation and u is the a coefficient that has to do with the specific environment into which the system operates (~1.6 for military bases).

At a point in the near or transient field, that is out of the maximum radiation axis and located at least one diameter far from it, the power density is calculated using the same formulas and then the calculated value is reduced by 100 $(-20\ dB)$.

Inside the far field though the power density in a point out of the main axis is given by:

$$S = \frac{P\ G(\theta)}{4\pi R^2} \quad (12)$$

where $G(\theta)$ is derived from the radiation diagram given by the manufacturer of the antenna. However, the most usual expressions of it are:

$$G(\theta) = \begin{cases} 32 - 25 log\partial\ dB_i, if\ 1^\circ \le \partial \le 48^\circ \\ -10\ dB_i, if\ 48^\circ \le \partial \le 180^\circ. \end{cases} \quad (13)$$

The estimated values are compared with two categories of Permissible Exposure Levels. The first one is the category of professionally exposed personnel and the second one that of common people ([6]).

The levels of the former are larger than the latter. When the estimated values are larger than the first category's PELs the area is characterized as red zone and no personnel (professionals or not) are allowed to enter it. When the estimated value is larger than the second category's PELs but lower than that of the first category the area is characterized as yellow zone and only professionals are allowed to enter. Iin any other occasion the area is characterised as green zone and there are not any entrance restrictions.

In the case were other RF radiating systems are operating inside the considering base they have to be taken into account for more accurate calculation of exposure zones. This can be done by simply adjust every systems exposure ratio (calculated value /limit) in order to calculate the exposure ratio of all relevant sources.

4 Real Case Interference Calculations

As have already discussed, the case of a new RADAR system installation inside a military base is investigated. Inside the base a great amount of already installed equipment exists included three Military Systems (named Y, R and Z). The new RADAR is working on commercial (IFF) frequency.

Following the methodology described in previous paragraphs for the electromagnetic interference analysis, technical specifications and location co ordinations of every installed radio system inside base are collected. We compare the operation frequencies of them (receivers) with the operation frequency of the new one (transmitter). Assuming Radar X is that one proposed to be installed and it operates at $1030\ x_x$, $1090\ R_x$ (MHz). The other systems in the base operate at:

$2{,}7\ -\ 3{,}1\ GHz$ (Radar Y), $1 - 10{,}75\ GHz$ (Receiver R), $1030\ T_x$, $1090\ R_x\ MHz$ (SSR Radar Z). Consequently, only the Receiver R seems to be interfered by Radar X.

The next step is to compute R's received power, which is: $P_{Rx} = 21{,}46\ dBm$ which is larger than it's sensitivity that is between -60 and $-80\ dBm$. If the Receiver R is not inside the Radar's transmission beam, we compute the received power on θ_{3dB}, which is: $P_{Rx}\ =\ 18{,}46\ dBm > -60\ dBm$. This result indicates that nterference occurs between Receiver R and Radar X.

In addition to previous calculations possible interference caused by unwanted RF products have to be examined.

Table 1: Comparison of systems Harmonic Frequencies

	RADAR X	RECEIVER R	RADAR Y
1st harmonic	X	X	
2nd harmonic	X	X	
3nd harmonic		X	
4th harmonic		X	

Table 1 present the interference between base's systems and new RADAR's first four harmonic frequency. When interference occurs between two systems it is indicated by an X symbol.

As shown the 2nd and 3nd harmonic frequencies of the new radar are inside the bandwidth of Radar Y. Thus we compute the received power of the interfered system Y for the second harmonic: $P_{Rx} = -\ 54{,}1\ dBm$ and for the 3rd $P_{Rx} = -\ 56{,}8\ dBm$, which are larger than it's sensitivity ($-115 dBm$). Therefore Radar Y is interfered by the Radar X. Consequences of this interference can be confronted by appropriate selection (increase) of the sensitivity threshold of the Receiver of Radar Y which however leads to reduction of systems operational performance.

Furthermore, Receiver R seems to have an interference problem caused from radio emissions of Radar X inside almost its entire bandwidth. Specifically the received power of R from Radar X is larger than its sensitivity. The same happens with the power densities of the first harmonic frequencies of its carrier. In addition, the performance of Receiver R is probably interfered from inter modulation products that might be created due to emissions of Radar X, because it will be installed too close to it. Consequently, Receiver R will be interfered by Radar X.

Over and above, inter-modulation products have to be taken into consideration though it is very difficult to accurate calculate them because of the non deterministic way they are appear. This is the reason we only take into account the main system's frequency sums which in our case do not import any further problem.

The next step is to examine shadowing effects. Using AREPS we simulated the radio coverage of RADAR X and Y prior and after the new RADAR installation. Figures present the simulation results for the case of RADAR Y. As far as RADAR X is concerned the shadow effects were negletable and thus we did not incorporate the corespondence simulation results in this work.

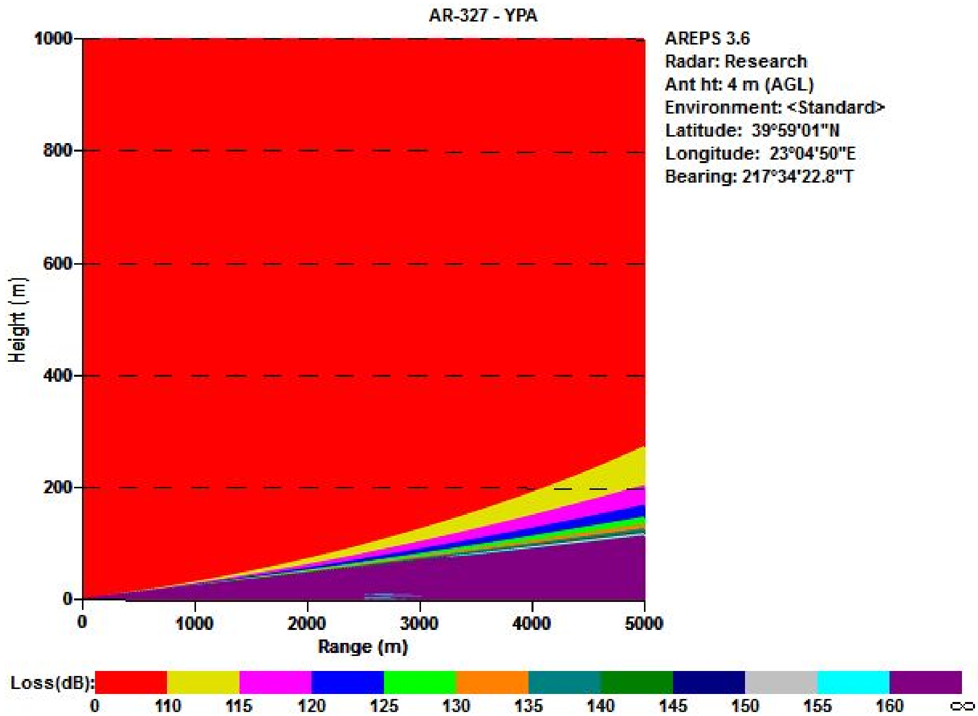

Figure 2: The radio coverage of radar Y before installation of new RADAR

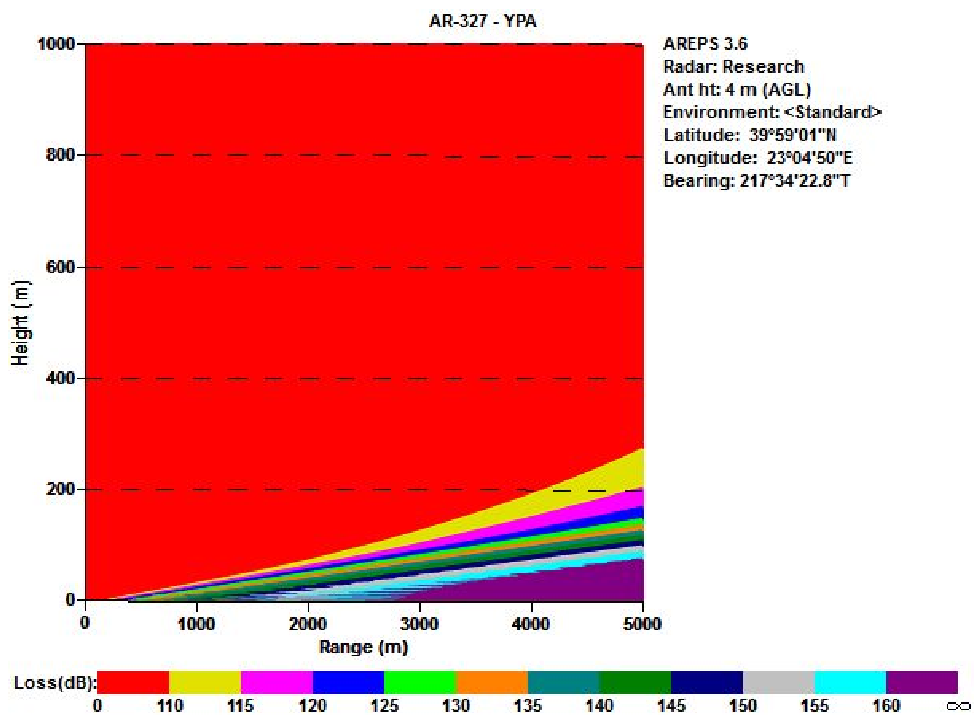

Figure 3: The radio coverage of radar Y after installation of new RADAR

As shown in Figures 3 and 4 some reflections are created at low heights. Comparing though their power with receivers sensitivity it is shown that they do not interfere the system.

5 Real Case Exposure Zones Calculation

Although the RF exposure investigation was performed in the case of the new RADAR system installation, the results were not representatives of the followed methodology. In order to incorporate more representative results we present the results of a second real case scenario. In this case a radio amateur's UHF repeater was under study in order to be installed inside a military base. In this scenario the system transmits only continuous wave in contrast to the pulsed emission of the previously described RADAR system. The antenna after installation would be fixed in a height of about 6 meters. Table 2 summarizes the technical specifications of the system under consideration.

Table 2: Technical specification of UHF repeater and antenna

Transmit Power	20 W
Bandwidth	407 – 470 MHz
Antenna Gain	9 dBd
Antenna Length	0,8 m
Antenna Height	6 m

The PELs for common people and professionals are: $1.42\,W/m^2$ and $10.17\,W/m^2$ (average value), respectively. In Figure 4 the estimated results for critical zone identification are graphically presented.

With red and yellow color are indicated the estimated red and yellow zones, respectively. The green zone is not specific colored but it is assumed to be every region excluding the indicated ones.

As shown by Figure 4 the model analysis estimated that 60^o from the main radiation axis and at distance $1.6m$ from the antenna, is not safe for the personnel to stay because they will be overexposed to electromagnetic radiation. The same happens at 20° from both sides of the axis of maximum radiation till $2.3\,m$ from the antenna. As for the common people, the zones that they should not stay inside are: 60° from both sides of the axis of maximum radiation till $4.3\,m$ from the antenna and also 20° from both sides outside the direction of maximum radiation till $6.2\,m$ from the antenna.

It has to be noted that in the presented graphical results only radiation of the system under consideration is involved (single system examination). The incorporation of other systems' radiation (multi system examination) is given further in this paper only numerically because graphical representation is almost identical.

Furthermore, in order to validate our theoretical results we performed experimental measurements after the installation of the system inside base ([3]). A Narda NBM-500 field meter with isotropic E-field and B-field sensors and an Anritsu Spectrum Master, Spectrum analyzer with a directive antenna was used. Elimination of electromagnetic noise was achieved by stopping the operation of every transmitter in the area (both military and civil owned). The measured values were used in order to specify the exact exposure zones, taking into account the computed uncertainty of measurement (2.4 %) using the well established BIPM ([2]) method. Table 6 presents the estimated and measured exposure zones inside maximum radiation axis for the case of single and multi-system examination.

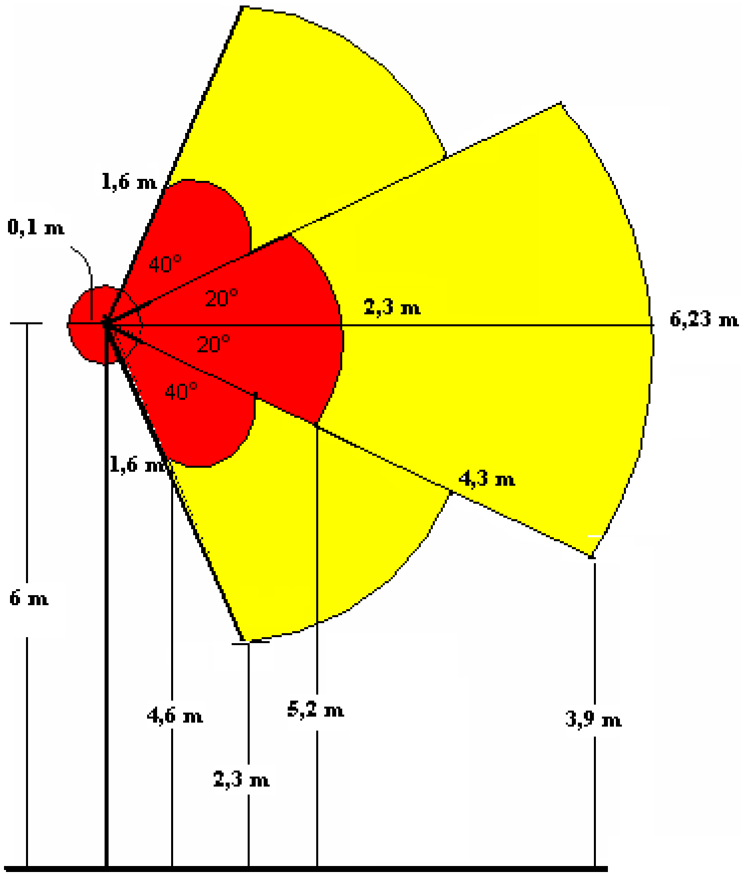

Figure 4: Estimated RF exposure safety zones due to modeling approach

Table. 6: Estimated and measured Exposure/Safety Zones

Zone	Estimated (single system)	Estimated (multi system)	Measured
Red	$0 - 2.3\ m$	$0 - 2.302\ m$	$0 - 2\ m$
Yellow	$2.3 - 6.26\ m$	$2.3001 - 6.26001\ m$	$2 - 6\ m$
Green	$> 6.23\ m$	$> 6.23001\ m$	$> 6\ m$

Measured zones are the same for both scenarios because of the uncertainty involvement and the long distance between the systems under consideration.

Comparison between the estimated and actual exposure/safety zones indicates that the adopted modeling approach gives results that are in good agreement with the actual situation.

6 Conclusion

In the current work a modeling approach suitable for systems interference analysis and electromagnetic radiation exposure identification was presented. The theoretical background was briefly discussed and critical parameters were identified.

Two different system configurations were examined. In the first, the system was a pulsed wave RADAR operating in civil aviation frequency. Interference of this system with other systems inside a military base (were the site survey was performed) was investigated and characteristic results were presented. We concluded that prior to the installation of the newly RADAR critical decisions about the performance degradation of the already installed systems had to be done.

The system was a UHF repeater that was considering for installation inside the same military base. This scenario was selected in order for the electromagnetic exposure analysis results to be more representative of the method's capabilities due to the transmitted continuous wave. RF Exposure Analysis results were graphically presented. Comparisons with experimental measurements was pointed that the followed method is accurate enough.

It seems that the considering methods both for interference and RF exposure analysis could be used in a systematic manner prior installation of new RF equipment as a preventive tool, in order to avoid unnecessary future corrective actions.

The experimental reproduction of the numerical results is underway. Also, the mathematical model is currently considered for interfacing with a Graphical

Unit (GUI) in order to be user friendly. Last but not least, in order to have more accurate simulation results, electromagnetic propagation critical parameters are investigated for different military base environments.

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