POLITECNICO DI TORINO

Master's Degree in Electrical Engineering

Master's Degree Thesis

Contribution to the National Study on Population Exposure to Electromagnetic Fields

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Abstract

The master's thesis is in collaboration with ARPA (Regional Agency for the Protection of the Environment) of the region Valle d'Aosta (ARPA VdA). The thesis results will contribute to the national epidemiological study on the population's non-ionising electromagnetic (EM) fields exposure. The study is part of the "EMF research activity program" ("Programma di Attività e Ricerca CEM") on the initiative of the Italian Ministry of Environment and Energy Security. The program is divided into three activities A, B, and C, and the goals are to collect, process, and disseminate data to investigate the risks associated with exposure to low- and high-frequency EM fields. The analysis results in the formulation of EM field exposure indicators for Extremely Low Frequencies (ELF) and Radio Frequencies (RF) to contribute to the national study covering the other regions of Italy.

The thesis uses data from finite element method (FEM) simulations and measurements and performs data manipulation and interpretation in compliance with national laws.

The thesis focuses on the two main research topics associated with Activity A, described in the following. All these activities, conducted for the ARPA VdA, will merge into the national study, in coordination with all the regional ARPA agencies so that the results obtained for all regions can be harmonised and aggregated.

Framing the work and approaching the activities

The master's thesis first starts with a brief description of the ARPA which is the promoter of this master's thesis. Then to enter into the topics of the thesis, the analysis goes back to Maxwell's equations, and try to answer why for example the focus is on the electric field for the radio frequencies spectrum and why instead the attention is for the magnetic field in the extremely low frequencies domain. The demonstrations are followed by the analysis of current legislation, starting from international guidelines drafted in 1998 by ICNIRP (International Commission on Non-Ionizing Radiation Protection) that has been followed by European transposition and finally, by the firsts Italian laws on the topic in 2001. Then how the legislation went through updates in the following years, up to the last one for radio frequencies occurred and the end of 2023 that higher the quality objectives and the attention values to comply with the increasing demand of services. Before proceeding with the study there is one last chapter on the electromagnetic sources and how these fields are generated, both from antennas, providing services to users connected via mobile phones and from high voltage power lines whose purpose instead is to transmit power over long distances. At this point, the thesis is properly introduced and it dives into the core activities that will create the indicators for the national epidemiological study.

Electromagnetic field computation in residential buildings via FEA simulations and validation measures

This is the first activity of the EMF research program. Activities are ordered with letters, therefore this is Activity A, divided into radio frequencies, and extremely low frequencies.

Radio Frequencies (RF) exposure indicator

The propagation of electromagnetic waves from EM sources in the radio frequency spectrum (4G-5G, TV broadcast and radio antennas) on the environment is evaluated using the QGIS software for cartography and geometric aspects and the EmLAB software, for computing the radio frequency electromagnetic field analysis.
In this activity, the objective is to select the centroids of each residential building obtained by a combination of planimetry from the cadastre and the regional cartography. Then get the data like RF service providers' power absorptions of the radiating systems. This data will then be merged into a FEA simulation. Experimental validation of the results will also be conducted by measuring the actual field values in specific locations identified via the simulations. The aim of this activity is not to check compliance with exposure limits but to create an exposure indicator. Therefore, the partial results obtained in this project will be further elaborated and integrated by other environment agencies and ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) to perform a national scale evaluation of the population exposure to RF electromagnetic fields. Furthermore, the obtained data will be useful also for estimating the relation between simulated open field condition and actual conditions.

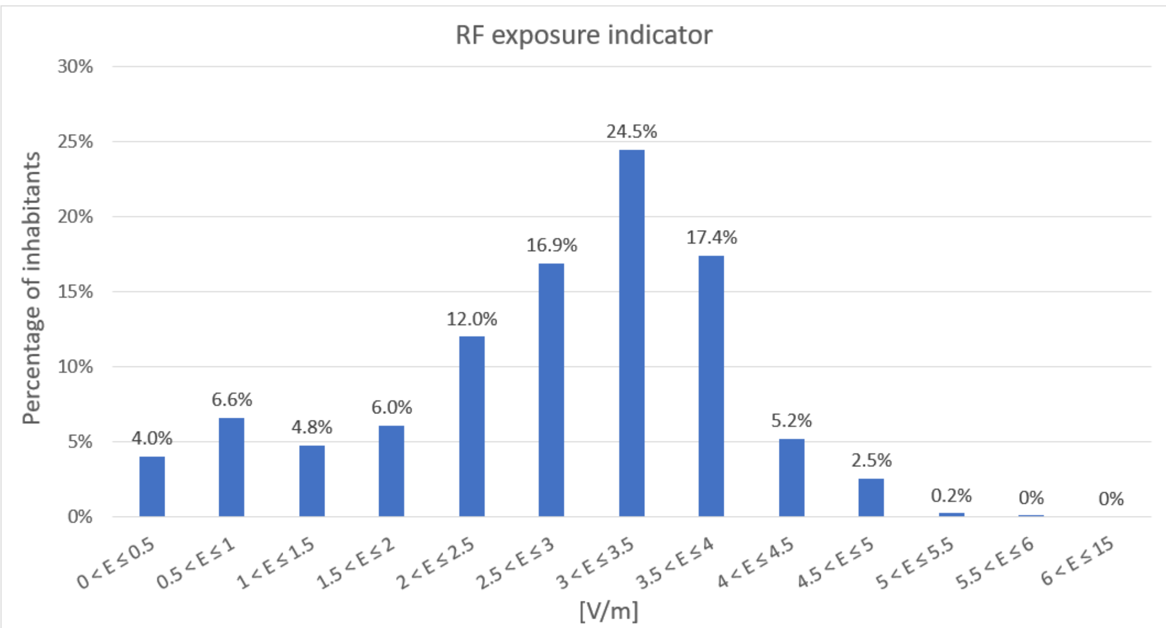

Figure 1: Histogram of the RF exposure indicator

Extremely Low Frequencies (ELF) exposure indicator

The second part concerns low-frequency fields produced by high-voltage electric power lines (50 Hz). Utilising experimental data obtained from Terna, the Italian transmission system operator (TSO), and combining them again with the cartography aspect in QGIS software, it is possible to create the second exposure indicator, differently from RF, in ELF the simulations are computed using the WinEDT software.
In particular, this activity will focus on residential buildings falling within a law-defined range of proximity to the high-voltage power line passing across Aosta and Sarre. Once again, the idea is to validate the simulations with measurement and extend the simulations to the entire power line, evaluating the magnetic field generated in the buildings' centroids. Results will be elaborated and presented with plots and shapefiles which indicate the citizens living close to the power line's overall exposure to the magnetic field. Also in this case the obtained exposure indicator will be analysed as a contribution to a national contest, when all the reports will be available the final version of the indicator will be realized on a national scale.

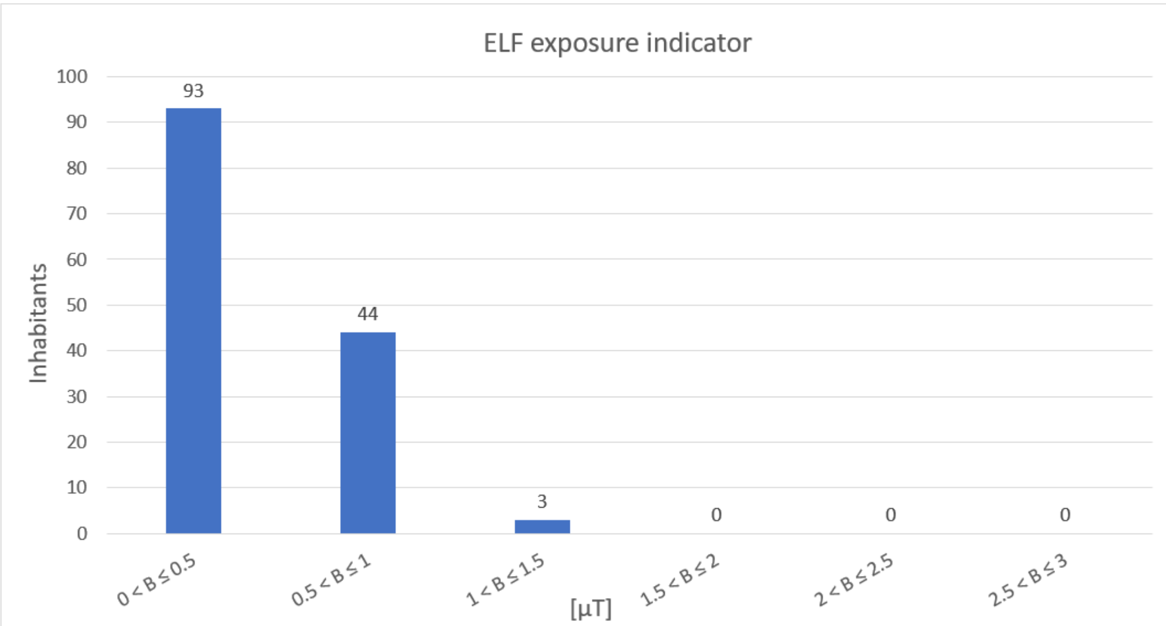

Figure 2: Histogram of the ELF exposure indicator

Dosimetry and personal exposure analysis to EMF

The second activity of the EMF research program is Activity B, and it is about determining the average exposure to electromagnetic fields of a person who is to be included in a statistical category. This entails the provision of a specific measurement instrument, designated as a dosimeter, to an individual for a period of 24 hours, during which time the individual is required to carry the dosimeter on a typical working day. The individual in question may be identified as a "high school student", "university student", "office worker", "working from home worker", or "on-field worker". According to the national subdivision, the data collected from all the ARPA will be aggregated by ISPRA (the Institute for Environmental Protection and Research that coordinates all the ARPA) to statistically define a daily average exposure for that category of workers. This is the initial stage of characterization for a study that may be further developed in the future with more detailed categorizations. The objective of this study is to ascertain whether a specific demographic is more susceptible to electromagnetic fields and, if so, to establish a foundation for future investigations into potential health consequences.

Focus on 5G signals measurements

Given that 5G is a relatively new technology, it must be monitored and, in particular, tests and measurements must be conducted. This, in a future vision, will help monitor this technology and set the basis for future investigations and monitoring of the electromagnetic fields. The purpose is to get confident with the change of paradigm and be updated in the sector to keep the role as guarantor of the population. This analysis, conducted primarily with the use of measurement instruments, will allow the monitoring of single services, differentiating from the previous activities where the field values were the result of broadband measures aggregating multiple services from different providers.

Results and individual contributions

The main goal of this project is to perform the required simulations according to correct assumptions and evaluate the data to obtain the required exposure indicators. According to Figure 1 and Figure 2, it is possible to see the histograms deriving from exposure indicators evaluation.
The personal contribution is to assist ARPA Valle d'Aosta in the study and deliver significant results, consistent with the ones collected in the other regions covered by this national study. The role of the ARPA is to protect citizens. Even if it was not the priority of the study, a check of the critical points that came out, was done as the ARPA is responsible for spotting it to the responsible (that could have been either Terna or the antenna operator). ARPA also has the power to approve new infrastructures, therefore the respect of limits is of interest and results are stored for future needs.
The future trend is towards adopting new technologies that will change the environmental and landscape setting, mainly of urban sites. The ongoing study will serve first hand as an assessment of the actual situation, and on the second hand as a guide to adopting low-impact technologies and strategical spatial planning to achieve a good compromise between the spread of impactful sources and environmental protection.
Another important result is acquiring the critical tools to analyse and manage a real situation. Unlike theory, in which the relations are rigorous and sometimes suffer from approximations to simplify analytical treatments, in reality, it is not possible to avoid critical aspects; it is, therefore, necessary to be able to reconcile theoretical aspects with the evidence of reality by investigating possible explanations and seeking feedback.

Acknowledgements

Before proceeding with the discussion, we feel it is our duty to dedicate this space of the paper to the people who contributed to make it possible.

First of all, we would like to thank our professor Aldo Canova who was able to guide us in our research, in the realization of the project and in the writing of the paper.

We are very much tankful to ARPA Valle d'Aosta for this unique opportunity. We have to thank in particular Valeria Bottura, Filippo Berlier, Erik Imperial, Leo Cerise, Simone Malacarne and all the other collegues for their amazing support, kindness and welcoming to us. We are honoured to have worked for you and with you, and the excellent outcomes of this thesis are the results of our synergetic cooperation.

We sincerely thank our families, specifically our parents for their support, backing and for their precious time; we both have one sister to thank, they were always supporting us and encouraging our decisions.

There are too many colleagues, friends and best friends we should thank, therefore we won't name them. They know how precious they were in difficult and tough moments, they are aware that the good memories we carry with us are mainly associated to them. We are glad to have shared these years with them.

Finally, we want to thank the Electric Engineering Department of the Politecnico di Torino and the Politecnico di Torino for the wealth of knowledge transferred to us over the years.

"Many thanks to all of you"
Danilo & Edoardo

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1. Introduction and Objectives

1.1 Introduction of the study

The rapid advancement of technology over the past few decades has led to an increase in human exposure to electromagnetic fields (EMFs) without any precedent. These fields, which are generated by many sources such as mobile phones, wireless communication networks, power lines, and household appliances, have become ubiquitous in modern society. While the benefits of these technologies are undeniable and tangible in everyday life, there is a growing concern about the potential health impacts of chronic EMF exposure on the population.
Epidemiological studies, exposure assessment studies and experimental carcinogenesis studies are the solution for understanding the potential health effects associated with EMF exposure. These studies aim to identify correlations and possible causative links between EMF exposure and various health outcomes by systematically collecting and analysing data from large groups of people. Previous research in this domain has produced mixed results, with some studies suggesting a possible association with adverse health effects such as cancer, neurodegenerative diseases, and reproductive issues, while others have found no significant risks.
This thesis aims to contribute to the ongoing scientific debate by participating in the EMF research programme focused on the exposure of the population to electromagnetic fields, produced by high-voltage power lines and radio frequency radiating systems. The study comprehends data collection, analysis and statistical methodologies to assess the levels of EMF exposure across different demographics and geographical regions. Given that attention values, quality objectives and exposure limits associated with EMF exposure, are determined by Italian laws, the thesis contextualizes and explains them; it shows how they have been established starting from international studies and guidelines.
The EMF research programme is structured in different areas of analysis. ARPA VdA, as the organization responsible for handling the work for its respective region, is involved in three activities, coded as A, B and C, which cover:

- **Activity A - Electromagnetic field computation in residential buildings via FEA simulations and validation measures**

  - **Radio Frequencies (RF) exposure indicator**

  The propagation of electromagnetic waves from EM sources in the radio frequency spectrum (4G-5G, TV broadcast and radio antennas) on the environment is evaluated using the QGIS software for cartography and geometric aspects and the EmLAB software, for computing the radio frequency electromagnetic field analysis.
  In this activity, the objective is to select the centroids of each residential building obtained by a combination of planimetry from the cadastre and regional cartography.

Then get the data like power absorptions of the radiating systems by RF service providers. This data is then merged into a FEA simulation. Experimental validation of the results is also conducted through measurement of the actual field values in specific locations identified via the simulations. The aim of this activity is not to check compliance with exposure limits, but to create an exposure indicator. Therefore, the results are elaborated and presented with plots that indicate the overall exposure of Aosta citizens to the electromagnetic fields, contributing to the national study.

– **Extremely Low Frequencies (ELF) exposure indicator**

The second part concerns low-frequency fields produced by high-voltage electric power lines (50 Hz). Utilizing experimental data obtained from Terna, the Italian transmission system operator (TSO), and combining them again with cartography from QGIS software, it is possible to create the second exposure indicator.
In particular, this activity focuses on residential buildings falling within a law-defined range of proximity to the high-voltage power line passing by Aosta. Once again, the objective is to validate the simulations with measurement and subsequently extend the simulations to the entire power line.
Results are elaborated and presented with plots that indicate the citizens living close to the power line's overall exposure to the magnetic field. Also in this case the exposure indicator contributes to the national study.

- **Activity B - Dosimetry and personal exposure analysis to EMF**
  The second activity of the EMF research programme is about determining the average exposure to electromagnetic fields of a person who is to be included in a statistical category. This entails the provision of a specific measurement instrument, designated as a dosimeter, to an individual for a period of 24 hours, during which time the individual is required to carry the dosimeter on a typical working day. The individual in question may be identified as a "high school student", "university student", "office worker", "working from home worker", or "on-field worker". According to the national subdivision, the data collected from all the ARPAs will be aggregated by ISPRA (the Institute for Environmental Protection and Research that coordinates all the ARPAs) to statistically define a daily average exposure for that category of workers. This is the initial stage of characterization for a study that may be further developed in the future with more detailed categorizations. The objective of this study is to ascertain whether a specific demographic is more susceptible to electromagnetic fields and, if so, to establish a foundation for future investigations into potential health consequences.

- **Activity C - Focus on 5G signals measurements**
  The third activity of the EMF research programme is focused on the measurement of 5G waves. Given that 5G is a relatively new technology, it must be monitored and, in particular, tests and measurements must be conducted. This, in a future vision, will help monitor this technology and set the basis for future investigations and monitoring of the electromagnetic fields. The purpose is to get confident with the change of paradigm and be updated in the sector to keep the role as guarantor of the population. This analysis, conducted primarily with the use of measurement instruments, allows the monitoring of single services, differentiating from the previous activities where the field values are the result of broadband measures aggregating multiple services from different providers.

This study evaluates the propagation of electromagnetic waves from radio frequency sources (4G-5G, TV and radio antennas) using QGIS for cartography and EmLAB for electromagnetic analysis and examines low-frequency EMF from high voltage power lines with data from Terna. The aim is to select centroids of residential buildings from cadastral and regional maps, merge data in a FEM analysis simulation, and validate the results with on-field measurements. The following chapters describe the ARPA and its role in society, review the existing literature on EMF and the exposure risks and health effects, analyse the sources of the fields, describe the methodologies employed in this study, present the findings of the analysis, and discuss the conclusions. Through this examination, the hope is to shed light on the complex relationship between electromagnetic fields and human health and to contribute to the national study to safeguard and inform Italian citizens by creating the exposure indicators requested by the EMF research activity programme.

1.2 Objectives of the thesis

The thesis focuses on the two parts of Activity A where the objectives are to accurately simulate in open field the EMF spreading out over the residential area of Aosta's city, and subsequently to validate with measures and characterize EMF exposure of the population of Aosta. By addressing these objectives, this thesis seeks to enhance the understanding of EMF exposure and its implications, ultimately contributing to the development of safer and healthier living environments.
To perceive these main objectives, some steps are requested:

- Obtain efficient map-type files that contain all the information needed to proceed with analysis.
- Elaborate the exposure indicator for RF in terms of creating a histogram which represents the population exposure and a cartographic file for a visual representation of the average field values.
- Elaborate the exposure indicator for ELF in terms of histogram and cartographic file.
- Collect data for the other two activities, which will be useful in national evaluations of the EMF research programme.

In order to achieve these main objectives, other crucial steps must be undertaken. These operations do not directly show on the research programme, but they are necessary skills required to process and conduct it:

- Know what geographical information system (GIS) software are and how to use them.
- Interface with different simulation software, understand their structure, parameters imposition and formatting of input and output files.
- Interact with administrative bodies and operate according to national procedures and agreed standards.

2. What the ARPA is and what it does

2.1 ARPA's history

The acronym ARPA (Agenzia Regionale per la Protezione dell'Ambiente - Regional Agency for the Protection of the Environment) identifies a series of bodies, part of the public administration, that are present in every Italian region. The standard name for these entities differs only in the two autonomous provinces of Trento and Bolzano, where there are APPAs (Agenzie Provinciali per la Protezione dell'Ambiente - Provincial Agency for the Protection of the Environment), which perform similar functions to the regional agencies. The individual units, of regional or provincial competence, are coordinated by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale - Superior Institute for Environmental Protection and Research), which is directly supervised by the Ministry of the Environment and Protection of Land and Sea. The first ARPAs were formed in 1995 following the 1993 referendum that revoked the authority in environmental matters from the Local Health Units (USLs) [1]. In that scenario, the forerunner administrations were six: Emilia-Romagna, Liguria, Piemonte, the Autonomous Province of Trento, Toscana and Valle d'Aosta, then, over the years, the other regions joined the network of agencies until the process was completed in 2006 with the arrival of ARPA Sardegna. This network is an example of a federative system, aimed at bringing together territorial knowledge, local environmental issues and national environmental policies.

2.2 ARPA Valle d'Aosta

Figure 2.1: ARPA VdA logo

Getting to the heart of the matter, the ARPAs' tasks include monitoring the environment (analysing the physical, chemical and biological factors of water, air and soil), monitoring short- and long-term weather and climate dynamics, providing technical support to administrations in environmental matters, carrying out analysis activities for the public and private sectors, and facilitating the dissemination of issues concerning environmental protection or the current state of health of the environment. In order to perform their task properly, ARPAs are divided into sections. In particular, ARPA Valle d'Aosta is divided into four main operational branches:

- Air: working in the field of quality monitoring from emissions to meteorological reporting.
- Physical Agents: dealing with the field of the electromagnetic spectrum, from extremely low frequency (ELF) signals to the limit of ionising radiation.
- Soil: working on its composition, the search for pollutants and environmental remediation procedures.
- Water: dealing with quality monitoring in the areas of surface water, groundwater and wastewater.

The thesis falls into the physical agents department, in this specific case it is focused on the non-ionizing portion of electromagnetic radiation diving into both extremely low frequency and radio frequency. Non-ionising is when waves do not carry enough energy to break chemical bonds and produce ionisation. As the energy is associated with the frequency, non-ionizing waves are under the threshold fixed at a frequency around 10^{15}. It is this region of the electromagnetic spectrum that in the study is appealed as electromagnetic fields [2].

2.3 Studies of the EMF Research Programme

The EMF Research Programme states that each participant in activities, such as ARPAs, can undertake projects from different survey areas, of which an overview is proposed below.

2.3.1 Exposure assessment studies

Exposure assessment studies focus on evaluating the current and near-future status of sources and their impact on public exposure. In addition to global considerations, specific analyses are also carried out with the cooperation of civilians, belonging to well-defined population groups, with the aim of constituting a significant sample on a national scale. This further analysis is expected to define occupational exposure and distinguish the various contributions that make up the overall exposure according to routinely frequented microenvironments. Moreover, research and development of signal measurement procedures for new communication technologies are also included in these activities. ARPA VdA selected projects belonging to this section, which are deeply discussed in this work.

2.3.2 Epidemiological studies

The word epidemiology refers to the science which analyses a given factor and its effects on the population. This discipline is widely used in the biomedical field because it allows to obtain statistical correlations between one or more causes and one or more effects, but it is usually not definitive because, like in the treated case of the electromagnetic fields' effects, the population under study is still exposed to many other factors. To confirm a correlation more steps are required, other studies have to be conducted to support the collected data and, if in vitro and in vivo tests don't show the same results, the strength of the preliminary correlation is a lot reduced. It is also important to remember that an ethical study cannot deliberately expose people to a potentially dangerous factor. Epidemiological studies could be divided into two macro-categories:

- Observational studies: in this type of study, a supervision activity and a data elaboration are simply carried out, without going to disrupt the standard conditions of the population sample. Usually, the analysis is done on data which could be already collected.
- Experimental studies: in this type of study, the action of the research team is net. The factor on which the analysis is performed is introduced for just a part of the sample, and differences between the parts are monitored. This approach is typical of clinical trials, for studying drugs e.g., in which a control sample is not exposed to the analysed factor to prove the specificity of the effects.

2.3.3 Experimental carcinogenesis studies

The third area of interest in this programme is the production of studies which may help to establish if there is indeed a causal relationship between prolonged exposure to electromagnetic fields and the development of cancer diseases. New research activities may be undertaken based on recent results obtained from mouse models; the carcinogenicity of electromagnetic fields is also evaluated, analysing the possibility of being considered as a facilitative factor in the development of this type of disease. These studies take time to reach reliable conclusions and are often outsourced by the ARPAs themselves to third-party laboratories and specialized research foundations.

3. Electromagnetic fields

3.1 Brief history

Electromagnetism, one of the four fundamental forces of nature, has had a rich and revolutionary history, influenced by many distinguished scientists [3]. The foundations of electromagnetism were laid in the 18th century, but it was in the 19th century that the field made great strides. Hans Christian Ørsted discovered in 1820 that an electric current generates a magnetic field, marking the beginning of the modern theory of electromagnetism. Michael Faraday, with his experiments on electromagnetic induction, demonstrated that a varying magnetic field can induce an electric current, introducing the concept of lines of force to represent electric and magnetic fields. James Clerk Maxwell, through his famous "Maxwell equations", unified electric and magnetic fields, showing that electric and magnetic fields propagate as electromagnetic waves at the speed of light. Heinrich Hertz experimentally confirmed the existence of these waves, proving the validity of Maxwell's theories. These scientists, known as the fathers of electromagnetism, radically transformed the understanding of the universe, laying the foundations for countless technological innovations, from radio to modern telecommunications.

3.2 Theory

The theory behind the electromagnetic fields can be quite broad and complex. As this is not the focus of the thesis, this section serves to report only the theoretical background needed for a proper understanding of the work carried out. In particular, a focus is on why simulations and measurements are different between high-voltage power lines and cell towers. Of course, the theory background starts from Maxwell's equations.

Figure 3.1: James Clerk Maxwell

3.2.1 Maxwell's equations

1. **Gauss's Law for the Electric Field**:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \tag{3.1}$$

2. **Gauss's Law for the Magnetic Field**:

$$\nabla \cdot \mathbf{B} = 0 \tag{3.2}$$

3. **Faraday's Law of Induction**:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3.3}$$

4. **Ampère-Maxwell Law**:

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{3.4}$$

These equations enclose all the electromagnetic phenomena. As they are very general, some simplifications, dictated by the application of the laws, are necessary.

3.2.2 Near and Far field

In the epidemiological study, the analysis of the electromagnetic field produced by a power line or the one produced by a cell tower completely differs in terms of distance from the source. Indeed, when simulating and measuring the electromagnetic field for power lines, as the spots are electromagnetically close to the source (the line itself), the region is called "near field" while for antennas, the region is called "far field". This is not only related to the physical distance between the source and the spot of the measure, but also to the frequency of the service that determines the wavelength of the signal. This is a general definition associated to EM waves, but there is not an exact point of switching between near field and far field, as it is a smooth transition. Generally, for antennas, the start of the far field is set to be at:

$$Far\ field\ region > \frac{2D^2}{\lambda} \tag{3.5}$$

Where: $D = maximum\ linear\ dimension\ of\ the\ antenna$
$\lambda = wavelength\ of\ the\ EM\ waves$

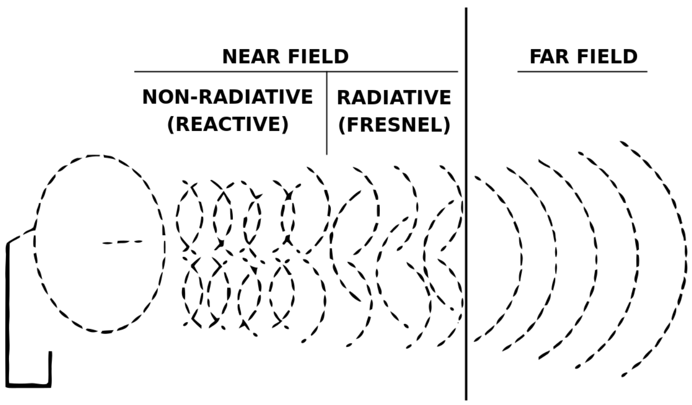


Figure 3.2: Near and Far Field from the source

From this simple formula is possible to show that for an antenna, almost always it is the case of far-field:

$$\frac{2D^2}{\lambda} = \frac{2D^2 \cdot f}{c} = \frac{2 \cdot 0.01^2 \cdot 30 \cdot 10^9}{299792458} = 0.02\ m \tag{3.6}$$

Where, for example $D = 10\ cm$ and $f = 30\ GHz$.
It can be seen that any point away 20 cm on is in the far field region.

3.2.3 Far field

When it comes to far-field an important assumption can be made, which is to assume the propagation to be a plane wave, which means, as the system in consideration is far from the source, the wavefront is considered to be a plane. With this assumption, it is possible to demonstrate the wave equations for electric and magnetic fields, starting from Maxwell's equations [4] [5] [6].
Starting with the last two Maxwell's equations reported here, and with the Ampere-Maxwell equation (Equation 3.4); ignoring the current term, and assuming that there are no other sources of electromagnetic field other than the one in consideration it is possible to conclude (also assuming to be in the vacuum):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{3.7}$$

$$\nabla \times \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{3.8}$$

Wave Equation for the Electric Field

Applying the curl operator ($\nabla\times$) to Faraday's law of induction (3.7):

$$\nabla \times (\nabla \times \mathbf{E}) = -\nabla \times \frac{\partial \mathbf{B}}{\partial t} \tag{3.9}$$

And using the vector identity for the curl of the curl:

$$\nabla \times (\nabla \times \mathbf{E}) = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2 \mathbf{E} \tag{3.10}$$

Please note that in general, the vector triple product [7]:

$$A \times (B \times C) = B \cdot (A \cdot C) - (A \cdot B) \cdot C \tag{3.11}$$

In vacuum, Gauss's law for the electric field (or first maxwell equation: Equation 3.1) $\nabla \cdot \mathbf{E} = 0$ implies that $\nabla(\nabla \cdot \mathbf{E}) = 0$. Therefore:

$$\nabla \times (\nabla \times \mathbf{E}) = -\nabla^2 \mathbf{E} \tag{3.12}$$

Substituting it into Equation 3.9:

$$-\nabla^2 \mathbf{E} = -\nabla \times \frac{\partial \mathbf{B}}{\partial t} \tag{3.13}$$

Therefore:

$$-\nabla^2\mathbf{E} = -\frac{\partial}{\partial t}(\nabla \times \mathbf{B}) \tag{3.14}$$

Substituting $\nabla \times \mathbf{B}$ from Ampère-Maxwell's law (or the fourth Maxwell's equation, Equation 3.8):

$$\nabla^2\mathbf{E} = \mu_0\epsilon_0\frac{\partial^2\mathbf{E}}{\partial t^2} \tag{3.15}$$

This is the wave equation for the electric field:

$$\nabla^2\mathbf{E} - \mu_0\epsilon_0\frac{\partial^2\mathbf{E}}{\partial t^2} = 0 \tag{3.16}$$

Wave Equation for the Magnetic Field

Similarly to what has been done so far can also be made for the magnetic equation. Applying the curl operator ($\nabla\times$) to Ampère-Maxwell's law (3.8):

$$\nabla \times (\nabla \times \mathbf{B}) = \mu_0\epsilon_0\nabla \times \frac{\partial\mathbf{E}}{\partial t} \tag{3.17}$$

Using the vector identity for the curl of the curl again:

$$\nabla \times (\nabla \times \mathbf{B}) = \nabla(\nabla \cdot \mathbf{B}) - \nabla^2\mathbf{B} \tag{3.18}$$

In vacuum, Gauss's law for the magnetic field ($\nabla \cdot \mathbf{B} = 0$) implies that $\nabla(\nabla \cdot \mathbf{B}) = 0$. Therefore:

$$\nabla \times (\nabla \times \mathbf{B}) = -\nabla^2\mathbf{B} \tag{3.19}$$

Substituting it becomes:

$$-\nabla^2\mathbf{B} = \mu_0\epsilon_0\frac{\partial}{\partial t}(\nabla \times \mathbf{E}) \tag{3.20}$$

From Faraday's law of induction (Equation 3.3), is known that:

$$\nabla \times \mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \tag{3.21}$$

Therefore:

$$-\nabla^2\mathbf{B} = \mu_0\epsilon_0\frac{\partial}{\partial t}\left(-\frac{\partial\mathbf{B}}{\partial t}\right) \tag{3.22}$$

Simplifying:

$$\nabla^2\mathbf{B} = \mu_0\epsilon_0\frac{\partial^2\mathbf{B}}{\partial t^2} \tag{3.23}$$

This is the wave equation for the magnetic field:

$$\nabla^2\mathbf{B} - \mu_0\epsilon_0\frac{\partial^2\mathbf{B}}{\partial t^2} = 0 \tag{3.24}$$

Finally, the solutions of the two equations can be found.

Solutions to the Wave Equations for Electromagnetic Fields

The wave equation for the electric field is:

$$\nabla^2\mathbf{E} - \mu_0\epsilon_0\frac{\partial^2\mathbf{E}}{\partial t^2} = 0 \tag{3.25}$$

A general solution to this equation is a plane wave, which can be written as:

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \tag{3.26}$$

The wave equation for the magnetic field is:

$$\nabla^2\mathbf{B} - \mu_0\epsilon_0\frac{\partial^2\mathbf{B}}{\partial t^2} = 0 \tag{3.27}$$

A general solution to this equation is also a plane wave, which can be written as:

$$\mathbf{B}(\mathbf{r}, t) = \mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \tag{3.28}$$

Separating the complex solutions into their real and imaginary parts, it is typically the real part used for the solution:

$$\mathbf{E}(\mathbf{r}, t) = \mathrm{Re}\left\{\mathbf{E}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}\right\} = \mathbf{E}_0\cos(\mathbf{k}\cdot\mathbf{r}-\omega t) \tag{3.29}$$

$$\mathbf{B}(\mathbf{r}, t) = \mathrm{Re}\left\{\mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}\right\} = \mathbf{B}_0\cos(\mathbf{k}\cdot\mathbf{r}-\omega t) \tag{3.30}$$

Note that in an electromagnetic wave, the electric and magnetic fields are perpendicular to each other and to the direction of propagation $\mathbf{k}$. Additionally, there is a phase and amplitude relationship between the two fields:

From Faraday's law:

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \tag{3.31}$$

The curl of $\mathbf{E}$:

$$\nabla\times\mathbf{E} = \nabla\times(\mathbf{E}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}) = \mathbf{E}_0\times(i\mathbf{k})e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} = i(\mathbf{E}_0\times\mathbf{k})e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \tag{3.32}$$

The time derivative of $\mathbf{B}$:

$$\frac{\partial\mathbf{B}}{\partial t} = \frac{\partial}{\partial t}(\mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)}) = -i\omega\mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \tag{3.33}$$

Thus, Faraday's law becomes:

$$i(\mathbf{E}_0\times\mathbf{k})e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} = i\omega\mathbf{B}_0 e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} \tag{3.34}$$

Simplifying:

$$\mathbf{E}_0\times\mathbf{k} = \omega\mathbf{B}_0 \tag{3.35}$$

And finally:

$$\frac{\mathbf{E}_0}{\mathbf{B}_0} = \frac{\omega}{\mathbf{k}} = \lambda\cdot f = c \tag{3.36}$$

where c is the speed of light in vacuum, given by:

$$c = \frac{1}{\sqrt{\mu_0\epsilon_0}} \tag{3.37}$$

It is possible to conclude that, as the speed of light is $c \approx 3\cdot 10^8\ m/s$ in the case of far field situation, the analysis only focuses on the electric field, while there is no interest in measuring or computing simulations of the magnetic field as it is negligible. This, indeed, is what has been done in the radio frequency section of Activity A.

3.2.4 Near field

For high voltage power lines, the assumption made is not any more true. Indeed, it is possible to see at a 2D electric field distribution to understand that assuming a plane wave is not reasonable to evaluate the field between the lines and the ground:

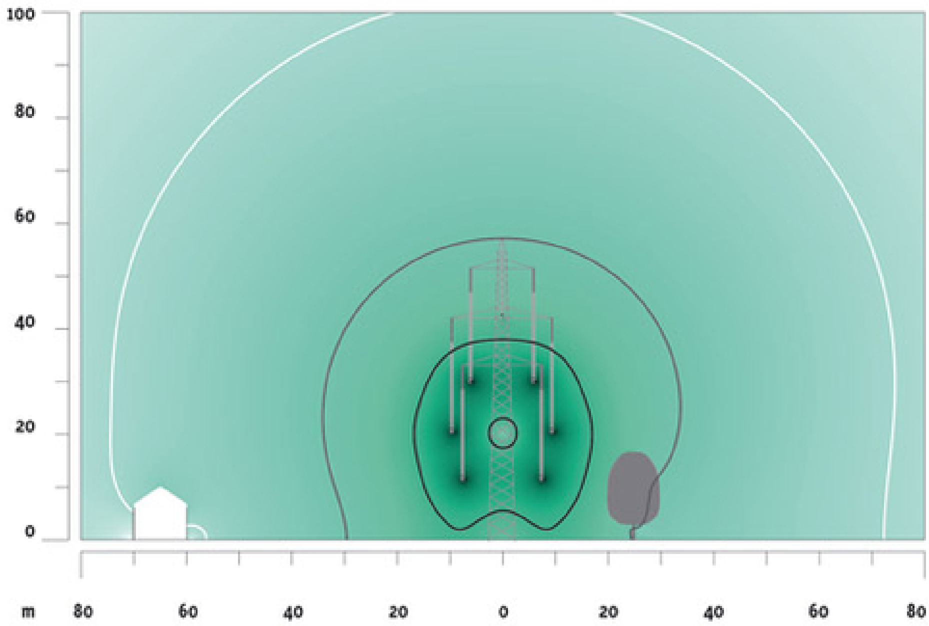


Figure 3.3: 2D section of electric field produced by high-voltage power line [8]

This implies that for high voltage electric power lines there are two measurements, one for the electric field and the other one for the magnetic field, which, with respect to the far field case, are not directly linked any more, and are independent one from another.
In this perspective, also the laws set two thresholds, one for the electric field generated by high-voltage power lines, and another, for the magnetic field (which is the most important one).

3.2.5 Multi-sources

Another big difference between the radio frequency system and the ELF system is that in the first, the field evaluated in a point is the result of a sum of sources acting together, therefore both from a regulatory side and from a measurement point of view, it must be that the overall limit is respected from all the contributions. This also means that sources with different carrier frequencies must be properly summed (in simulation) or a broadband measurement instrument must be used. However, the situation for high voltage power lines is different because almost always there is only one line running above, and the effect rapidly diminishes with distance. So, unless particular cases (which are not considered in this study), ELF source is only one, which has a specific frequency of 50 Hz, the frequency of the electric grid. Particular analysis can be performed in the presence of multiple power lines crossing at a specific point, but this is not the case in the present thesis.

4. Electromagnetic fields and Health

If the benefits of electromagnetic fields are well known and part of everyday life, the prolonged exposure or overexposure of the population to these fields may harm people's health. For this reason of monitoring population exposure, the EMF research programme financed by the Italian government is being conducted by the ARPAs. To properly monitor the situation, some limitations have been set by national laws, following European principles and directives. These guidelines have been set through a deep scientific analysis of studies and literature dedicated to finding adverse health effects of EM field exposure.
The aim of this section is to give an overview of the main studies, understand the criteria upon which the European Commission has set the limits, and also investigate how, on an Italian basis, these rules have been applied.

4.1 Scientific studies and international guidelines

The literature of scientific studies in this field is broad and does not provide compelling evidence of the harm of the EM fields. Not to deviate from the focus of the thesis purpose, only documents that lead to the national laws, which set the limits, are considered.
To start from the beginning, in 1974, the International Radiation Protection Association (IRPA) [9] formed a working group on non-ionizing radiation (NIR), which examined the problems arising in the field of protection against the various types of NIR. At the IRPA Congress in Paris in 1977, this working group became the International Non-Ionizing Radiation Committee (INIRC). In cooperation with the Environmental Health Division of the World Health Organization (WHO), the IRPA/INIRC developed a number of health criteria documents on NIR as part of WHO's Environmental Health Criteria Programme, sponsored by the United Nations Environment Programme (UNEP). Each document includes an overview of the physical characteristics, measurement and instrumentation, sources, and applications of NIR, a thorough review of the literature on biological effects, and an evaluation of the health risks of exposure to NIR. These health criteria have provided the scientific database for the subsequent development of exposure limits and codes of practice relating to NIR. At the Eighth International Congress of the IRPA (Montreal, 18–22 May 1992), a new, independent scientific organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), was established as a successor to the IRPA/INIRC.
The ICNIRP is still present today and is an association registered in Munich, Germany, as a non-profit organization with a scientific mission (Statutes). It is formally recognized as an official collaborating non-state actor by the World Health Organization (WHO) and the International Labour Organization (ILO) [10]. The functions of the Commission are to investigate the hazards associated with the different forms of NIR, develop international guidelines on NIR exposure limits, and deal with all aspects of NIR protection [11].

In 1998 the ICNIRP published the "ICNIRP guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)" [11]. In this paper, many epidemiological studies and laboratory results are analysed, extrapolations from animal experiments to effect on humans are made, and exposure criteria and reference levels are defined for practical assessment. The document ends by providing suggested restrictions depending upon the frequency of the EM field, and reference levels are provided for a practical exposure assessment purpose through tables and plots.
The restrictions in these guidelines are based on scientific data and knowledge available at that time. To provide an adequate level of protection from exposure to time-varying EMF as agreed on in the EU environment policy based on four principles [12], within which the precaution principle [13] "where there is uncertainty about the risk of environmental harm, the precautionary principle allows or requires protective measures to be taken without having to wait until the harm materialises" following the logic "better safe than sorry". So, as there were (and still are) some uncertainties, limits are set (much) lower than the threshold found in scientific studies and literature in order to limit as much as possible other effects that possibly has not been taken into consideration.
The main information collected in the ICNIRP Guidelines (1998) [11] (that became a book in 1999 [14]) can be divided into two main sections:

- Biological basis for limiting exposure from 1 Hz to 100 kHz;
- Biological basis for limiting exposure from 100 kHz to 300 GHz.

Each section analyses the available bibliography on both direct and indirect effects of electric and magnetic fields. In 2010, according to new findings and studies conducted over the years, the update in the frequency range from 1Hz to 100kHz was published [15] and in 2020 [16] another one for the range 100kHz to 300GHz. The updated results are described below.

- **1 Hz - 100 kHz**: The basis for the guidelines is two-fold: Exposure to low-frequency electric fields may cause well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects. In addition, the only well-established effects in volunteers exposed to low-frequency magnetic fields are the stimulation of central and peripheral nervous tissue and the induction in the retina of phosphenes, a perception of faint flickering light in the periphery of the visual field (neurobehavioural effect). As a reference, the thresholds:
  - Direct perception (10% most sensitive volunteers) 2 – 5 kV/m at 50 – 60 Hz;
  - Annoying feeling (5% most sensitive volunteers) 15 – 20 kV/m at 50 – 60 Hz;
  - Minimum threshold for the perception of faint flickering light in the periphery of the visual field, around 5 mT at 20 Hz, rising at higher and lower frequencies.

  In these studies, the phosphenes are thought to result from the interaction of the induced electric field with electrically excitable cells in the retina. Thus, the perception of surface electric charge, the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes are well established and can serve as a basis for guidance. Studies have also been conducted for the neuroendocrine system, neurodegenerative disorders, cardiovascular disorders, reproduction and development, cancer, and chronic effects, but data do not indicate that low-frequency electric and/or magnetic fields affect them.

To sum up, there are a number of well-established acute effects of exposure to low-frequency EMFs on the nervous system as the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes. There is also scientific evidence that brain functions such as visual processing and motor coordination can be transiently affected by induced electric fields. However, all these effects have thresholds below which they do not occur and can be avoided by meeting appropriate restrictions on electric fields induced in the body. The suggested thresholds are represented in the plots in Figure 4.1 and Figure 4.2, distinguishing between the general public and workers.

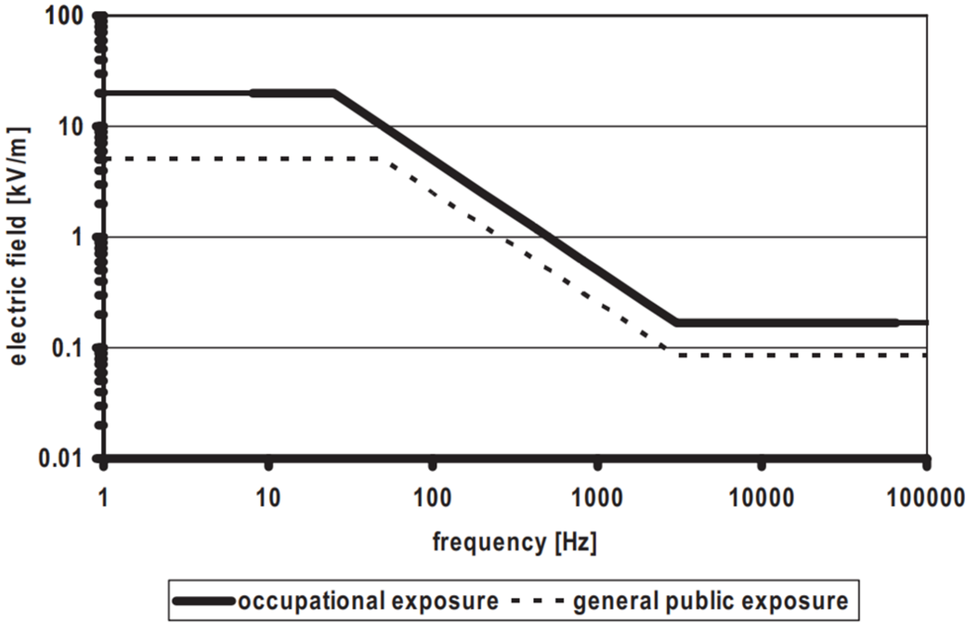


Figure 4.1: Reference levels for exposure to time-varying electric fields [15]

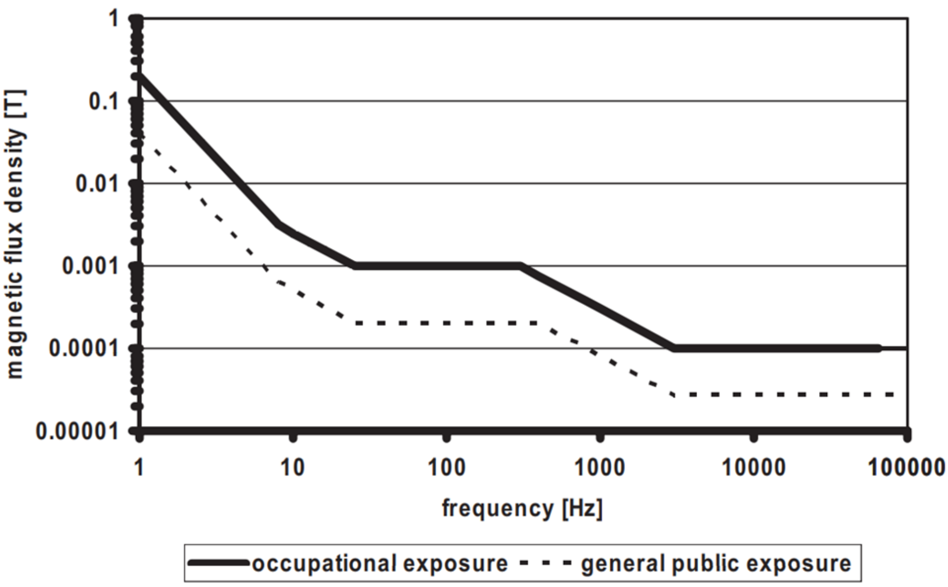


Figure 4.2: Reference levels for exposure to time-varying magnetic fields [15]

Epidemiological studies have consistently found that everyday chronic low-intensity (above 0.3 – 0.4 µT) power frequency magnetic field exposure is associated with an increased risk of childhood leukaemia.
WHO's cancer research institute, IARC (International Agency for Research on Cancer), evaluated low-frequency magnetic fields in 2002 and classified them in category 2B, which translates to "possibly carcinogenic to humans" [17]. However, a causal relationship between magnetic fields and childhood leukaemia has not been established, nor have any other long-term effects been established. The absence of established causality means that this effect cannot be addressed in the basic restrictions. However, risk management advice, including considerations on precautionary measures, has been given by WHO (2007a and b) and other entities.

- **100 kHz - 300 GHz**: It is important to note that ICNIRP only uses operational thresholds to set restrictions where they are lower (more conservative) than those demonstrated to adversely affect health in the radio frequency literature, or where the radio frequency literature does not provide sufficient evidence to deduce an adverse health effect threshold. For the purpose of determining thresholds, evidence of adverse health effects arising from all radio frequency EMF exposures is considered, including those referred to as 'low-level' and 'non-thermal', and including those where mechanisms have not been elucidated. Also, no theoretical distinction has been made between continuous (e.g., sinusoidal) and discontinuous (e.g., pulsed) EMFs. When it comes to high frequencies, nerve stimulation became almost irrelevant compared to temperature rise. One effect is the change of permeability of cell membranes. If the pulse is sufficiently intense and brief, exposure to the resultant EMFs may cause cell membranes to become permeable, which in turn can lead to other cellular changes. However, there is also no need to specifically set restrictions to protect against this effect, as the restrictions designed to protect against smaller temperature rises also protect against this. So the main aspect to take into account is the temperature rise. Radio frequency EMFs can generate heat in the body, and it is important that this heat is kept to a safe level. It is important to note that these guidelines restrict radio frequency EMF exposure to limit temperature rise rather than absolute temperature, whereas health effects are primarily related to absolute temperature. This strategy is used because it is not feasible to limit absolute temperature, which is dependent on many factors that are outside the scope of these guidelines, such as environmental temperature, clothing and work rate. This means that if exposure caused a given temperature rise, this could improve, not affect, or impair health depending on a person's initial temperature. For example, mild heating can be pleasant if a person is cold, but unpleasant if they are already very hot. The restrictions are therefore set to avoid significant increases in temperature, where "significant" is considered in light of both potential harm and normal physiological temperature variation. Before proceeding, it is necessary to introduce the Specific Absorption Rate (SAR[1]) and highlight the distinction between body core temperature and local temperature. Body core temperature refers to the temperature deep within the body, such as in the abdomen and brain, and varies substantially as a

[1]SAR, Specific Absorption Rate, is defined as the amount of EM energy absorbed by human body tissue per unit mass and is expressed in W/kg. SAR tests, therefore, measure the percentage of electromagnetic energy absorbed by the human body when it is in the proximity of a radio frequency magnetic field.

function of such factors as sex, age, time of day, work rate, environmental conditions and thermoregulation. For example, although the mean body core temperature is approximately 37°C, this typically varies over a 24-h period to meet physiological needs, with the magnitude of the variation as large as 1°C [18]. As thermal load increases, thermoregulatory functions such as vasodilation and sweating can be engaged to restrict body core temperature rise. Recent theoretical modelling and generalization from experimental research across a range of species predicts that exposures resulting in a whole-body average SAR of approximately 6 W/kg, within the 100 kHz to 6 GHz range, over at least a1-hourr interval under thermoneutral conditions (28°C, naked, at rest), is required to induce a 1°C body core temperature rise in human adults. A higher SAR is required to reach this temperature rise in children due to their more efficient heat dissipation [19]. However, given the limited measurement data available, ICNIRP has adopted a conservative position and uses 4 W/kg averaged over 30 min as the radio frequency EMF exposure level corresponding to a body core temperature rise of 1°C. A reduction factor of 10 was applied to this threshold for occupational exposure to account for scientific uncertainty, as well as differences in thermal physiology across the population and variability in environmental conditions and physical activity levels. The capacity of an individual to regulate their body core temperature is of particular significance, given that it is contingent upon a multitude of factors that are beyond the scope of the guidelines. These encompass central and peripherally-mediated alterations to blood perfusion and sweat rate (which are, in turn, influenced by a range of additional factors, including age and specific medical conditions), in addition to behaviour and environmental conditions. Thus, the basic restriction for occupational exposure becomes a whole-body average SAR of 0.4 W/kg, averaged over 30 min. As the general public cannot be expected to be aware of exposures and thus to mitigate risk, a reduction factor of 50 was applied for the general public, making the whole-body average SAR restriction for the general public 0.08 W/kg, averaged over 30 min.
To sum it up the SAR associated to the temperature rise of 1°C is:

Condition	**SAR (W/kg)**	**Time Interval**
Theoretical Modelling	6 W/kg	1 hour
ICNIRP Conservative Threshold	4 W/kg	30 min
ICNIRP Occupational Exposure	0.4 W/kg	30 min
ICNIRP General Public Exposure	0.08 W/kg	30 min

Table 4.1: Summary of SAR thresholds and conditions related to body core temperature rise

As a comparison, a human adult generates a total of approximately 1 W/kg at rest [20], nearly 2 W/kg standing and 12 W/kg running [21]. In addition to body core temperature, excessive localized heating (local temperature) can cause pain and thermal damage. There is extensive literature showing that skin contact with temperatures below 42°C for extended periods does not cause pain or damage cells). The present guidelines treat radio frequency EMF exposure that results in local temperatures of 41°C or greater as potentially harmful. For some types of exposure, rapid temperature rise can result in "hot spots," heterogeneous temperature distribution over tissue mass.

This suggests the need to consider averaging over smaller time intervals for certain types of exposure. Hot spots can occur for short-duration exposures because there is not sufficient time for heat to dissipate (or average out) over tissue. This effect is more pronounced as frequency increases due to the smaller penetration depth. To account for such heterogeneous temperature distributions, an adjustment to the steady-state exposure level is required. This can be achieved by specifying the maximum exposure level allowed, as a function of time, in order to restrict temperature rise to below the operational adverse health effect thresholds.
The results can be grouped into two plots, one for the general public and another for the workers.

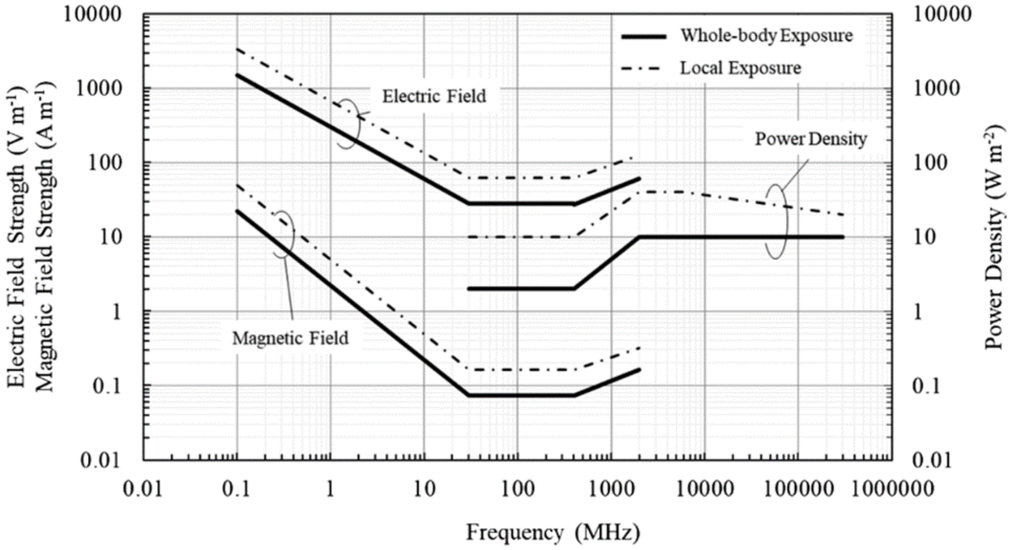


Figure 4.3: Reference levels for time-averaged general public exposures of $\geq$ 6 min

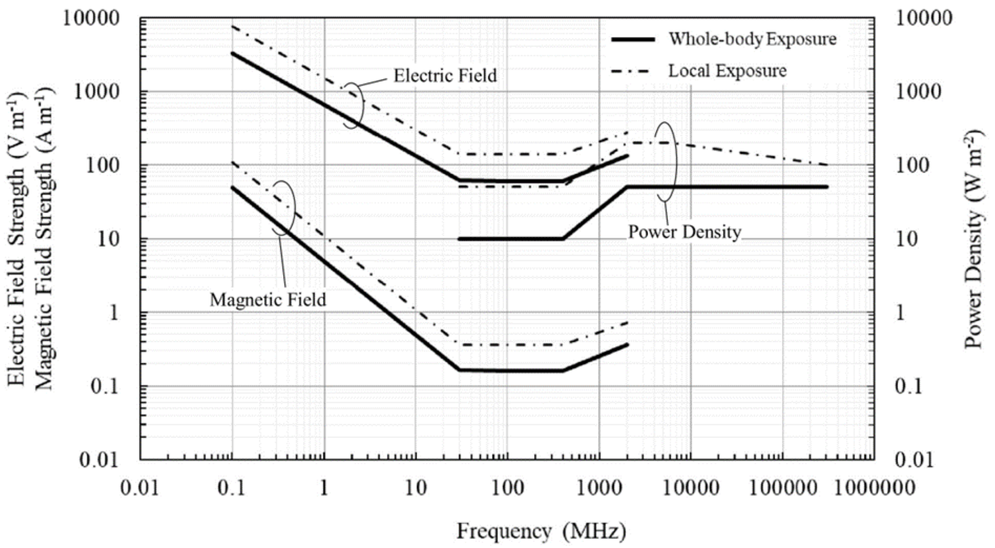


Figure 4.4: Reference levels for time-averaged occupational exposures of $\geq$ 6 min

Finally, some consideration on the simultaneous exposure to multiple frequency fields.
It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. Additivity should be examined separately for the effects of thermal and electrical stimulation, and the basic restrictions below should be met.
In the guidelines, there are many formulas to help sum up different frequency sources, but this goes beyond the purpose of this thesis, therefore the deepening is left to the reader.

4.2 European regulations and laws

The next step of the process is to look at what the European Commission has done to adopt those standards.
The main document to take into consideration is the "Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)" [22].
This came out right after the first ICNIRP guidelines and the council recommended member states, in order to provide for a high level of health protection against exposure to electromagnetic fields, to adopt a framework of basic restrictions and reference levels. The target is to achieve respect for the basic restrictions given in Annex II for public exposure by setting the reference levels in Annex III of the document. It is therefore necessary to define what is intended with basic restrictions and reference levels.

- Basic restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields are based directly on established health effects and biological considerations. Depending upon the frequency of the field, the physical quantities used to specify these restrictions are magnetic flux density (B), current density (J), specific energy absorption rate (SAR), and power density (S). Magnetic flux density and power density can be readily measured in exposed individuals, while this is not the case for the SAR. That is why the Council also set the reference levels.

- Reference levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Some reference levels are derived from relevant basic restrictions using measurements and/or computational methods and some reference levels address perception and adverse indirect effects of exposure to EMFs. The derived quantities are electric field strength (E), magnetic field strength (H), magnetic flux density (B) and power density (S). Some quantities such as magnetic flux density (B) and power density (S) serve both as basic restrictions and reference levels, at certain frequencies.

Aware of the differences here is a sum up of the basic restrictions set by the EU council. Depending on frequency, the following physical quantities (dosimetric/exposimetric quantities) are used to specify the basic restrictions on electromagnetic fields:

- Between 0 and 1 Hz basic restrictions are provided for magnetic flux density for static magnetic fields (0 Hz) and current density for time-varying fields up to 1 Hz, in order to prevent effects on the cardiovascular and central nervous system.

- Between 1 Hz and 10 MHz basic restrictions are provided for 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 localised heating of tissues. In the range 100 kHz to 10 MHz, restrictions on both current density and SAR are provided.

- Between 10 GHz and 300 GHz basic restrictions on power density are provided to prevent heating in tissue at or near the body surface.

The basic restrictions, given in Table 4.2, are set so as to account for uncertainties related to individual sensitivities, environmental conditions, and for the fact that the age and health status of members of the public vary.

Frequency range	**Magnetic flux density (mT)**	**Current density (mA/m²) (rms)**	**Whole body average SAR (W/kg)**	**Localised head and trunk SAR (W/kg)**	**Localised limbs SAR (W/kg)**	**Power density S (W/m²)**
0 Hz	40	—	—	—	—	—
0-1 Hz	—	8	—	—	—	—
1-4 Hz	—	$\frac{8}{f}$	—	—	—	—
4-1000 Hz	—	2	—	—	—	—
1000 Hz-100 kHz	—	$\frac{f}{500}$	—	—	—	—
100 kHz-10 MHz	—	$\frac{f}{500}$	0,08	2	4	—
10 MHz-10 GHz	—	—	0,08	2	4	—
10-300 GHz	—	—	—	—	—	10

Table 4.2: Basic restrictions for electromagnetic fields[1] (0 Hz to 300 GHz)

Reference levels of exposure are provided for the purpose of comparison with values of measured quantities. The respect of all recommended reference levels ensures respecting all basic restrictions. If the quantities of measured values are greater than the reference levels, it does not necessarily follow that the basic restrictions have been exceeded. In this case, an assessment should be made as to whether exposure levels are below the basic restrictions. The reference levels for limiting exposure are obtained from the basic restrictions for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. A summary of the reference levels is given in Table 4.3. The reference levels are generally intended to be spatially averaged values over the dimension of the body of the exposed individual, but with the important proviso that the localised basic restrictions on exposure are not exceeded. In certain situations where the exposure is highly localised, such as with hand-held telephones and the human head, the use of reference levels is not appropriate. In such cases, respect of the localised basic restriction should be assessed directly.

[1]f is the frequency in Hz

Frequency range	**E-field strength (V/m)**	**H-field strength (A/m)**	**B-field (μT)**	**Equivalent plane wave power density S_{eq} (W/m^2)**
0-1 Hz	—	$3{,}2 \times 10^4$	4×10^4	—
1-8 Hz	10 000	$3{,}2 \times 10^4/f^2$	$4 \times 10^4/f^2$	—
8-25 Hz	10 000	$4000/f$	$5000/f$	—
0,025-0,8 kHz	$250/f$	$4/f$	$5/f$	—
0,8-3 kHz	$250/f$	5	6,25	—
3-150 kHz	87	5	6,25	—
0,15-1 MHz	87	$0{,}73/f$	$0{,}92/f$	—
1-10 MHz	$87/f^{1/2}$	$0{,}73/f$	$0{,}92/f$	—
10-400 MHz	28	0,073	0,092	2
400-2 000 MHz	$1{,}375 \times f^{1/2}$	$0{,}0037 \times f^{1/2}$	$0{,}0046 \times f^{1/2}$	$f/200$
2-300 GHz	61	0,16	0,20	10

Table 4.3: Reference levels for electromagnetic fields[1] (0 Hz to 300 GHz, rms values)

4.3 National laws

The Italian regulatory body doesn't limit to transform the guidelines into national limits, but also determines who is responsible for checking the rules are being respected, who is responsible for authorizations and provides normative and who has to draft technical guides on how to proceed with measurements and simulations. In this context, many actors and documents come out, but once again the idea is to limit the sources to the strict necessary to frame the thesis into the regulatory context. On the 22^{nd} of February 2001 the law on protection from exposure to electric, magnetic and electromagnetic fields is written and published on the official journal on the 7^{th} of March 2001 [23]. The law is composed of 17 articles dealing with the aims of the law, the scope of application "This law has as its object installations, systems and equipment for civil, military and police purposes, which may result in the exposure of workers, female workers and the general public to electric, magnetic and electromagnetic fields with frequencies between 0 Hz and 300 GHz", the State functions, the environmental and landscape protection measures, authorisation procedure for the construction and operation of power lines, powers of the regions, provinces and municipalities, and eventually controls and sanctions.
A particular focus is on the Article 14.1 where the role of control is left to the ARPA: "The provincial and municipal administrations, in order to exercise the health and environmental control and supervision functions for the implementation of this law, shall use the structures of the Regional Agencies for the Protection of the Environment (ARPA), referred to in Decree-Law No 496 of 4 December 1993, converted, with amendments, by Law No 61 of 21

[1] f as indicated in the "Frequency range" column

January 1994. The competences in the field of supervision in the workplace attributed by the provisions in force remain unaffected".
Limits are set in the D.P.C.M. 08/07/2003 (application decrees law 36/2001). For ELF, in particular for high voltage power lines at 50Hz limits are defined in the article 3 [24]. "In the case of exposure to electric and magnetic fields at the frequency of 50 Hz generated by power lines shall not exceed the exposure limit of 100 µT for magnetic induction and 5 kV/m for the electric field, taken as rms values. As a precautionary measure to protect against possible long-term effects that may be associated with exposure to magnetic fields generated at grid frequency (50 Hz), in areas children's play areas, in living environments, in school environments and in places used for durations of not less than four hours daily, the magnetic induction is assumed to have an attention value of 10 µT, to be considered as the median of the values over 24 hours under normal operating conditions". Also, the quality objective for the design of new power lines or designated areas with >4 hours/day in the proximity of power lines is set to 3 µT. Here is a sum-up table with the ELF limits:

Field	**Frequency**	**Exposure limits**	**Attention values**	**Quality objectives**
Electric	50 Hz	5000 V/m	-	-
Magnetic		100 µT	10 µT	3 µT

Table 4.4: Exposure limits, attention values and quality objectives for grid frequency electromagnetic waves (50 Hz).

It is of interest to notice that for the electric field, there are no attention values or quality objectives, this is because there is no reason to lower the exposition as it has been proved that the electric field can be easily shielded by any thin layer in between the source and the body. For example, already a leaf is enough to shield the electric field and even in the worst case where there is nothing in between, the human skin acts as a shield and therefore the electric field does not reach the human organs that are the ones to protect.
For radio frequency, as there is a wider frequency spectrum, an annex is given [25]. The main results can be summed up in the following table:

<table>
<tr><th>Field</th><th>Frequency</th><th>Exposure limits</th><th>Attention values</th><th>Quality objectives</th></tr>
<tr><td rowspan="3">Electric</td><td>$0.1 < f \leq 3$ MHz</td><td>60 V/m</td><td rowspan="3">6 V/m</td><td rowspan="3">6 V/m</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>20 V/m</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>40 V/m</td></tr>
<tr><td rowspan="3">Magnetic</td><td>$0.1 < f \leq 3$ MHz</td><td>0.2 A/m</td><td rowspan="3">0.016 A/m</td><td rowspan="3">0.016 A/m</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>0.05 A/m</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>0.01 A/m</td></tr>
<tr><td rowspan="3">Power density</td><td>$0.1 < f \leq 3$ MHz</td><td>-</td><td rowspan="3">0.1 W/m^2 (3 MHz-300 GHz)</td><td rowspan="3">0.1 W/m^2 (3 MHz-300 GHz)</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>1 W/m^2</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>4 W/m^2</td></tr>
</table>

Table 4.5: Exposure limits, attention values and quality objectives for radio frequency electromagnetic waves.

It is important to notice that in the years more studies have been carried out. Even if this topic has many uncertainties, and many more studies are needed to fully comprehend the effects of electromagnetic fields, the rules try to stay updated as much as possible, and in particular try to keep the pace with international guidelines. So, as there have been updates in the ICNIRP guidelines, also the Italian laws have changed, and in particularly at the end of 2023, the quality objectives for radio frequencies have been raised. Notice that the increase of the quality objectives did not affect the exposure limits at all, which remain the ones set by the D.P.C.M. 08/07/2003.
In particular in article 10 of the law 30/12/2023 n.214 [26] there is said: "After the expiry of the period referred to in paragraph 1, in the absence of specific regulatory provisions for adaptation and until such time as they are definitively adopted, the warning values and quality objectives referred to in Tables 2 and 3 of Annex B to the Prime Ministerial Decree of 8 July 2003, published in Official Gazette no. 199 of 28 August 2003, are provisionally and as a precautionary measure fixed at a value of 15 V/m for electric field strength E, at a value of 0.039 A/m for magnetic field strength H, and at a value of 0.59 W/m² for power density D".
The increasing request for services (dictated by the increasing number of devices, users, and services mainly across big cities) and the non-evidence of the potential harm of electromagnetic fields with this intensity (once again the exposure limits are already cautious, quality objectives and attention values are even more strict for the precautionary principle) drove the increment of this values. The renewed table appears:

<table>
<tr><th>Field</th><th>Frequency</th><th>Exposure limits</th><th>Attention values</th><th>Quality objectives</th></tr>
<tr><td rowspan="3">Electric</td><td>$0.1 < f \leq 3$ MHz</td><td>60 V/m</td><td rowspan="3">15 V/m</td><td rowspan="3">15 V/m</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>20 V/m</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>40 V/m</td></tr>
<tr><td rowspan="3">Magnetic</td><td>$0.1 < f \leq 3$ MHz</td><td>0.2 A/m</td><td rowspan="3">0.039 A/m</td><td rowspan="3">0.039 A/m</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>0.05 A/m</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>0.01 A/m</td></tr>
<tr><td rowspan="3">Power density</td><td>$0.1 < f \leq 3$ MHz</td><td>-</td><td rowspan="3">0.59 W/m^2
(3 MHz-300 GHz)</td><td rowspan="3">0.59 W/m^2
(3 MHz-300 GHz)</td></tr>
<tr><td>$3 < f \leq 3000$ MHz</td><td>1 W/m^2</td></tr>
<tr><td>$3 < f \leq 300$ GHz</td><td>4 W/m^2</td></tr>
</table>

Table 4.6: Updated exposure limits, attention values and quality objectives for radio frequency electromagnetic waves.

Notice that differently to the extremely low frequencies (Table 4.4) the attention values and the quality objectives are the same.
As discussed in the theory of Chapter 3 the relevant component of the electromagnetic fields in the radio frequency spectrum is the electric part. In fact, in the radio frequency analysis, the study focuses on the electric field, both for simulations and validation measures. Therefore, to better understand the values, in Figure 4.5 a plot has been made to compare the ICNIRP guidelines limits, the Italian limits and the attention values (same as quality objectives) in terms of both electric field and power density.

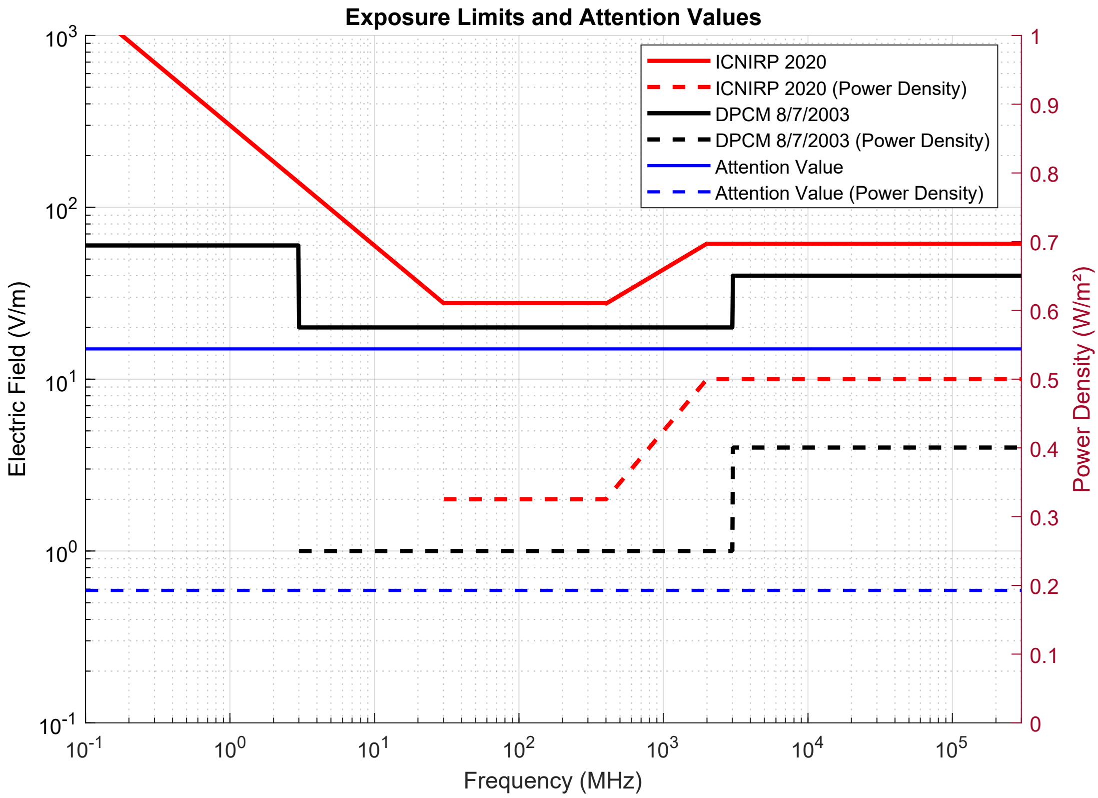


Figure 4.5: Comparison between international guidelines and national transposition

As said previously, the Italian laws take care also of other aspects like, how to measure and monitor the respect of the limits. The focus of this chapter was to reconstruct the hierarchy in terms of laws and guideline that set the threshold of the parameters that are being monitored in the ARPAs' study.
A brief overview of the main other laws is given to complete the normative chapter, but there won't be a dive into them. When necessary, they are recalled in the proper section of the activities being conducted.
In the 2008 decrees [27] specific to power lines (both lines and cabins) there are the procedures for measuring and evaluating magnetic induction and the calculation methodology for determining the buffer zones.
In 2021 it was implemented the directive (EU) 2018/1972 of the European Parliament and of the Council of 11 December 2018 establishing the European Electronic Communications Code [28]. This document set the list of conditions which may be attached to general authorisations, rights of use of radio spectrum and rights of use of numbering resources, also the conditions of access to the broadcasting of digital radio and television services for viewers and listeners etc.
In the regional laws there are the procedures for issuing authorisations, each region can therefore have a different form of authorisation, all of which however must be in line with what is defined in the communications code defined in Legislative Decree 259 of 2003 [29] and its amendments, the last and most substantial of which took place in 2021 to comply with the amendment of the equivalent European code. For the Valle d'Aosta region the current laws to consider are: LR25/2005 [30] for the radio frequency and LR8/2011 for the ELF [31].

Finally, in the CEI standards and technical guides there are all the technical procedures for measurements, simulations, an so on. CEI standards are often taken over in laws and do not contain the administrative procedures for authorisations.
Main CEI standards for RF:

- CEI 211-7 Guide for the measurement and evaluation of electromagnetic fields in the frequency range 100 kHz - 300 GHz, with reference to human exposure.
- CEI 211-10 Guide for setting up a radio base station to comply with high frequency electromagnetic field exposure limits.

Each guide has specific appendices that focus and expand on the principles contained in the mother guide for certain specific installations or sources, for example in 211-7 there are 5 appendices: monitoring stations, radar, broadband systems, radio TV, mobile telephony.
Main CEI standards for ELF:

- CEI 211-6 Guide for the measurement and evaluation of electric and magnetic fields in the frequency range 0 Hz - 10 kHz, with reference to human exposure.
- CEI 11-60 Guide to the thermal limit of outdoor overhead power lines with voltage greater than 100 kV.
- CEI 106-11 Guide for the determination of buffer zones for power lines according to the provisions of DPCM 8 July 2003 (ART. 6) [24]:
  part 1: Overhead and cable power lines;
  part 2: First approximation distance for medium-low voltage substations.

4.4 Absence of EMF

Although European, national and regional regulations set limits on the exposure of people to electromagnetic fields, it is worth remembering that total absence can lead to even worse effects. The purpose of this section is to analyse what are the effects of the total absence of electromagnetic fields, meaning without also the natural (non-artificial) ones.
Natural electromagnetic fields can be attributed to two main sources: Schumann resonance and terrestrial magnetic field.

- Schumann resonance. This phenomenon is related to atmospheric discharges (lightning) that constantly excite the atmosphere generating stationary waves in the Earth-Ionosphere cavity [32]. These waves consist of a stronger fundamental harmonic of about 7.83Hz and weaker higher harmonic orders. The intensity is quite low, of about 0.01 V/m for the electric field, and 1–10 nT for the magnetic field [33].
- Natural terrestrial magnetic field.Normally terrestrial magnetic field is approximable to a static magnetic field, it only experiences small variations in the short term, but it is not uniform, it can vary considerably by moving position; it is characterized by an intensity between 30nT (in the equatorial area) and 70nT (in the polar areas). From the point of view of a human being, who is for most of the time in motion, the perception of the magnetic field is different, the effects may no longer be like a static field.

Talking about both the natural electromagnetic fields and the terrestrial magnetic field, it has been proven they have a strong effect on circadian rhythms. According to [34] an experiment has been conducted in order to check the effects attributable to these phenomena. Two groups have been sent to different underground rooms, one conventional room and the other one completely shielded from both electric and magnetic fields. Both groups experienced an alteration of physiological and circadian rhythms, but people in the shielded room showed a more irregular and longer pattern. This remarks the importance of magnetic fields in normal life and is suggests a correlation between variable fields and organisms. As a second step, in the same study, a weak 10Hz electric field stress was applied to the shielded room and this lead to a significant restoration of the physiological rhythms. This additional part of the experiment shows that a complex organism like the human being, which has developed in the presence of a weakly variable electromagnetic stress, needs this stimulus for proper functioning.

4.5 Framing of the study in the regulatory context

At this point, the reason the ARPAs are conducting the study should be clear. The already mentioned law of the 7^{th} March 2001, article 14 places the ARPAs in charge of monitoring, controlling and supervising the respect of the limits. As stated in article 6 of the D.P.C.M. of the 8^{th} of July 2003, ARPAs are also involved in defining the calculation methodology for determining buffer strips with the approval of the Ministry of Environment and Land and Sea Protection; more details on the procedure are in the respective activity chapters. In particular, the same ministry in November 2018 promoted the "Programme for the promotion of research activities and technical-scientific experimentation, as well as the coordination of data collection, processing and dissemination activities in order to investigate the risks associated with exposure to low and high-frequency electromagnetic fields [35]". With the pandemic, the EMF research programme has suffered a setback, and therefore the first procedures and initiatives have taken place in 2021. From there, the ARPAs had to choose which activities to undertake and coordinate the work together, postponing the actual start of the work in 2023. In the mentioned decree, divided into nine articles, the ministry officially launched the EMF research programme, by allocating funding and directing initiatives to undertake. In article 4.1 there is a table with a list of activities that can be carried out to take part in the programme and the ARPA VdA has chosen three activities:

1. Studies aimed at assessing EMF emissions (RF and ELF fields) from various sources, exposure scenarios and levels from new and emerging technologies and from changes in the use of established technologies; Activity A.

2. Surveys aimed at quantifying personal exposure to EMFs, assessing the contribution of different sources, and identifying the determinants of exposure in the general population, its subsets and different microenvironments; Activity B.

3. Development of methods for collecting personal or environmental exposure data based on commonly used devices (such as mobile electronic devices) and techniques such as crowd-sensing. In this case, a focus on the measurement of 5G technology; Activity C.

Each ARPA was free to choose the activities to carry out. The aim is to contribute together collecting as much data as possible to define the population exposure indicators.

5. Electromagnetic field's sources and cartography

5.1 Frequency range

What goes by the name of electromagnetic radiation is not always easily recognized and, especially for people outside academic circles, there is much confusion. This phenomenon is simply the manifestation of the electromagnetic field, but it immediately arouses strong images in people, although it would be correct to first analyse what really the entire electromagnetic spectrum contains in terms of frequencies and distinguish those that are ionizing phenomena from those that are non-ionizing phenomena.

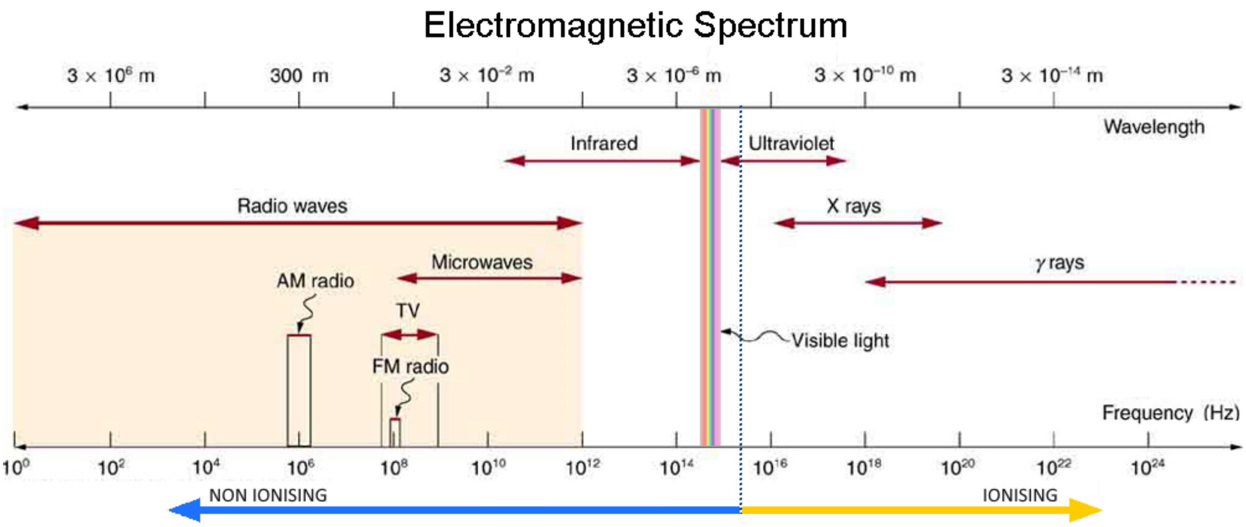


Figure 5.1: Electromagnetic spectrum

Ionizing radiation consists of that part of the electromagnetic spectrum characterized by wavelengths such that there is interaction between waves and atoms. This type of radiation is dangerous because by changing the atomic and molecular structure, it can bring tissue damage or damage the genetic makeup within the DNA by impairing cell replication or giving rise to mutated cells that can be the cause of cancer events. The frontier of ionizing radiation is in fact ultraviolet radiation; this portion of the spectrum is characterized by moderately high energy content and wavelengths on the order of 10^{-8}m. This type of radiation is attributable to the development of skin cancer diseases, so it constitutes the real boundary between the two natures. Non-ionizing radiation concerns that part of the electromagnetic spectrum such that the energy carried is not sufficient to change the atomic structure and the wavelength is much greater than the size of cells or molecules. In this frequency range, there are all communication systems, from radios to the most modern systems, to visible light and the ultraviolet part. All communication technologies, from radar to most modern mobile services, they all operate with frequencies well below the visible range. This means that only non-ionising field is involved. To help show how the frequencies analysed in this work are divided, in table 5.1 it is proposed the subdivision suggested by ITU-R [36]:

Band	***Denomination***	***Frequency***	***Common usage***
ELF	Extremely Low Frequency	0.03 - 300Hz	Power transmission lines, appliances supplied by the grid
ULF VLF LF MF HF	Ultra Low Frequency Very Low Frequency Low Frequency Medium Frequency High Frequency	0.3 - 3kHz 3 - 30kHz 30 - 300kHz 0.3 - 3MHz 3 - 30MHZ	Industrial process (induction heating), AM broadcasting
VHF UHF SHF EHF	Very High Frequency Ultra High Frequency Super High Frequency Extremely High Frequency	30 - 300MHz 0.3 - 3GHz 3 - 30GHz 30 - 300GHz	FM broadcasting, Wi-Fi systems, TV broadcasting, microwave ovens, radio tower, mobile phone: 2G-GSM: 900/1800MHz 3G-UTMS: 1.9/2.1GHz 4G: up to 2.6GHz

Table 5.1: Nomenclature of frequency range according to ITU-R

According to Table 5.1, the work is divided into two main areas:

- Signal transmission, dealing with all those high frequencies involved in the transmission of communication signals. The carrier frequency can vary a lot, but in all the cases the aim is to transmit signals and information.
- Power transmission, dealing with low frequency (50 or 60Hz) involved in the electric power transmission system. This time, a big amount of energy to be delivered is the aim of the infrastructure.

5.2 Signal transmission

This is the widest frequency range. It ranges from less than a hundred kHz of radio waves to tens of GHz of the most modern 5G communication systems. Obviously, because of the wide range of action, it is possible to identify a very large number of sources; for lower frequencies, there are televisions and radios, while for higher frequencies there are mobile phones, WiFi devices and base transceiver stations, which, while not normally handled by users, are essential for the mobile phone system. The radio frequency information transceiver system, especially for telephony services, is based on stations located throughout the territory to ensure signal coverage. These stations are called base transceiver stations (in Italian "stazioni radio base") and their structure is well established and easily schematized:

- Service. This is the basic unit that goes to make up the antenna. The word service is intended for what the final consumer uses, for example, a given carrier frequency used for internet connection rather than the ability to receive and make calls. Multiple services can be provided by the same antenna.

- Antenna. Depending on the service provided, they can be in the classic form of a sector or parabola (more common in radio links). Antennas are those parts dedicated to the actual transceiving of signals. They carry out their function in a certain portion of space, identifiable through the radiation pattern, proper to the antenna under consideration; generally, for sector antennas, the opening angle of the radiation beam in plan is about 60, 90 or 120 degrees. When uniform coverage over the territory is needed, it is most likely that a single antenna is not enough; for 360° coverage, three elementary antennas are usually used with an offset in space of 120°. It is important to distinguish between an antenna and a transmitter because the antenna is just a piece of metal and the transmitter is the electronic circuitry that sends signals to the antenna that then irradiates into the air.

- Radiating system. It is the composition of the antenna and the transmitter system. Normally, antennas are passive components (except for new generation devices) and they are commanded by a proper device which manages the digital traffic.

- Base Transceiver Station. Combining the radiating system with a support results in the complete base transceiver station. The functions of the support, which may be in the form of a scaffold, metal truss, or pole, are primarily to provide structural rigidity to the system, to move the radiating system away from houses and people, and to provide an elevated position to encounter as few obstacles as possible to ensure the best signal propagation.

Base transceiver stations are easily recognizable in everyday life simply by looking around, and they base their operation on a phenomenon quite similar to a really simple theoretical model: the dipole antenna.

5.2.1 Dipole antenna

A dipole antenna is the simplest example of an antenna for the irradiation of electromagnetic fields. The fundamental principle is the oscillating dipole, which consists of two charges that vary over time and can be treated analytically. Starting from a dipole of static charges q_1 and q_2, of equal module and opposite sign, positioned in vacuum at a distance a to each other, it is possible to investigate the electric field that permeates the surrounding space [5], [37]. In Figure 5.2 it is possible to see the described system for a better comprehension.
To evaluate the electric field $\mathbf{E}$ in a given point P, it is preferable to calculate firstly the electric potential $\mathbf{V}$ of the charges' distribution as summation of scalar values and after derive in components, according to $\mathbf{E} = -\nabla V$.

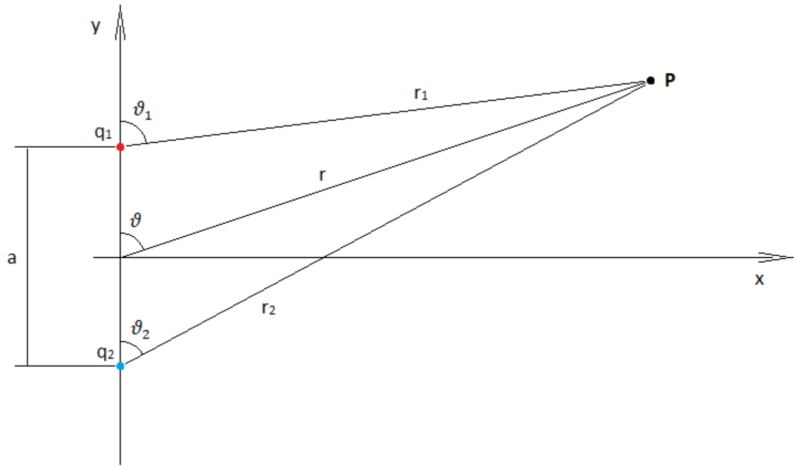


Figure 5.2: Geometry definition of the problem

Static electric dipole

For a two charges system, the electric potential in a generic point in the space results in:

$$V(P) = \frac{1}{4\pi\epsilon_0}\left(\frac{q_1}{r_1} + \frac{q_2}{r_2}\right) \tag{5.1}$$

In this specific case, the charges are just different in sign (q_1 is positive and q_2 is negative) so it is possible to simplify in:

$$V(P) = \frac{q}{4\pi\epsilon_0}\frac{r_2 - r_1}{r_2 \cdot r_1} \tag{5.2}$$

According to the far field approximation, because it is more important to know the field expression far from the antenna, it is possible to do two approximations:

- The two angles individuated by the vertical axis, each charge and the point P in the space can be considered the same, and equal to θ in Figure 5.2: $\theta_1 = \theta_2 = \theta$.
- The two distances between the point P and each charge can be approximated to the distance between the point P and the midpoint of the dipole antenna: $r_1 = r_2 = r$.

With these approximations the final formula of the electric potential V becomes:

$$V(P) = \frac{q}{4\pi\epsilon_0}\frac{a \cdot cos(\theta)}{r^2} \tag{5.3}$$

Defining the dipole moment, a vectorial quantity which has the same direction of the dipole axis, the sense from the negative charge to the positive one and a magnitude of: $|\mathbf{p}| = q \cdot a$, it is possible to define two other formulations for the electric potential:

$$V(P) = \frac{p \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^2} = \frac{\mathbf{p} \cdot \mathbf{u_r}}{4\pi\epsilon_0 \cdot r^2} \tag{5.4}$$

With the symmetry of the geometry, it is much easier to proceed in the analysis adopting plane polar coordinates instead of Cartesian coordinates, with either a new definition of the operator ∇:

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right) \rightarrow \nabla = \left(\frac{\partial}{\partial r}, \frac{1}{r}\frac{\partial}{\partial \theta}\right) \tag{5.5}$$

Applying the relation between electric potential and electric field it is possible to obtain the formula final of the electric field generated by a static dipole:

$$\mathbf{E} = E_r \mathbf{u_r} + E_\theta \mathbf{u}_\theta = -\frac{\partial V}{\partial r}\mathbf{u_r} - \frac{1}{r}\frac{\partial V}{\partial \theta}\mathbf{u}_\theta \tag{5.6}$$

Each component can therefore be calculated as:

$$E_r = -\frac{\partial V}{\partial r} = -\frac{\partial}{\partial r}\left(\frac{p \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^2}\right) = \frac{2p \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^3} \tag{5.7}$$

$$E_\theta = -\frac{1}{r}\frac{\partial V}{\partial \theta} = -\frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{p \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^2}\right) = \frac{p \cdot sin(\theta)}{4\pi\epsilon_0 \cdot r^3} \tag{5.8}$$

Oscillating electric dipole

As previously said, the dipole antenna is an oscillating electric dipole. The two charges change in time, maintaining the relation $q_1 = -q_2 = q$, but the value q changes in the time according to a sinusoidal evolution. The time dependence of the charges represent a time dependence for the dipole moment: $p(t) = p_0 \cdot sin(\omega t)$.
Replacing this new formulation of the dipole moment in the electric field formulation in the static version 5.7, 5.8 it is possible to see time dependence:

$$E_r = -\frac{\partial}{\partial r}\left(\frac{p(t) \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^2}\right) = \frac{2p_0 \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^3} sin(\omega t) \tag{5.9}$$

$$E_\theta = -\frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{p(t) \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^2}\right) = \frac{p_0 \cdot sin(\theta)}{4\pi\epsilon_0 \cdot r^3} sin(\omega t) \tag{5.10}$$

These two new formulations do not properly represent a wave because there is not the concept of propagation. There is again a distinction between near field and far field. According to 5.9, 5.10 there is no difference between generation and reception of the perturbation, they happen simultaneously and there is no propagation delay. In this condition, there is only the possibility to see the time temporal periodicity of the phenomena.
Including in the discussion the delay due to propagation and so the far field conditions, it is possible to properly see the wave with both spatial and temporal periodicity.

$$t_{recieving} = t_{generation} - \frac{r}{c} \tag{5.11}$$

The time in 5.9, 5.10 is the generation time, the propagation is not included, and so they become:

$$E_r = \frac{2p_0 \cdot cos(\theta)}{4\pi\epsilon_0 \cdot r^3} sin\left(\omega t - \frac{\omega}{c} r\right) \tag{5.12}$$

$$E_\theta = \frac{p_0 \cdot sin(\theta)}{4\pi\epsilon_0 \cdot r^3} sin\left(\omega t - \frac{\omega}{c} r\right) \tag{5.13}$$

Another consequence of the far field approximation is that, in real life, antennas are placed to work with theta angles far from 0 or π and so, the contribution of E_r is negligible in respect to E_θ. For this reason, the magnitude of the electric field in normal conditions is approximated to only its component in $\mathbf{u}_\theta$: $E \simeq E_\theta$.

5.2.2 Antennas

To irradiate a signal it is possible to use many types of antennas and each shape of antenna has its characteristics. One important feature of an antenna is the principal direction of the beam, but also the typical frequency is a fundamental parameter. Among the different types of antenna frequencies can vary from around 1MHz of monopole antennas (radio mast or radiating tower), to GHz of parabolic antennas passing through sector antennas which are more widely discussed. Just for the sake of completeness, it is worth mentioning that parabolic antennas are used in a very wide frequency range, the various applications differ in size because very large structures are used for lower frequencies (radio link for example), whereas the higher frequencies go, the smaller the size.

Architecture of a sector antenna

The sector antenna is the most used shape for the final irradiation of the signal, especially in mobile phone technology. The architecture depends on its size, but generally, it consists of a fibreglass enclosure to ensure protection of the inner parts against the weather conditions. Inside the enclosure, there are the radiative elements. As visible in Figure 5.3, each element consists of a series of metal patches wired on the back of the sustaining plate. To complete the system, an aluminium reflector screen is placed behind the sector to limit the propagation along unwanted directions.[38], [39].

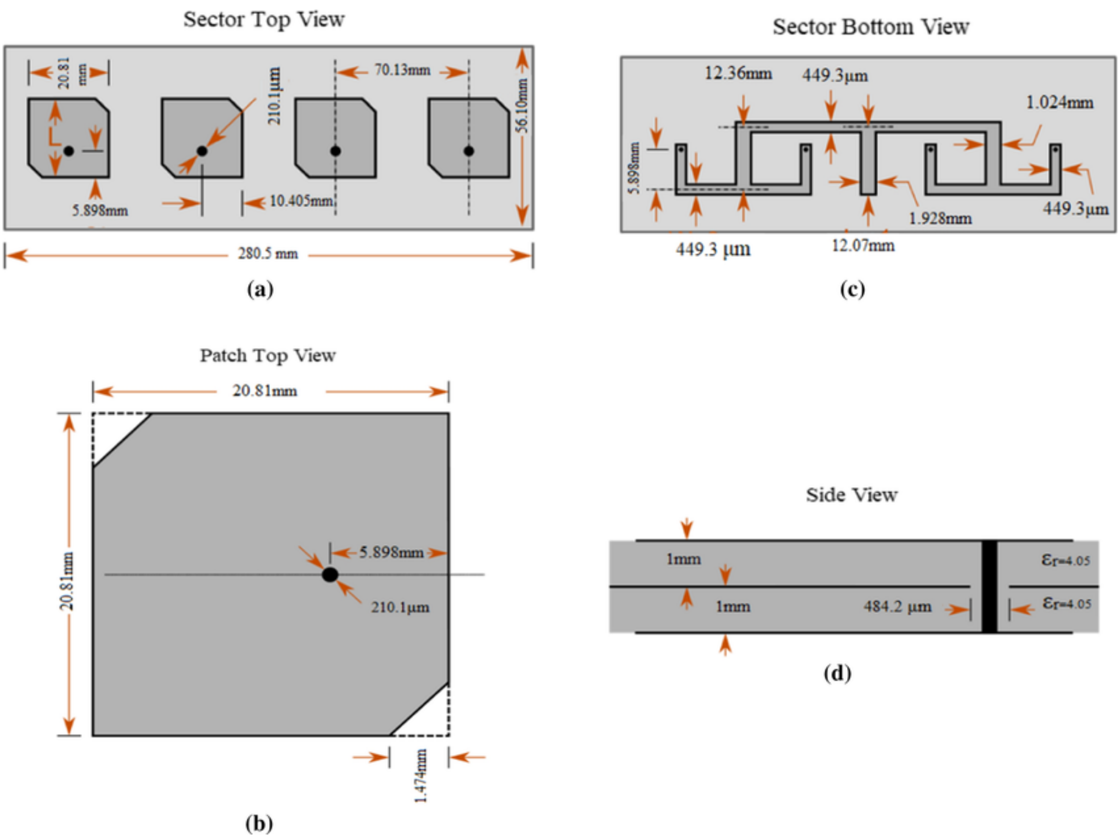


Figure 5.3: Interior of a sector antenna [38]

Typically, this type of antenna is placed on already existing buildings or dedicated structures, and they are almost always installed with a down-tilt angle. This is for two main reasons: to better ensure coverage for the people and to avoid interference between signals (they emit at different angles). Optimal tilt angles are achievable both electrically and mechanically: electric tilt is realized in the antenna enclosure, by tilting the elements or supplying them with a properly phase-shifted signal and mechanical tilt is obtained by acting on the entire enclosure during the installation. Each antenna has a diagram which shows the gain in the surrounding space, this is called radiation pattern, and it allows seeing how the lobes are disposed; in Figure 5.4 it is possible to see a window of the software EmLAB in which the radiation pattern is reported among other features of the selected antenna.

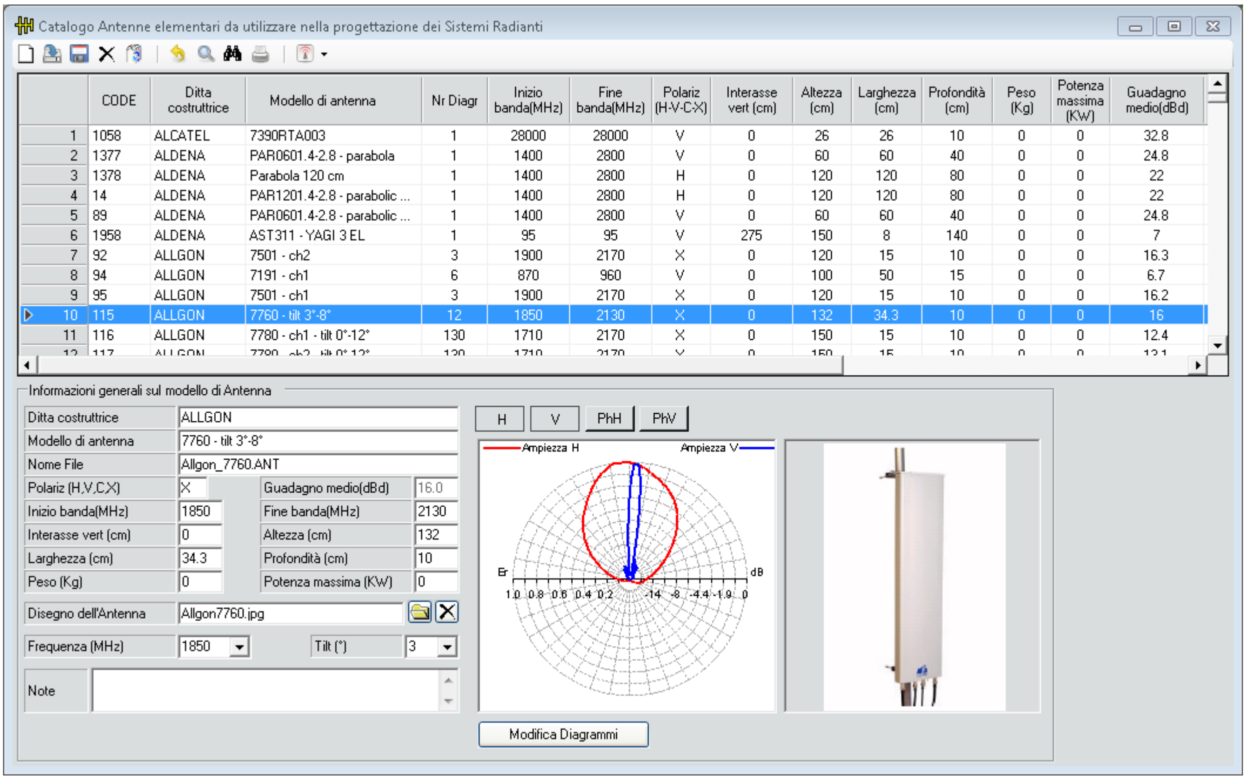


Figure 5.4: Features of an antenna, example

Figure 5.4 clearly shows the shape of the gain distribution in the space. This graph uses polar coordinates where the antenna is located in the centre of the grid. In red is shown the shape from above, on the horizontal plane and in blue is the shape from the side, which means the projection on the vertical plane.
Looking at the chart reported in Figure 5.4, it is immediately visible that the selected antenna is strongly non-isotropic. In fact, it is possible to see that the gain has a maximum of about 5° towards the left on the horizontal plane and a drastic reduction for wider angles. A similar situation happens on the vertical plane, in this case, the antenna shows by itself a tilt of about 3° downwards and has a narrow lobe with less than 10° of angular opening. This kind of graphic is very common with sector antennas, they are built to have a main lobe characterized by best performances and some secondary lobes with a much weaker irradiation capacity.

5.2.3 System

A system is the union of an antenna and a transmitter device. They can be realized in a unique solution like in last-generation antennas or split into two different parts and connected by specific wires. In this second scenario, the antenna is a passive component and simply acts like an irradiating element in a case; the generation of the correct signal is performed by the transmitter. Normally each antenna has more than a single irradiating element in its case so it is possible that an antenna, studied to work at different frequencies, is connected to different transmitters and so it is part of different systems.
In Figure 5.5 it is possible to see a window of the software EmLAB, a program later discussed, which shows a radiation pattern of a system:

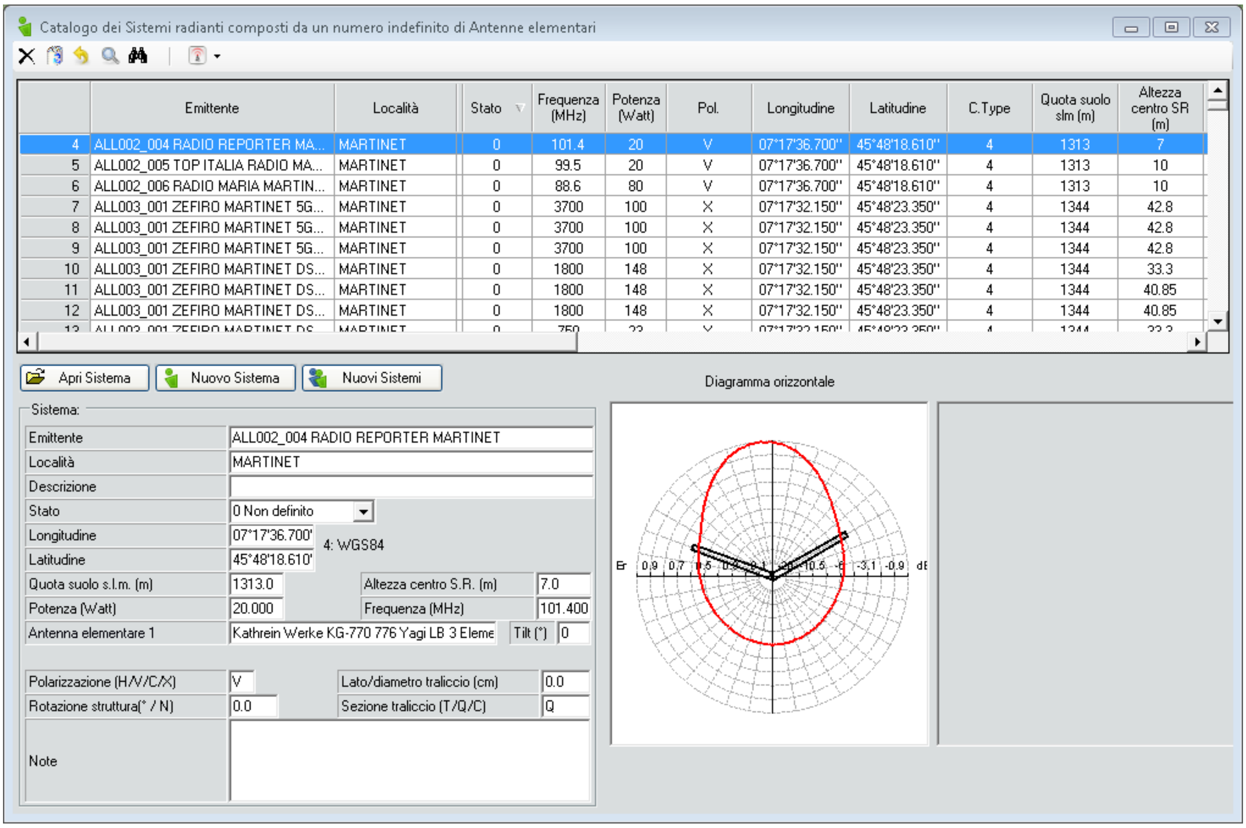


Figure 5.5: Example of a system

Using a sector antenna, the service is provided with a non-isotropic coverage. If the client of certain services is concentrated in specific sectors, it is possible to provide the due coverage with only a few antennas pointing towards the interested directions.
On the other hand, in urban applications, for example, it could be necessary to cover the entire 360°. Normally, in this case, operators install multiple systems relative to different antennas to have multiple antennas pointing in different directions equipped with the same service but managed by different systems.
In Figure 5.6 it is proposed another window of the software EmLAB in which it is represented another radiation pattern of a 5G3600 system, in this case, it is not a simple pattern any more, and therefore defined as radiation solid:

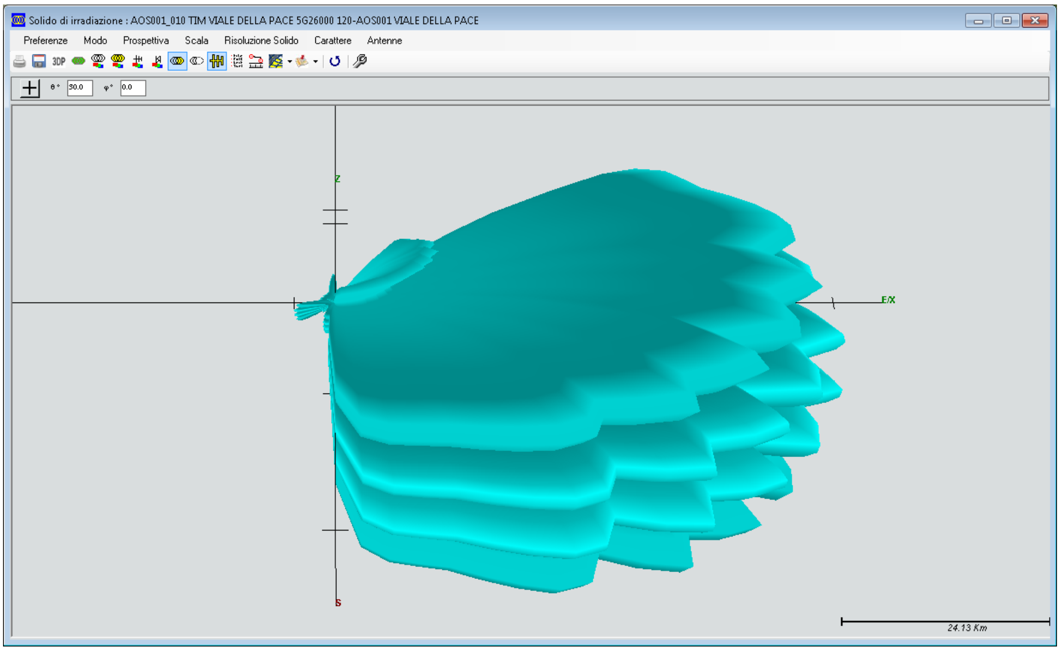


Figure 5.6: Radiation solid of a system

In Figure 5.6 the 5G technology is well recognized from the particular shape of the solid. In fact, it can be seen that there is a jagged multipoint termination and not a homogeneous front. This fact is due to the innovative beam sectorization method introduced in this latest technology, to serve with greater power only the area that requires it; without increasing over the entire radiated area, but only within the specific sector.

5.2.4 Base Transceiver Station

A base transceiver station (BTS), or cell tower, is the composition of many antennas with many systems and a structure of support. In rural areas, it is possible to see a standard configuration of three sector antennas evenly spaced on a support, but in more densely populated areas mobile operators may adopt the co-siting solution. With this setting, one single support can accommodate more systems to have a more compact solution.
Cell towers not only consist of the union between antennas and support structure, in the definition of BTS it is also considered the supply system to provide power to the antennas and the signal mixing system to manage the data flow. Furthermore, for obvious reasons, the BTS is equipped with the lightning protection system (LPS) to protect all its components. There are four different types of BTS:

- Raw land. In this configuration, the radiative systems can be positioned up to 30m in height thanks to poles or metallic trellis with a strong base.
- Roof top. Systems are placed on small scaffolds on top of buildings. This is a common solution in cities where the height from the soil is already provided by the building itself.
- Co-locato. This installation uses already existing structures to install antennas. The main difference between this solution and co-siting is that the services provided by the two systems are different, like radio masts.

- Micro-cells. This solution involves the use of small antennas to recreate low visual impact BTS for those areas like historical centres or remote and hard-reaching sites.

Talking about microcells, it is important to remember that each type of BTS has to submit to strong legislation in terms of permissions. Building a raw land BTS means realizing an impactful structure, mainly for the landscape; in fact, this is why local administrations are asked to have effective land management (in Italian "piani urbanistici") in order to avoid any kind of problem and dedicate specific areas to eventually build BTS.
BTS are also useful in localization. With less precision than GPS, phone cells are also used to determine the position of devices which are linked to specific cell towers. The name cell phone derives from the cell subdivision that BTS form in the space, like a mesh determined by nodes. As for the measurements, in order to have a referred position, each BTS is well located with its coordinates. In Figure 5.7, it is possible to see an EmLAB window, the software that is used later for the simulations in radio frequency, which shows different systems in a single BTS in the city of Aosta:

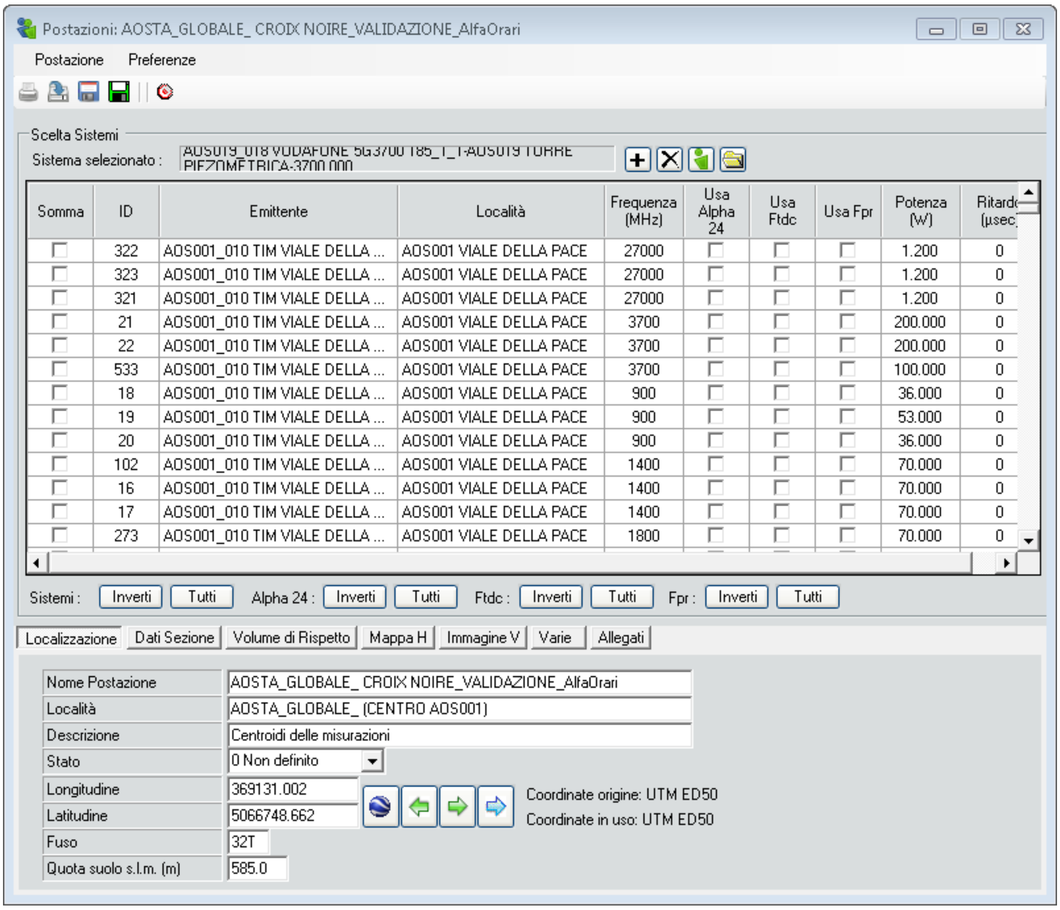


Figure 5.7: Example of some systems included in a workstation

For the selected system it is possible to see that latitude and longitude are well-defined, in a specific coordinates system, in order to identify the workstation, not less important it is also reported the altitude, in order to consider the morphology of the surrounding space as well.

5.3 Power transmission

Electric power transmission, at 50Hz is classified under the ELF frequencies category, shown in Table 5.1 the European transmission frequency. Unlike the previous part on radio frequency, in which it was correct to suppose far field approximations, ELF is characterized by near field conditions. According to this, it is no longer possible to evaluate the magnetic field only as a function of the electric field 3.36, those conditions led to neglect of the influence of the magnetic field in the presence of very low electric field values such as those in far field conditions for radio frequencies.
In this part of the spectrum, electric and magnetic fields act independently. Power lines and electric substations are electromagnetic sources because they both work with high voltage and high current:

- High voltage is necessary to reduce losses across the lines. Although the strongly reactive behaviour, power lines are made up of metal conductors and, due to their resistance, they dissipate heat according to Joule's law. Keeping constant the transmitted power with having a higher voltage means lower flowing current and so minor losses.

- High current because the demanded power, even if provided at high voltage, is high enough to involve currents from tens to hundreds and more of ampere.

It is possible to shield or minimize electric and magnetic fields for power transmission, but there would be also drawbacks. Insulated electrical cables have several layers surrounding the conductor, and one of these consists of a metallic shielding and armour layer.
This part of the enclosure not only gives structural resistance and protection from crushing, but its primary task is to confine the electric field in the area occupied by the insulation layer thanks to the replication of ground potential. This technology of insulated cables is not widely used to prevent electric field propagation for two main reasons:

- Cost. Insulated cables are much more expensive than electric naked conductors, the cost depends on the insulator adopted, and they are used especially when discharge distances in air cannot be ensured (buried electrical lines, industrial and civil applications).

- Necessity. Although HV power line generates discrete electric fields, the attenuation provided by just a wall between source and measurement point is enough to maintain the values under the warning threshold.

The presence of a metallic shield or armour also affects the magnetic field, in these parts of the cable not negligible eddy currents establish and contrast the action of the primary magnetic field. These currents, however, are responsible for losses associated with Joule effect.
It is also possible to minimize the magnetic field generated by a power line in not dissipative way, by altering the normal disposition of the conductors. Normal trellises (delta pylons) provide for the presence of the three-phase conductors almost completely coplanar with each other, this positioning criteria is not ideal to have low values of magnetic field.
The procedure by which the cable arrangement is changed is called *split phase* [5]. This method find application especially in LV, in terminal distribution in the buildings, when high currents lead to exceeding thresholds, but it is strongly limited for two reasons:

- Complexity and cost. Splitting phase requires dividing each phase into multiple branches, but the system acquires a structural complexity, the disposition has to be feasible in a cost-effective way because more branches lead to an increase in the insulation material used.

- Temperature. The realization of a more complex cable structure results in a deterioration of the heat exchange conditions. The total exchange surface increases, but so do the heat sources to be cooled, which are in conflict with each other.

5.3.1 Electric power lines

The standard configuration of an HV power line consists of a set of three main conductors for power transmission and one or two ground wires (in Italian "funi di guardia") with the main purpose of lightning protection. This type of geometry does not involve great complications from the modelling point of view, even in the configuration with several conductors per phase. The elementary source is in fact a conductor of indefinite length, and the presence of several phases or several conductors is handled by the superposition principle.
Each conductor in a power line does not maintain a straight position at every single point, between two consecutive pylons it assumes a catenary arrangement and there are two ways to deal with this fact: working with cautionary assumptions or elaborating a more complex model of the line. The first way is the one used by the normative CEI 211-4, according to it the conductors can be treated like straight conductors but with a height with respect to the soil given by the worst case, when the cable is subject to maximum deflection [40].
According to the same normative, there is also the possibility of working in a second way, i.e. with finite elements simulations that break down the overall source into several sections to approximate the actual layout from the cable and calculate the composition of the contributions at the desired point or in a portion of space approximated by a mesh.

Power line in plane regions

With a procedure explained in CEI 211-4 [40], it is possible to evaluate the electric and magnetic fields analytically. For the electric field in particular there are strong assumptions which limitate the field of application such as: same geometry along the path, flat terrain approximating an ideal homogeneous conductor. In this analysis on power lines, the electric field evaluation is not performed, but it is worth introducing some interesting aspects that characterize this discussion. In particular, there are three main concepts [5]:

- Method of images. This first aspect is used to model the closing of field lines to the ground. According to this method, the terrain with its electric permittivity can be replaced with the same material in which the original electric line is suspended, as long as an equal number of sources, of the opposite nature and mirrored to the interface, are inserted.

- Reverse analysis. Normally the evaluation of electric fields in electrostatics starts from well known charges, for a power line this information are not available from the beginning. In this case, the analysis starts from the potential of the surface of each conductor, the only useful available information. By defining a system of equations that expresses the electric potential of each conductor, including ground wires and mirror sources, as a function of charges and coefficients defined by geometry and distances, it is possible to find a matrix expression that can be inverted to evaluate the lineal charges of the conductors.

$$\mathbf{V} = p\ \mathbf{Q}\ \rightarrow\ \mathbf{Q} = p^{-1}\ \mathbf{V} \tag{5.14}$$

These charges are now the basis for the evaluation of the electric field generated by three indefinite wires.

- Electrostatic sequence. A time variable regime, like the 50Hz used in European power transmission system, is represented like a sequence of electrostatic regimes with different values for each field calculation, thanks to the very high propagation speed of EMF.

For the magnetic field, the classical Laplace formulation or differential form of Biot-Savart formulation finds application. In this case of undefined rectilinear conductors, some geometrical simplifications occur, and the standard relation is the Biot-Savart law (integral form of Biot-Savart):

$$\mathbf{H} = \frac{I}{2\pi r}\mathbf{u}_\phi \tag{5.15}$$

Where r is the distance between the centre of the conductor (assumed as a line) and the analysed point, I is the current passing through the conductor and $\mathbf{u}_\phi$ is the circumferential versor determined by the cross product between the versor of the current density $\mathbf{k}$ and the radial distance $\mathbf{u_r}$:

$$\mathbf{u}_\phi = \mathbf{k} \times \mathbf{u_r} \tag{5.16}$$

In Figure 5.8 there is the visual representation, in this case the wire has been represented vertically.

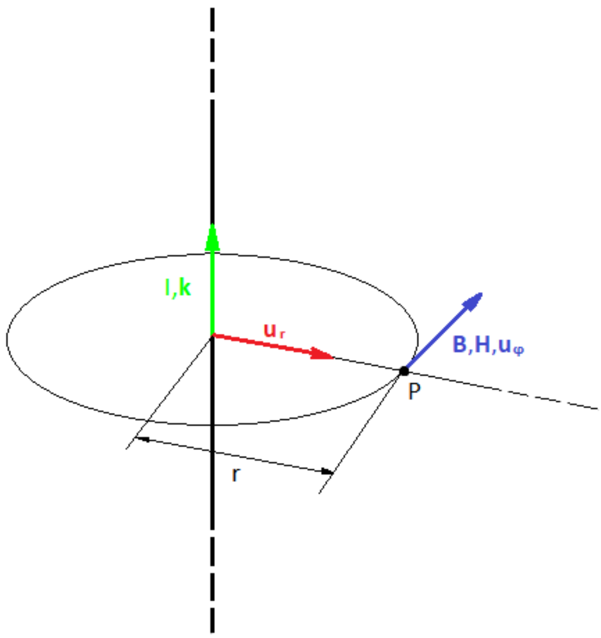


Figure 5.8: Visual representation of Biot-Savart law

With the presence of multiple wires, the superposition principle allows considering all the effects. For multiphase power lines must be taken into consideration that each single contribution has its own time phase from the multiphase regime. It is possible to define an overall formulation composed by two parts, because both the components on horizontal (real) and vertical (imaginary) axis are time-dependent [5]:

$$\mathbf{H(t)} = H_x(t) + iH_y(t) \tag{5.17}$$

This way of considering the various contributions according to their respective phases is called "coherent combination". It is possible to perform the analysis in another way, with an "incoherent combination", by adding together the squares of the RMS values and taking the square root to form the overall RMS. This second formulation does not ensure the worst case scenario, but it is useful when no phase relations are available and a cautionary evaluation is necessary [41].

Power lines in general

According to CEI 211-4 [40], the suggested formulations become inconsistent when the geometry is different from a flat surface with same height conductors. The normative itself the is open to external formulations that can provide an additional tool in cases of necessity where land and power line configurations are complex. This is the reason many dedicated software have been created and especially the GIS software, to have a well-defined basis for the conformation of the territory and implement more rigorous analyses. To achieve more detailed simulations, and to have a more realistic conformation, the assumption of straight line have been abandoned. In order to achieve a compromise between rigour and complexity of the simulation, it was decided not to faithfully reproduce the catenary, but to approximate its course with a series of consecutive segments. In this way, each single segment gives a contribution to the overall effect (electric or magnetic field), and each segment is only enabled when centroids are in the nearby.
In this case the analysis concerns the magnetic field principally and for its evaluation it is used the differential form of Biot-Savart integrated on the segments (or catenary cord) along the path defined by its extreme points P_1 and P_2:

$$\mathbf{H}_{elem} = \frac{I}{4\pi}\int_{P_1}^{P_2} \frac{d\mathbf{l}\times\mathbf{r}}{r^3} \tag{5.18}$$

In this case the composition is double even in time independent regime, because all the segments of a single conductor acts in phase, while to take into account the other two conductors (in a single circuit line) it is necessary to use the superposition principle. With time dependant currents the same assumptions made for flat terrain and straight line conductors can be made, in a specific point the magnetic field can be evaluated with a phasor approach and after decomposed according 5.17, [41], [5]. In order to map a volume and have an idea of how the values are spread around the power line, finite element method (FEM) analysis is required. By dividing the surrounding volume into elementary volumes, the magnetic field is calculated at the vertices and interpolated according to FEM analysis. This process is no longer feasible analytically, it is left to specific software that implements these calculation methodologies.

5.4 Coordinate systems

A coordinate system is a mathematical framework that allows the description of the position of points in space. In general, a coordinate system enables the representation of geometric objects—such as points, lines, and surfaces—using one or more numbers, known as coordinates. Depending on the application and the dimensional space, different types of coordinate systems can be used. For instance, in two-dimensional space, Cartesian coordinates (using x and y axes) are commonly used, while spherical or cylindrical coordinates might be applied in three-dimensional contexts.
Coordinate systems are essential in various fields such as engineering, cartography, physics, and geodesy. They provide a consistent reference for defining the spatial relationships between objects and for performing calculations involving distances, angles, and transformations.
In this work there are four reference systems that are used: WGS84, ED50/UTM zone 32, Cassini-Soldner, Gauss-Boaga.

5.4.1 WGS84

The WGS84 (World Geodetic System, 1984) is a global coordinate system developed by the United States Department of Defence, primarily for GPS (Global Positioning System) applications. It is a geocentric system, meaning that the origin is located at the Earth's centre of mass. The coordinates in WGS84 are expressed in terms of latitude, longitude, and height above the reference ellipsoid (a mathematically defined surface approximating the shape of the Earth). The reference ellipsoid used in WGS84 has the following parameters:

- Semi-major axis: 6378137 meters;
- Flattening: 1/298.257223563.

WGS84 is the standard for most global mapping and navigation systems, making it the most widely used geodetic coordinate system in the world.

5.4.2 ED50/UTM zone 32

The ED50 (European Datum 1950) is a geodetic datum used to map and survey Europe during the mid-20th century. It is based on the Hayford ellipsoid (International Ellipsoid, 1924) and was primarily used before the adoption of modern global systems like WGS84.
The UTM (Universal Transverse Mercator) system divides the Earth into 60 zones, each covering 6 degrees of longitude. Zone 32 refers to the area between longitudes 6°E and 12°E. ED50 combined with UTM Zone 32 was commonly used in Central Europe for large-scale mapping projects.

5.4.3 Cassini-Soldner projection

The Cassini-Soldner projection is a type of cylindrical map projection that preserves distances along the central meridian. This projection is conformal along the meridian, meaning that angles are preserved, but it introduces distortion as the distance from the central meridian increases. The projection is mainly used for small-area mapping where the distortion is minimal. It was historically applied in military and cadastral surveys. Unlike WGS84, which is a global system, Cassini-Soldner is better suited for local mapping projects.

5.4.4 Gauss-Boaga projection

The Gauss-Boaga projection is a variant of the Transverse Mercator projection, specifically designed for Italy. It is based on the Bessel ellipsoid (a reference ellipsoid introduced in 1841) and was adopted as the standard projection for Italy's topographic and cadastral mapping. The projection divides Italy into two zones:

- **West zone**: Central meridian at 9° E;
- **East zone**: Central meridian at 15° E.

This projection is still used today in many Italian cartographic systems, particularly in national cadastral maps.

6. Radio Frequency (RF) exposure indicator

6.1 Activity description

As previously mentioned in Chapter 4.5, in 2018 the Italian Ministry of the Environment and Land and Sea Protection started the EMF research programme. This programme consists of several activities that each ARPA can undertake to evaluate risks related to electromagnetic field exposure. With Activity A, ARPA VdA decided to evaluate the emission of EMF and calculate exposure indicators for the population at extremely low frequency (ELF) and high frequency (RF). These indicators practically make use of histograms and adapted maps, which are divided into intervals of field strength in relation to the number of people exposed to them. This chapter focuses on the RF part of the programme, but some assumptions remain valid for both parts. To get to the point of defining the RF exposure indicator, there are some analyses to be done. As a first step, the nation is divided into regions, but they are too wide to be treated as a whole. The Revenue Agency defines indeed much smaller portions called census zones to perform economic and statistical analysis. Those census zones are perfectly suited for this purpose, according to [42] they are small parts of territory homogeneous from an economic and socio-environmental point of view.
The minimum required of ARPA VdA for this activity is to perform the indicators' evaluation on at least two census zones, but to have a more robust indicator for RF it is chosen to perform the analysis on the whole municipality of Aosta. Defined the area of interest of this activity, electromagnetic fields are evaluated in each building of Aosta; the procedure has to be formalized. The EMF research programme suggests two different alternatives: measurements or simulations:

- Measurements: in this way, the RF electric field would be measured exactly with the correct attenuation in the real condition. On the other hand, this method involves the full cooperation of the population, which should allow people to enter the house to carry out measurements.
- Simulations: in this way, the RF electric field would be estimated at the desired points using software to model the system of sources with far fewer logistical problems. As with all simulations, a validation activity based on measurements is required.

To have both a strong indicator and a low impact on the population, the choice of simulations is made. From a view of the horizontal plane, the points to use as markers in the simulation are easily recognizable. They are the centroids of the buildings, but as this is a 3D simulation, it also requires the height of the point to be taken into consideration. The height of the simulation is a crucial aspect. For a risk exposure analysis, the worst-case scenario would be on the top of each building, or at the same height of the irradiating antennas where BTS are directly visible and there is no attenuation by surrounding walls. But this is not the case, this is an analysis to characterize citizens' exposure levels. The best condition to evaluate the height is in the most significative point of each building, this means the average height or the most populated floor. To have a standard value of this parameter, ARPA VdA made a preliminary study on the buildings in Aosta. In this study, it was looked for a common aspect or a certain height or number of floors that represent the real distribution of buildings. As a preliminary stage, all the buildings with a residential intended use have been considered. This stage showed a prevailing abundance of buildings with two or three above-ground floors, with an associated height between seven and ten metres. Keeping into account that a one-room apartment to have all the permissions and the habitable has to be bigger than $28m^2$, restricting the analysis the numbers slightly change, but the pattern remains the same, in Figure 6.1 and Figure 6.2 it is possible to see the summarized results:

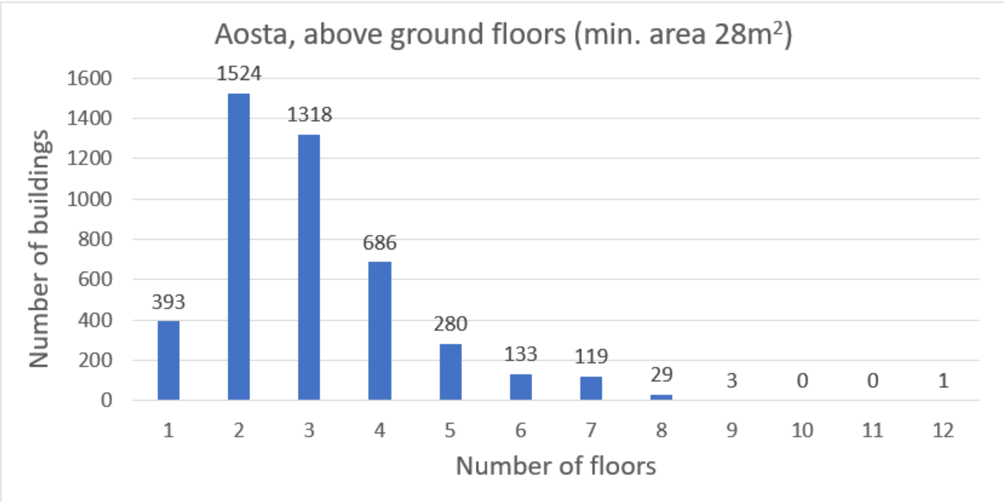


Figure 6.1: Floor distribution in Aosta

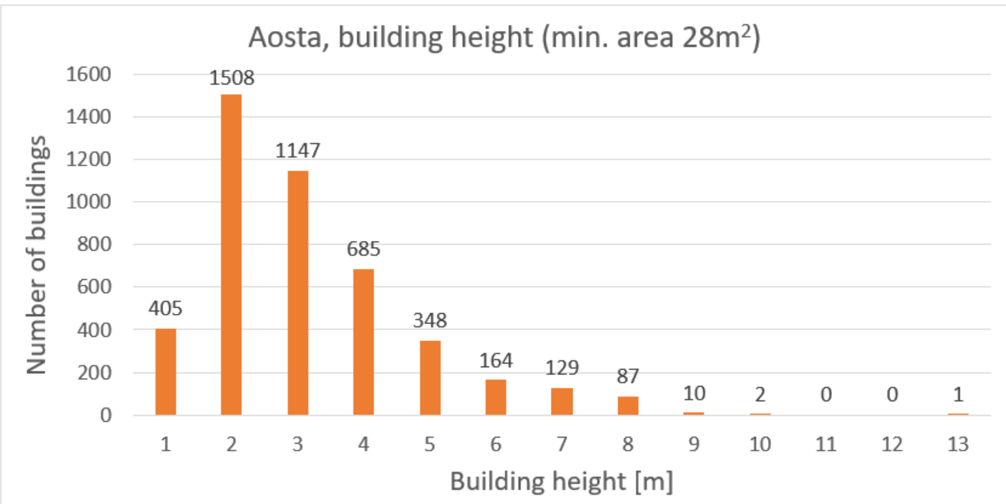


Figure 6.2: Height distribution in Aosta

According to 6.1 and 6.2 it is possible to see that the numbers of floors two and three are the most common configurations. The height, instead, is expressed intending the ground floor 4m height and the following 3m height each one. Taking into consideration that four metres for the ground floor is typical in Aosta, in other sites this characteristic may not be respected. Including the height analysis in the national frame, the guidelines have highlighted the same value. The simulations have been set to 5m in height. This number allows the study to keep significance even in Aosta because it sets the simulation point in a hypothetical second floor at 1m off the floor. This is a consideration that perfectly matches the height study, and it is reasonable also on a national scale.

6.2 QGIS

To associate exposure levels and specific geographical areas (census zones) or with specific points in space (centroids), it is necessary to work with files that include information of a geographic nature. This need, as also recommended in the definition phase of the EMF research program itself, is solved by using GIS software. The word GIS is an acronym meaning Geographic Information System and refers to software which allows handling data of various nature. These software are widely used and promoted for their versatility even by the European Union like the PVGIS, a work environment that allows to obtain data about solar radiation and photovoltaic systems, up to QGIS, the software which has been used in this project.
QGIS is one of the most diffuse open-source GIS software in the world, it was created in 2002 and now it is sustained by a strong community worldwide. This software develops on a C++ and Python basis, and it is open to many operative systems [43]. In this project, it has been used version 3.28.15 which is an update of the version called "Firenze".

Figure 6.3: QGIS loading window with logo and version

QGIS is structured to work with different files in the form of layers. The files that have to be manipulated, in the opening phase, are assigned to a layer to have them all stacked one on top of the other. Just by drag and drop it is possible to arrange the layer disposition to bring in the foreground the desired one, and it is also possible to change the transparency of a layer to show what there is directly under. In this way it is straightforward to assess overlaps, intersections or pass features and so on, especially using the processing tools available in the software. In 6.4 it is shown the correct arrangement of layers to avoid having hidden elements. A third way to correctly display the layers consists in their activation/deactivation, as *Layer2* in the same image.

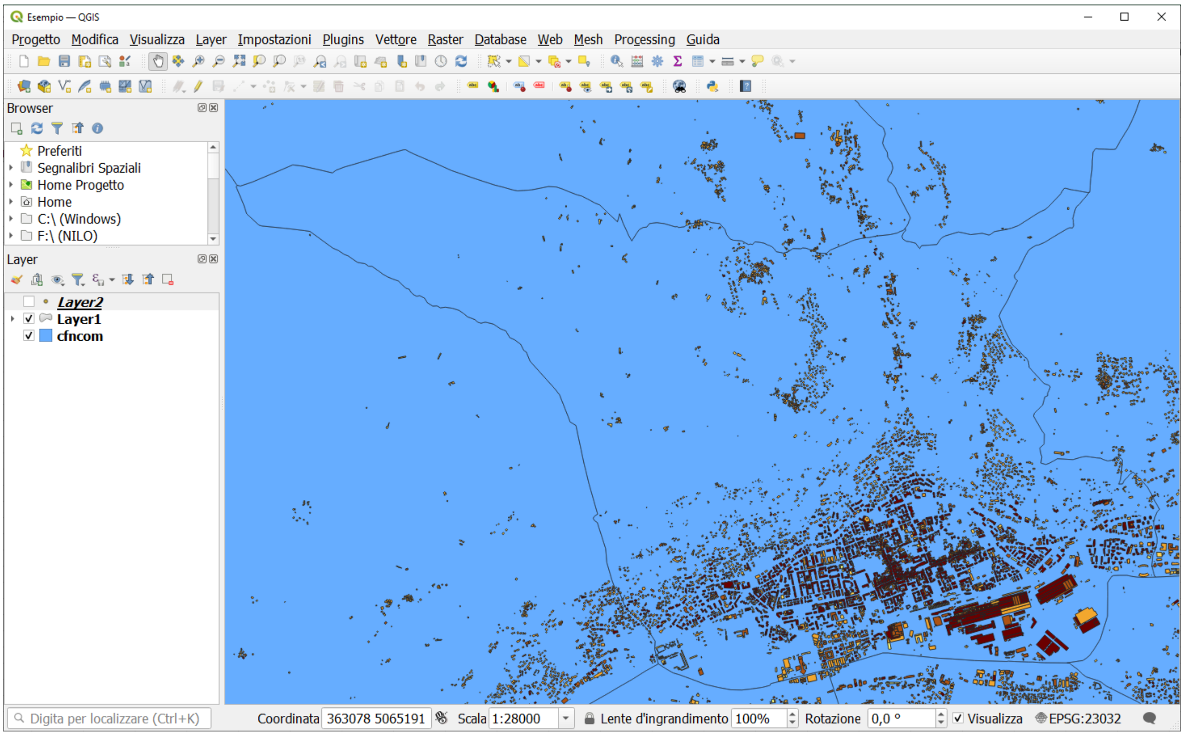


Figure 6.4: Normal view of a project in QGIS

The QGIS software allows the manipulation of different types of files. Among the many available, here is briefly described the organization of the three typologies mainly used in this project:

- **Shapefile**: This name refers to a family of files, characterized by different extensions but having the same name. This system allows splitting a large amount of information into a number of specific files. It is a vector format, the method used to describe geometries. For a successful reading of a shapefile, the different files must share the name and must be stored in the same folder. Between them must be present at least three fundamental files:
  - *.shp*: containing the data related to the definition of geometries;
  - *.shx*: containing the geometry identification indexes;
  - *.dbf*: containing the features of the file, called attributes, in a specific table.

  It is also possible to have files with other extensions containing ancillary information, they are not essential, but automatically generated when necessary by the working environment. In Figure 6.5 is shown the set of files necessary to correctly open the generic file “Tabella_Postazioni_2021”.

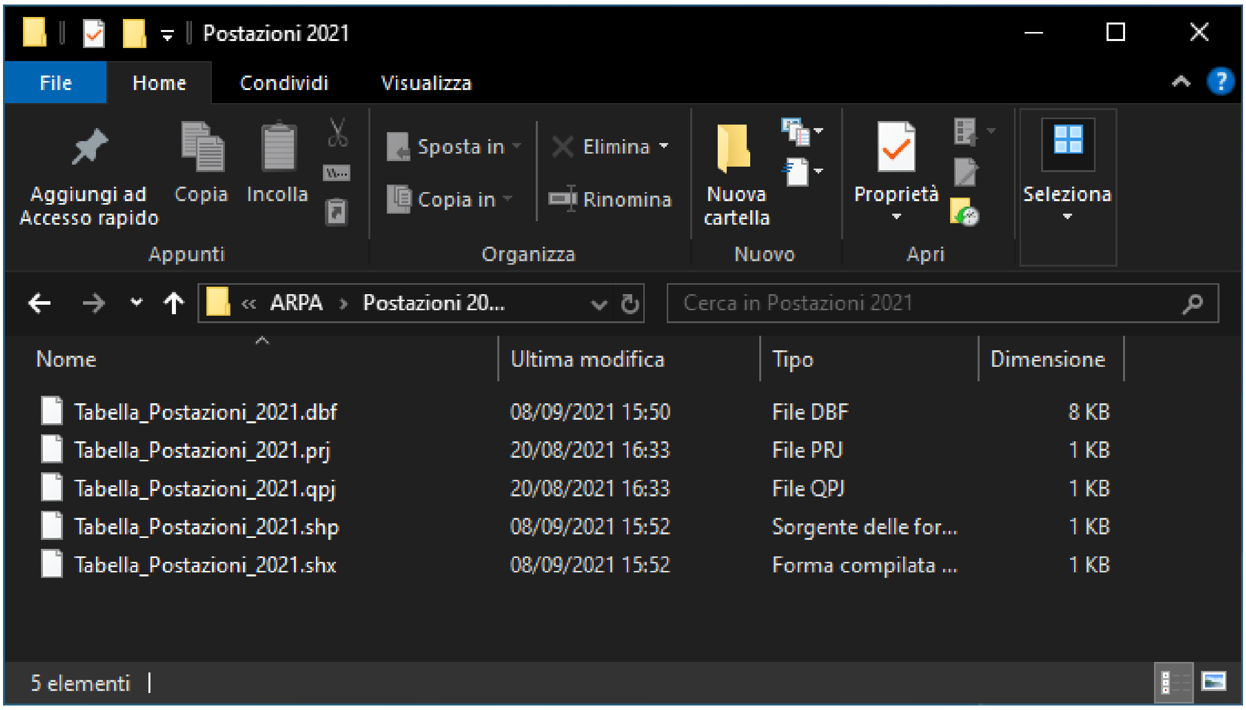


Figure 6.5: Set of files saved in the same folder, mandatory and ancillary

- **Raster**: This name refers to those files that represent images. They are organized in elementary cells, in a QGIS environment similar to pixels, and they can still be associated with additional but elementary information such as the position occupied by the single cell. They are not supported by a specific database but can be very useful tools to represent, for example, features that change even point by point as an orthophoto.

- **CSV**: This name identifies a very versatile file type. As these files are very common and not very elaborate, comma-separated values files can be used to transfer attributes between software and allow a more accurate manipulation outside the QGIS environment. They are opened without a specific geometry, so they act like attribute tables and are very useful for generating new and more complex elements interacting with other layers. These files are mainly used for transferring information between QGIS and Excel, mainly for the post-processing of the results.

6.2.1 Coordinate systems

In all GIS software, it is of fundamental importance to set up a proper coordinate system to allow the software to read and correctly interpret the geographical information of the opened file. Each file is coded in its specific coordinate system like it is written in a specific language; with an incorrect match, the geometries are still located, but not in the right spot, and therefore data coming from different files may not be properly aggregated. As previously mentioned, the demanded simulations have to be conducted about the real location of a building and its use, for example, an office rather than a flat. To have both these information, different files are used: Aosta's cadastral file and the regional buildings' file.

6.2.2 Regional files

The regional buildings' file, from now on "Edificato", is a database of all the buildings of Aosta Valley in 2011. It is coded in the coordinate system WGS84, and it has attributes like the height of the foot and of the top of each building referred to sea level, the surface of each building particle and an associated ID. This file has been taken into consideration because it is the latest updated and more accurate, at the same time this file cannot be used alone because it does not have any information about the intended use of each building.
Aosta's cadastral file, from here "Catasto", is another database of buildings, but is limited to the municipality of Aosta. It uses the Italian cadastral coordinate system which is a Cassini-Soldner system, and it has attributes like the intended use and the surface of each building. Again, this file cannot be used on its own because it lacks information on the sea level altitude of the buildings. Moreover, its coordinate system is not supported by QGIS. The Cassini-Soldner system used by the Italian cadastre is based on a complex system of reference points called trigonometrical points, which are used in different partial maps to reconstruct the national territory.
For the geographical analysis, it has been chosen to use the coordinate system EPGS:23032 or ED50/UTM zone 32N to have better compatibility with other settings. Working in this system means that both the file have to be converted, this is possible on QGIS.

6.2.3 File manipulation

Each QGIS project has its reference system talking about coordinates, it acts like a general definition, but each layer can have its system. This is possible to have the correct overlapping of different layers, but it is better to work with a single system. To change the coordinates, it is possible to use the reprojecting tool; it allows taking a file in a supported system and transferring it to another supported system. This procedure has been conducted only on the Edificato file because WGS84 was among the available. After that, it has been obtained a new Edificato file which has the same characteristics as before, but it is expressed in the desired system. For the Catasto file, this procedure is not possible because the Cassini-Soldner system used to define this file is not directly available on QGIS, there are other versions of this coordinate system, but they are referred to other parts well away from the interested area. In the absence of the correct coordinate decoding format, the Catasto file is processed in the wrong way, with no possibility of deriving useful information. To solve this problem, QGIS offers the possibility to define a custom coordinate system by setting several definitions. The system is written as a string of characters and the crucial part of the definition of the system is the centre of development (in Italian "centro di emanazione"), which is the reference for the entire project. The Catasto file has been provided by the municipality of Aosta which also provided the coordinates of the centre of development, that is the south-west corner of the cathedral's bell tower, just below the beginning of the roof [44]. It is possible to see the point in Figure 6.6.

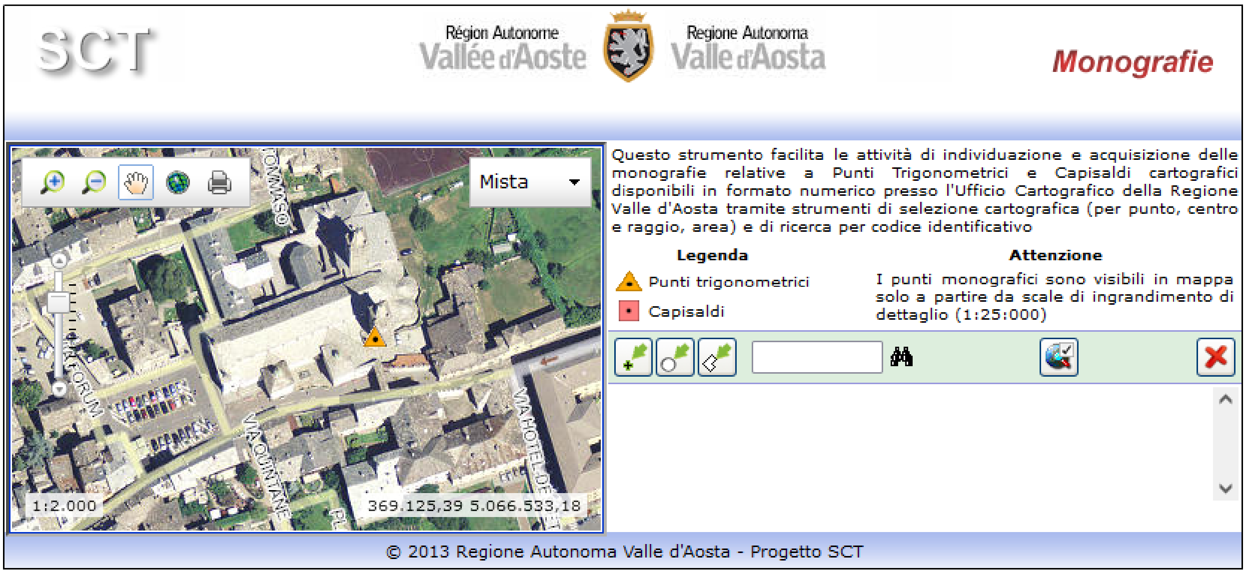


Figure 6.6: Location of the centre of development, the tilt angle is due to the orthophoto

The coordinates have been provided in the Gauss-Boaga system and with a conversion they have been transported to ED50/UTM zone 32N. Inserting these data in the communication window, Figure 6.7, it has been possible to set the correct visualization format to the layer. Now the last thing to do to have also this file in optimal condition is to use the reprojecting tool like for the Edificato file. At this point, both the files are in the correct format, and both have been transported in EPSG:23032, ED50/UTM zone 32.

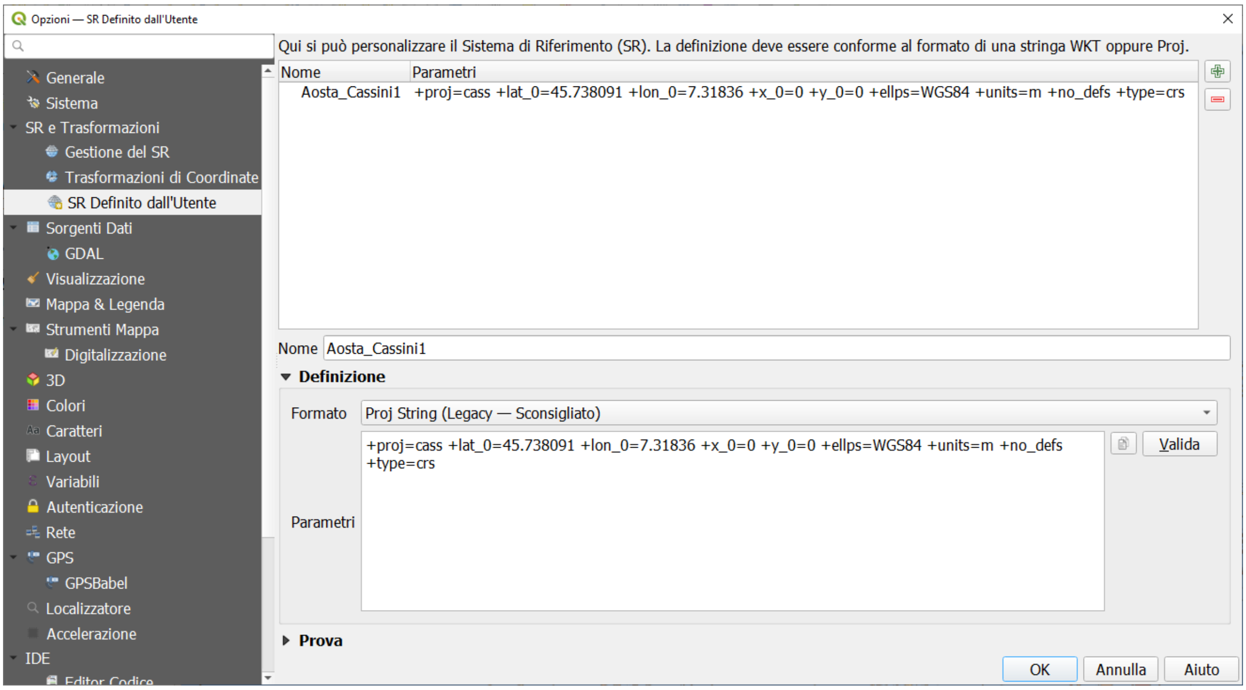


Figure 6.7: Definition of the new system of coordinates for Catasto file

6.2.4 Attributes and centroids

To define the centroids and carry on the analysis, one file is enough, but it must have all the necessary attributes. At this point the information in both files are not complete, the Edificato file still misses the intended use and the Catasto file still misses the height above sea level. It is necessary to exchange attributes between the layers.
With the coordinate change the two layers now match and, even if there is not a complete overlap, the differences due to different mapping modes are negligible and do not affect the attributes transfer. In Figure 6.8 it is possible to see the final situation of the two layers. As visible in the legend, the Catasto layer is represented in red while the Edificato one is in green. There are some differences between the layers, but they are in the order of about 5m, they are of little importance and consistent with the initial approximation assumptions.

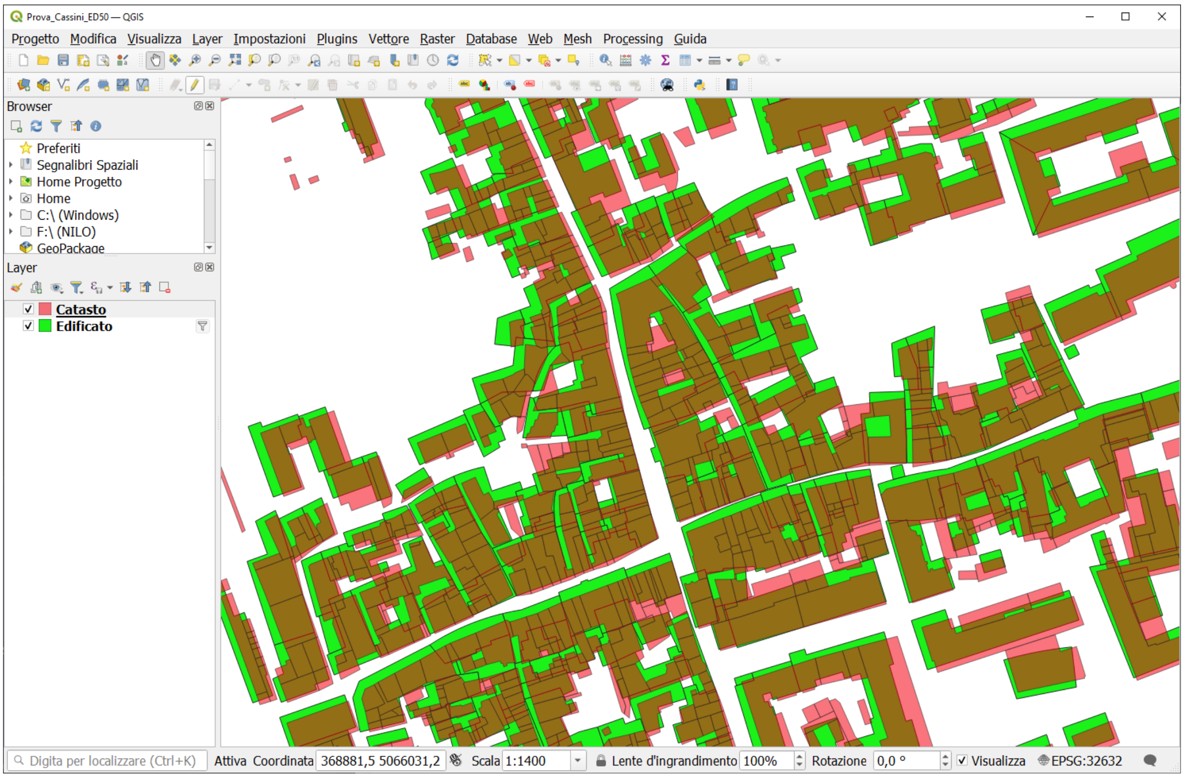


Figure 6.8: Layers after the coordinates' correction. Aosta, Croix de Ville

As shown in the previous figure, the portioning of buildings also shows some differences. This does not represent a problem, especially because the two layers are going to merge in a single layer, to have a complete file with all the needed attributes, that is used to get the centroids for the simulations.
To do this operation, the software QGIS has a specific tool. Under the category of general vector operations, it is called *Add attributes by position*. This tool takes a layer in input and adds, for each geometry, one or more attributes from a second layer; the addition is done only if the geometry of the input layer respects a certain condition, user-defined, with a geometry of the second layer. In case of multiple matches, there is the possibility to choose what attribute to keep. In this case, it is chosen to set the overlap criteria and to keep the attribute of the one with the higher overlapping percentage, as shown in Figure 6.9.

This is a mutual process, there is the possibility to transfer the intended use to the Edificato layer or the altitude to the Catasto one. Both transfers have been performed in order to compare results and continue the analysis on the best one. Both the results were acceptable, but it has been chosen to use the Edificato for mainly one reason: the Catasto file is slightly older and some modifications to existing buildings were not updated.

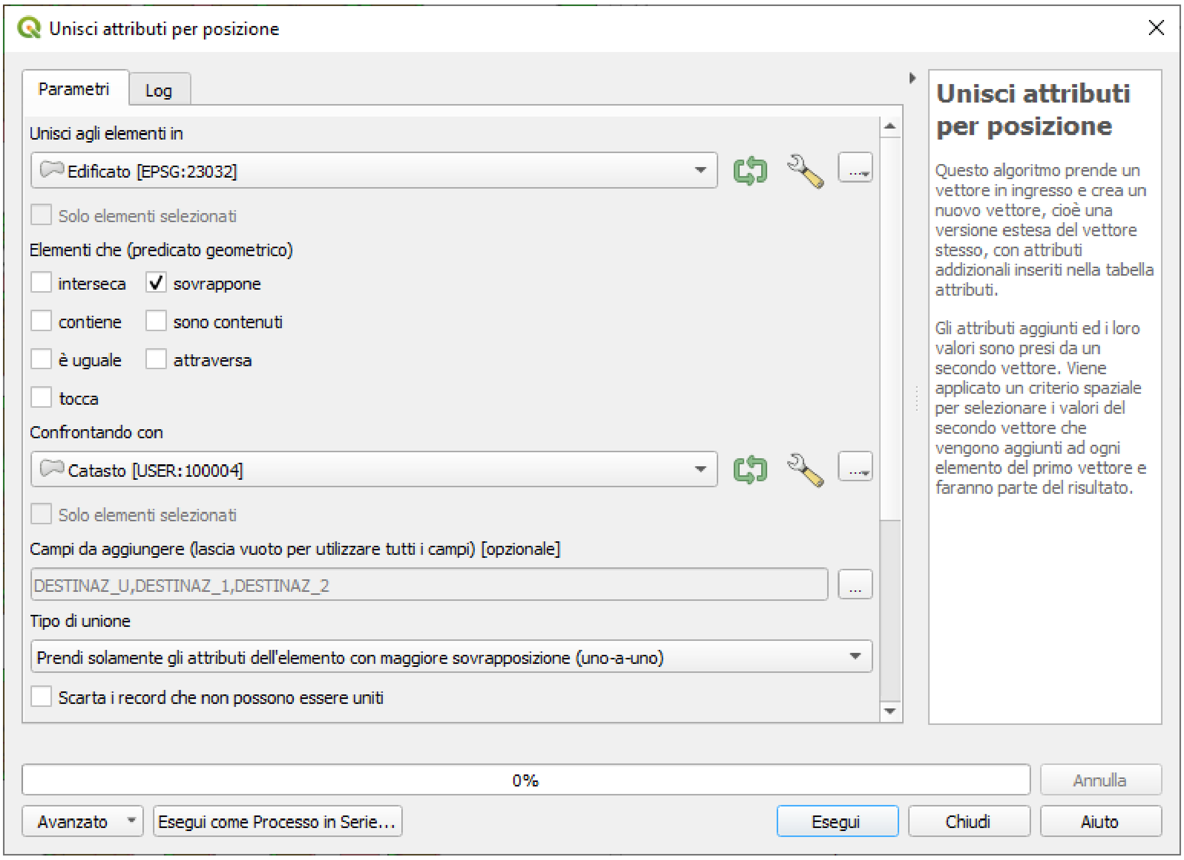


Figure 6.9: Dialogue window to set the parameters of the attributes transfer

With the final version of the cartographic file, it is possible to proceed. To perform the simulation in a single point for each building, it is necessary to start from the geometry of each one. Setting the centroids by hand would take a long time, and it would be imprecise, so it has to be done with the software. As a powerful program, QGIS has this feature; it allows calculating the centroid of a geometry with a specific tool. Simply by selecting the desired layer, the algorithm calculates the coordinates of each centroid and locates it on the map, like in Figure 6.10. This new layer, which is called Centroidi, has all the attributes of the original Edificato layer but is condensed in a single point. Just by opening the attribute table, it is possible to calculate, with a proper expression, the coordinates in latitude and longitude as new attributes.
The last procedure of the preliminary part, to obtain the points in which to conduct the simulation, is to filter the database of points that respect the intended residential use.

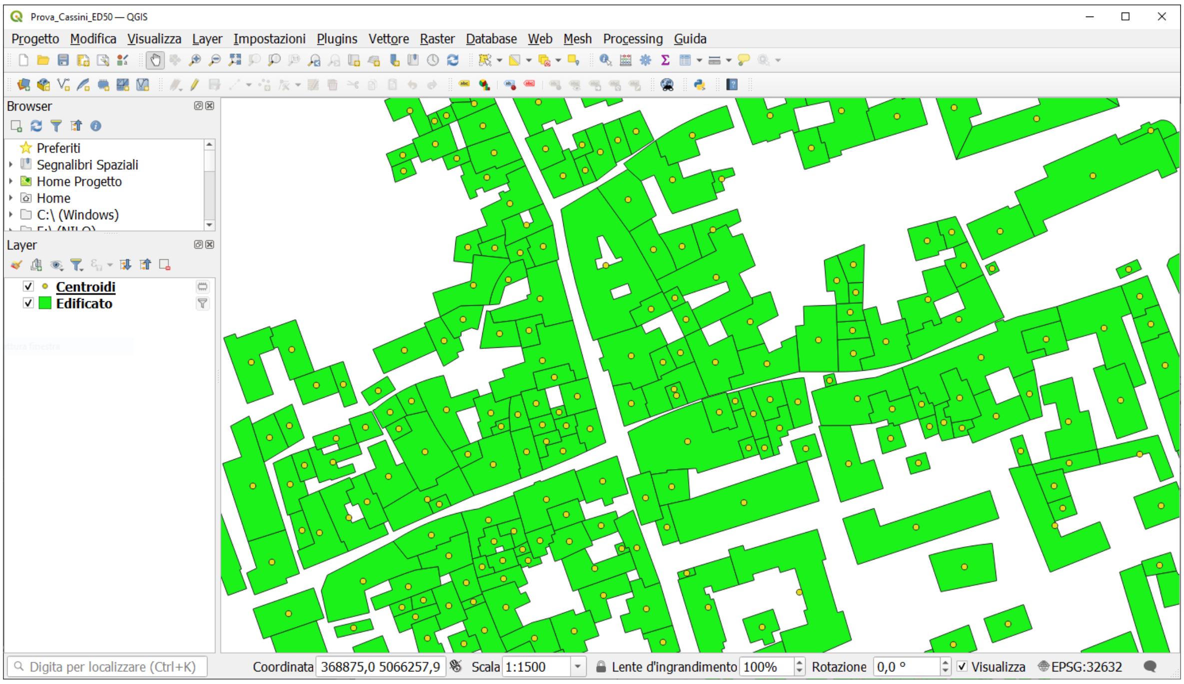
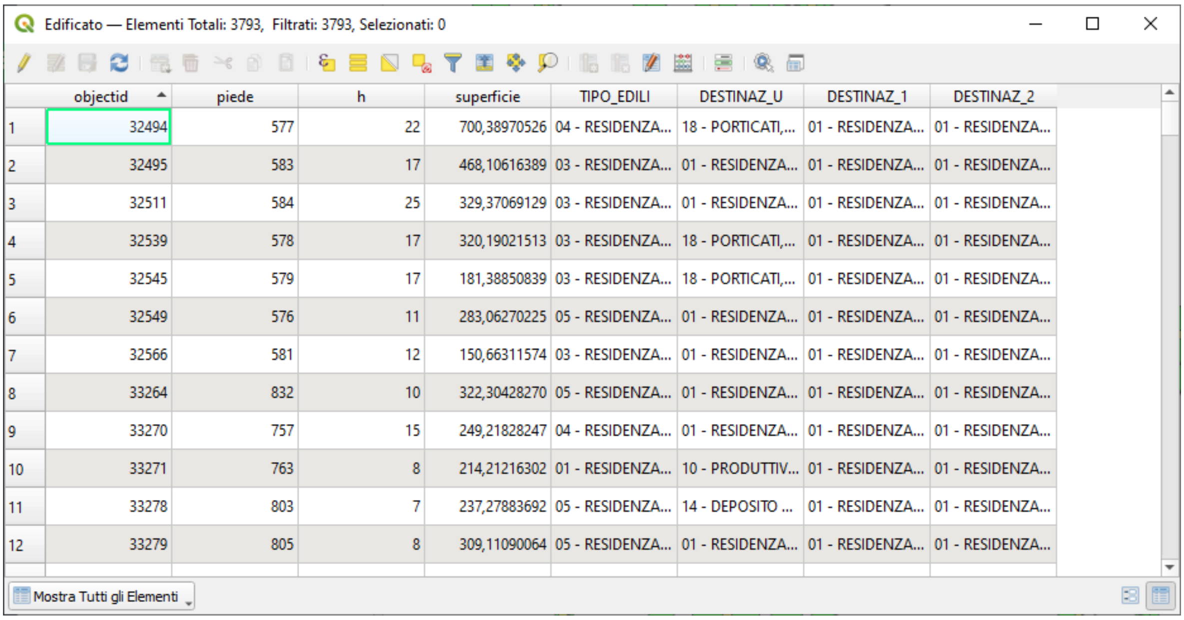


Figure 6.10: Edificato layer and relative centroids layer. Particular: Aosta, Croix de Ville

As previously told, this simulation has to be conducted only in those buildings that have a residential use and so, putting a filtering sentence, it is possible to select only the desired centroids and complete the preliminary file manipulation. In Figure 6.11 it is possible to see the attribute table of the layer Edificato after the filtering procedure, in particular, all the buildings with at least a residential intended use have been selected.


Edificato — Elementi Totali: 3793, Filtrati: 3793, Selezionati: 0

	objectid	piede	h	superficie	TIPO_EDILI	DESTINAZ_U	DESTINAZ_1	DESTINAZ_2
1	32494	577	22	700,38970526	04 - RESIDENZA...	18 - PORTICATI,...	01 - RESIDENZA...	01 - RESIDENZA...
2	32495	583	17	468,10616389	03 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
3	32511	584	25	329,37069129	03 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
4	32539	578	17	320,19021513	03 - RESIDENZA...	18 - PORTICATI,...	01 - RESIDENZA...	01 - RESIDENZA...
5	32545	579	17	181,38850839	03 - RESIDENZA...	18 - PORTICATI,...	01 - RESIDENZA...	01 - RESIDENZA...
6	32549	576	11	283,06270225	05 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
7	32566	581	12	150,66311574	03 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
8	33264	832	10	322,30428270	05 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
9	33270	757	15	249,21828247	04 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...
10	33271	763	8	214,21216302	01 - RESIDENZA...	10 - PRODUTTIV...	01 - RESIDENZA...	01 - RESIDENZA...
11	33278	803	7	237,27883692	05 - RESIDENZA...	14 - DEPOSITO ...	01 - RESIDENZA...	01 - RESIDENZA...
12	33279	805	8	309,11090064	05 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...	01 - RESIDENZA...

Mostra Tutti gli Elementi

Figure 6.11: Attributes table of the layer Edificato

6.3 EmLAB

EmLAB is one of the software used in this study with ARPA VdA. It is a calculation software of Aldena, an Italian brand founded in 1979 operating in the field of telecommunications. Its footprints come from an even bigger experience that started in 1929. EmLAB is the goal of a project started in 1980 with the decision to make a specific software, and it was officially born in 2006 after previous versions and a lot of knowledge were achieved [45]. From the first release, EmLAB evolved and in this study, it has been used version 3.25.1.1 of April 2024 shown in Figure 6.12. Other ARPAs do not use this software because they developed custom software, ARPA VdA relied on EmLAB and, as an important client, cooperates in its updating by reporting critical issues to be fixed and necessary functions to be added. EmLAB is a calculation software used to design antenna systems and to evaluate electromagnetic parameters or the proper shape of the irradiation solid. There are a lot of available software, but EmLAB tries to open its compatibility to other manufacturers' products, to have a database of components directly characterized by the producer.

Figure 6.12: EmLAB starting window

As shown in Figure 6.12, EmLAB is structured in three main windows, the same format has been used to summarize the elements in a BTS in Chapter 5:

- Antennas: this is a catalogue of all the antennas available. Each device is registered with its details like the model, the manufacturer, the electric, and geometric data.
- System: it is a database of the coupling antenna-transmitter. In this window, it is possible to apport modifies to existing systems or generate a new one. To create a new system an antenna has to be selected and equipped with the service defining the power supplied in nominal and normal operation, the orientation and tilt, the location in terms of coordinates and other useful information like a description to help the user.

- Workstations: this tab opens a window containing a database of the already existing base transceiver stations treated like projects. In this page they are fully described in all their aspects; by clicking on the name the software reveals which systems are equipped site by site and their features, EmLAB itself calls this window “catalogue of grouped radiating systems”. In this window BTS can be treated even in group, this allows to describe networks and study more systems in different sites simultaneously.

6.3.1 Operations in EmLAB

To perform simulations in EmLAB the user has to select the Workstations tab (in Italian “postazioni”), create or chose an existing element which could be a network or a single site workstation and open it. Now, the user still can apport changes to the project, but working on a specific system affect all the projects in which that specific system is used. To avoid this, there are two possibilities: change the desired parameters, proceed in the simulation but discard the changes, closing the project or clone the entire project. In the second way, the software generates a copy of the entire project and saves the loaded systems as new versions of those existing with other names (it adds a *_number of version* at the end), in this way it is possible to perform changes without compromise the original format of the network project. As told, opening the site, the software shows the systems equipped, like in Figure 6.13, and some useful information in form of some tabs and a table.

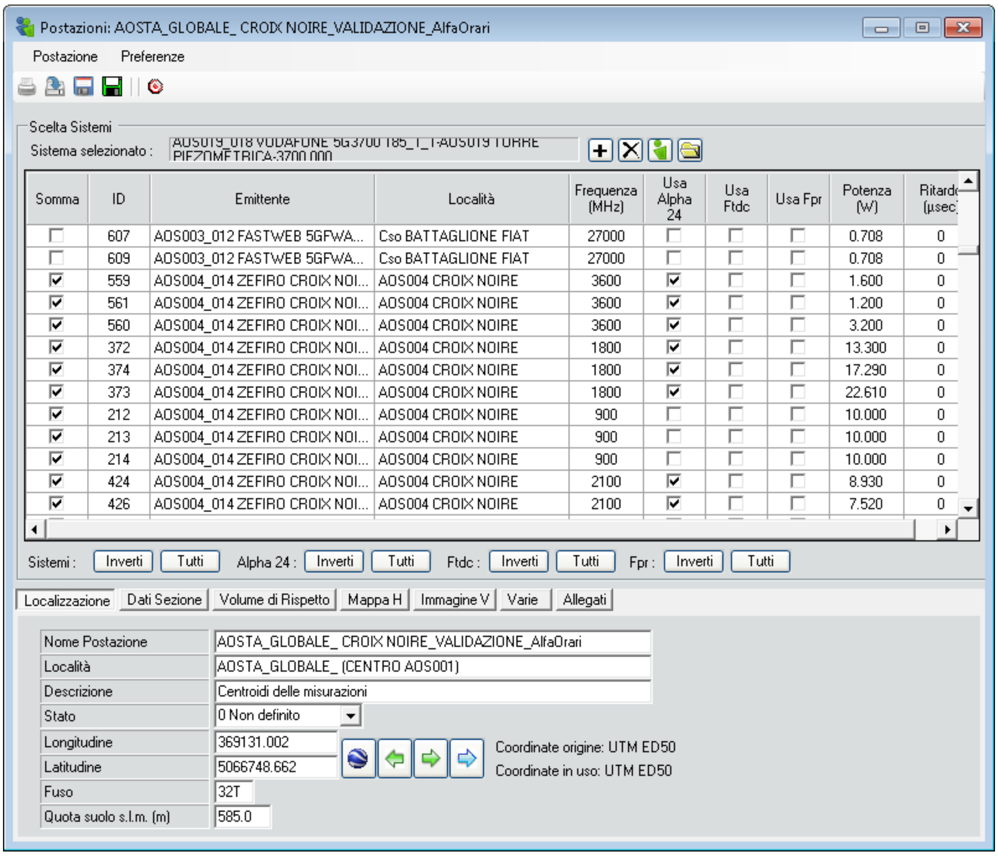


Figure 6.13: Example of a network of workstations, view after the selection

Talking about the tabs, they are in the lower half of the window, and they can be summarized as:

- Localization: this tab has the general information of the network. Each project has a name and an optional description, the location is defined by name and coordinates in terms of latitude, longitude, fuse and height above sea level.
- Section data: it is a tab used to perform simulations focused on the evaluation of the pattern of EMF generated in the surrounding of the network. These simulations can be performed in 2D and 3D.
- Compliance volume: this tab is used to set and perform simulations on the volume, surrounding the sources, in which the electric field is higher than a certain imposable limit. Again, this analysis can be modelled in 2D or 3D.
- H Map: this is the tab to set the features of the used map. The centring, the name of the file, the length of the side and so on.
- Other ancillary tabs: to set other information and comments.

The table, instead, is in the central part of the window, and it has, between the others, some important information like:

- Sum: this is a flag column, if it is flagged the system is considered active in the following simulations. It is convenient to simply flag and unflag this voice to temporarily exclude some systems, on the other hand if a system has been terminated by the supplier it is also possible to remove it from the network.
- ID and Broadcaster: they are identification features, the first one is a short number and the other one gives some more information like the BTS, the operator and the technology.
- Power: the maximum amount of power supplied by the transmitter to that specific service.
- Use alpha 24: this is another flag column, if it is not flagged the software uses the nominal power declared by the operator as irradiated power. With the flag, the power used in the simulation is the product of the nominal power and the α_{24} coefficient given by the operator for that service.

Coefficient α_{24}

Before proceeding further, it is worth exploring a newly introduced concept: the α_{24} coefficient. As already mentioned, a system consists of an antenna and a transmitter, and this last device can operate at variable power depending on the traffic it has to handle. Normally the rated power of the transmitter is never reached and the operators themselves, in the definition phase when a system is activated, give a parameter called *Declared* α_{24} which must never be exceeded by the operator. The α_{24} coefficient then is a ratio between the input power to the system and the rated power. Since the needed power varies with the traffic, this coefficient changes along the day. The “24” in the name means that the final coefficient used for the analysis is the average on 24 hours, in order to describe the average behaviour of the irradiation. Each operator has a database of the irradiated power and so the α_{24} for each system on an hourly or bi-hourly basis. The value of this coefficient is settable in the tab Systems, where all the systems are defined, or directly starting from the window in Figure 6.13. By double-clicking on the desired system, the software opens its page and if selecting the Electrical Data tab it is possible to set the correct value.

6.3.2 Punctual simulations

The software EmLAB is designed to perform distributed simulations or point calculations in specific locations. With the prospective to perform calculations for every centroid that meets the requirements of the city of Aosta, the point calculation function is crucial. This type of simulation is available starting from the Workstation page by clicking on the icon named "Control Points". This selection leads to a new window, showed in Figure 6.14, in which the user can upload a list of points in CSV format with the specific function and use them as control points for the simulation. After the importation of the points, simply pressing the "Update fields previsions" key, the simulation starts and concludes relatively fast just compiling the missing fields in the table of points. At this point it is also possible to export the results of the simulation, there are two format available but in this case it has been used the .txt format for its versatility.

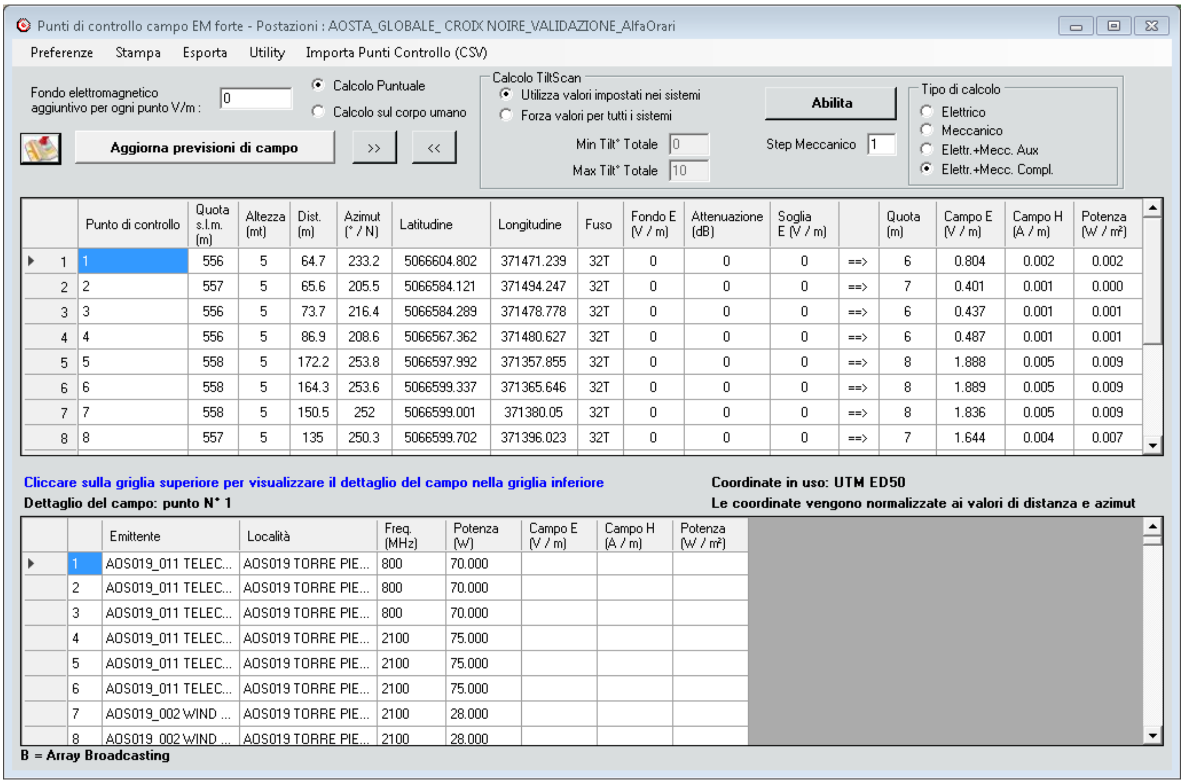


Figure 6.14: Control points window, the simulation is already finished because of the full fields

In this window it is also possible to set some important parameters like the attenuation that a point experiences because of the shielding towards the sources, the background field in case of other sources that have an effect but are not modelled in this simulation or the threshold, according to the normative discussed in chapter 4, it is possible to set a value which represent the limit and have a quick colour report if any point exceeds; it is not important the right match, it could also be a simple condition that is under analysis. In the same figure it is possible to see that the imported data relative to the coordinates are used to compile automatically the columns "Distance" and "Azimuth"; these are the values actually adopted in the simulation, and they are referred to the point that has been set as the origin of the simulation (in this case it has been chosen to use the workstation AOS004).

6.4 Validation

The first goal is to have a link between the simulated universe in the software and the measured universe. As stated in the ministerial procedure, it is required to conduct a simulation on at least ten points belonging to a single census zone and compare them with measurements taken in the same points.
This is done not to validate the internal calculus algorithm of the software, but it is done to ensure that the real conditions are well interpreted by the software and there is a compatibility with the measured values. This operation is possible only if the simulation is conducted after the measurements to replicate those conditions and so, after the individuation of the site, a set of measures must be taken. To choose the area in which to locate the ten points for the validation it is useful to look at the distribution of the Workstations which irradiate on the city, this disposition is shown in Figure 6.15, and it shows that a Workstation is particularly suitable for this.

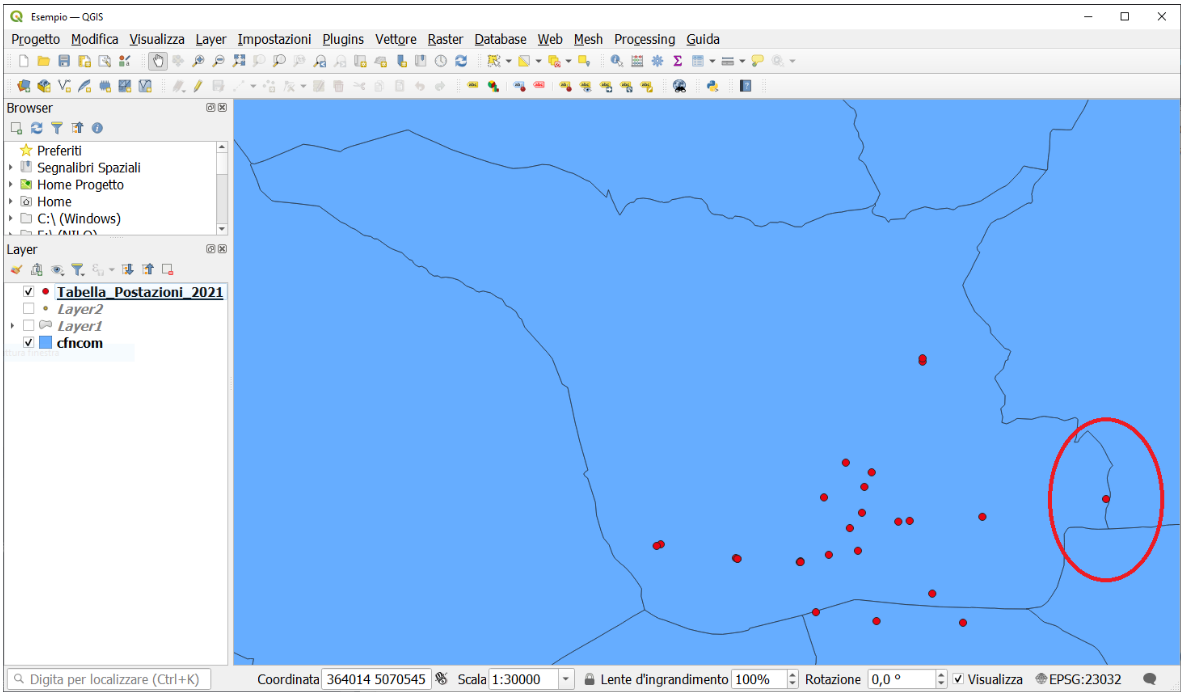


Figure 6.15: Distribution of the workstations, in evidence the workstation AOS004

The Workstation in Figure 6.15 is AOS004, it is located in "Croix Noire" and it has been highlighted because it is fairly isolated (it is more than one kilometre away from the nearest one) so it is correct to assume that the other does not affect this area (especially considering the buildings in between) and it is significative because it has a lot of systems of different operators. The main advantage of having only this workstation operating in this area is that it is easier to set the real α_{24} coefficient for each system. Associated with this workstation, the operating procedure states that the set of measurements has to be performed in the same census zone. The choice made was to take the same census area as the workstation, Figure 6.16, which contained residential buildings useful for taking measurements. In particular, in pink is represented the location of the spot measurements and in red the workstation.

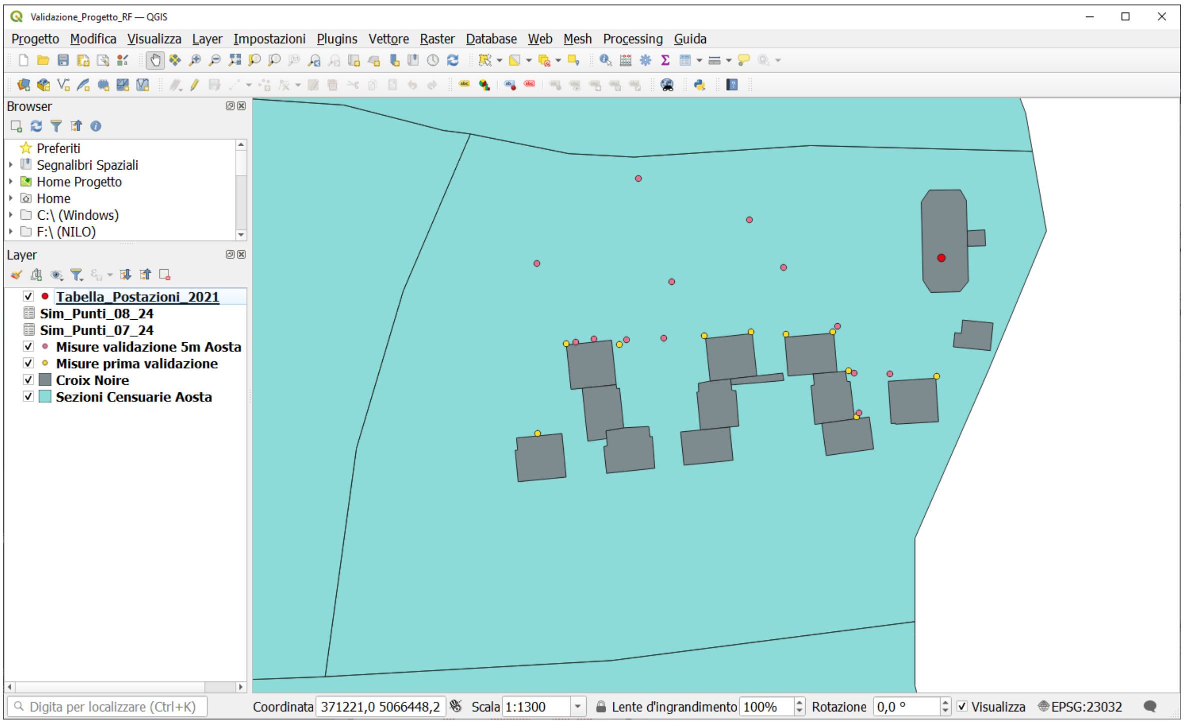


Figure 6.16: Disposition of the measurement points in the selected census zone

6.4.1 Measurements

The measurements aim to validate the model used to simulate the values on EmLAB and therefore understand with which degree of certainty the model can be used to have a good estimation of the actual field values. Before proceeding, some considerations can be done. It is preferable to measure lower values than the simulated ones, this is because, as already said, the simulation is done in open field conditions, where there are no walls and buildings between the source and the receiving point. This must be taken into account and, to properly validate the model, it is necessary to use the actual antenna powers of the day of the measurement. It is a right of the ARPA to know the α_{24} coefficient to reconstruct the daily mean power of the antennas.

Instrumentations

To perform the measurements, the selected instrument is the Wavecontrol SMP2, shown in Figure 6.17.

Figure 6.17: Measurement instrument for the activity

This instrument is capable of measuring signals between 0Hz and 60GHz, but the probe limits the real bandwidth. The selected one limits the bandwidth between 100kHz and 8GHz which is good for the purpose of the activity as it can be seen in Table 4.6 that the RF bandwidth limits are 100kHz - 300GHz, but none of the considered technologies in Aosta reach frequencies greater than 8GHz.

Figure 6.18: Probe for RF measures

	WPF8
Frequency range	100 kHz - 8 GHz
Sensor type	Isotropic RMS diode technology
Type of frequency response	Flat
Measurement range	0.2 - 130 V/m (CW) 0.2 - 20 V/m (RMS)
Dynamic range	52 dB
Sensitivity	0.2 V/m
Resolution	0.02 V/m (until 7.5 V/m) 0.1 V/m (from 7.5 V/m to 130 V/m)
Frequency response	± 1.5 dB (250 kHz – 6 GHz) + 0.5 / - 2.5 dB (6.5 GHz - 8 GHz) - 3 dB (100 kHz)
Linearity	± 0.5 dB (0.5 V/m - 100 V/m)
Isotropic deviation	± 1 dB (@ 2 GHz)
Calibration	ISO 17025 accredited (ILAC)
Calibration period	24 months (recommended)
Temperature range	- 20 ºC to 50 ºC
Temperature response	+ 0.1 / - 1 dB (related to 20 ºC)
Dimensions	28.4 cm x 6 cm Ø
Weight	95 g
Attenuation at 50/60 Hz	> 80 dB

Figure 6.19: Technical data of the probe

6.4.2 Procedure

To validate the simulation model of the radio frequency waves, a well-defined protocol (see Appendix A) is dictated by the ISPRA (Higher Institute for Environmental Protection and Research) and the SNPA (National System for Environmental Protection). The document contains the operative procedure to validate the previsional calculations in a defined site with a source of radio frequency electromagnetic waves produced by radiobase stations. The gist of it is that 10 or more measurements must be done in a validation area in a single census section. The measurements must be done at the most frequent above-ground floor, which was 5m above the ground (first floor). The measurements are done outside the building to avoid the attenuation and uncertainty of the wall, and they must be carried at the most exposed point, possibly in visibility with the nearest station.
The measurements can be carried out over the 24 hours of the day through a monitoring unit or in alternative it is possible to proceed with at least 6-minute-long measures along the day, as previous measurements of other ARPAs showed that the difference between 6 minutes and 24 hours measures is within the uncertainty of the instrument. Finally, the correct α_{24} coefficient of the day is asked to the service providers to correct the simulation and better correlate the simulation and the measurements.
The ARPA VdA decided, to speed up the procedure, to do 10 measurements, 6 minutes each at 5 meters from the ground in the defined census zone shown in Figure 6.16.

Figure 6.20: Picture of the on-site measurement procedure

Once the instrument is set, the registration can start and data acquisition with it. The results are stored in the internal memory and can be downloaded on the laptop. An example of the result of the measurement is in Figure 6.21.

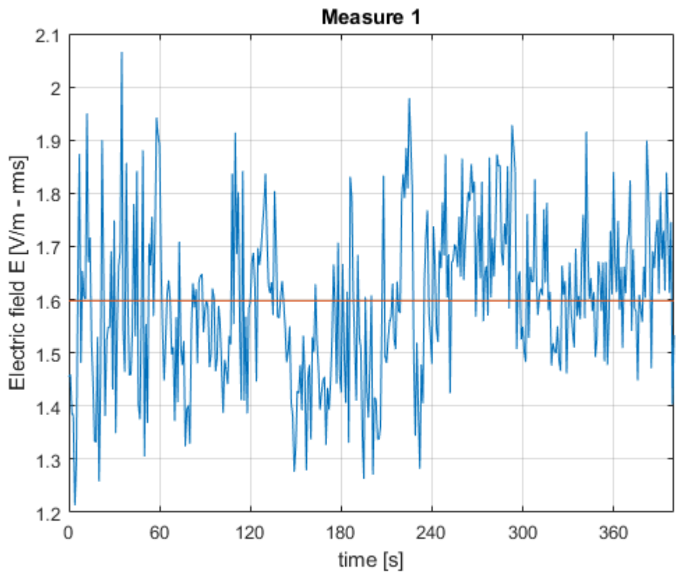


Figure 6.21: Example of Wavecontrol SMP2 data acquisition

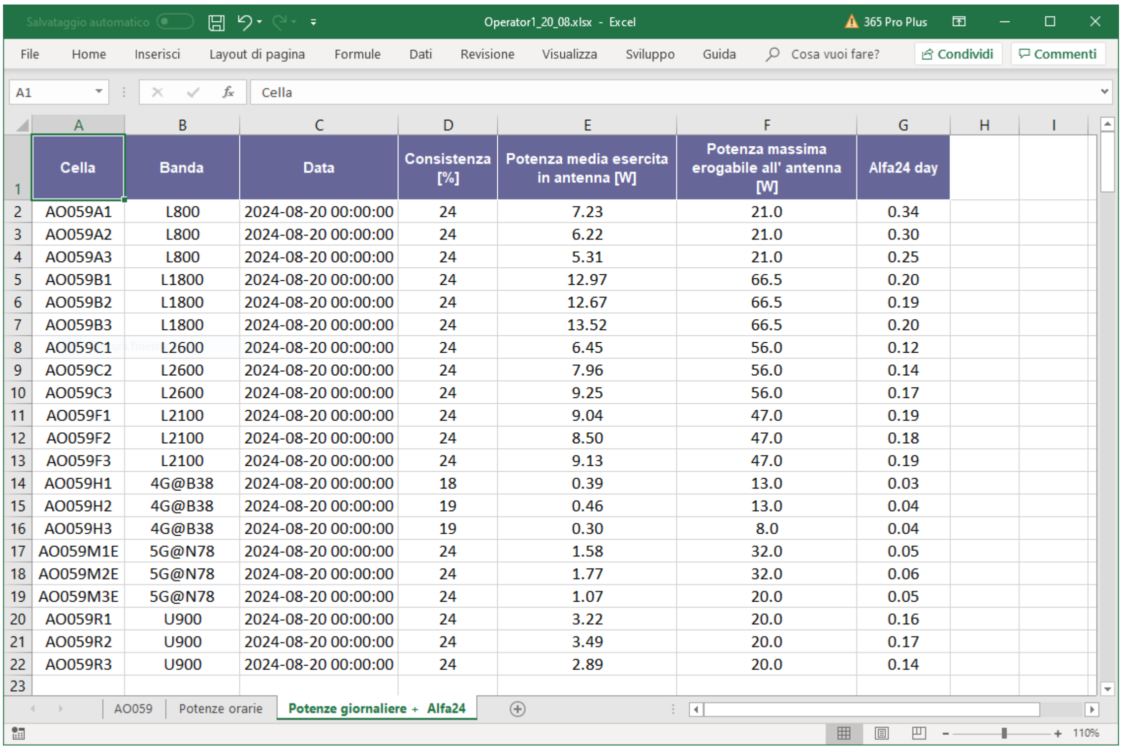
The instrument gives both the instantaneous values measured each second and the plot. It also evaluates the average 1.6 V/m for this measure.

6.5 Data processing and comparison

This section is the joint of the results of simulations and measurements. In particular, it was explained how the EmLAB simulations were conducted, and also how the measurements were conducted. At this point, for the validation of the model, it is necessary to compare the measures with simulation in the same point, and find the error between them.

6.5.1 Measurements data manipulation

The simulation process is divided in two phases: in the first one the measurements are compared with the cautionary simulation with the maximum α_{24} coefficient defined in authorization phase, while in the second the comparison is done with a simulation that shows the actual condition during the measurements. In order to perform this second simulation, the power set for each system has to be the same value it was during the measurements. It is possible to know this parameter simply by asking operators to communicate the real α_{24} coefficient or, even better, the hour-by-hour version for each system. Importing those data in the EmLAB, according to the previously described procedure, the simulation can be conducted and the data extrapolated. In particular, as the measurements are limited to a specific census zone, the simulation is done with respect to the area mentioned, and therefore also the only active radiobase workstation is the one named AOS004. In Figure 6.22 it is possible to see the daily weighted α_{24} coefficient of an operator, the name cannot be revealed to not create prejudice or give publicity.



Cella	Banda	Data	Consistenza [%]	Potenza media esercita in antenna [W]	Potenza massima erogabile all' antenna [W]	Alfa24 day
AO059A1	L800	2024-08-20 00:00:00	24	7.23	21.0	0.34
AO059A2	L800	2024-08-20 00:00:00	24	6.22	21.0	0.30
AO059A3	L800	2024-08-20 00:00:00	24	5.31	21.0	0.25
AO059B1	L1800	2024-08-20 00:00:00	24	12.97	66.5	0.20
AO059B2	L1800	2024-08-20 00:00:00	24	12.67	66.5	0.19
AO059B3	L1800	2024-08-20 00:00:00	24	13.52	66.5	0.20
AO059C1	L2600	2024-08-20 00:00:00	24	6.45	56.0	0.12
AO059C2	L2600	2024-08-20 00:00:00	24	7.96	56.0	0.14
AO059C3	L2600	2024-08-20 00:00:00	24	9.25	56.0	0.17
AO059F1	L2100	2024-08-20 00:00:00	24	9.04	47.0	0.19
AO059F2	L2100	2024-08-20 00:00:00	24	8.50	47.0	0.18
AO059F3	L2100	2024-08-20 00:00:00	24	9.13	47.0	0.19
AO059H1	4G@B38	2024-08-20 00:00:00	18	0.39	13.0	0.03
AO059H2	4G@B38	2024-08-20 00:00:00	19	0.46	13.0	0.04
AO059H3	4G@B38	2024-08-20 00:00:00	19	0.30	8.0	0.04
AO059M1E	5G@N78	2024-08-20 00:00:00	24	1.58	32.0	0.05
AO059M2E	5G@N78	2024-08-20 00:00:00	24	1.77	32.0	0.06
AO059M3E	5G@N78	2024-08-20 00:00:00	24	1.07	20.0	0.05
AO059R1	U900	2024-08-20 00:00:00	24	3.22	20.0	0.16
AO059R2	U900	2024-08-20 00:00:00	24	3.49	20.0	0.17
AO059R3	U900	2024-08-20 00:00:00	24	2.89	20.0	0.14

Figure 6.22: Declared α_{24} coefficient of an operator

6.5.2 Comparison between EmLAB and Measurements

As the protocol states, all the values contribute to the average value, describing the census area, and also the standard deviation is evaluated in order to have an idea of how much values are spread out.
Taking multiple measurements is necessary for a set of reasons:

- The instrument uncertainty. As it is shown in Figure 6.19 the probe and therefore the measuring instrument has a sensitivity of 0.2 V/m which can affect the measure.
- α_{24}. These coefficients are averaged on 24 hours, or if the operator gives them (not mandatory by law) over 1 hour. The measure only last 6 minutes which is a tenth of it and therefore the actual power may differ from the one estimated with the coefficient.
- Reduction in variability. There are random errors associated to measurements, that may be caused by multiple reasons. Taking multiple measurements helps into cancelling out the randomness.
- Identification of anomalies. If a measure differs completely from the expected value it is easier to be spotted if the other are coherent and the measure or further investigation can be carried out.

The results of the simulation are visible in table 6.1. The values relative to the ten points used for this analysis show that the maximum irradiation condition is not suitable to describe normal operation of the workstations. By analysing the data, it is clear that the cautionary simulation by itself overestimates the field value.

Place	Measure [V/m]	Simulation [V/m]	Delta
1	0.869	2.337	62%
2	1.813	5.826	69%
3	1.714	5.927	71%
4	1.834	5.845	69%
5	1.494	5.360	72%
6	2.056	6.646	69%
7	1.829	6.973	74%
8	2.184	6.341	66%
9	1.451	3.989	64%
10	1.607	5.580	71%
AVG	1.685	5.482	69%
st dev	0.348	1.300	—

Table 6.1: Comparison between simulation with maximum α_{24} coefficients and measurements

According to the table the deltas between simulation and measures, referred to the simulated values themselves, amounts on average to 69%. This overshoot means that the actual conditions must be considered, because the differences are too high, so the basis assumptions have to be changed. In particular, this value is closely related to the correction coefficient which is introduced and discussed later, in the Model correction paragraph. Setting the actual α_{24} coefficients for each system in the workstation it is time to evaluate if the simulation program actually manages the real conditions showing results compatible with the measurements. In table 6.2 it is summarized the report of the simulation in the same analysed points.

Place	Measure [V/m]	Simulation [V/m]	Delta
1	0.869	0.826	-5%
2	1.813	1.922	6%
3	1.714	1.943	12%
4	1.834	1.896	3%
5	1.494	1.680	11%
6	2.056	2.177	6%
7	1.829	2.194	17%
8	2.184	2.030	-8%
9	1.451	1.257	-15%
10	1.607	1.742	8%
AVG	1.685	1.767	5%
st dev	0.348	0.411	—

Table 6.2: Comparison between simulation with actual α_{24} coefficients and measurements

In this second table, the first noticeable aspect is that, as expected, the results of the simulation are lower according to the irradiated power reduction. This time the delta analysis clearly shows much lower percentages and, in particular, this values cannot be interpreted as a real difference, because it has to be taken into account that even the measurement instrument has an instrumental uncertainty. The delta values in the table deviate within a window of less than ±20% and this is fully compatible with the instrument. According to 6.2 and the deriving conclusions, the correlation is strong enough to officially validate the simulation system and proceed with the analysis.

Unexpected criticalities

In order to show what has really happened in this validation procedure, it is worth to spend some time analysing an occurred problem. The validation procedure has been done twice because the first time, some points of the sample showed inconsistencies while compared with the measurements.

Place	Measure [V/m]	Simulation [V/m]	Delta
1	0.2146	1.508	86%
2	1.963	1.917	-2%
3	1.667	1.860	10%
4	1.260	1.453	13%
5	1.220	1.180	-3%
6	1.245	0.875	-42%
7	0.9298	0.732	-27%
8	0.7822	0.479	-63%
9	1.002	0.534	-88%
10	0.5662	1.080	48%
AVG	1.085	1.162	7%
st dev	0.483	0.490	—

Table 6.3: First and discarded comparison for validation

In table 6.3 is possible to see the final report of the first validation and even if the averages are not much different between one another, two measures (n°1 and n°10) show a much lower value than the simulated one. This first phenomena is probably due to the fact that they were not in line of view with the emitting station. For these reason an attenuation should be considered, but it is not easy to find a rule for the attenuation as there could be multiple walls in between with different materials but also windows. An even more interesting fact is that there are three measures that immediately stand out (in particular, measures n°6, n°8, and n°9 have a measured value which reaches almost double of the simulated one. The possible explanations are:

- Geometry. In particular, reflections can be the cause of why the measure is greater than the simulation. As it can be seen from Figure 6.16 the location of two of the three points is in the "cone" between the buildings, and it is visible with both yellow or pink dots (they have been double-checked to ensure consistency). Also, the discrepancy between measure and simulation increases by diving into the cone.

- Positioning with respect to the radiating system and side lobes. This is more related to how the side lobes are modelled in the software, and as they are not the main one they might not be very precise. According to special EmLAB simulations showed in figures 6.23 and 6.24, it is clear that side lobes could have an influence due to the opening of the beam.

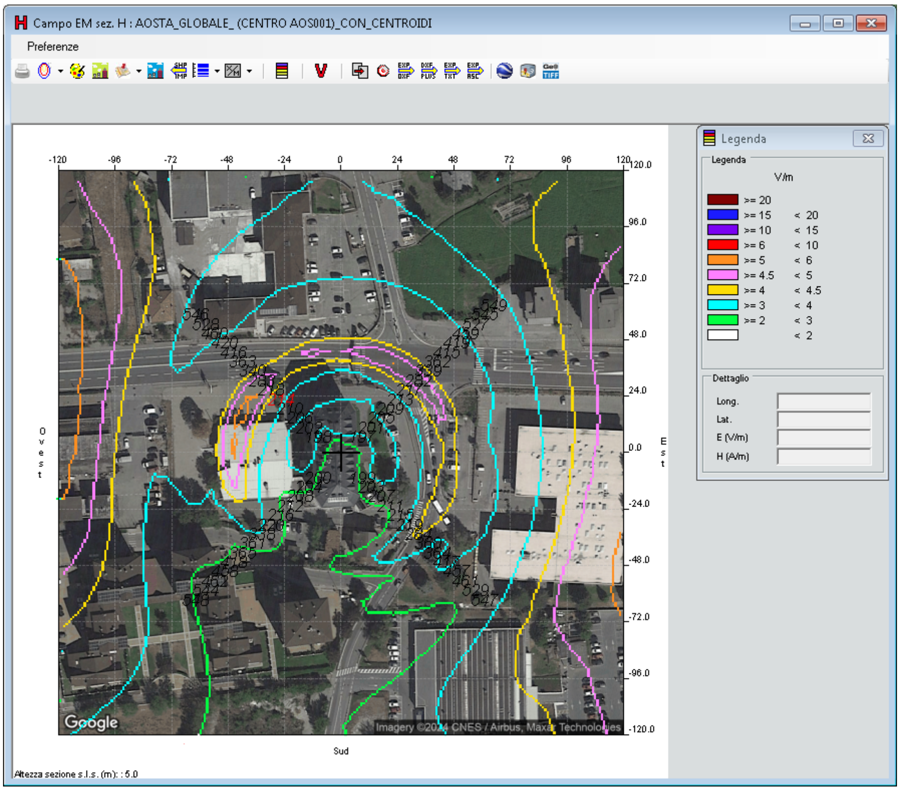


Figure 6.23: 2D simulation at 5m height with maximum declared α_{24} coefficients

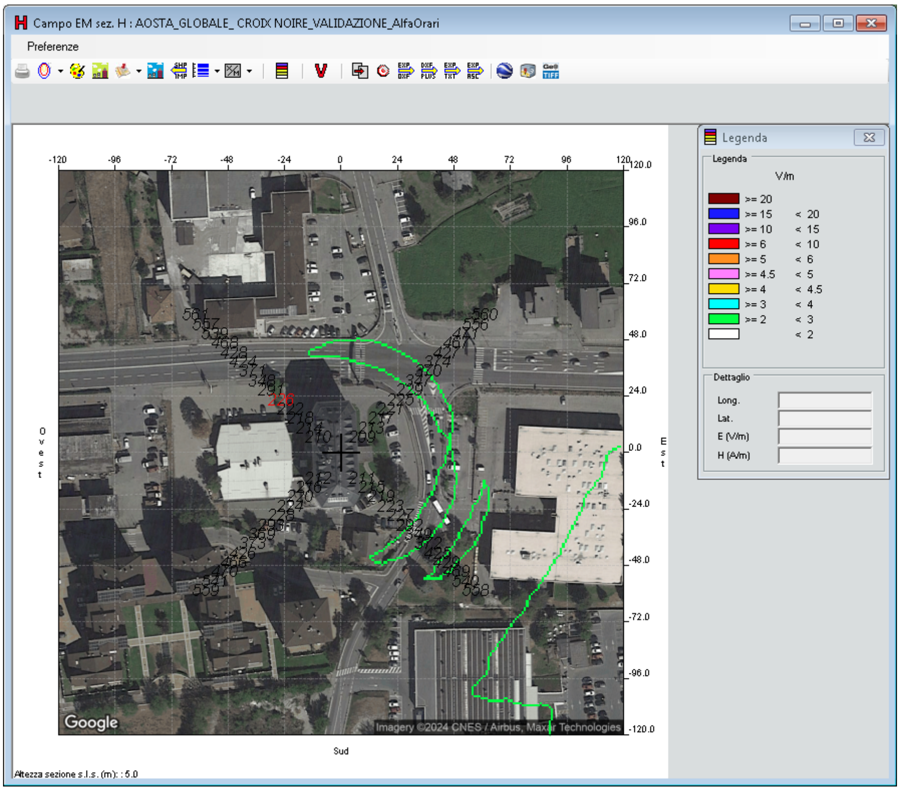


Figure 6.24: 2D simulation at 5m height with actual α_{24} coefficients

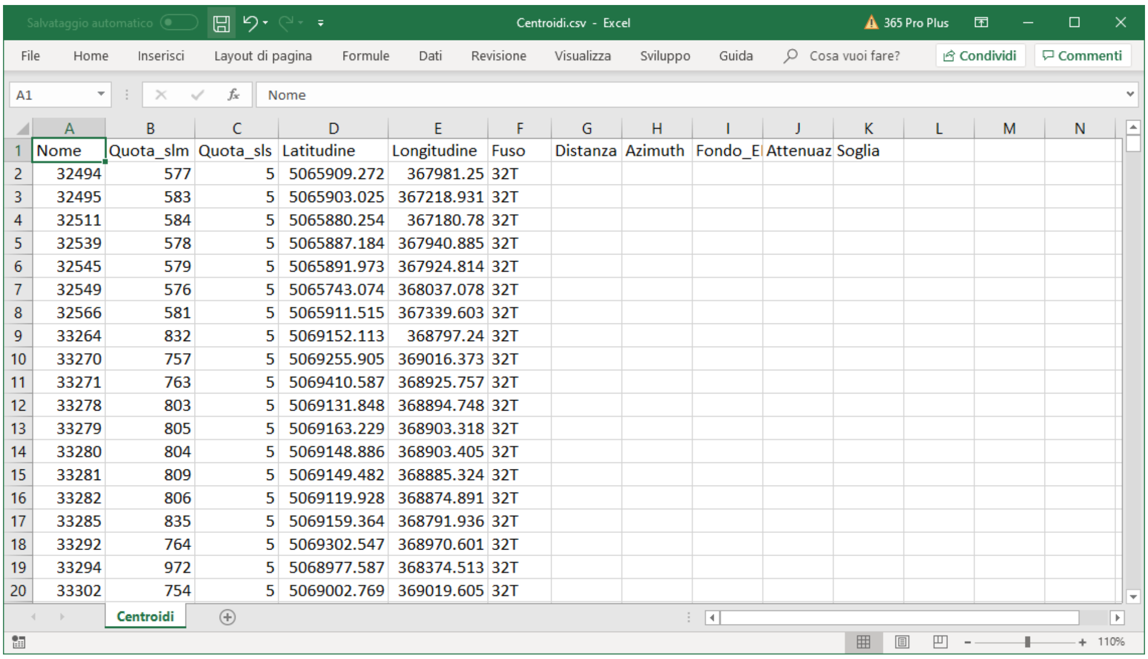
- Sensitivity of the instrumentation. A contribution (which for sure can't be the only explanation) is associated to the instrument sensitivity, from datasheet in Figure 6.19 0,2V/m, which is relevant compared to the intensity of the measures.

- Anomalous moment. A possibility of having a very high demand in that period that doesn't appear in the simulation, where the α_{24} coefficient is an average on the 24 hours could also be the explanation. This can be easily checked with another set of measurements, to see if it actually was an unfortunate moment, or if it is related to something else.

For all the reasons mentioned above it has been decided to take a second set of measurements in order to check first the abnormal measurements and second perform ten measurements to use for the validation of the model. The results on the abnormal points have been confirmed even in the second set of measurements, and therefore it is now very likely that it was not a causality of the moment.

6.6 Extending the simulation and results

According to the results achieved in the validation phase, the analysis can be extended to the entire municipality of Aosta. Thanks to the file manipulation done in the QGIS environment, the last version of the Edificato file led to the creation of a new file: Centroidi. This file contains the coordinates of each point and to insert those data in EmLAB it is necessary to have them in a CSV format, because it does not work with shapefiles. Selecting the relative exporting function, the attribute table of the Centroidi layer has been exported, and it has been time for an arrangement. EmLAB needs a specific format 6.25 to properly read an imported file, so using an ancillary software like Microsoft Excel the attribute table has been rearranged by deleting those information that were no longer useful in this stage.



Nome	Quota_slm	Quota_sls	Latitudine	Longitudine	Fuso	Distanza	Azimuth	Fondo_E	Attenuaz	Soglia
32494	577	5	5065909.272	367981.25	32T					
32495	583	5	5065903.025	367218.931	32T					
32511	584	5	5065880.254	367180.78	32T					
32539	578	5	5065887.184	367940.885	32T					
32545	579	5	5065891.973	367924.814	32T					
32549	576	5	5065743.074	368037.078	32T					
32566	581	5	5065911.515	367339.603	32T					
33264	832	5	5069152.113	368797.24	32T					
33270	757	5	5069255.905	369016.373	32T					
33271	763	5	5069410.587	368925.757	32T					
33278	803	5	5069131.848	368894.748	32T					
33279	805	5	5069163.229	368903.318	32T					
33280	804	5	5069148.886	368903.405	32T					
33281	809	5	5069149.482	368885.324	32T					
33282	806	5	5069119.928	368874.891	32T					
33285	835	5	5069159.364	368791.936	32T					
33292	764	5	5069302.547	368970.601	32T					
33294	972	5	5068977.587	368374.513	32T					
33302	754	5	5069002.769	369019.605	32T					

Figure 6.25: Standard import format in EmLAB, only few fields need to be compiled out

These remaining fields are useful not only to identify the points and their features, but they also play an important role in the next phase, when the simulation is completed and each calculated value have to be associated to the starting point of belonging.
This simulation is carried on following two important principles:

- Open field conditions: The simulation is carried out without taking into account the attenuation of any interposed elements. Suffice it to say that just not being in line of sight, because of a tree for example, can have a significant impact. It would certainly be possible to perform a simulation taking into account the attenuations provided by walls and other elements, but not in this case where the situation of each point has to be assessed with respect to each antenna.

- Maximum authorized α_{24} coefficient: Normally, operators do not provide their services at full power, simply to avoid waste and to have some margin if the demand should increase. However, since it is not possible to know with what power the services will be provided, it is precautionary to refer to the maximums declared in the authorization stage.

As mentioned, this simulation results in a cautionary analysis. These criteria result in increased simulated values compared to actual conditions, but it is an acceptable condition because if the situation is not problematic in this way, for sure there are no problems in reality, with lower irradiated power and higher attenuations. Given these conditions, the simulation can now be carried out. Since this is a point simulation, calculations are not performed in order to form a mesh and to map an area and establish level curves like it is a finite element analysis, only the imported points are analysed, so the calculation time required is considerably reduced. In less than a minute, all points were processed, and the results were ready for export in .txt format.
When a report of a simulation is exported from EmLAB in a text document, a header with a brief summary of the settings is added at the beginning of the file, before the useful data. In order to visualize the situation in QGIS this header is removed and, with an Excel elaboration, the file is converted to a .CSV report. The .CSV file has been imported in QGIS with the other layers and with the tool *Add attributes according to field value* it is possible to create a new layer (and so a new shapefile) in which the attributes table contains all the fields of the starting layer and some selected fields from the layer that is aspected to be merged. Using the name of the element as the comparison attribute, it is therefore possible to associate each centroid with its calculated electric field value and thus have an updated and for now complete version of the Centroids file. The simulation part is now concluded with the association of the electric field value to each centroid, but to perceive the goal of the EMF research programme other considerations must be made. At this level, although it is not among the objectives of this simulation that need further elaboration, the results obtained so far show that even under cautious conditions the quality objectives are met in all centroids. For further numerical and qualitative considerations, please refer to the next chapter. To have an idea of how the electric field simulated values are distributed in the municipality of Aosta, in Figure 6.26 it is shown the preliminary report. Thanks to the feature “Graduated” it is possible to associate a colour, defined in a given colour scale, according to the value of an attribute.

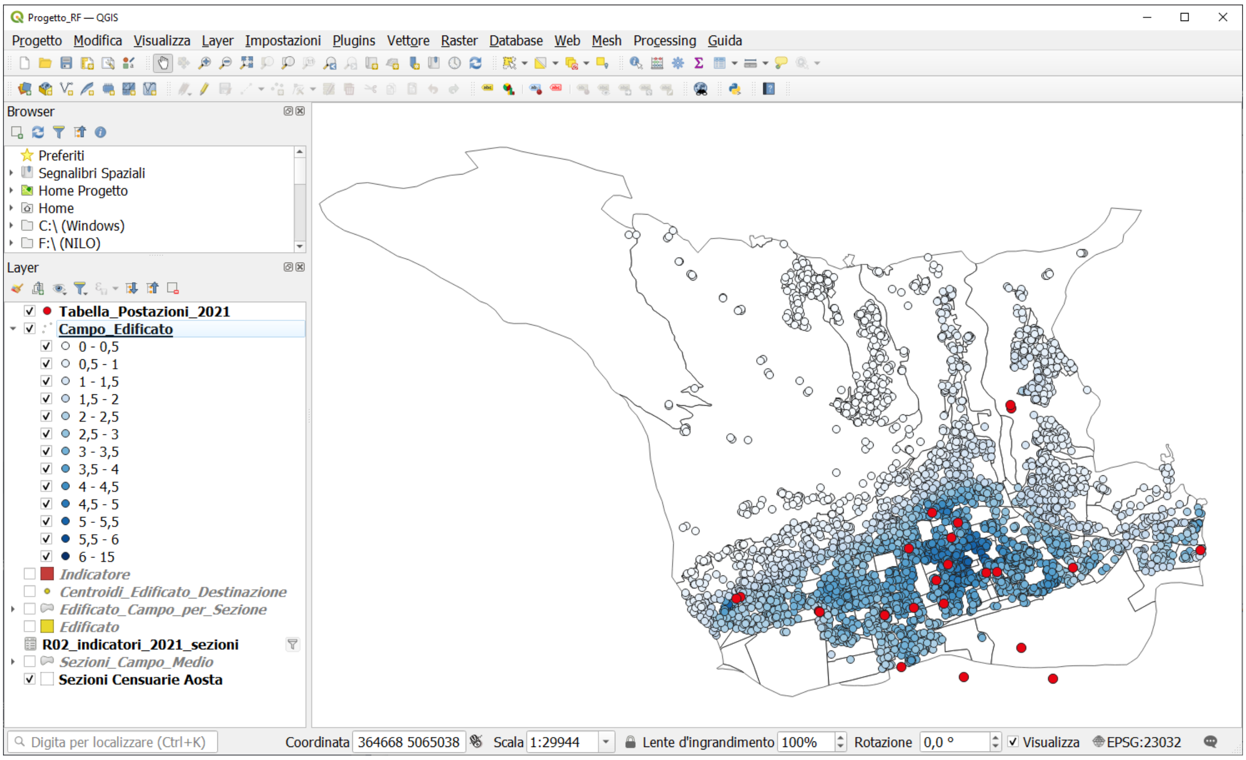


Figure 6.26: Report of the simulation, the colour represents the electric field intensity according to the legend on the left. In red the workstations

6.7 RF exposure indicator

The indicator required by the EMF research programme, activity A, consists of a histogram defining how many people are exposed to a value of electric field fitting in a certain band and a map showing which areas are most exposed. All the evaluation conducted so far does not yet take into account the number of people; so far, it has been limited to assessing the simulated field in several points representing the buildings. It is therefore necessary to integrate population data, it is furthermore important to associate a number of inhabitants to each of the identified buildings and to define the ranges of each band that is used to categorize the results.

With respect to the values used to define the bands of electric field, in the first stage all ARPAs used the most convenient way. To uniform the procedure and avoid further data analysis to compare the results, the ARPAs together with ISPRA decided to set each class with a range of 0.5V/m. This criterion is followed up to the exposure limit of 6V/m, for the data that exceed this threshold it has been decided to not perform further distinction. According to that thirteen classes of exposure have been set and, although the task of this analysis is not to ensure compliance with the exposure limits, none of the points exceeded and so the last class remained empty. A crucial aspect that has to be taken into account is that this analysis is like a picture of the situation. It has been conducted with reference to specific conditions, which could change in future if the operators, owners of the radiating systems, decide to apport changes to the installed devices. This project has been conducted with reference to the day 20/08/2024.

To calculate the number of people for each building, a new QGIS operation is needed. Thanks to the cooperation between ARPA VdA and the local regional administration, it has been possible to include in the available files also the shapefile representing the census zone of all the Aosta Valley. This file, also consulted in the validation phase to establish the border of the area in which to perform the measurements, contains all the census zones of the entire region divided according to the municipality. The important data in the attribute table do not finish with the municipality (which is certainly important to properly filter the useful data) and the ID number of each zone, this file contains indeed the relative population expressed in number of inhabitants; this information is crucial, and it has to be included in the attribute table of the last version of the file Centroidi. Importing both the layers in QGIS it is time to perform a new merging procedure with the tool *Add attributes by position*. This time the base layer is Centroidi and the attributes that have to be merged come from the layer of census zone. In particular, the information of interest are the ID number of the zone and its population. Updated the Centroidi file with the desired information, the analysis has to proceed in Excel. The attribute table at this moment contains for each point the ID number of the census zone to which it belongs and its total population, not the specific number of inhabitants of the specific building. To solve this problem, it is possible to use a simple algorithm which uses as assumption uniform inhabitation in the census zone:

- Phase 1: the Centroidi attributes table also contains the geometrical details of the original buildings. Knowing the surface and the height of the buildings it is possible to calculate the volumes (This part could be also done in QGIS like the third one).

- Phase 2: in this step, the relative volume occupied by each building in its census zone is calculated. This is possible thanks to the function *Sumif*, which allows performing additions under defined conditions. In particular, the condition is based in the ID number of the section to form the denominator of the fraction used to establish the weight of the building.

- Phase 3: this step defines the population attributable to each building as the product of the weight of the building and the population of its census zone and rounds the result to the closest integer.

- Phase 4: a final check is conducted to ensure the consistency of rounding and the match between the total population and the sum of the number of inhabitants calculated for each building.

Applying these steps allows obtaining the number of people per building and, summing again with electric field as condition using the *Sumif* function to check the belonging range, it is possible to form the data structure of the indicator itself. The only detail still to be taken care of is the final graphic form. To do that, a quick data processing via Excel resulted in the final histogram visible in Figure 6.27:

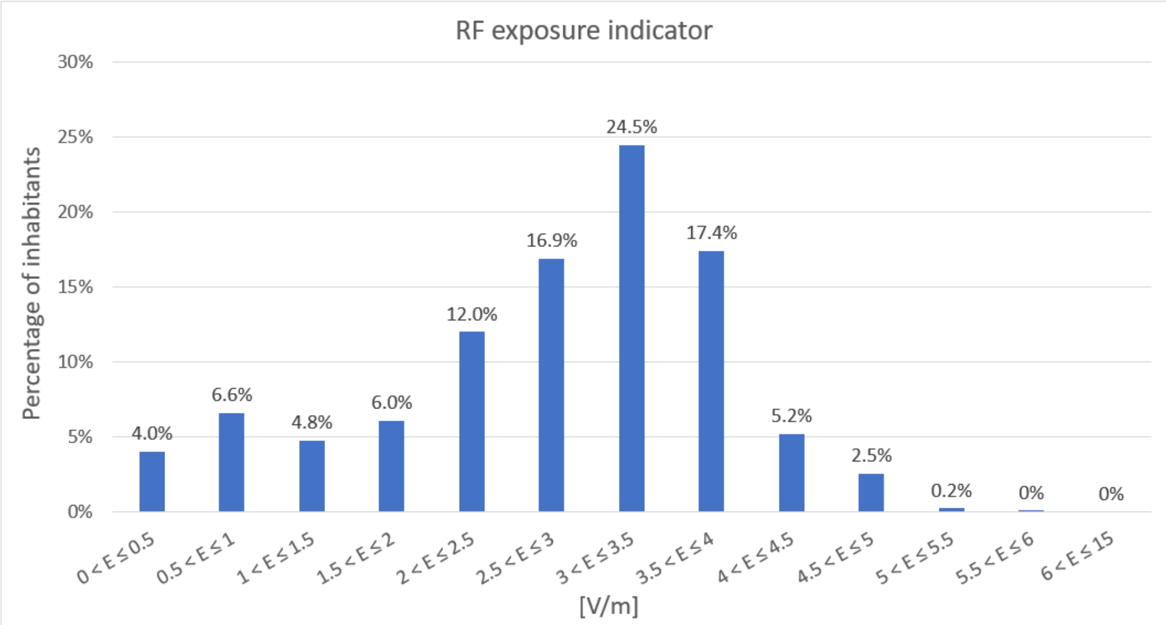


Figure 6.27: RF exposure indicator in form of histogram as requested in EMF research programme

This histogram only provides summary information, showing for each electric field interval the number of inhabitants whose exposure falls within the range. It does not provide any indication of how is the distribution over the territory. In this respect, the EmLAB report alone, reprocessed with QGIS, in the previous paragraph, was better. In order to mix the features of both the elements, it is worth to evaluate the average value of electric field for each census zone weighted on the number of people for each building. This new indicator is more accurate if evaluated with a weighted average than the arithmetic one, because it takes into account the fact that a larger building reasonably have more inhabitants and so it impacts more in the average. To perform this calculation both Excel and QGIS have been used, according to this procedure:

- Phase 1: To calculate the weighted average for each census zone, the starting point is the Centroidi layer. In Excel environment, using the function *"Sumif"* to evaluate the numerator and the function *"Countif"* for the denominator. In this way, the numerator of the fraction is composed by adding only the product field-inhabitants in a specific census zone and the denominator is the sum of the inhabitants in that census zone. The weighted average field is available for each centroid for its specific census zone.

- Phase 2: To pass the information from the centroids to the census zone, it has been used the QGIS function *Add attributes by position*. In this way selecting the census zone layer as the destination, the updated Centroidi layer as the starting point and the right attribute to be added, the exchange of information is completed.

- Phase 3: This step is the one which really reach the starting goal. Until now, the information on the average field per census zone have remained written in attributes tables. To make them easily visible, it is necessary to associate a colour to each zone according to the calculated average field. This is possible changing the standard settings in the symbology of the layer.

As a reference, using the same colour scale adopted for Figure 6.26, it is possible to see the map of Aosta with the information about the average electric field for each zone, Figure 6.28

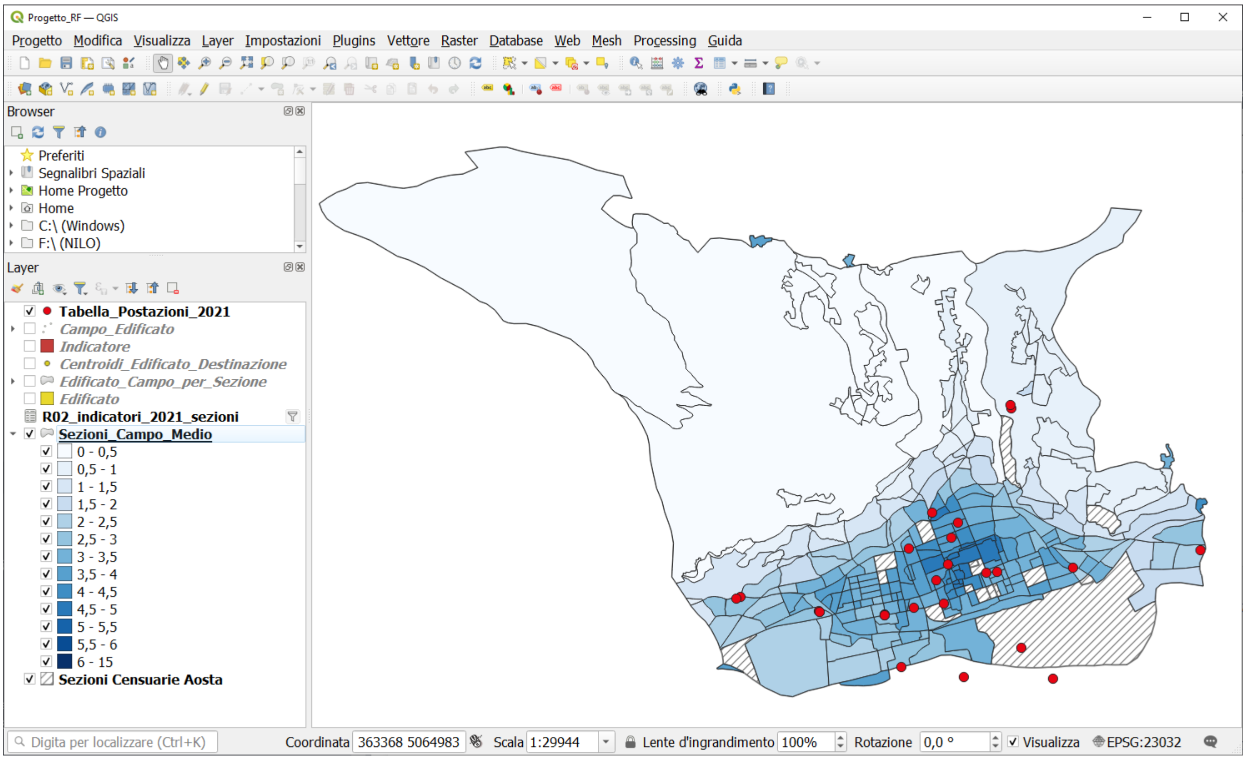


Figure 6.28: Representation of average field values per census zone

In Figure 6.28 it is possible to see three particular features of this analysis. The first one is that some zones are filled with a different pattern (grey dashed areas), this is because there were no residential buildings in those census zones and so there is not any available information about these zones. To highlight this fact, a different pattern has been adopted. The second feature is that, on the northern and eastern borders, there are some census zones with a really different colour than their neighbouring areas. This is not due to hotspots where electromagnetic fields radiation is concentrated on, this is only because those tiny areas do not count by themselves, they belong to a census zone that principally develops in more exposed position, but therefore share the average values with their main part.
The third feature is the most important, it was also noticeable in Figure 6.26, and it is a direct consequence of an assumption made. The central part of the city is represented with intenser colour, and it means higher values of electric field. This is not corresponding to the actual conditions; in that area many operating workstations are present, but there is also a dense network of constructions, which in fact greatly limit the actual exposure in those areas. The trend shown, although with different values, could have been found if the simulation had been conducted on the upper floors of each building, where the shielding effect of the buildings is considerably reduced, and the open field assumption is more appropriate.

6.7.1 Model correction

In order to have a better representation of the real conditions, it is necessary to do some considerations about attenuation and power reduction. It has to be said that among the scheduled further activities there is the evaluation of a correction coefficient which is used directly on the fields calculated by the simulations to keep in consideration the attenuating factors, but it is only possible to conduct this analysis when all the ARPAs have concluded their preliminary work of investigation. This coefficient will be evaluated according to the weighted significance of the regional data and a statistical analysis on national basis. The need for a correction coefficient is clearly visible, obviously cautionary conducted simulations have to be rescaled to reflect actual data and apport useful contributions.
In the small reality of Aosta Valley and this analysis, the correction coefficient should be close to 0.3 according to the comparison conducted in the comparison paragraph.
To avoid this value to be too restrictive to be used on a national scale, and to avoid the risks associated to extending it to all the municipality of Aosta, a more precautionary value must be used. Furthermore, this factor derives from an analysis conducted in a specific place, with a specific disposition of irradiating systems and buildings and so it can result too specific. The wrong evaluations of this coefficient could lead to wrong analysis, in both way:

- Too low coefficient. This eventuality could be a problem because a too small coefficient implies a strong reduction of the values; in this case if reflection phenomena occur at some points (like in the validation case), the application of this coefficient may lead to an underestimation of the field and to simulated values lower than reality.
- Too high coefficient. This eventuality, on the contrary, could be a problem because it would translate in a too low attenuation, losing the original concept of correction coefficient and not representing tactual conditions.

According to other reports of other ARPAs, this coefficient is expected to be about 0.5, which is more cautionary than 0.3 (it implies a smaller reduction), but it is specific of their conditions. In brief, for the final coefficient all the contributions will be taken in consideration to have the best representation of the average behaviour.

Reduction coefficient estimation

For this work only, it is possible to hypothesize a reductive coefficient that takes regulatory and statistical aspects into account in a reasonable manner. The reduction coefficient mainly takes into account two phenomena: the reduction of the power and the attenuation of the surroundings.

- Power reduction. According to the national database held by ISPRA, in which the operators communicate the average daily irradiated power in respect to the rated one for each system on national scale, the actually used average power amounts to the 65% of the declared maximum power. This consideration, taking into account that power and electric fields are quadratically linked, leads to, field values that are about the 80% of the maximum, on average.
- Attenuation. According to the normative D.M. 5/10/2016 [46], a wall with no windows between source and investigation point provides an attenuation of 6dB on the power and

so a factor 0.5 on the electric field. Keeping in consideration that there is for sure the possibility to have more than one wall to take account, but there are also windows which do not provide any significant attenuation, it is possible to estimate a contribution to the attenuation of around 0.4 (in power), and so 0.6 about the magnitude of the field.

According to these references, on a purely exploratory basis as ISPRA and ARPAs will then make more detailed considerations, it is possible to estimate the reductive coefficient as:

$$0.8 \cdot 0.6 = 0.48 \tag{6.1}$$

Since, as already mentioned, this section deals with prediction assumptions and not with a specific and rigorous calculation, it is possible to approximate this coefficient to the value of 0.5 and apply it to the results obtained previously. In this way, the distribution on the histogram changes as the exposure values are reduced. In Figure 6.29 it is possible to see the comparison between the two versions.

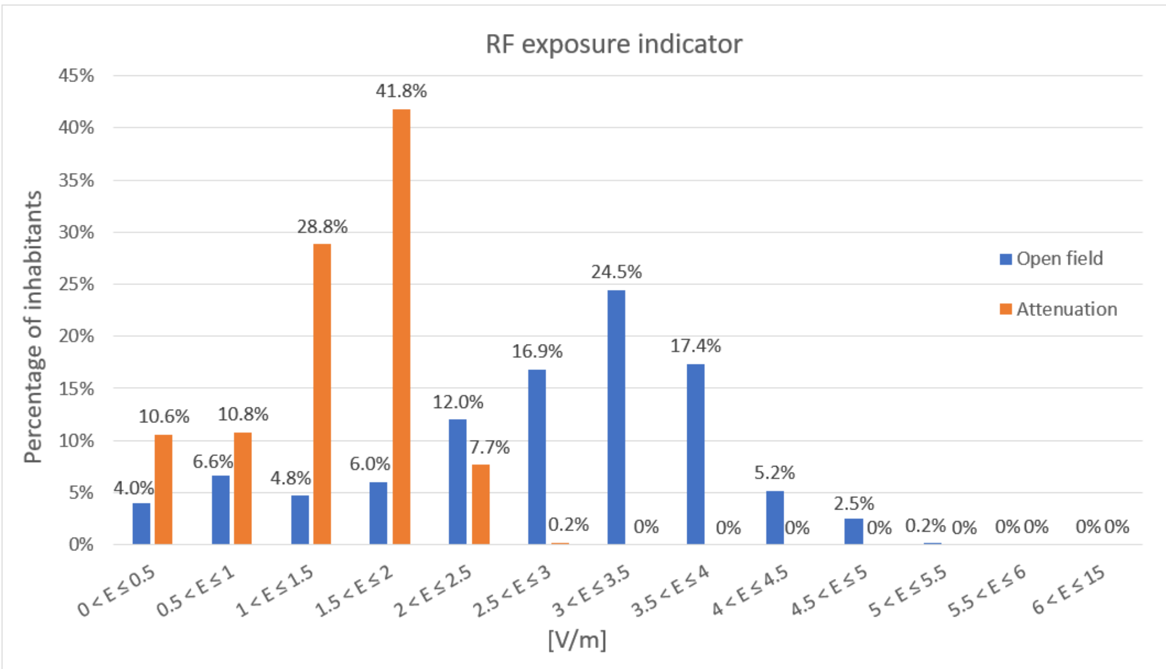


Figure 6.29: Comparison between the open field and the attenuated version of the histogram

With the application of the corrective coefficient, the histogram is more concentrated towards classes with lower field values. This condition, which better represents the actual conditions, highlights an even better situation than before with lower exposures. At the same time, the application of the mentioned coefficient, also affects the map representing the census zones with a specific colour according to the average value of electric field. In particular, as visible in Figure 6.30 the colours are lighter, they tend more towards white, which means lower exposure than in 6.28.

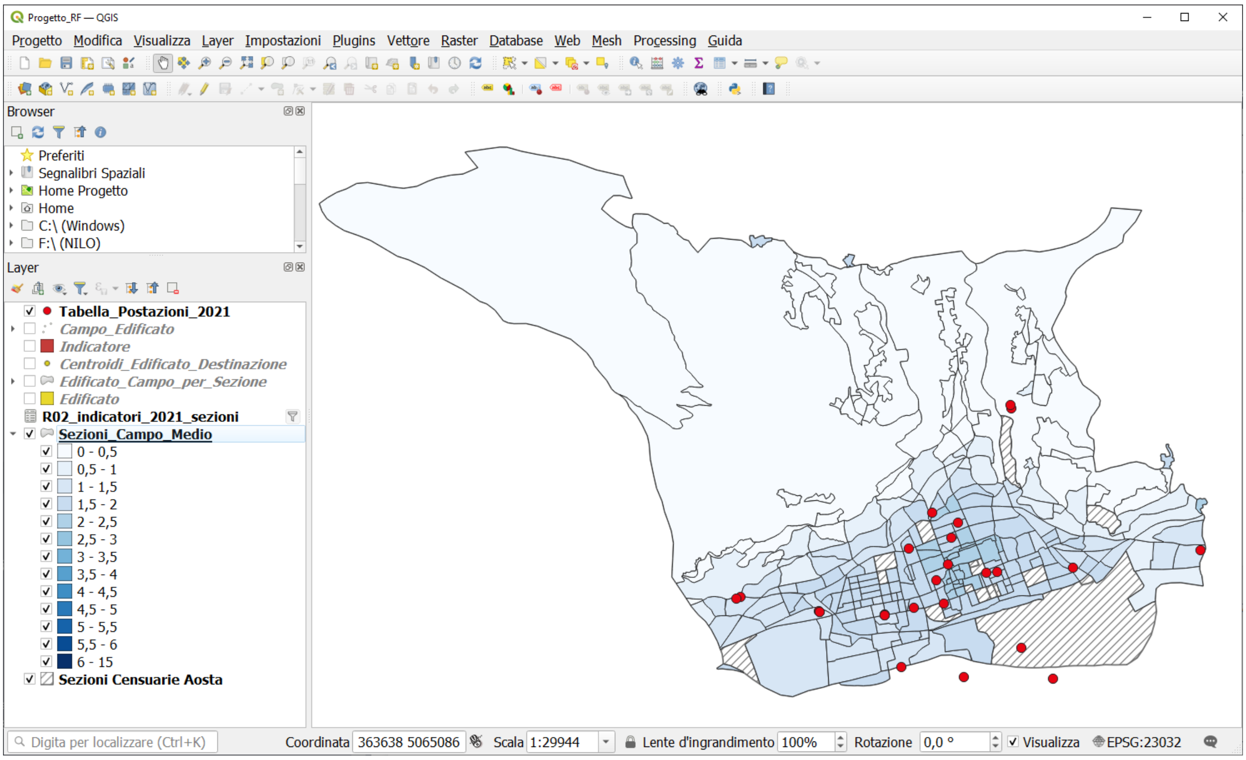


Figure 6.30: Average field values per census zone, after correction

7. Extremely Low Frequency (ELF) exposure indicator

7.1 Activity description

The EMF research programme consists of a global evaluation of electromagnetic fields exposure. In the second part of Activity A, ARPA VdA has to evaluate the emission of EMF and calculate the exposure indicator for the population. In this specific case, the frequency is 50Hz, the one of the electric power grid. This indicator is conceptually similar to the one for RF, but it also has many differences that are discussed in this chapter.
Radio frequencies and extremely low frequencies are different from many points of view, but in this case, the main difference lies in the investigated areas. Radio frequencies are used to transmit signals between antennas directly through the atmosphere, which implies that the effects of the field permeating the atmosphere itself are detectable even far away from the sources. For extremely low frequencies, the phenomena are concentrated in a much narrower portion of space. While it makes sense for a radio base station to measure the characteristic electric field magnitude at a distance of hundreds of metres, for a power line at those distances there would be no significative influence.
Unlike for the RF part, where it was investigated the electric field, for the ELF part the characteristic quantity is the magnetic field generated by the sources. This is because of the assumptions which the analysis is carried out with. The main goal is still to evaluate the exposure in residential contexts. According to that the simulations have to be conducted in points which are inside buildings; thanks to the walls the electric field generated by a power line is strongly attenuated and under any threshold of interest if the walls of the building also contain a metal reinforcement, the attenuation may be even greater as a Faraday cage effect occurs (depending on the mesh).
As mentioned in Chapter 6, the study of the exposure indicator can be conducted with simulations and with measurements and again, to have less impact on the population, the simulation way is preferable. According to this, the protocol asks for a validation measurement, similarly to RF. To select the points in which to do the simulations, the same procedure of the RF part has been undertaken: the analysis inspects the centroids of the buildings at a height of 5m with respect to the soil.In this case, however, as mentioned, it is not necessary to investigate the entire township of Aosta. Magnetic field emissions from power lines are strongly path-related and exert their influence in small portions of space since they are not designed to irradiate like antennas. ISPRA and ARPAs, in order to standardize the procedure, defined a guideline and set that for each investigated power line the area interested in the simulation is the projection on the soil of a buffer of specific dimensions directly related to the rated voltage of the power line itself.

According to this guideline procedure, three standards have been defined for single-circuit lines:

- 132kV: for lines with this rated voltage, the buffer must have a semi-amplitude of 20m;
- 220kV: for lines with this rated voltage, the buffer must have a semi-amplitude of 30m;
- 380kV: for lines with this rated voltage, the buffer must have a semi-amplitude of 40m.

In this case, semi-amplitude are referred to the middle point of the route of the line. These values have been obtained according to a previous internal analysis adopting two evaluation criteria: $0.4\mu T$ with annual average currents and $3.0\mu T$ with a maximum daily median. An example of a simulation of the magnetic field propagation of a 132kV power line is reported in Figure 7.1; for more details, consult Appendix B.

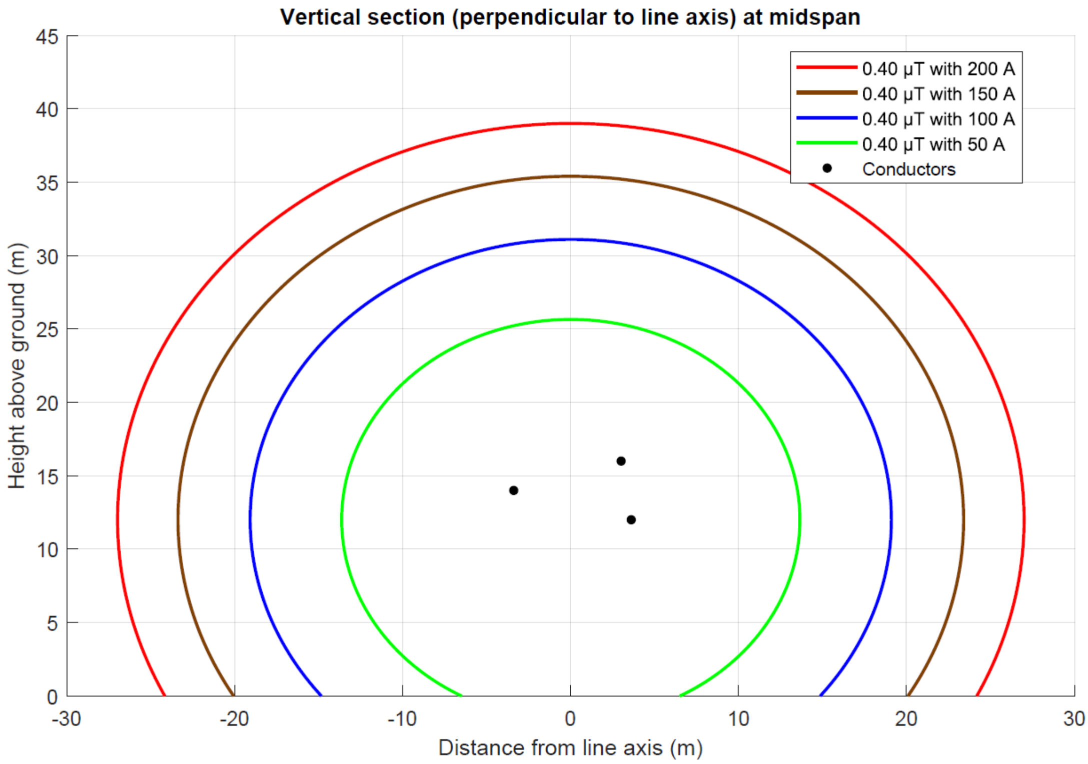


Figure 7.1: Magnetic field distribution around a 132kV power line

To evaluate the ELF exposure indicator, it is chosen a power line with a rated voltage of 132kV called T.504 which connects the substation "Aosta Ovest", located in Aymavilles (AO), to a derivation pylon near the hydroelectric plant of Signayes, a hamlet of Aosta (AO). This power line is chosen because it crosses the municipalities of Aosta and Sarre, passing over residential areas useful for the analysis. There are other possibilities available, but, mainly due to visual impact, modern power lines are built away from houses and villages and this power line is one of the most significant in the area. It has a rich database of information both from the aspect of geographical and electrical characterization, but the most important feature is that it generates a buffer that accommodates a fair number of buildings, ensuring statistical significance to the sample.

7.2 QGIS

7.2.1 File manipulation

To have the correct list of centroids for the simulation, it is necessary to perform a similar procedure as done in the RF section. This time, the Edificato file includes also the municipality of Sarre. Aymavilles has been excluded from the evaluation because, although the substation Aosta Ovest is located in this municipality, there are no buildings in the buffer. Also, the municipality of Jovencan is affected by the power line, but no buildings are in the buffer and so, as Aymavilles, it has been excluded from the study.
Another useful file is the shapefile relative to power lines routing. This shapefile, realized by the cooperation between ARPA VdA and Terna, contains all the routes of the HV power lines in Aosta Valley. When opening this layer in QGIS and applying a filter, only the T.504 route was selected. To create the area of investigation around the power line, QGIS has a specific tool called "Buffer" which allows creating a strip centred on a specific element, with a specified thickness as shown in Figure 7.2

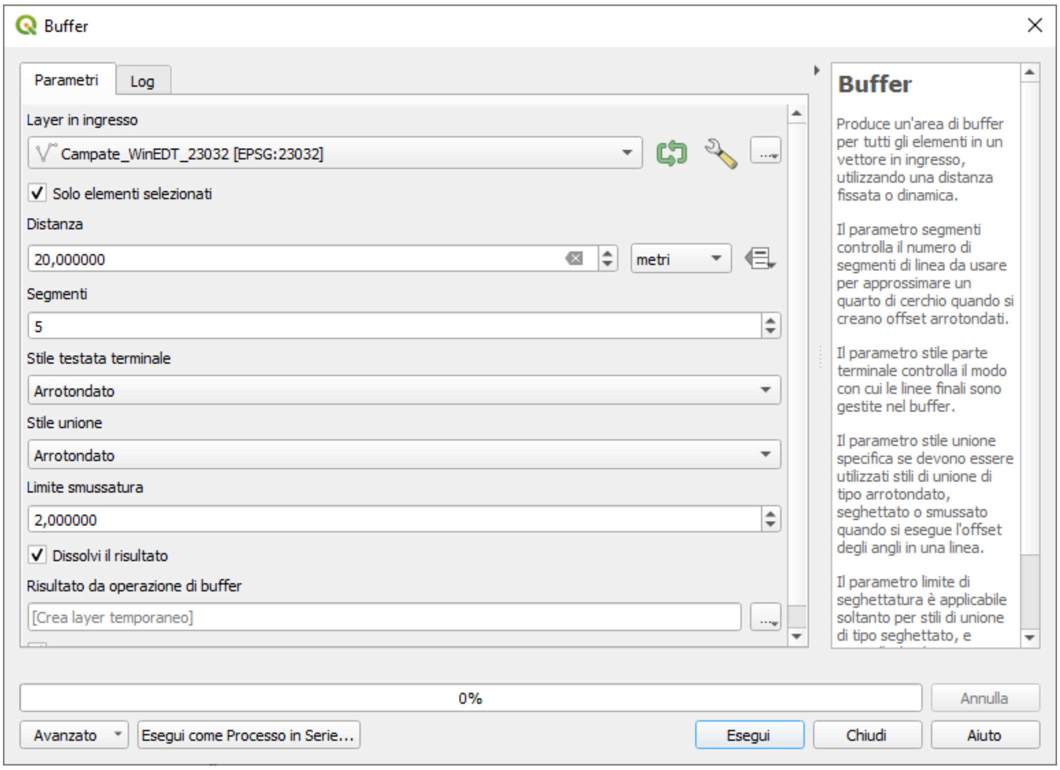


Figure 7.2: Communication window of buffering tool

In this window it is possible to set the semi-amplitude of the buffer and select the option "Dissolve the result" to have a unique buffer and not many segments, one for each segment used to define the power line itself. With the buffer representing the influence area, it is time to select the buildings. To perform a correct selection, it has been used the same tool adopted in RF file manipulation to merge attributes from the "Catasto" and the "Edificato" layers. This tool performs an overlap analysis to have an exchange of attributes only between those elements which coexist in the same location. In Figure 6.9 it is possible to see the communication window of the tool, this time the starting layer has been the "Edificato" of Aosta and Sarre and the comparison layer has been the buffer. In this way, selecting as criterion "Overlap" and as transferred attribute the name of the line, it has been possible to execute the algorithm and simply filter the buildings looking for those which had "T.504" as an attribute. This is a cautionary approach because in this way all the buildings that even touch the buffer are included. In addition, the analysis on intended use of buildings was only available for the municipality of Aosta, for the municipality of Sarre it has been decided to cross-reference the available data between shapefiles and orthophotos and have at least a summary analysis excluding visibly non-residential buildings. Once the selection of buildings has been completed, in order to have many points instead of many polygons, the centroids of each geometry have been calculated, and their coordinates have been extracted. After a comparison with an orthophoto some of the extracted centroids have been removed from the treatment because they were not connected to residential buildings.

7.3 WinEDT

WinEDT is another of the software used in this project. It is a software being part of a suite released by SE.DI.COM, an Italian company operating in the field of territory modelling and simulation solutions to study the interaction with the technological world. This company has always been involved in making simulation tools suitable for realities such as ARPAs and other control bodies since the first risk evaluations have been requested in 1999.
SE.DI.COM offers two suites to its clients: one suite called RPT which is much more focused on the design phase of telecommunication and radio-electric systems and one called EDT which is focused on territorial evaluations and verifications [47]. WinEDT is a work environment in which the users can perform a risk assessment of one or multiple factors in a georeferenced project, this is the main feature. It is compatible with orthophotos, shapefile and many file formats. To work in the WinEDT environment, it is necessary to have two files:

- *.prj*: this family of files is used to define the base project. They contain data about the conformation of the terrain and define the portion of land under analysis.

- *.wrk*: this kind of files define the work environment, everything that is modelled (sources, buildings) is saved in this type of file.

In particular, ARPA VdA, in close cooperation with Terna, has created a file which is a database of all high voltage power lines in the region. This file contains not only the georeferenced position of each individual pylon, but also the structural conformation of each one in terms of: typology, height, distance between cables and support, and other useful information. This provides a complete and detailed mapping of the lines, with the chance to have the most faithful reproduction possible of the spans and their distances from the ground. An overview of the total file is visible in Figure 7.3:

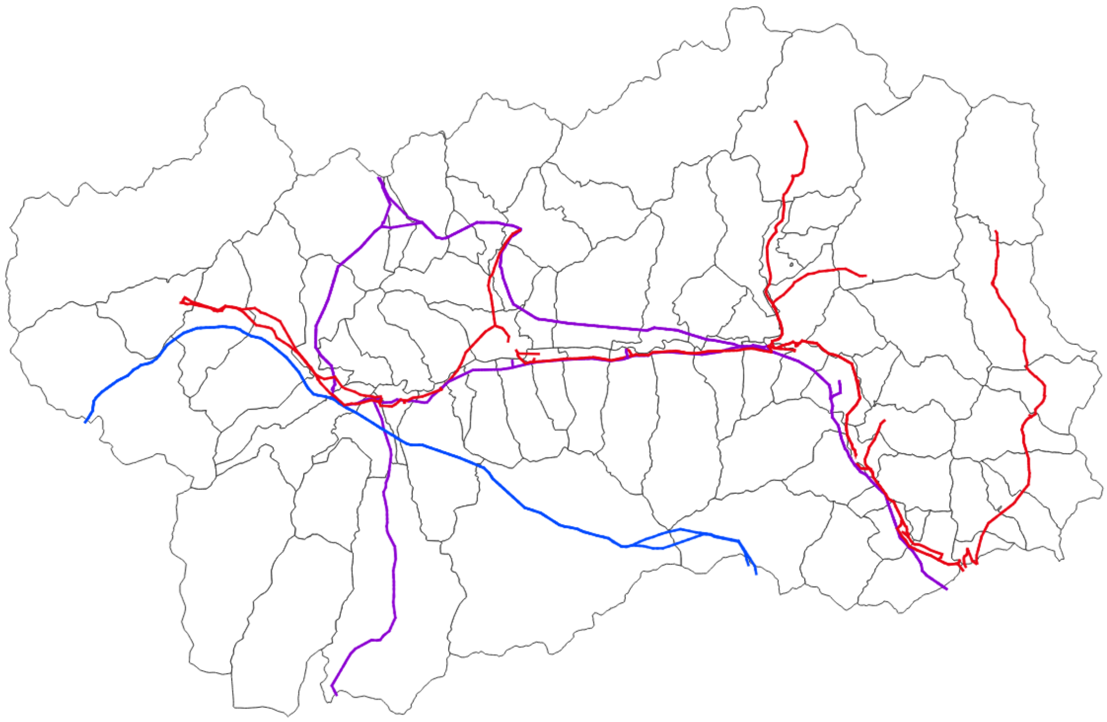


Figure 7.3: Overview of the HV network of Aosta Valley

To ensure a complete comprehension of Figure 7.3 it is worth to highlight the meaning of the used colours:

- Power lines with a rated voltage of 132kV are represented in red;
- Power lines with a rated voltage of 220kV are represented in purple;
- Power lines with a rated voltage of 380kV are represented in blue.

Similar to QGIS, it is also possible in WinEDT to load files of different formats (including Shapefile) in the form of layers. Differently from QGIS, this faculty does not allow the same operations, it is just a visual aspect to have better rendering for the simulations. WinEDT has also the possibility to have a comparison with maps and orthophotos; in its structure it is provided that the geometry opened as fundamental layer is organized in a grid.
With this instrument, it is possible to activate and deactivate the available maps or ortophoto for each rectangular mesh. This feature of being able to set per grid unit as well as for the whole project is very useful in order not to burden the file processing. Using graphic layers can lead to performance slowdowns. these files are usually very heavy, and loading them over the entire project can hinder even the simple dragging of the map portion.

7.3.1 Operations in WinEDT

To perform magnetic field simulations in WinEDT the user have to select “Elf” in the menu bar and select the voice “Analysis”. In this way the program opens a dialogue window called *ELF Magnetic Field Analysis*, that is shown in Figure 7.4, in which the user is asked to first define the sources that it is intended to use and then set the parameters necessary to perform the simulation. The first tab is called “Span selection”, it allows selecting those spans that are used in the analysis. The selection is possible in a rectangular shape by tracking a rectangle on the map or selecting singularly the two opposite corners.

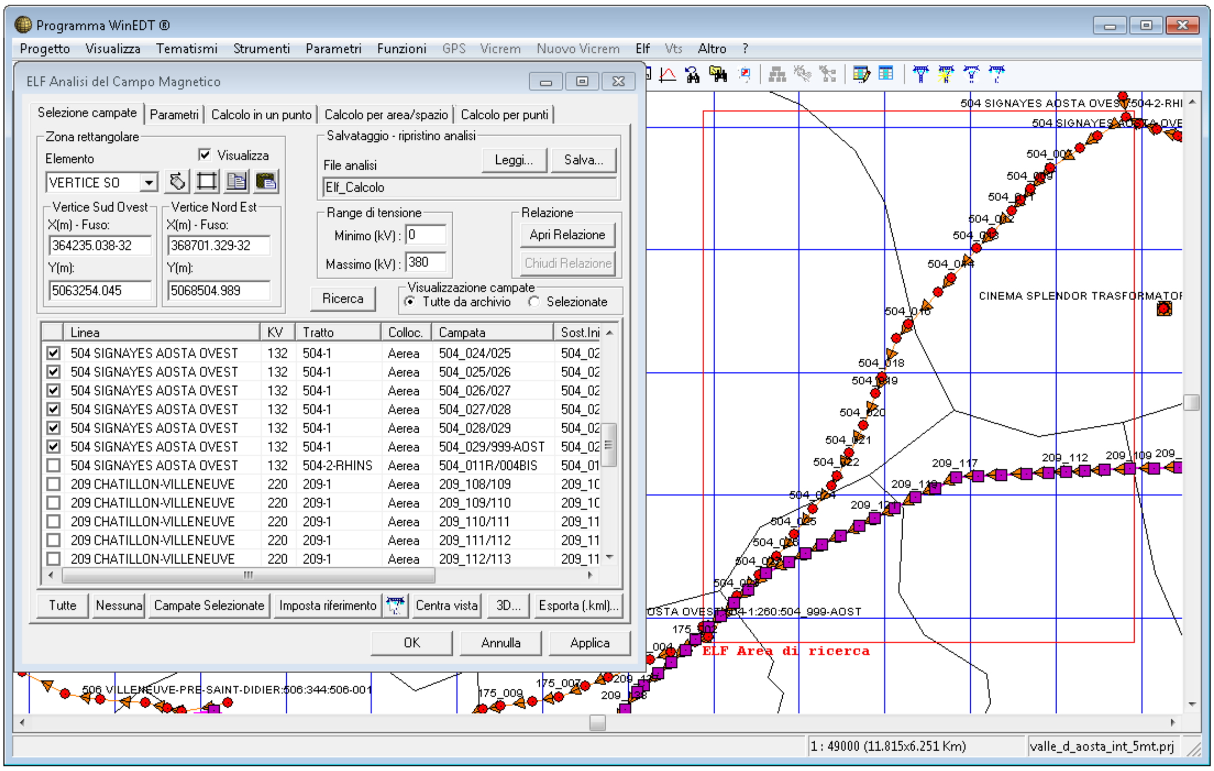


Figure 7.4: ELF Magnetic Field Analysis window, “Span selection” tab

If other traits are included during the selection process, they can be deselected and excluded from the simulation in the lower part of the window. In the case shown in Figure 7.4, also other spans have been enclosed in the selection, but they have been excluded removing the flag because they were of other power lines, like T.209 Chatillon-Villeneuve, or of other branches of the same interested line, like the T.504-2 which continues towards Rhins and not towards Aosta Ovest. It is also possible to load a pre-existing selection of spans, this feature is really useful because it allows to perform the selection process once and just by saving it in a specific .elf file, it is available for future analysis.
When the selection of the spans is terminated, the source characterization has to be completed in the “Parameters” tab.
In this tab the user is asked to electrically define the sources setting the current for each power line (if the relative spans were not selected in the previous tab, the set value is irrelevant), to set the scale adopted to show the available visual representations and to select the way in which to combine contributions between the different conductors. In Figure 7.5 it is possible to see that the only significant value of current, T.504, is set at the value of 110A (the average current of the previous year, 2023) and the contributions of all the conductors are added together in coherent combination (keeping consideration of the electrical phases).

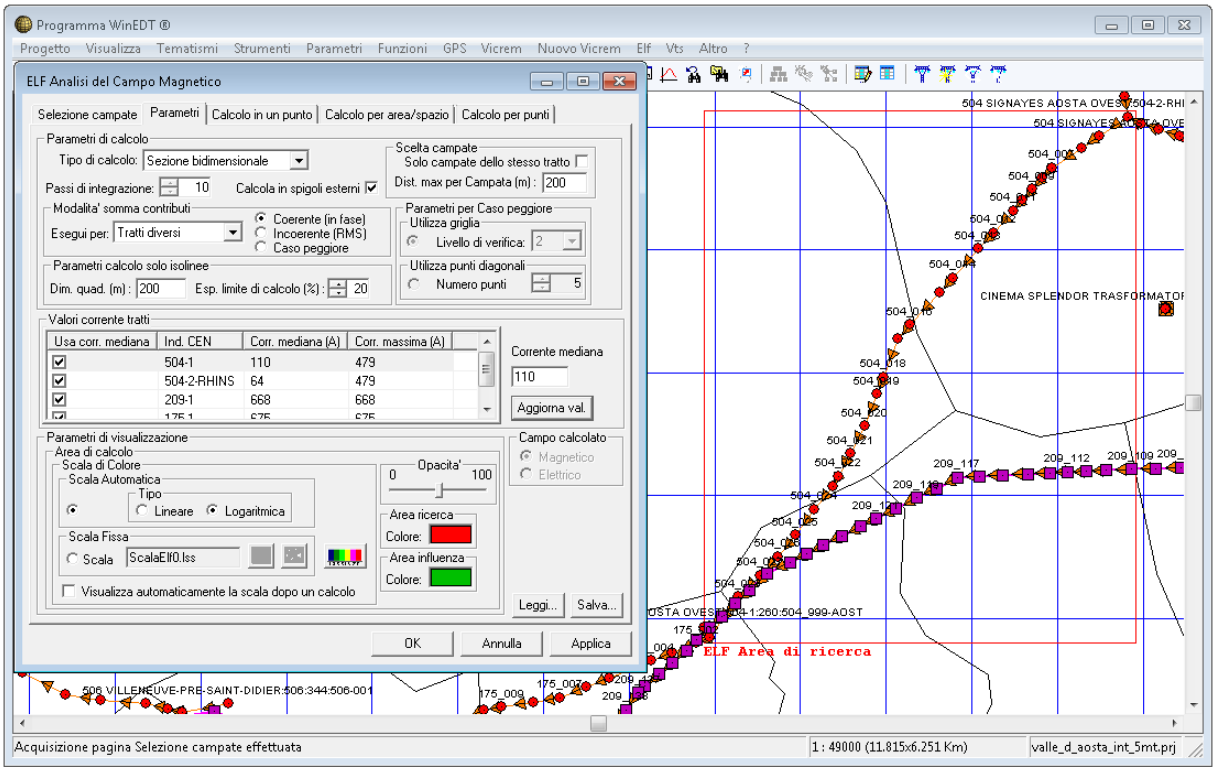


Figure 7.5: ELF Magnetic Field Analysis window, "Parameters" tab

The other three remaining tabs in these windows allows doing different types of simulations. The first tab is the single point simulation, in this tab there is the possibility to insert a single point in the analysis and evaluate the magnetic field in that position.
The second tab is dedicated to surface simulations. The user defines a rectangular area and the evaluation is made in that specific selection. It is possible to have both a 2D and a 3D report for this analysis, and this is of course a powerful instrument to evaluate buffers around the power lines and real exposure of specific points.
2D simulations give the magnetic field value representation projected on the terrain, and it is a hybrid report because the land is represented in 3D for better comprehension.
3D simulations, on the other hand, adopt the same terrain model, but focus on identifying the prismatic volume around the spans defined by a threshold value that can be set during the definition phase. More details about the results of these kinds of simulations are given in forthcoming paragraphs.
The last tab is the magnetic field evaluation in a list of points; in this tab there is the possibility to import a specific list of point to be evaluated. This feature is the most important when a complex simulation has to be done; single spot simulations are useful for validations or local studies, in this project it is necessary to evaluate many points at the same time and so, for the final simulation, this tab has been used.

7.4 Validation

For the ELF part of the EMF research programme, the number of measurements necessary to validate the model is reduced to one. It was asked to perform one measurement (differently from the RF procedure which asked for at least ten) as agreed in the ELF exposure indicator procedure (full version in Appendix B). This choice is motivated by the fact that electromagnetic fields produced by high voltage power lines are much more predictable, and the effect quickly decay with distance, while this is not true for RF electromagnetic fields which depend on many factors and sources. Working with ELF means focusing on the magnetic field, which has a different behaviour. Suffice it to say that the presence of a person nearby the instrument when measuring an electric field significantly perturb the measured value, whereas for a magnetic field measurement the effect is completely negligible. This is because a body can concentrate electric field lines and interfere with the normal distribution, but it is almost completely transparent to magnetic field lines since its relative magnetic permeability is very close to one.
To sum up all the considerations carried so far, and to compare ELF with RF analysis, a table has been created 7.1.

Property	**Radio Frequency**	**Extremely Low Frequency**
Field	Electric [V/m]	Magnetic [µT]
Number of sources	Multiple	1
Number of measures	10	1
Measure time span	6 min	24 hours
Proximity sensitivity	No	Yes
Wall attenuation	Yes	No

Table 7.1: Comparison between ELF and RF analysis

In addition, it must be taken into account that, as with radio frequencies the effect of the magnetic field has been neglected because it was related to electric fields that were too low, here too, considerations must be made. Being always in the near-field condition, as mentioned above, it has to be taken into account that electric and magnetic fields have mutually independent formulations. It is worth mentioning that even materials normally used in construction can provide an effective shield to reduce electric field values inside dwellings below threshold values. However, this shielding action is not exerted against the magnetic field, which easily penetrates walls without receiving any attenuation [5].
In order to have the measurement for validation, it has been chosen to evaluate a set of measurements recently performed in a site located in the same area of investigation. This site is located near Arpuilles, a hamlet of Aosta, really close to the power line T.504 Signayes-Aosta Ovest. In Figure 7.6 it is possible to see the branch of the power line used in this analysis, for reasons of privacy it was chosen not to go into further detail by defining the house of the validating site specifically.

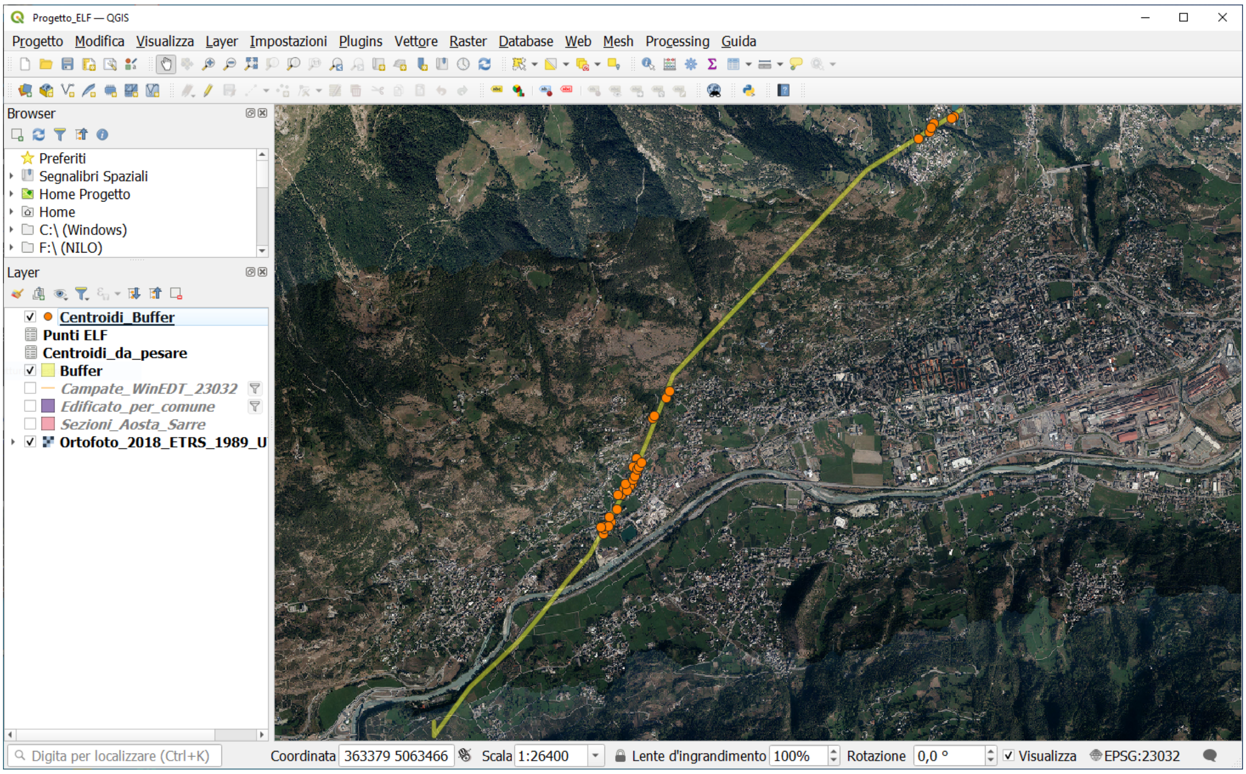


Figure 7.6: Route of the power line T.504, in yellow the relative buffer and in orange the centroids

7.4.1 Measurements

To start the measurement procedure that is then used to validate the entire model, it is important to choose the most significant spot. As this indicator is reserved for residential buildings, it is important to get approval to take measurements in a real house. Once got the approval, multiple measures must be taken in order to find the right spot of the building. Since this is only needed for validating the simulations, theoretically everywhere is fine, but a more appropriate location is inside the house, in the point with the highest measured field. This is to have the confirmation that the magnetic field is not influenced by the presence of walls. Moreover, because the original purpose of this simulation is to avoid measuring the magnetic field house by house, but, as there is the opportunity, it is necessary to do it properly at least once.
In the following are the instrumentations used for the measurements. The need for multiple instruments for these measures (different with respect to the RF analysis where only one instrument was used) is that the instrument Wavecontrol SMP2 with the ELF probe is used for a preliminary set of measures of the magnetic field. Then the measure for the validation is done with the Emdex II (always magnetic field) and finally the Emdex Snap is used to evaluate the electric field (as a side measurement not for the indicator).
In particular, with the instrument Wavecontrol SMP2 (the same one used for the validation measures in the RF analysis, Figure 6.17) and the appropriate probe in Figure 7.7 it was possible to do some short trial measures to understand where to place the other instrument for the actual measure.

Figure 7.7: Probe for ELF measures

	Electric Field	Magnetic Field
Sensor type	Isotropic patented electrodes	
Frequency range	1 Hz – 400 kHz	1 Hz – 400 kHz
Field Strength Mode		
Measurement range	1 V/m to 100 kV/m	50 nT - 30 mT @ 50 Hz 50 nT - 10 mT (100 Hz - 10 kHz) · Upper range increases linearly with decreasing frequency below 100 Hz · Upper range decreases linearly with increasing frequency above 10 kHz
Graphical display	RMS, Axis Values, AVG, MAX, MIN, PEAK, RMS time graph	
Peak value	digital realtime	digital realtime
Resolution	< 0.4 mV/m above 8 Hz	< 0.1 nT (at 50 Hz) and < 0.05 nT above 100 Hz
Noise level	< 1 V/m (10 Hz - 400 kHz)	< 50 nT (10 Hz – 400 kHz)
Weigthed Peak Method mode		
Measurement range	200 % (min)	200 % (min)
Graphical display	PEAK (%), AXIS VALUES (%), AVG (%), MAX (%), MIN (%), RMS (%), Time graph	
Standards/Limits	EU Directive 2013/35/EU, IEEE, ICNIRP, BGV B11. Easy software update to future modifications and to other limits.	

Figure 7.8: Technical data of the probe

The instrument left in the house for measuring the magnetic field was the Emdex II, this instrument shown in Figure 7.9 has only to be turned on and to be left in place for the time required for the measure. After that, the data is automatically stored on the internal memory and can be downloaded directly on the PC to be elaborated and analysed.
In this case, as the measurements invade others' property, the instrument has been left for more than the required time (around ten days), as can be visible in Figure 7.15, so that if one day there was a problem with the line the measures were still valid the other days.

Figure 7.9: Emdex II

Feature	Specification
Meter Purpose	Multi-Functional Magnetic Field Measurement System
Recording	Yes
Data Collection	Actual Measurements
Range	0.01 - 300 µT
Resolution	0.01 µT
Typical Accuracy	± 1-2%
Frequency	Broadband: 40 - 800 Hz Harmonic: 100 - 800 Hz
Max Sample Rate	1.5 Seconds
Internal Memory	512 kb
Display	Alphanumeric 8-Character
Measurement Method	True RMS
Typical Battery Life	Up to 7 Days
Dimensions	16.8 x 6.6 x 3.8 cm
Weight	341 grams

Figure 7.10: Technical data of the Emdex II

For the measure of the electric field instead, it was used the Emdex Snap, with particular attention to how the measures have to be carried out to measure the electric field properly.

Figure 7.11: Emdex Snap

Feature	Specification
Meter Purpose	Digital Magnetic Field Survey Meter
Recording	No
Data Collection	None
Range	0.01 - 100 µT
Resolution	0.01 µT
Typical Accuracy	± 1-3%
Frequency	40 - 1,000 Hz
Max Sample Rate	0.5 Seconds
Internal Memory	None
Display	Alphanumeric 8-Character
Measurement Method	True RMS
Typical Battery Life	Over 120 Hours
Dimensions	11.7 x 7.1 x 3.8 cm
Weight	170 grams

Figure 7.12: Technical data of the Emdex Snap

7.4.2 Procedure

Magnetic Field

As said the magnetic field measure took more days, therefore before proceeding it was necessary to find the spot where the magnetic field was higher. Therefore, with the instrument Wavecontrol SMP2, some quick measures have been carried out in the spots shown in the following figures.

Figure 7.13: Ground floor measures

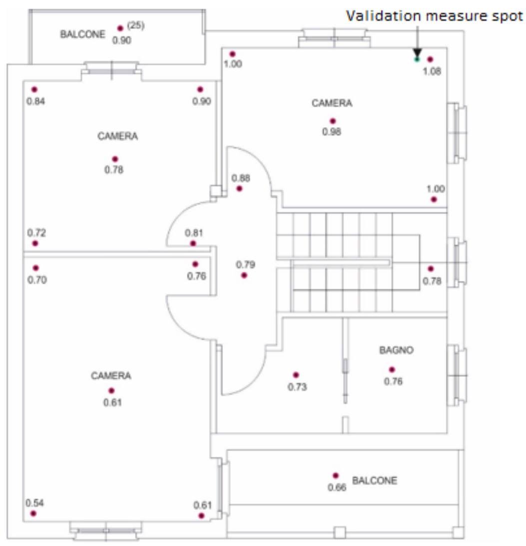


Figure 7.14: First floor measures

In Figure 7.14 is highlighted the spot where the long measure has been carried out, because that is the place inside the house with the highest magnetic field.
Once again for the long measurement it is used the Emdex II which samples are stored into the internal memory and subsequently downloaded on the PC.
The result of the acquisition are summed up in the plot in Figure 7.15.

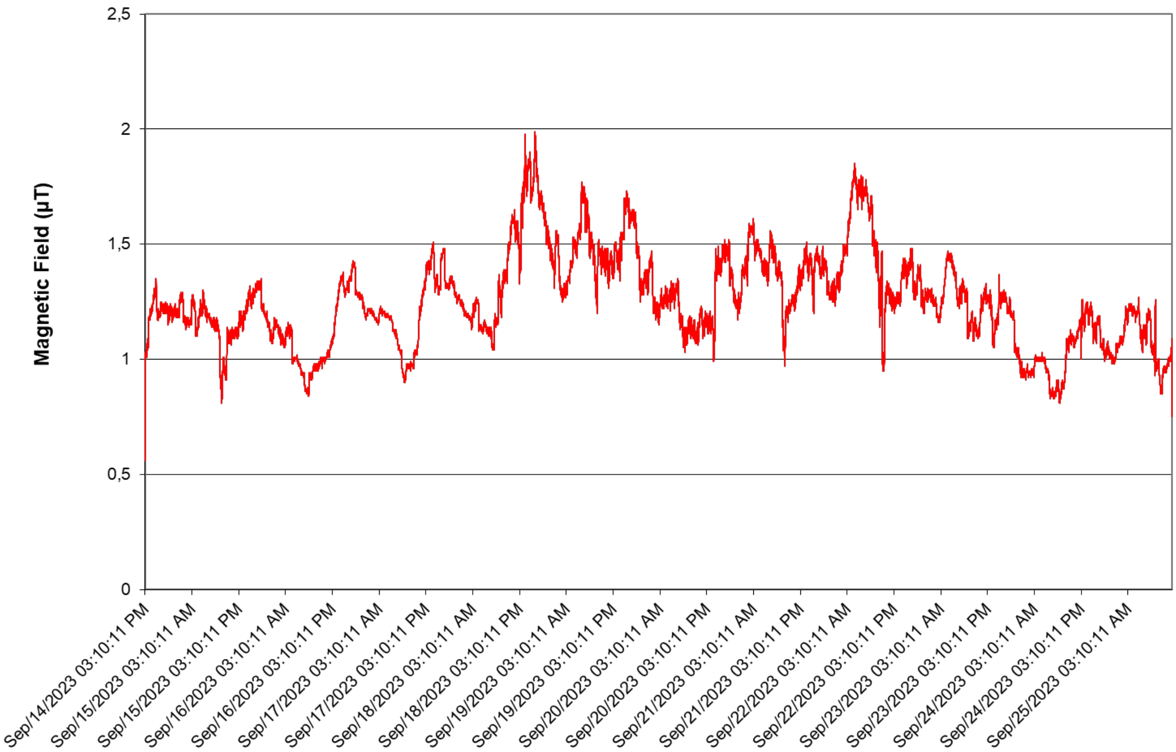


Figure 7.15: Validation measurement result

The daily medians can be summed up in the following table:

Date	Daily median [µT]
15/09/2023	1.17
16/09/2023	1.10
17/09/2023	1.21
18/09/2023	1.38
19/09/2023	1.46
20/09/2023	1.24
21/09/2023	1.39
22/09/2023	1.38
23/09/2023	1.24
24/09/2023	1.01

Table 7.2: Daily medians of the magnetic field measure

Electric Field

Even if the electric field is not of a big interest, a measure was done just to check that the law is being respected. This time the measure for the electric field doesn't require a long timespan as the result depends only on the voltage and not the current passing by. Therefore, an instantaneous measure with the instrument Emdex Snap was carried out, paying attention to stay away from the instrument. This is because the human body attracts flux lines that find a preferable path, as the body is conductive, and the feet are very close to the ground. There is no need to demonstrate it as when holding it in hands the measured value is zero, while moving away from the instrument the value increases. In general, it must be held away from any possible objects, especially away from fences, poles and metal objects that can absorb the electric field. Moreover, to have the worst-case scenario the measure must be done outside as the wall or the roof attenuates the measure (even more if there is metallic armour inside).
Not to false the measurement, it was used a stick to maintain the distances between the person and the instrument, as shown in Figure 7.16. Furthermore, the instrument used for the measure was inserted between two specifically designed aluminium plates, that serve the purpose of straightening the field lines that cross the instrument.

Figure 7.16: ELF electric field measure

In the figure it is also possible to see that the measure was carried under the line which is the place with the highest electric field value. Nevertheless, the measure was not warning at all as the maximum measured value was under 600V/m where the limits set by laws are 5000V/m, therefore the electric ELF measure once again is proved to be not of interest for the creation of the ELF indicator.

7.5 Data processing and comparison

The first consideration that can already be made is the fact that the current flowing in the power line and the magnetic field are strictly related, it can be seen from the plot in Figure 7.17 that the current and magnetic flux have almost the same shape, and this also prove what already has been said on the single source influence which differs from the RF analysis.

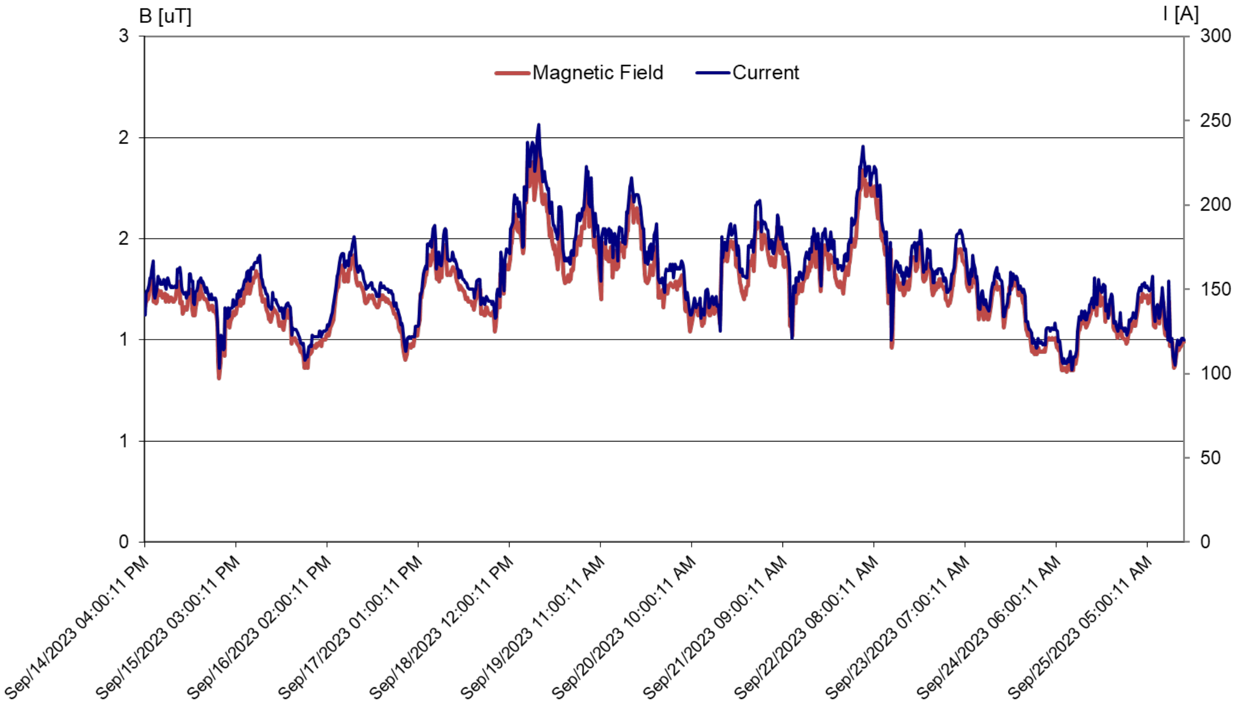


Figure 7.17: Comparison between line current and measured magnetic field

With the validation measure completed, in order to obtain a parameter that can be used to validate the simulations, the "average ratio index Rm" is calculated:

$$R_m = \frac{\sum_{i=1}^{n} R_i}{n} \qquad where \quad Ri = \frac{B_i}{I_i} \tag{7.1}$$

In Equation 7.1 the Rm (average ratio index) is given by the average of the ratios between the measured instant magnet flux B_i and the provided instant current I_i.
This parameter can now be used with any current to directly find the magnetic flux in that exact spot where measures have been carried out.
To extend the validity of the simulations, it is important to validate this measure by checking the Rm of the spot with a simulation in the same spot, and by giving in input the same current the result should be the same magnet flux. For this purpose, it was used the median current of the year 2023 as the indicator, requires the results to be of the precedent year. In particular, it is not possible to use the current of this year, as the median depends also on the remaining months and can't be evaluated yet.
The results of the validation are that the average ratio index Rm is $0.00794\frac{\mu T}{A}$, the median

current of the year 2023 is $110A$ and therefore:

$$B_{2023} = R_m \cdot I_{2023} = 0.00794 \cdot 110 = 0.873\ \mu T \tag{7.2}$$

At this point it is time to perform the relative simulation to compare the values. Setting the same point in the WinEDT project, which means setting the same coordinates but also the same height of the measure, the calculation of the magnetic field can be computed by assigning the right current at the high-voltage power line. Once again, as can be seen in Figure 7.19 and Figure 7.18 the simulation is in "open field", but this time as previously discussed is not a problem, as the walls do not affect the magnetic field.
The results of the simulation look promising, as the magnetic flux is very close to the value calculated with the average ratio index. In particular, the simulated one is $B_{sim} = 0.871\ \mu T$, and with a correlation index above 99.7%, there is no need for any correction of the model as it was done for the RF analysis.

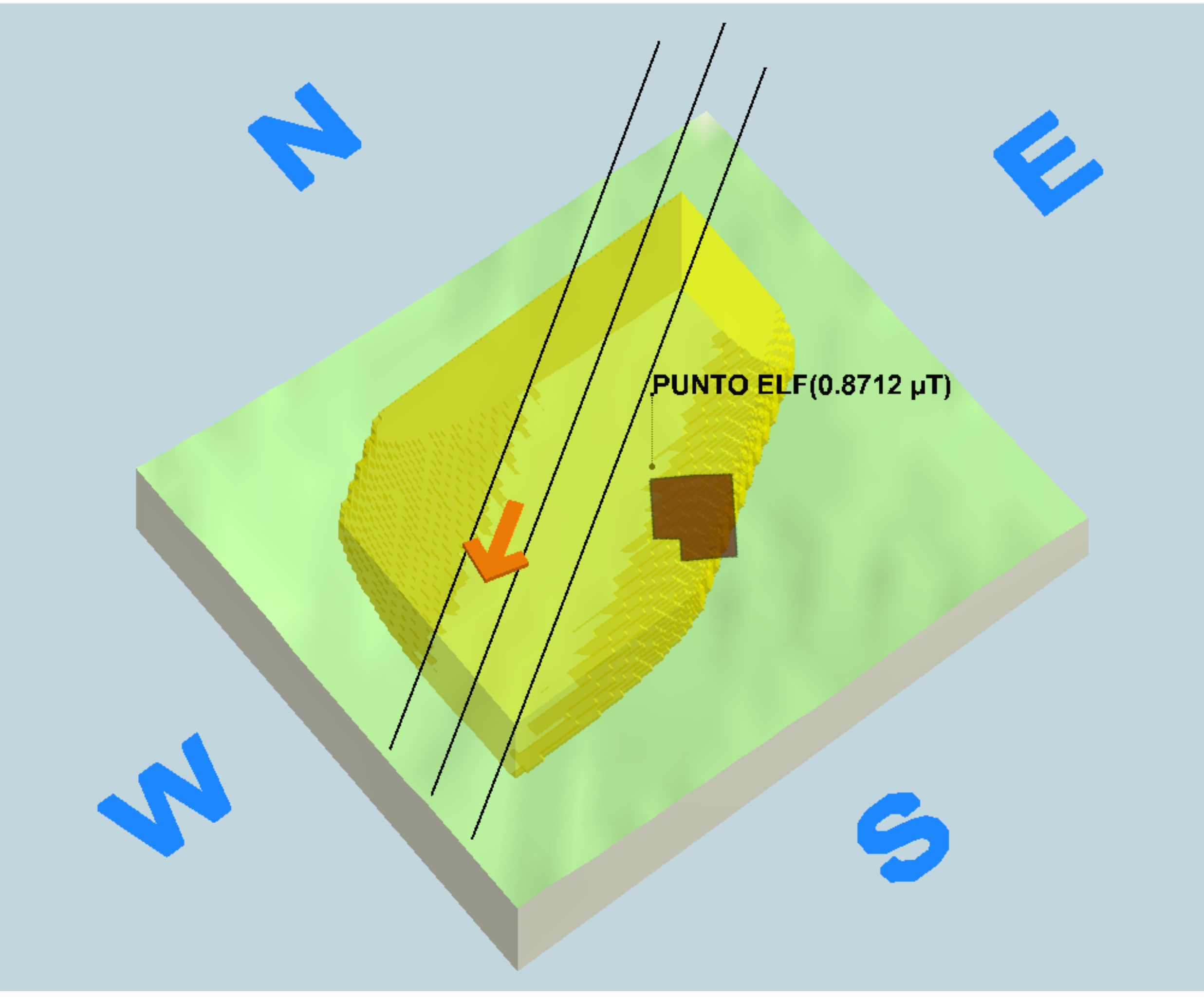


Figure 7.18: Simulation result at the validation house - pt. 1

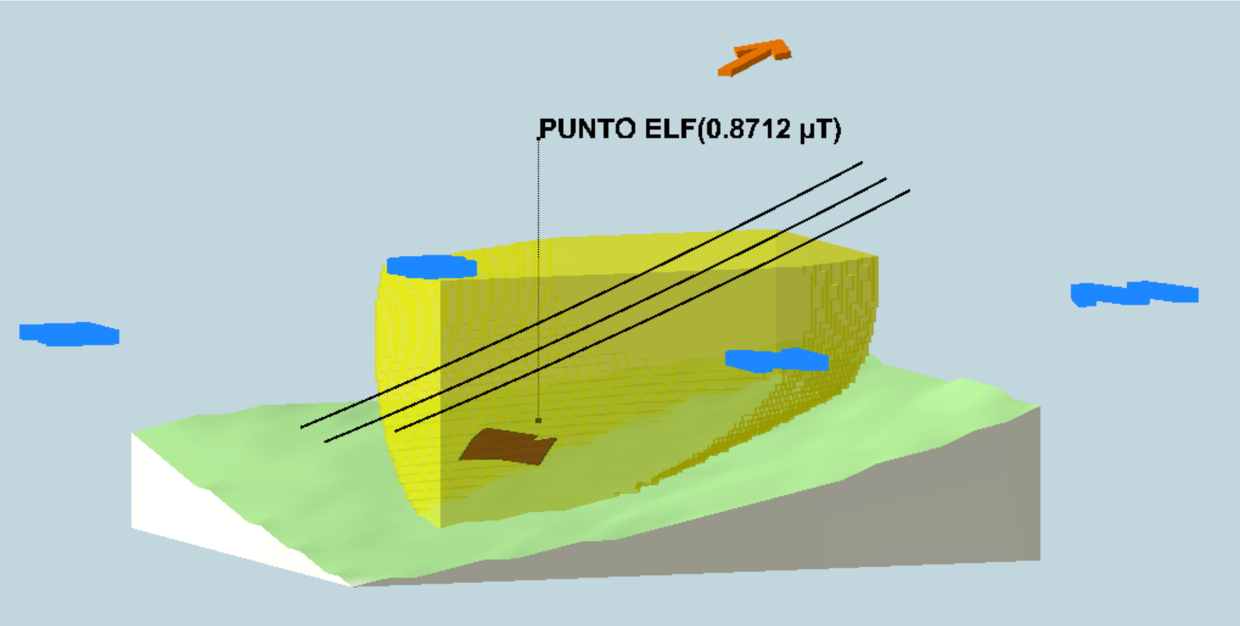


Figure 7.19: Simulation result at the validation house - pt. 2

To sum up the main results of the validation, here is a table:

Parameter	Value
Average ratio index R_m	$0.00794\frac{\mu T}{A}$
Current of year 2023	110 A
Calculated magnetic field	0.873 μT
Simulated magnetic field	0.871 μT
Correlation index	99.7%

Table 7.3: Validation ELF procedure results

Validated the simulation in this point, is possible to extend it to the whole high voltage power line, in particular, there is no need to measure the magnetic flux in each residential building falling into the defined corridor, but the simulation can be done in a non-invasive way as a reliable alternative.

7.6 Extending the simulation and results

The validation measurement has revealed a really strong accuracy for the simulation model and so, it is possible to extend the calculation algorithm to all the centroids highlighted in the previous paragraphs. Selecting the export function in QGIS, the data of the centroids is converted in a .CSV file which has to be manipulated to match the importing criteria of WinEDT, some columns are useless for the software, and it needs a header to properly interpret the information. In figures 7.20, 7.21 it is possible to see the standard input format for WinEDT.

N° Progr.	Nome punto	Longitudine/Est	Latitudine/Nord	Quota	Torre	C.M. stimato	C.M. calcolato
LISTA_PNT_RX	[Arpa Valle D'Aosta]	UTM_ED50		(m)	(m)	B (µT)	B [µT]
1	52323	366086.636-32	5065910.594	728.00	5.00		0.4454
2	56506	366099.723-32	5065931.315	729.00	5.00		0.6846
3	32927	365796.871-32	5065165.098	608.00	5.00		0.3840
4	33009	365682.367-32	5064961.929	591.00	5.00		0.3107
5	48229	365827.345-32	5065278.666	610.00	5.00		0.7054
6	48795	365925.059-32	5065371.514	621.00	5.00		0.2984
7	49072	365848.383-32	5065333.926	619.00	5.00		0.7538
8	49813	365749.873-32	5065060.931	602.00	5.00		0.2192
9	50019	365903.431-32	5065348.525	622.00	5.00		0.5505
10	50243	365694.227-32	5065001.895	601.00	5.00		0.7383
11	50252	365732.739-32	5065103.090	611.00	5.00		0.7498
12	51114	365683.737-32	5065024.680	601.00	5.00		0.5837
13	51216	365724.025-32	5065026.704	601.00	5.00		0.3270
14	51258	365881.415-32	5065318.711	617.00	5.00		0.6688
15	54905	365805.930-32	5065279.523	610.00	5.00		0.2738
16	55269	365663.644-32	5065019.617	601.00	5.00		0.2858
17	60064	365862.655-32	5065373.263	626.00	5.00		0.5310
18	42626	368367.583-32	5068264.223	986.00	5.00		0.5444
19	42649	368404.541-32	5068333.583	968.00	5.00		0.3143
20	44360	368378.372-32	5068300.189	982.00	5.00		1.0027
21	32971	365978.103-32	5065539.288	619.00	5.00		0.2122
22	46344	365953.996-32	5065478.750	617.00	5.00		0.3051
23	46653	365955.011-32	5065584.144	633.00	5.00		0.2267

Figure 7.20: Import document, data format

ROSSO = Obbligatorio	NERO= Facoltativo BLU = Univoco	TIPO DI DATO	DIMENSIONE	CONDIZIONI
Numero progressivo:	Numero progressivo (es. 1,2,3,4,...)	Intero		>0
Nome punto:	Nome assegnato al punto all'interno della lista	Stringa	32	
Longitudine/Est:	Il tipo di rappresentazione delle coordinate deve essere specificato nel campo [Sis. Rif.]	Stringa	32	
Latitudine/Nord:	Il tipo di rappresentazione delle coordinate deve essere specificato nel campo [Sis. Rif.]	Stringa	32	
Quota:	Quota del suolo s.l.m. nel punto considerato	Reale	5.2	
Torre:	Altezza del punto rispetto al suolo: se la cella e' vuota si considera un valore NULLO	Reale	5.2	
C.E.M. stimato:	Campo magnetico stimato: se la cella e' vuota si considera un valore NULLO	Reale	5.4	
C.E.M. calcolato:	Campo magnetico calcolato: se la cella e' vuota si considera un valore NULLO	Reale	5.4	
Sis. Rif:	Indica il sistema di riferimento in cui sono espresse le coordinate del punto e deve assumere uno dei seguenti valori:			
	GSI : Coordinate geografiche; datum Roma 40; longitudine riferita al meridiano di Greenwich;			
	ROMA : Coordinate geografiche; datum Roma 40; longitudine riferita al meridiano di MonteMario;			
	GSE : Coordinate geografiche; datum ED50; longitudine riferita al meridiano di Greenwich;			
	WGS84 : Coordinate geografiche; datum WGS84;longitudine riferita al meridiano di GreenWich;			
	GB : Coordinate piane; proiezione Gauss-Boaga; datum Roma40; unità di misura metri;			
	UTM_WGS84 : Coordinate piane;proiezione UTM; datum WGS84; unità di misura metri (X - fuso,Y);			
	UTM_ED50 : Coordinate piane;proiezione UTM; datum ED50; unità di misura metri (X - fuso,Y);			
	Il sistema di riferimento va specificato nella riga **2** colonna **3.**			
UNITA' DI MISURA:	Indica l'unita' di misura per il campo magnetico simulato e/o calcolato e assume solo il seguente valore:			
	µT;			
NOTA: Il campo progressivo non puo' mai essere lasciato vuoto per nessun record,altrimenti tutti I dati relativi a quel record e a tutti I successivi non saranno importati.				

Figure 7.21: Import document, data standards

Also in this case the simulation is in open field, but differently from what has been said for radio frequencies, in this case is it doesn't affect the simulation at all. As already mentioned, it can be assumed that the walls of normal houses (the power line in question passes through sometimes inaccessible areas where there are no large buildings) do not exert a shielding action, and they can be considered transparent to the radiation. An important assumption in this simulation frame is that the used value of current is the average annual current of the power line in the previous year. In this case, the simulation has been performed with a current of 110A across the line, the data relative to the year 2023. Once the data are in the correct format, it is possible to import the entire set of points and the calculations are performed for each one according to the set current value. Therefore, the raw results are ready to be analysed and arranged according to the structure of QGIS import procedure. In order to do this, also WinEDT has a function which allows to export data in .CSV format and, with a quick manipulation so simply sort the columns in the correct way, the final file containing the results of the simulation is ready to be opened in QGIS and to be used to evaluate the exposure indicator. In this phase the values of magnetic field are in a different layer with respect to the centroids, with the tool *Add attributes according to field value* it is possible to solve this problem by adding the attribute relative to calculated magnetic field to those points which have the same ID number. The layer Centroidi used in this analysis is correctly updated with the results of the simulation, in Figure 7.22 it is possible to see the representation of the layer with differently coloured points according to the magnitude of magnetic field and the scale on the left of the figure. For better comprehension, the buffer of the power line is also represented in yellow and the screen is split in half.

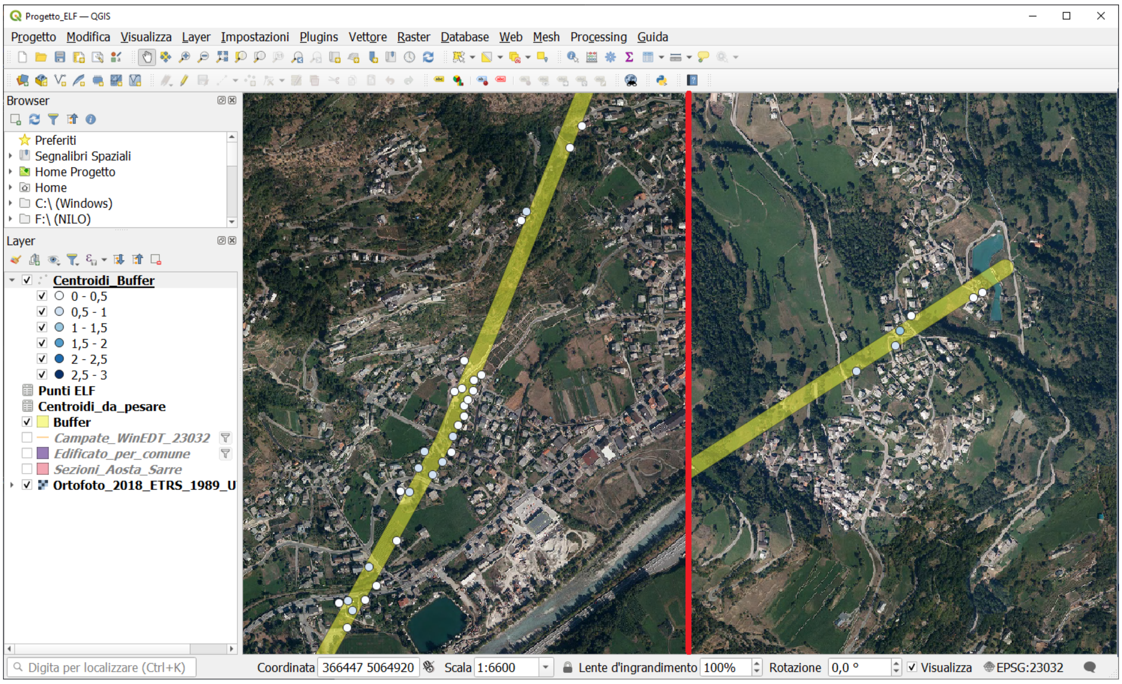


Figure 7.22: Report of the ELF simulation imported in QGIS

It is immediately possible to see that the values involved outline very small magnetic field values, and it is emphasized by the presence of very light colours.

7.7 ELF exposure indicator

The EMF research programme in the activity A asks to evaluate the exposure indicator in form of a histogram defining how many people are exposed to a certain value of magnetic field and in form of a shapefile which summarizes all the field values of all the analysed centroids. For the histogram, the procedure adopted by the ARPAs defined six bands of opening 0.5μT from 0 up to 3μT. As done before for the RF part of this project, with the report of the simulation it is time to evaluate the histogram which is one of the graphic representation of the indicator. To make the histogram, each centroid has to be equipped with the relative population. In this case the process is slightly different because only the buildings in the buffer have to be considered, and the considerations cannot be extended to the census zone. This different way to evaluate the indicator is strictly linked to the nature of the source; a radio-electric workstation is studied to irradiate electric field in wide areas, while the effects of irradiated EMF of a power line become negligible in less than 100m far from the source. The extended analysis, as done for RF, is useless. The categorization of the number of inhabitants according to the field value has been performed in two steps: after a first attribute exchange in QGIS to have the necessary data, the analysis continued in Excel.

- Inhabitants in each building. With the function *"Sumif"*, using the same procedure explained in RF part, it has been calculated the relative contribution of each building to the total volume of the census zone taking as assumption that the inhabitants are evenly distributed. The final number of people for each building has been calculated as the product between the population of the census zone and the relative contribution in volume of the building itself.

- Categorizing in classes of exposure. According to the partial result of the population associated to a magnetic field value, with another combination of *"Sumif"* functions, the numbers of people for each building have been added up according to the magnetic field belonging class.

The final histogram is visible in Figure 7.23.

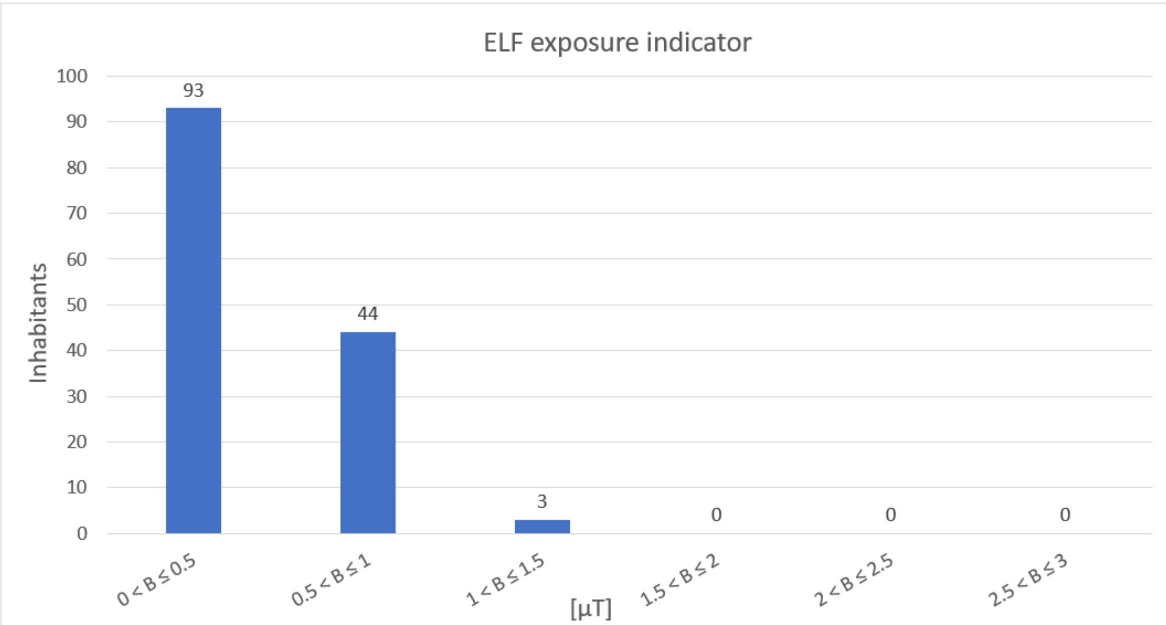


Figure 7.23: ELF exposure indicator in form of histogram, as requested in EMF research programme

7.7.1 Division by cities

This time the histogram in Figure 7.23 represents directly the number of inhabitants because it is not possible to distinguish a priori how many inhabitants are attributable to the municipality of Sarre, how many are attributable to Aosta and immediately assess the percentages. To have a deeper separation, another couple of passages in Excel are required. In particular, the centroids have to be separated according to the municipality (this attribute has already been imported in prevision of a further separation) and referred to the total population. The two final histograms are visible in Figure 7.24 and in Figure 7.25. According to what previously said, it is clearly visible from the percentages that the ELF phenomena involves a smaller number of inhabitants because it is more localized along the power lines and the power lines themselves are usually located in dedicated areas with as few dwellings as possible.

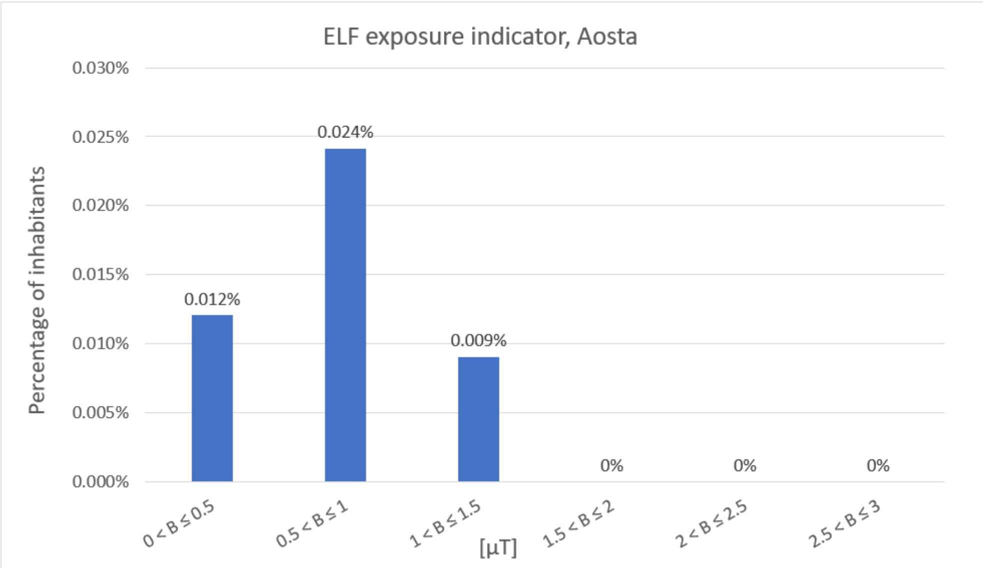


Figure 7.24: ELF exposure indicator referred to Aosta

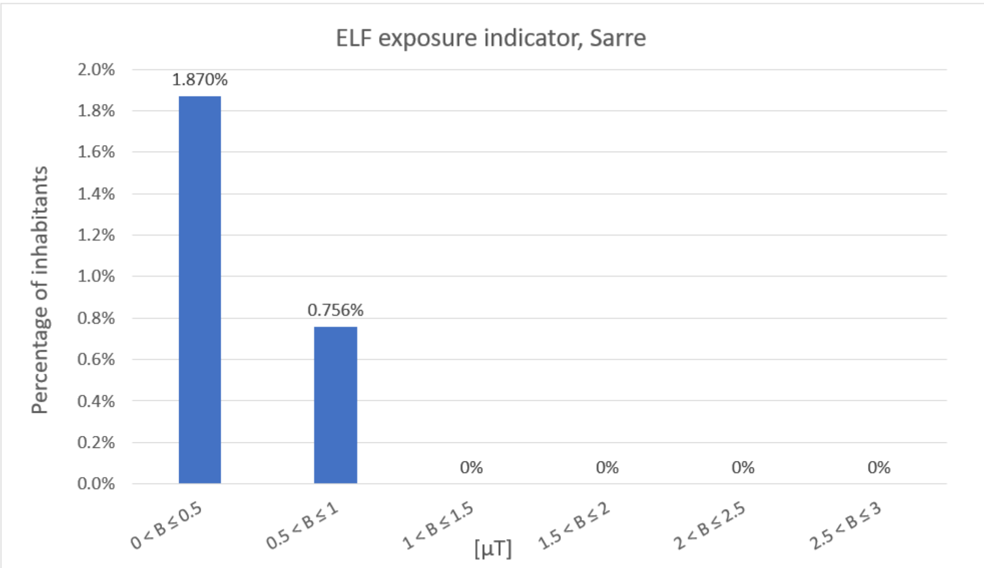


Figure 7.25: ELF exposure indicator referred to Sarre

8. Complementary Activities of the EMF Research Programme

As mentioned in the introduction (Chapter 1), the epidemiological study comprehends more than just Activity A. Even if the core of this master thesis is Activity A (divided into the two sub-activities RF and ELF) it is appropriate to provide some information also on the other two activities that are part of the EMF research programme. It is important to remember that these two activities are focused on the radio frequency electromagnetic waves, therefore the ELF part can be considered finished.

8.1 Dosimetry and personal exposure analysis to EMF

Activity B changes perspective with respect to Activity A, in particular, A is focused on simulating and measuring the field intensity in specific spots, which could be the centroid of the building at the height of 5 meters or the places where the measurements for the validation have been carried out. B instead, is not associated with places or spots any more, but is now associated with a person that is to be classified in one of the defined categories: “high school student”, “university student”, “office worker”, “working from home worker”, or “on-field worker”.

The reason for this change of perspective is that for a complete determination of exposure to electromagnetic fields, contributions from personal use sources and indoor sources such as Wi-Fi devices must be added to the assessments based on outdoor sources, which give rise to environmental exposure. This is the main reason why the Activity B is performed. These contributions can be determined using personal dosimeters that also allow the detection of signals in predefined frequency bands. In this way, the different sources that cause the individual’s exposure over time can be analysed singularly. With the acquisition of personal dosimeters and the establishment of a daily diary, measurement campaigns can be carried out that are oriented towards measuring the contributions to individual exposure due to indoor sources and those of personal use such as the mobile phone. Individual exposure can also be compared with environmental exposure due to fixed outdoor sources.

Concerning the use of personal devices such as smartphones, a “citizen science” activity can also be set up with the use of a specific app that can monitor how device use influences individual exposure.

For all the details and procedures of Activity B, ISPRA has defined a protocol that is attached as Appendix C, as it is an internal communication document and can’t be found online.

8.1.1 Dosimeter

Once again, this activity is a broadband measurement which means that it is not focused on a single signal and a limited frequency, but it gets a broad band of frequencies. In particular, the purchased instrument shown in Figure 8.1 has a bandwidth from 50 MHz to 6 GHz.

Figure 8.1: Dosimeter used for Activity B

Frequency range	50 MHz to 6.0 GHz continuous frequency coverage
Frequency bands	Pre-defined or fully customizable lists of center frequencies (selectable in software)
Measurement bandwidth	35, 75 and 100 MHz
Dynamic range	> 60 dB raw dynamic range (0.02 – 20 V/m nominal range); Measurement range extension using *high sensitivity mode* (up to 6V/m) or *high field strength mode* (up to 60 V/m).
Sensitivity (6V/m range) RMS field strength	Measurement frequency — Typical lower detection limit 80 – 250 MHz — < 0.01 V/m 250 – 4500 MHz — < 0.005 V/m 4500 – 6000 MHz — < 0.009 V/m
Spectrum analyzer mode	Wideband gapless frequency scan over the full frequency range

Figure 8.2: ExpoM-RF 4 technical data

The ExpoM-RF 4 is a flexible wideband personal radio frequency exposure meter that incorporates a data logger and global positioning system (GPS) localisation functionality. The capacity to undertake band-selective measurements enables a detailed differentiation of different electromagnetic field sources. The dosimeter is capable of performing simultaneous true-RMS and peak detection of the measured signals. The capacity to configure specific band lists that consist of arbitrary frequencies between 50 MHz and 6 GHz provides a good degree of flexibility, rendering it inherently future-proof with respect to potential changes in frequency band allocations and regulations. The ExpoM-RF 4 is equipped with different sensitivity settings, allowing it to be utilised in scenarios where low minimum detection limits are necessary, as well as in locations where high field strength is anticipated. Its

built-in Wi-Fi connectivity facilitates real-time transmission of measurement data to mobile devices or cloud services. The device is accompanied by utility software, which is essential for transferring and displaying the measurement data acquired to a PC and for modifying the device and data logger settings. Finally, the dosimeter has a multitude of functionalities, for example, the KML[1] export function allows (if the GPS was activated while measuring) to associate field values to places on Google Earth.
To properly use this device, some calibration is necessary. At the moment of ordering, the 25 selective bands must be specified, these are chosen by the user and calibrated by the producer in an anechoic chamber. In this study, the subdivision that was used is described in Table 8.1. These ranges were chosen by a mutual agreement between ARPAs and ISPRA, the details are reported in Appendix C.

Band	**Bandwidth [MHz]**	**Central frequency [MHz]**	**From frequency [MHz]**	**To frequency [MHz]**
Radio FM	35	97.5	80	115
DAB VHF	75	211.5	174	249
TV DVBT UHF 1	100	520	470	570
TV DVBT UHF 2	100	620	570	670
5G N28 UL	75	717.5	680	755
5G N28 DL	35	777.5	760	795
L800 UL	75	812.5	795	830
L800 DL	35	847.5	830	865
GSM + U900 UL	35	897.5	880	915
GSM + U900 DL	75	952.5	915	990
L1500	75	1472	1434.5	1509.5
DCS + L1800 UL	75	1747.5	1710	1785
DCS + L1800 DL	75	1842.5	1805	1880
DECT	35	1890	1872.5	1907.5
U2100+L2100 UL	75	1950	1912.5	1987.5
U2100+L2100 DL	75	2140	2102.5	2177.5
WiFi (DFS)	100	2445	2395	2495
L2600 UL	75	2535	2497.5	2572.5
L2600 DL	75	2660	2622.5	2697.5
L3500 lk	75	3469	3431.5	3506.5
5G N78 1	100	3650	3600	3700
5G N78 2	100	3750	3700	3800
WiFi HyperLAN 1	100	5250	5200	5300
WiFi HyperLAN 2	100	5550	5500	5600
WiFi HyperLAN 3	100	5650	5600	5700

Table 8.1: Frequency bands and their corresponding bandwidths

[1]KML is a file format used to display geographic data within Internet-based, two-dimensional maps and three-dimensional Earth browsers.

8.1.2 Measurements

Before proceeding with the measurements, there is one last step, which is to set the parameters with which the dosimeters sample. This specific instrument offers, when sampling all 25 bandwidths, a sample every 4 seconds minimum up to 6000 seconds.
In this study, a time interval of 5 seconds was chosen to allow the battery to survive for the overall 24-hour sampling period. Finally, for privacy reasons, the GPS option was disabled and then the device was delivered to the first person to carry for the next 24 hours.
In Figure 8.3 are shown the results of the acquisition of the instrument in the time window between 7.30 and 16.30.

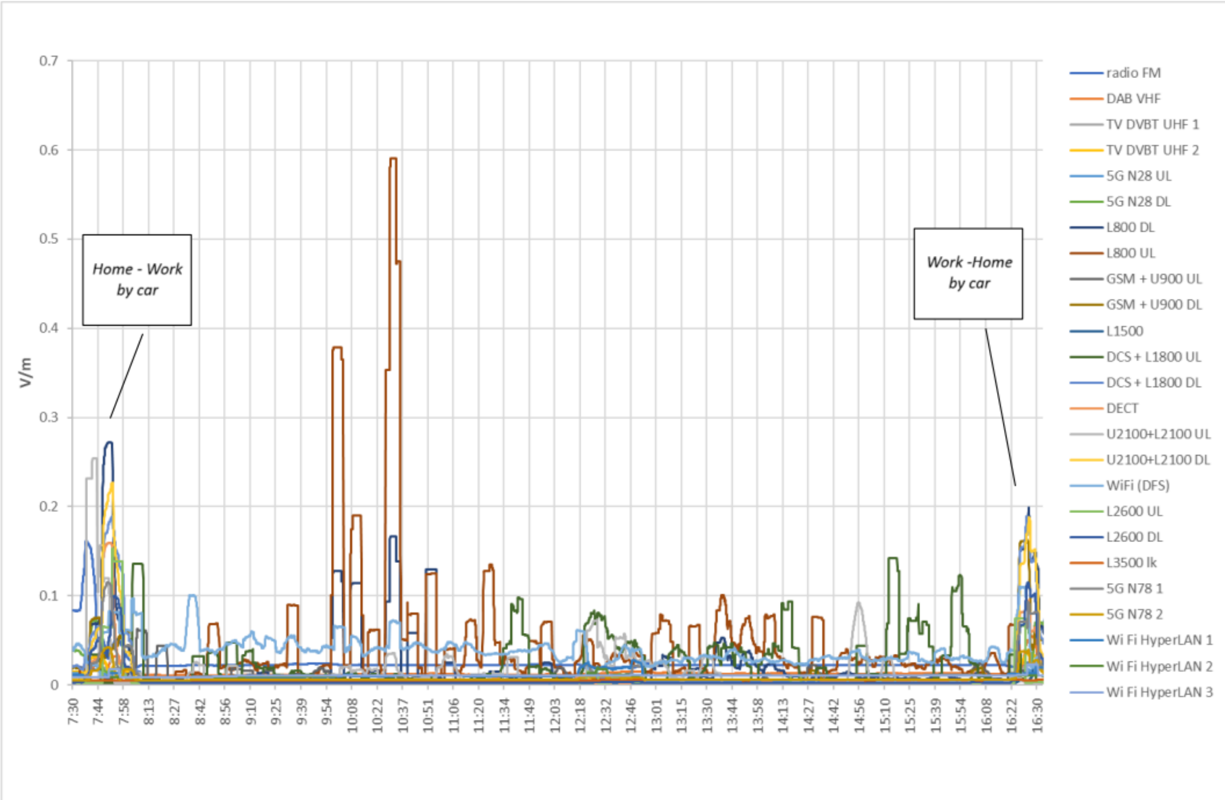


Figure 8.3: Office worker electric field exposure (AVG 6 min)

The plot is characterized by a initial part where the individual is moving to work from home (around 30 min), the main central part where the subject is in the office, with a launch break between 12.15 and 12.45, and finally the moving back home.
This plot is definitely overcrowded, therefore to better analyse the situation it is possible to manipulate the data. What it should already be observed is the scale of the measurements, which is quite limited, as the highest value is less than 0.6V/m. But, the overall exposure is the significant one, therefore it is good that the single contributions are this low.

8.1.3 Data Manipulation

To better analyse and interpret the plot, it is possible to zoom in, and look at the most significative signals that are acting on the instrument as they have been measured.
The first zoom, shown in Figure 8.4 is when the person was in the office, and what can be noticed are four signals:

- radio FM: Negligible electromagnetic background due to FM radio stations.
- L800 UL and DCS + L1800 UL: Related to the mobile telephony uplink, which is when the mobile phone sends data to the antenna (the opposite is the downlink).
- DFS: Associated with the WiFi of the office.

What can be observed is that the Wifi that was one of the reasons why Activity B is conducted (to verify internal sources of electromagnetic fields) is relatively low to the quality objectives. It is possible to conclude that even if in this case the individual is very close to the source of the electromagnetic fields, there is not much to worry about as the devices are designed to respect laws and the values do not exceed, nor get close, to warning levels.

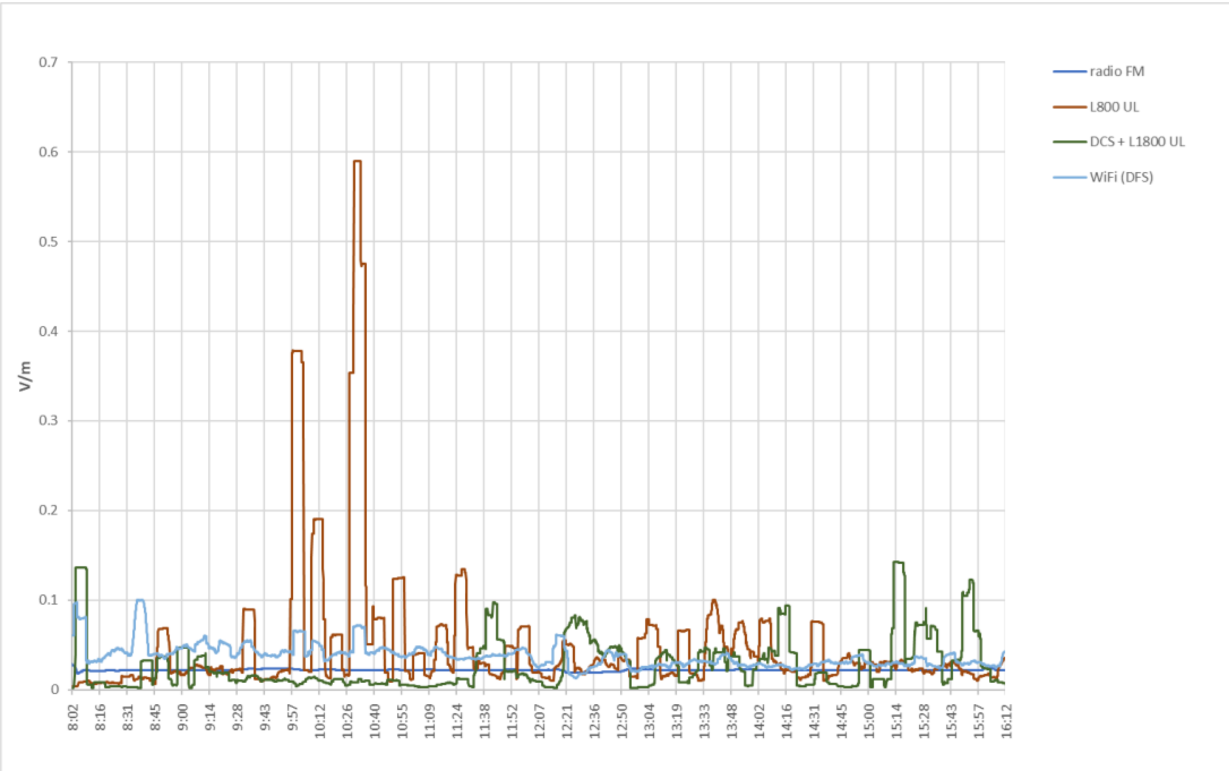


Figure 8.4: Office worker electric field exposure (AVG 6 min) - Zoom in office hours

In Figure 8.5 are reported the most significative measured electric fields. What it should be noticed is the fact that in this time, when the individual carrying the device is outdoor, as expected the overall exposure is increased. This is true for all the signals, from FM radio to telephony, as there are no walls around the individual.

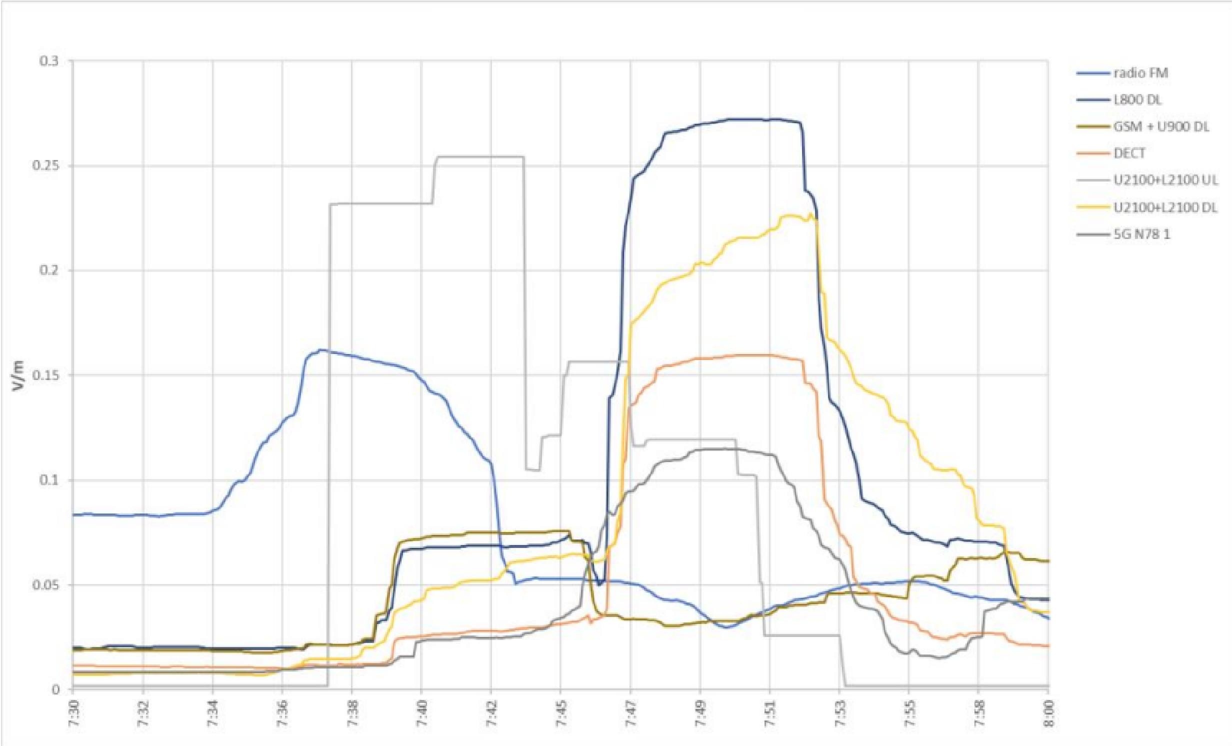


Figure 8.5: Office worker electric field exposure (AVG 6 min) - Zoom in transfers

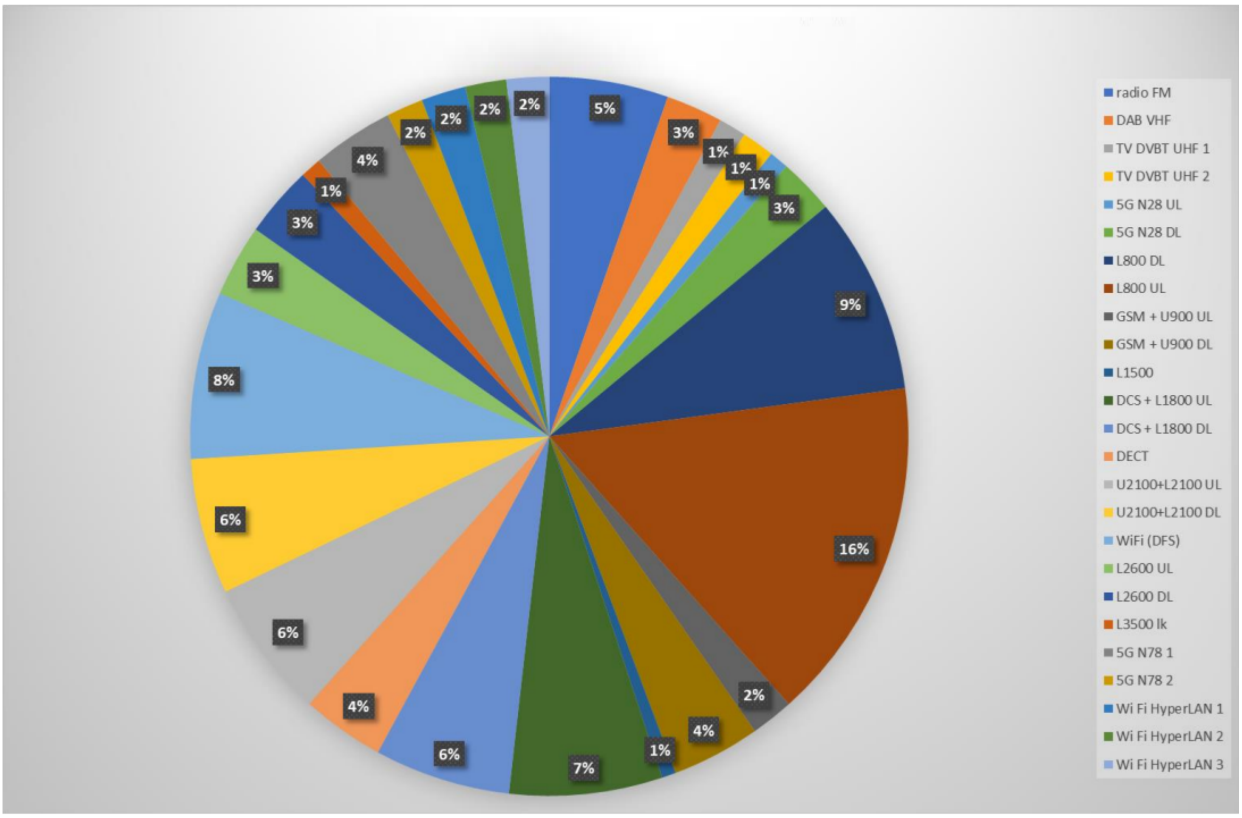


Figure 8.6: Office worker electric field exposure (AVG 6 min) - Percentages

In Figure 8.6 there is an alternative way of looking at the results, which is to weight the signals by their contribution to the overall electric field that is the one that must respect the limits (and possibly the quality objectives). In particular, the main four resulting contributes are:

- L800 UL - 9%;
- L800 DL - 5%;
- WiFi (DFS) - 8%;
- WiFi HyperLAN 2 - 7%.

which are basically mobile connection and office WiFi. It is interesting to notice as out of four, three contributes are generated by devices that are not antennas or stations. Especially inside the buildings the major contributes are related to personal devices.
Finally, in Figure 8.8 is reported the total electric field exposure, the plot that puts together all contributions and finds the overall electric field. This plot has two signals, the blue one is for the RMS instantaneous values, while the orange one is always RMS but averaged on 6-min time span, as required by law. Similarly to Activity A, also in these experiments the measured values are way lower than watch thresholds.

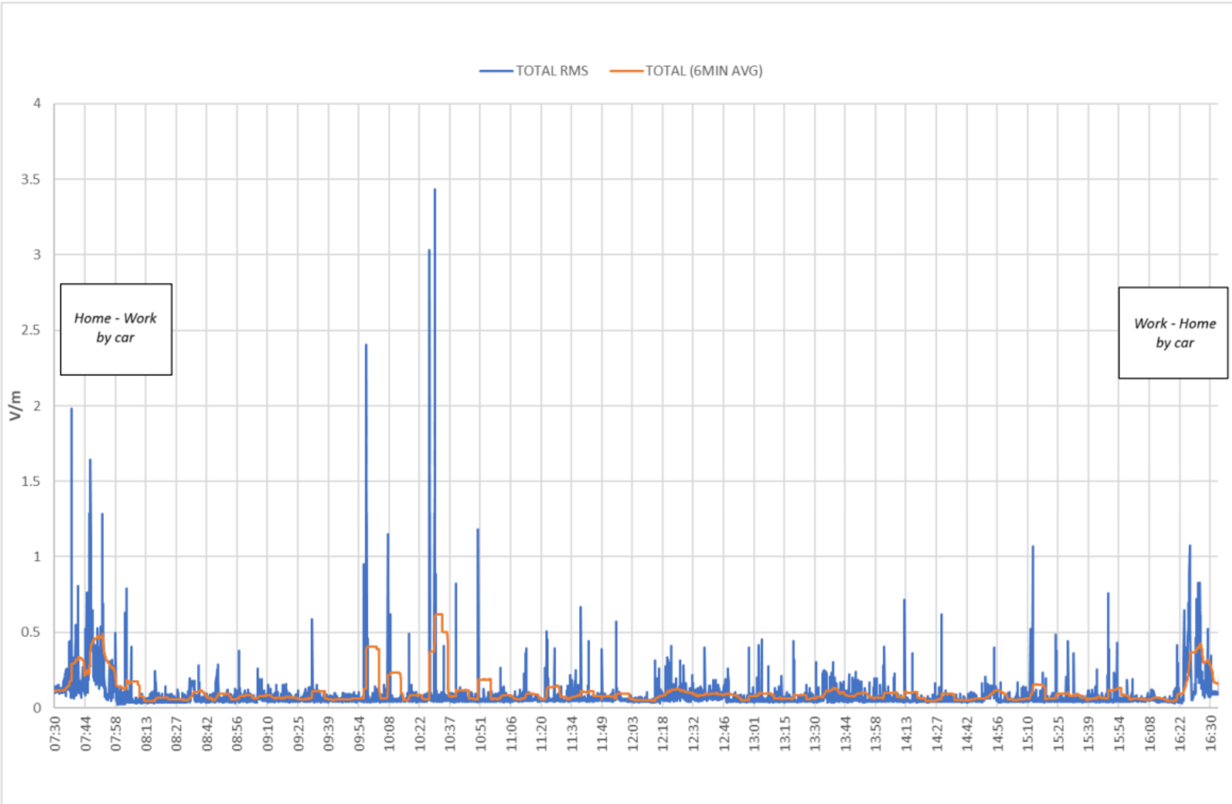


Figure 8.7: Office worker total electric field exposure

These data, together with all the users found from ARPA VdA, and then with all the ARPAs, will contribute in defining an exposure indicator for all the mentioned categories. This job of collecting everything and extrapolating results will be done by the ISPRA as soon as all the regional agencies have finished their work.

8.1.4 Extra

Once explained how to interpret and manipulate the data, it is necessary to enrich the database with as many measurements as possible. To complete the analysis, in Figure 8.8 is reported the electric field behaviour of some selected signals. And in particular, what really shines on top of the others are the 2100 UL and WiFi signals.
These spikes are associated to the switching on of the mobile phone in the morning, and the synchronization of the phone after the night break. Once again, this proves that the exposure to radio frequency electric fields is increased by the use of personal devices more than the outside stations and stuffs.

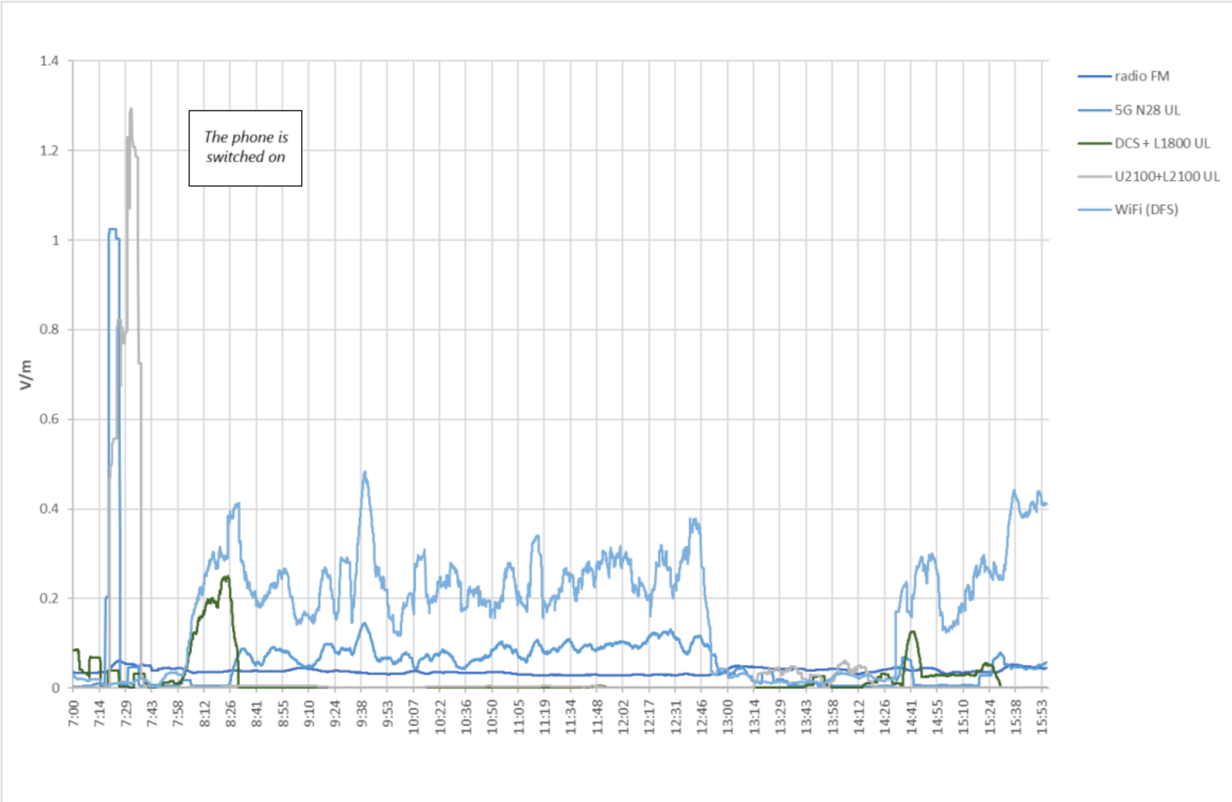


Figure 8.8: From home worker, electric field exposure (AVG 6 min)

8.1.5 Considerations

From the study carried out, exposure to the electric field remains well below the values stipulated by current legislation. Despite extremely low electric field values, it was possible to assess overall exposure to the electric field and to highlight the contributions of the different signals related to the various transmission technologies.
It is emphasized that in houses or workplaces which are relatively far from fixed sources, the exposure to electric fields is more related to contributions generated by personal devices. This is noticeable because the measuring instrument clearly revealed frequency bands related to signals in uplink mode, (signal transmission generated by the personal device towards the fixed radio station) so, in this case, the exposure to the field is due to the personal use of smartphones or personal computers.

Analysing car journeys, on the other hand, it can be seen that when travelling near fixed sources (radio base stations located throughout the territory), the downlink component prevails (transmission of the downlink signals (signal transmission generated by the fixed radio station towards the personal device), so that, in this case, exposure to the electric field is affected by the traffic telephone traffic and the distance from the fixed sources. The study shows that the way in which personal devices are used is important in determining exposure, which can be managed by the user of the devices (e.g. by keeping personal devices and WiFi networks at an appropriate distance), while for fixed sources, personal exposure depends on the distance from the radio stations, for which compliance with the limits set by the limits set by the regulations in force must be guaranteed by the operators of the installations and ensured by the ARPA on the territory.
It is worth remembering that the limited number of people on which the dosimetry activity of ARPA VdA can be extended cannot be representative when extended on a national scale. In fact, this monitoring activity can only be completed when all participating regional agencies have finished collecting data on their sample. In order to obtain a greater significance of the data, in fact, each regional entity has been assigned a sample whose size is linked to the actual population residing in that territory.

8.2 Focus on 5G signals measurements

The new 5G technology has brought about major changes in the way these signals are measured compared to the signals of previous generations. This is mainly due to the fact that the handling of control and traffic signals takes place on different beams between which, in most cases, there is no simple correlation. This has led the entire international radio-telecommunications world to move forward to identify the correct way to measure the signals emitted in order to assess the exposure of the population to this type of technology. Even at a national level, the system of Environmental Protection Agencies has made great efforts to define correct and effective measurement and assessment procedures for EMF exposure generated by next-generation 5G installations. Activity C is the one completing the EMF research activity study, as the peculiarity of this activity is that it focuses on a specific kind of signal. The measure now is a narrowband and not broadband, as it was for Activity A (RF) and Activity B, so it analyses only a small range of frequencies.

8.2.1 Spectrum analyser

The measurement chain supplied to the Agency consists of a Fieldox 32 GHz portable spectrum analyser (Figure 8.9, produced by Keysight) and a 30 MHz - 6 GHz triaxial antenna (model ARIA-6000 manufactured by AGOS, Figure 8.10).
This report shows the results of the measurements carried out with the portable vector spectrum analyser, which allowed the acquisition of 5G signals and in general of signals generated by active antennas. By way of example, a Dynamic Spectrum Sharing DSS 700 signal in the air and a real 5G signal recorded on a generator are shown.

Figure 8.9: Spectrum Analyser

Figure 8.10: Spectrum Analyser's probe

8.2.2 Key definitions

Before proceeding and look at the results, it is important to understand what are signal under measurement, and define some key concept:

- **Electromagnetic Exposure** measures the amount of radiation emitted from sources such as mobile networks.

- **Channel Power** is a fundamental parameter used to quantify the total power emitted by a signal within a specific bandwidth. In this case, the center frequency of the signal is 763 MHz, with a bandwidth of 10 MHz.

- **Dynamic Spectrum Sharing (DSS)** is a technology that allows 4G and 5G signals to coexist by sharing the same frequency band dynamically. This means that, despite the technology being used (4G or 5G), the occupied bandwidth remains the same. It is possible to focus on measuring one of these signals, which can be used to extrapolate the maximum power level according to technical standards.

- **Max Hold Trace** captures the highest measured values at each frequency point over time, thus showing the peak power levels. However, these values are strongly influenced by the traffic at the time of measurement. Although this approach is more conservative, it does not necessarily represent the maximum possible power output of the signal.

- **Average Trace** represents the mean power levels over time. It provides a more realistic estimation of the signal's behavior, smoothing out fluctuations caused by traffic or environmental conditions. This is useful for assessing real-time exposure levels.

- **Min Hold Trace** shows the minimum power values recorded, which typically represent the signal generated by control channels that are always active. This trace is useful for determining the baseline power level of the control signals.

8.2.3 DSS 700 Signal Measurement Setup

Two types of measurements were conducted:

- **Channel Power Measurement:** Performed with varying trace modes (Max Hold, Average, Min Hold) to assess the differences between each measurement mode.

  Channel Power Mode:

  – Frequency Span: 12 MHz;

  – Resolution Bandwidth (RBW): 1 MHz;

  – Video Bandwidth (VBW): 3 MHz;

  – Trace Average: 50 counts.

  Channel Power Results

  The results of Max and Min Hold measurements are respectively reported in Figure 8.11 and Figure 8.12.

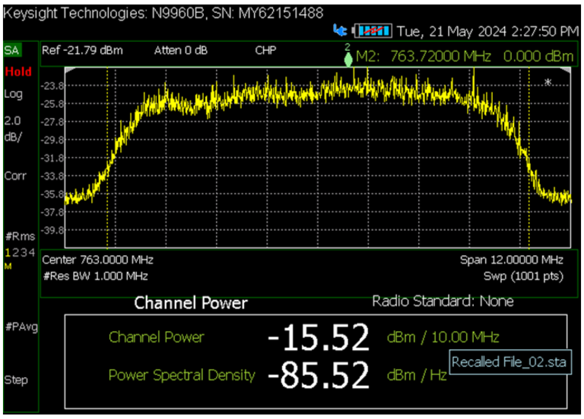


Figure 8.11: Max Hold measurement result

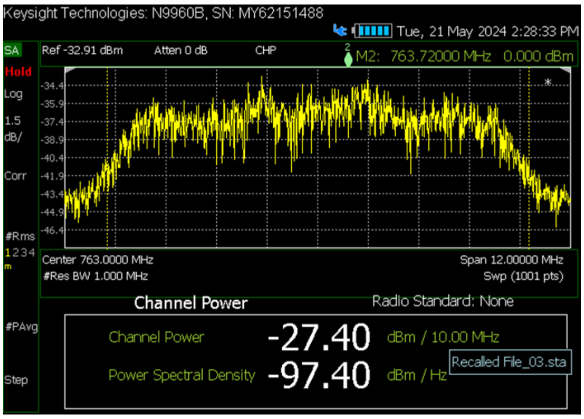


Figure 8.12: Min Hold measurement result

- **Zero Span Measurement:** Used to extract more detailed information about the signal's temporal behaviour.

  Zero Span Mode:

  – Frequency Span: 0 MHz;

  – RBW: 1 MHz;

  – VBW: 3 MHz;

  – Sweep Time: 20 ms.

Zero Span Results

Zero Span measurements focus on capturing the signal's temporal characteristics without sweeping across a range of frequencies.

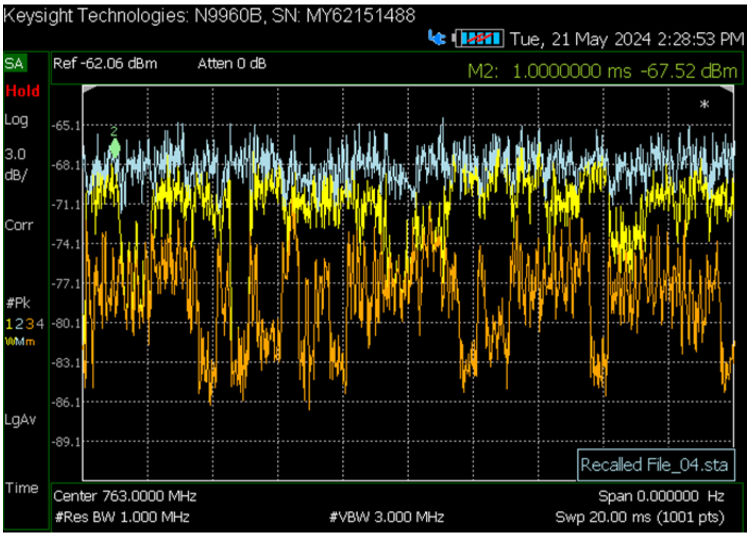


Figure 8.13: Zero Hold measurement result

Clear Write, Max Hold, and Min Hold Traces in Zero Span

The Clear Write, Max Hold, and Min Hold traces in Zero Span provide important insights. When the Min Hold trace remains at a relatively high level, this indicates the presence of continuous control signals. Conversely, a sharp drop in the Min Hold trace signifies traffic signals, which are only present intermittently. By comparing these traces, the analyser can differentiate between control and traffic signals, allowing a more detailed understanding of the signal structure.

8.2.4 5G signal from generator

5G Signal Measurement

The 5G signal measured was centered at 3680.01 MHz, with a bandwidth of 80 MHz. Both idle and forced traffic conditions were measured to evaluate the behavior of control and traffic signals.

Idle Mode

In idle mode, only the control signals, known as SSB (Synchronization Signal Blocks), are transmitted. These signals help the device synchronize with the network but do not carry traffic data. The Zero Span measurement provided a clear view of the SSB structure, showing clusters of SSB blocks, where the most intense ones correspond to beams directed toward the measurement antenna.

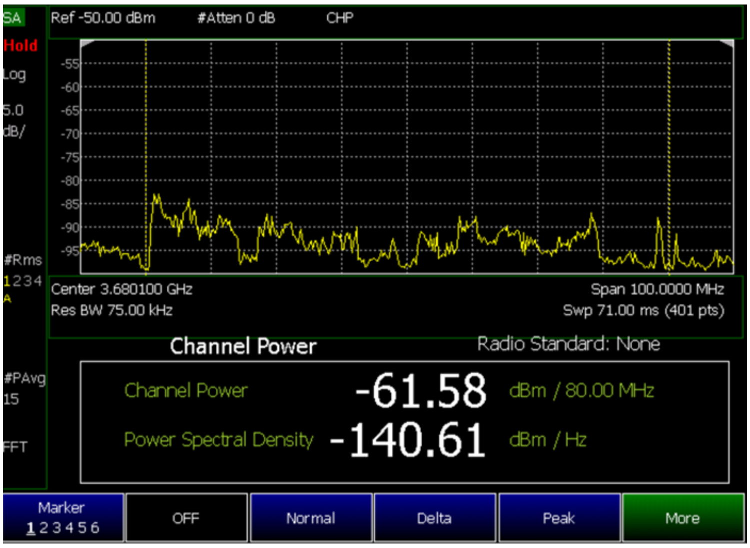


Figure 8.14: Synchronization signals measurement (no data transfer)

UDP Traffic Mode

In this mode, traffic is generated by the User Datagram Protocol (UDP), which forces the transmission of user data. In Figure 8.15 there is the evaluation of a complete signal, including both control and traffic beams. By comparing the power of the traffic beam with that of the SSB, it is possible to get a more comprehensive understanding of the signal's characteristics under load.

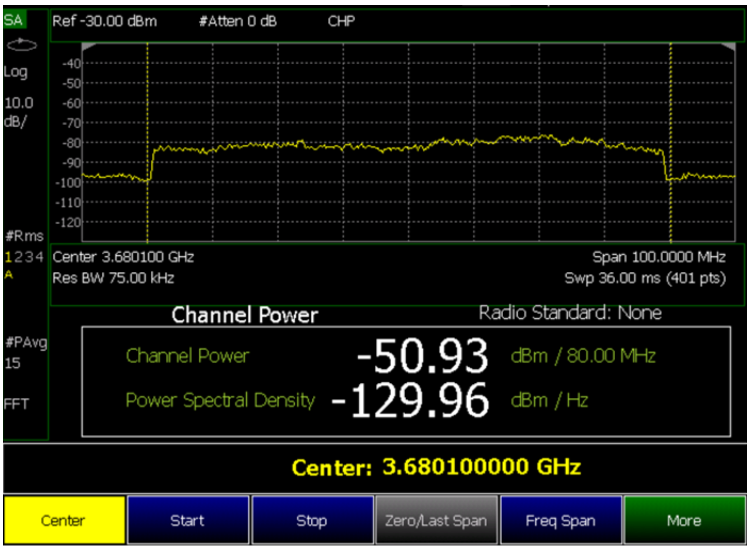


Figure 8.15: Complete signal measurement (with data transfer)

UDP Traffic Mode in Span Zero

Span zero measurements can be used to verify signal structure information for both SSBs and traffic slots. A traffic measurement via a downlink UDP transfer is shown in the figure. The spectra in Span Zero allow us to see the entire plot and thus also the traffic beams.

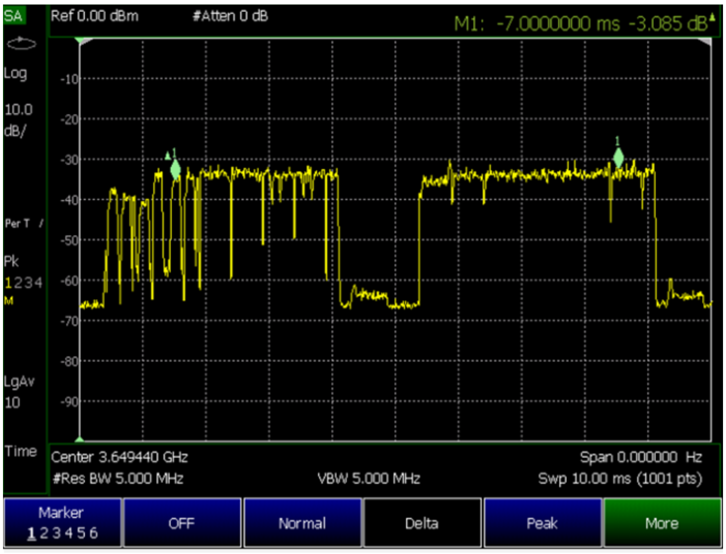


Figure 8.16: Span Zero UDP signal measurement

Real-Time Measurements and Vector Mode

The analyser used is also capable of real-time analysis, displaying a spectrogram[1] that highlights all contributions present in the signal, including Synchronisations Signal Block (SSB) and traffic beams. This mode is particularly powerful for signal analysis but requires experience to interpret correctly, especially in adjusting the colour scale and capturing the signal at the right moment. In Figure 8.17 is possible to see the correlation between the

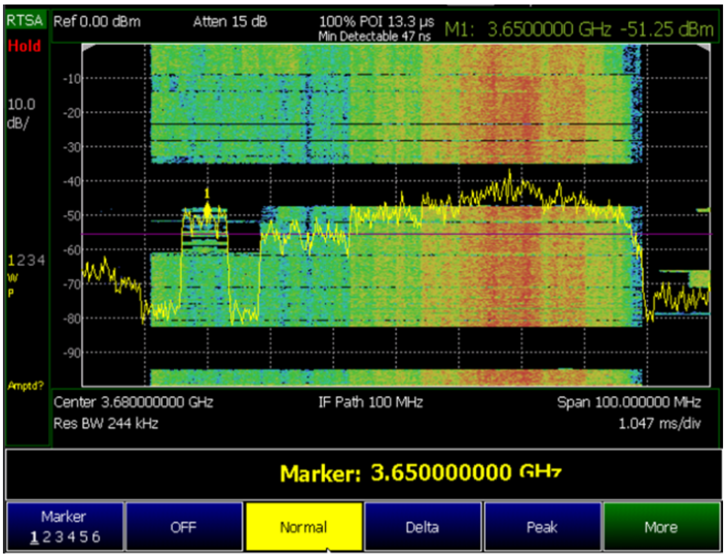


Figure 8.17: Spectrogram results of signal measurement

signal intensity and the scale colour. This is an alternative way to extrapolate data and get to the desired results.

[1]A spectrogram is a visual representation of the spectrum of frequencies of a signal as it varies with time (see Figure 8.17).

8.2.5 Considerations

The measurements conducted by ARPA Valle d'Aosta offer valuable insights into the behaviour of DSS and 5G signals, contributing to a better understanding of electromagnetic exposure from next-generation mobile networks. By utilizing different measurement modes, including Channel Power, Zero Span, and Real-Time analysis, it was possible to capture a comprehensive picture of the signals under both idle and traffic conditions.
The report highlights the importance of selecting the appropriate measurement techniques depending on the type of signal and the information sought. Whether analysing control signals, traffic beams, or the signal as a whole, each mode provides a different perspective that, when combined, leads to a detailed understanding of signal behaviour and its potential impact on electromagnetic exposure.
Even if these measurements do not yield significant results, the purpose of this activity was to get confident with measuring 5G signals generated by these new technologies. The ARPA's role is to ensure the protection of citizens, therefore the need to stay up to date with these new technologies is a must that they have to respect.

9. Conclusions

In little more than 150 years, society has gone from the analytical formulation of electromagnetic fields by James Clerk Maxwell to the most modern 4 and 5G communication technologies, but even more than this is the fact that it is only in the last 30 years that the technologies used in the field of telecommunications have developed rapidly. In all this era of technological advancement, it is certainly fair to ask whether and what the possible side effects of these technologies might be, but at the same time it would be appropriate to wait for definite results from the development of studies and research. This lack of objective and solid data, in the current state of affairs, leaves room for gratuitous speculation that, without scientific basis or following fanciful reasoning, wreaks havoc among the population by generating alarmism.

The aim of this work is not to obtain incontrovertible results for or against the safety of using electromagnetic fields. Aspects related to the effects of exposure to these factors are left to other studies that have been and will be conducted in the future to establish an unambiguous position on the subject. The objective of this work is to study and carry out exposure assessments on a small reality such as the Aosta Valley so that these conclusions can be used at a national level as a contribution to the drafting of institutional reports, like the EMF research programme, linked to state bodies and European directives.

An important result is acquiring the critical tools to analyse and manage a real situation. Unlike theory, in which the relations are rigorous and sometimes suffer from approximations to simplify analytical treatments, in reality, it is not possible to avoid critical aspects; it is, therefore, necessary to be able to reconcile theoretical aspects with the evidence of reality by investigating possible explanations and seeking feedback.

The results themselves are promising. First, because they comply with Italian laws. Even if it was not the reason the study was carried out, this information was reassuring and can be divulged to citizens to fight against fake news and well-known conspiracy theories. Second, because there are these institutions that are taking care of citizens and the environment, it is only through continuous and patient work that these results can be obtained, and the population be protected. Finally, this sets the path for future works, and in particular, for the monitoring of new paradigms, like 5G.

The future trend is towards adopting new technologies that will change the environmental and landscape setting, mainly of urban sites. The ongoing study serves first hand as an assessment of the actual situation, and on the second hand as a guide to adopting low-impact technologies and strategical spatial planning to achieve a good compromise between the spread of impactful sources and environmental protection.

9.1 Personal contributions

The last step of this report highlights the personal contributions to the national EMF research programme, in particular:

- Understanding requirements and needs of the ARPA;
- Deep analysis of the theory of electromagnetism and the sources of the electromagnetic field, both in the radio frequency spectrum and in the extremely low-frequency range;
- Understanding of the hierarchical order of regulations;
- Workflow planning coordination with the ARPA and the entire execution on us:
  - Approach to the work, time management, and tasks division;
  - Cartography manoeuvres, aggregation of files, and attribute transfers on QGIS software;
  - Simulations on finite element analysis software: EmLAB and WinEDT;
  - Measurements (in this case with some assistance from colleagues of the ARPA);
  - Correlations and interpretation of the results.
- Drafting of the technical report;
- Delivering results in compliance with the directives of the ISPRA and the work made by other ARPAs;
- Divulgation and dissemination of the results, to help to debunk conspiracy theories.

Appendix A.

RF measurement validation protocol

Programma di promozione di attività di ricerca e di sperimentazione tecnico-scientifica, nonché di coordinamento dell'attività di raccolta, di elaborazione e di diffusione dei dati al fine di approfondire i rischi connessi all'esposizione a campi elettromagnetici a bassa e alta frequenza – "Progetto ricerca CEM"

"Campi elettromagnetici e salute: studi di valutazione dell'esposizione e approfondimento sui possibili rischi delle esposizioni a lungo termine a basse e alte frequenze"

Attività A – Indicatori di esposizione ambientale

Protocollo per le misure di validazione a RF

Febbraio 2024

Indice

1. Introduzione

Questo documento riporta la procedura operativa da seguire per la validazione strumentale dei calcoli previsionali delle aree di studio individuate, effettuati nell'ambito dell'Attività A "Indicatori di esposizione ambientale", per le sorgenti a Radio Frequenza (RF) costituite unicamente dalle Stazione Radiobase.

In particolare, lo scopo del documento è quello di fornire metodologia per svolgimento delle misure di validazione nelle aree di studio individuate, tenendo conto delle diverse condizioni che si possono presentare in campo, al fine di uniformare le scelte da effettuare e rendere il più possibile omogenei e confrontabili i risultati ottenuti da ciascuna Agenzia.

2. Metodologia di misura

Si definisce l'Area di Validazione coincidente a una Sezione Censuale ISTAT 2021, all'interno della quale effettuare un numero di misure almeno pari a 10, in modo da garantire la significatività statistica dei dati misurati.

Le misure sono effettuate alla quota stabilita dall'analisi dell'edificato dell'Area di Studio (piano fuori terra più frequente), in corrispondenza del punto più esposto, identificato con una preliminare indagine quali-quantitativa dell'area, ove possibile con l'impianto più vicino posto in visibilità col punto di misura.

Le misure avranno luogo in uno spazio esterno (ad es. balcone, lastrico solare o in facciata all'edificio alla quota stabilita), al fine di ridurre i fattori di incertezza dovuti, nel caso di misure in interno, all'assorbimento delle pareti.

Se non è disponibile uno spazio esterno alla quota stabilita, si effettuano le misure ad un'altra quota; in mancanza di altre soluzioni, ove possibile, sul tetto dell'edificio.

Nel caso di indisponibilità di spazi esterni, si eseguono le misure all'interno degli edifici, comunque sempre in presenza di una finestra che consenta di porsi in visibilità all'impianto più prossimo al punto di misura.

Le misure possono essere eseguite sulle 24 ore per mezzo di una centralina di monitoraggio. I risultati saranno confrontati con quelli ottenuti dalle valutazioni previsionali con l'utilizzo di un fattore alfa24_day fornito, a richiesta, dal gestore o reperibile dal database contatori.

In alternativa, è possibile prevedere tempi di misura più brevi di 24 ore, i cui risultati saranno confrontati con quelli ottenuti dalle valutazioni previsionali utilizzando un opportuno fattore alfa24, ricavato dalla curva alfa24_day dell'impianto fornita dal gestore[1].

In alternativa alle misure sulle 24 ore, è possibile effettuare misure su 6 minuti durante il periodo diurno, in quanto è stato dimostrato da sperimentazioni svolte su campo[2] che la differenza tra i valori misurati su 6 minuti e su 24 ore ricadono all'interno dell'incertezza strumentale.

Le misure saranno ripetute in più aree di validazione, con la finalità di verificare la ripetibilità dei risultati.

3. Misure facoltative indoor

Al fine di approfondire l'influenza delle attenuazioni dovute alla presenza di pareti degli edifici si propone di effettuare anche uno o più set di misure indoor, se possibile nelle stesse aree di censimento dove vengono eseguite le misure outdoor.

I risultati delle misure, effettuate sulle 24 ore per mezzo di una centralina di monitoraggio o per tempi di misura brevi, saranno confrontati con quelli ottenuti dalle valutazioni previsionali e con i risultati delle misure outdoor, con l'obiettivo di indagare ed approfondire l'esposizione della popolazione in un contesto reale.

[1] Selezionando le sole misure all'esterno, ARPA Piemonte ha verificato che lo scarto tra i valori misurati e calcolati è mediamente tra il 50% e il 60%. Questo dato corrisponde bene alla statistica che viene fuori dall'analisi dei contatori di potenza degli impianti presenti nell'area, ottenuta considerando una settimana di dati di potenza esercita nelle ore diurne confrontati con le medie su 24 ore da autorizzazione, centrata su un valore medio intorno al 53%. Sarebbe interessante, quindi, verificare se dalle misure in altre aree urbane emergono scarti analoghi (magari confermati anche dall'analisi dei contatori), per poter determinare un eventuale fattore di correzione applicabile alla valutazione in modo da fornire una stima più realistica dell'indicatore.

[2] Cfr. Chiara Pedroli et al, 2023, "Caratterizzazione statistica delle misure in continuo di campo elettrico emesso da sorgenti a radiofrequenza in Piemonte", Convegno Nazionale AIRP Cagliari, 27-29 settembre 2023

Appendix B.

ELF Exposure indicator procedure

Attività A sui CEM ELF – Procedura indicatore di esposizione

Di seguito si riportano le modalità operative per il popolamento dell'indicatore di esposizione all'induzione magnetica a 50 Hz.

Corridoi di indagine e ricerca recettori

Per l'individuazione dei recettori esposti vanno considerati, per le linee in terna singola, i corridoi bidimensionali con al centro il tracciato di semiampiezza pari a: **20 m** per le linee a 132 kV; **30 m** per quelle a 220 kV e **40 m** per quelle a 380 kV.

La definizione di tali distanze si ricava dalle simulazioni, sia calcolando le circonferenze isolivello a 0,4 µT con le correnti medie annue tipiche come dato di input (vedi grafici in Allegato), sia calcolando le circonferenze isolivello a 3,0 µT con la massima mediana giornaliera tipica della corrente come dato di input. In entrambi i casi per la maggior parte delle linee l'estensione laterale di tali circonferenze è sovrapponibile [1].

L'individuazione dei recettori presenti in prossimità delle linee ad alta e altissima tensione si ottiene in modo semplice dai tracciati georeferenziati, fissando un opportuno *buffer* ed andando ad intersecare tale corridoio con lo shape dell'edificato. Nel caso non si disponga di tali informazioni, in alternativa, è possibile, partendo dalle mappe dell'Atlante della Rete, individuare la collocazione su Google Earth Pro, ad esempio, di una stazione elettrica e da questa seguire dalle immagini aeree il tracciato di una linea a 380 kV fino a quando esso non interferisca con l'abitato. Individuati gli edifici vicini al tracciato, questi si possono visualizzare con Street View e capire se si tratta di abitazioni o di altra tipologia di immobile (vedi esempio in Allegato).

Calcoli previsionali

Per il calcolo previsionale del livello medio annuo di esposizione a lungo termine all'induzione magnetica presso i recettori, almeno all'altezza di 5 m da terra ed eventualmente ad altre altezze, si userà la corrente media annua della linea.

Nel caso in cui si disponesse di tutti i dati di input necessari (corrente, profilo della linea e geometria delle teste) si può effettuare direttamente il calcolo previsionale.

Nel caso in cui non si disponesse di tutti i dati di input necessari, effettuando dei sopralluoghi presso le abitazioni e misurando sul posto l'altezza da terra dei conduttori e l'altezza da terra degli attacchi ai sostegni, si può ricostruire il profilo delle tre catenarie nello spazio. Fotografando la testa dei due sostegni della campata in esame è possibile ricavarne la geometria, assimilandola a quella delle teste tipiche più diffuse.

Nel caso non si disponesse del software di calcolo, si può ricorrere alla Piattaforma WebNIR al seguente indirizzo:

https://www.webnir.eu/launcher.php?id=13&area=CEM

che consente di fare il calcolo previsionale bidimensionale (adattamento al web del programma di calcolo "Campi 4.1" realizzato dal Dott. D. Andreuccetti dell'IFAC-CNR di Firenze, di cui è disponibile il manuale).

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[1] *Vedi anche gli articoli:*
V. Bottura e altri "Controlli sugli elettrodotti di alta tensione transitanti sul territorio della Valle d'Aosta" Convegno Nazionale Agenti Fisici, Alessandria, 2016.
N. Colonna e altri "Individuazione e caratterizzazione dei recettori ad elevata esposizione all'induzione magnetica a 50 Hz da linee elettriche ad alta e altissima tensione". Convegno Nazionale AIRP, Roma 2021.

Misure di validazione e ai fini della stima dell'esposizione

Almeno presso uno dei recettori di cui sopra dovrà essere effettuata una misura in continuo dell'induzione magnetica preferibilmente della durata complessiva di 24 ore, anche in più sessioni di almeno 8 ore, purché venga registrato il fronte di salita, o di discesa del livello (ai fini della corretta correlazione corrente-campo).

Nel caso in cui non vi fosse la disponibilità dei recettori ad ospitare la strumentazione di misura, si effettueranno, in prossimità della linea, misure di durata più breve, presidiando la strumentazione.

Dopo la misura si richiedono a TERNA le correnti circolanti al quarto d'ora, relative al periodo di misura, insieme alla corrente media annua, relativa all'anno solare precedente. Una volta ricevute tali informazioni si possono correlare i valori dell'induzione magnetica misurata con i dati di corrente *(vedi Allegato al D.M. 29/05/2008, G.U. n. 153 del 02/07/2008, al paragrafo 5.2.1)* e stimare presso il recettore indagato il livello medio annuo di esposizione all'induzione magnetica.

Per il calcolo previsionale di validazione del modello si userà la corrente circolante durante la misura in continuo, registrata al quarto d'ora. Per la validazione si ritiene accattabile uno scostamento tra il livello calcolato e quello misurato non superiore al 30%.

Stima della popolazione esposta (indicatore)

Per la costruzione dell'indicatore si dovrà valutare il numero di edifici presenti all'interno della sezione censuaria che ricadono nel corridoio di indagine: la valutazione della popolazione sarà effettuata in quel sottoinsieme di edifici (ad esempio, tramite parametrizzazione della popolazione col numero di edifici).

Sarà restituito un istogramma con il numero di residenti esposti, suddiviso su intervalli di ampiezza pari a 0,5 μT (vedi tabella seguente).

Classe	**Intervallo di esposizione (μT)**	**Numero di residenti esposti**
0	< 0,5	
1	0,5 – 1,0	
2	1,0 – 1,5	
3	1,5 – 2,0	
4	2,0 – 2,5	
5	2,5 – 3,0	
6	> 3,0	

Georeferenziazione dei recettori esposti

Va restituito uno shape file georeferenziato con la posizione dei recettori individuati, il singolo recettore sarà caratterizzato dal livello medio di esposizione a lungo termine.

Le singole ARPA, volendo, possono approfondire anche casi differenti da quelli qui citati.

Appendix C.

Dosimetry and personal exposure: Document for dosimetry surveys

Programma di promozione di attività di ricerca e di sperimentazione tecnico-scientifica, nonché di coordinamento dell'attività di raccolta, di elaborazione e di diffusione dei dati al fine di approfondire i rischi connessi all'esposizione a campi elettromagnetici a bassa e alta frequenza – "Progetto ricerca CEM"

"Campi elettromagnetici e salute: studi di valutazione dell'esposizione e approfondimento sui possibili rischi delle esposizioni a lungo termine a basse e alte frequenze"

Attività B - Dosimetria ed esposizione personale:

Documento programmatico per i rilievi dosimetrici

Gennaio 2024

Indice

1. Introduzione

Questo documento, redatto nell'ambito del "Progetto ricerca CEM" finanziato dal Ministero dell'Ambiente e della Sicurezza Energetica, riporta le linee programmatiche relative all'attività B) dell'area di ricerca "Esposizione": "Dosimetria ed esposizione personale"

In particolare, lo scopo del documento è quello di fornire i dettagli tecnici utili alla implementazione dei rilievi dosimetrici.

2. Obiettivo del progetto

Al fine di ottenere una determinazione completa ed esaustiva dell'esposizione a campi elettromagnetici, occorre integrare le valutazioni basate sulle sorgenti installate in ambiente esterno, che danno luogo ad una esposizione ambientale, con i contributi dovuti a sorgenti di uso personale e a sorgenti indoor, quali i dispositivi Wi-Fi. Tali contributi possono essere determinati per mezzo di dosimetri personali che consentono di individuare anche i segnali in determinate bande di frequenza e, quindi, le diverse sorgenti che causano l'esposizione dell'individuo nel tempo.

L'obiettivo dello studio è pertanto rappresentato dalla misura in continuo del campo elettrico cui è esposto un campione di popolazione, con la possibilità di attribuire alle diverse tipologie di sorgenti radio, TV, Wi-Fi, telefonia 2G, 3G, 4G, 5G i contributi al campo elettrico globale per un'analisi statistica sui diversi contributi dei singoli impianti/sistemi/emittenti all'esposizione della popolazione.

Con l'utilizzo di dosimetri personali e di un diario giornaliero, possono essere realizzate campagne di misura orientate a misurare i contributi all'esposizione individuale dovuti alle sorgenti indoor ed a quelle di uso personale quale il telefonino. Si potrà inoltre confrontare l'esposizione individuale con quella ambientale dovuta alle sorgenti fisse outdoor.

In relazione all'uso di dispositivi personali (smartphone), può anche essere sviluppata un'attività di "Citizen science" con l'uso di una app specifica in grado di monitorare le modalità di utilizzo del dispositivo che influenzano l'esposizione individuale. Per meglio definire l'esposizione nell'ambiente indoor, potranno inoltre essere realizzate campagne di caratterizzazione di dispositivi quali Wi-Fi, baby monitor, ecc.

3. Fasi dell'attività

L'attività si articola nelle seguenti fasi:

- Definizione delle specifiche tecniche dei dosimetri selettivi in frequenza, definizione del diario giornaliero, dei criteri di scelta del campione e di metodi di analisi dei dati.

- Attività di monitoraggio finalizzate alla stima dell'esposizione a radiofrequenza da sorgenti fisse outdoor, sorgenti fisse indoor e da dispositivi mobili di uso personale, tramite l'utilizzo dosimetri selettivi in frequenza. Per le Agenzie che vorranno farne uso, sarà messa a disposizione una app per smartphone in grado di rilevare i tempi e le modalità di utilizzo del dispositivo.
- Raccolta, analisi dei dati a livello nazionale e redazione di un rapporto sull'esito della campagna di misura.

4. Definizione delle specifiche tecniche dei dosimetri selettivi in frequenza

Di seguito sono forniti i requisiti minimi dei dosimetri da utilizzare nell'ambito dei rilievi.

- Dispositivo: dosimetro personale in grado di misurare il segnale di campo elettrico su almeno 15 bande di frequenza contemporaneamente, impostabili dall'utente, registrando tali valori nel tempo. La misura deve fornire, per ciascuna banda, il contributo complessivo di campo elettrico su 3 assi.
- Intervallo di frequenza: almeno da 88 MHz a 6 GHz, suddivisibile in almeno 15 bande impostabili dall›utente
- Intervallo dinamico di misura: almeno da 0.5 V/m a 60 V/m
- Tipo sonda: triassiale
- Anisotropia complessiva: entro ± 3dB fino a 6 GHz
- Tipo di Misura: True RMS e valore di picco
- Intervallo di memorizzazione: impostabile dall'utente, almeno tra 5 secondi e 3 minuti
- Durata della memoria: con tasso di campionamento 10s e misura su 10 bande, superiore a 24 ore
- Sensibilità: almeno 10 mV/m
- GPS: possibilità di attivare la misura GPS per la posizione
- Peso: Inferiore a 500 g (con batterie)
- Temperature di funzionamento: almeno tra - 5°C e 40°C
- Funzioni:
    - Misura triassiale
    - trasferimento dati e interfaccia per impostazione parametri via seriale/ottica/USB

- acquisizione di livelli medi e massimi di campo elettrico, anche tramite analisi sw

- Altre caratteristiche:
  - controllo e possibilità di visualizzazione dello stato batteria, anche attraverso il software dedicato
  - protocollo di comunicazione e lista dei comandi per il controllo da remoto del dosimetro, attraverso il software dedicato
- Software di interfaccia e controllo
  - compatibile con sistemi operativi Windows 7 e 10 per PC a 32 e 64 bit.
  - creazione di grafici esportabili
  - possibilità di esportazione dati acquisiti in formato testo con delimitazioni standard
- Taratura: calibrazione base

5. Configurazione dei dosimetri selettivi in frequenza

I dosimetri saranno configurati con le bande predefinite indicate nella tabella sottostante e un tempo di acquisizione di 10 secondi, per consentire durate di acquisizione ininterrotte di 24 ore.

N. banda	Ampiezza di banda [MHz]	Nome della banda	Ampiezza di banda da configurare [MHz]	Frequenza centrale da configurare [MHz]	Da [MHz]	A [MHz]
1	88 - 108	Radio FM	35	97,5	80	115
2	174 - 240	DAB VHF	75	211,5	174	249
3	470 - 702	TV DVBT UHF 1	100	520	470	570
4		TV DVBT UHF 2	100	620	570	670
5	703 - 748	5G N28 UL	75	717,5	680	755
6	758 - 788	5G N28 DL	35	777,5	760	795
7	791 - 821	L800 DL	35	812,5	795	830
8	832 - 862	L800 UL	35	847,5	830	865
9	880 - 915	GSM + U900 UL	35	897,5	880	915
10	917 - 965	GSM + U900 DL	75	952,5	915	990
11	1452 - 1492	L1500	75	1472	1434,5	1509,5
12	1710 -1785	DCS + L1800 UL	75	1747,5	1710	1785
13	1805 - 1880	DCS + L1800 DL	75	1842,5	1805	1880
14	1880 - 1900	DECT	35	1890	1872,5	1907,5
15	1920 - 1980	U2100+L2100 UL	75	1950	1912,5	1987,5
16	2110 - 2170	U2100+L2100 DL	75	2140	2102,5	2177,5
17	2400 -2480	WiFi (DFS)	100	2445	2395	2495

N. banda	Ampiezza di banda [MHz]	Nome della banda	Ampiezza di banda da configurare [MHz]	Frequenza centrale da configurare [MHz]	Da [MHz]	A [MHz]
18	2500 - 2570	L2600 UL	75	2535	2497,5	2572,5
19	2570 - 2690	L2600 DL	75	2660	2622,5	2697,5
20	3458 - 3500	L3500 lk	75	3469	3431,5	3506,5
21	3560 - 3800	5G N78 1	100	3650	3600	3700
22		5G N78 2	100	3750	3700	3800
23	5150 - 5350	Wi Fi HyperLAN 1	100	5250	5200	5300
24	5470 - 5725	Wi Fi HyperLAN 2	100	5550	5500	5600
25		Wi Fi HyperLAN 3	100	5650	5600	5700

6. Modalità di rilevazione dei dati

Per effettuare la valutazione dell'esposizione giornaliera su target di persone con tipologia diversa di attività saranno effettuate misure con il dosimetro indossato durante l'intera giornata (24 ore): al momento di coricarsi, il dosimetro sarà posizionato sul comodino o comunque in prossimità del letto.

Questo monitoraggio consente di valutare l'esposizione giornaliera media e cumulativa della persona che indossa il dosimetro in funzione dell'attività, della posizione rispetto alle SRB o a sistemi Wi-Fi e dell'utilizzo del dispositivo personale.

Saranno svolte misure giornaliere di 1-2 giorni, facendo indossare lo stesso strumento a più soggetti.

7. Scheda di rilevazione giornaliera

La scheda di rilevazione giornaliera, riportata in Allegato 1, sarà consegnata personalmente e in via formale nella scheda saranno indicati, oltre alle generalità di chi lo indossa, anche:

- Tempo di utilizzo, cioè inizio e fine della misura. Si può pensare di avere un'omogeneità rispetto all'orario di utilizzo e qui predefinire la durata.
- Target di utilizzo: lavoro in ufficio, smart working, itinerante, studenti delle scuole medie o superiori, studenti universitari, focus su spostamenti extraurbani su mezzi pubblici, utilizzo in occasione di eventi e sale di attesa.
- Indicazione per eventuale tempo di utilizzo del proprio telefono cellulare.
- Indicazione della distanza del router Wi-Fi dalla postazione di lavoro.

8. Criteri di scelta del campione

Secondo quanto concordato nel corso delle riunioni di coordinamento, si lascerà alle singole Agenzie la scelta della tipologia del campione: dipendenti, familiari, studenti, associazioni, ecc.

In generale, verranno considerate le seguenti tipologie:

1) Dipendenti delle Agenzie che lavorano in presenza
2) Dipendenti delle Agenzie che lavorano in smart working
3) Dipendenti delle Agenzie che lavorano in campo
4) Dipendenti delle Agenzie che viaggiano su mezzi pubblici extraurbani
5) Studenti delle scuole medie inferiori
6) Studenti delle scuole medie superiori
7) Studenti universitari
8) Presenza di molte persone (eventi o sale di attesa)

Si riportata nella tabella seguente il riepilogo delle scelte effettuata da ciascuna Agenzia partecipante al progetto.

Agenzie partecipanti all'Attività B	Dipendenti Agenzia in Ufficio	Dipendenti Agenzia in Smart working	Dipendenti Agenzia durante attività in campo	Studenti scuole medie inferiori	Studenti scuole superiori	Studenti universitari	Eventi e sale d'attesa
ARPA Piemonte	X	X	X			X	X
ARPA Valle d'Aosta	X	X	X		X		
APPA Bolzano	X	X					
APPA Trento	X	X	X				
ARPA Emilia-Romagna	X	X					
ARPA Toscana	X	X	X		X	X	
ARPA Molise	X	X	X				
ARPA Campania	X	X	X		X		
ARPA Sicilia	X	X		X	X		
ARPA Sardegna	X	X	X				
ISPRA	X	X					
Totale	**11**	**11**	**7**	**1**	**4**	**2**	**1**

Bibliography

[1] ARPA VdA. *Chi siamo*. URL: https://www.arpa.vda.it/it/chi-siamo/1230-le-arpa (cit. on p. 4).

[2] *Cosa sono i campi elettromagnetici*. Arpa Emilia-Romagna. URL: https://www.arpae.it/it/temi-ambientali/campi-elettromagnetici/scopri-di-piu/cosa-sono-i-campi-elettromagnetici (visited on 07/17/2024) (cit. on p. 5).

[3] Wikimedia Foundation. *Interazioni Fondamentali*. URL: https://it.wikipedia.org/wiki/Interazioni_fondamentali (cit. on p. 7).

[4] *derivation of wave equation from Maxwell's equations*. planetmath.org. URL: https://planetmath.org/derivationofwaveequationfrommaxwellsequations (cit. on p. 9).

[5] Aldo Canova. *Applied electromagnetism notes* (cit. on pp. 9, 29, 37, 38, 40, 82).

[6] Fisica Fast [Elia Rampi]. *Dalle equazioni di Maxwell alle equazioni delle onde*. YouTube, Aug. 2020. URL: https://youtu.be/ZQIDsgyfydk (visited on 07/17/2024) (cit. on p. 9).

[7] *Vector triple product*. Wikipedia. Feb. 2023. URL: https://en.wikipedia.org/wiki/Triple_product#Vector_triple_product (cit. on p. 9).

[8] *Campi elettromagnetici generati da elettrodotti*. Overtec.it. Oct. 2016. URL: https://www.overtec.it/articoli/news-e-offerte/campi-elettromagnetici-generati-da-elettrodotti (visited on 07/22/2024) (cit. on p. 12).

[9] *IRPA - INTERNATIONAL RADIATION PROTECTION ASSOCIATION*. www.irpa.net. URL: https://www.irpa.net/ (visited on 07/22/2024) (cit. on p. 13).

[10] *ICNIRP | Aim, Status & History*. www.icnirp.org. URL: https://www.icnirp.org/en/about-icnirp/aim-status-history/index.html (cit. on p. 13).

[11] ICNIRP. *ICNIRP GUIDELINES FOR LIMITING EXPOSURE TO TIME VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz) International Commission on Non-Ionizing Radiation Protection*. 1998. URL: https://www.icnirp.org/cms/upload/publications/ICNIRPemfgdl.pdf (cit. on pp. 13, 14).

[12] Christian Kurrer. *Environment policy: General Principles and Basic Framework | Fact Sheets on the European Union | European Parliament*. Europa.eu. Nov. 2019. URL: https://www.europarl.europa.eu/factsheets/en/sheet/71/environment-policy-general-principles-and-basic-framework (cit. on p. 14).

[13] *Principles of EU Environmental Law*. www.era-comm.eu. URL: https://www.era-comm.eu/Introduction_EU_Environmental_Law/EN/module_2/module_2_10.html#:~:text=Where%20there%20is%20uncertainty%20about (visited on 07/22/2024) (cit. on p. 14).

[14] ICNIRP and Ralf Löwe. *Reference Book: Guidelines on Limiting Exposure to Non-Ionizing Radiation. A reference book based on guidelines on limiting exposure to non-ionizing radiation and statements on special applications*. 2024. URL: https://www.icnirp.org/en/publications/article/reference-book-1999.html (visited on 08/05/2024) (cit. on p. 14).

[15] ICNIRP. «ICNIRP GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1 HZ -100 kHZ)». In: (2010). DOI: 10.1097/HP.0b013e3181f06c86. URL: https://icnirp.org/cms/upload/publications/ICNIRPLFgdl.pdf (visited on 08/14/2024) (cit. on pp. 14, 15).

[16] ICNIRP. «Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)». In: *Health Physics* 118 (May 2020), pp. 483–524. DOI: 10.1097/hp.0000000000001210. URL: https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf (visited on 08/14/2024) (cit. on p. 14).

[17] IARC. *IARC CLASSIFIES RADIOFREQUENCY ELECTROMAGNETIC FIELDS AS POSSIBLY CARCINOGENIC TO HUMANS. PRESS RELEASE N° 208*. 2011. URL: https://www.iarc.who.int/wp-content/uploads/2018/07/pr208_E.pdf#:~:text=Lyon%2C%20France%2C%20May%2031%2C%202011%20%E2%80%90%E2%80%90%20The%20WHO%2FInternational (visited on 08/16/2024) (cit. on p. 16).

[18] Thomas Reilly, Greg Atkinson, Ben Edwards, Jim Waterhouse, Kelly Farrelly, and Emma Fairhurst. «Diurnal Variation in Temperature, Mental and Physical Performance, and Tasks Specifically Related to Football (Soccer)». In: *Chronobiology International* 24 (Jan. 2007), pp. 507–519. DOI: 10.1080/07420520701420709. (Visited on 05/12/2020) (cit. on p. 17).

[19] Akimasa Hirata, Ilkka Laakso, Takuya Oizumi, Ryuto Hanatani, Kwok Hung Chan, and Joe Wiart. «The relationship between specific absorption rate and temperature elevation in anatomically based human body models for plane wave exposure from 30 MHz to 6 GHz». In: *Physics in Medicine and Biology* 58 (Jan. 2013), pp. 903–921. DOI: 10.1088/0031-9155/58/4/903. (Visited on 05/07/2022) (cit. on p. 17).

[20] Peter G Weyand, Bethany B Smith, and Rosalind F Sandell. «Assessing the metabolic cost of walking: The influence of baseline subtractions». In: (Nov. 2009). DOI: 10.1109/iembs.2009.5333126. (Visited on 05/24/2023) (cit. on p. 17).

[21] L. P. J. Teunissen, A. Grabowski, and R. Kram. «Effects of independently altering body weight and body mass on the metabolic cost of running». In: *Journal of Experimental Biology* 210 (Dec. 2007), pp. 4418–4427. DOI: 10.1242/jeb.004481. URL: https://jeb.biologists.org/content/210/24/4418 (cit. on p. 17).

[22] COUNCIL OF THE EUROPEAN UNION. *COUNCIL RECOMMENDATION of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz)*. July 1999. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999H0519 (visited on 08/05/2024) (cit. on p. 19).

[23] Gazzetta Ufficiale. *Legge quadro n.36 22/02/2001*. Normattiva.it, Mar. 2001. URL: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:legge:2001-02-22 (visited on 08/29/2024) (cit. on p. 21).

[24] Gazzetta Ufficiale. *Fissazione dei limiti di esposizione, dei valori di attenzione e degli obiettivi di qualita' per la protezione della popolazione dalle esposizioni ai campi elettrici e magnetici alla frequenza di rete (50 Hz) generati dagli elettrodotti*. Gazzettaufficiale.it, 2003. URL: https://www.gazzettaufficiale.it/eli/id/2003/08/29/03A09749/sg (visited on 08/16/2024) (cit. on pp. 22, 25).

[25] Gazzetta Ufficiale. *Fissazione dei limiti di esposizione, dei valori di attenzione e degli obiettivi di qualita' per la protezione della popolazione dalle esposizioni a campi elettrici, magnetici ed elettromagnetici generati a frequenze comprese tra 100 kHz e 300 GHz*. Gazzettaufficiale.it, 2003. URL: https://www.gazzettaufficiale.it/eli/id/2003/08/28/03A09711/sg (visited on 08/16/2024) (cit. on p. 22).

[26] Gazzetta Ufficiale. *Legge annuale per il mercato e la concorrenza*. Gazzettaufficiale.it, 2023. URL: https://www.gazzettaufficiale.it/eli/id/2023/12/30/23G00220/SG (visited on 08/17/2024) (cit. on p. 23).

[27] MINISTERO DELL'AMBIENTE E DELLA TUTELA DEL TERRITORIO E DEL MARE. *Approvazione della metodologia di calcolo per la determinazione delle fasce di rispetto per gli elettrodotti*. May 2008. URL: https://www.gazzettaufficiale.it/eli/gu/2008/07/05/156/so/160/sg/pdf (visited on 08/17/2024) (cit. on p. 24).

[28] Gazzetta ufficiale. *Attuazione della direttiva (UE) 2018/1972 del Parlamento europeo e del Consiglio, dell'11 dicembre 2018, che istituisce il Codice europeo delle comunicazioni elettroniche (rifusione)*. www.normattiva.it, Nov. 2021. URL: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2021 (visited on 08/17/2024) (cit. on p. 24).

[29] Gazzetta Ufficiale. *Codice delle comunicazioni elettroniche*. Normattiva.it, Aug. 2003. URL: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2003-08-01 (visited on 08/17/2024) (cit. on p. 24).

[30] Consiglio Regionale della Valle d'Aosta. *Legge regionale 4 novembre 2005, n. 25*. Consiglio.vda.it, Nov. 2005. URL: https://www.consiglio.vda.it/app/leggieregolamenti/dettaglio?pk_lr=3281&versione=V (visited on 08/18/2024) (cit. on p. 24).

[31] Consiglio Regionale della Valle d'Aosta. *Legge regionale 28 aprile 2011, n. 8*. Consiglio.vda.it, Apr. 2011. URL: https://www.consiglio.vda.it/app/leggieregolamenti/dettaglio?pk_lr=6401 (visited on 08/18/2024) (cit. on p. 24).

[32] Davis D. Sentman. *Handbook of Atmospheric Electrodynamics*. Vol. 8. H.Volland, 1995. Chap. Schumann Resonance (cit. on p. 25).

[33] Nurdan O zkucur Richard H.W. Funk Thomas Monsees. «Electromagnetic effects – From cell biology to medicine». In: *ScienceDirect* (2008) (cit. on p. 25).

[34] Wever R. «The effects of electric fields on circadian rhythmicity in men». In: *Life sciences and space research* 8 (1970), pp. 177–187 (cit. on p. 26).

[35] Ministry for the Environment, Protection of Land, and Sea. *Programma di promozione di attività di ricerca e di sperimentazione tecnico-scientifica, nonché di coordinamento dell'attività di raccolta, di elaborazione e di diffusione dei dati al fine di approfondire i rischi connessi all'esposizione a campi elettromagnetici a bassa e alta frequenza.* Nov. 2018. URL: https://www.mase.gov.it/sites/default/files/archivio/allegati/inquinamento_elettromagnetico/dd_156_RIN_16_11_2018.pdf (visited on 08/21/2024) (cit. on p. 26).

[36] ITU-R. *Recommendation ITU-R V.431-8, Nomenclature of the frequency and wavelength bands used in telecommunications.* Aug. 2015. URL: https://www.itu.int/dms_pubrec/itu-r/rec/v/R-REC-V.431-8-201508-I!!PDF-E.pdf (cit. on p. 28).

[37] Carlo Ricciardi. *Physics II notes* (cit. on p. 29).

[38] Darwin R. and P. Sampath. «Sub-6 GHz band massive MIMO antenna system for variable deployment scenarios in 5G base stations». In: *Microsystem Technologies* 28 (July 2022). DOI: 10.1007/s00542-022-05344-2 (cit. on p. 32).

[39] *Sector antenna.* Wikipedia. Feb. 2013. URL: https://en.wikipedia.org/wiki/Sector_antenna (cit. on p. 32).

[40] CEI. *Guida ai metodi di calcolo dei campi elettrici e magnetici generati da linee e da stazioni elettriche.* Sept. 2008 (cit. on pp. 38, 40).

[41] Zoppetti N. Andreuccetti D. «Campo magnetico disperso da elettrodotti ad alta tensione: una metodologia avanzata di valutazione basata su modelli 3D di linee elettriche e territorio». In: (2003). URL: http://embiolab.ifac.cnr.it/~zoppetti/MasterGIS/LezioneMasterGIS/ISE2003_IFAC_andreuccetti_zoppetti.pdf (cit. on p. 40).

[42] *Come leggere la visura.* Ministero dell'Economia e delle Finanze, Agenzia delle Entrate. URL: https://www.agenziaentrate.gov.it/portale/it/web/guest/schede/fabbricatiterreni/visura-catastale/come-leggere-la-visura (cit. on p. 43).

[43] *Spatial without Compromise.* QGIS Community. URL: https://www.qgis.org/ (cit. on p. 45).

[44] *Progetto SCT.* Regione Autonoma Valle d'Aosta. 2013. URL: https://mappe.regione.vda.it/pub/geonavitg/monografie.asp (cit. on p. 48).

[45] *Company.* Aldena Telecomunicazioni. URL: https://www.aldena.it/company/ (cit. on p. 53).

[46] Ministry for the Environment, Protection of Land, and Sea. *Approvazione delle Linee Guida sui valori di assorbimento del campo elettromagnetico da parte delle strutture degli edifici.* Oct. 2016. URL: https://www.mase.gov.it/pagina/decreti-inquinamento-elettromagnetico (cit. on p. 72).

[47] *About us.* SE.DI.COM S.R.L. URL: https://www.sedicomtech.com/site/en/home/chisiamo.php (cit. on p. 78).