L'ÉNERGIE AU CŒUR DES ONDES

RESSOURCES ET ENVIRONNEMENT :

GESTION "INTELLIGENTE"

Analyse des données spatio-temporelles de l'exposition aux ondes électromagnétiques en environnement extérieur issues de sondes autonomes, mesures in situ et paramètres d'antennes

Space-time data analysis of exposure to electromagnetic fields in outdoor environment from autonomous probes, in situ measurements and antennas parameters

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Résumé

L'étude repose sur une analyse inédite de l'exposition spatio-temporelle reposant sur le déploiement depuis quelques années de sondes autonomes de surveillance de l'exposition large bande dans plusieurs villes françaises. Le croisement de ces données de sondes avec les mesures d'exposition in situ détaillées en fréquence effectuées par l'Agence nationale des fréquences ainsi que la connaissance des antennes à proximité de ces sondes, permettent de tirer des conclusions statistiques sur l'exposition particulièrement sur la dimension temporelle et spatiale. En effet, l'étude montre qu'il existe plusieurs périodicités dans les mesures effectuées par les sondes (phénomène de saisonnalité, jour/nuit, jours de la semaine/weekend). Les données recueillies par les mesures in situ menées par l'ANFR croisées avec les antennes les plus proches du point de mesure révèle qu'une corrélation existe entre les données d'antennes et les résultats de mesure.

Abstract

The study rests on a new space-time analysis of the exposure based on the deployment of E field monitoring autonomous wideband probes in many French cities. Mixing probe's data with frequency selective in situ measurements carried out by ANFR and the knowledge of the nearby antennas, enable to conclude statistically on the exposure of the people. Indeed, the data gathered by probes reveals that different periodicity exist (seasonality, day/night, week days/weekend). The data gathered by in situ measurements carried out by ANFR crossed with closest antennas surrounding measurement position reveals that the correlation exists between the antennas knowledge and measurement results.

1 Introduction

The topic of assessment people's exposure to electromagnetic waves is a continuous subject of discussion which lead to important debate in the society. Many studies worldwide have shown assessment on the downlink human exposure due to cellular base station or on the uplink exposure due to personal equipment such as mobile phones [1, 2]. In France, Agence nationale des fréquences (ANFR) is in charge of the surveillance of public EMF exposure. Thousands in situ measurements are carried out each year [3] and ANFR has finely evaluated the level of exposure due to the deployment of 5G NR technology through measurements and simulations [4]. Moreover, compact electronic integration enables to create new techniques for EMF monitoring. Actually, city councils and ANFR have installed tens of autonomous monitoring probes which carry out broadband measurements of electric field many times per day [5]. This new technique of measurement offers the opportunity to analyze space-time variation of the level of exposure in various radio environment.

This paper makes a dual analysis of time and space variation of different type of measurement. Database of in situ measurement carried out all over the country and database of base station antennas are presented. Monitoring probe database is then exposed. The methodology is based on a complementary approach over time and space variation. Firstly, the variation of E field measured since installation are analyzed and some interesting behavior are detected such as day/night differences, week days/weekend differences or seasonality. Finally, after analyzing the time variation of monitoring probes, the question remains how the radio environment around the probes affects the level of exposure. In situ measurements are carried out by ISO 17025 accredited laboratories following ANFR protocol.

After installation of the monitoring probes, accredited in situ measurements have been carried out under each probe on the ground level including frequency selective measurement system in order to know the contribution of each technology/band. Since thousands of same kinds of measurements have been carried out every year, an analysis of the impact of radio environment on in situ measurements is presented. It shows that even with simple assumptions and assessment, correlation can be made between radio environment and frequency selective measurement. Conclusion shows that the techniques of dual analysis time and space are promising methods to reveal global and local patterns of the exposure linked to the usage of cellular network.

2 Available Data

2.1 ANFR’s antennas database and in situ measurement database

ANFR provide open source data regarding exposure of the people in France. There are two type of data available in raw data format or plotted over a map [3]. First type of data are the results of in situ measurement following ANFR protocol [9] which is in line with standard EN IEC 62232:2022 [10]. The results of the measurement are accessible: the broadband E field measurement and the frequency selective E field measurement. ANFR gives its agreement for base station installation and keeps the French national base station database up-to-date. On cartoradio website, it is possible to check the installed base station antennas everywhere in France including details such as technology (2G to 5G), frequency band, mobile operator, azimuthal direction, height of the antenna [3]. Information are provided for different types of network: TV broadcasting, radio broadcasting, point-to-point fixed radio relays and cellphone network. ANFR lists also other parameters describing the type of antennas, radiation pattern, Figure 1 shows an example of a map, here the red square is focus on ANFR’s headquarter. Cartoradio provides the locations of the base station and pink indicators show locations where an accredited in situ measurement has been carried out. Details of measurements and base stations are available by clicking on the indicators.

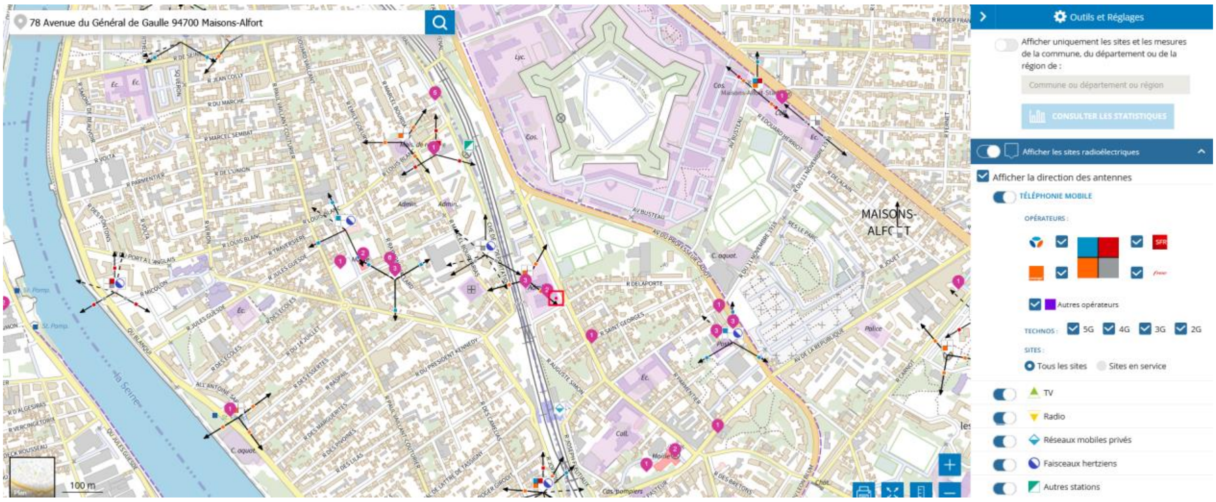

Figure 1: Printscreen of information provided on cartoradio.fr

ANFR analyses, on regular basis, the exposure to EMF due to base station antennas with:

- the yearly report which investigate the evolution of the exposure based on the outdoor and indoor measurement requested by French citizens,
- the report which investigates the evolution of the exposure specifically due to the 5G deployment,
- and the “city hall square” campaign which is carried out every three years in more than 1000 cities (80 % urban areas and sub-urban areas 20%),
- and others specific campaigns (smart meters, subway etc.).

These reports show that in very high majority of cases, greatest contribution to the overall exposure level is due to cellphone network (59% in 2021). In more than 20 % in 2021 of the cases there are nor major contributions because the measured level is low and close to the sensitivity threshold of measurement instrument. In the rest of the cases, the major contributions can come from WLAN, HF bands or Private mobile radio.

2.2 Monitoring probe database

City councils, ANFR and C2M Telecom Paris team have installed 152 autonomous monitoring probes. Monitoring probe were designed by EXEM company and are autonomous broadband probe measuring the three components of electric field between 80 MHz and 6 GHz. There are 152 autonomous probes installed among different cities in France since 2019. In general, probe is attached to outdoor electric pole or other street furniture to a certain height to avoid accessibility from pedestrians. The probes measure at multiple times of the day and night: every two hours between 1:00 AM and 11:00 PM and each measurement is averaged over 6 minutes. A website provided by EXEM company give access to the results of measurement of the probes [5]. Some of the autonomous probe monitoring data are publicly provided by city councils.

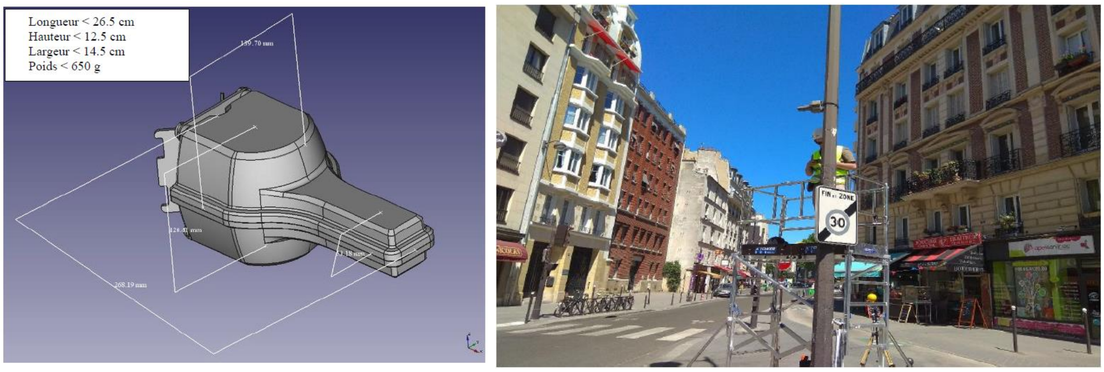

Figure 2: 3D shape of autonomous probe and a picture taken during installation of a probe on a street pole in Paris extracted from EXEM datasheet [12].

The following table 1 presents the number of autonomous probes per city, the name of city or conurbation authority where probes are installed and department code is also provided. Cities and conurbation authorities identify interesting probe position by targeting locations with a high density of base stations or close to children schools or public places with high rate of visitors.

Number of probes	Name of city or conurbation authority	Department name (number)
5	Lille Métropole	Nord (59)
9	Paris	Paris (75)
19	Massy	Essonne (91)
4	Grand Paris Sud	Essonne (91) and Seine-et-Marne (77)
7	Orléans Métropole	Loiret (45)
8	Eurométropole de Strasbourg	Bas-Rhin (67)
3	Mulhouse	Haut-Rhin (68)
10	Rennes	Ille-et-Vilaine (35)
50	Nantes Métropole	Loire-Atlantique (44)
33	Bordeaux Métropole	Gironde (31)
3	Marseille	Bouches-du-Rhône (13)

Table 1: Number of probes per city or conurbation authority

3 Methodology

3.1 Classical statistical analysis

The large amount of data enables to make classical statistical observations. Since measurements are done several times per day and per night starting from installation of the probe, it is possible to see if there is any common temporal behavior. Comparison can be carried out between week days and week-end days, or between weeks or between months by calculating the averaged value over time. Since electric E field is measured by the probe in volt per meter, the root mean square is used to assess the mean of the E field.

3.2 Principal component analysis (PCA)

PCA is a popular method of analyzing high-dimensional data [7]. It is an unsupervised statistical method which allows large datasets of correlated variables to be summarized into smaller numbers of uncorrelated principal components that explain most of the variability in the original dataset. Let suppose that the dataset X is a N-by-P matrix, with N observations which are the rows of X matrix and P variables which are the column of X matrix. There are mainly four steps involved in PCA:

1. Standardization of dataset X to characterize deviations between the observations

$$z_j^i = \frac{x_j^i - \overline{x_J}}{N} \tag{1}$$

   With j=1,…,P; i=1,…,N and z_j^i are the elements of standardized dataset called matrix Z.

2. Computation of covariance matrix

$$S = Z^T Z = \begin{pmatrix} \sigma_{z_1}^2 & \sigma_{z_1 z_2} & \cdots & \sigma_{z_1 z_P} \\ \sigma_{z_2 z_1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{z_P z_1} & \cdots & \cdots & \sigma_{z_P}^2 \end{pmatrix} \tag{2}$$

   With $\sigma_{z_1}^2$ variance of variable z_1, $\sigma_{z_1 z_2}$ covariance of variables z_1 with z_2.

3. Computation of eigenvalues and eigenvectors of the covariance matrix to identify the principal components. Our principal components that maximizes the variance of all projected points onto a 2D space, is the eigenvector of the covariance matrix associated with the largest eigenvalue. There are several techniques to compute eigenvalues and eigenvectors, one of the most use within PCA and in this study is the Singular Value Decomposition.
4. Extraction of scores and loadings: the PCA is then based on a decomposition of the data matrix into to two matrices V and U. The matrix V is k-by-P (with k is the number of principal components) matrix and is usually called the loadings matrix. The loadings can be understood as the weights for each original variable in the principal components space. The matrix U is called the scores matrix. It contains the original observations in a rotated coordinate system.

PCA is well known method to reduce the dimensions of a dataset, in our case, it can be helpful to find main components that characterize the time variability between the autonomous probe measurements. PCA would help to detect if the shapes of the monitoring probe level recorded have similarities or differences.

3.3 Correlation of in situ measurement with close radio environment

ANFR and its partners carry out thousands in situ measurements every year. Any French habitant can ask for a measurement at his accommodation or in any public space. The measurement protocol is defined by ANFR and is divided into two part [9]. The first part called ‘case A’ consist in a broadband E field measurement at three different heights (1.10 m, 1.50 m, 1.70 m), the level of exposure expressed in V/m is the root mean square (RMS) of the E field measured at the three levels during six minutes. The position of the probe is mainly based on a hot spot search, the technician does few measurements to evaluate where can be the position where the exposure is maximum. The knowledge of the transmitters in close proximity to the facilities help to better choose this position. The second part called ‘case B’ consist in a frequency selective E field measurement at the same position of case A. The results of the measurement give an overview of the contributions of the different technologies using any bands between 100 kHz and 6 GHz.

In parallel to the time analysis of the monitoring probe results, it would be interesting to check if a space analysis can be done based on the correlation of the knowledge of the base stations around a position of in situ measurement carried out by ANFR. As a starting point, a simple study can be done.
For each measurement, an extraction of the base stations close to the point of measurement is done thanks to ANFR database. An assessment of the level of exposure is done using simple following expression of the electric field:

$$E_{assessed} = \frac{\sqrt{30 * EIRP}}{d} \quad (3)$$

With d the distance between the base station and the position of measurement. The accuracy of base stations positions is 30 m. Therefore, the field level assessed from the location of the base stations can be gathered per cellphone bands used in France (700 MHz, 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz, 3500 MHz). The field assessed per band can then be compared to the field level measured during case B measurement.

4 Data analysis

4.1 Autonomous probe variability analysis

Figure 2 displays the Cumulative Distribution Function (CDF) of 152 monitoring probes. This figure shows the extend of measured values by monitoring probes. It shows that for a large amount of monitoring probes, the measured values are below 1 V/m. These plots show also that the number of measurements is very high and advanced techniques need to be used in order to tackle the variability between probes.

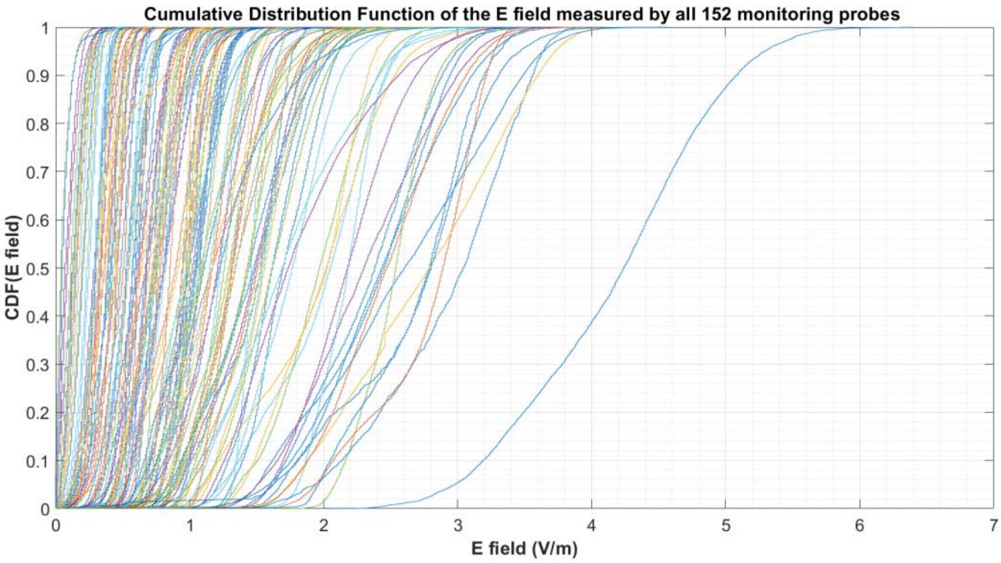

Figure 2: Cumulative Distribution Functions of E field measured by all probes

Raw data of measured E field by probe are too difficult to analyze, then, a selection of few probes is necessary. As a starting point, the RMS of E field of each probe has been calculated, and we selected three probes with the highest rms value and three probes with the lowest rms value.

Figure 3 shows the RMS value of the E field per month from installation of the probe until January 2023, except for probe Martignas-sur-Jalle which measurement has stopped in June 2022 for maintenance. A first look at figure 3 shows that, as expected, three highest probes are in a different scale of variation than three lowest probes. It displays also the evolution of the level exposure, based on the shape of probe Le Haillan and Nantes_01, we can conclude that the increase of the level exposure is very slow. This interpretation agrees with the observations made by ANFR during the past years. The plots of figure 3 reveals that a slight decrease of the level of exposure can be perceived on some probes during summer vacation time (July and August). It would be interesting to see if this phenomenon can be generalized to all probes.

A deeper analysis can be made, based on a different time scale analysis. Indeed, since measurement are made day and night, a remaining question is how is the level of exposure evolving between day and night. Figure 4 presents histogram of the 6 probes selected with an empirical timing separation: day is between 8 AM and 11 PM and night is between 11 PM and 8 AM. This plot shows that for three lowest probes, there are no difference between day and night, but for three highest probes the differences are remarkable. It reveals that the level of exposure is lower during night time, it is due to people’s usage of cellular network.

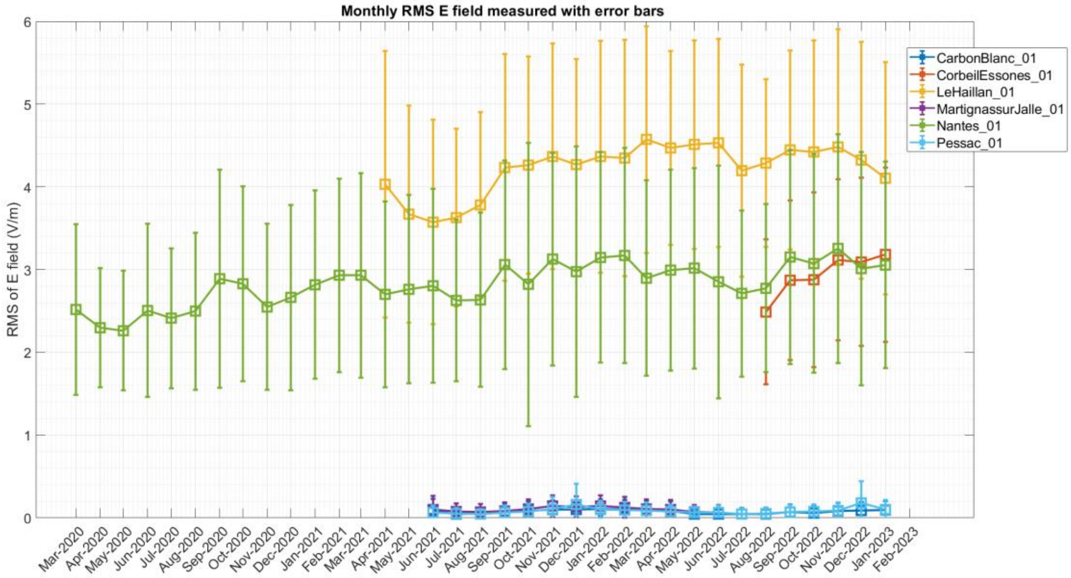

*Figure 3: RMS of E field monthly calculated with error bars equal to +/-2*standard-deviation for selected probes*

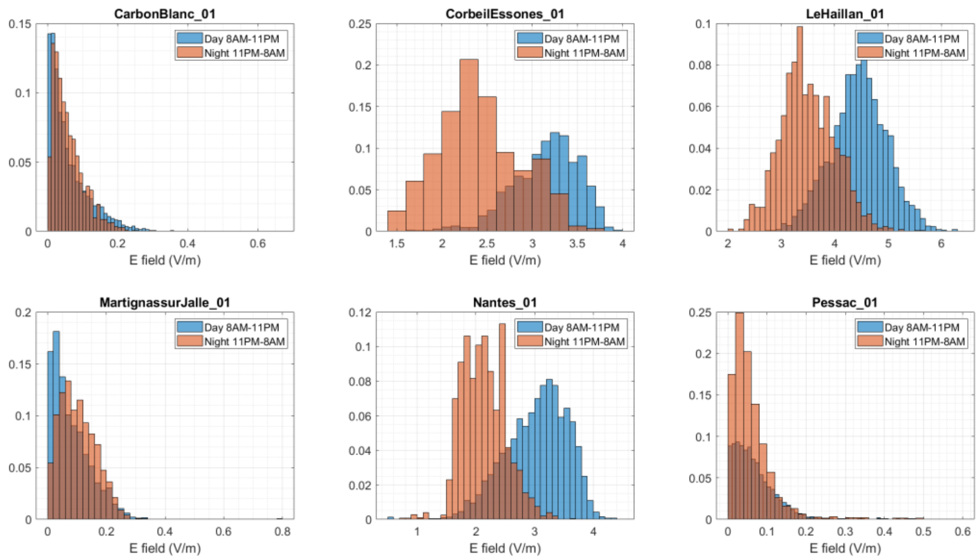

Figure 4: Day and Night histogram of selected probe (Day 8AM-11PM and Night 11PM-8AM)

The quantity of measurement and the coverage of many different cities (urban and sub-urban) enable to carry another type of analysis. Figure 5 displays the variation coefficient, also called relative standard deviation by extracting only the measurements done during working days and hours (Monday to Friday from 8 AM to 5 PM). Figure 5 shows that the variation coefficient is less than 30% for 86 % of the probes. For the 21 probes with variation coefficient which are higher than 30 %, most of the probes measure very low level of exposure or had some great variation due to repairs. It confirms the identified uncertainty of 30% due to daily variation communicated while doing measurement by ANFR at people accommodation.

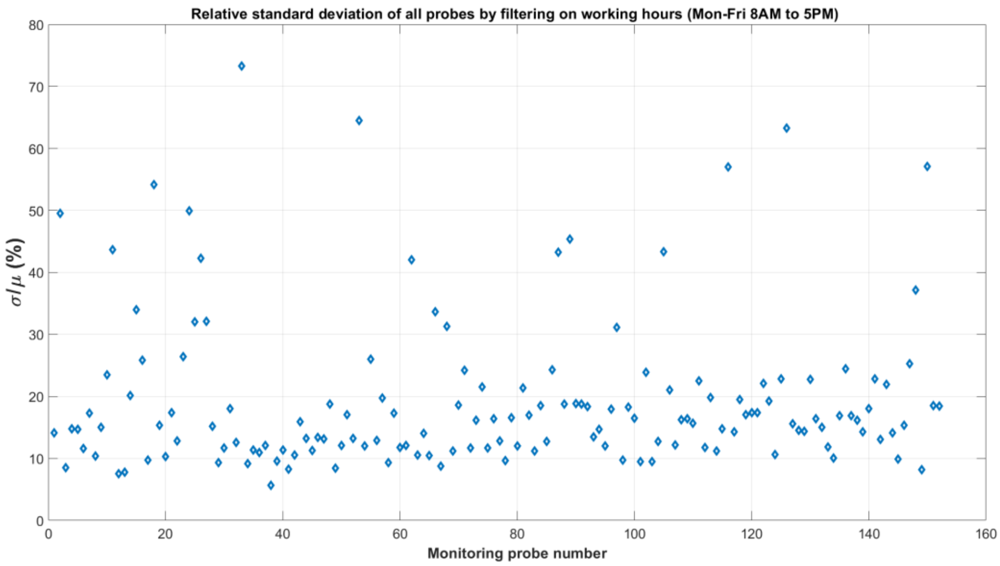

Figure 5: Relative standard deviation of all probes by filtering on the working hours (Monday to Friday from 8 AM to 5 PM)

4.2 PCA's results

Principal Component Analysis has been made on two set of measurement, the first set is the monthly averaged squared E field over the year 2022, the second set of measurement is the daily averaged squared E field over the month of December 2022. As explained in 3.1, the dataset needs to be standardized so it is preferable in our case to use the squared E field. First set of measurement will enable to make interpretation on the variation during a year. Second set of measurement will enable to make interpretation on the variation during a typical week of December 2022. The first set of measurement is composed by 110 probes and the second set is composed by 140 probes.

Figure 6 shows the monthly averaged squared E field represented in the two main principal components coordinates. The probes are represented with different markers for different French department. The first principal component is the direction of the data along which the observations vary the most (98%). The second principal component is the direction of the data along which the observations show the next highest amount of variation (0.6%). The probes separate into mainly two groups, the probes getting low values on 1st component and are all concentrated along the first component and the probes getting higher values on 1st component which are more spread out in the domain formed by the two components. In order to know what are the dissimilarities characterized by the 1st and 2nd component, the probes that bound the domain defined by principal components are selected.

The first component separates probe Le Haillan and probe Carbon blanc, the first component shows the differences between the magnitude of the E field. Figure 7 represents monthly averaged squared E field minus yearly averaged squared E field for extremum probes selected based on PCA. The subtraction has been made in order to facilitate the analysis. The comparison of north extremum (probe Marseille 03) with south extremum (probe Rennes 04) shows that the 2nd component of PCA characterizes the periodicity of level of exposure. Indeed, Marseille 03 has higher level of exposure in summer than in winter and Rennes 04 shape is opposite to Marseille 03. In conclusion, the two components separate high and low level of exposure and also separate probes which has higher levels in summer compared to winter. Figure 8 is the correlation circle for the original variable first dataset represented in the domain of two components found by PCA. The correlation circle confirms the previous interpretation, probes with high values on 2nd component are the ones with highest levels on summer compared to winter and probes with low values on 2nd component are the ones with lowest levels on winter compared to summer.

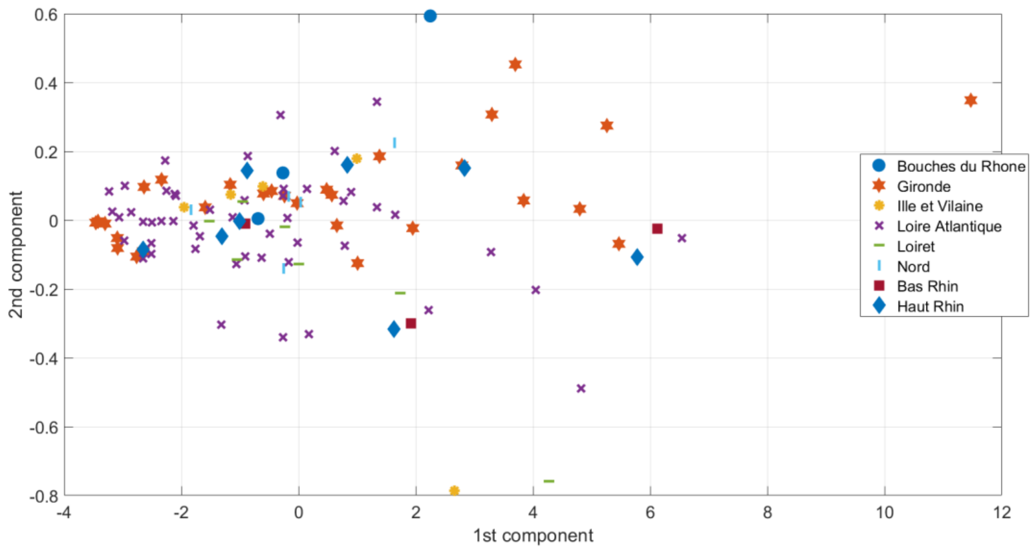

Figure 6: Monthly averaged squared E field (V/m)² over a year projected on two main principal components

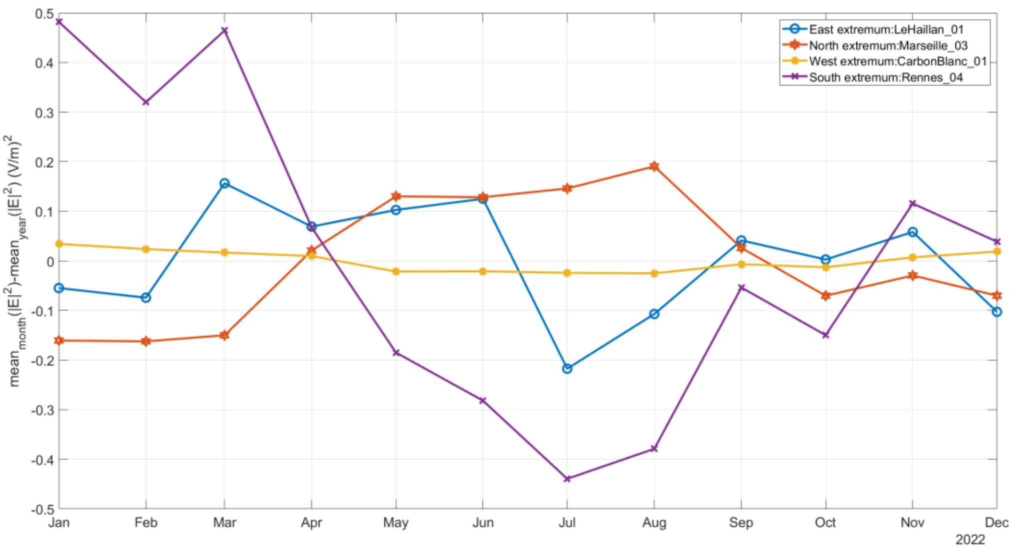

Figure 7: Monthly averaged squared E field minus yearly averaged squared E field for extremum probes (V/m)² selected based on PCA

Figure 9 shows the weekly averaged squared E field over the month of December 2022 projected on two main principal components. The first component separates again probe Le Haillan and probe Carbon blanc, the first component shows the differences between probe regarding the magnitude of the level of exposure. The second component separates the two extremum probes Corbeil-Essonnes and Paris2Connect 03. Figure 10 enables to show that the 2nd principal component separates probes where highest level of exposure are measured during the weekend to probes where highest level of exposure are measured from Monday to Friday. Figure 11 confirms this interpretation; correlation circle presents the original variables projected into the two principal components. It shows that the probes with high values on the second component are the ones which have measured higher level of exposure during the weekend.

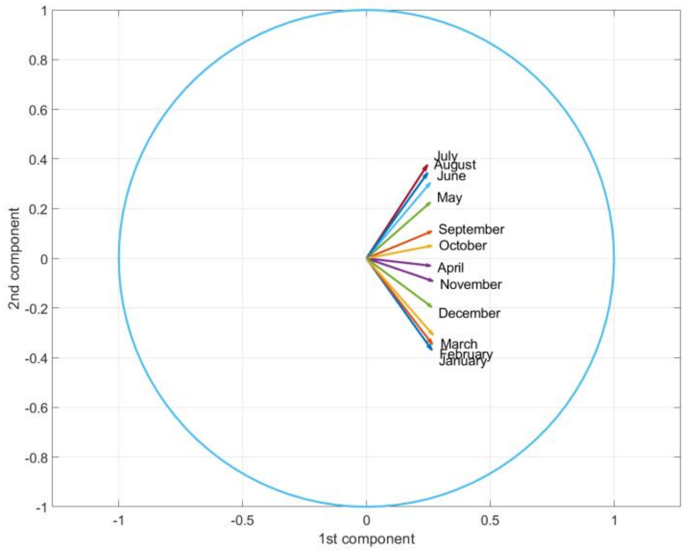

Figure 8: Correlation circle of the monthly averaged squared E field

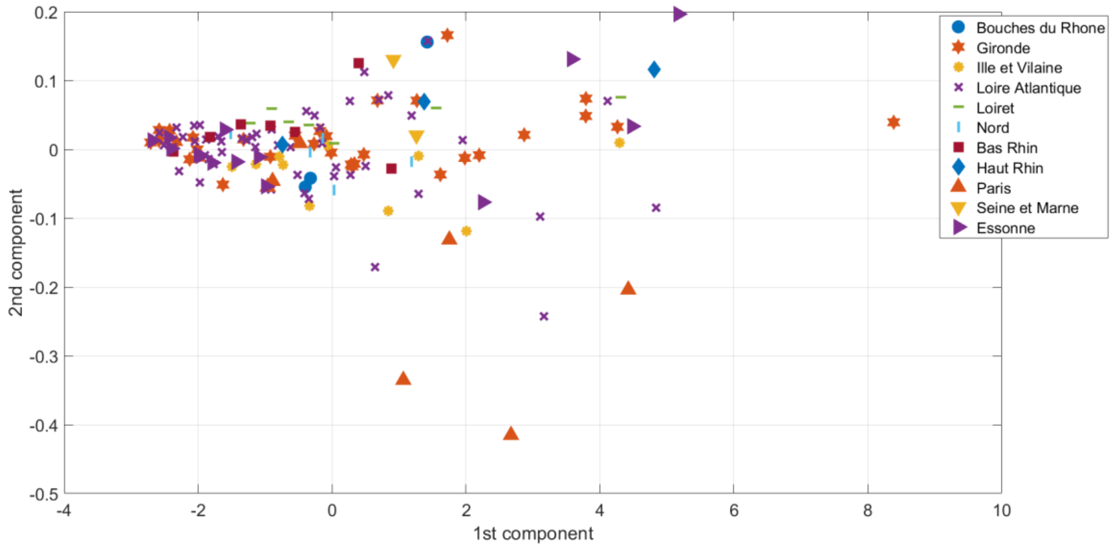

Figure 9: Daily averaged squared E field (V/m)² over the month of December 2022 projected on two main principal components

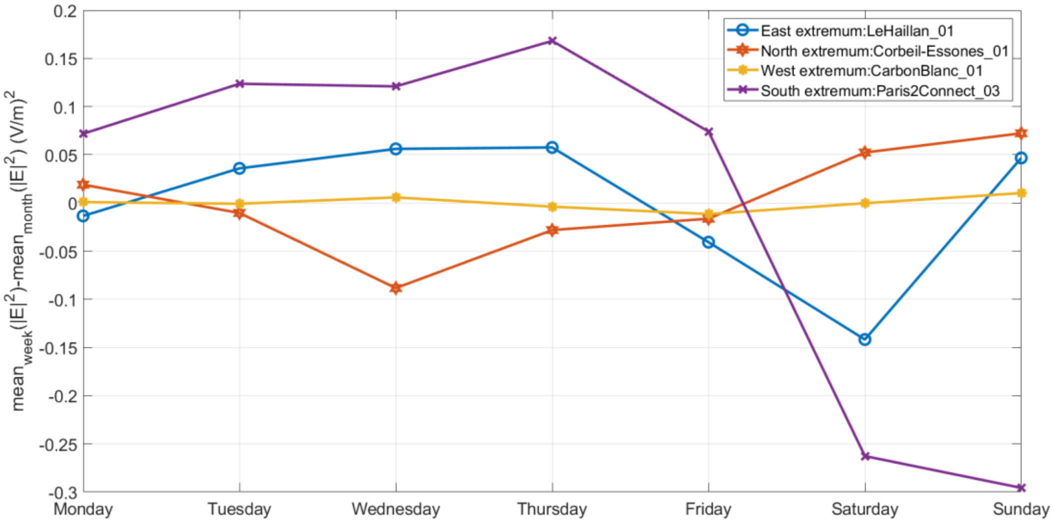

Figure 10: Weekly averaged squared E field minus monthly averaged squared E field for extremum probes (V/m)² selected based on PCA

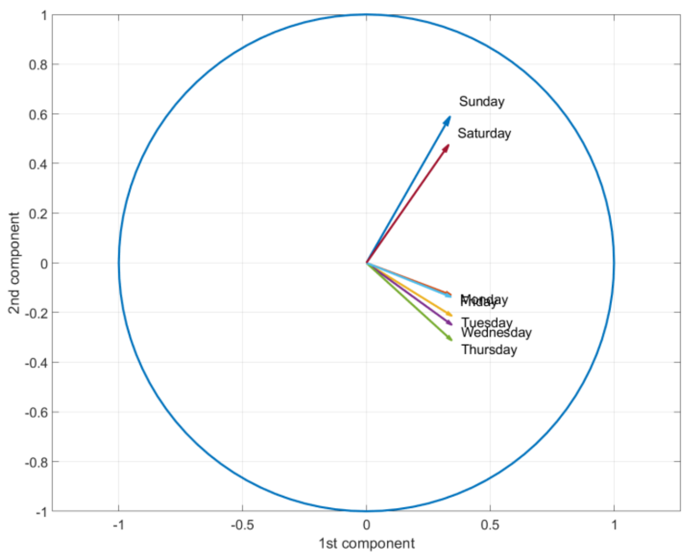

Figure 11: Correlation circle of the weekly averaged E field

The time domain analysis of monitoring probes showed the variation in amplitude of level of exposure, in terms of deviation between day and night. We also highlighted the different behavior that exists between probes which present different upper season (summer or winter) in terms of exposure. The same approach on the days of the week analysis revealed that different behavior exists between week days and weekend.

4.3 Relationship between in situ Measurement and close radio environment

In parallel to the time domain analysis, a space domain analysis has been made. The dataset used in this analysis is composed by in situ measurement carried out in 13 departments where probes were installed. As a starting point, we used two main filters to facilitate the analysis:

- Selection of measurements with broadband E field measurement (case A) higher than 1 V/m,
- Selection of measurement which major part come from cellular network (based on case B).

The choice of the threshold of 1 V/m come from the fact that we want to know if the absolute deviation ΔE_i is within +/-1 V/m. The absolute deviation is defined by

$$\Delta E_i = E_i^{measured} - E_i^{assessed} \quad (4)$$

With i=700 MHz, 800 MHz, 900 MHz, 1800 MHz, 2100 MHz, 2600 MHz or 3500 MHz.
These filters lead to an amount of 2078 measurements done in the 13 French departments. This dataset of hundred measurement has been carried out near monitoring probes. For every measurement point we extracted the antennas inside a circle with 500 m radius around measurement position. The ANFR database provides also the azimuthal direction each antenna. For every measurement, we excluded the antennas that are not pointing their beam towards measurement position. Prior to do the assessment for all bands and at all the measurements positions, we used reduction factor of the EIRP. Indeed, in the national guidelines written by ANFR to present the exposure simulation to base stations, a reduction factor of 4 dB is used for antennas with fixed beam and a reduction factor of 14.75 dB is used for beamforming antennas [11]. In our case, we tuned the reduction factors empirically in order to get the absolute deviation closest to zero. The reduction factors used in our studies are 15 dB for all bands except 3500 MHz and 30 dB for 3500 MHz. Figure 12 presents the histogram of absolute deviation between assessed and measured E field for each field, and same distributions have been plotted in box chart appearance. This figure enables to check that distributions are close to zero deviation and have different standard deviation. Table 2 shows the statistical parameters of the absolute deviation for each frequency band. Logically, the results show that a correlation exists between neighboring base stations and level of exposure per band. Table 2 shows that for all bands, for more than 83% of measurement, the simple assessment of E field is within +/- 1 V/m to the measurement of the E field.

	ΔE RMS	ΔE Standard Deviation	ΔE Median	Percentage of ΔE ∈ [-1 V/m, +1 V/m]
700 MHz Band	0.61	0.60	-0.01	91%
800 MHz Band	0.85	0.77	-0.28	86%
900 MHz Band	0.81	0.73	-0.25	87%
1800 MHz Band	0.80	0.80	0	83%
2100 MHz Band	0.77	0.74	0.16	87%
2600 MHz Band	0.69	0.69	0.03	89%
3500 MHz Band	0.34	0.33	0	98%

Table 2: Statistical parameters of ΔE per bands

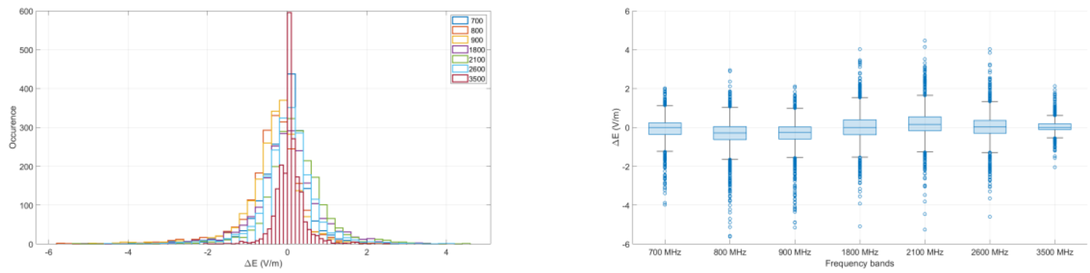

Figure 12: Histogram of ΔE (V/m) per bands and Boxchart of ΔE (V/m) per bands

5 Conclusion and perspectives

This study shares a totally new approach of monitoring of the exposure to electromagnetic field due to radio base stations. It shows that 152 monitoring probes installed by ANFR, Chaire C2M of Télécom Paris, city councils or conurbation authorities enable to explore the time domain aspect of exposure. The analysis has shown that the 152 monitoring probes have very different magnitude of level of exposure. It has been presented that for probes measuring remarkable levels, there is a difference of level of exposure between day and night. The phenomenon was expected but presented for the first time for France. During the analysis we discover that some probes measure a lower level of exposure in summer time. This interpretation has been confirmed with principal component analysis where it has been shown that the second component of PCA characterizes the difference between probes with higher level of exposure during summer or winter. PCA applied on the average week data of December 2022 enables also to conclude on the fact that the second component of PCA shows the difference between probes having higher level of exposure during working days or during the weekend.

Regarding the space domain analysis, the study showed that it is statistically right to consider that closest base stations are responsible for the level of exposure. It has been shown that it is even possible to assess very simply the E field and that for the great majority of the cases the absolute deviation is included into +/- 1 V/m.
In future works, it will be interesting to improve the Principal Component Analysis by focusing on probe measuring more remarkable levels to check if principal components can reveal another phenomenon. It will be also interesting to explore other time scale by increasing the number of variables. Regarding space domain analysis, it will be interesting to use other information provided in ANFR database (indoor/outdoor, generalization all over the country).

6 Acknowledgement

Cross analysis and conclusion will be shared by ANFR and Chaire C2M with other European laboratories within SEAwave project funded by the Horizon Europe Research and Innovation program [8]. Further investigation, will be done within SEAwave project. We deeply thank the students of ISEP school who have participated to the ANFR's Hackathon (FrHack! November 19th and 20th) and provide many good ideas regarding postprocessing techniques of monitoring signals. We greatly acknowledge EXEM company (ANFR's subcontractor) for in situ measurements, monitoring probes installation and to share all the probes results with ANFR.

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