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LONG TERM VARIATIONS MEASUREMENT OF ELECTROMAGNETIC FIELD EXPOSURES IN ALCALÁ DE HENARES (SPAIN).

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ABSTRACT

Electromagnetic radiowave exposure is a major concern in most countries due to possible adverse health effects. Over the last 10 years, many technological changes (digital television, mobile technologies, wireless networks…) have led to variations in the electromagnetic field (EMF) levels.

A large number of studies devoted to the analysis of EMF levels with personal dosimeters or computer models of the exposure of mobile stations have been conducted. However, the study of the exposure values, taking into account all the existing sources, and their evolution in a wide area, using measurements, has rarely been performed.

In this paper, we provide a comparison of the EMF exposure levels for the city of Alcalá de Henares (Spain) over a ten-year period using a broadband isotropic probe in the range from 100 kHz to 3 GHz. A statistical and spatial analysis of the measurements and their variations are also presented for the study of the global and local variations.

The measured values in the period from 2006 to 2015 were ranging from 0.02 to 2.05 V/m. Our global results show a moderate increase from 2006 to 2010 and they are almost invariant from 2010 to 2015. Although the whole dataset does not have relevant statistical difference, we have found marked local differences. In the city areas where the population density has remained unaltered, we have measured lower exposure levels. Conversely, new urban and industrial developments have demanded new resources which have potentially contributed to the observed increase in the measured electric field levels within these areas.

Keywords: Electromagnetic pollution, Radiofrequencies, Spatial Analysis, Trends

1. INTRODUCTION

Electromagnetic radiowave exposure is a major concern in most countries due to possible adverse health effects. For instance, in May 2011 the International Agency for Research on Cancer (IARC) (IARC, 2014), classified radio frequency EMF as possibly carcinogenic to humans (group 2B). This assumption was based on an increased risk of glioma, a malignant type of brain cancer associate with wireless phone use.

Over the last 10 years, many technological changes have led to variations in the electromagnetic field levels to which the public are exposed. In Spain, from 2005 to 2010, digital television was gradually introduced and finally analogue television was switched off (BOE, 2014). In 2004, mobile UMTS (Universal Mobile Telecommunications System) technology was introduced and, in 2013, LTE (Long Term Evolution) technology for mobile phones was released (CNMC, 2015). Also in this period, the use of wireless technologies has been increased and the number of wideband lines with Wi-Fi devices at home has been doubled (CNMC, 2015). Therefore, it is an objective of this work was to determine whether the general public exposure to radio frequency electromagnetic radiation follows the current trend of the increasing use of the radio spectrum or, to the contrary, that values have remained constant or have reduced through the adoption of newer digital communications standards.

In this period, a large number of studies devoted to the analysis of electromagnetic field level with personal dosimeters and a variable number of volunteers have been conducted (Beekhuizen et al., 2013; Danker-Hopfe et al., 2016; Frei et al., 2009; Joseph et al., 2010; Sagar et al., 2016; Urbinello et al., 2014b; Vermeeren et al., 2013; Viel et al., 2011). Additionally, models of the exposure of mobile stations have been created using maps and computer tools (Bechet et al., 2015; Bolte and Eikelboom, 2012; Calvente et al., 2015; Guxens et al., 2016; Urbinello et al., 2014c). The short term exposure variations have also been studied (Bolte and Eikelboom, 2012). In some of these studies, measurements were performed in different micro-environments such as offices or outdoor urban areas in order to characterize typical exposure levels in these places (micro-environmental studies). Other studies consist of population surveys where the personal exposure distribution in the population of interest was determined. Some of them finally concluded that site measurements cannot be used to accurately determine personal exposure (Thuróczy et al., 2008). Furthermore, some studies analyse different frequency bands but have concentrated on those related to mobile phone base stations emissions (Vrijheid et al., 2009), (Martens et al., 2015).

Epidemiological studies about the effects of base stations emissions have revealed some problems, especially when the actual exposure values have to be considered (Belpomme, D., Irigaray, P., & Hardell, 2008; Röösli, 2008). Röösli (Röösli, 2008) states “one major challenge in observational research is long term RF-EMF exposure assessment”. Also Röösli et al (Röösli et al., 2010) declares “some studies have focussed mainly on maximum exposure levels occurring over space and/or time, as appropriate for assessing compliance with safety limits, but not on exposure patterns in the general population”. The Norwegian Institute of Public Health does not recommend carrying on individual measurements because they are difficult to interpret and communicate (Norwegian Institute of Public Health, 2012). The ANSES - French Agency for Food, Environmental and Occupational Health & Safety recommends a better characterization of the real population exposure (measurement protocols, individual dosimeter, surveillance programs…) especially for children (ANSES, 2013). It is assumed that the main exposure for the general public comes from the use of mobile phones as exposure to the RF fields emitted by mobile phones is generally more than a 1000 times higher than from base stations and the likelihood is greater of any adverse effect being due handsets (ITU, 2012). However, IARC Word Cancer Report 2014, in terms of mobile phones and cancer and environmental exposures from transmitters declares "with regard to environmental exposures from transmitters, including television, radio and military transmissions as well as mobile phone networks, the evidence is inadequate due to lack of high quality studies with accurate individual exposure assessment" (Stewart et al., 2014).

The exposure from other sources such as Wi-Fi systems, microwave links, radio or TV is considered much lower than mobile phones. For instance, wireless systems typically emit ten times less peak power than mobile phones (0.1 – 0.2 W). Mobile phones use low power transmitters that are less than 2 W peak. But, the typical output power of a mobile phone ranges from 0.01 to 0.1 W, which takes into account the operation of adaptive power control (ITU, 2012). At the same time, the improvements in transmission networks and the deployment of Universal Mobile Telecommunications System (UMTS) technology have led to a significant reduction in the exposition of the population compared to older Global System for Mobile Communications (GSM) mobile phones (HPA, 2012). Furthermore, the overall increase of the use of these systems implies a potentially higher exposure level. In conclusion, it is not generally recommended to neglect a priori the contributions from other RF sources than mobile phone base stations and also and it is necessary to have a better knowledge of the real exposure values taking into account all the existing sources.

Usually, local regulations follow the guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (ICNIRP, 1998). For this research, National and International Regulations have been taken into account. These recommendations show the exposure limits for the general public. In the Spanish case, these guidelines are incorporated in two different laws: Real Decreto 1066/2001 (BOE, 2001) and Orden CTE/23/2002 (BOE, 2002). Moreover, there are several international organizations involved in this field. IEC Technical Committee 106 (IEC, 2016) is responsible for preparing international standards on measurements and calculation methods to assess human exposure to electric, magnetic and electromagnetic fields. As mentioned before, ICNIRP (ICNIRP, 1998) gives recommendations on limiting exposure for the frequencies in the different Non Ionizing Radiations subgroups. The IEC and ICNIRP have agreed on the sharing of responsibilities for EMF standards (IEC, 2016). EMF exposure limits are developed by ICNIRP and EMF exposures assessment standards developed by the IEC. The IEEE also prepares compliance assessment standards for EMF in the frequency range 3 kHz to 300 GHz (IEEE, 2002), (IEEE, 2006). The IEEE and IEC also have a formal sharing arrangement (IEC, 2016).

The International Telecommunications Union (ITU) has published several recommendations about measurements, protocols and technical standards related to EMF emissions and protection. Recommendation ITU-T K.61 (ITU, 2003) provides guidance on measurement methods that can be used to achieve a compliance assessment. Recommendation ITU-T K-83 (ITU, 2011) gives guidance on how to make long term measurements for the monitoring of EMF in the selected areas that are under public concern, in order to show that EMFs are under control and under the limits. Recommendation ITU-T K.100 (ITU, 2014) provides information on measurement techniques and procedures for assessing compliance with the general public EMFs exposure limits when a new Base Station is put into service. Recommendation ITU-T K.113 (ITU, 2015) provides guidance on how to make radio-frequency electromagnetic field (RF-EMF) maps for assessing existing exposure levels over large areas of cities or territories and for an appropriate public disclosure of the results, in a simple and understandable way.

This research faces the problem of the electromagnetic exposure from that point of view, namely that it is better to assess the cumulative exposure from all RF sources. We have characterized the electric field values and their evolution using wideband and time averaged measurements, instead of using personal dosimeters or simulation models. Using a broadband probe, we have measured the values of the Electric Field in a wide area (35 km2) over a ten year period, taking into account all the possible sources from 100 kHz to 3 GHz. A detailed description of the measurement equipment and protocol are given in section 2.

1.1 Influential factors over the period of study

Alcalá de Henares is a city located in the Autonomous Community of Madrid at about 35 kilometres northeast of the city of Madrid in Spain (40°28′N 3°22′W). The total municipal area is 87.7 km2 but the population is concentrated in a smaller one, with the city being organized into 5 districts. Although population movements in the city have occurred within the period considered by this study, the total number of habitants has remained consistent at around 200,000. Table 1 gives the official population data obtained for each district from the National Institute of Statistics (INE, 2016) and shows that there has not been any significant variations.

District	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
D. I	36.86	35.99	36.76	36.96	34.38	34.26	34.33	34.41	33.28	32.71
D. II	57.98	57.03	57.88	57.79	60.12	59.69	59.15	58.85	57.17	56.12
D. III	25.35	24.59	24.92	24.85	28.64	28.84	29.07	29.26	28.59	28.53
D. IV	32.34	31.49	32.08	32.03	31.02	31.26	32.04	33.43	34.08	34.61
D. V	48.85	49.62	52.00	52.94	49.96	49.64	49.34	48.91	47.64	46.77
Total	201.38	198.72	203.65	204.57	204.12	203.69	203.92	204.82	200.77	198.75

Table 1. Population in Alcalá de Henares in the period 2006-2015 (Thousands of habitants) (INE, 2016).

Official data about the use of spectrum or data traffic specifically related to the city of Alcalá de Henares is not available, although there are national and regional trends which have been publically documented. Obviously, there could be slight differences but, as Alcalá de Henares does not have any special condition about the use of the electromagnetic spectrum, it can be assumed without significant error that national and regional trends are very similar to local ones. The main telecommunication services in the city are TV broadcast, mobile telephony and wireless networks. In 2006, TV emissions were mainly analogue, mobile emissions were from GSM base stations and Wi-Fi sources were low. In 2010, digital television was settled and mobile UMTS was introduced. In 2015, UMTS coverage has been generalized, LTE systems have started to be rolled out and Wi-Fi networks are practically universal.

In 2006, there were 6 national, 2 regional and 1 local analogue channels. Since 2010 there are 7 national or regional TV broadcast transmission multiplex and one local, offering 40 channels of digital television. Therefore, the use of the spectrum in terms of the number of television channels is similar over the period of our study.

The number of mobile telephony base transceiver stations (BTS) in Spain has doubled in the period 2006-2014 to face the increasing voice and data requirements of a modern society, as shown in table 2. Specifically, in Alcalá de Henares, the number of BTS locations was 50 in 2006 and 69 in 2015. Some of those locations are shared by up to four different companies, and therefore the total number of deployed BTS has increased by over 80%, from 74 in 2006 to 134 in 2015 (MINETAD, 2016).

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
GSM900	24,998	26,850	27,869	28,255	31,582	34,817	38,121	40,918	42.408
DCS1800	20,178	21,290	22,780	23,285	21,639	21,242	21,761	20,949	19,978
UMTS	16,921	22,874	27,382	31,304	34,324	42,474	46,281	45,273	47,260
LTE	0	0	0	0	0	0	0	5,649	14,654
Total	62,097	71,014	78,031	82,844	87,545	98,533	106,163	112,789	124,300

Table 2. Number of mobile base stations in Spain. Source: National Institute of Statistics (INE, 2016).

According to table 3, the number of mobile lines (number of handsets in use) as well as the number of homes with mobile lines has been increased about 9 % in the period 2006-2014. The consumption of voice minutes has increased about 38 % in the same period. The main rise has been in data consumption. Although the official data does not cover the whole period, the number of wideband lines is almost three times higher from 2010 to 2014. Data demand has grown approximately 115 % in two years, and it is expected that this will be five times higher within the next five years.

	2006	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
Total Mobile lines in Spain x10^6.	45.68	48.42	49.62	51.05	51.40	52.59	50.67	50.16	50.81
Number of lines per 100 inhabitants	103.8	108.1	108.7	110.4	110.5	112.7	108.2	107.3	109.2
Billions (10^9) of Voice minutes in Spain	57.82	67.78	71.11	70.56	71.42	72.48	70.16	71.15	79.73
Wideband mobile lines in Spain (%)					23.7	37.1	52.9	67.0	78.3
Mobile data 10^3 TB							97.623	133.89	208.52

Table 3. Millions of mobile lines in Spain, Number of Mobile Lines per 100 inhabitants in Spain, Billions (10^9) of voice minutes in Spain, percentage of mobile wideband lines per 100 inhabitants and mobile data consumption. Source: National Institute of Statistics (INE, 2016)

Regarding to the use of Wireless technologies at home, table 4 shows the evolution of the percentage of homes with broadband connections. It can be assumed that every line is connected to at least, one Wi-Fi router. This assumption is based on the fact that the access to broadband services was given using copper lines (ADSL) and more recently using optical fibre. The supply companies usually provided customers with a Wi-Fi router at the moment of signing their contracts. It can be seen that the number of broadband lines and the percentage of homes with a broadband connection, has been doubled over the period of our study. Data traffic consumption within homes has risen about 80% over the period 2011-2014.

	2006	2007	2008	2009	2010	2011	2012	2013	2014
Broadband Lines $x10^6$	6.69	8.06	9.14	9.80	10.65	11.16	11.52	12.24	13.00
Homes (%)	15.2	18.0	20.0	21.2	229	23.9	24.6	26.2	28.0
Data 10^6 TB						3.51	3.85	4.91	6.53

Table 4. Number of broadband lines, percentage of homes with broadband connection and home data consumption. Source: National Institute of Statistics (INE, 2016).

In summary, the data shows a greater use of the radio electric spectrum (table 2) for television and especially for mobile phones and wireless technologies for the period under study. At the same time, significant technological changes have been introduced and widely adopted such as Wi-Fi, UMTS or LTE (table 3 and Table 4). Therefore, it is interesting to show if the actual electromagnetic exposure level has followed the trends of the consumption or, to the contrary, the technological evolution has helped to maintain the observed levels of electromagnetic fields within the 100 kHz to 3 GHz frequency range. Although it is generally assumed that exposure levels for the population have been increased, to the authors' knowledge, no long-term study with real measurements for the same location has been reported. Therefore, this research introduces the comparison of exposure levels in a ten-year period, taking into account the technological evolution of the main services.

The rest of the paper is organized as follows. In section 2, the equipment, methodology and the selection of the measurement points are described and compared to international recommendations. In section 3, the measured values and their evolution for the period 2006-2015 are analysed from a statistical, spatial and temporal points of view. The discussion of the results is given in section 4. Finally, the main conclusions of the research are drawn in section 5.

2. MATERIALS AND METHODOLOGY

2.1 Measurement equipment and procedure

In terms of the strategies and methodologies to monitor RF-EMF exposure, two types of measurement procedures have been used, fixed-location and mobile (personal) monitoring. Fixed-location measurements with a spectrum analyser (narrowband) are very accurate for determination of exposure at a specific point in time and space, but they are time and resource intensive in terms of equipment, costs and trained personnel. Portable exposure meters (PEMs) allow collecting numerous measurements with relative little effort at different locations but precise exposure estimates for a large number of individuals are far beyond what is usually realistic. Furthermore, this approach is very expensive and time-consuming for large studies, and long term measurements. Thus, there is a need for validated exposure assessment methods that do not require individual measurements or very expensive and time-consuming measurements (Viel et al., 2011), (Urbinello et al., 2014a). Broadband measurement is the optimal solution for a large number of measurements in a wide area involving various sources (from various locations) or a single source with various frequencies, because it is not as expensive as narrowband measurement and gives a value of the total electric field in that specific point. Considering this general case, it can be easily proved mathematically that if the value measured by the equipment does not exceed the most restrictive exposure limit in the frequency band to be measured, then the contributions at different frequencies will also be below the said limit, since the total value is calculated as the square root of the addition of the square value of each individual contribution (ITU, 2011). We have also chosen a broadband isotropic probe as measurement device. The broadband isotropic probe provides an independent measurement of frequency, which integrates all of the emissions in a desired frequency band and from every possible location.

Two methods are recommended for assessing compliance with the general public EMFs exposure frequency: selective measurements (narrowband) or non-selective measurements (broadband). The frequency selective measurement is based on EN50413 and IEC 62311. The broadband measuring is based on EN 50413 and IEC 62311 (ITU, 2011). It allows obtaining the total radiation level in the form of electric field strength in the frequency band of interest, averaged over a certain period of time.

This type of measurement equipment are stated in ITU recommendations, and require: a minimum detection level of 1 V/m, a dynamic range > 40 dB, linearity of 1.5 dB, probe isotropy < 2.5 dB (ITU, 2014), a minimum rms measurement range 0.3-20 V/m; and a sensitivity 0.3 V/m (ITU, 2015). In our work, a Narda EMR-300 Broadband RF Survey Meter and a Narda Isotropic Probe 18C were used for electric field intensity and power density to cover 100 kHz to 3 GHz range with 0.01 V/m resolution, detection level of 0.2 V/m, a dynamic range of 60 dB, linearity ±0.5 dB , isotropic deviation ±1.0 dB, an rms measurement range of 0.2 to 320 V/m, a sensitivity 0.2 V/m. These were supported on a non-metallic Tripod EMCO 11689C. A Garmin 72 GPS receiver was used to accurately determine the location of the measurement site.

Measurements have been performed in the range of 100 kHz to 3 GHz. This includes all the usual broadcast and mobile services: FM (88-108 MHz), DAB (174-223), TETRA (380-400), DVB-T/TV (470-830), GSM900 (UL 880-915 DL 925-960), GSM1800 (UL 1710-1785 DL 1805-1880) DECT (1880-1900) UMTS (UL 1920-1980 DL 2110-2170) LTE800 (DL 791-821 UL 832-862), LTE 1800 (DL 1805-1880 UL 1710-1785) LTE2600 (DL 2620-2690 UL 2500-2570) and WIFI 2G (2400-2500). For continuity of comparison, recent implementation of the 5 GHz band is not considered.

Figure 1 shows the position of these services in the frequency spectrum (for clarity mobile bands are marked as M1 and M2), the probe frequency range and the limits for general public in terms of frequency according to (ICNIRP) (ICNIRP, 1998) and Spanish Regulations (BOE, 2001), (BOE, 2002). The parameter that determines the compliance, or non-compliance, is the level of cumulative exposure which can be measured with a broadband meter. As can be seen in the figure, the most restrictive value is 28 V/m in the range of 10 to 400 MHz. So, if the cumulative measured level is lower than 28 V/m in the measured range (100 kHz to 3 GHz), the compliance of the site is verified.

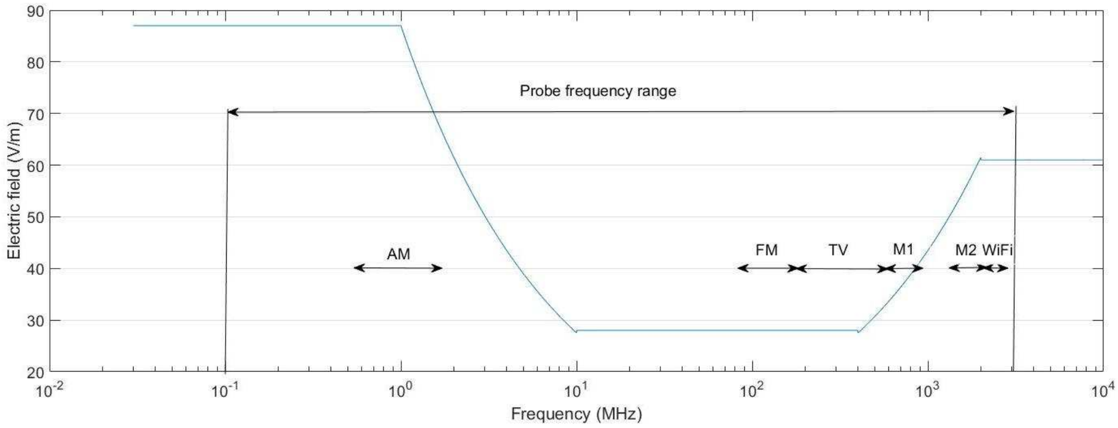


Figure 1. Probe measurement range, main services in the city of Alcalá de Henares and ICNIRP limits for general public exposure.

In principle, the emitted power from radio and TV transmitters do not vary considerably over time. In contrast, the radiated power of a BTS does vary with time. For mobile communications systems using adaptive power control, the BTS power level is not constant in time; the emitted power varies with time depending on factors such as traffic variation and dynamic power control (ITU, 2014)**,** (Bürgi et al., 2014). To take this into account, limits are usually expressed as RMS values of a continuous wave averaged over a defined period. For example, ICNIRP limits are to be averaged over any 6-minute period below 10 GHz and over a 68/f 1.05-minute period for frequencies exceeding 10 GHz and it should be continuous, in order to avoid losing data (ITU, 2003), (ITU, 2011). In our case, the instantaneous measured values were automatically averaged during 6 minutes using the root- mean-square mode of the device.

The EMF strength varies with spatial position due to the effect of reflection and scattering from nearby structures. Multi-path reflections can create non-uniform field distributions, creating a highly complex problem for RF-EMF exposure modelling. The measurement point should be chosen so that it represents the highest level of exposure that a person may be subjected to. This maximum may be determined empirically with suitable field measuring equipment. To avoid coupling with the probe, measurement should not be conducted in the close vicinity of metallic objects (Beekhuizen et al., 2013), (ITU, 2003), (ITU, 2011). In our case, the measurements were carried out at outdoor locations that were accessible to the general public, at ground level on the pavement, in an open area. Each measured point was assessed at different heights between 1.1 and 1.7 m and the largest value reported has been used for comparison with the exposure limit (ITU, 2014). When no significant variations were noticed, the device was held at a height of 1.5 m, as recommended in ITU-T K.61 (ITU, 2003) and in (Aerts et al., 2013b).

2.2 Statistical and graphical tools

A statistical analysis of the data has been performed (using Statgraphics Centurion (Statpoint Technologies, 2009)) to study the evolution of the measurements. In order to present the measured data in an easily comprehensible to understand way, we have created heat maps of the RF-EMF exposure by means of a GIS. ITU-T K.113 describes three possible methods (or a suitable combination of them) to generate RF-EMF maps: Drive test measurements, Theoretical calculations and Grid method (ITU, 2015). The drive test method consists of continuously collecting metrics from a moving vehicle. RF-EMF maps can be constructed by theoretical calculations and a further test in a representative sample of locations should demonstrate that calculated values are representative of actual measured levels. Grid method consists of a selection of the spots located at the vertices of a grid on a map of the city. Regardless of the method, if there is discrepancy between results, data obtained through averaged measurements over six minutes (either with broadband or frequency selective equipment) are to prevail.

If the map is created using a model that computes the field strengths of different frequency bands, corresponding to different exposure sources, detailed information about the transmitters, the three dimensional environment, and powerful radio wave propagation algorithms would be needed to estimate RF-EMF exposure in indoor or outdoor locations (Beekhuizen et al., 2013), (Beekhuizen et al., 2014). To develop a map from a reduced set of hotspots, as in our research, it is necessary to select the appropriate interpolation technique (Aerts et al., 2013b). Different spatial interpolation methods have been applied (Naoum S. and Tsanis I.K., 2004) such as spline interpolation, Inverse Distance Weighting (IDW) and kriging methods.

The use of kriging as interpolation technique has some distinct advantages. It takes into account the spatial structure of the interpolated variable (here, the electric-field strength), determines the best estimator of the variable (the error is minimized at all points), and it gives us information about the accuracy of the interpolation, by calculating an error. The kriging variance can also be used to quantify the model uncertainty, and to assist the sample search strategy in identifying potentially interesting regions in the study area based on a given condition (Aerts et al., 2013a), (Aerts et al., 2013b).

The measured data has been plotted on the city map using ArcGIS (ESRI, 2016). ArcGIS uses a geostatistical interpolation method that automates the most difficult aspects of building a valid kriging model. The main advantage is that this method automatically calculates the parameters to receive accurate results through a process of subsetting and simulations. This software allows using IDW, splines and different kinds of kriging using several types of variogram adjustment (spherical, circular, stable, Gaussian...).

3. RESULTS

3.1 Selection of measurement locations

For the selection of the measurement sample points, a variety of the different outdoor urban environments of Alcalá de Henares has been considered. These were urban areas with different kind of flats, residential areas with small houses, and commercial and industrial areas. The location of mobile phone base stations in 2006 (shown as blue triangles in figure 2) has been taken into account in the selection of the measurement points. The locations of the mobile base stations in 2015 are also given (shown as green squares in figure 2). The number of BTS locations was 50 in 2006 and 69 in 2015. Some of those locations are shared by up to four different companies, and therefore the number of BTS stations was 74 in 2006 and 134 in 2015 (MINETAD, 2016). Official data from City Council and Spanish Government about their locations have been considered. The measurement points were obviously chosen in 2006 and, although the city has new developments, for a better comparison, the locations have been kept the same in 2010 and 2015. All measurements were performed between October and December, during the morning, from 10:00 to 14:00.

Figure 2 also shows the location of the 78 measurement points on the city map (red dots). The area covered is 35 km^2. The density of the measurement points is 2.2 points per square km.

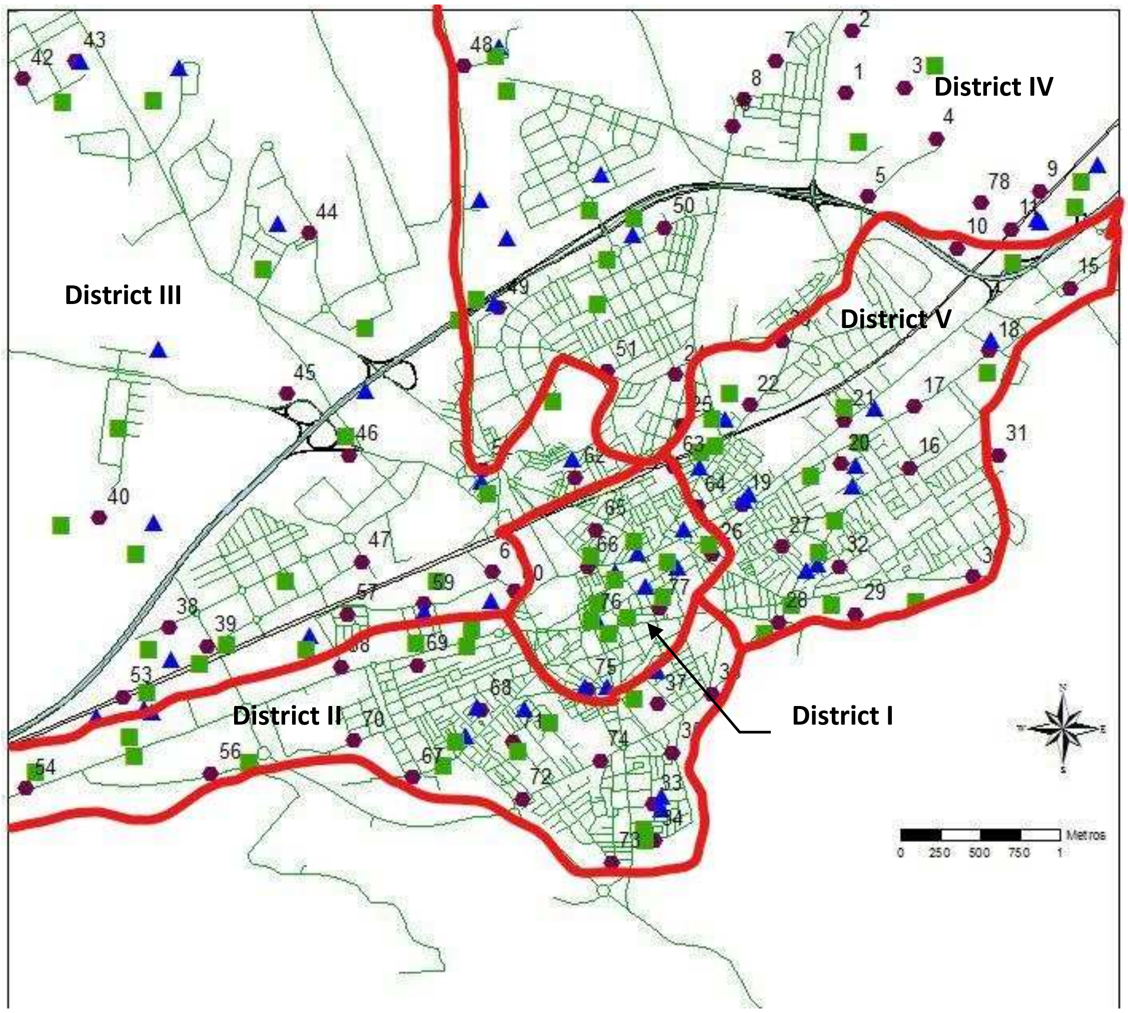


Figure 2. Location of the base stations in 2006 (triangle), in 2015 (square), measurement points (circle) and district limits (red lines).

3.2 General trends and variations

As described in the previous section, measurements were performed at 78 locations covering all the populated areas of Alcalá de Henares. This includes residential, commercial, industrial and educational parts of the city. A statistical analysis of the data has been performed to study the evolution of the measurements. Different types of distributions have been tested and the results show that data fits to a lognormal distribution in all cases.

The distribution of the measurement values for 2006, 2010 and 2015 is shown in figure 3. The data are fitted to a lognormal distribution. The p-value of the distribution fitting in 2006 is 0.735. As it is much bigger than 0.05, the data fit to a lognormal distribution with a confidence greater than 95%. In 2010 and 2015, the data fits to a lognormal distribution with the p-value of the distribution fitting being 0.423 and 0.407 respectively and also the confidence is greater than 95%. The very adequate fitting to a probability distribution gives a powerful tool to evaluate such wide areas. We have performed our study in a 35 square kilometre area and obviously, it is unmanageable to measure every part of the city. The statistical approach gives a tool to manage this situation as it allows to calculate the probability of finding a measured value greater than the permitted limit.

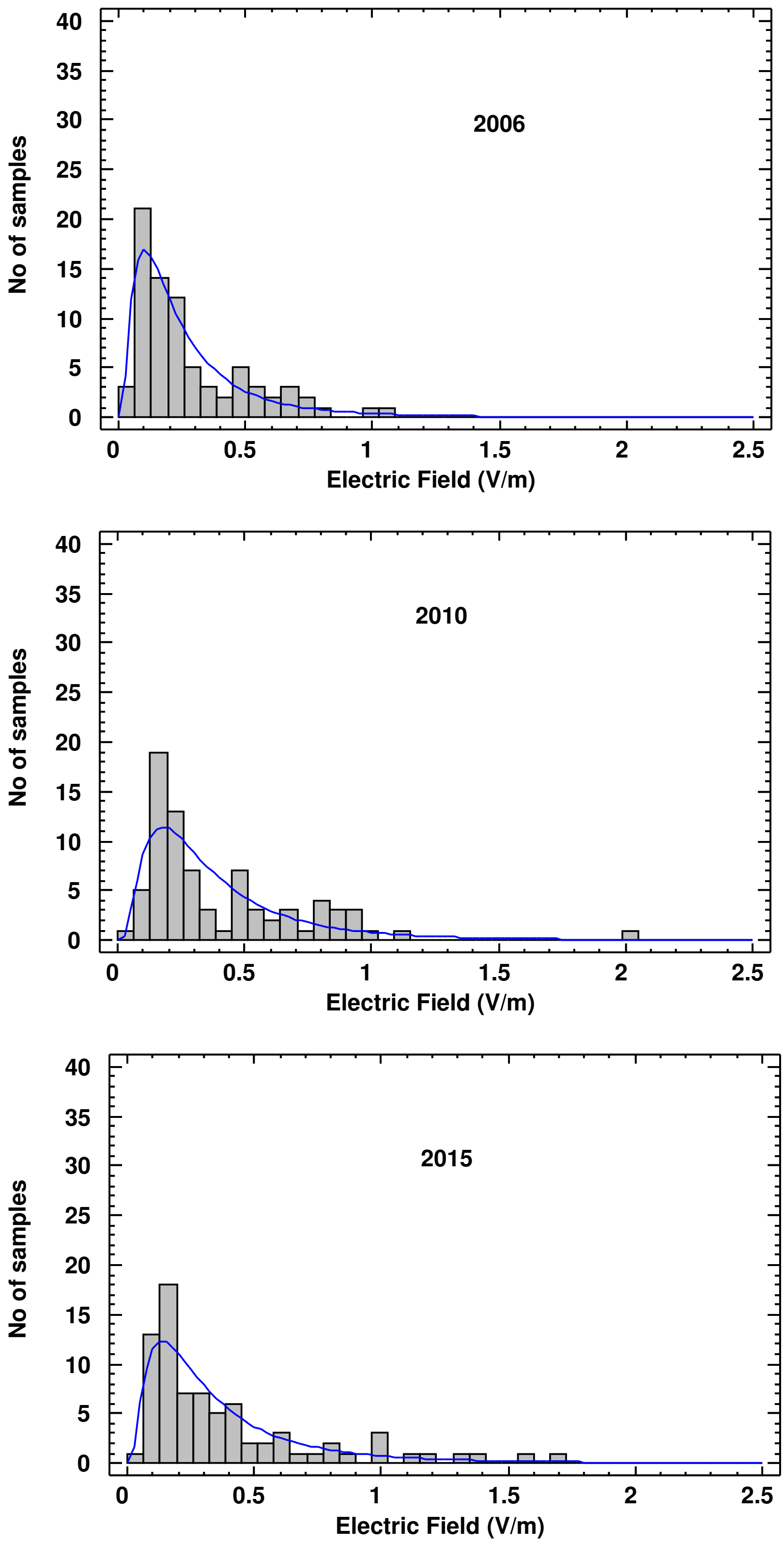
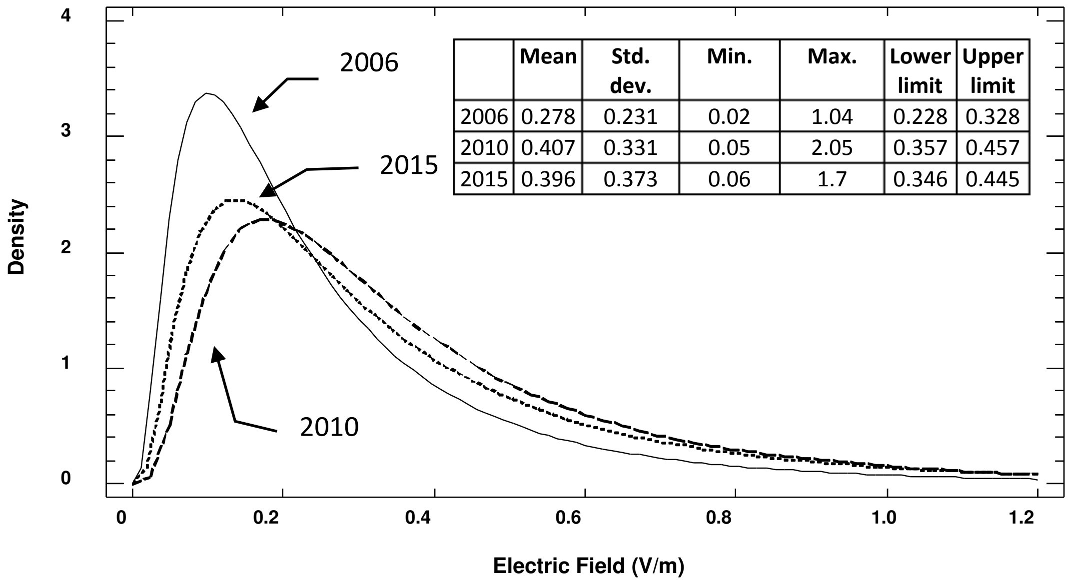


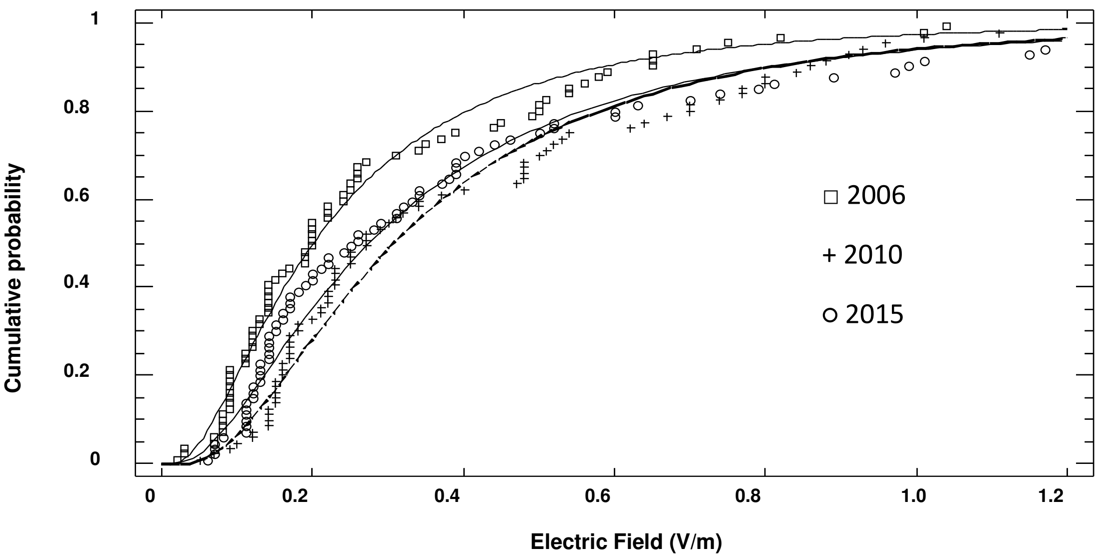
Figure 3. Distribution of the electric field measured values in 2006, 2010 and 2015.

The main statistical values for the period under study are shown in figure 4. In 2006, the values were ranging from 0.02 to 1.04 V/m. In 2010, the values were ranging from 0.05 to 2.05 V/m and finally, in 2015, the values were ranging from 0.06 to 1.7 V/m. The mean values for each period were 0.277 V/m, 0.406 V/m and 0.395 V/m respectively. These results show a moderate increase from 2006 to 2010 and they are almost invariant from 2010 to 2015. The lower and upper limits given in figure 4.a show the limits of the deviation of the 95 percent confidence interval.



	Mean	Std. dev.	Min.	Max.	Lower limit	Upper limit
2006	0.278	0.231	0.02	1.04	0.228	0.328
2010	0.407	0.331	0.05	2.05	0.357	0.457
2015	0.396	0.373	0.06	1.7	0.346	0.445

(a)



(b)

Figure 4. Comparison and main statistical values of Electric field strength density functions (a) and cumulative probability functions (b) over the period 2006 to 2015.

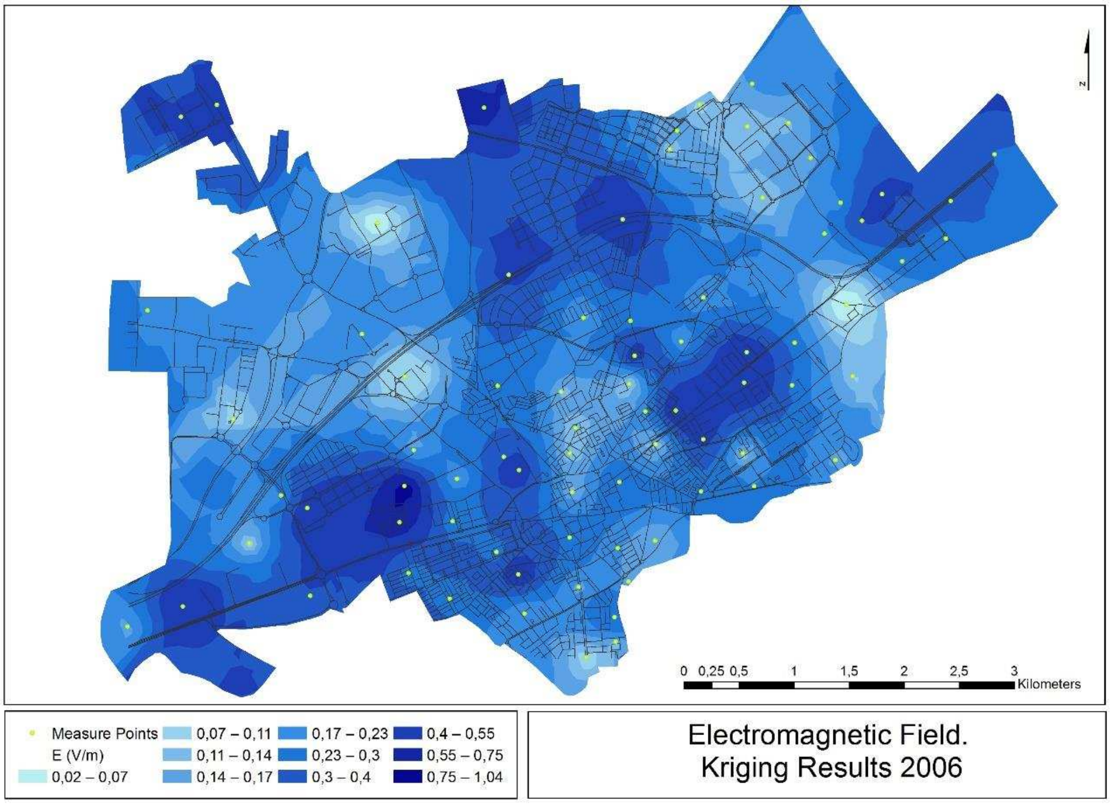
Figure 4.a shows a comparison of the density functions for the period under study. As can be seen, the values have increased from 2006 to 2010 or to 2015 but they have kept almost constant from 2010 to 2015. Figure 4.b shows the cumulative probability function for the same period. The statistical comparison between 2006 and 2010 gives a p-value of 0.0018 and the

comparison between 2006 and 2015 gives a value of 0.0000. Oppositely, the comparison between 2010 and 2015 gives a value of 0.3005. This means that there is a statistical difference between 2006 and 2010 or 2015, but there is not a difference between 2010 and 2015. In other terms, there is not significant difference between the exposure levels in 2010 and 2015.

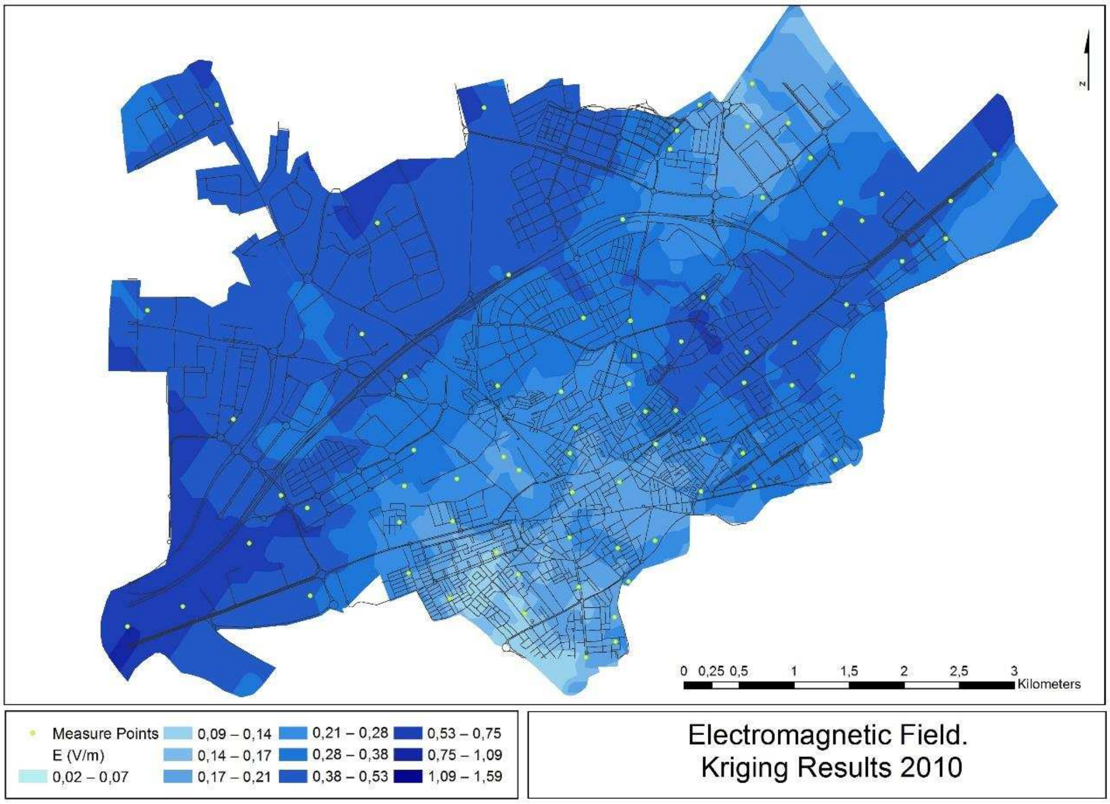
For a better understanding, the values have been represented on a map for the different measurement campaigns. Different types of interpolation have been tested as shown in table 5. Stable kriging gives the best results for 2006 dataset. The error is also the lowest for 2010 and 2015 datasets. For clarity, the RMS error is only given for the stable ordinary kriging in 2010 and 2016. The results of the spatial variations for the period under study are presented in figure 5. According to the aforementioned results, the stable kriging interpolation method has been used to plot the colour maps.

Dataset	**Interpolation**	**RMS error**
2006	Radial Basis Functions	0.240
2006	IDW	0.247
2006	Spherical ordinary kriging	0.237
2006	Kbessel ordinary kriging	0.235
2006	Jbessel ordinary kriging	0.235
2006	Gaussian ordinary kriging	0.236
2006	Circular ordinary kriging	0.238
2006	**Stable ordinary kriging**	**0.234**
2010	**Stable ordinary kriging**	**0.292**
2015	**Stable ordinary kriging**	**0.341**

Table 5. RMS error for different interpolation techniques.



Electromagnetic Field.
Kriging Results 2006



Electromagnetic Field.
Kriging Results 2010

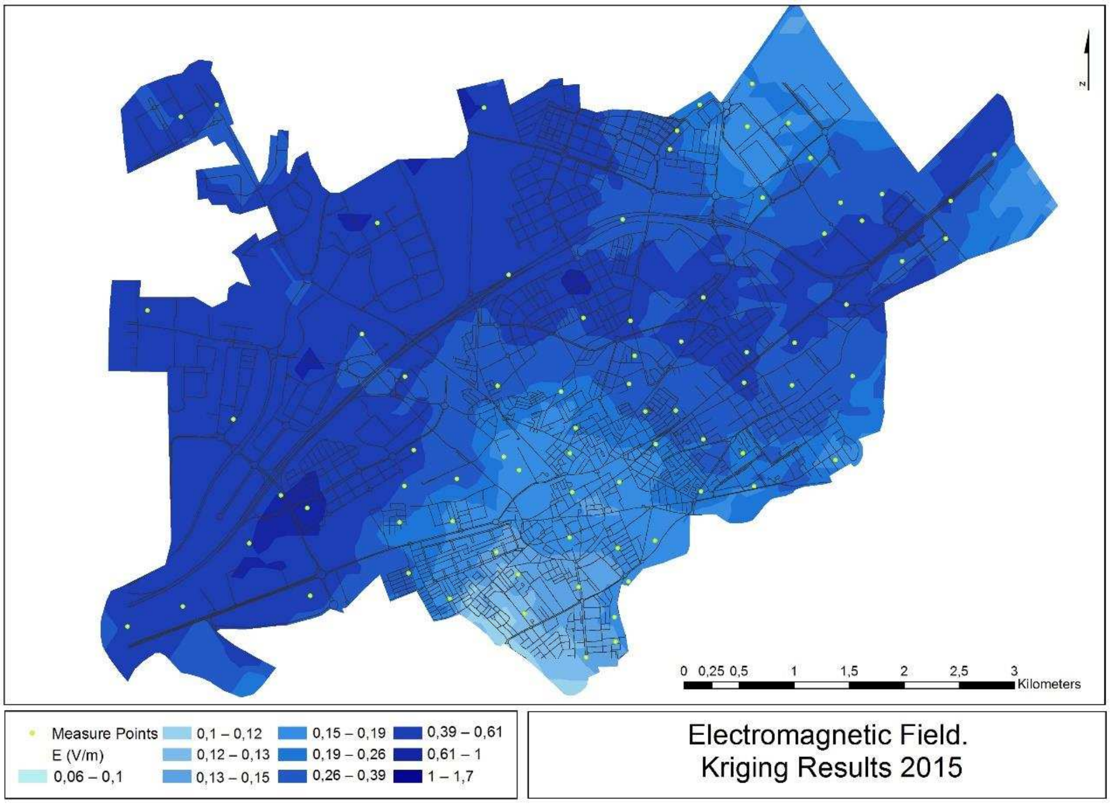


Figure 5. Electric Field levels spatial variation in 2006, 2010 and 2015.

3.2 Local trends

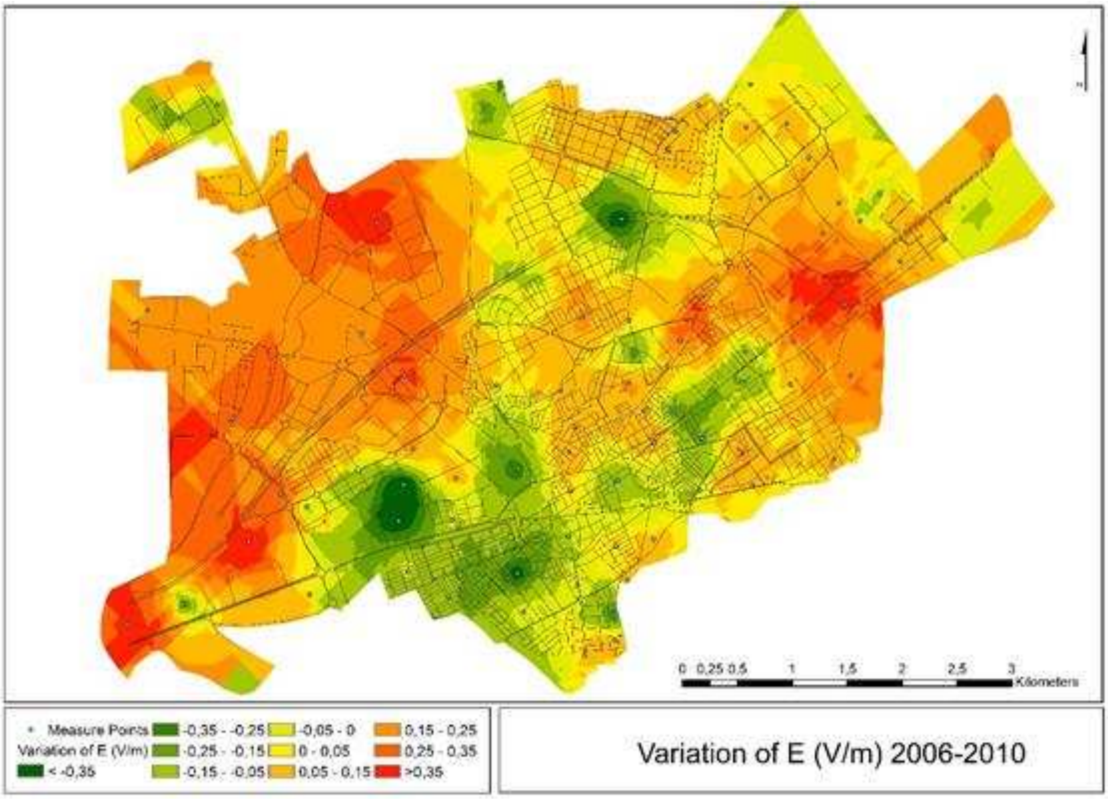
As mentioned in the previous section, if we consider the entire annual datasets for 2010 and 2015 there is negligible statistical difference between them. Despite this general trend, from figure 5 we can see significant local variations within the districts of Alcalá de Henares over the period of this study. Districts I and II (see Fig. 2) correspond to the city centre and other areas that have consistent populations (from Table 1). Conversely, new urban and industrial developments were carried out in districts III, IV and V.

Table 6 shows the mean electric field values measured over the five central districts of Alcalá de Henares. These mean values have been calculated by simply averaging the measured values for that district. The number of measured points is also shown. It can be seen that for the city centre districts the mean values of the electric field strength have remained constant or decreased during the period 2006-2015. For the other districts, new developments have necessitated new infrastructure and resources which have led to an overall increase in the measured electric field levels.

Using ArcGIS Maps Algebra tool, we have obtained the difference between each pair of maps plotted in figure 5. These variations in measured electric field strength are shown in figure 6. The green regions on these maps represent areas where the electric field values have decreased during the period under study. Conversely, areas shown in red represent areas where the electric field values are higher than in the previous measurement. Yellow zones represent areas where the electric field strength remains unchanged. The results presented in figure 6 emphasise that the mean electric field strength has increased (mainly red) in the newly developed areas around the motorway (districts II, IV and V), while in the city centre (districts I and II) the levels have decreased (predominantly green).

District of Alcalá de Henares (no. of measurement locations)	**Electric field strength (V/m)**		
	2006	**2010**	**2015**
D. I (14)	0.231	0.302	0.196
D. II (19)	0.334	0.365	0.290
D. III (15)	0.335	0.465	0.613
D. IV (17)	0.224	0.439	0.460
D. V (13)	0.249	0.512	0.430
Total (78)	0.278	0.407	0.396

Table 6. Mean values of Electric Field strength (V/m) in the different districts of Alcalá de Henares.



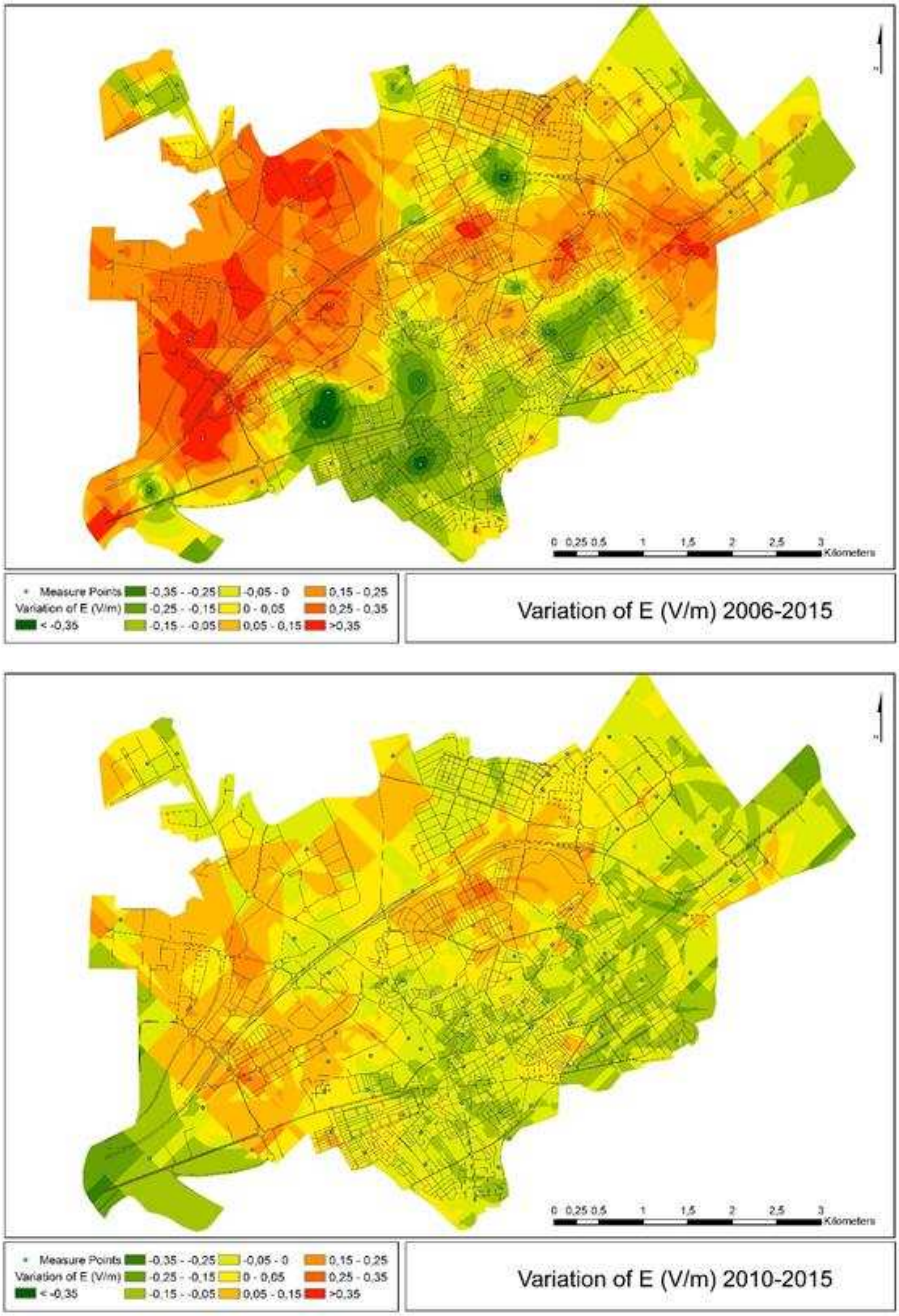


Figure 6. Difference plot showing the variation in Electric Field strength spatial variation between 2006 and 2010, 2010 and 2015 and 2006 and 2015. Green shows a decrease in E-field strength over time, red shows an increase in E-field strength over time.

4. DISCUSSION

The main strengths of this study are its measurement-based design, its long term data collection, and its numerous measurements representing a very wide urban area (35 km^2). Broadband frequency measurements have been performed from 100 kHz to 3 GHz according to national and international regulations using a 6-minute averaging period. Their locations have been kept constant throughout the study. This kind of broadband measurement is suitable for public exposure assessment and is in accordance with Spanish exposure Regulations (BOE, 2001) and the ICNIRP guidelines on which they are based (ICNIRP, 1998).

An objective of this work was to determine whether the general public exposure follows the current trend of the increasing use of the radio spectrum or, to the contrary that values have remained constant or have reduced through the adoption of newer digital communications standards. Official statistical data shows a greater use of the radio electric spectrum for television and especially for mobile phones and wireless technologies. The number of BTS located in Alcalá de Henares has been doubled in the period 2006 to 2015. At the same time, significant technological changes have been introduced and widely adopted. In 2006, the measured electric field values for the city ranged from 0.02 to 1.04 V/m, in 2010 this increased to between 0.05 to 2.05 V/m and finally, in 2015 the values ranged from 0.06 to 1.7 V/m. For the whole dataset these results show a moderate increase from 2006 to 2010 and they are almost invariant from 2010 to 2015. This general tendency is largely consistent with the increase of radio resources from 2006.

Conversely, there are local variations that do not follow this rule. The city centre and other areas that have remained more or less unchanged for the period under study (districts I and II), have reduced their mean values. This probably suggests that in spite of the increased use of mobile resources and the number of BTS, the technological evolution has helped to maintain or even reduce the electric field levels. Other factors may have influenced this such as changes of frequency planning or BTS locations. A greater density of measurements in these districts to create a higher spatial resolution study could help to identify other underlying reasons. New urban and industrial developments were carried out within districts III, IV and V and this has lead to an increase in the measured electric field levels. It obviously indicates a human influence in the increase of the exposure levels.

One limitation of this study is the restriction of the measurements to an outdoor urban environment at ground level. Although measurements performed at around 1.5m from the ground in open areas that are also free from any electromagnetic shielding, comply with ITU-T K.61 (ITU, 2003), it can be difficult to find suitable locations within a busy city. Indoor exposure levels might be more relevant for personal exposure assessment, especially as a large part of modern life is spent indoors - either at home or at work. Furthermore, data collected at ground level does not represent the spatial 3D variation of the electric field and therefore will not necessarily represent the exposure level for someone inside the 2nd or 3rd floor of a building.

5. CONCLUSIONS

This work considers the long term evolution of radio frequency electric field values from 2006 to 2015 for the city of Alcalá de Henares, Spain. This study has been based on 78 measurement locations across a 35 square kilometre area of the city, providing an average sample density of 2.2 points per square km. During the period considered, officially published statistical data shows a greater use of the radio electric spectrum for television and especially for mobile phones and wireless technologies. At the same time, significant technological changes have been introduced and widely adopted, such as the switch to digital television broadcasting and the proliferation of Wi-Fi. In 2006, the measured mean electric field value was 0.277 V/m, in 2010 this increased to 0.406 V/m and finally, in 2015 this was 0.395 V/m. The greatest increase in the exposure level of electric field strength occurred between 2006 and 2010. This general trend is largely consistent with the increase of radio resources at that time.

The statistical analysis of the measured data shows that it fits a lognormal distribution with a confidence greater than 95%. These results show a moderate increase of the global mean values from 2006 to 2010 and that they are almost invariant from 2010 to 2015. Using this statistical analysis, we can conclude that the probability of finding a value of 14 V/m (half of the prescribed public exposure limit) is less than 0.01% and the probability of finding a value of 28 V/m is negligible. This statistical approach is a valuable tool to evaluate wide areas from a reduced, but statistically valid, set of measurements. The measured values have been plotted on the city map using a Geographic Information System and this has revealed local variations during the period under study. In the areas of the city where the population has remained consistent and despite the higher use of the mobile and wireless services, the measured electric field values have remained constant or have even reduced more recently. In contrast, in the newly developed areas, where infrastructure and services have been introduced, the mean electric field value has increased.

This study only considers to the last ten years and unfortunately, there is no measurement data prior to 2006. This restricts us from making a comparison to the situation before mobile telephony was introduced. A narrowband measurement based study could help to a better understanding of the actual influence of the different sources (radio, TV, Mobile, WiFi etc) in the observed exposure values. The authors intend to continue and refine this work over the coming decades.

Conflicts of interest

There are no potential conflicts of interest related to this work. The authors have not received financial support to conduct this research, from public or private institutions or companies.

REFERENCES

Aerts, S., Deschrijver, D., Joseph, W., Verloock, L., Goeminne, F., Martens, L., Dhaene, T., 2013a. Exposure assessment of mobile phone base station radiation in an outdoor environment using sequential surrogate modeling. Bioelectromagnetics 34, 300–11. doi:10.1002/bem.21764

Aerts, S., Deschrijver, D., Verloock, L., Dhaene, T., Martens, L., Joseph, W., 2013b. Assessment of outdoor radiofrequency electromagnetic field exposure through hotspot localization using kriging-based sequential sampling. Environ. Res. 126, 184–191. doi:10.1016/j.envres.2013.05.005

ANSES, 2013. Opinion of the French Agency for Food, Environmental and Occupational Health & Safety concerning the update of the “Radiofrequency electromagnetic fields and health” expert appraisal.

Bechet, P., Miclaus, S., Bechet, A.C., 2015. An analysis of the dependence of the electromagnetic exposure level in indoor environment on traffic direction, instantaneous data rate and position of the devices in a WLAN network. Measurement 67, 34–41. doi:10.1016/j.measurement.2015.02.035

Beekhuizen, J., Vermeulen, R., Kromhout, H., Bürgi, A., Huss, A., 2013. Geospatial modelling of electromagnetic fields from mobile phone base stations. Sci. Total Environ. 445, 202–209. doi:10.1016/j.scitotenv.2012.12.020

Beekhuizen, J., Vermeulen, R., van Eijsden, M., van Strien, R., Bürgi, A., Loomans, E., Guxens, M., Kromhout, H., Huss, A., 2014. Modelling indoor electromagnetic fields (EMF) from mobile phone base stations for epidemiological studies. Environ. Int. 67, 22–6. doi:10.1016/j.envint.2014.02.008

Belpomme, D., Irigaray, P., & Hardell, L., 2008. Electromagnetic fields as cancer-causing agents. Environ. Res. 107, 289–290. doi:10.1016/j.envres.2008.01.017

BOE, 2014. Real Decreto 805/2014, de 19 de septiembre, por el que se aprueba el Plan Técnico Nacional de la Televisión Digital Terrestre y se regulan determinados aspectos para la liberación del dividendo digital.

BOE, 2002. Orden CTE/23/2002. por la que se establecen condiciones para la presentación de determinados estudios y certificaciones por operadores de servicios de radiocomunicaciones. s.l.

BOE, 2001. Real Decreto 1066/2001. por el que se aprueba el Reglamento que establece las condiciones de protección del dominio público, restricciones a las emisiones radioeléctricas y medidas de protección sanitaria frente a emisiones radioeléctricas. s.l.

Bolte, J.F.B., Eikelboom, T., 2012. Personal radiofrequency electromagnetic field measurements in the Netherlands: Exposure level and variability for everyday activities, times of day and types of area. Environ. Int. 48, 133–142. doi:10.1016/j.envint.2012.07.006

Bürgi, A., Scanferla, D., Lehmann, H., 2014. Time Averaged Transmitter Power and Exposure to Electromagnetic Fields from Mobile Phone Base Stations. Int. J. Environ. Res. Public Health 11, 8025–8037. doi:10.3390/ijerph110808025

Calvente, I., Fernández, M.F., Pérez-Lobato, R., Dávila-Arias, C., Ocón, O., Ramos, R., Ríos-Arrabal, S., Villalba-Moreno, J., Olea, N., Núñez, M.I., 2015. Outdoor characterization of radio frequency electromagnetic fields in a Spanish birth cohort. Environ. Res. 138, 136–143. doi:10.1016/j.envres.2014.12.013

CNMC, 2015. Telecommunications and Audiovisual Sector Economic Report 2015. Barcelona.

Danker-Hopfe, H., Dorn, H., Bolz, T., Peter, A., Hansen, M.-L., Eggert, T., Sauter, C., 2016. Effects of mobile phone exposure (GSM 900 and WCDMA/UMTS) on polysomnography based sleep quality: An intra- and inter-individual perspective. Environ. Res. 145, 50–60. doi:10.1016/j.envres.2015.11.011

ESRI, 2016. ArcGIS Online Help [WWW Document]. URL http://doc.arcgis.com/en/arcgis-

online/ (accessed 12.21.16).
Frei, P., Mohler, E., Neubauer, G., Theis, G., Bürgi, A., Fröhlich, J., Braun-Fahrländer, C., Bolte, J., Egger, M., Röösli, M., 2009. Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields. Environ. Res. 109, 779–785. doi:10.1016/j.envres.2009.04.015
Guxens, M., Vermeulen, R., van Eijsden, M., Beekhuizen, J., Vrijkotte, T.G.M., van Strien, R.T., Kromhout, H., Huss, A., 2016. Outdoor and indoor sources of residential radiofrequency electromagnetic fields, personal cell phone and cordless phone use, and cognitive function in 5–6 years old children. Environ. Res. 150, 364–374. doi:10.1016/j.envres.2016.06.021
HPA, 2012. Health Effects from Radiofrequency Electromagnetic Fields.
IARC, 2014. World Cancer Report 2014.
ICNIRP, 1998. Guideline, I. C. N. I. R. P.Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Heal. Phys 74, 494–522.
IEC, 2016. IEC Partners [WWW Document]. URL http://www.iec.ch/dyn/www/f?p=103:45:0 (accessed 12.21.16).
IEEE, 2006. IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. IEEE Std C95.1-2005 1–238.
IEEE, 2002. IEEE Std C95.3-2002, Recommended Practice for Measurements and Computations of Radio Frequency Electromagnetic Fields with Respect to Human Exposure to Such Fields, 100 kHz-300 GHz. IEEE Std C95.3-2002 (Revision IEEE Std C95.3-1991) 126. doi:10.1109/IEEESTD.2002.94226
INE, 2016. Instituto Nacional de Estadística [WWW Document]. URL http://www.ine.es/inebmenu/mnu_padron.htm (accessed 12.21.16).
International Electrotechnical Commission (IEC), 2016. IEC - TC 106 Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure [WWW Document].
ITU, 2015. K.113 : Generation of radiofrequency electromagnetic field level maps [WWW Document].
ITU, 2014. K.100 : Measurement of radio frequency electromagnetic fields to determine compliance with human exposure limits when a base station is put into service [WWW Document].
ITU, 2012. ITU-T K.91 Guidance for assessment, evaluation and monitoring of human exposure to radio frequency electromagnetic fields [WWW Document].
ITU, 2011. K.83 : Monitoring of electromagnetic field levels [WWW Document].
ITU, 2003. K.61 : Guidance to measurement and numerical prediction of electromagnetic fields for compliance with human exposure limits for telecommunication installations [WWW Document].
Joseph, W., Frei, P., Roösli, M., Thuróczy, G., Gajsek, P., Trcek, T., Bolte, J., Vermeeren, G., Mohler, E., Juhász, P., Finta, V., Martens, L., 2010. Comparison of personal radio frequency electromagnetic field exposure in different urban areas across Europe. Environ. Res. 110, 658–663. doi:10.1016/j.envres.2010.06.009
Martens, A.L., Bolte, J.F.B., Beekhuizen, J., Kromhout, H., Smid, T., Vermeulen, R.C.H., 2015. Validity of at home model predictions as a proxy for personal exposure to radiofrequency electromagnetic fields from mobile phone base stations. Environ. Res. 142, 221–226. doi:10.1016/j.envres.2015.06.029
MINETAD, 2016. Niveles de Exposición [WWW Document]. URL http://www.minetad.gob.es/telecomunicaciones/Espectro/NivelesExposicion/Paginas/niveles.aspx (accessed 12.21.16).
Naoum S. and Tsanis I.K., 2004. Ranking spatial interpolation techniques using a GIS-based DSS | Global NEST Journal. Glob. NEST J. 6, 1–20.
Norwegian Institute of Public Health, 2012. Low-level radiofrequency electromagnetic fields –

an assessment of health risks and evaluation of regulatory practice.
Röösli, M., 2008. Radiofrequency electromagnetic field exposure and non-specific symptoms of ill health: A systematic review. Environ. Res. 107, 277–287. doi:10.1016/j.envres.2008.02.003
Röösli, M., Frei, P., Bolte, J., Neubauer, G., Cardis, E., Feychting, M., Gajsek, P., Heinrich, S., Joseph, W., Mann, S., Martens, L., Mohler, E., Parslow, R.C., Poulsen, A.H., Radon, K., Schüz, J., Thuroczy, G., Viel, J.-F., Vrijheid, M., Neubauer, G., Feychting, M., Hamnerius, Y., Kheifets, L., Kuster, N., Ruiz, I., Schüz, J., Überbacher, R., Wiart, J., Röösli, M., Blettner, M., Schlehofer, B., Breckenkamp, J., Kowall, B., Schmiedel, S., Reis, U., Potthoff, P., Schüz, J., Berg-Beckhoff, G., Schreier, N., Huss, A., Röösli, M., Schröttner, J., Leitgeb, N., Vrijheid, M., Armstrong, B., Bedard, D., Brown, J., Deltour, I., Iavarone, I., Krewski, D., Lagorio, S., Moore, S., Richardson, L., Vrijheid, M., Cardis, E., Armstrong, B., Auvinen, A., Berg, G., Blaasaas, K., Brown, J., Carroll, M., Chetrit, A., Christensen, H., Hutter, H., Moshammer, H., Wallner, P., Kundi, M., Preece, A., Georgiou, A., Dunn, E., Farrow, S., Bornkessel, C., Schubert, M., Wuschek, M., Schmidt, P., Neitzke, H., Osterhoff, J., Peklo, K., Voigt, H., Schmiedel, S., Bruggemeyer, H., Philipp, J., Wendler, J., Merzenich, H., Schuz, J., Schüz, J., Mann, S., Viel, J., Clerc, S., Barrera, C., Rymzhanova, R., Moissonnier, M., Hours, M., Cardis, E., Breckenkamp, J., Neitzke, H., Bornkessel, C., Berg-Beckhoff, G., Frei, P., Mohler, E., Neubauer, G., Theis, G., Bürgi, A., Fröhlich, J., Braun-Fahrländer, C., Bolte, J., Egger, M., Röösli, M., Joseph, W., Verloock, L., Martens, L., Radon, K., Spegel, H., Meyer, N., Klein, J., Brix, J., Wiedenhofer, A., Eder, H., Praml, G., Schulze, A., Ehrenstein, V., Thomas, S., Kühnlein, A., Heinrich, S., Praml, G., Nowak, D., Kries, R. von, Radon, K., Thomas, S., Kühnlein, A., Heinrich, S., Praml, G., Kries, R. von, Radon, K., Thuróczy, G., Molnár, F., Jánossy, G., Nagy, N., Kubinyi, G., Bakos, J., Szabó, J., Viel, J., Cardis, E., Moissonnier, M., Seze, R. de, Hours, M., Knafl, U., Lehmann, H., Riederer, M., Person, C., Toutain, Y., Hénaff, M. Le, Toutain, G., Bolte, J., Pruppers, M., Kramer, J., Zande, G. Van der, Schipper, C., Fleurke, S., Kluwer, T., Kamp, I. Van, Kromhout, J., Joseph, W., Vermeeren, G., Verloock, L., Heredia, M., Martens, L., Bürgi, A., Frei, P., Theis, G., Mohler, E., Braun-Fahrländer, C., Fröhlich, J., Neubauer, G., Egger, M., Röösli, M., Neubauer, G., Cecil, S., Giczi, W., Petric, B., Preiner, P., Fröhlich, J., Röösli, M., Neubauer, G., Prince, J.A., Fröhlich, J., Frei, P., Mohler, E., Bürgi, A., Theis, G., Braun-Fahrländer, C., Egger, M., Röösli, M., Helsel, D., Röösli, M., Frei, P., Mohler, E., Braun-Fahrländer, C., Bürgi, A., Frohlich, J., Neubauer, G., Theis, G., Egger, M., Kühnlein, A., Heumann, C., Thomas, S., Heinrich, S., Radon, K., Gati, A., Hadjem, A., Wong, M., Wiart, J., Frei, P., Mohler, E., Bürgi, A., Fröhlich, J., Neubauer, G., Braun-Fahrländer, C., M, atQ-t R., Röösli, M., Regel, S., Gottselig, J., Schuderer, J., Tinguely, G., Retey, J., Kuster, N., Landolt, H., Achermann, P., Vermeeren, G., Joseph, W., Olivier, C., Martens, L., 2010. Conduct of a personal radiofrequency electromagnetic field measurement study: proposed study protocol. Environ. Heal. 9, 23. doi:10.1186/1476-069X-9-23
Sagar, S., Struchen, B., Finta, V., Eeftens, M., Röösli, M., 2016. Use of portable exposimeters to monitor radiofrequency electromagnetic field exposure in the everyday environment. Environ. Res. 150, 289–298. doi:10.1016/j.envres.2016.06.020
Statpoint Technologies, 2009. Statgraphics [WWW Document]. STATGRAPHICS® CENTURION XVI USER Man. URL http://www.statgraphics.com/resources-downloads (accessed 12.21.16).
Stewart, B., Wild, C.P., (Eds), 2014. IARC Publications Website - World Cancer Report 2014.
Thuróczy, G., Molnár, F., Jánossy, G., Nagy, N., Kubinyi, G., Bakos, J., Szabó †, J., 2008. Personal RF exposimetry in urban area. Ann. Telecommun. - Ann. des télécommunications 63, 87–96. doi:10.1007/s12243-007-0008-z
Urbinello, D., Huss, A., Beekhuizen, J., Vermeulen, R., Röösli, M., 2014a. Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of Basel and Amsterdam. Sci. Total Environ. 468–469, 1028–33.

doi:10.1016/j.scitotenv.2013.09.012
Urbinello, D., Joseph, W., Huss, A., Verloock, L., Beekhuizen, J., Vermeulen, R., Martens, L., Röösli, M., 2014b. Radio-frequency electromagnetic field (RF-EMF) exposure levels in different European outdoor urban environments in comparison with regulatory limits. Environ. Int. 68, 49–54. doi:10.1016/j.envint.2014.03.007
Urbinello, D., Joseph, W., Verloock, L., Martens, L., Röösli, M., 2014c. Temporal trends of radio-frequency electromagnetic field (RF-EMF) exposure in everyday environments across European cities. Environ. Res. 134, 134–142. doi:10.1016/j.envres.2014.07.003
Vermeeren, G., Markakis, I., Goeminne, F., Samaras, T., Martens, L., Joseph, W., 2013. Spatial and temporal RF electromagnetic field exposure of children and adults in indoor micro environments in Belgium and Greece. Prog. Biophys. Mol. Biol. 113, 254–263. doi:10.1016/j.pbiomolbio.2013.07.002
Viel, J.-F., Tiv, M., Moissonnier, M., Cardis, E., Hours, M., 2011. Variability of radiofrequency exposure across days of the week: A population-based study. Environ. Res. 111, 510–513. doi:10.1016/j.envres.2011.02.015
Vrijheid, M., Mann, S., Vecchia, P., Wiart, J., Taki, M., Ardoino, L., Armstrong, B.K., Auvinen, A., Bédard, D., Berg-Beckhoff, G., Brown, J., Chetrit, A., Collatz-Christensen, H., Combalot, E., Cook, A., Deltour, I., Feychting, M., Giles, G.G., Hepworth, S.J., Hours, M., Iavarone, I., Johansen, C., Krewski, D., Kurttio, P., Lagorio, S., Lönn, S., McBride, M., Montestrucq, L., Parslow, R.C., Sadetzki, S., Schüz, J., Tynes, T., Woodward, A., Cardis, E., 2009. Determinants of mobile phone output power in a multinational study: implications for exposure assessment. Occup. Environ. Med. 66, 664–71. doi:10.1136/oem.2008.043380