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**TÍTOL DEL TFC: SAR evaluation averaging in the human body using
numeric methods**

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Overview

This document contains an explanation about the power deposition inside a human body arising from exposure to RF sources and the associated dosimetry (SAR) and an introduction to the FDTD method.

It also contains a series of objectives to solve to improve the analysis of SAR from communication devices used inside a vehicle. Those objectives were programmed with Matlab, and its simulations were realized with the LC program.

In the first objective there's an explanation of all the types of file that the LC program uses, the objective consists obtain all the electric field information for the whole body of the model.

In the second objective there's explained the twelve-algorithm method and how it is used to improve the results.

At the end of the project there's an Annex with the programs realized to accomplish the objectives.

To my father, and his worries for
unconscious use of technology.

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INTRODUCTION

The main objective of this document is to rise consciousness of the collateral effects using cell phones. Demagogy is not an objective; this is just a call for a correct and responsible use of technology. This project is itself a study of SAR levels produced in a new, and electromagnetically harsh, environment like the car and the hands free of the cell phone.

In the first chapter the SAR issue and its entire story are introduced. In the last subchapters the correct SAR levels according to international guidelines are specified and the physical consequences of high SAR levels are explained.

In the second chapter the work-on-field objectives that are going to be solved, which will improve the results, are described.

In the third chapter the FDTD method, which is the numerical electromagnetic method in which the LC software is based, is introduced.

In the fourth, fifth and sixth chapters the development of the work-on-field objectives are described. And in the last chapter we can find the experimental results

CHAPTER 1. THE SAR ISSUE

1.1. What does SAR mean?

SAR is the acronym for Specific Absorption Rate, and is a measure of the power per unit mass absorbed by a conducting body when exposed to an electromagnetic field, especially in the radiofrequency (RF) range. High SAR levels may be harmful for the human body because an excessive temperature increase is produced. For that reason some institutions have produced exposure guidelines and some governments decided to adopt limits for safe exposure to RF energy produced by mobile devices. Those limits are assumed to be safe for short-term exposures. There is no scientific consensus for effects arising from long term exposures, other than thermal.

The agency in charge of the electromagnetic fields' safety is the WHO (World Health Organization) a specialized agency of the United Nations. This organization specifies that mobile phone handsets are low-powered RF transmitters, emitting maximum powers in the range of 0.2 to 0.6 watts. But despite of the low levels of power, it is known that cell phones are the nearest device, emitting electromagnetic waves, to the body. That's the reason why the IEEE (Institute of Electrical and Electronics Engineers) and many national governments have established safety limits for exposure to various frequencies of electromagnetic energy based on SAR. Those limits must be at or below 1.6 watts per kilogram (W/kg) taken over a volume of 1 gram of tissue.

Several international and national organizations have published exposure guidelines for RF exposure, being the most relevant the International Committee for Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE). Those guidelines are not identical but differ only on minute details. Several governments have adopted limits based on these guidelines, mainly in USA and Canada based on IEEE guide, and in the EU, Japan, Australia, New Zealand and some others based on ICNIRP guidelines. Although cell phones are low power emitters, with peak emitted powers in the range of 2W and average values in the range of 125 mW, they are used very close to the body and can produce high power deposition, reaching the limits in the guidelines, which are around 2 W/kg averaged over 10 g or 1 g of tissue and over 6 min exposition duration.

RF Energy deposited in the body produces tissue heating... This heating effect depends on the power emitted by the cell phone and on the pattern of energy dissipation inside the body, which is a function of the frequency, distance and position of the phone relative to the body. The eyes are particularly vulnerable to RF energy in the microwave range, and prolonged exposure to high levels of microwave energy can lead to cataracts. Other living tissues that are sensible to this problem are the brain and the genitals (specially the male ones).

In conclusion I must say that all the cell phones companies must fulfill these levels, and all the companies do fulfill them. But even with these precautions people are skeptical in front of the radiation issue. This is normal because the long-term effects of exposure to electromagnetic radiation remain unclear. While some studies have found a statistical relationship between cell phone use and cancer (mainly brain tumors), some others have not.. Additional studies are needed to develop a better understanding of how electromagnetic radiation affects the human body.

1.2. Basic Restrictions (SAR) and reference levels (E,H)

Basic restrictions, in the ICNIRP guidelines, are specified by the quantity responsible for a given effect, that is current density and power deposition inside the body. However basic quantities are difficult to measure. For that reason reference levels associated to quantities external to the body (exposure) are specified. Where appropriate, the reference levels are obtained from the basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies. They are given for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. Table 1 summarizes basic restrictions for power deposition in the ICNIRP guidelines for occupational exposure and exposure of the general public. The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded.

For low-frequency fields, several computational and measurement methods have been developed for deriving field-strength reference levels from the basic restrictions.

Exposure characteristics	Frequency range	Whole-body average SAR (W/Kg)	Localized SAR (head and trunk) (W/Kg)	Localized SAR (limbs) (W/Kg)
Occupational exposure	up to 1 Hz	—	—	—
	1-4 Hz	—	—	—
	4 Hz-1 kHz	—	—	—
	1-100 kHz	—	—	—
	100 kHz-10 MHz	0.4	10	20
General public exposure	10 MHz-10 GHz	0.4	10	20
	up to 1 Hz	—	—	—
	1-4 Hz	—	—	—
	4 Hz-1 kHz	—	—	—
	1-100 kHz	—	—	—
	100 kHz-10 MHz	0.08	2	4
	10 MHz-10 GHz	0.08	2	4

Table 1 Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz.

The simplifications that have been used to date this did not account for phenomena such as the inhomogeneous distribution and anisotropy of the electrical conductivity and other tissue factors of importance for these

calculations. The frequency dependence of the reference field levels is consistent with data on both biological effects and coupling of the field. Magnetic field models assume that the body has a homogeneous and isotropic conductivity and apply simple circular conductive loop models to estimate induced currents in different organs and body regions.

1.3. Physical consequences of high SAR levels

The following paragraphs provide a general review of relevant literature on the biological effects and potential health effects of electromagnetic fields with frequencies of 100 kHz to 300 GHz.

1.3.1. Basic restrictions

Different scientific bases were used in the development of basic exposure restrictions for various frequency ranges:

- Between 1 Hz and 10 MHz, basic restrictions are provided on current density to prevent effects on nervous system functions;
- Between 100 kHz and 10 GHz, basic restrictions on SAR are provided to prevent whole-body heat stress and excessive localized tissue heating; in the 100 kHz–10 MHz range, restrictions are provided on both current density and SAR;
- Between 10 and 300 GHz, basic restrictions are provided on power density to prevent excessive heating in tissue at or near the body surface.

1.3.2. Direct effects of electromagnetic fields

Reproductive outcomes. Two extensive studies on women found no evidence for adverse effects on the fetus. However, seven studies on pregnancy produced both positive and negative results. In some of the larger epidemiological studies of female plastic welders and physiotherapists there were no statistically significant effects on rates of abortion or fetal malformation. By contrast, other studies, on similar populations of female workers, found an increased risk of miscarriage and birth defects. A study of male radar workers found no association between microwave exposure and the risk of Down's syndrome in their offspring.

Overall, the studies on reproductive outcomes and microwave exposure suffer from very poor assessment of exposure and, in many cases, small numbers of subjects. Despite the generally negative results of these studies, it will be difficult to draw firm conclusions on reproductive risk without further epidemiological data on highly exposed individuals and more precise exposure assessment.

Cancer studies. Studies on cancer risk and microwave exposure are few and generally lack quantitative exposure assessment. There are epidemiological studies that found no evidence of increased morbidity or mortality from any cause and others that reported no increase in cancer risk among children

chronically exposed to radiation from a large microwave transmitter near their homes. More recent studies have failed to show significant increases in nervous tissue tumors among workers and military personnel exposed to microwave fields. Moreover, no excess total mortality was apparent among users of mobile telephones, but it is still too early to observe an effect on cancer incidence or mortality.

Overall, the results of the small number of epidemiological studies published provide only limited information on cancer risk.

Volunteer studies. Studies demonstrated that, as the frequency increases from approximately 100 kHz to 10 MHz, the dominant effect of exposure to a high-intensity electromagnetic field changes from nerve and muscle stimulation to heating. At 100 kHz the primary sensation was one of nerve tingling, while at 10 MHz it was one of warmth on the skin. In this frequency range, therefore, basic health protection criteria should be such as to avoid stimulation of excitable tissues and heating effects. At frequencies from 10 MHz to 300 GHz, heating is the major effect of absorption of electromagnetic energy, and temperature rising more than 1–2 °C can have adverse health effects such as heat exhaustion and heat stroke.

Cellular and animal studies. There are numerous reports on the behavioral and physiological responses of laboratory animals, including rodents, dogs, and nonhuman primates, to thermal interactions of EMF at frequencies above 10 MHz. Thermosensitivity and thermoregulatory responses are associated both with the hypothalamus and with thermal receptors located in the skin and in internal parts of the body. Afferent signals reflecting temperature change converge in the central nervous system and modify the activity of the major neuroendocrine control systems, triggering the physiological and behavioral responses necessary for the maintenance of homeostasis. Exposure of laboratory animals to EMF producing absorption in excess of approximately 4 W/kg has revealed a characteristic pattern of thermoregulatory response in which body temperature initially rises and then stabilizes following the activation of thermoregulatory mechanisms. The early phase of this response is accompanied by an increase in blood volume due to the movement of fluid from the extracellular space into the circulation and by increases in the heart rate and intraventricular blood pressure. These cardiodynamic changes reflect thermoregulatory responses that facilitate the conduction of heat to the body surface. Prolonged exposure of animals to levels of microwave radiation that raise the body temperature ultimately lead to failure of these thermoregulatory mechanisms. Several studies with rodents and monkeys have also demonstrated a behavioral component of thermoregulatory responses. Decreased task performance by rats and monkeys has been observed at SAR values in the range 1–3 W/kg. In monkeys, altered thermoregulatory behavior starts when the temperature in the hypothalamic region rises by as little as 0.2–0.3°C. The hypothalamus is considered to be the control center for normal thermoregulatory processes, and its activity can be modified by a small local temperature increase under conditions in which rectal temperature remains constant. At levels of absorbed electromagnetic energy that cause body temperature rises in excess of 1–2°C, a large number of physiological effects have been characterized in studies with cellular and animal systems.

These effects include alterations in neural and neuromuscular functions; increased bloodbrain barrier permeability; ocular impairment (lens opacities and corneal abnormalities); stress-associated changes in the immune system; hematological changes; reproductive changes; teratogenicity; and changes in cell morphology, water and electrolyte content, and membrane functions. Under conditions of partial-body exposure to intense EMF, significant thermal damage can occur in sensitive tissues such as the eye and the testis.

There has been considerable recent interest in the possible carcinogenic effects of exposure to microwave fields with frequencies in the range of widely used communications systems, including hand-held mobile telephones and base transmitters. Briefly, there are many reports suggesting that microwave fields are not mutagenic, and exposure to these fields is therefore unlikely to initiate carcinogenesis. By contrast, some recent reports suggest that exposure of rodents to microwave fields at SAR levels of the order of 1 W/kg may produce strand breaks in the DNA of testis and brain tissues.

In a large study of rats exposed to microwaves for up to 25 mo, an excess of primary malignancies was noted in exposed rats relative to controls. However, the incidence of benign tumors did not differ between the groups, and no specific type of tumor was more prevalent in the exposed group than in stock rats of the same strain maintained under similar specificpathogen-free conditions. Taken as a whole, the results of this study cannot be interpreted as indicating a tumor-initiating effect of microwave fields.

Recent studies using athermal levels of microwave irradiation have found no effects on the development of melanoma in mice or of brain glioma in rats.

Further study is needed to determine whether the results can be found in other animal models in order to be able to generalize the results to humans. It is also essential to assess whether results found in transgenic animals are applicable to humans.

CHAPTER 2. OBJECTIVES

2.1. First thoughts

When I decided exactly which topic would be interesting to develop in a project, I thought that I would like to do something related to the effects of the electromagnetic fields on the human body. Technologies are improving at a vertiginous speed, and every time faster. We are not conscious of how all these technologies are going to affect to our living rhythm or much more important, to our health. It's because of that I decided to work in a field that I found useful.

I had no any idea of which measures were being taken so I had to move. Asking, searching and being perseverant I found that SAR was the most representative parameter of what I wanted, and the most studied.

Luckily I found a person who did a project and he told me that I could improve the results of the project by solving some problems that they had found.

2.2. This Project

In this project we will work on computational models of a vehicle with a human body inside. The program used for the simulations is LC of *Cray Inc.*.

2.2.1. LC

LC was developed as a simulation tool for the analysis of the electromagnetic properties of high speed electrical interconnects. A full three-dimensional circuit is modeled, so all interactions are automatically included in the solution. The model can be excited by numerous types of waveforms, and the transient response measured using common values such as voltage and current. Circuit parameters such as inductance, capacitance, and impedance can be derived from the transient response, and frequency-domain results such as S-parameters can also be calculated. Far field radiation patterns can be obtained.

LC is primarily an electromagnetic simulation and uses the Finite-Difference Time-Domain (FDTD) technique. FDTD is a full wave explicit solution of Maxwell's equations in three dimensions. In FDTD, the rectangular volume enclosing the model is discretized into a large number of small cells, which may be uniformly-sized, or may vary in size within the simulation space. The dielectric, permeable, loss and conducting material properties of each cell are incorporated into the field updates, which are performed iteratively in small time steps.

Background

Currently a model of transportation vehicle with a human body inside has been developed within the "Grup de Compatibilitat Electromagnetica (GCEM), DEE-UPC". LC is used to obtain the fields inside the vehicle for different sources. Some preliminary estimation of power deposition (SAR) has also been

performed. LC does not provide SAR calculation, so information about electromagnetic fields and geometry must be exported and the SAR computation produced elsewhere. Currently, Matlab is used for this task.

There are mainly three issues that must be solved in order to have a significant SAR estimation:

2.2.2. First point

Currently only information about 3 planes, representing the most important parts (or the most sensible) of the body, are obtained: the brain, the heart and the genitals.

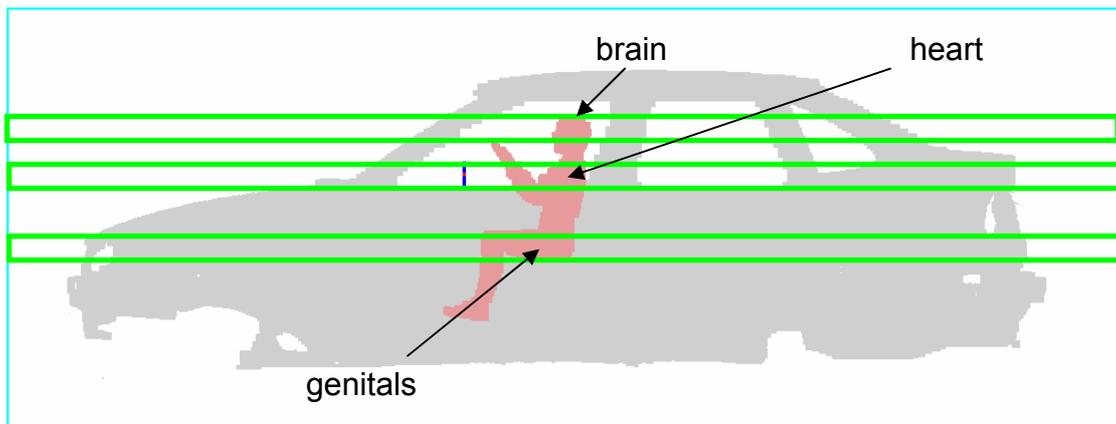


Fig. 1 Human body on a vehicle with three probe planes

In order to find the maximum SAR values and produce significant averages as specified by the standards, calculation must be performed over the whole human body model

2.2.3. Second point

The FDTD method obtains field components that do not refer to the same spatial position: different components are referred to the mid-point of the simulation cell sides. So combining the three field components to obtain the absolute value of the field is not correct.

This fact is especially important for cells that are in contact with different materials. When there are cells of air in contact with cells of human tissue this calculus is an average of the two cells. The air has a much higher electric field value than the human tissue, and this produces large errors in the computation of SAR value, unless these cells are treated manually.

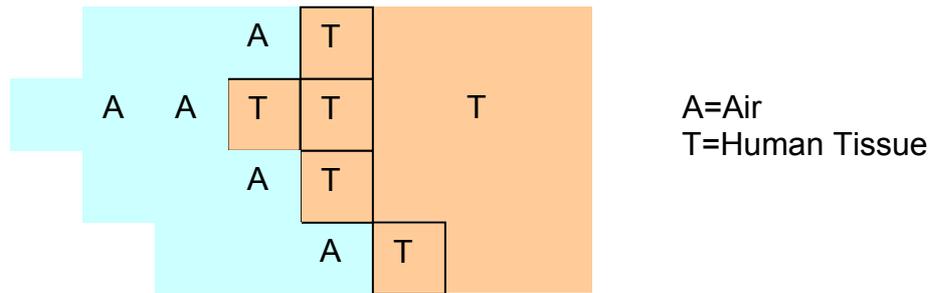


Fig. 2 Air cells in contact with human tissue cells

This can be solved by centering the electric field components and refer them to the centre of the simulation cell using what is known as the “twelve components” approach.

2.2.4. Third point

By using the approach above a correct SAR estimation in a simulation cell can be obtained. Because of modeling requirements, cell sizes of about 3 x 3 x 3 mm are currently used. However, international standards specify SAR values averaged over 1 g or 10 g of tissue. These volumes are much larger than the simulation cell used, so different cells must be combined and averaged to obtain values that can be compared to guidelines. Because the 1g or 10 g volumes do not need to be regularly shaped (i.e. cubic or oblong), specific algorithms have been developed in the scientific community to perform this average and find the maximum value of SAR.

CHAPTER 3. INTRODUCTION TO THE FDTD METHOD

3.1. Description of the behavior of the method

The FDTD method belongs to the group of numeric modeled differential methods which work in the time domain. Basically its behavior is: the equations in Maxwell's differential form expressed in Cartesian coordinates are transformed into equations of central differences, then they are distributed in a three-dimensional mesh and they are implemented on an algorithm to do simulations with the designed models. The solution to the equations is found through a leap-frog algorithm, where the electric field value is found in a determinate time step; as follows, with the electric field value found, the magnetic field value in the next time step, repeating this process the field value for all the points in the simulation space. This it is shown in the Fig. 3, where the electric and the magnetic field values are obtained in a time-step way. This process is performed in a number of time-steps chosen by us, in function of the time necessities we require.

Examining the Maxwell's equations in a differential form:

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} - \frac{1}{\mu} (\vec{M}_{font} + \sigma^* \vec{H})$$

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon} \nabla \times \vec{H} - \frac{1}{\varepsilon} (\vec{J}_{font} + \sigma \vec{E})$$

We observed that the time derivate of the electric field, E, depends on the rotational of the magnetic field, H. So we can say that a change in the electric field, indicated by the time derivate, depends on the changes that the magnetic field suffers in space, indicated by the rotational. From here the basic FDTD equation is extracted, the new electric field value depends on its previous value and on the difference between both magnetic field values, next to the point where the electric field is calculated and before. This fact is also shown in Fig. 1, because the electric and magnetic field values are placed following this special separation which implicitly marks the rotational.

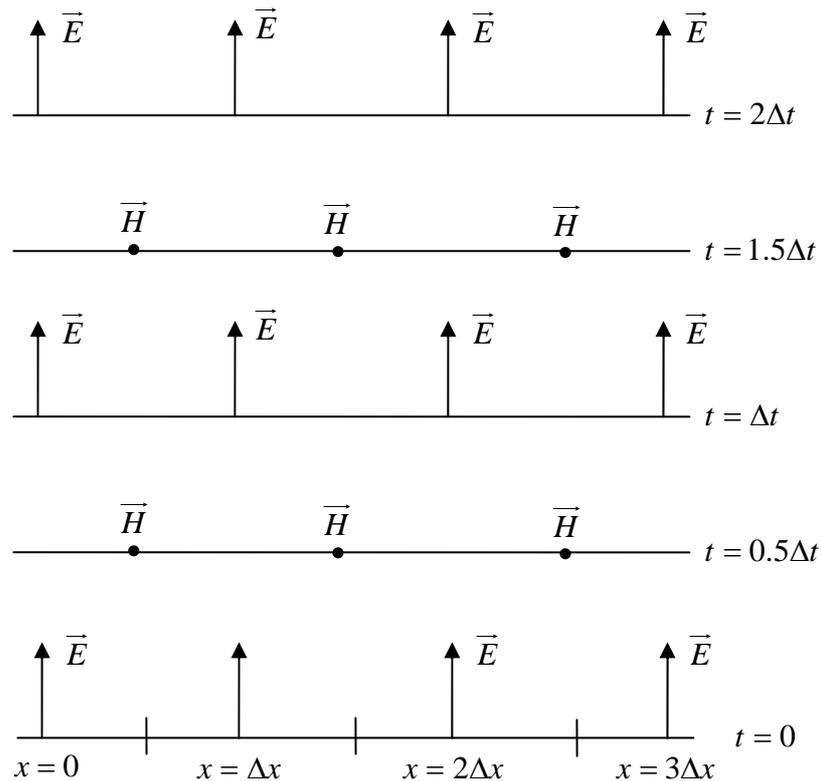


Fig. 3 “Leap-Frog” behavior for the time derivatives of the FDTD algorithm

The magnetic field is calculated in the same way. From the previous value and with the electric field values of the surrounded points, the magnetic field is found.

This description is as valuable for one dimension as for two and three dimension problems. The difference resides in that in the case of multiple dimensions is necessary to consider the difference in the space in all the correspondent directions.

To use the FDTD method it is necessary to establish a computational domain or a simulation space. The electric and magnetic fields are calculated for every point in these simulation spaces. It is also necessary to define the material in every point of the domain. FDTD allows us to use any material if we are able to determinate its permeability, permittivity and its conductivity. Finally it is necessary to add an excited source to the model, being able to model it as an incident plane wave, as a current in a cable or as an electric field between two metallic plaques where a voltage difference is created.

3.2. Why use FDTD

The reasons of the great interest produced by the FDTD method are many; but the most important one is that FDTD doesn't use linear algebra. FDTD avoids the difficulties that linear algebra carries, like the limitation of the models size that use integral equation and finite frequency domain elements.

Another advantage of the FDTD is that it deals with the impulsive behavior naturally; this is because it works on the time domain, and it allows FDTD to calculate the impulsional answer of an electromagnetic system. This way it is possible to obtain wave forms in time in a big frequency range as well as the answer in stationary regime in a determinate frequency, just with a simulation. For the same reason FDTD is able to calculate directly the nonlinear answer.

FDTD is also good because it allows a systematic design where the definition of a new model is done with the generation of the mesh and it doesn't suppose a complex process of reformulation of an integral equation for each model.

Moreover, in FDTD is embarrassing parallel and E and H are not referred to the same point, this allows to work on the processing in parallel.

Even with all these advantages FDTD has a great problem. As the discretization of the volume is done in little cells (smaller than the smaller wavelength of the model) it requires a great memory capacity, but despite this we have the positive aspect that the computers capacity grows really fast.

Another aspect related to the computers growing is that FDTD finds the electric and magnetic fields in all the points of the simulation space, it allows to create animations of these fields propagation through the computational domain. As the graphic capacity of the computers is growing fast FDTD is benefited in representing videos in color with a great amount of data.

In contrast with all these characteristics we have another method called FEM that divides the model in triangular forms. Because of this the method is much more exact, but a problem appears when using it. What we get is a matrix of a great amount of equations and incognitos. The equations we must choose depend on which parameter we want to calculate.

FDTD uses the Maxwell equations to get its results, so there's no problem choosing the equation neither having lots of equations.

CHAPTER 4: 1ST OBJECTIVE: SAR EVALUATION ON THE OVERALL VOLUME

LC computes fields (E, H) for all cells in the model. However for the sake of disk space preservation only results for the specified “probes” are saved... Probes can take the form of a point, a line or a plane. But despite having probe planes, LC calculates E and H for the whole body. Our goal is to find the file were LC save **all** E, H results and to learn how to read them.

4.1. File extensions

LC uses a lot of different files. To understand the behavior of the program and to solve the 1st objective I studied all the files and analyzed their structure.

4.1.1. BYU file

This file is the

The two first lines of the file give information about the number of values that there are next to them. They always have the same structure:

```
1 2500 2401 9604
1 2401
```

The first value of the header is always ‘1’, there’s nothing relevant to it. The second number (2500) shows the number of points that the plane that we want to read has. The third number (2401) shows the number of nodes the plane has, which is the last group of numbers in the file. Finally the last number (9604) indicates the amount of nodes that are described in its list. It has the next structure:

```
1 2 52 -51 2 3 53 -52 3 4
54 -53 4 5 55 -54 5 6 56 -55
6 7 57 -56 7 8 58 -57 8 9
59 -58 9 10 60 -59 10 11 61 -60
11 12 62 -61 12 13 63 -62 13 14
64 -63 14 15 65 -64 15 16 66 -65
```

The most useful part of the file is the part between the header and the node list, the coordinate list of every point in the plane. This information is represented this way:

```
0.00000E+00 5.00000E+01 5.00000E+00 0.00000E+00 5.00000E+01 1.00000E+01
0.00000E+00 5.00000E+01 1.50000E+01 0.00000E+00 5.00000E+01 2.00000E+01
0.00000E+00 5.00000E+01 2.50000E+01 0.00000E+00 5.00000E+01 3.00000E+01
```

```

0.00000E+00 5.00000E+01 3.50000E+01 0.00000E+00 5.00000E+01 4.00000E+01
0.00000E+00 5.00000E+01 4.50000E+01 0.00000E+00 5.00000E+01 5.00000E+01
0.00000E+00 5.00000E+01 5.50000E+01 0.00000E+00 5.00000E+01 6.00000E+01
0.00000E+00 5.00000E+01 6.50000E+01 0.00000E+00 5.00000E+01 7.00000E+01
0.00000E+00 5.00000E+01 7.50000E+01 0.00000E+00 5.00000E+01 8.00000E+01

```

Every line is formed by six values, which represent two different coordinates. The three first values refer to the x, y, z component of the first point in the plane and the next three numbers the same but for the following point, the rest of the lines have the same format. The number of coordinates listed is the one indicated in the header; in this case we will find 2500 groups of three values. The order the points are listed depends of the plane orientation; in this case we fixed 'y' and varies first 'x' and then 'z'.

4.1.2. LCX file

The LCX file format is a text file format that describes an LC model. It is both written and read as a native model file format by LC.

The file is structured as a sequential collection of segments, and each segment is composed as a set of records. Different segment types are used to store different types of model data. Generally only one segment of a particular type is present in a file, but it's also possible to have duplication. Each segment is introduced by a unique keyword.

The file header segment must be the first in the file. The other segments may come in any order. For the list segments, omission indicates that there are no items in the list. For parameter segments, omission indicates that the default parameters should be used. As follows the segment types are listed, the keyword indicates the first line of each segment to identify which of them is:

Segment Type	Keyword	Usage	Definition
File header	LCX	Mandatory	The file header segment serves to identify the LCX file type and provide some information about its origin
Material list	materials	Optional	The material list segment provides a list of the materials which are defined in the model. Each geometry block of the model is composed of one of the materials defined in the material list segment.
Block list	blocks	Optional	The block list segment contains the blocks of geometry which defines the material composition of the model space, plus block

			definitions for source excitation, loads, and probes to monitor and record the simulation results.
Dialog list	dialogs	Optional	The purpose of the dialog list segment is to save the user's preferred layout of the dialogs on the display. When a dialog is displayed, this list is examined to see if the user has saved a preferred dialog layout. If so, then that layout is used. If none is defined, then the default layout is used.
Pulse list	pulses	Optional	Pulses given in the pulse list segment define a grouping of probes which may be windowed in time. This mapping provides an easy conversion from raw probe values into circuit parameters such as inductance and capacitance. It also provides the information required to convert the time domain probe results into the frequency domain.
Sweep list	sweeps	Optional	Sweeps record simulation results like probe blocks, but do not have a model region associated with them, like probe blocks. Sweeps are conceptually in the far field region, an arbitrarily large distance from the model. Sweeps use an on-the-fly discrete fourier transform to record the results in the frequency domain.
Calculation list	calculations	Optional	Calculations can combine probe results with algebraic operators. The result of a calculation is similar to a probe, and thus many of the

			calculation parameters are identical to the probe parameters.
Multiport list	multiports	Optional	Multiport loads connect an electromagnetic simulation to a SPICE circuit. Any number of nodes of the SPICE circuit can be patched into arbitrary regions of the model space by associating port blocks with the multiport load.
Plane Wave Source list	planes	Optional	A list of any number of plane wave source definitions can appear between the planes and end records. Each list item has the follow format.
Model parameters	model_parameters	Optional	The model parameters are values which affect the overall model interpretation.
Mesh parameters	mesh_parameters	Optional	The mesh parameters affect the overall model simulation.
Plot parameters	plot_parameters	Optional	The plot parameters establish default values for the evaluation of pulses during post-processing.
Sequence parameters	seq_parameters	Optional	Sequence numbers are used as a quick look up for automatically naming blocks. These values are used as an aid during automatic block naming, but are not required by the naming algorithm within LC.
Far field parameters	far_parameters	Optional	The far field parameters define a set of frequencies of interest. Far field data is accumulated for these frequencies during a simulation run.

4.1.3. OUT file

In this file the values measured for the probe are saved. An OUT file is created for every time step; they all have the same structure. The information is represented in lines of six values of the correspondent magnitude. It is important to clearly understand to which point in the plane each value refers to. This depends on the orientation taken by the plane. Whichever the orientation is, the values are listed varying first the 'x', then 'y' and then 'z' (actually only two of the three coordinates varies, the fixed coordinate does not change).

In a file with 'y' orientation the first point will be (x,y,z), the next value will be (x+ Δ x,y,z), where Δ x is the cell size in the y-edge, the next in (x+2 Δ x,y,z) and the same successively until we reach the maximum value of the plane in the edge. The next point would be (x,y,z+ Δ z), and the next (x+ Δ x,y,z+ Δ z) until we arrive to the end of the y-edge, repeating this sequence until we reach the end of the z and y-edge.

An example of an OUT file is:

```
1.14008E-07 8.56238E-01 1.73002E+00 2.64563E+00 3.65873E+00 4.89380E+00
6.66285E+00 9.86347E+00 1.74082E+01 4.02269E+01 4.01080E+01 1.86103E+01
1.21909E+01 1.00006E+01 9.14231E+00 8.72536E+00 8.43616E+00 8.15948E+00
7.85907E+00 7.53345E+00 7.19672E+00 6.87172E+00 6.58497E+00 6.35736E+00
6.21027E+00 6.15976E+00 6.21293E+00 6.37107E+00 6.62778E+00 6.97014E+00
7.38027E+00 7.83080E+00 8.29714E+00 8.74933E+00 9.15691E+00 9.49182E+00
9.72833E+00 9.84351E+00 9.81676E+00 9.63591E+00 9.29069E+00 8.78051E+00
```

4.2. Resolution of the 1st objective

LC makes a mesh of the whole model before initializing calculations, and as follows calculates the magnitude (in our case electric field) for the whole body. But none of the described files contains the results for all the body. The most approximate is the .OUT file, and it contains results just for the specified probes. Simulating we discovered a file that occupies a lot of space. It is the .CHK file. The .CHK files are a dumped memory of a certain program that needs to keep some computational information to be able to recover the last session without any problem. In the case of LC, the .CHK is not referred to any other readable extension. It is shown as binary data only recognizable by the LC program. Summarizing, we can't take all the model distributed information because we are unable to read this data; we can only get the FDTD calculations by introducing probe planes.

An easy way to do this heavy work is to generate an algorithm which modifies the problem description file (.lcx) file writing in the block list all the probe planes covering the entire model.

In the block list there are four different block types:

- Geometry blocks: Geometry blocks define the material parameters within the model space. During a simulation, these blocks are broken down into cells, and each cell takes on the material parameters of its parent block.
- Load blocks: Load blocks create simple single port loads within the model space.
- Probe blocks: Probe blocks monitor the electromagnetic field values during a simulation. The results can be displayed or saved for later analysis.
- Source blocks: Source blocks provide excitation for the model during the simulation.

The Probe blocks are described as block_type_3 and they have the next parameters (The parameter Value is the one that we chose to create the planes we want):

Keyword	Parameter	Description	Value
block_type	integer	The probe block data type (3).	block_type_3
name	string	The name of the probe.	Plain** (** two digits number that varies)
color	integer	Color of the probe.	25 (green)
fill_pattern	integer	Transparency of the probe.	7
visible	integer	If non-zero, then the probe is visible	1
min	coordinate	A list of three floating point values which define the minimum coordinate of the block bounding box.	It is searched by the program.
max	coordinate	A list of three floating point values which define the maximum coordinate of the block bounding box.	It is searched by the program.
output_type	integer	The probe output type of the probe.	1
component	integer	The component type of the vector field output. Applicable for electric or magnetic field intensity, current density, or power density output types.	1
value_type	integer	The value type of the probe.	2
form_type	integer	The form type of the probe.	3 (Plane)
Orientation	string	The alignment direction for a line or plane probe.	1, 2 or 3 (X,Y or Z))
Save_output	integer	If non-zero, then the probe output is saved to a file or set of files as the simulation runs.	1
Filename	string	The output file name, or output file name pattern.	Plain** (** two digits

			number that varies)
time_factor	integer	The number of time steps to run the simulation before calculating a new probe value. The default value of 0 indicates that the probe should be calculated for every time step.	4
End	"probe"	Keyword marking the end of the item.	

The function that contains the entire algorithm is named: "full_probe.m" (see Annex).

This function opens the .lcx file of interest and fills another .lcx file with the same name but finishing in '_' which is filled with all the additional information. First it copies all the information, first the probe block type while at the same time it finds the model limits and the cell size for the three directions. Then it fills the file, next to the previous information, with probe planes in all directions and for the whole body. And finally it fills the file with the information after the probe block type.

To test our function we generated a simple model simulating a head with a cell phone irradiating next to it:

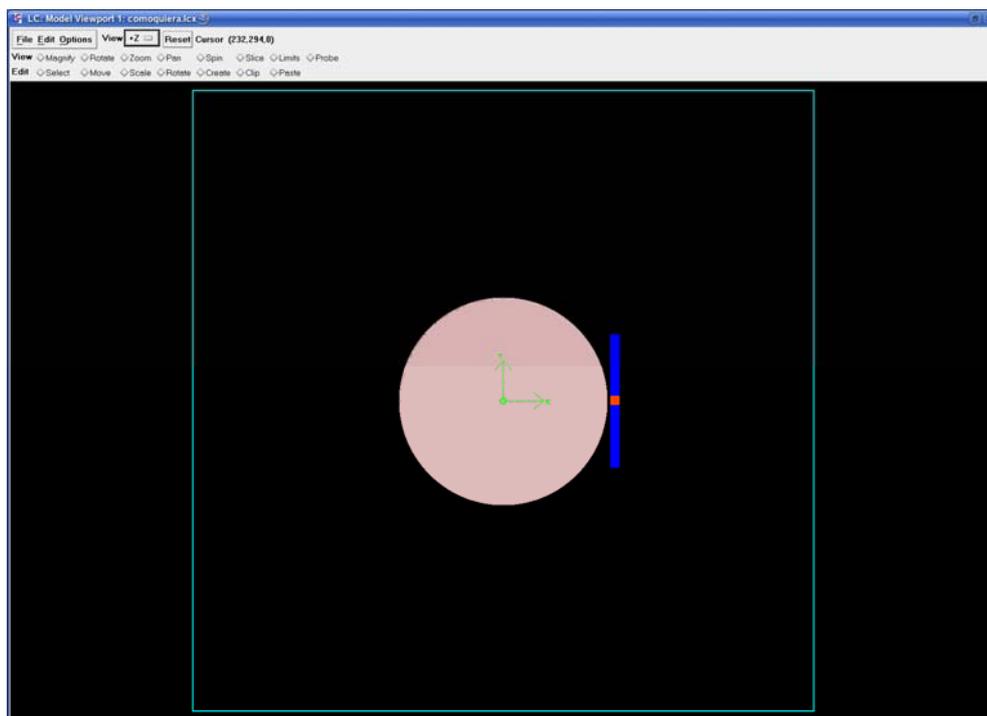


Fig. 4 Testing LC model viewport

And in three dimensions:

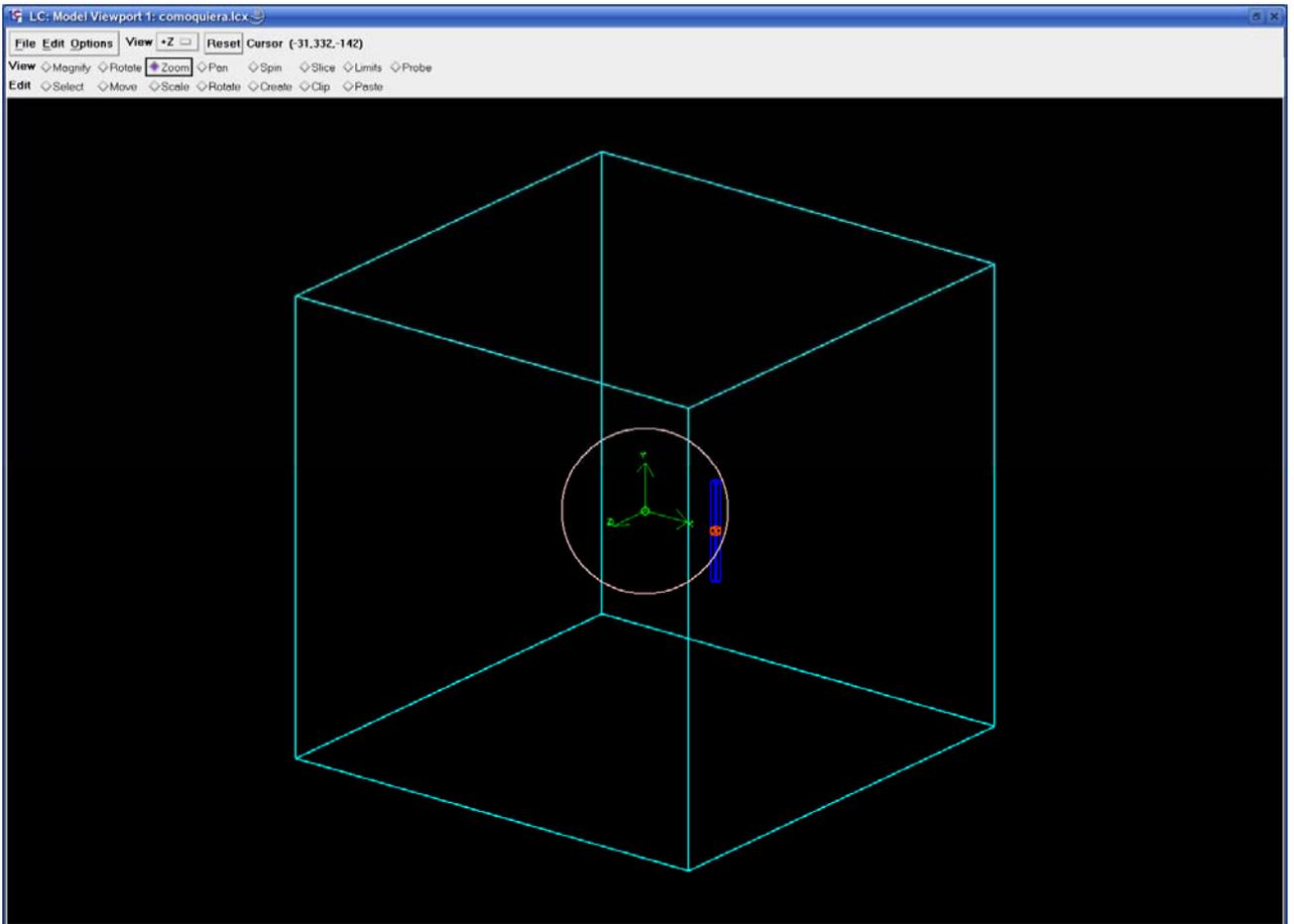


Fig. 5 Testing LC 3D model viewport

Once we saved the file as 'testingfile.lcx' we created a blank 'testingfile_.lcx' where we will have the same model but filled with probe planes. We execute our function on Matlab by introducing:

```
full_probe('testingfile.lcx');
```

The 'testingfile_.lcx' will be filled and we are able to open it with LC. If we open it we obtain a block list of our main elements and lots of probe planes for all directions:

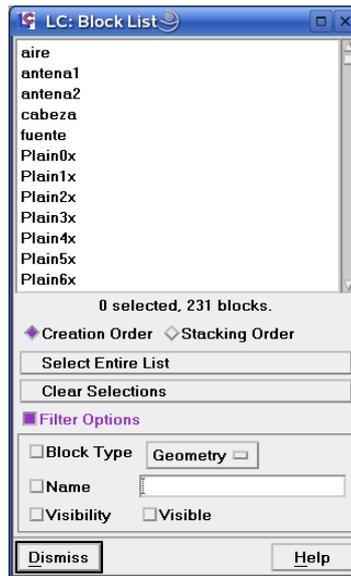


Fig. 6 Block list

And the testing LC model viewport fills up with planes:

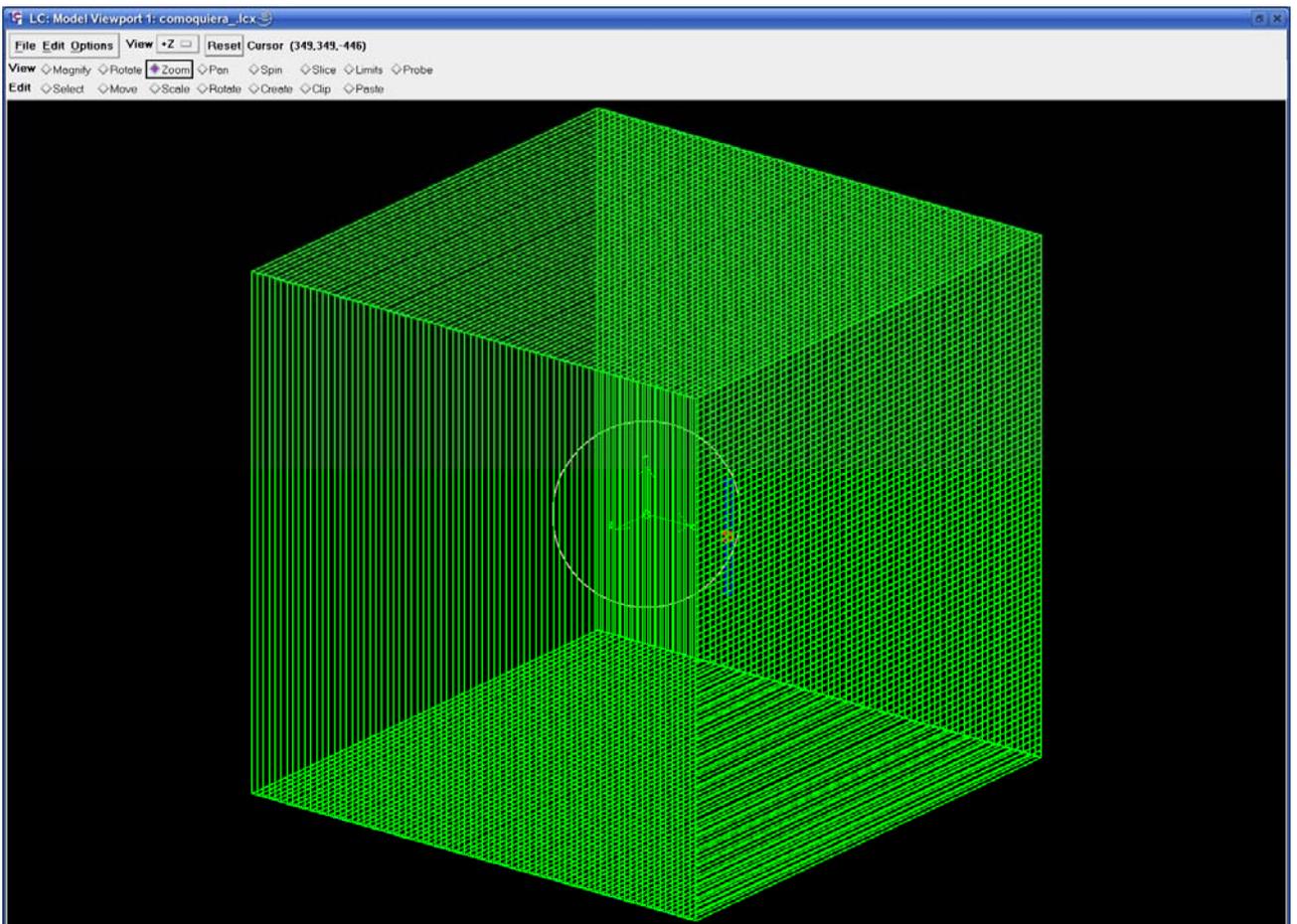


Fig. 7 Testing LC 3D model viewport filled with planes

This way we finish the first objective.

CHAPTER 5: 2ND OBJECTIVE: CENTERING E USING THE TWELVE-COMPONENTS APPROACH

5.1. What the twelve-components approach is

The electromagnetic field calculated by LC for each cell (i,j,k) is defined by the position of its components in FDTD. They are referred in the middle of the arista that connects a cell with the next one:

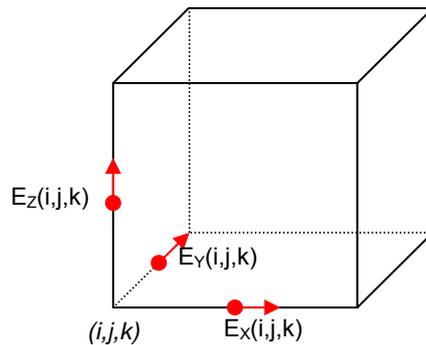


Fig. 8 Placement of the electromagnetic field using just FDTD

LC uses the three-component method to assume an electromagnetic field with its components in the same point, but with this method the combination of the three different components in the middle of the cell to obtain the absolute value is not correct.

A better method is the six-component method. It consists in calculating every component with the two adjacent ones and referring the result to the vertex of the cube:

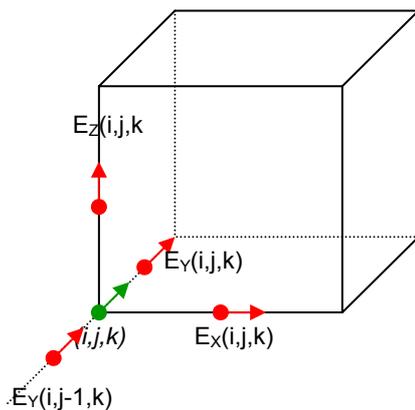


Fig. 9 Six-component for Y

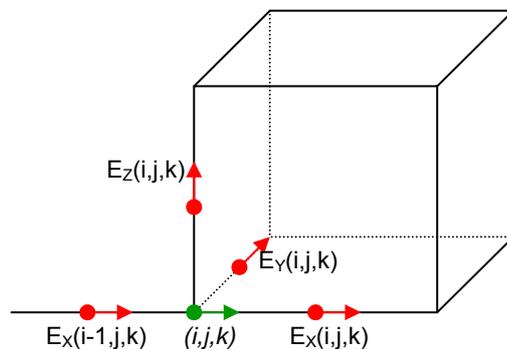


Fig. 10 Six-component for X

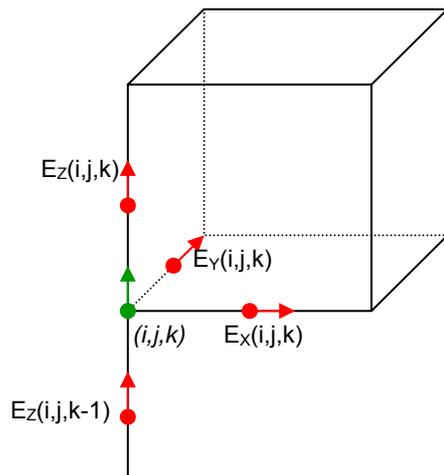


Fig. 11 Six-component for Z

$$E'_y(i, j, k) = \frac{E_y(i, j, k) + E_y(i, j - 1, k)}{2}$$

This method is better than the before one, but the final field is not referred to the “center” of the cube, it is referred for a vertex.

Finally, in the twelve-component method, the field refers to the middle of the cell, averaging the values of the components correspondent to the ones surrounding the cell:

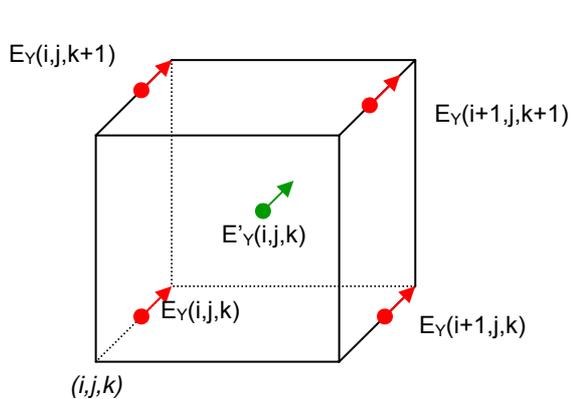


Fig. 12 twelve-component for Y

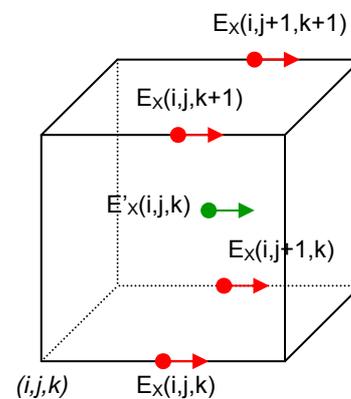


Fig. 13 twelve-component for X

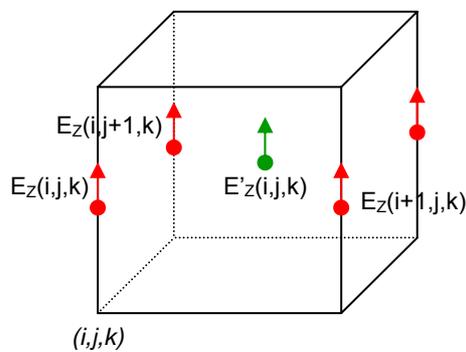


Fig. 14 twelve-component for Z

The averaging used is the following one:

$$E'_z(i, j, k) = \frac{E_z(i, j, k) + E_z(i, j + 1, k) + E_z(i + 1, j, k) + E_z(i + 1, j + 1, k)}{4}$$

5.2. Resolution of the 2nd objective

To implement the twelve-component algorithm I obtained the electric field values for a model. Those values are contained in the .OUT files, as I explained in 4.1.3. There will be many .OUT files for a single simulation.

The first thing that the function does is reunite all the data on a vector and then it applies the twelve-component algorithm (See Annex).

To use the function we have to give the limits of the three coordinates, this information can be taken from the function of the previous objective. We also have to indicate the name of the last and the second to last .OUT files. This is because we have to define a time sweep that obtained that every .OUT file is displaced 90° and using these two we have that:

$$\left. \begin{aligned} E_1 &= A \cdot \sin(\omega t + \varphi) \\ E_2 &= A \cdot \sin(\omega t + \varphi + 90^\circ) = A \cdot \cos(\omega t + \varphi) \end{aligned} \right\}$$

And if we add E_1 and E_2 squared:

$$(E_1 + E_2)^2 = A^2 \cdot (\sin^2(\omega t + \varphi) + \cos^2(\omega t + \varphi)) = A^2$$

We can obtain the amplitude of the electric field in every cell.

To call the function we have to type:

```
twelvecomp(xx,yy,zz,'Plain049.out','Plain050.out')
```

Where xx, yy, zz are the limits.

After saving all the cell's amplitudes on a vector, the twelve-component method is used, and the SAR is calculated for each material.

We did the simulation of the same model (Fig. 5) of the 1st objective for just a plane, and we got its .OUT files. Then we used our function and we obtained the SAR distribution without the twelve-component method:

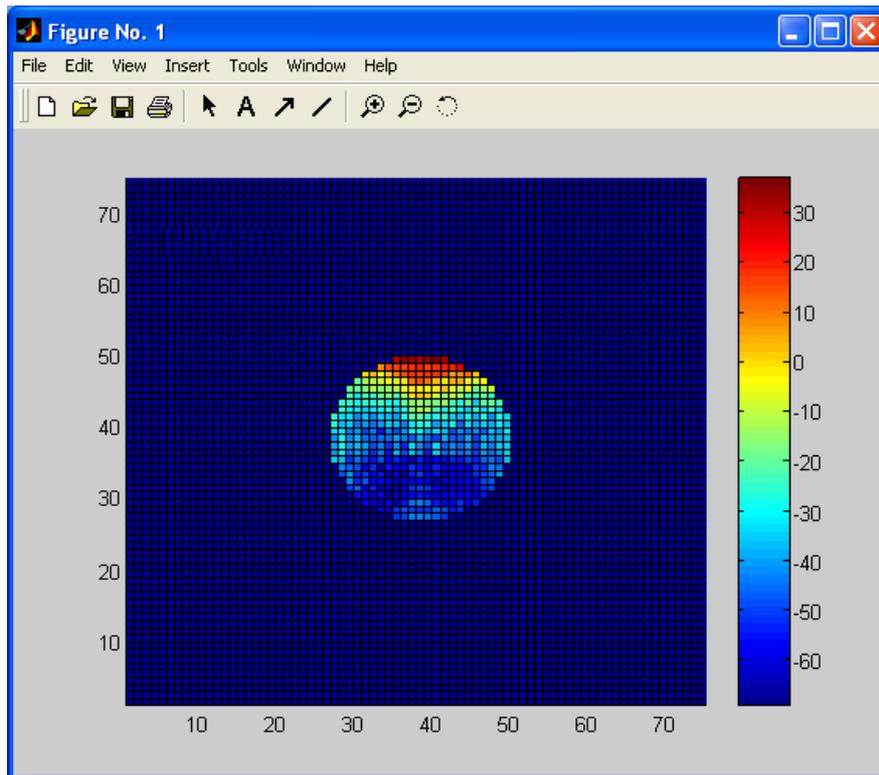


Fig. 15 SAR distribution in dBs

And the same diagram using the twelve-component method:

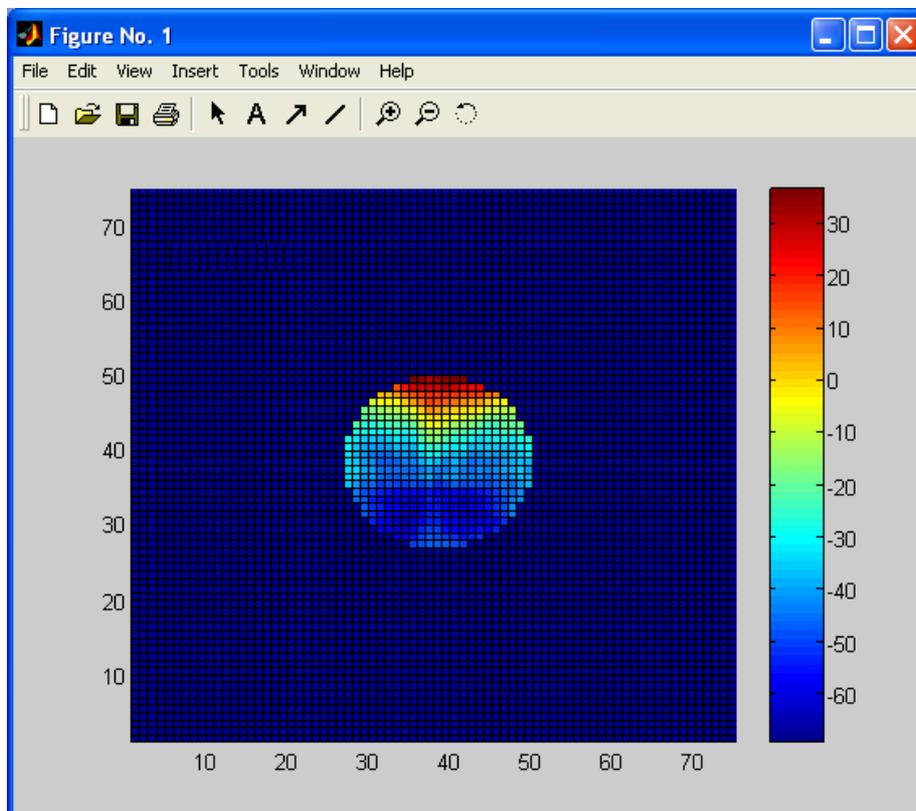


Fig. 16 SAR distribution in dBs using the twelve-component method

The reason why a dBs scale is used is because of a representation issue. If we had plotted our data in a linear scale the difference between the higher point and the near ones would be enormous. Matlab would paint the pale blue points in blue like the air and this way we wouldn't be able to see the propagation of the wave through the sphere of tissue.

CHAPTER 6: CONCLUSIONS

SAR is a great reference to avoid the negative effects of the electromagnetic field (EMF) in the human body. Our EM sources should be tested to accomplish the reference levels. To realize this testing we should material with the greater grade of precision and accuracy.

LC is a really powerful program, but there are some improvements that would help measuring SAR.

If we want to obtain the SAR distribution for a whole model we have to think that the computational cost will be really big and, as I said of FDTD, this would be a problem if we didn't have the positive aspect that the computers capacity grows really fast.

Using the twelve-component method we have solved the problem on which in some points of a human body strange results appeared. This averaging eases the wave propagation diagram showing a perfectly correct representation.

A great study of the LC file format has been necessary to elaborate this project, the complexity and the massive information complicated its study. An improvement on my EMF knowledge has been got as well as my Matlab programming language level. But I think that the most important think has been accomplished my primary objective of working and understanding the SAR measures and its repercussions.

THANKFULLNESS

I want to thank my parents for supporting me all these years.

I want to thank Micke Vachery for correcting my English and Ricardo for helping me so much in the bioengineering and instrumentation laboratory.

Finally I want to thank to Javier Ozón for sending me to Óscar Casas, to Óscar Casas for sending me to Marcos Quílez, and lots of thanks to Marcos Quílez for sending me to Pere Riu and helping with all the management in the EPSC, and to Pere J. Riu for giving me the opportunity of working on this field and under his direction.

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ANNEX

Full_probe function

```

function y=full_probe(LCX)
%This program fills an LC model with probe plains
%y=full_probe(LCX)
%Where LCX is the address of a .lcx file. It is necessary to have another
%file with the same name but finished by _

fid=fopen(LCX,'r');
LCX2=[LCX(1:length(LCX)-4),'_lcx'];
fid2=fopen(LCX2,'w');
sent=' ';
XX=0;
YY=0;
ZZ=0;
XX2=0;
YY2=0;
ZZ2=0;
resx=0;
resy=0;
resz=0;
[sent]=fgetl(fid);
if(fid==-1)
    disp('File does not exist')
else
    %It copies the part before the probes
    while(strcmp(sent,'block_type 3')~=1)%||(strcmp(sent,'block_type 4')~=1)
        %We obtain the limits of the evaluation model
        fprintf(fid2,'%s\n',sent);
        %The minimum
        if(strcmp(sent(1:3),'min')==1)
            if(sent(4)==' ')
                sent=sent(5:length(sent));
                [mm]=sscanf(sent,'%d');
                xx=mm(1);
                yy=mm(2);
                zz=mm(3);
                if(xx<XX)
                    XX=xx;
                end
                if(yy<YY)
                    YY=yy;
                end
                if(zz<ZZ)
                    ZZ=zz;
                end
            end
        end
    end
end

```

```

    end
end
%The maximum
if(strcmp(sent(1:3),'max')==1)
    if(sent(4)==' ')
        sent=sent(5:length(sent));
        [mm]=sscanf(sent,'%d');
        xx=mm(1);
        yy=mm(2);
        zz=mm(3);
        if(xx>XX2)
            XX2=xx;
        end
        if(yy>YY2)fprintf(fid2,'%s\n',sent);
            YY2=yy;
        end
        if(zz>ZZ2)
            ZZ2=zz;
        end
    end
end
end
[sent]=fgetl(fid);
end

% We obtain the cells size in all directions
whilefeof(fid)==0)
    [sent]=fgetl(fid);
    if(strcmp(sent(1:3),'cel')==1)
        if(strcmp(sent(4:7),'l_dx')==1)
            sent=sent(10:length(sent));
            resx=sscanf(sent,'%f')
        end
        if(strcmp(sent(4:7),'l_dy')==1)
            sent=sent(10:length(sent));
            resy=sscanf(sent,'%f')
        end
        if(strcmp(sent(4:7),'l_dz')==1)
            sent=sent(10:length(sent));
            resz=sscanf(sent,'%f')
        end
    end
end
end
fclose(fid);
fid=fopen(LCX,'r');
while(strcmp(sent,'block_type 3')~=1)
    [sent]=fgetl(fid);
end

%It fills the file with probe plains
%In the X direction

```

```

ii=0;
while(XX<XX2)
    fprintf(fid2,'block_type 3\n');
    fprintf(fid2,'name Plain%dx\n',ii);
    fprintf(fid2,'color 25\n');
    fprintf(fid2,'fill_pattern 7\n');
    fprintf(fid2,'visible 0\n');
    fprintf(fid2,'min %d %d %d\n',XX,YY,ZZ);
    XX=XX+resx;
    fprintf(fid2,'max %d %d %d\n',XX,YY2,ZZ2);
    fprintf(fid2,'output_type 1\n');
    fprintf(fid2,'component 1\n');
    fprintf(fid2,'value_type 2\n');
    fprintf(fid2,'form_type 3\n');
    fprintf(fid2,'orientation 1\n');
    fprintf(fid2,'save_output 1\n');
    fprintf(fid2,'filename Plain%dx\n',ii);
    fprintf(fid2,'time_factor 4\n');
    fprintf(fid2,'end probe\n');
    ii=ii+1;
end
%In the Y direction
ii=0;
while(YY<YY2)
    fprintf(fid2,'block_type 3\n');
    fprintf(fid2,'name Plain%dy\n',ii);
    fprintf(fid2,'color 25\n');
    fprintf(fid2,'fill_pattern 7\n');
    fprintf(fid2,'visible 0\n');
    fprintf(fid2,'min %d %d %d\n',XX,YY,ZZ);
    YY=YY+resy;
    fprintf(fid2,'max %d %d %d\n',XX2,YY,ZZ2);
    fprintf(fid2,'output_type 1\n');
    fprintf(fid2,'component 1\n');
    fprintf(fid2,'value_type 2\n');
    fprintf(fid2,'form_type 3\n');
    fprintf(fid2,'orientation 2\n');
    fprintf(fid2,'save_output 1\n');
    fprintf(fid2,'filename Plain%dy\n',ii);
    fprintf(fid2,'time_factor 4\n');
    fprintf(fid2,'end probe\n');
    ii=ii+1;
end
%In the Z direction
ii=0;
while(ZZ<ZZ2)
    fprintf(fid2,'block_type 3\n');
    fprintf(fid2,'name Plain%dz\n',ii);
    fprintf(fid2,'color 25\n');
    fprintf(fid2,'fill_pattern 7\n');

```

```

fprintf(fid2,'visible 0\n');
fprintf(fid2,'min %d %d %d\n',XX,YY,ZZ);
ZZ=ZZ+resz;
fprintf(fid2,'max %d %d %d\n',XX2,YY,ZZ2);
fprintf(fid2,'output_type 1\n');
fprintf(fid2,'component 1\n');
fprintf(fid2,'value_type 2\n');
fprintf(fid2,'form_type 3\n');
fprintf(fid2,'orientation 3\n');
fprintf(fid2,'save_output 1\n');
fprintf(fid2,'filename Plain%dz\n',ii);
fprintf(fid2,'time_factor 4\n');
fprintf(fid2,'end probe\n');
ii=ii+1;
end
XX
YY
ZZ
%Copies what's left in the LCX file on the LCX1 file
whilefeof(fid)==0)
    fprintf(fid2,'%s\n',sent);
    [sent]=fgetl(fid);
end
fprintf(fid2,'%s\n',sent);
fclose(fid);
fclose(fid2);
end

```

twelvecomp function

```

function y=twelvecomp(xx,yy,zz,OUT,OUT_)
%This function centers E on all the cells generated by the LC program,
%using the twelve components algorithm

%We apply the twelve-components algorithm finding the four E needed to
%calculate the centered E for each component

ii=1;
fid=fopen(OUT,'r');
kk=1;

%We save all the data of the last time step on a vector
whilefeof(fid)~=1)
    [sent]=fgetl(fid);
    if(length(sent)>11);
        sent1=sent(2:12);
        E(ii)=sscanf(sent1,'%f');
        ii=ii+1;
        if(length(sent)>23)

```

```

sent2=sent(14:24);
E(ii)=sscanf(sent2,'%f');
ii=ii+1;
if(length(sent)>35)
    sent3=sent(26:36);
    E(ii)=sscanf(sent3,'%f');
    ii=ii+1;
if(length(sent)>47)
    sent4=sent(38:48);
    E(ii)=sscanf(sent4,'%f');
    ii=ii+1;
if(length(sent)>59)
    sent5=sent(50:60);
    E(ii)=sscanf(sent5,'%f');
    ii=ii+1;
if(length(sent)>71)
    sent6=sent(62:72);
    E(ii)=sscanf(sent6,'%f');
    ii=ii+1;
end
end
end
end
end
end
end
end

ii=1;
fid=fopen(OUT_,'r');

```

% We save all the data of the 90° before timestep on a second vector

```

while(!feof(fid))
    [sent]=fgetl(fid);
    if(length(sent)>11);
        sent1=sent(2:12);
        E1(ii)=sscanf(sent1,'%f');
        ii=ii+1;
    if(length(sent)>23)
        sent2=sent(14:24);
        E1(ii)=sscanf(sent2,'%f');
        ii=ii+1;
    if(length(sent)>35)
        sent3=sent(26:36);
        E1(ii)=sscanf(sent3,'%f');
        ii=ii+1;
    if(length(sent)>47)
        sent4=sent(38:48);
        E1(ii)=sscanf(sent4,'%f');
        ii=ii+1;
    if(length(sent)>59)

```


%SAR is calculated for each material of the model

```
EE(1:75,1:75)=EE(1:75,1:75).^2;
```

```
SAR=EE;
```

```
SAR(1:26,1:75)=0;
```

```
SAR(27,1:34)=0;
```

```
SAR(27,42:75)=0;
```

```
SAR(28,1:32)=0;
```

```
SAR(28,44:75)=0;
```

```
SAR(29,1:30)=0;
```

```
SAR(29,46:75)=0;
```

```
SAR(30,1:29)=0;
```

```
SAR(30,47:75)=0;
```

```
SAR(31,1:28)=0;
```

```
SAR(31,48:75)=0;
```

```
SAR(32,1:28)=0;
```

```
SAR(32,48:75)=0;
```

```
SAR(33,1:27)=0;
```

```
SAR(33,49:75)=0;
```

```
SAR(34,1:27)=0;
```

```
SAR(34,49:75)=0;
```

```
SAR(35,1:26)=0;
```

```
SAR(35,50:75)=0;
```

```
SAR(36,1:26)=0;
```

```
SAR(36,50:75)=0;
```

```
SAR(37,1:26)=0;
```

```
SAR(37,50:75)=0;
```

```
SAR(38,1:26)=0;
```

```
SAR(38,50:75)=0;
```

```
SAR(39,1:26)=0;
```

```
SAR(39,50:75)=0;
```

```
SAR(40,1:26)=0;
```

```
SAR(40,50:75)=0;
```

```
SAR(41,1:26)=0;
```

```
SAR(41,50:75)=0;
```

```
SAR(42,1:27)=0;
```

```
SAR(42,49:75)=0;
```

```
SAR(43,1:27)=0;
```

```
SAR(43,49:75)=0;
```

```
SAR(44,1:28)=0;
```

```
SAR(44,48:75)=0;
```

```
SAR(45,1:28)=0;
```

```
SAR(45,48:75)=0;
```

```
SAR(46,1:29)=0;
```

```
SAR(46,47:75)=0;
```

```
SAR(47,1:30)=0;
```

```
SAR(47,46:75)=0;
```

```
SAR(48,1:32)=0;
```

```
SAR(48,44:75)=0;
```

```
SAR(49,1:34)=0;
```

SAR(49,42:75)=0;
SAR(50:75,1:75)=0;

$y=10*\log(\text{SAR}+1\text{E}-3)$;